Analysis of the First Direct Samples of Early Solar System Water

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Over the past 3 decades, NASA has become increasingly aware of the fundamental importance of water, and aqueous alteration, on primitive solar system bodies. Liquid water is apparently as essential to life as is carbon. All classes of the most primitive astromaterials that the space agency has studied show some evidence of interaction with aqueous fluids. NASA can also observe cryo-volcanism of several small solar system bodies (e.g., Saturnian and Jovian moons), and so are certain of the continuing and widespread importance of aqueous processes across the solar system. Nevertheless, the space agency is still lacking fundamental information such as the location and timing of the aqueous alteration and the detailed nature of the aqueous fluid itself. A major impediment to the understanding of aqueous alteration has been the apparent absence of direct samples of aqueous fluids in meteorites.

NASA's understanding of early solar system fluids took a dramatic turn 10 years ago with the discovery of fluid inclusion-bearing halite crystals in the matrix of two freshly fallen brecciated H chondrite (meteorite) falls—Monahans and Zag. The halites were dated by potassium-argon, rubidium-strontium, and iodine-xenon systematics to be 4.5 billion years old. Johnson Space Center (JSC), in collaboration with Virginia Polytechnic Institute and State University, began examining both meteorites for the presence of aqueous fluid inclusions, which were immediately found.

Fluid inclusions are micro-samples of fluid that are trapped at the crystal/fluid interface during growth (primary) or some later time along a healed fracture (secondary) (figure 1). Both varieties of fluid inclusions are found in Monahans and Zag halite. The presence of secondary inclusions in the halite indicates that aqueous fluids were locally present following halite deposition suggesting that aqueous activity could have been episodic. In any fluid inclusion analysis, it is thus critical to separately analyze the primary and secondary inclusions, if possible, thereby yielding temporal information on fluid compositional changes. Heating/freezing measurements were made on the halite fluid inclusions for both Monahans and Zag, determining that the fluids were trapped at approximately 25°C (77°F). These are the first direct measurements of aqueous alteration temperature in any astromaterials, and are also important because they demonstrate unequivocally that these halites have never been subsequently heated. A disadvantage of halite is that it is so readily dissolved in the terrestrial atmosphere, unless extreme care is taken with the samples. Understanding this problem, NASA maintains the Monahans and Zag samples in curation-grade, dry nitrogen-filled cabinets waiting for technology to catch up with the samples, to finally permit chemical and isotopic analyses of the trapped water droplets and to discover their origin. This time has finally arrived.

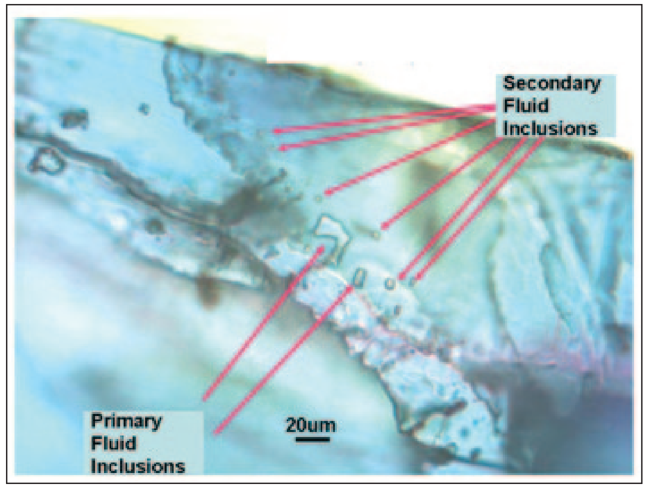

Fig. 1. *Monahans halite with target fluid inclusions indicated. Scale bar measures 20 micrometers.*

The first step has been to measure the hydrogen and oxygen isotopic composition of the fluid inclusions' aqueous solutions to understand the origin of these fluids. The oxygen and hydrogen isotopic composition of the aqueous fluids will be compared to determine which of these bodies were the parent objects: asteroids, comets, micrometeorites, interplanetary dust particles, giant planet moons. The aqueous fluids will also be compared to the Earth's water. Testing of JSC's hypothesis is that the oxygen and hydrogen isotopic composition of the aqueous fluids in meteorites (in fluid inclusions) will be shown to be most similar to cometary coma water, and also similar to the water being ejected from cryo-volcanoes on Jovian and Saturnian moons. The bulk composition of the fluid inclusion-bearing phases in each meteorite will be measured, as a further guide to the aqueous fluid bulk composition. This will further test the hypothesis that the water was not asteroidal in origin for the halite, at least.

Several Zag and Monahans halite crystals have been selected for secondary ion mass spectrometry (SIMS) analysis by a collaborator at Hokkaido University (Japan), who modified his Cameca 1270 SIMS with a special internal freezing stage. The aqueous fluid inclusions have to be frozen before being exposed (by sputtering) for analysis in the SIMS. After a great deal of effort, NASA developed the correct sample preparation and analytical techniques to obtain quality oxygen and hydrogen isotopic measurements of individual aqueous fluid inclusions in the halites. Figure 1 shows one Monahans halite crystal, indicating the fluid inclusions that were analyzed. The SIMS freezing stage holds the sample temperature to about -150°C (-238° F) (during measurements by liquid nitrogen. Fluid inclusions in the depth of approximately 50 micrometers (µm) from the halite surface have been succeeded to measure. The sizes of inclusions were about 5µm. Initial results of this work are shown in the figure 2. The observed distribution of isotopic variations of fluid inclusions seems to be results of interaction between comet-like water and meteorite silicates. These may be results of temporal information on compositional change of asteroidal fluid by episodic events. Now, techniques are being optimized to permit a reduction in the errors and to target specific individual fluid inclusions—a necessary capability to permit the measurement of temporal changes in aqueous compositions by distinguishing between preselected primary and secondary fluid inclusions. The team now has a unique sample suite that is being analyzed by a unique instrument, thus providing critical information on the activity of water in the early solar system—information that can be obtained in no other manner.

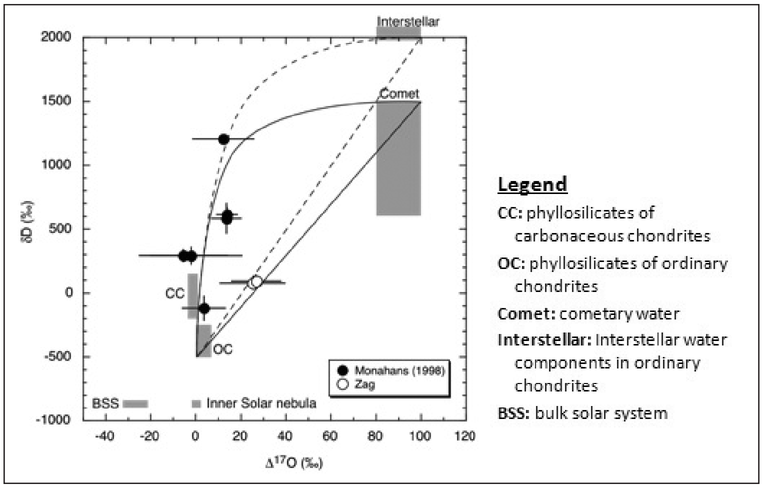

Fig. 2. *Results of the analysis of oxygen and hydrogen isotopes of several Monahans and Zag halite fluid inclusions. Lines are expected mixing lines between cometary (or interstellar) water and ordinary chondrite.*

The team hypothesizes that organics being carried through the parent body of the halite have been deposited adjacent to the fluid inclusions, where they have been preserved against any thermal metamorphism. These are being analyzed using confocal Raman spectroscopy at the Carnegie Geophysical Institution (Washington, DC). These organics will be compared with those found in chondrites and Wild-2 comet coma particles to determine whether these classes of organics had an origin within aqueous solutions.

Finally, the team is locating and analyzing fluid inclusions in other meteorites. Fluid inclusions in six other meteorites have already been located to broaden the scope work and extend it to other primitive water-bearing solar system objects.