ANCIENT MARTIAN LIFE IN ALLAN HILLS 84001? STATUS OF SOME CURRENT CONTROVERSIES. A. H. Treiman, Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston TX 77058, USA (treiman@lpi.jsc.nasa.gov).

Four lines of evidence were taken to suggest that ALH 84001 contained traces of ancient martian life preserved in its carbonate mineral masses [1]: abundance of organic compounds (PAHs), disequilibrium mineral assemblages, morphology of sub-micron magnetite crystals, and presence of objects comparable in size and shape to bacteria. This evidence is predicated on the carbonate globules having formed at temperatures conducive to life. Here, I review evidence on carbonate formation temperature, martian origin of organic compounds, and bacteria-shaped objects.

Formation Temperature: A precondition for signs of life associated with the carbonate masses [1] is that the masses formed at T amenable to life (as we know it) [2], <~150°C. The formation T of the carbonates is poorly constrained [3,4]; most current hypotheses suggest either formation at low T<~200°C from water-rich fluid (possibly saline) or formation at T >~250°C from CO_2-rich fluid. Relevant evidence can not be interpreted unambiguously, in part because the geologic context of ALH 84001 is unknown, and in part because of its complex history [5].

The range of elemental compositions of the carbonates has been taken as indicating quasi-equilibrium at high T, ~700°C [4,6]. The fine-scale chemical zoning of the carbonates requires that this high T must have lasted only a short time, as might be expected in an impact event [4,7]. On the other hand, the elemental compositions could have formed at chemical disquilibria at low T [8,9]. The absence of hydrous minerals in ALH 84001 can be explained in either model. At higher T, the absence of hydrous minerals may reflect the presence of CO_2-rich fluid [4,7,10,11]. At low T, one can invoke slow reactions or very saline aqueous fluids [12-14].

The oxygen isotopic compositions of the carbonates may suggest equilibrium at low T from hydrous fluids [3], although the inferred temperatures depend on what O isotope composition is taken for the depositing fluids [15]. On the other hand, the O isotopes also appear consistent with carbonate growth either from aqueous solutions at variable low T or from carbonic fluids at T > ~500°C [11].

The carbonates in ALH 84001 occur as fracture fillings, lacy patches, and rounded volumes among and within pyroxene and plagioclase glass. These textures have been interpreted as : void-fillings (low-T) [1,16]; products of solution / precipitation (indeterminate T) [10,14], or solidified carbonate melt (high T) [7].

Considerable work has gone to the temperature significance of sub-micrometer magnetites in the carbonates. Equant magnetites have been interpreted as biogenic: magnetosomes from magnetotactic bacteria [1,17], although these shapes might equally well form without life. Elongate magnetite grains, some epitaxial on carbonates and some with axial screw dislocations, have been suggested as products of vapor deposition at high temperature [18,19], although similar magnetite shapes occur in bacteria [20]. Also, it is possible that the elongate magnetites formed at high T, but after the carbonates formed [5]. Magnetites are also present in void spaces in the carbonate, either as the product of decarbonation at high T [21] or as entrapped from the aqueous fluid that deposited the carbonates [22].

Summary. There is no consensus on the formation T or mechanism of carbonate masses. The bulk of evidence, in my opinion, is not consistent with T>400°C [4,6,7]. At present, there seems no way to tell whether the carbonates formed at moderate or low T: hotter or colder than ~150°C.

Organic Matter: McKay et al. [1] presented evidence that the carbonate pancakes in ALH 84001 are enriched in polycyclic aromatic hydrocarbons, PAHs, which are organic compounds commonly formed from (or by) biological organisms. Absence of PAHs near the meteorite's fusion crust implied that the PAHs are martian. Confirming evidence included the high abundance of organics in ALH 84001 [23]. Work here has followed many interconnected threads.

Are PAHs associated with the carbonate globules? The association was amplified by [24] and confirmed by XANES analyses [25]. An early abstract from the McKay group states that some carbonate globules have low PAH content [26]. Recent TOFSIMS analyses on polished surfaces found PAHs evenly distributed through the silicate and oxide minerals, but less abundant in the carbonates [27]; this result seems improbable.

Are the PAHs martian? The absence of PAHs near ALH 84001's fusion crust suggests that they are pre-terrestrial [1,24]. It has been claimed that the PAHs are similar to those of Antarctic ice, and hence contaminants, supported by experiments on solubility, transport, and adsorption behavior of PAHs [28]. These results have been strongly criticized [24].

Are the PAHs biogenic? The PAHs in ALH 84001 are claimed to be like those produced by degradation of bacteria [1,24] (possibly not martian [28]). But the variety and abundances also show similarities to PAHs in CM chondrite meteorites and common interplanetary dust particles [29]. The PAHs could also have formed inorganically (Fischer-Tropsch reaction), possibly catalyzed by magnetite grains [30]. But, it may be impossible to determine the origin of the PAHs, because Antarctic weathering can degrade most distinguishing characters of biogenic PAHs [31].

Are other organics martian? Probably not. All (nearly) the organic carbon in ALH 84001 has live ^{14}C, meaning that it formed fairly recently on Earth [32]. Similarly, amino acids extracted in bulk from ALH 84001 have abundances and chirality typical of Earth biological matter [33].

Summary. It seems likely that the PAHs in ALH 84001 are (at least in part) martian, but that other organic matter is terrestrial. It is not known whether the PAHs are biogenic or not, nor whether this issue can be resolved.

Possible Biogenic Objects: The most publicly compelling line of evidence is the presence of bacteria-shaped objects (BSO) in carbonate masses [1,34]. However, their identification as biogenic is ambiguous in the absence of internal structures (contrary to early hints [35]), undisputed martian biochemicals (see above), and biologic community structures (e.g., [36]). Morphology alone is problematic; BSOs can arise in many ways (e.g., [37]).

Too Small? At the 1996 press conference on ALH 84001, the BSOs were claimed to be too small for life: 20-100 nm [1] vs. >200 nm diameter for free-living bacteria [38]. The BSOs enclose too little volume to contain the requisite molecules for Earth life [2,38], a point contested by some [39]. The BSO size range has been extended to 750 nm, and there is some evidence of Earth bacteria as small as 80 nm [40]. The smaller objects in ALH 84001 could also be bacterial appendages, not whole organisms [41].

Inorganic? The 100 nm elongate BSOs may be magnetite crystals which formed at high temperature [14,19]. Aligned 'swarms' of ~100 nm BSOs [1] may be magnetite crystals epitaxially oriented on carbonate mineral substrates [19,42,43] or irregularities on mineral surfaces [14]; McKay et al. may no longer consider the swarms biogenic [40].

Terrestrial? In the absence of (bio)chemical characterizations, it remains possible that the BSOs are terrestrial. Endolithic organisms are well known [44]; fungi and bacteria can live in Antarctic meteorites [45]. Spores of these organisms, and larger biologic objects like diatom tests [46], are distributed worldwide by wind. BSOs have been found in lunar meteorites from Antarctica, which presumably never experienced clement conditions before landing in Antarctica [34]. This last result suggests that BSO in ALH 84001 are terrestrial, although McKay [47] reports never having found BSOs in lunar rocks or other meteorites.

Artificial? Some BSOs figured in [1] have been suggested to be artifacts of sample preparation [18]. This claim is disputed [40], and scanning force microscopy measurements appear to suggest the BSOs are not artificial [48]. Yet, the morphology of some images, especially the popular "worm," is suggestive of coating artifact.

Summary. The bacteria-shaped objects in ALH 84001 are visually appealing, but their actual identity remains uncertain.

Conclusions: The hypothesis that ALH 84001 contains traces of ancient martian life [1] has not been proved nor disproved, and all parts of the hypothesis remain controversial. So far, it has not been shown that the carbonate masses formed at a high temperature inimical to life. This failure is not proof of the hypothesis, it is merely not a disproof. To me, it seems likely that the PAHs in ALH 84001 formed on Mars, but this is not proof of martian biology. The missing link is the correlation between observed PAHs and those of degraded bacteria - that link may have been permanently severed [31]. The "Mars Bugs" are under siege, attacked from all sides and so far with few reinforcements.

Whether it is proved correct or not, the hypothesis of [1] has stimulated interest and research on ALH 84001, other martian Meteorites, and Mars itself. Renewed interest in science is good for the nation, and renewed funding is beneficial to the research community. But this debate has left some me some difficult questions. 1. Are the standards for publication less stringent for 'hot-topic' papers than for 'routine' papers? 2. Why has it been so difficult to reach consensus about ALH 84001? Are the carbonates so intractable that our best scientists cannot agree on their formation temperature within 700°C? Or are we not nearly as clever as we think? 3. How will NASA fare if the 'life in ALH 84001' hypothesis is conclusively refuted?

References: [1] McKay et al. (1996) *Science 273*, 924. [2] Nealson K.H. (1997) *J. Geophys. Res. 102*, 23675. [3] Romanek et al. (1994) *Nature 372*, 655. [4] Harvey & McSween (1996) *Nature 382*, 49. [5] Treiman A. (1998) *Meteorit. Planet. Sci. 33*, in press. [6] Mittlefehldt D. (1994) *Meteoritics 29*, 214. [7] Scott E. et al. (1997) *Nature 387*, 377. [8] Valley J. et al. (1997) Science 275, 1633. [9] Treiman & Romanek (1998) *Meteorit. Planet. Sci. 33*, in press. [10] Kring D. et al. (1998) *Geochim. Cosmichim. Acta 62*, 2155. [11] Leshin L. et al. (1998) *Geochim. Cosmochim. Acta 62*, 3. [12] Warren P. (1998) *J. Geophys. Res. 103*, 16759. [13] McSween & Harvey (1998) *Meteorit. Planet. Sci. 33*, A103. [14] Treiman A. (1995) *Meteoritics 30*, 294. [15] Hutchins K. & Jakosky B. (1997) *Geophys. Res. Lett. 24*, 819. [16] McKay G. & Lofgren G. (1977) *LPS XXVIII*, 921. [17] Thomas-Keprta K. et al. (1998) *LPS XXIX*, Abs. 1495. [18] Bradley J. et al. (1997) *Nature 390*, 454. [19] Bradley J. et al. (1996) *Geochim. Cosmochim. Acta* **60**, 5149-5155. [20] Thomas-Keprta K. et al. (1997) *LPS XXVIII*, 1433. [21] Brearley A.J. (1998) *LPS XXIX*, Abs. 1757. [22] Blake D. et al. (1998) *LPS XXIX*, Abs. 1347. [23] Grady M.M. et al. (1994) *Meteoritics* **29**, 469. [24] Clemett S. et al. (1998) *Faraday Disc. 109*, in press. [25] Flynn G.et al. (1998) *Meteorit. Planet. Sci. 33*, A50. [26] Thomas K. et al. (1995) *LPS XXVI*, 1409. [27] Stephan T. et al. (1988) *Meteorit. Planet. Sci. 33*, A149. [28] Becker L. et al. (1997) *Geochim. Cosmochim. Acta 61*, 454. [29] Bell J. (1996) *Science 274*, 2121. [30] Anders E. (1996) *Science 274*, 2119. [31] Sephton M. & Gilmour I. (1988) *Meteorit. Planet. Sci. 33*, A142. [32] Jull A. et al. (1998) *Science 279*, 366. [33] Bada J. et al. (1998) *Science 279*, 362. [34] Sears D. & Kral T. (1998) *Meteorit. Planet. Sci. 33*, in press. [35] Swartz M. (1996) *Texas Monthly Nov*. [36] Schopf J. (1993) Science 260, 640. [37] Peiming W. & Odler I. (1990) *Proc.12th. Intl. Conf. Cement Micros.*, 382-402. {Thanks to C. Capobianco} [38] Maniloff J.; Nealson K.H., Psenner R. & Loferer M. (1997). *Science* **276**, 1775-1776. [39] Folk R.L. (1997) *Science* **274**, 1287; *Science* **276**, 1776. [40] McKay D.S. et al. (1997) *Nature 390*, 455. [41] Thomas-Keprta K. et al. (1998) *LPS XXIX*, Abstr. #1495, LPI (CD-ROM). [42] Bradley J. et al. (1998) *Meteorit. Planet. Sci. 33*, in press. [43] Bradley J. et al. (1997) *Meteor. Planet. Sci. 32*, A20. [44] Friedmann E. & Weed R. (1987) *Science 236*, 703. [45] Steele I. et al. (1998) *Meteorit. Planet. Sci. 33*, A149. [46] Burckle L. & Delaney J. (1998) *Meteorit. Planet. Sci. 33*, A26. [47] McKay D. et al. (1996) *Science 274*, 2123. [48] Steele A. et al. (1998) *J. Microsc. 189*, 2.