MICROANALYSIS OF UNIQUE FINE-GRAINED MINERALS IN THE MARTIAN
METEORITE ALH84001

Kathie L. Thomas1, Chris Romanek2, David S. McKay3, Lindsay P.
Keller4, and Everett K. Gibson5; 1Lockheed Martin, 2400 Nasa Rd. 1, Houston, Tx, 77058, 2SREL,
University of Georgia, Aiken SC 29802, 3NASA/JSC, SN, Houston, TX 77058, 4MVA Inc., 5500/200
Oakbrook Pkwy, Norcross GA, 30093, 5NASA/JSC, SN4, Houston, TX 77058

ALH84001 is an igneous martian meteorite, consisting primarily of orthopyroxene (opx) and
accessory phases including chromite, maskelynite, and carbonate [i.e., 1,2]. Trace amounts of augite,
apatite, olivine, and pyrite have also been observed [i.e., 1, 2]. In this work, we use transmission
electron microscopy (TEM) to describe the chemistry and mineralogy of ultra fine-grained (nanometer-
sized) regions in ALH84001. These regions include optically dark inclusions in the opx and Fe-rich
grains rimming carbonate spheroids. These Fe-rich rims have precluded prior characterization because
of their ultra fine grain size.

In general, carbonate spheroids occur as interstitial grains and range in size from ~10 µm to
several hundred micrometers in diameter. Carbonate spheroids have been previously described as being
compositionally zoned (Ca-rich cores with alternating Fe-, Mg-rich bands) [i.e., 1-3] suggesting
multiple episodes of fluid deposition in combination with cyclic changes in fluid composition.
Examination of fine-grained regions in ALH84001 may reveal clues about the composition of fluids and
temperatures at which the carbonate spheroids and other fine-grained minerals were formed [4].

Methods

A relatively flat region measuring 700 µm², which contained no fewer than 20 carbonate
spheroids, was mapped with wavelength dispersive spectroscopy for major and minor elements using a
 Cameca 100 SX microprobe. In addition, three regions ~60 µm in diameter were cored from
 ALH84001 thin sections using a micro-coring device. An orange carbonate spheroid, ~50
µm in diameter, dominated one region; the second sample was composed mainly of opx with dark
inclusions, and the third sample was composed mainly of white, translucent material. The three samples
were embedded in epoxy, thin sectioned using an ultramicrotome, and analyzed using a JEOL 2000
FX transmission electron microscope (TEM) [technique completely described in 5 and 6].

Results and Discussion: Chemical Mapping and TEM Analysis

Chemical Mapping

The mapped area contains four large carbonate spheroids, ranging from ~80-250
µm in diameter, and ~20 small carbonate spheroids, <20 µm in diameter. In general, the larger
carbonate spheroids are composed of Ca-rich cores surrounded by alternating bands of Mg-, and Fe-rich
carbonates. The largest spheroid has a core composed of bands varying in Ca composition; the center of
the core is Ca-rich surrounded by alternating bands of Ca-poor and Ca-rich carbonates. Others have
suggested that ankerite (Ca(Fe,Mg)(CO3)2) [2] and calcite (CaCO3) [3] are located in carbonate
cores; however, our largest carbonate core contains small amounts of both Mg and Fe. The larger
carbonate spheroids have external rims composed of thin bands of alternating Mg- and Fe-rich minerals.
Approximately one-third of the smaller carbonate spheroids are dominated by Ca-rich cores. Sulfur-
and Cl-bearing mineral phases were associated with the exterior rims of all larger and some smaller
spheroids. Two Al-rich glass phases, maskelynite and regions with an Al-rich opx-like composition, are
also present within the mapped area.

TEM Analysis

Glasses

We have found three types of glasses with distinct compositions have been observed in
ALH84001 (Fig. 1): (a) translucent glass with a maskelynite composition, (b) glass regions (~0.5 µm-
2.0 µm) with opx-like compositions and a high Al content (ranging from 0.8-3.3 wt.% ) which are
located between the opx matrix and rims of the carbonate spheroid, and (c) Si-rich glasses (~0.5 µm-1.0
µm; ~90% SiO2) which are located near the opx-like glass regions. Oxygen isotopic analysis of
maskelynite has shown it to be magmatic [7]. Shock glasses with a opx-like composition would be
likely in a meteorite composed mainly of opx which has experienced two shock metamorphic events [2].

Magnetites

Thin (1-5 µm) Fe-rich rims, which surround the zoned carbonate centers, are composed of
abundant fine-grained magnetite grains. Individual grains range from ~10-100 nm in diameter. EDS

and high resolution TEM data are consistent with magnetite ($\text{Fe}_3\text{O}_4$). The EDS analyses of magnetites include some element contribution from the carbonate matrix in which they are embedded or suggest that other phases could be coating the magnetite grains. Within the Fe-rich rims of carbonate spheroids, magnetites are always present. However, not all Mg-Fe carbonates have embedded magnetite grains. The dark inclusions within opx we analyzed are composed of fine-grained magnetites.

**Accessory Elements** Additional elements observed in the EDS spectra of magnetite-rich regions include Cl, P, or S. Although not all of these elements are detected simultaneously, Cl and P can range up to $\sim 1.0$ wt.\% and S can range up to $\sim 4.0$ wt.\%. Examination of the fine-grained matrix material containing the magnetites shows discrete S-rich regions (S ranges from 2.9-29.0 wt.%). These S-rich regions have corresponding high Fe (>55 wt.\%) and low oxygen (4.7-18.0 wt.\%) indicating the presence of Fe-sulfides. We have not observed discrete regions which are enriched in Cl and P.

**Formation of Fine-Grained Magnetites** In many meteoritic materials, magnetite and phyllosilicates are the common secondary minerals formed during low temperature aqueous alteration [8], and a similar origin is plausible for the magnetites in ALH84001. For example, Orgueil (CI) contains secondary magnetites, most likely formed by aqueous alteration; this meteorite also contains gypsum suggesting the presence of a saline fluid phase [9]. It has been implied that aqueous fluids within the Martian crust were highly saline [2]. The association of magnetite with carbonates, along with considerable phyllosilicates, is a common assemblage in heavily aqueously altered meteorites (CI and CM) and in hydrated IDPs. However, the lack of significant clay formation coupled with the unusually fine-grained nature of the magnetite in ALH84001 suggests that alternative processes may be responsible for their formation. Secondary magnetite in other meteorites usually displays frambooidal or plaquelette morphologies with average grain sizes clustering tightly about 0.3 $\mu$m [10]. The magnetites described in this abstract are an order of magnitude finer in grain size than those in other meteorites. An intriguing observation is that the magnetites observed in ALH84001 show interesting similarities to those formed as a by-product of certain biological activities [i.e., 11].

![Figure 1. Atomic Si-Mg-Fe ternary diagram](image)

Figure 1. Atomic Si-Mg-Fe ternary diagram shows the range of compositions for three types of glasses observed in ALH84001. In general, the pyroxene-like composition glasses are enriched in Al compared to clinopyroxene and orthopyroxene. The Si-rich glasses include minor amounts of Fe (<0.5 wt.\%), Mg (<2.2 wt.\%), and Ca (<3.2 wt.\%).