Fluid inclusions in Astromaterials: Direct samples of early solar system aqueous fluids

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Introduction We have become increasingly aware of the fundamental importance of water, and aqueous alteration, on primitive solar-system bodies (Zolensky et al., 2008). All classes of astromaterials studied show some degree of interaction with aqueous fluids. We have direct observations of cryovolcanism of several small solar system bodies (e.g. Saturnian and Jovian moons) (Lellouch et al., 2002), and indirect evidence for this process on the moons Europa, Titan, Ganymede, and Miranda, and the Kuiper Belt object Charon (Cook et al., 2007), and so are certain of the continuing and widespread importance of aqueous processes across the solar system. Nevertheless, we are still lacking fundamental information such as the location and timing of the aqueous alteration and the detailed nature of the aqueous fluid itself.

Fluid Inclusions in Meteoritic Halite Two thermally-metamorphosed ordinary chondrite regolith breccias (Monahans 1998, hereafter simply “Monahans” (H5) and Zag (H3-6)) were found by us to contain fluid inclusion-bearing halite (NaCl) crystals (Zolensky et al. 1999, 2000) dated by K-Ar, Rb-Sr and I-Xe systematics to be ~4.5 billion years old (Zolensky et al., 1999, 2000; Whitby et al., 2000; Bogard et al., 2001), and thus the trapped aqueous fluids and solids are at least as ancient. Heating/freezing studies of the aqueous fluid inclusions in Monahans halites Zolensky et al., 1999) demonstrated that they were trapped near 25°C, and their continued presence in the halite grains requires that their incorporation into the H chondrite asteroid occurred after that body’s metamorphism ended, since heating would have caused fluids to exit the halite (Zolensky et al., 1999). The initial results of our O and H isotopic measurements on Monahans and Zag halite brine inclusions (Yurimoto et al., 2014) can be explained by simple model mixing asteroidal and cometary water.

These halites also contain solids with a wide mineralogy, including abundant organics which we have been investigating by FTIR, µ-L^{2}MS, Raman spectroscopy, STXM-XANES, NanoSIMS, and UPLC-FD/QToF-MS (Kebukawa et al., 2014; Chan et al., 2018). These organics show a wide chemical variation, representing organic precursors, intermediates and reaction products that possibly include life’s precursor molecules. The halite crystals exhibit a diverse organic content that includes a mixture of C- and N-bearing materials comprising macromolecular carbon exhibiting a wide range of structural order, non-conjugated aromatic molecules, imine, nitrile and/or imidazole compounds, and amino acids. The solids and organics contain excesses of neutron-rich isotopes of H, O, N and Cr, requiring a very cold formation location. The enrichment in ^{15}N reflect sources of interstellar ^{15}N such as ammonia and amino acids. Our study reveals that the halite parent body, possibly a trans-neptunian object injected into the inner solar system by giant planet migration and becoming a C, P or D class asteroid (Vokrouhlický et al., 2016), shows evidence for a complex combination of biologically- and prebiologically-relevant molecules.

Locating Fluid Inclusions In Other Astromaterials The presence of fluid inclusions in the rather fragile halite crystals in Monahans and Zag suggested that fluids must have also been preserved in other meteoritic minerals, such as carbonates and silicates. This is supported by the discovery of decrepitated fluid inclusions in the nakhlites, appearing as dark trails through augite grains (Bridges et al., 2000). Therefore, we have been carefully examining newly-prepared thin sections of CM and CI chondrites for fluid inclusions, locating potential aqueous fluid inclusions in Ivuna (CI), Murray (CM2), Mighei (CM2), Sayama (CM2), ALH 84029 (CM2), Tagish Lake (C2) and LON 94101 (CM2), and Sutter's Mill (C2) in carbonate, sulfide, olivine and enstatite crystals (Fig. 1). Optical, SEM and synchrotron X-ray computed tomography imaging indicate that calcite and sulfides in Sutter's Mill have abundant, though very small, fluid inclusions (Tsuchiyama et al., 2014; Zolensky et al., 2017). The success of this survey demonstrates that we can expect to find aqueous fluid inclusions in numerous, varied meteorites. These inclusions had not been previously detected because they are very small (none larger than a few micrometers), and because of the high potential for creating spurious fluid inclusions during standard sample preparation procedures.

Implications It is well recognized that aqueous fluids, especially brines, were important in the early Solar System. Such fluids are probably present today below the surfaces of the icy moons Europa and Callisto (Hartogh et al., 2011). Brown and Hand (2013) proposed that NaCl and KCl dominate the non-ice component of the leading hemisphere of Europa, and that the most abundant salts in Europa ocean brines are chlorides. Samples of ancient, inner solar system water have survived in the form of aqueous fluid inclusions in chondrites and, probably, other classes of meteorites. Meteoritic fluid inclusions thus offer a unique opportunity to study early Solar System brines in the laboratory. Inclusion by inclusion analyses of the trapped fluids in carefully-selected samples will, in the immediate future, provide detailed information on the evolution of aqueous fluids as they interacted with anhydrous solid materials, and the evolution of prebiotic organic compounds. Thus, real data can replace calculated fluid compositions in thermochemical calculations of the evolution of water and aqueous reactions in comets, asteroids, moons and the terrestrial planets (Zolotov, 2008). Analysis of the organics that accompany these brine samples will shed important new light on the origin of life.

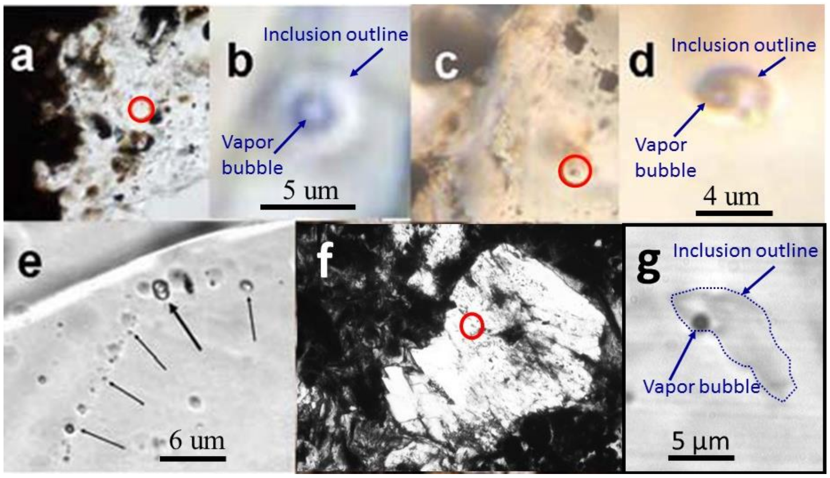

Figure 1. Two phase fluid inclusions in estraterrestrial calcite. (a) Primary fluid inclusion in the Murray CM2 chondrite at low mag. (circle). (b) Same Murray inclusion at high mag. (c) Primary fluid inclusion in the Tagish Lake C2 chondrite at low mag. (circle). (d) Same inclusion at high mag. (e) Secondary fluid inclusions in Tagish Lake. (f) Primary fluid inclusion in the Ivuna CI chondrite at low mag. (red circle). (b) Same Ivuna inclusion at high mag.

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