THE HISTORY OF ALH 84001 REVISED: MULTIPLE SHOCK EVENTS. Allan H. Treiman Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston, TX 77058 (<treiman@lpi.jsc.nasa.gov>).

The geologic history of martian meteorite ALH 84001 is more complex than previously recognized, with evidence for four or five crater-forming impacts onto Mars. This history of repeated deformation and shock metamorphism is perhaps responsible for the complexity of textural relationships in ALH 84001. This revised history appears to weaken some arguments that have been offered for and against the hypothesis of ancient martian life in ALH 84001.

Introduction. The basic geologic history of martian meteorite ALH 84001 was in dispute well before [1] suggested that it is host to possible traces of ancient martian life. Had ALH 84001 experienced one shock event and two episodes of carbonate deposition [2], or vice versa [3]? Since [1], intense scrutiny of ALH 84001 has uncovered many new observations which do not fit easily into the proposed geological histories. From this new and often contradictory data, I have tried to construct a self-consistent geological history. The recognition here of multiple shock events extends the work of [3] and is more consistent (in my opinion) with available data than the single-shock scenarios of [2] or [4].

Methods and Samples. These results are based on petrographic observations on 9 thin sections of ALH 84001 (#s 7, 8, 36, 85, 90, 142, 145, 168, 308), and critical readings of the literature.

Early Impacts. ALH 84001 formed originally from basaltic magma (event Cα), and was experienced some post-magmatic chemical equilibration and/or metasomatism (Cβ [5]). Its first impact event, I1, is inferred from the deformation D1, which produced the granular-textured bands ("crush zones") that transect the original igneous fabric. D1 involved intense shear, seen best by the stringers of chromite grains, some of which are folded and refolded. D1 may represent excavation or rebound flow of rock beneath a large impact crater. D1 was followed by, and possibly related to intense thermal metamorphism, Cγ, in which the granular band material was annealed (Fig. 1) and the chemical compositions of its minerals were homogenized. The next impact, I2, produced feldspathic glass from some of the igneous (and recrystallized) feldspar and silica in ALH 84001 [6], and also the fractures (Fr2) in which carbonate 'pancakes' were deposited

Carbonate Deposition. Next, the zoned carbonate globules and pancakes were deposited in fractures (Fr2) and throughout the rock [1-3,6]; this is event Cδ. The pancakes appear to be filling open fractures, but the globular carbonates appear to have formed principally by replacement of feldspathic glass [6], although locally it appears that carbonates replace orthopyroxene or other crystalline silicates (e.g., [7].)

Late Shocks. After carbonate deposition, ALH 84001 was subjected to two or three additional shock events. Most prominent was D3 (impact I3), in which feldspar and feldspathic glass was melted, carbonate globules were faulted [2,3] and disaggregated ([8], Fig. 2), and the rock was fractured. Chemical effects here (Cε) include mixing of carbonate into feldspathic glass and formation of vapor from the glass ([4], Fig. 2). Deformation D4 is defined by the results of [9], which show that the rock was fractured and deformed the rock without significant heating, permitting remnant magnetization directions to vary across fracture surfaces. D4 is assigned to impact event I4. Finally, ALH 84001 was ejected from Mars in impact I5, which could also be the same as I4.

Results. By its crystallization age alone [10], ALH 84001 is inferred to be from the martian highlands [3,11]. The present revised history of multiple impacts is consistent with the photogeology of the martian highlands, which shows impact crater upon impact crater, ejecta blanket upon ejecta blanket. Given this geologic setting, it seems only reasonable that ALH 84001 should have experienced a complex shock history. By photogeology, most of these impacts should be of ancient age (Noachian in the martian stratigraphic column). This is consistent with the Ar-Ar age of ~4.0 Ga [12], which could date I1, I2, or I3.

Conclusions for Life(?). Recognition of this complex history for ALH 84001 may help resolve some apparent contradictions among recent results pertaining to the possibility of ancient martian life in ALH 84001.

There has been significant controversy about the origin of submicron-sized magnetite grains in the meteorite, with claims that they formed by biogenic activity [1] or high-T vapor deposition [13]. But not all the magnetite grains in ALH 84001 need have formed simultaneously. The sub-micron rounded magnetite grains in the carbonate globules could be contemporaneous with carbonate deposition, possibly at low temperature. The elongate magnetite grains, some epitaxial on carbonates, which are claimed to be characteristic of vapor deposition could be ascribed to the vapours of event I3/Cε.

The paleomagnetic results of [9] were used to suggest a low temperature origin for the carbonates in ALH 84001. [9] showed that remnant magnetism in ALH 84001 had been rotated along a fracture, and that the rock had not been heated above 110°C since that rotation. [9] inferred that the rotation surface (fracture) was

Fr2 that hosts the carbonate pancakes. But this cannot be so, as the high temperatures of I3/Cε followed formation of the carbonate globules. Thus, the deformation detected by [9] must post-date I3, and so is not germane to formation of the carbonates.

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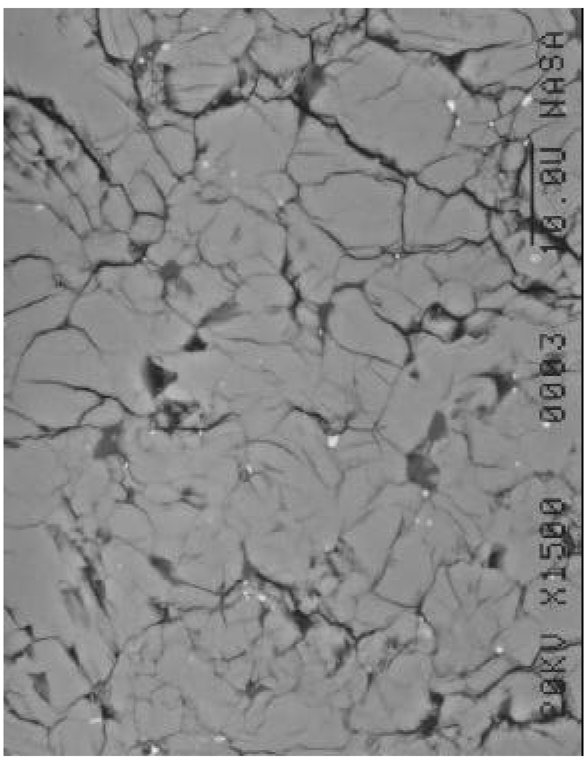

Fig. 1 BSE image of granular band area showing annealed (recrystallized) texture, and absence of clastic texture at <20 µm lengthscales. Medium gray is orthopyroxene, dark is plagioclase glass, bright is chromite. This texture demonstrates that the Cγ thermal event was intense enough to recrystalize or anneal the granular band material produced in D1.

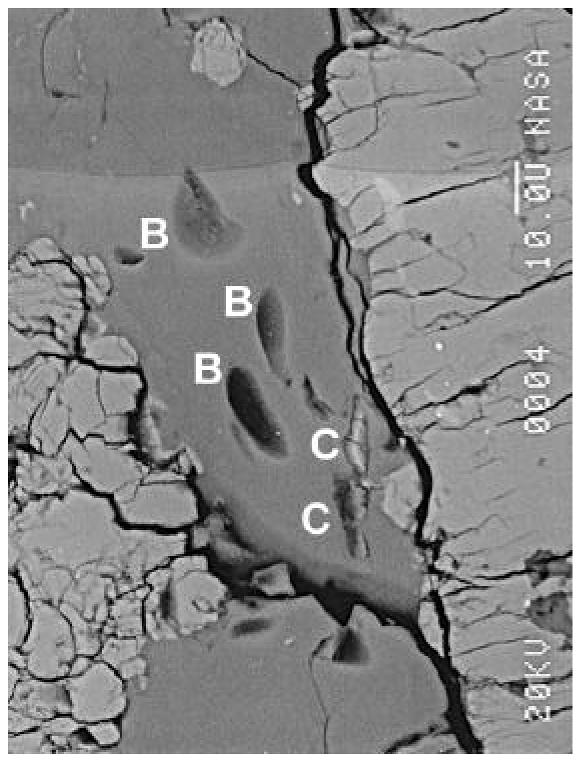

Fig. 2. BSE image of plagioclase-composition glass (medium gray) containing elongate bubbles (B) and fragments of carbonate-oxide material (C). Brighter material to right and left is orthopyroxene. Carbonate fragments (C) exhibit portions of the typical internal layering of carbonate globules (siderite -> magnesite, magnetite-rich layers). This texture demonstrates that (at least locally) plagioclase was melted and vapors were produced after formation of carbonate globules.