

## Electron Holography Reveals Nanometer Scale Magnetic Structure of Framboidal Magnetite and its Formation Process

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Small solar system bodies were formed as agglomerates of dust and ices 4.6 billion years ago. Several million years after asteroid formation [1], the ice melted due to radioactive heating inside the larger asteroids [2] and/or highly energetic impacts [3]. Then, water plays several major roles in the chemistry of asteroids, both in mineralization and in the formation of organic compounds. Currently, bulk liquid water no longer exists in meteorites. We see only the signature of water in ancient asteroids as veins of hydrothermally deposited minerals [4] or water trapped in salt crystals [5] in meteorites. The Tagish Lake meteorite, which is a unique Type 2 carbonaceous chondrite, has a signature of aqueous process in the matrix that is abundant micrometer-sized polyhedral particles of magnetite [6]. The framboids are three-dimensionally ordered colloidal crystals of magnetite nanoparticles. The uniformity of the size distribution and the similar morphology of the magnetite nanoparticles in each of the colloidal crystals suggest that they were formed through homogeneous nucleation from a highly supersaturated isolated solution in a single nucleation event.

Here we show evidence of how magnetite nanoparticles assembled into periodic structures based on a nanometer scale paleomagnetic method using electron holography in an examination of the framboidal magnetite in the Tagish Lake carbonaceous chondrite [7]. An attractive force such as magnetism never contributes to the formation of colloidal crystals [8], but the repulsive force caused by the surface charge of the magnetite is able to work. To overcome the repulsive force, the density of magnetite nanoparticles in a solution must be sufficiently high in an isolated solution as a water droplet parches in microgravity. We used electron holography to visualize the magnetization of the meteoritic minerals for the first time and found that magnetite grains in the framboid have no external magnetic force, i.e., they have a flux-closure vortex structure, which allowed the formation and preservation of the colloidal crystals. We conclude that these framboids formed in tiny water droplets with pH of 7-12 containing ions such as Ca<sup>2+</sup> and Mg<sup>2+</sup> at levels of 10<sup>-14</sup>-10<sup>-15</sup> mol m<sup>-2</sup>, just before exhaustion of water during thermal alteration in a hydrous asteroid.

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