吸収・位相トモグラフィーによるMIL090657隕石マトリクスの3次元観察

3D-observation of matrix of MIL 090657 meteorite by absorption-phase tomography

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MIL 090657隕石(CR2.7)は水質変成をほとんど受けていない始原的な炭素質コンドライトの一つであり[1]，Paris隕石[2]と並んで，マトリクス中に彗星塵に特徴的に含まれるGEMS（glass with embedded metal and sulfide）に類似した非晶質珪酸塩が報告されている．これまでに，この隕石のマトリクスには，サブミクロンサイズの粒状珪酸塩からなる岩相(岩相1)，GEMSに類似した非晶質珪酸塩からなる岩相(岩相2)，層状珪酸塩をもつ岩相(岩相3)が報告されており，岩相1，2には豊富な有機物も存在している[3,4]．また、岩相1，2は組成や組織の違いによってそれぞれ2種類のサブタイプに細分できる[5]．このような様々な岩相の構成物やそれらの隣接関係を明らかにすることは，原始太陽系星雲や小天体の集積・変成過程を考える上で重要である．

これまでの研究ではSEMやTEMによる2次元観察に限られていたが，本研究では様々な岩相の構成物やそれらの隣接関係を３次元的に明らかにするために，2種類のCT法（DET[6]，SIXM[7]）を用いたMIL 090657隕石マトリクスの観察を行った．DET（dual-energy micro tomography）は，2種類のX線エネルギーでの吸収コントラストから鉱物種を識別する方法であり，SIXM（scanning-imaging x-ray microscopy）は，位相コントラスト像と吸収コントラスト像の同時撮影から有機物のような軽元素からなる物質を識別できる.両者を組み合わせることで、有機物や空隙だけでなく，層状珪酸塩や炭酸塩などの水質変成物の識別も可能となる[8].

本研究では、MIL 090657隕石マトリクスの欠片（~100μm）を樹脂埋めしたpotted buttをFE-SEM/EDSにより詳細に観察・分析し，その結果をもとにして，FIB（FEI Helios NanoLab G3 CX）を用いて岩相1，2及びその境界から３個のCT用試料（約30-50μmサイズのハウス型、以降H1，H3，H5と呼ぶ）を作成した．CT撮影は，放射光施設SPring-8のBL47XUにおいて，DETによる7 keV，8 keVでの撮影（画素サイズ：~40及び~80 nm）と，SIXMによる撮影（8 keV，画素サイズ：~100 nm，H3のみ）を行った．

この結果，岩相1，2の他に，H1，H3から新たに岩相4, 5, 6を発見した．岩相4，5，6のマトリクスは主に鉄の含有量の異なる層状珪酸塩で構成されると考えられる．岩相4には硫化鉄やフランボイダルマグネタイトが見られた．岩相5はマグネタイトや炭酸塩を，岩相6はクラックを持つ無水珪酸塩を内部に含んでいた．岩相1，2，4，５には空隙が多く，岩相6にはほとんど空隙は観察されなかった．岩相4は岩相1と接しており，境界の見分けはつきにくい．岩相2，5，6は互いに隣接し，特に岩相6は他の岩相との境界がはっきりしていた．岩相1と岩相2の境界領域を含むH5中には，その両方に金属鉄や輝石などの大きな粒子（5~10μm）が存在し，岩相1と2の境界は3次元的にもシャープではなかった．

以上のように，３次元観察により多様な岩相が新たに見出され，MIL 090657隕石は複雑な集積・変成過程を経たことが推察される．水質変成に弱い非晶質珪酸塩をもつ岩相2は最も始原的であり，岩相2と層状珪酸塩からなる岩相（岩相5，6）が接していることは，岩相5，6が水質変成後に岩相2とともに集積したものと考えられる．一方，岩相1と2の境界は明瞭でなく，これらは共通の集積物であり、岩相１は弱い水質変成を受け、その後弱い熱変成[3]を受けた可能性が示唆される．

[1] Davidson et al. 2015, 46th LPSC, 1603. [2] Leroux et al. 2015, GCA, 170: 247-265. [3] Cao et al. 2016, 47th LPSC, 2427. [4] Sugimoto et al. 2016, Goldschmidt Workshop on Experimental Cosmochemistry, 15. [5] 杉本ほか. 2016, 日本鉱物科学会年会講演要旨集, 161. [6] Tsuchiyama et al. 2013, GCA, 116: 5-16. [7] Takeuchi et al. 2013, J. Synch. Rad., 20: 793-800. [8] Tsuchiyama et al. 2017, 48th LPSC, 2680.

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MIL 090657 meteorite (CR2.7) is one of the least altered primitive carbonaceous chondrites [1]. This meteorite has amorphous silicates like GEMS (glass with embedded metal and sulfide), which are characteristically contained in cometary dust, in matrix [2,3] as with the Paris meteorite [4]. Three lithologies have been recognized; lithology-1 (L1) dominated by submicron anhydrous silicates, lithology-2 (L2) by GEMS-like amorphous silicates and lithology-3 (L3) by phyllosilicates [2]. Organic materials are abundant in L1 and L2 [2,3]. L1 and L2 were further divided into sub-lithology respectively based on their textures and compositions [5]. These studies were performed by 2D SEM and TEM observations of sample surfaces and thin sections that are unable to reveal what constitute each lithology and how these lithologies are distributed and related to each other. This information will provide important insights into alteration and aggregation processes on asteroids and in the early solar nebula.
In this study, MIL 090657 matrix was examined in 3D using two types of X-ray tomography; DET (dual-energy tomography) [6] and SIXM (scanning-imaging X-ray microscopy) [7]. Mineral phases can be discriminated based on absorption contrasts at two different X-ray energies in DET. In SIXM, materials composed of light elements such as water or organic materials can be identified based on phase and absorption contrasts. By combining these methods, we can discriminate not only organic materials from voids but also hydrous alteration products, such as hydrated silicates and carbonates, from anhydrous minerals [8].
In this study, we first observed cross sections of MIL 090657 matrix fragments (~100 mm) in detail using FE-SEM/EDS. Based on the results, three house-shaped samples (30~50 mm) were extracted from L1, L2 and their boundary (H1, H3 and H5, respectively) using FIB. 3D imaging of these samples were conducted at BL47XU of SPring-8, a synchrotron radiation facility, with ~30-40 nm/voxel and ~70-80 nm/voxel at 7keV and 8keV in DET and ~100 nm/voxel at 8keV in SIXM.
We found new lithologies that we named L4, L5 and L6 in H1 and H3 in addition to L1 and L2. L4. L5 and L6 are mainly composed of probably phyllosilicates with different Fe contents. Sulfide and framboidal magnetite were recognized in L4. L5 includes magnetite and carbonate and L6 includes anhydrous silicates having cracks inside. L1, L2, L4 and L5 are porous while few voids were observed in L6. L4 adjoins to L1 with boundary, which is not very distinct. L2, L5 and L6 adjoin to each other, and the boundaries of L6 with L2 and L5 are clear. In H5, coarse mineral grains (~5-10 mm) such as Fe-metal and enstatite are present in L1 and L2. L1-L2 boundary is not sharp in 3D.
In conclusion, we found a variety of lithologies by 3D observation for the first time, suggesting that the MIL 090657 meteorite experienced complex alteration and aggregation histories. As L2 is dominated by amorphous silicates, which are extremely susceptible to aqueous alteration, this is presumed to be the most primitive lithology. The contact between L2 and phyllosilicate-bearing lithologies (L5 and L6) with clear boundaries indicates that they were aggregated after aqueous alteration of L5 and L6. The indistinct boundary between L1 and L2 is suggesting that these two lithologies might originally be the same aggregate composed of amorphous silicates and coarse mineral grains. L1 might have experienced weak aqueous alteration followed by mild thermal alteration [2], while L2 did not undergo aqueous alteration.

[1] Davidson et al. 2015, 46th LPSC, 1603. [2] Cao et al. 2016, 47th LPSC, 2427. [3] Sugimoto et al. 2016, Goldschmidt Workshop on Experimental Cosmochemistry, 15. [4] Leroux et al. 2015, GCA, 170: 247-265. [5] Sugimoto et al. 2016, JAMS Ann. Congr. Abstr., 161. [6] Tsuchiyama et al. 2013, GCA, 116: 5-16. [7] Takeuchi et al. 2013, J. Synch. Rad., 20: 793-800. [8] Tsuchiyama et al. 2017, 48th LPSC, 2680.

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