Fluid inclusions in extraterrestrial samples: Fact or fiction?

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Introduction

Over the years there have been numerous reports of liquid inclusions in meteorites (see Roedder, 1968-onward). Roedder (1) reviews the reported occurrences of liquid inclusions in meteorites and states that "*silicate-melt inclusions are expectable and apparently ubiquitous, but the presence of actual liquid inclusions (i.e., with moving bubbles at room temperature) would seem almost impossible.*" The reason for this conclusion is that meteorites (presumably) form in space at high temperatures and very low pressures where liquid water (or carbon dioxide) is not stable.

Perhaps the most infamous report of fluid inclusions in meteorites was that of Warner et al. (2). In that study, the authors reported the presence of two-phase, liquid-vapor inclusions in a diogenite from Antarctica (ALHA 77256). This report of fluid inclusions generated considerable interest in the meteorite community, and caused many to question existing models for the origin of the diogenites. This interest was short-lived however, as later investigations of the same samples showed that the inclusions were most likely artifacts (3).

Rudnick et al. (3) showed that many of the inclusions in meteorites prepared at the Johnson Space Center contained a fluid that fluoresced strongly under the laser beam on the Raman microprobe. They interpreted this to indicate that the inclusions contained Almag oil used in the preparation of thin sections. Presumably, the Almag oil entered empty vesicles along fractures that were opened intermittently during cutting.

Here, the occurrence of unambiguous fluid inclusions that could not have been introduced during sample preparation are described in samples from two different extraterrestrial environments. One environment is represented by the SNC (martian) meteorites ALH 84001 and Nakhla. The second environment is represented by the Monahans 1998 meteorite that fell recently in the USA.

SNC (martian) Meteorites

The precursors of the martian meteorites are ultramafic igneous extrusive and/or intrusive rocks that were blasted from the surface of Mars during an impact event. Similar igneous rocks on earth commonly contain fluid inclusions along with the more abundant silicate, sulfide and carbonate melt inclusions. As such, it is reasonable to expect that the SNC meteorites should contain fluid inclusions that represent fluid trapped in the rocks while they were on the surface of Mars.

Nakhla

The Nakhla SNC meteorite was observed to fall near the village of El-Nakhla, El-Bahariya in Egypt on June 28, 1911. Several stones were immediately collected by Dr. W. F. Hume of the Geological Survey of Egypt. The two-phase inclusion found in the Nakhla sample is tubular in shape and is about 8 microns long (Fig. 1). The inclusion is one of several dozen inclusions forming a healed fracture that cuts through an orthopyroxene crystal. Most of the inclusions along the fracture are dark with noticeable microfractures extending from the inclusion into the surrounding mineral, indicating that the inclusions have decrepitated. This behavior is common for high-density liquid fluid inclusions in terrestrial samples. A few other inclusions along the fracture were clear (transparent) but did not contain a visible bubble. This is because either the inclusions were empty, or contained only liquid with no vapor bubble, or contained a bubble that was motionless and hidden in a corner of the inclusion. The bubble in the one unambiguous fluid inclusion in this fracture plane was in constant, slow motion, proving that the inclusion did indeed contain a liquid phase.

Although it was not possible to conduct the types of tests normally used to determine fluid inclusion compositions because of the manner in which the sample had been prepared, the difference in index of refraction between the liquid and the vapor bubble is consistent with the inclusions containing liquid and vapor carbon dioxide, although it is possible that the inclusion contained liquid water and water vapor.

ALH 84001

The second SNC sample that contained liquid inclusions with moving bubbles was ALH84001. ALH84001 was found on December 27, 1984 in the Far Western Icefield of Allan Hills, Antarctica. The inclusions in this sample are spherical to negative-crystal shaped, about 1-2 microns in diameter, and not along an obvious fracture (Fig. 1). The fact that the inclusions are not along a fracture suggests that the inclusions are primary and contain the magmatic fluid that exsolved from the crystallizing melt as the igneous rock formed on Mars. As such, the inclusions can provide valuable information about degassing early in Mars history. As with the inclusion in Nakhla, no direct chemical tests could be conducted on these inclusions, but the optical behavior of the inclusions suggests that they contain liquid and vapor carbon dioxide.

Implications

The occurrence of (presumably) carbon dioxide fluid inclusions in both the Nakhla and ALH 84001 meteorites suggests that carbon dioxide was migrating through these igneous rocks at some time during or after their formation on Mars. If the carbon dioxide was present at or near magmatic temperatures, pyroxene (enstatite) would not be stable in the presence of carbon dioxide, and would react to form a carbonate and a silica-rich phase (4). This is consistent with a high temperature origin for the carbonates in the SNC meteorites, as originally proposed by Harvey and McSween (5). This interpretation also suggests that the carbonates were present in the rocks before they were ejected from the martian surface. However, by analogy with terrestrial samples, the carbonates did not necessarily have to form as a result of the impact event but, rather, may have formed as a result of natural high temperature igneous metasomatic processes before the impact.

Monahans 1998

Monahans 1998 fell on March 22, 1998, in the town of Monahans, Texas and was collected immediately (6). One of the stones was broken open at Johnson Space Center less that 72 hours later and was found to contain purple halite (NaCl). Crystals of sylvite (KCl) are present as inclusions within the larger halite crystals, similar to the occurrence of halite and sylvite in terrestrial evaporites. The purple color of the halite is probably due either to exposure to solar and galactic cosmic rays, or (more likely) by exposure to beta decaying 40K in the sylvite. The presence of halite/sylvite solely within one breccia component shows that it formed on the parent asteroid, before final aggregation of the meteorite.

Primary and secondary aqueous fluid inclusions are present in the halite. The inclusions range up to 15 microns in longest dimension. At room temperature, a few of the inclusions contain vapor bubbles (Fig. 2) that are in constant motion, proving that the inclusions contain both liquid and vapor. Microthermometric analysis of the inclusions indicates that, in addition to Na^+ and K^+, the aqueous liquid contains additional divalent cations such as Ca^{2+} or Mg^{2+}. Most of the inclusions do not contain a vapor bubble at room temperature, suggesting a low formation temperature (less than 100°C, and probably less than 50°C), assuming that the formation pressure was low - a few 10s of bars at most. The halite precipitated relatively rapidly, based on its polycrystalline texture.

Figure 2. Isolated liquid - vapor inclusion in halite in the Monahans 1998 meteorite. The scale bar equals 10 microns.

Most of inclusions occur along healed fractures in the halite and are demonstrably secondary in nature. Other inclusions are isolated and may represent primary inclusions trapped during initial halite deposition. The presence of both primary and secondary inclusions in the halite could indicate prolonged or episodic introduction of aqueous fluids into the halite depositional environment.

The presence of aqueous inclusions and evaporites within an H5 chondrite is very exciting. Apparently, water was more common on asteroids than we realize, and chondrite metamorphism paths should be reconsidered. Halite was noticed in Monahans 1998 because of its purple color and large grain size, and this permitted special sampling and thin-sectioning procedures to be employed which preserved the halides. It is possible that halite is commonly present in chondrites, but has been overlooked, resulting in errors in bulk Cl determinations for chondrites. It is also possible that a fraction of the sulfate/halide efflorescence noted on Antarctic meteorites is derived from halite, rather than from indigenous contaminants in the ice.

References:

[1] Roedder, E (1984) Fluid Inclusions. *Mineralogical Society of America, Reviews in Mineralogy, 12*, 646 p. (2) Warner JL, et al. (1983)*Journal of Geophysical Research Supplement* 88:A731-A735. [3] Rudnick RL, et al. (1985)*Journal of Geophysical Research Supplement* 90:C669-C675. (4] Koziol AM and Newton, RC (1995) *American Mineralogist 80*, 1252-1260. [5] Harvey RP and McSween HY, Jr. *Nature 382*, 49-51. (6) Zolensky et al. (1999) 30th LPSC Abstracts.

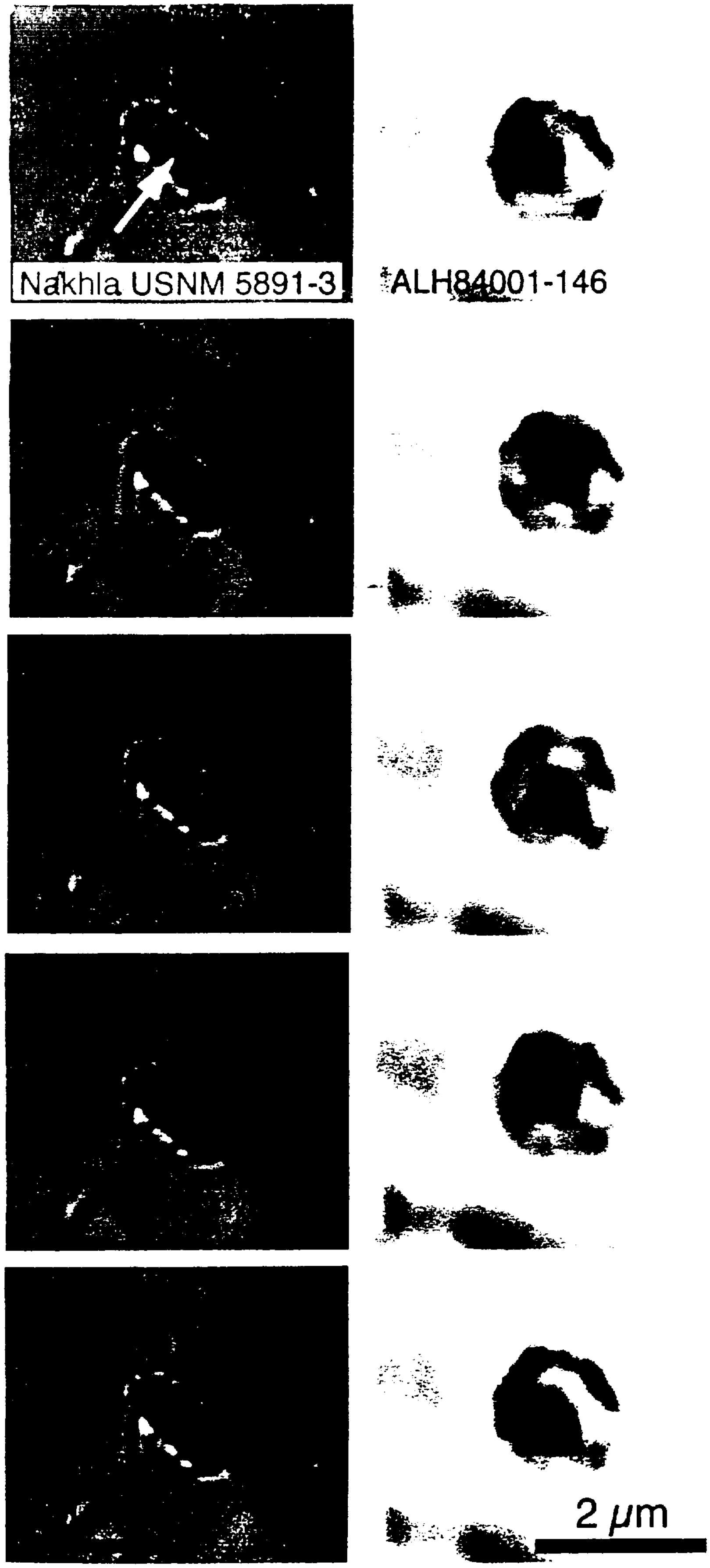

Figure 1. The two photographic sequences shown on the left are images captured from a video tape showing moving bubbles in fluid inclusions in Nakhla meteorite sample USNM 5891-3 and Allan Hills meteorite sample ALH84001-146. Comparing the positions of the bubbles in the photographic sequences shows that the bubble is in slightly different locations within the inclusion in the different frames. When viewed on the video tape, the bubbles in these two inclusions are in constant motion, providing conclusive evidence that the inclusions contain a low-to-moderate viscosity liquid phase (in addition to the moving bubble).