The magnetite colloidal crystal in the meteorite formed 4.6 billion years ago

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1. Introduction

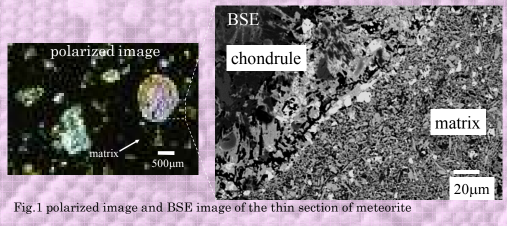


Fig.1 polarized image and BSE image of the thin section of meteorite

Meteorite matrix have preserved information on the early solar system (Fig. 1). To date, most of researches investigating the meteorites have been focused on mineralogy, measuring the chemical compositions, isotopic ratios and so on.
In the present work, detailed observation was carried out on the magnetite with highly ordered three dimensional, namely colloidal crystals. As is the case with crystal surface or morphology, these aggregates structures also reflected environment in which they formed in the parentbody. Investigating these objects from the view point of the colloidal science and crystal growth, we will provide new valuable information to the planetary science.

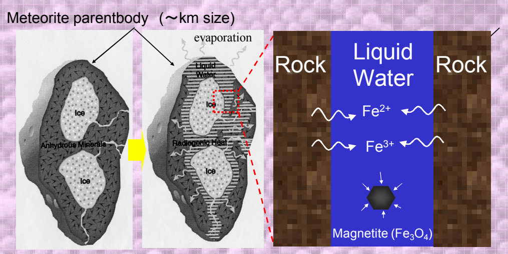
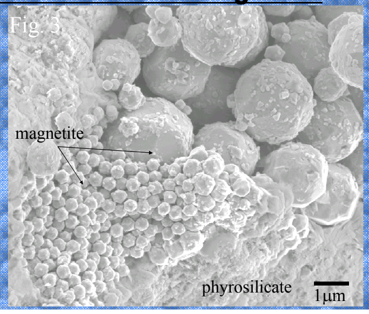


Fig. 2 The model of aqueous alteration on the meteorite parentbody. (Rosenberg et al., 2001)

Fig. 2 shows model of aqueous alteration process in meteorite parentbody (Rosenberg et al., 2001). Radiogenic heat melted ice to water, in which nucleation and aggregation of fine magnetite particles took place.

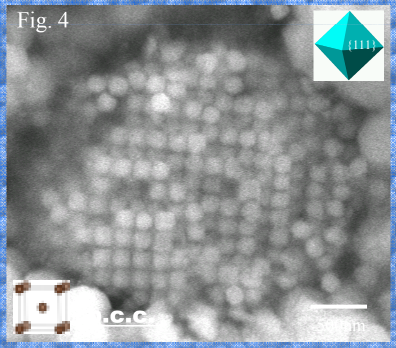
2. Observations and Discussion

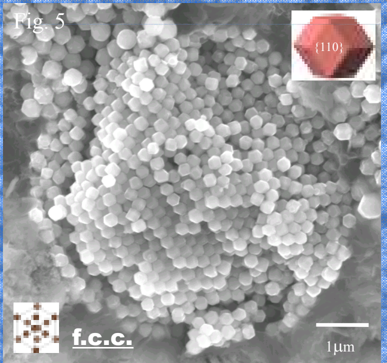
2-1 Occurrence of Magnetite



Tagish Lake carbonaceous chondrite has porous structure and magnetite (Fe_3O_4) fine particles are found frequently in those interstices of matrix (Fig. 3). These magnetite particles were formed when aqueous alteration took place. Such as olivine and pyroxene were altered to phyrosilicates.

2-2 Lattice structure of colloidal crystals





Although magnetite particles usually appear randomly in the matrix (e.g. Fig. 3), there are areas where the size of particles is uniform. Furthermore, they are aligned in a regular periodic 3D structure, and form colloidal crystals. We could observe several types of colloidal crystals in this meteorite. Fig. 4 is one with b.c.c. (body centered cubic) lattice structure comprised by 150nm particles. Fig. 5 is one with f.c.c (face centered cubic) lattice structure comprised by 200nm particles.

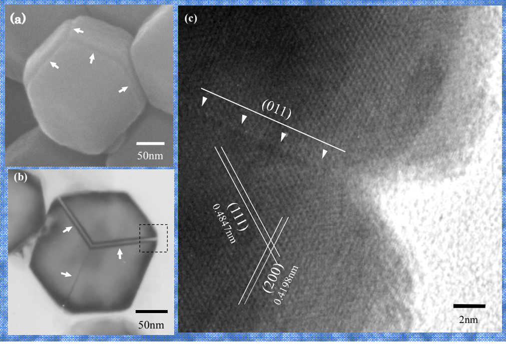
Fig. 6 is the colloidal crystal with f.c.c. and h.c.p.(hexagonal close packing) lattice structure comprised by 600nm particles. The f.c.c. and h.c.p. structure could not distinguish by the applied observation method.

Fig. 7

morphology of particles	diameter of particles [nm]	lattice structure of colloidal crystal
{111}	182 ± 6	BCC
{110}	207 ± 3	FCC
{311} {110} {100}	657 ± 20	FCC

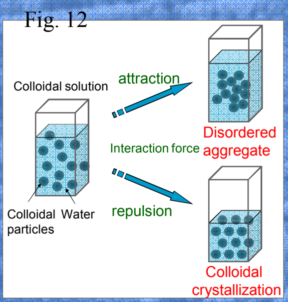
Fig. 7 shows the relationship of the lattice structure of the colloidal crystal and the morphologies and size of the particles. It was found that the size or morphology of the particles determine the lattice structure of colloidal crystal.

2-3 Characteristics of Rhombic dodecahedron particles



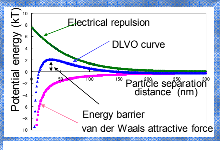
The particles of the colloidal crystal of Fig. 5 is only formed by {110} faces, so it forms rhombic dodecahedron. Fig. 8 indicates why the colloidal crystal can only form f.c.c. structure. It is interesting to note that this particle has the depressed area on certain edge (arrows in Fig. 9 (a),(b)). HR-TEM investigations of the depressed edge exposed mismatch of lattice, which could result in the boundaries of the crystals (c). These morphologies and structures are similar to those of multiple twin particles.

2-4 How to form the colloidal crystals?

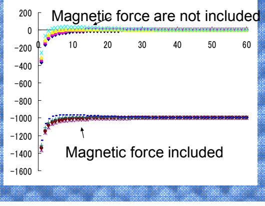


One of the characteristics of the colloidal crystal is the interaction force between the particles are repulsion. If the interaction force are attractive, particles form the flocculation (Fig. 12).

2-5 DLVO curve of magnetite



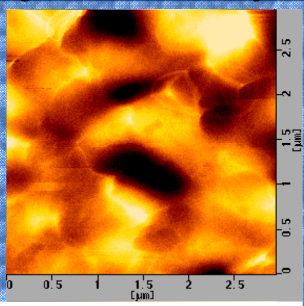
DLVO curve･･･ sum of the van der Waals attraction and the electrostatic repulsion.
$V = V_A + V_R$



size = 200nm (most common size in this meteorite)
Debye length κ^{-1}= 10nm (Stumm and Morgan, 1981)
Zeta potential ζ= -40～40mV (Zhong-Xi et al., 1998)

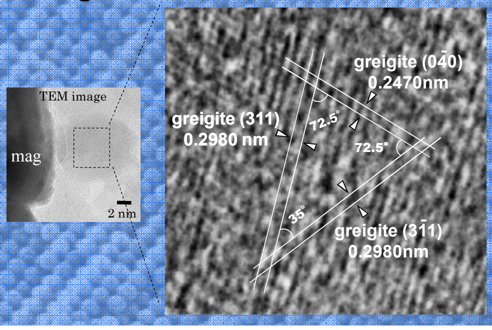
DLVO curve of the magnetite in the pure water indicate always large attractive force within the 100nm of particle distance. However, it requires more than 5-10 kT of the energy barrier to keep the particles dispersed, magnetic force enable to achieve this value.

2-6 MFM Measurement of magnetite colloidal crystals



Magnetite has magnetic moment when its diameter is bigger than few nm. Magnetic Force Microscopy (MFM) measurement to the magnetite colloidal crystals was carried out. The orientation of the magnetic moment of the magnetite particles found to be random. If the colloidal crystal had formed by magnetic force in the solution, each magnetic orientation must be align, and north pole of one particles contact with south pole of neighbor particles.

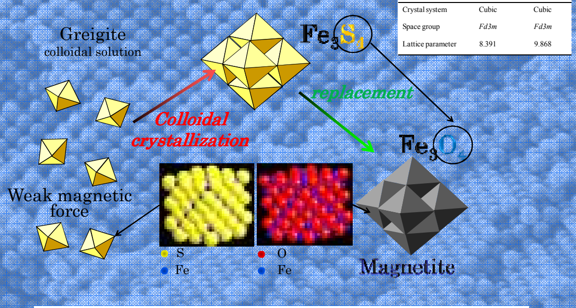
2-7 The Greigite occurs together with magnetite



EDS measurement to magnetite colloidal crystal detects not only Fe and O but also S. Analyzing the high resolution TEM image, these were identified to greigite which is composed by few nm sizes crystalline. The magnetite particles accompany with the greigite in most cases, which indicate the greigite have deep relation in generation of magnetite.

2-8 Possible formation mechanism of magnetite colloidal crystal

	Magnetite	Greigite
Crystal system	Cubic	Cubic
Space group	*Fd3m*	*Fd3m*
Lattice parameter	8.391	9.868



Schematic diagram of the possible formation mechanism of magnetite colloidal crystal. At first, greigite which has weak magnetic force has formed. Then, they dispersed in the solution, and form colloidal crystals. Finally, replacement of S to O makes magnetite particles.

3. Conclusions

Well arranged colloidal crystals of magnetite were found in Tagish Lake meteorites.

These colloidal crystals were classified into several types by it's lattice structure, b.c.c., f.c.c., and h.c.p.. These structures found to be depending on the morphology of the constituent particles.

The morphology bounded only by {110} face was not expected considering its crystallographic structure. HR-TEM observation revealed these are multiple-twin particles.

To form magnetite colloidal crystals in the meteorite other materials which has not or no magnetic force, such as greigite, must nucleate firstly.

4. References

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