

## DETERMINATION OF THE THREE-DIMENSIONAL MORPHOLOGY OF ALH84001 AND BIOGENIC MV-1 MAGNETITE: COMPARISON OF RESULTS FROM ELECTRON TOMOGRAPHY AND CLASSICAL TRANSMISSION ELECTRON MICROSCOPY;

Kathie L. Thomas-Keprta<sup>1,2</sup>, Simon J. Clemett<sup>1</sup>, Cindy Schwartz<sup>3</sup>, Mary Morphew<sup>3</sup>, J. Richard McIntosh<sup>3</sup>, Dennis A. Bazylinski<sup>4</sup>, Joseph L. Kirschvink<sup>5</sup>, Susan J. Wentworth<sup>1</sup>, David S. McKay<sup>6</sup>, Hojatollah Vali<sup>7</sup>, Everett K. Gibson, Jr.<sup>6</sup>, and Christopher S. Romanek<sup>8</sup>; <sup>1</sup>Lockheed Martin Space Operations, 2400 NASA Road 1, Mail Code C23, Houston, TX 77058 (kthomas@ems.jsc.nasa.gov), <sup>2</sup>Texas Southern University, 3100 Cleburne Ave., Houston, TX 77004, <sup>3</sup>Department of Molecular, Cellular & Developmental Biology, University of Colorado, Boulder, CO 80309, <sup>4</sup>Iowa State University, Department of Microbiology, 207 Science I, Ames, IA 50011, <sup>5</sup>California Institute of Technology, Division of Geological and Planetary Sciences, 1200 East California Boulevard, Pasadena, CA 91125, <sup>6</sup>NASA Johnson Space Center, Mail Code SN, Houston, TX 77058, <sup>7</sup>McGill University, Department of Earth and Planetary Sciences, 3450 University Street, Montreal, PQ H3A 2A7, Canada, and <sup>8</sup>Savannah River Ecology Laboratory, Drawer E, University of Georgia, Aiken, SC 29802.

**Introduction** Dated at ~3.9 billion years of age, carbonate disks [1], found within fractures of the host rock of Martian meteorite ALH84001, have been interpreted as secondary minerals that formed at low temperature [e.g., 2] in an aqueous medium [e.g., 3]. Heterogeneously distributed within these disks are magnetite nanocrystals that are of Martian origin. Approximately one quarter of these magnetites have morphological and chemical similarities to magnetite particles produced by magnetotactic bacteria strain MV-1 [4], which are ubiquitous in aquatic habitats on Earth. Moreover, these types of magnetite particles are not known or expected to be produced by abiotic means either through geological processes or synthetically in the laboratory. The remaining three-quarters of the ALH84001 magnetites are likely products of multiple processes including, but not limited to, precipitation from a hydrothermal fluid, thermal decomposition of the carbonate matrix in which they are embedded, and extracellular formation by dissimilatory Fe-reducing bacteria. We have proposed that the origins of magnetites in ALH84001 can be best explained as the products of multiple processes, one of which is biological.

Recently the three-dimensional (3-D) external morphology of the purported biogenic fraction of the ALH84001 magnetites has been the subject of considerable debate [6]. We report here the 3-D geometry of biogenic magnetite crystals extracted from MV-1 and of those extracted from ALH84001 carbonate disks using a combination of high resolution classical and tomographic transmission electron microscopy (TEM). We focus on answering the following questions: (1) which technique provides adequate information to deduce the 3-D external crystal morphology?; and, (2) what is the precise 3-D geometry of the ALH84001 and MV-1 magnetites?

**Methods** Both classical TEM imaging (procedure described in [4]) and electron tomography (procedure described in [7]) techniques have advantages and

disadvantages in the determination of the 3-D geometry of nano-crystals.

*Classical TEM imaging* yields the explicit crystallographic orientation associated with projected images yet provides only a few projected images typically with a limited tilt range (e.g.,  $\pm 45$  degrees).

*Electron tomography* supplies the complete image tilt sequences necessary for morphological reconstruction (e.g.,  $\pm 75$  degrees) yet provides little crystallographic information. Another drawback is that bright field electron tomography of magnetite is complicated by interference effects associated with strong Bragg diffraction which can limit the amount of useful information that can be extracted from the tomographic reconstruction. Since the desired result is defining only the convex hull of a magnetite crystal, limitations in bright field imaging can be resolved provided the crystal of interest is spatially isolated.

### Results and Conclusions

*MV-1 magnetites:* Twelve randomly selected single-domain MV-1 magnetites display a truncated hexa-octahedral geometry in both the full 3-D reconstruction (Fig.1A-D) and images of summed tomographic slices (Fig.1E-H). Variation in the expression of {111}, {110} and {100} faces is observed. While irregular morphologies have been observed in MV-1 magnetites within the pseudo-single domain and superparamagnetic size range, single-domain magnetites appear to exclusively display a truncated hexa-octahedral morphology.

*ALH84001 magnetites:* Tomographic analysis results include full 3-D reconstruction and images of summed tomographic slices. Results will be presented at this conference. Most of the ALH84001 magnetites, which were selected by classical TEM imaging for tomographic analysis, are indeed consistent with truncated hexa-octahedral geometry and display well-defined {110} and {100} faces. One magnetite that was interpreted to have a truncated hexa-octahedral

geometry using classical TEM imaging, however, was shown by tomography to be a slightly asymmetric octahedron instead. *This asymmetric magnetite clearly demonstrates a valuable lesson; i.e., there is a real potential for crystal morphology to be identified incorrectly if classical TEM imaging is the sole basis for morphological interpretation.*

**Summary** The use of *both* classical TEM imaging and electron tomography is necessary to unambiguously determine the external geometry of nano-magnetite crystals. The 3-D geometry of both MV-1 and a fraction of the ALH84001 magnetite crystals appear identical; both populations are consistent with

truncated hexa-octahedral geometry with well-defined  $\{110\}$  faces.

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**References:** [1] Borg, L.E. *et al.* (1999) *Science* **268**, 90; [2] Valley, J.W. *et al.* (1997) *Science* **275**, 1633. [3] Warren, P.H. (1998) *JGR-Planets* **103**, 16759. [4] Thomas-Keprta K.L. *et al.* (2002) *AEM*, **68**, 3663. [5] Thomas-Keprta, K. L. *et al.* (2001) *PNAS* **98**, 2164. [6] Golden D. C. *et al.* (2003) *LPSC XXXIV*, CD-ROM #1970. [7] Clemett, S. J. *et al.* (2002) *Amer. Min.* **87**, 1727.

Figure 1. Tomographic reconstruction of a single MV-1 crystal. (A-D) An idealized truncated hexa-octahedron, a reconstructed tomographic image, and an indexed color reconstruction of the same tomographic image where green surfaces correspond to  $\{111\}$  faces, blue correspond to  $\{100\}$  faces, and red correspond to  $\{110\}$  faces. Crystal is  $\sim 100$  nm in the longest direction. (E-F) Summed serial sections of a single MV-1 crystal when viewed down the  $[10\bar{1}]$  and  $[111]$  zone axes. (G-H) Summed serial sections of a second MV-1 crystal viewed along the same two zone axes described in E-F. Crystals in E-H are  $\sim 100$  nm in the longest direction.

