THREE-DIMENSIONAL MORPHOLOGICAL ANALYSIS OF ALH84001 MAGNETITE USING ELECTRON TOMOGRAPHY; Kathie L. Thomas-Keprta[1-2], Simon J. Clemett[1], Joel Shimmin[3], Mary Morphew[3], J. Richard McIntosh[3], Dennis A. Bazylinski[4], Joseph L. Kirschvink[5], Susan J. Wentworth[1], David S. McKay[6], Hojatollah Vali[7], Everett K. Gibson, Jr.[6], and Christopher S. Romanek[8]; [1]Lockheed Martin Space Operations, 2400 NASA Road 1, Mail Code C23, Houston, TX 77058 (kthomas@ems.jsc.nasa.gov), [2]Texas Southern University, 3100 Cleburne Ave., Houston, TX 77004, [3]Department of Molecular, Cellular & Developmental Biology, University of Colorado, Boulder, CO 80309, [4]Iowa State University, Department of Microbiology, 207 Science I, Ames, IA 50011, [5]California Institute of Technology, Division of Geological and Planetary Sciences, 1200 East California Boulevard, Pasadena, CA 91125, [6]NASA Johnson Space Center, Mail Code SN, Houston, TX 77058, [7]McGill University, Department of Earth and Planetary Sciences, 3450 University Street, Montreal, PQ H3A 2A7, Canada, and [8]Savannah River Ecology Laboratory, Drawer E, University of Georgia, Aiken, SC 29802.

Introduction: Martian meteorite ALH84001 contains μm-sized carbonate assemblages situated within cracks and fissures, which have been dated at ~3.91 *Ga.* [1]. These are interpreted as secondary minerals formed at low temperature [*e.g.*, 5,11] in an aqueous medium [7,12]. Dispersed within these carbonates are nm-sized, single crystal magnetites. Some of these magnetites have chemical and physical properties nearly identical to intracellular magnetite crystals produced by magnetotactic bacteria strain MV-1 [8-10]. The MV-1 magnetite morphology has been described as truncated hexa-octahedral, Fig. 1. In the natural terrestrial environment, truncated hexa-octahedral magnetite appears only to be produced through biogenic mediation [8 and refs. therein]. By inference, and in the absence of a credible inorganic explanation, we have suggested that those ALH84001 magnetites, which are indistinguishable from MV-1 magnetites, were mediated by similar biogenic processes on early Mars [2,8-10].

Controversy: Recently, the crystal morphology of MV-1 and, by inference, that of ALH84001 magnetite has been the subject of considerable debate [2,4]. Previous descriptions of theses morphologies were based on classical transmission electron microscope (TEM) imaging of individual crystals over a wide range of tilt angles ($\geq \pm 45^{o}$) (technique described in [2]).

Methods: We report here the crystal morphologies of MV-1 and ALH84001 magnetites as calculated by back-projection using electron tomography, Figs. 2&3. In the present study, we used a 300 keV TEM with a field emission gun (Tecnai F-30 from FEI Inc.), equipped with a 2048 x 2048 pixel CCD camera from Gatan Inc. to image magnetite crystals over tilt ranges of $\sim \pm 72^{o}$ in 2^{o} tilt intervals. The images were aligned for back-projection, either manually, or through the use of fiducial 5 nm Au spheres affixed to the specimen prior to microscopy. Three-dimensional (3-D) reconstructions were computed using weighted back-projection of the tilted views [3]. The tomograms were viewed and analyzed as a series of slices 1.0 nm thick, taken parallel to the specimen-supporting grid, using the IMOD software package [6]. The shape of each magnetite crystal was determined by defining the external contour of a given magnetite in each slice and assembling a stack of these contours in 3-D. To aid in visualization, the stacked contour array was reduced to an optimal mesh by Delaunay triangulation. The surface normal to each of the triangles in the mesh was calculated and the triangle faces colored according to the orientation of that surface normal relative to the principal crystallographic axis of magnetite. Green surfaces correspond to {111} orientations, blue surfaces to {100} orientations, and red surfaces to {110} orientations. Triangles whose surface normal did not correspond to one of the principal axes were colored gray.

Conclusions: Within the experimental and numerical uncertainties of the deconvolution, the tomographic reconstruction of both MV-1 and ALH84001 magnetites are equivalent and correspond to a truncated hexa-octahedral morphology.

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Figure 1. Idealized representation of a magnetite crystal displaying a truncated hexa-octahedral geometry; with eight {111} octahedral (green), six {110} dodecahedral (red) faces, and six {100} cubic (blue) faces. The [111], [110] and [10$\bar{1}$] zone axis are indicated with respect to the crystal.

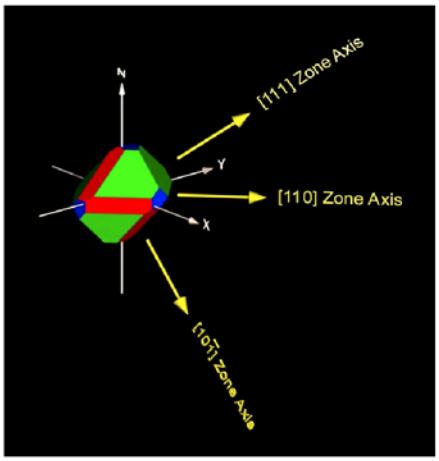
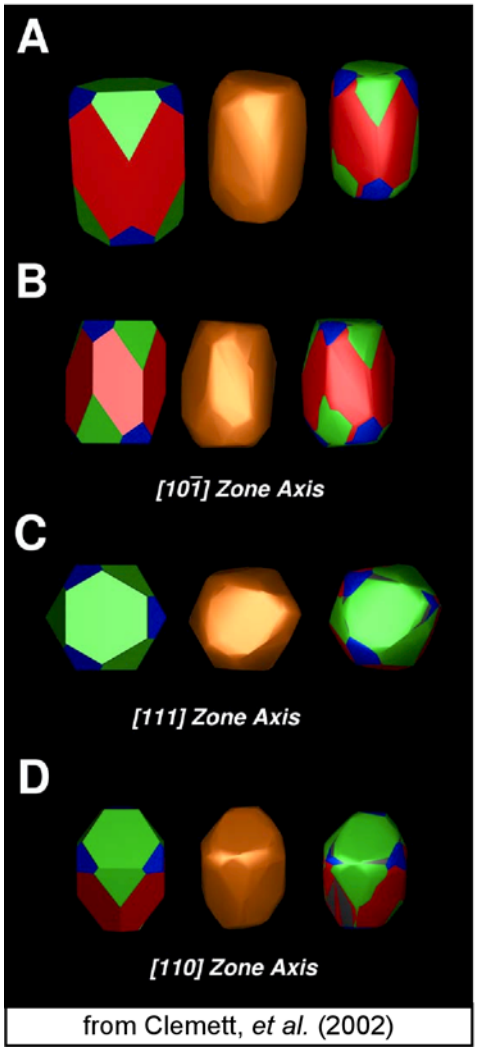


Figure 2. (Bottom Left) Tomographic reconstruction of a single MV-1 crystal (~100 nm in the longest dimension) in four orientations (A-D). From left to right, an idealized truncated hexa-octahedron, a reconstructed tomographic image, and an indexed color reconstruction of the same tomographic image where the green surfaces correspond to {111} faces, blue correspond to {100} faces, and red correspond to {110} faces.

Figure 3. (Bottom Right) Tomographic reconstruction of a single ALH84001 magnetite crystal. Views A-D same as those in Figure 2. View E is a classical TEM image of the magnetite crystal, while views F and G are the calculated 2-D projections of the tomographic data set when viewed along the [10$\bar{1}$] & [111] zone axis.



from Clemett, *et al.* (2002)