DISCOVERY OF ABUNDANT TREMOLITE IN A CARBONACEOUS CHONDRITE FRAGMENT FROM THE ALMAHATA SITTA METEORITE.

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Introduction: Almahata Sitta (AhS) is classified as an anomalous, polymict ureilite and was observed prior to Earth impact as the F-type asteroid 2008 TC$_3$ [e.g., 1-2]. As part of our characterization of this unusual meteorite [e.g., 3], we have been using microscopic infrared spectroscopy (μ-FTIR) to measure the mineralogy of fragments identified as carbonaceous chondrites (CC). In fragment 202 we have discovered unambiguous spectral evidence for a minimum of several vol% amphibole (specifically, tremolite), a mineral that is not known to occur in volumetrically significant abundances (defined here as >1%) in carbonaceous chondrites.

Background: AhS fragment 202 consists of partly altered chondrules in a fine-grained matrix and contains unusually abundant magnetite; it has been tentatively classified as C2 based on mineralogy, chemistry, and texture [*e.g.,* 4]. That work determined that the matrix (all components that are not chondrules) is dominated by relatively Mg-rich serpentine plus poorly crystalline saponite. Partially altered chondrules contain olivine and minor pyroxene and alteration phases (e.g., sulfide). Magnetite is distinct in composition from that in CI, CK, CV, or CR [5]. New chemical, petrographic, and isotopic data are presented in a companion paper [6].

Spectral Analysis: Two major benefits of infrared spectroscopy are sensitivity to mineralogy (chemistry and structure) and the ability to detect H_2O/OH^-. We use a Thermo Scientific iN10 FTIR microscope to measure reflectance from 4,000 - 400 cm^{-1} (2.5 - 25 μm) at a spectral resolution of 4 cm^{-1}. We measured a whole-fragment map of AhS 202 from a polished mount at 200 μm/pixel resolution; we zeroed out pixels that fell off the sample or on fusion crust. We averaged the remaining 163 pixels to obtain the bulk spectrum of the fragment. We acquired targeted measurements of individual minerals and matrix at spot sizes as small as 40 x 40 μm. We show spectra converted to emissivity via Kirchhoff's Law; [7] describes details of the instrument and data processing.

Results: The whole-fragment spectrum of AhS 202 exhibits an overall similarity with low petrologic type CC meteorites (Figure 1). However, there are differences in the positions and number of absorption band minima and maxima that indicate a difference in mineralogy. In the course of identifying minerals in the μ-
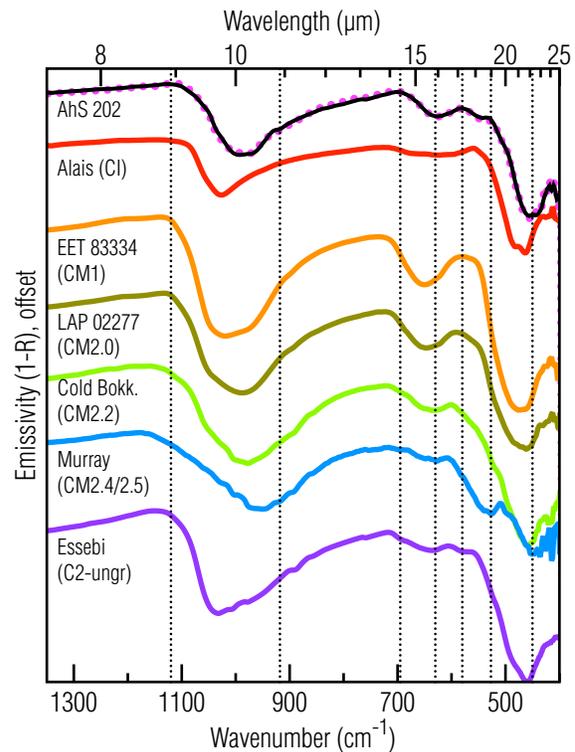

Fig. 1. Average AhS 202 (black) and modeled spectra (dotted pink) compared to CC. Non-AhS sample spectra from [8]. Vertical lines denote key features in AhS 202.

FTIR map of AhS 202, we observed a silicate spectral signature that included features not consistent with phyllosilicates, olivine, or pyroxene, the dominant silicates in CC meteorites. Targeted measurements isolating the silicate allow us to unambiguously identify it as the amphibole tremolite (Figure 2). Subsequent review of the electron microprobe analyses (EPMA) of these grains, initially thought to be pyroxene, confirmed they are tremolite [6]. These spectra also exhibit a clear ~2.7 μm OH$^-$ feature (not shown).

As a first step in determining modal mineralogy, we used a spectral library of major component spectra taken from the μ-FTIR map to linearly model [9] the bulk spectrum. Specifically, we selected spectra representing the dominant spectral signatures of phyllosilicate, olivine, magnetite, and tremolite (sulfides are spectrally neutral). The fit is shown in Figure 1 and demonstrates that the bulk spectrum can be replicated
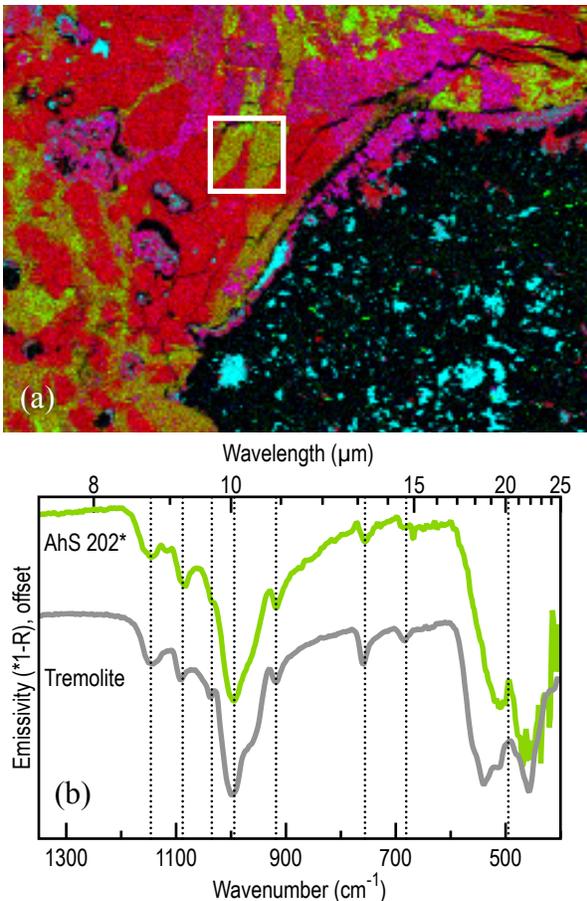
Figure 2. (a) Location of targeted spectral measurement on colorized X-ray map of AhS 202. Red=Mg, Green=Ca, Blue=Al, Cyan=S. White box denoting spectral measurement area is 50 x 50 μm. (b) Spectral measurement from AhS 202 and terrestrial tremolite.

extremely well with these components. Retrieved vol% abundances are: phyllosilicate = 77±2%, olivine = 12±<1%, magnetite = 6±<1%, and tremolite = 5±<1%. We consider this to be a *minimum* tremolite abundance as the matrix phyllosilicate spectra likely also include a small amount of tremolite. The olivine is spectrally determined to be ~Fo_{70} [10], consistent with EPMA chemistry [6]. We are working to isolate the (spectral) end member phyllosilicate spectra so that future models will distinguish between the abundances of Mg-serpentine, smectite (saponite), and septochlorite.

We also used this library to model the mineralogy of each individual pixel in the map to obtain the physical distribution of each component. Focusing on tremolite, we find that it is present within chondrules as well as outside of them (as is also observed in BSE images, *e.g.,* Figure 2 and [6]).

Discussion: Amphibole is exceedingly rare in chondritic meteorites. Terrestrially, tremolite is formed at elevated temperatures and pressures associated with greenschist facies metamorphism. Although some CI and CV meteorites have been heated to temperatures as high as 700°C, these events have not resulted in the conditions required for the widespread formation of abundant amphibole [*e.g.,* 11-12]. The only previously described occurrence of amphibole in a CC is in Allende ($CV3_{oxA}$) [13], where minor veins (~0.2 μm wide) of talc and calcic amphibole (hornblende) have been identified in phenocrysts of clinoenstatite within chondrules (and also as inclusions within chondrule olivine). In Allende, these phases are attributed to retrograde hydration of enstatite, and their presence implies relatively higher temperature conditions than are generally attributed to aqueous alteration (*i.e.,* <~150°C). The distribution of these phases points towards metamorphism on the parent body that liberated fluid from serpentine at temperatures >~300°C [13]. Volumetrically significant (~10-15%) abundances of amphibole have been identified only in the R chondrites LaPaz Icefield (LAP) 04840 (ferri-magnesio-hornblende) and Miller Range (MIL) 11207 (edenite) [14, 15], where they are inferred to represent metamorphism on a disrupted and reassembled parent body.

The identification, distribution, and high modal abundance of tremolite in AhS 202 has petrogenetic implications that are summarized in a companion paper [6]. In short, it is likely that tremolite formed on the parent body. We suggest 202 has experienced substantially different temperature, pressure, and fluid interaction conditions than virtually all other CC, potentially on a parent body of considerable mass. This work also demonstrates the value of spectroscopy for distinguishing mineralogy, including the presence of water in the form of H_2O/OH^-, providing a valuable complement to chemical data.

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