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Heating experiments of the Tagish Lake meteorite: Investigation of the effects of short-term heating on chondritic organics

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Abstract—We present in this study the effects of short-term heating on organics in the Tagish Lake meteorite and how the difference in the heating conditions can modify the organic matter (OM) in a way that complicates the interpretation of a parent body’s heating extent with common cosmothermometers. The kinetics of short-term heating and its influence on the organic structure are not well understood, and any study of OM is further complicated by the complex alteration processes of the thermally metamorphosed carbonaceous chondrites—potential analogues of the target asteroid Ryugu of the Hayabusa2 mission—which had experienced posthydration, short-duration local heating. In an attempt to understand the effects of short-term heating on chondritic OM, we investigated the change in the OM contents of the experimentally heated Tagish Lake meteorite samples using Raman spectroscopy, scanning transmission X-ray microscopy utilizing X-ray absorption near edge structure spectroscopy, and ultraperformance liquid chromatography fluorescence detection and quadrupole time of flight hybrid mass spectrometry. Our experiment suggests that graphitization of OM did not take place despite the samples being heated to 900 °C for 96 h, as the OM maturity trend was influenced by the heating conditions, kinetics, and the nature of the OM precursor, such as the presence of abundant oxygenated moieties. Although both the intensity of the 1s−σ* exciton cannot be used to accurately interpret the peak metamorphic temperature of the experimentally heated Tagish Lake sample, the Raman graphite band widths of the heated products significantly differ from that of chondritic OM modified by long-term internal heating.
INTRODUCTION

Carbonaceous chondrites exhibit a wide range of aqueous and thermal alteration characteristics, while some are known to demonstrate mineralogical and petrologic evidence of having been thermally metamorphosed after aqueous alteration. Their occurrences challenge the initial view of which carbonaceous chondrites, that have experienced pervasive aqueous alteration, were not extensively heated. This group of dehydrated meteorites are commonly referred to as thermally metamorphosed carbonaceous chondrites (TMCCs), and their relatively flat visible near-infrared reflectance spectra resemble that of C-, G-, B-, and F-type asteroids that typically have low albedos (Gaffey et al. 1989; Hiroi et al. 1993, 1996). The surfaces of these dark asteroids, which include the C- and B-type target asteroids—Ryugu and Bennu of the ongoing sample return missions, Hayabusa2 and OSIRIS-REx, respectively—are potentially composed of both hydrous and dehydrated minerals, and thus TMCCs are among the best samples that can be studied in the laboratory to reveal the true nature of these carbonaceous asteroids.

Although many TMCCs were previously categorized as Ivuna-type (CI) and Mighei-type (CM) chondrites, they are not strictly CI/CM because they exhibit isotopic and petrographic characteristics that significantly deviate from typical CI/CM, and hence were given the term “CI/CM-like chondrites.” TMCCs consist mainly of dehydrated phyllosilicates, have higher bulk O isotopic compositions (CI-/CM-like chondrites: $\delta^{17}O = +9$ to $12\%_{\text{oo}}$, $\delta^{18}O = +17$ to $22\%_{\text{oo}}$. CM chondrites: $\delta^{17}O = -1$ to $+3\%_{\text{oo}}$, $\delta^{18}O = +5$ to $11\%_{\text{oo}}$), and lower H$_2$O and C contents relative to CI/CM chondrites (Ikeda 1992; Clayton and Mayeda 1999; Tonui et al. 2014). Examples of TMCCs include the C2-ung/CM2TIV Belgica (B)-7904, Yamato (Y)-, Y-82162, Y-86720, Y-980115, and Wisconsin Range (WIS) 91600 (e.g., Akai 1988; Tomeoka et al. 1989a, 1989b; Ikeda 1991, 1992; Nakamura 2005; Nakato et al. 2008; Burton et al. 2014; Tonui et al. 2014; King et al. 2015b; Chan et al. 2016a). Thermal alteration is virtually complete in B-7904 and Y-86720, thus they are considered typical endmembers of TMCCs exhibiting complete dehydration of matrix phyllosilicates (Nakamura 2005; Tonui et al. 2014). The estimated heating durations of TMCCs are surprisingly short when compared to parent body heating with heat sources derived from in situ decay of radionuclides that could last millions of years. The heating conditions of TMCCs were estimated to be 10 to 10$^5$ days at 700°C to 1 to 100 h at 890°C, which suggest that they have experienced short-term heating possibly induced by impact and/or solar radiation (Nakamoto et al. 2008; Yabuta et al. 2010; Chan et al. 2017b).

While the petrology and chemistry of TMCCs have only recently been extensively characterized, we have just begun to study in detail how short-term heating influences their organic contents. We investigated the change in the organic content of the carbonate-poor lithology of the experimentally heated Tagish Lake C2 meteorite, as the chemical and bulk oxygen (O) isotopic compositions ($\delta^{17}O = +8$ to $9\%_{\text{oo}}$, $\delta^{18}O = +18$ to $19\%_{\text{oo}}$) of this lithology bear similarities to that of the TMCCs (Clayton and Mayeda 2001; Engrand et al. 2001; Zolensky et al. 2002). The Tagish Lake meteorite has a bulk carbon (C) content of approximately 4 wt%, of which about <2 wt% comes from IOM and <1 wt% from carbonate C (Pearson et al. 2006; Alexander et al. 2014). Carbonates are relatively uncommon in the carbonate-poor lithology which occur as sparse fine polycrystalline grains of <5 μm (Zolensky et al. 2002), so the contribution of carbonate C to the bulk C content is expected to be lower in this lithology. The carbonate-poor lithology also contains abundant organic nanoglobules with aliphatic and oxygenated function groups that have elevated $\delta D$ and $\delta^{15}N$ values, which suggests a highly primitive, possibly presolar origin for the organics, and their formation in the cold molecular clouds and the outer protosolar disk at extremely low temperatures ($\leq 250$°C) (Nakamura et al. 2002; Nakamura-Messenger et al. 2006). The bulk O isotopic composition and the presence of organic nanoglobules indicate that aqueous alteration occurred at low temperatures (<100°C) (Zolensky et al. 2002). The isotopic compositions ($\delta D = +815$ to 1844%oo, $\delta^{13}C = -14.7$ to $-13.3\%_{\text{oo}}$, $\delta^{15}N = +53$ to 57) of the IOM extracted from the Tagish Lake meteorite are intermediate between that of the IOM in typical CI, CM, and Renazzo-type (CR) chondrites (Herd et al. 2011; Alexander et al. 2014). The more aqueously altered lithology is drawn closer to the least metamorphosed ordinary chondrites (OC), Vigarano-type (CV), and Ormans-type (CO) chondrites, which suggests that the isotopic variation was to a certain extent influenced by aqueous alteration. Nevertheless, only limited changes were observed for the C content, isotopic, and structural properties of the IOM in the Tagish Lake meteorite samples that exhibit different extents of aqueous alteration, which offers another line of evidence toward a low-temperature alteration history (Yabuta et al. 2007; Alexander et al. 2014).

The low-temperature aqueous alteration history of the Tagish Lake meteorite, its moderate IOM abundance relatively unaltered by aqueous processing, and its quick retrieval (frozen) upon an observed fall event without direct hand contact (Brown et al. 2000), justify this meteorite as the perfect and organically pristine candidate for the study of the change in the
OM content by experimental heating. With the use of Raman spectroscopy, scanning transmission X-ray microscopy (STXM) utilizing X-ray absorption near edge structure (XANES) spectroscopy, and ultraperformance liquid chromatography fluorescence detection and quadrupole time of flight hybrid mass spectrometry (UPLC-FD/QToF-MS), we analyzed the compositions of the organic solids and the amino acid contents of the experimentally heated (short-term heating) Tagish Lake samples in detail.

SAMPLES AND METHODS

The Tagish Lake meteorite has two main lithologies—carbonate-poor (the dominant lithology) and carbonate-rich (less abundant lithology) (Zolensky et al. 2002) (Fig. 1). Different Tagish Lake meteorite fragments also exhibit a wide variation in the organic content that correlates to the extent of parent body aqueous alteration (Tagish Lake specimens showing an increasing degree of aqueous alteration: 5b [the least aqueously altered] <11h <11i <11v [the most aqueously altered]), where the amino acid abundances are higher in the fragments which show a lower degree of aqueous alteration, while the IOM C contents only decrease slightly with a considerable increase in the aromatic content in the more aqueously altered lithology (e.g., Herd et al. 2011; Glavin et al. 2012; Alexander et al. 2014).

To ensure that our heating experiments and the interpretation of the resulting organic content were not significantly influenced by sample heterogeneity, we selected only the carbonate-poor lithology of the Tagish Lake meteorite (#11). The carbonate-poor lithology was located by mineral identification via X-ray computed tomography (XRCT) at the High-Resolution X-ray Computed Tomography Facility at The University of Texas at Austin. Tomographic imaging was critical in identifying internal lithologic and mineralogical differences, which we used to decide where to make the initial slice into the sample and prepare thin sections. The initial samples were then characterized by scanning electron microscopy (SEM) and energy-dispersive spectrometry (EDS) to verify the carbonate-poor lithology based on elemental mapping and comparison to the XRCT images (Fig. 1).
We then subsampled the carbonate-poor lithology into four equal portions, each weighing approximately 200 mg. Half of the samples was used in this study, while the other half was analyzed to determine the variation in chemical, petrography, mineralogy, and bulk O isotope compositions upon heating, using synchrotron X-ray diffraction (XRD) analysis at the High Energy Accelerator Research Organization (KEK) using beam line BL-3A, and SEM/EDS, electron probe microanalyzer equipped with a wavelength dispersive spectrometer (EPMA/WDS), transmission electron microscopy (TEM), and laser fluorination mass spectrometer at JAXA/ISAS. The results of the second portion of the sample are discussed in Nakato et al. (2016).

**XRCT**

The Tagish Lake meteorite sample was scanned at the University of Texas High-Resolution X-ray Computed Tomography Facility using the Xradia microXCT Scanner (Zeiss). The detector permits cone-beam acquisition, and under the ultrahigh-resolution mode, 882 slices were collected covering the entire scan volume in a single rotation. Images were obtained by relatively low-energy X-rays (80 kV), 10W, 2.5 s acquisition time, with a spatial resolution (voxel size) of 46 μm.

**SEM/EDS**

Secondary electron (SE) imaging and mineral elemental compositions were obtained using the Zeiss SUPRA 55VP field-emission (FE) SEM at the Structural Engineering Division, NASA Johnson Space Center (JSC) (Fig. S1). Fragments of the Tagish Lake meteorite were mounted in indium and prepared in the same manner as described in Chan et al. (2016b). The SEM parameters were: accelerating voltage = 20 kV; aperture = 120 mm (largest); high current mode = on; beam size = approximately 3–5 nm; incident beam current = 9.2–9.3 nA; working distance ~ 6 mm.

**Heating Experiments**

Subsamples (~100 mg) of the carbonate-poor Tagish Lake lithology were subjected to heating experiments at 600 and 900 °C for 1 and 96 h; i.e., (1) 600 °C/1 h, (2) 600 °C/96 h, (3) 900 °C/1 h, and (4) 900 °C/96 h. During the experiments, the heating chamber was kept under a controlled environment. To reproduce the secondary iron-bearing minerals in B-7904 heated chondrite that contains both Fe and Fe\(^{2+}\), a Fe metal rod was put in the chamber with the O fugacity kept at the condition closer to that of the iron-wüstite (IW) buffer. The estimated pressure was below $5 \times 10^{-3}$ Pa. The detailed experimental configuration is shown in Nakato et al. (2008).

**Raman Spectroscopy**

The unheated and heated Tagish Lake samples were analyzed using a Jobin-Yvon Horiba LabRam HR (800 nm) Raman microprobe at NASA JSC. The excitation source was a 514 nm (green) laser. The slit width and the confocal pinhole aperture were set at 100 μm and 200 μm, respectively, and an 1800 grooves/mm grating was used to disperse the Raman signal. The laser beam was focused through a microscope equipped with an 80× objective (numerical aperture = 0.75), and the Raman backscattered light was collected from the same objective. At this magnification and for the laser used, the minimum achievable spot size was approximately 1 μm, and the laser power at the sample surface was ≤450 μW. At least 12 spectra were collected on each raw matrix grain (flattened between two glass slides) in the spectral range of 100–4000 cm\(^{-1}\). This spectral range includes the first- and second-order Raman bands of carbon. The exposure time for each spectrum was 15 s and three accumulations were obtained for each analytical spot to identify and discard spurious signals, such as those from cosmic rays, leading to a total acquisition time of up to 450 s with the use of an Extended Range option to collect data in various spectral windows.

The peak position ($\omega$) and full width half-maximum (FWHM, $\Gamma$) of each Raman band were determined by simultaneous peak fitting to the two-peak Lorentzian and Breit–Wigner–Fano (BWF) model (Ferrari and Robertson 2000) with a linear baseline correction (Figs. S2 and S3 in supporting information). Wavelength calibration against a silicon wafer sample was checked daily prior to sample analyses. Details of the Raman technique are given in Chan et al. (2017b) and Kebukawa et al. (2017).

**STXM-XANES**

Focused ion beam (FIB) thin sections of the heated and unheated Tagish Lake samples were prepared using a FIB (Hitachi, FB2200) at ISAS/JAXA for three STXM-XANES analyses (February 2016, May 2016, and December 2016). We subsampled FIB sections for each STXM-XANES analysis in order to investigate the sample heterogeneity. C-XANES measurements were performed using the compact-STXM installed at BL-13A beamline of the Photon Factory (PF), High Energy Accelerator Research Organization (KEK), and the
STXM installed at beamline 5.3.2.2 of the Advanced Light Source, Lawrence Berkeley National Laboratory. The details of these instruments are described in Kilcoyne et al. (2003) and Takeichi et al. (2016). The C-XANES spectra were acquired using a “Stacks” method, with the energy step sizes of 0.1 eV in the region of 283–295.5 eV, 0.5 eV in the regions of 280–283 eV and 295.5–301.0 eV, and 1 eV in the region of 301–310 eV. The acquisition time for each energy step varied from 1 to 5 ms. The C-XANES spectra were corrected with background and analyzed by the subtraction of a linear regression using aXis2000 software, and then normalized to the intensity at 292 eV.

**UPLC-FD/QToF-MS**

The amino acid extraction was conducted at NASA JSC in the same manner as described in Chan et al. (2018). Porcelain mortars and pestles were scrubbed and washed with dilute soap solution, rinsed with Millipore Integral 10 UV (18.2 MΩ cm, <3 parts-per-billion [ppb] total organic carbon) ultrapure water, hereafter referred to as “water,” immersed in 20% citric acid and sonicated at room temperature for 60 min. All tools, glassware, and ceramics were rinsed with water, wrapped in aluminum foil, and sterilized by heating in air at 500 °C for 24 h. Volumetric flasks were only rinsed with copious water. Amino acid standards and other laboratory chemicals such as ammonium hydroxide (NH₄OH) (28–30 wt%), sodium hydroxide (NaOH), hydrochloric acid (HCl) (37%), methanol, hydrazine monohydrochloride, o-phthaldialdehyde (OPA), and N-acetyl-l-cysteine (NAC) were obtained from Fischer Scientific, Sigma-Aldrich, or Acros Organics. Poly-Prep® prepacked ion exchange columns (AG 50W-X8 resin, 200–400 mesh, hydrogen form) were obtained from Bio-Rad. Solutions of sodium borate were prepared from solid sodium tetraborate decahydrate (Sigma Ultra 99.5–100% purity) that was heated in air at 500 °C for 24 h prior to dissolution in water. Amino acid standard solutions were made by dissolving individual amino acid solutes in water, and were combined into a standard mixture analyzed by UPLC-FD/QToF-MS on a daily basis.

The unheated and heated Tagish Lake meteorite samples were powdered and transferred to individual glass ampoules. Sterilized (500 °C, 24 h) laboratory quartz samples were subjected to the same heating experiment and amino acid extraction procedures and analyzed as procedural blanks.

One milliliter of water was added to each glass ampoule containing separate samples, and the ampoules were flame-sealed and heated to 100 °C for 24 h in an oven. After the hot water extraction, the samples were cooled to room temperature and centrifuged for 5 min to separate water supernatant from solid particulate. Exactly half of the water supernatant (500 µL) was transferred to a small test tube (10 × 75 mm), dried under vacuum (Savant™ SPD131DDA SpeedVac™ Concentrator), flame-sealed in a larger test tube (20 × 150 mm) containing 6 N HCl, and then subjected to acid vapor hydrolysis for 3 h at 150 °C in order to liberate amino acids in bound or precursor forms. After the vapor hydrolysis procedure, the test tubes were rinsed with water, and the bottom of the test tubes were opened to retrieve the inner small test tubes, and this portion of the sample is hereafter referred to as the “hydrolyzed extract,” representing the total amino acid contents of the samples. The remaining hot-water extract was rinsed with 2 × 1 mL water and the supernatant was transferred to individual test tubes, this portion of the sample is hereafter referred to as the “nonhydrolyzed extract” (not described further in this study), containing only the free amino acids. Both hydrolyzed and nonhydrolyzed samples were then brought up in 3 × 1 mL of water and desalted on a cation exchange resin. Amino acids were eluted with 2 × 3.5 mL of 2 M NH₄OH. The eluates were collected in small test tubes and evaporated to dryness. The samples were transferred to small sample vials, redissolved in 100 µL of water, and stored at −20 °C. Immediately before UPLC-FD/QToF-MS analysis, the samples were derivatized with OPA/NAC fluorescent derivatization (Glavin et al. 2006). Of the thawed sample, 25 µL was dried under vacuum, resuspended in 20 µL 0.1 M sodium borate buffer (pH 9), and derivatized with 5 µL OPA/NAC in 1 mL autosampler glass vials. The derivatization reaction was then quenched after 15 min at room temperature with 75 µL of 0.1 M hydrazine hydrate.

The amino acid abundances and distributions were measured by UPLC-FD/QToF-MS at NASA JSC, using a Waters ACQUITY ultrahigh performance LC and a Waters ACQUITY fluorescence detector connected in series to a Waters LCT Premier ToF-MS. About 25 µL of the derivatized samples were separated using a Waters BEH C18 column (2.1 × 50 mm, 1.7 µm particle size) followed by a second Waters BEH phenyl column (2.1 × 150 mm, 1.7 µm particle size). Chromatographic conditions were: column temperature, 30 °C; flow rate, 150 µL min⁻¹; solvent A (50 mM ammonium formate, 8% methanol, pH 8.0); solvent B (methanol); gradient, time in minutes (%B): 0 (0), 35 (55), 45 (100). The electrospray and mass spectrometer conditions have been described by Glavin et al. (2006). Amino acids in the samples were identified by correlating sample compounds with known standards.
using the representative masses and fluorescence responses of the OPA/NAC amino acid derivatives at the expected chromatographic retention times.

RESULTS

The Tagish Lake meteorite fragments heated under the four experiments show distinctive textural, mineralogical, structural, and chemical changes (Fig. 2). The mineralogy and texture of the Tagish Lake samples heated at 900 \( ^\circ \)C show the closest resemblance to that of the strongly heated TMCCs due to the dehydration of hydrous minerals such as phyllosilicates and formation of magnetite, and recrystallization back into anhydrous fine-grained (<100 nm) secondary olivine, pyroxene, Fe-Ni metal, and troilite (Nakato et al. 2016). Therefore, while phyllosilicates (e.g., saponite and serpentine), magnetite, and Fe-Ni sulfides are common mineral phases observed in the matrix of the unheated carbonate-poor lithology of the Tagish Lake meteorite (Zolensky et al. 2002), the Tagish Lake samples heated to 900 \( ^\circ \)C show mineral assemblages of predominantly anhydrous silicates, metal, and troilite (Nakato et al. 2016). Upon heating at 900 \( ^\circ \)C, oxidation of organics has reduced the total C contents of the Tagish Lake samples down to approximately 20% of that of the unheated counterpart, and thus the majority of the IOM was decomposed after heating (Nakamura, personal communication). Short-term heating derived from impact events on the parent body can dehydrate the hydrous minerals and liberate a large amount of water vapor. Water under high temperature and pressure conditions (above the critical point) has a reduced dielectric constant (from \( \sim 80 \) to \(<10\) which exhibits properties similar to organic solvent (Savage 1999; Katritzky et al. 2001; Yabuta et al. 2007; Aubrey et al. 2008). Supercritical water is also known to be capable of decomposing and oxidizing organic compounds such as alkanes, aromatics, and nitrogen-containing compounds (Bleyl et al. 1997; Savage 1999), which elucidates the reduction in total C upon heating at 900 \( ^\circ \)C. This also accounts for the increase in the abundance of metallic Fe produced by the reduction of silicate FeO. The changes in mineralogical and isotopic compositions are discussed in more detail in a separate paper. In this paper, we focus on the changes observed in the organic contents of the meteorite fragments.

Raman C Parameters of the Tagish Lake OM

OM in the Unheated Tagish Lake Meteorite

Carbonaceous materials feature Raman bands in the first- and second-order regions. The most typical peaks are the first-order defect (D) band at \( \sim 1350—1380 \) cm\(^{-1}\) and the graphite (G) band at \( \sim 1580—1590 \) cm\(^{-1}\) (Tuinstra and Koenig 1970a, 1970b). The peak parameters of the D and G bands, such as the peak center locations (usually referred to as peak position, \( \omega \)), peak widths in terms of full width half-maximum (FWHM, \( \Gamma \)), and the peak intensity ratios between the D and G bands (\( I_D/I_G \)), were documented to systematically correlate with various properties of
OM in meteorites. The combination of these peak parameters describes the overall size distribution of the crystalline domains and the metamorphic history of the carbonaceous host (Beyssac et al. 2002; Quirico et al. 2003; Bonal et al. 2006, 2007; Busemann et al. 2007; Aoya et al. 2010; Kouketsu et al. 2014; Homma et al. 2015; Chan et al. 2017b).

Due to the sample heterogeneity of the Tagish Lake meteorite (Zolensky et al. 2002), and the adoption of different analytical methods and peak fitting algorithm, the Raman parameters of the OM in the Tagish Lake meteorite reported by different studies (Nakamura et al. 2002; Matrajt et al. 2004; Busemann et al. 2007; Quirico et al. 2014) are not necessarily the same (Table S1 in supporting information). Nevertheless, all studies are in agreement that the IOM in the Tagish Lake meteorite contains abundant, highly disordered organic material. We have also analyzed separately three of the unheated subsamples from the carbonate-poor lithology of the Tagish Lake meteorite, and the Raman peak parameters of the OM are consistent within this study (Fig. 3).

Heating Experiments

A reduction in the fluorescence background intensity was observed after the Tagish Lake meteorite samples were subjected to the short-term heating experiments (Fig. 4a). The unheated Tagish Lake meteorite fragment has the highest Raman intensity across the 100–4000 cm$^{-1}$ spectral range, which is accompanied by an intense fluorescence signal leading to a steep background slope in the first-order D and G bands spectral region between 1300–1600 cm$^{-1}$. Accordingly, the $I_D/I_G$ ratio increases as the Tagish Lake meteorite sample was exposed to higher heating temperatures (Figs. 3b and 4b). However, while the Raman band parameters show a clear correlation to the heating temperature, heating duration affects these parameters to a lesser extent. For instance, while samples heated to 900 °C for 96 h (shown as the diagonal-line-patterned symbols in Fig. 3) has a lower fluorescence intensity, lower $\Gamma_D$ and $\omega_D$ values than the 1 h counterparts, this trend is opposite for the samples heated to 600 °C. The difference in the 1 h and 96 h heating durations might not be significant enough to cause any observable variation in the Raman signatures.

C-XANES Analysis of the Tagish Lake OM

OM in the Unheated Tagish Lake Meteorite

C-XANES spectroscopy is useful for detecting organic functional groups albeit incapable of characterizing the structure of the entire organic molecule. The OM in the Tagish Lake meteorite bears similarities to the IOM in the highly primitive CI, CR, and CM carbonaceous chondrites (Cody et al. 2008a; Alexander et al. 2014; Le Guillou et al. 2014), in terms of the types and relative abundance of the chemical moieties. The C-XANES spectra of the unheated Tagish Lake meteorite sample (Fig. 5a) reveal an absorption feature at ≈285.0 eV that is assigned to the 1s–π* transition of alkenyl and aromatic (C=C) carbon (Cody et al. 2008a). The weak peak at around 286.5 eV indicates a minor contribution of ketones (C=O), and at ≈287.5 eV indicates aliphatic carbon (CH$_x$). However, the 287.5 eV feature is not distinctive in the Tagish Lake meteorite, probably due to (1) the small H/C and aliphatic/aromatic ratios of the OM in the more aqueously altered lithology of the Tagish Lake meteorite compared to those of primitive CC (e.g., Herd et al. 2011; Alexander et al. 2014), and/or (2) C-XANES is less sensitive to the aliphatic carbon in complex macromolecular OM. The highly aromatic-rich nature of the OM suggests that this Tagish Lake sample is more comparable to the aqueously altered specimens such as 11v and 11i rather than 5b analyzed in previous studies (e.g., Herd et al. 2011), while the Tagish Lake sample analyzed in Cody and Alexander (2005) was acquired from the JSC collection and suggested to be 11v-like. The peak centered at ≈288.5 eV corresponds to a 1s–π* transition associated with carbonyl carbon in carboxyl moieties and esters (O–C=O) (Lessard et al. 2007). In some locations, a small peak at 290.5 eV can be observed, which is assigned to the 1s–π* of carbonate. Differences in the presence and intensities of the abovementioned peaks measured on different days on FIB sections extracted from adjacent areas of the same sample chip indicate significant sample heterogeneity (Fig. 5a).

Heating Experiments

Due to the significant sample heterogeneity, it was difficult to directly correlate any systematic variation in the organic structure to the extent of heating (Fig. 5). The aromatic feature (C=C) at ≈285.0 eV was expected to be more prominent in the heated samples as thermal annealing typically converts $sp^2$ C into aromatic $sp^3$ C and leads to an increase in the size of the aromatic moieties (Dischler et al. 1983; Derenne and Robert 2010). However, as shown in Fig. 5b, the 285.0 eV peak intensity of the 900 °C samples (magenta and red lines) is not always higher than the unheated (black lines) or the 600 °C samples (blue and green lines). We have also conducted C-XANES spectral fitting following the procedure described in Bernard et al. (2010) (Fig. 6), derived from Gaussian fits to the major X-ray absorption features, in order to provide better quantification estimates for the absorption band intensities. An example of a decomposed spectrum is...
provided in Fig. S4 in supporting information. However, we did not observe any distinct trend among the peak area ratios (carboxyl to aliphatic, ketone to aliphatic, and aromatic to aliphatic) across samples that were heated to different extents, as any apparent trend observed were compensated by the error bars which represent sample heterogeneity (Fig. 6). In addition, no systematic change was observed for the aliphatic (CH$_n$ at ~287.5 eV) and graphene (at ~291.6 eV) structures upon heating. A 1s–σ* exciton peak is expected if highly conjugated $sp^2$ bonded C domains were present, as in the long-term thermally metamorphosed type 3 chondrites (Cody et al. 2008b), but the peak is absent in the C-XANES spectra of all the experimentally heated Tagish Lake samples. Nevertheless, the apparent lack of trends in the peak area ratio may be hidden by molecular transformation into polycyclic aromatic hydrocarbons (PAHs) that shows several resonances at

Fig. 3. Comparison of the C Raman band parameters of the OM in the heating-experimental products of the Tagish Lake meteorite to the OM in chondrites and IDPs (cyan symbols). Data of the chondrites and IDPs were obtained from Chan et al. (2017a). Uncertainties are 1σ standard deviation of the mean. (Color figure can be viewed at wileyonlinelibrary.com.)
the range of 285–291 eV, in addition to main $\pi^*$ transition at ~285 eV. For example, the 285–291 eV regions of the C-XANES spectra of benzene (which has 3 $\pi^*$ states) and anthracene (which has 7 $\pi^*$ states) are distinct from each other, as benzene has several minor peaks between 287 and 291 eV in addition to a prominent broad peak at ~285 eV, whereas anthracene is comparatively featureless between 287 and 291 eV, while the main feature at ~285 eV is shown as two smaller peaks at around 284 and 286 eV, respectively (Gordon et al. 2003). Therefore, while the intensity at ~287.5 eV is reduced in response to the loss of aliphatic carbon upon heating, heating also simultaneously increases the size of polycyclic aromatic domains (increasing the number of $\pi^*$ states) that show different resonances across the 285–291 eV region of the C-XANES spectrum, which could then lead to a non-systematic variation in the peak area ratio.

**Heating Experiments—Changes in the Amino Acid Content**

The procedural-blank-subtracted amino acid contents of the 6 M HCl-vapor hydrolyzed, hot-water extracts from the unheated and experimentally heated Tagish Lake meteorite samples show peaks that were identified by comparison with amino acid standards, fluorescence, retention time, and mass (Fig. 7; Table 1). The total amino acid abundance (free + bound) of the identified amino acids in the unheated Tagish Lake sample was about 89 parts-per-billion (ppb), which is consistent with the low amino acid abundance observed for the aqueously altered lithology of the Tagish Lake sample (sample 11i, 40–100 ppb) and other TMCCs (e.g., Y-980115 ~300 ppb) in the literature (Pizzarello et al. 2001; Kminek et al. 2002; Herd et al. 2011; Glavin et al. 2012; Burton et al. 2014; Chan et al. 2016a). The relative amino acid abundance (normalized to glycine) of the unheated Tagish Lake sample is also comparable to the aqueously altered lithology of Tagish Lake (Fig. 7).

It is often assumed that the abundance in the aliphatic moieties, including the amino acid content, would be significantly reduced by decarboxylation or conversion into aromatic C upon pyrolysis. Amino acids can be decomposed at temperatures as low as 100 °C (Pietrucci et al. 2018), while proteic amino acids are typically more thermodynamically unstable than non-proteic amino acids (e.g., $\beta$-alanine, $\gamma$-aminobutyric acid [$\gamma$-ABA]) (Kitadai 2016). Therefore, heating up to 600–900 °C is expected to destroy amino acids through processes such as decarboxylation, deamination, and
chain homolysis, which can result in the formation of a variety of simple volatile organic compounds such as amines, carboxylic acids, and hydrocarbons (e.g., Ratcliff et al. 1974; Bada et al. 1995; Pietrucci et al. 2018). While the relative amino acid abundances are similar between the unheated and heated Tagish Lake meteorite samples (Fig. 7), the total (identified) amino acid abundances of the heating experiment product increased by nearly 10-fold from ~89 ppb in the unheated sample to ~760 ppb in the sample heated to 900 °C for 96 h. The total abundances of the nonprotein-forming D-amino acids also increased by a factor of 4–5 in the 900 °C experiments. These results are completely unexpected as any amino acids present in the samples are susceptible to thermal decomposition at high temperatures. One possibility of the increase in the amino acid abundance subsequent to heating is that amino acids are formed from simple precursor molecules such as CO, N₂, and H₂ which serve as feedstock for mineral-catalyzed Fischer–Tropsch-type (FTT) reactions (e.g., Yoshino et al. 1971; Anders et al. 1973; Chan et al. 2012; Pizzarello 2012). The FTT reactions lead to the formation of primarily straight-chain amino acids (e.g., glycine, β-alanine, γ-ABA, ε-amino-n-caproic acid [EACA]) of which the amino group is on the carbon farthest from the carboxylic acid. However, when heated to 900 °C, the minerals commonly associated with FTT reactions such as montmorillonite clay and magnetite are at expense to form anhydrous silicates, metal, and troilite in the Tagish Lake samples (Fig. 2). Although metals can also act as FTT reactions catalysts (Dry 2002), hydrogenation of CO to hydrocarbons is a very slow process in the absence of a suitable catalyst (Lancet and Anders 1970; Hayatsu and Anders 1981). The mineral phases of which the formation thresholds are above

Fig. 5. C-XANES spectra of different FIB sections from the Tagish Lake meteorite samples before and after heating to 600 and 900 °C for 1 and 96 h, obtained on separate dates. The spectra are presented in two subplots: (a) spectra are grouped according to the heating conditions, and (b) spectra are grouped according to different analytical dates. The spectra have been offset vertically to enhance readability. (Color figure can be viewed at wileyonlinelibrary.com.)
350–400 K, such as olivine, Fe, and FeS, are not effective catalysts for the FTT reactions, whereas the phases formed at lower temperatures (e.g., montmorillonite clay and magnetite) are. This elucidates a higher abundance of organic compounds in meteorites containing these mineral phases. Therefore, the formation of amino acids via the FTT reactions in the absence of these effective catalysts should be hindered rather than enhanced. When focusing on the yield of the four-carbon amino acids ABA, the abundances of the straight-chain γ-ABA are not always higher than that of the branched isomers in the heated samples (Fig. 7), which again testify against the production of amino acids via the FTT reactions. The amino acid contents were hampered by the enrichment in the L-enantiomers (e.g., the L-enantiomeric excesses (L ee) of aspartic acid in the unheated Tagish Lake sample = −1.3% and 900 °C 96 h experiment product = 36.9%), and thus the other cause for the apparent increase in the amino acid abundance is that the amino acids were potentially terrestrial contaminants, possibly introduced via additional sample handling during the heating experiments. Even though the aqueously altered Tagish Lake sample is commonly known to exhibit a large L ee of ~45 to 99% for the proteic amino acids threonine, serine, aspartic, and glutamic acids (Glavin et al. 2012), it is difficult to completely eliminate the possibility of a contribution from terrestrial contamination for this work, in particular when compound-specific isotopic analysis was implausible due to the low amino acid abundance in this lithology. In addition, Glavin et al. (2012) observed a racemic ratio for the indigenous alanine in the Tagish Lake meteorite, and yet the alanine in the experiments exhibits L ee. Therefore, the carbonate-poor lithology of the Tagish Lake meteorite in this study corresponds to the aqueously altered counterparts with very low amino acid abundance, and a confident interpretation of the change in the amino acid content upon heating is challenging at present. Therefore, we direct our focus onto the insoluble macromolecular material in the Tagish Lake meteorite.

**DISCUSSION**

**IOM in the Unheated Tagish Lake Sample**

The high abundance of aromatic material in the aqueously altered lithology of the unheated (without being treated with experimental heating) Tagish Lake...
The amino acid content of the acid hydrolyzed hot-water extract of the aqueously altered lithology (#11i) of the Tagish Lake meteorite was given by Glavin et al. (2012).

Asp = aspartic acid; Glu = glutamic acid; Ser = serine; Thr = threonine; Gly = glycine; Ala = alanine; ABA = aminobutyrlic acid; AIB = aminoisobutyric acid; EACA = ε-amino-γ-caproic acid.

Table 1. Summary of the average abundances (in ppb) of identified amino acids in the blank-corrected 6 M HCl-hydrolyzed (total) hot-water extracts of the unheated and experimentally heated Tagish Lake meteorite measured by UPLC-FD/QToF-MS.

<table>
<thead>
<tr>
<th></th>
<th>Unheated</th>
<th>600 °C 96 h</th>
<th>900 °C 1 h</th>
<th>900 °C 96 h</th>
<th>Unheated 11i</th>
</tr>
</thead>
<tbody>
<tr>
<td>d-Asp</td>
<td>3.8 ± 3.5</td>
<td>5.7 ± 2.9</td>
<td>6.3 ± 5.3</td>
<td>61.3 ± 49</td>
<td>&lt;1</td>
</tr>
<tr>
<td>L-Asp</td>
<td>3.7 ± 0.3</td>
<td>n.d.</td>
<td>8.5 ± 0.6</td>
<td>132.9 ± 13.3</td>
<td>2.6 ± 0.5</td>
</tr>
<tr>
<td>L-Glu</td>
<td>18.3 ± 9.1</td>
<td>n.d.</td>
<td>12.2 ± 6.8</td>
<td>198.5 ± 108</td>
<td>&lt;5.8</td>
</tr>
<tr>
<td>d-Glu</td>
<td>1.7 ± 0.8</td>
<td>n.d.</td>
<td>2.2 ± 2.3</td>
<td>32.2 ± 16.5</td>
<td>0.2 ± 1.6</td>
</tr>
<tr>
<td>d-Ser</td>
<td>0.3 ± 0.2</td>
<td>2.3 ± 2.4</td>
<td>1.5 ± 2</td>
<td>&lt;0.7</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>L-Ser</td>
<td>2.9 ± 0.5</td>
<td>n.d.</td>
<td>6.8 ± 1.6</td>
<td>46.9 ± 17.7</td>
<td>2.1 ± 0.9</td>
</tr>
<tr>
<td>d-Thr</td>
<td>&lt;0.8</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>L-Thr</td>
<td>1.2 ± 0.1</td>
<td>n.d.</td>
<td>4.3 ± 3</td>
<td>30.9 ± 6.3</td>
<td>1.3 ± 0.4</td>
</tr>
<tr>
<td>Gly</td>
<td>21.9 ± 15.4</td>
<td>48.9 ± 47.3</td>
<td>31.1 ± 18.7</td>
<td>116.6 ± 114.1</td>
<td>9.7 ± 4.2</td>
</tr>
<tr>
<td>β-Ala</td>
<td>13.8 ± 1.3</td>
<td>24.4 ± 8</td>
<td>11.4 ± 4.1</td>
<td>7.8 ± 5.7</td>
<td>13.5 ± 0.7</td>
</tr>
<tr>
<td>d-Ala</td>
<td>&lt;1.1</td>
<td>&lt;1.1</td>
<td>&lt;0.8</td>
<td>7.1 ± 0</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>L-Ala</td>
<td>4.2 ± 0.3</td>
<td>n.d.</td>
<td>6.2 ± 0.2</td>
<td>50.3 ± 17.7</td>
<td>&lt;1.6</td>
</tr>
<tr>
<td>γ-ABA</td>
<td>4.3 ± 2.1</td>
<td>5.8 ± 3.7</td>
<td>1.3 ± 0.5</td>
<td>1.3 ± 0.9</td>
<td>1 ± 0.5</td>
</tr>
<tr>
<td>d-β-ABA</td>
<td>&lt;3.6</td>
<td>6.3 ± 8.1</td>
<td>0.4 ± 0.2</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>L-β-ABA</td>
<td>n.d.</td>
<td>&lt;24.2</td>
<td>1.7 ± 1.6</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>α-AIB</td>
<td>9.3 ± 11.5</td>
<td>&lt;17.6</td>
<td>3.1 ± 2</td>
<td>&lt;0.2</td>
<td>1.3 ± 0.2</td>
</tr>
<tr>
<td>d,l,γ-AIB</td>
<td>&lt;3.7</td>
<td>&lt;37.8</td>
<td>1.2 ± 1.7</td>
<td>&lt;0.1</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>EACA</td>
<td>&lt;2</td>
<td>n.d.</td>
<td>2.4 ± 0.2</td>
<td>72.3 ± 41.5</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>Total</td>
<td>~89.1</td>
<td>~133.8</td>
<td>~99.4</td>
<td>~760.3</td>
<td>~41.5</td>
</tr>
<tr>
<td>Total d-amino acids</td>
<td>~8.5</td>
<td>~8.3</td>
<td>~33.8</td>
<td>~41</td>
<td>~12.1</td>
</tr>
</tbody>
</table>

The amino acid content of the acid hydrolyzed hot-water extract of the aqueously altered lithology (#11i) of the Tagish Lake meteorite was given by Glavin et al. (2012).

Asp = aspartic acid; Glu = glutamic acid; Ser = serine; Thr = threonine; Gly = glycine; Ala = alanine; ABA = aminobutyrlic acid; AIB = aminoisobutyric acid; EACA = ε-amino-γ-caproic acid.

meteorite sample is clearly reflected in the C-XANES spectra, unbiased by the OM heterogeneity in the samples (Fig. 5a). The IOM in the Tagish Lake meteorite has the highest aromaticity among all analyzed C1-2 chondrites (Cody and Alexander 2005; Alexander et al. 2014), and is associated with elevated aromatic content and thus resembles that of the mildly heated CM, CV, and CO chondrites (Cody and Alexander 2005; Alexander et al. 2014). In this study, the Tagish Lake meteorite sample exhibits a high abundance of hydrous inorganic materials (e.g., phyllosilicates), a low aliphatic organic content (Fig. 5a), and amino acid abundance (Table 1), which correspond to the most extensively aqueously altered Tagish Lake lithology (e.g., Pizzarello et al. 2001; Zolensky et al. 2002; Herd et al. 2011; Glavin et al. 2012; Alexander et al. 2014). Raman spectroscopy indicates that the IOM in the Tagish Lake meteorite is composed predominantly of highly disordered C (Fig. 3). While the Raman parameters of the IOM show affinity to that of the primitive meteorites and clearly deviate from that of the heavily heated CV and CO chondrites, we can appreciate a uniqueness in the Tagish Lake OM as its D band parameters and δD values do not strictly overlap with those of the other primary meteorites, but rather occur in regions which indicate a higher disordered nature (Fig. 3). Matrajt et al. (2004) suggested a similarity between the Raman spectra of the OM in the Tagish Lake meteorite and chondritic interplanetary dust particles (IDPs). Although the OM in the unheated Tagish Lake
meteorite in our study is also shown to be highly primitive in nature, its C-XANES and Raman spectra are distinct from those obtained for IDPs. The C-XANES spectra of IDPs have a large absorption of aromatic, ketone, and carbonyl C (e.g., Feser et al. 2003; Flynn et al. 2003; Keller et al. 2004). A substantial fraction of the IDP OM is O substituted, and its carbonyl to aromatic C area ratio is higher than that of the Tagish Lake OM (Fig. 5), which suggests a higher thermal/aqueous processing in the latter. The Raman C $\Gamma_G$ value of the Tagish Lake OM is significantly lower than that of IDP OM (Figs. 3c and 3d) (Chan et al. 2017a). The more comparable $\Gamma_G$ values between the heated Tagish Lake and IDP OM are consistent with their higher O contents compared to the unheated Tagish Lake OM.

The dehydration process experienced by the Tagish Lake meteorite was distinctive from long-term parent body metamorphism since graphitization did not take place, as suggested by the absence of the 1s→σ* exciton peak in the C-XANES spectra that would indicate highly conjugated $sp^2$ bonded C domains (graphene structure) (Cody et al. 2008b). Despite the aqueous alteration-induced heating and dehydration processes of the parent body, the heating regime would still be considered to have occurred at “low temperatures” (<300 °C) as no significant C loss has been observed, in contrast to most hydrothermally altered chondritic samples (Yabuta et al. 2007). There is also a small contribution from the oxygenated components as shown by the weak peaks around 288.5 eV in the C-XANES spectra (Fig. 5a) which indicates carboxyl (O=C=O) moieties. The contribution from these oxygenated moieties indicates the onset of a late-stage oxidation process associated with the aqueous event, which echoes with the high abundance of magnetite frambooids and plaquettes in the Tagish Lake meteorite which were formed via oxidation of sulfides (Zolensky et al. 2002; Chan et al. 2016b). The consumption of O in forming the oxides has clearly removed a significant amount of O from the alteration fluid and limited the extent of oxidation of the organic phases.

Although the IOM has experienced a certain extent of heating associated with the dehydration process, the plotted Raman parameters of the aqueously altered lithology of the Tagish Lake meteorite are closer to the region of highly primitive (unheated) meteorites (CMs/CRs) and clearly deviate from that of CV and CO chondrites (Fig. 3). This is because (1) the heating event was associated with a shorter term (<10 million years [Ma]), late-stage, low-temperature (<300 °C) aqueous alteration where water acted as a thermal buffer that substituted long-term (>100 Ma), high-temperature (400–950 °C) parent body thermal metamorphism (e.g., Grimm and McSween 1989; Keil 2000; Fujiya et al. 2013), (2) the aqueous event occurred at lower temperatures, as no significant C loss was associated with the heavily altered lithology (Yabuta et al. 2007), and (3) the Tagish Lake IOM precursor material has a highly primitive nature so that heating induced by short-term aqueous alteration did not extensively anneal the OM. Although primitive OM tends to be susceptible to heating, heating on a short-term basis does not have the required energy to fully transform the highly primitive into highly mature organics.

On the basis of these observations, it is reasonable to conclude that the starting IOM in the Tagish Lake sample prior to the heating experiments was composed of predominantly aromatic structures with a small contribution of short- and highly branched aliphatic hydrocarbons and oxidized $sp^2$ bonded carbon, such as carboxyls and ketones (Fig. 5). NMR spectra reveal that the CO moieties (~COOR and C=O) of the OM in the aqueously altered Tagish Lake meteorite are not protonated, and therefore the CO groups are ketones and not aldehydes (Cody and Alexander 2005).

**Influence of Short-Term Heating on Raman Spectral Features**

The most prominent change observed for the Raman spectrum feature in response to short-term heating is the reduction in the overall spectrum intensity. In fact, the intensity of the Raman signal does not always reflect the OM content as it can also be influenced by many other parameters, such as the focus of the laser. Nevertheless, a very consistent trend has been observed for the heated samples as they all exhibit lower Raman intensity and fluorescence background than the unheated counterpart (Fig. S5 in supporting information). A similar effect of heating on the fluorescence background has been observed for the thermally altered CM chondrites, which suggests that the background can be influenced by the size, distribution, and concentration of OM within the sample matrix (e.g., Quirico et al. 2014). Laser-induced fluorescence related to OM has been attributed to the presence of heteroatoms (e.g., N, O, and S) of conjugated C bonds and aliphatic components (Matrajt et al. 2004; Caro et al. 2006; Busemann et al. 2007), and can be correlated to the reduction in the bulk C content and IOM H/C ratios (Alexander et al. 2007, 2013). Nevertheless, the abundance of heteroatoms in the Tagish Lake IOM is lower than that of IDPs, as suggested by the less prominent ~286.5 eV feature which can be assigned to ketones (C=O), nitrile (C≡N), and/or nitrogen heterocycles (C=N=C) in the unheated Tagish Lake sample (e.g., Cody et al. 2008a; Yabuta et al. 2014) (Fig. 5).
The reduction in the fluorescence background in the heated Tagish Lake sample corresponds to the decarboxylation and dehydrogenation of the aliphatic OM (despite its small abundance) in the meteorite, as the OM in the heated Tagish Lake meteorite gains maturity through thermal annealing by losing hydrogen and heteroatoms (i.e., the hydrogenated amorphous carbons (a-C:H) fraction) to form polyaromatic structures, leads to an increase in the C=C aromatic abundance and reduction in the aliphatic content. Therefore, the H/C ratio of IOM is commonly used as an indicator of the degree of heating in the thermally altered carbonaceous chondrites (Naraoka et al. 2004; Alexander et al. 2007). Heating of the hydrated Tagish Lake sample results in the dehydration of the hydrous minerals (principally saponite and serpentine) for which the released O could further oxidize the OM, while further dehydrogenation could lead to the development of polycondensed aromatic structures, and ultimately a reduction in the overall organic C content through oxidative conversion of IOM to CO2.

While the Raman data indicate that the OM in the heated Tagish Lake meteorite has experienced thermal annealing by losing hydrogen and heteroatoms to form polyaromatic structures, the C-XANES data do not exhibit such a consistent trend between the samples that were subsampled and analyzed on different days. Although the C-XANES data are significantly affected by sample heterogeneity, the narrow spread of the Raman data (represented by the 1σ standard deviation of the mean, n = 11–38) suggests that the trend of the heating effect is significant and not hindered by sample heterogeneity. The theoretical analytical spot size of Raman analysis (~1 μm) is much larger than that of C-XANES (~30 nm) and is therefore representative of the overall organic structure and is less influenced by the OM heterogeneity at the smaller scale.

The D band parameters show a clear trend between the OM structure and the heating temperature (Fig. 3a). The D band corresponds to the breathing modes in rings, which is attributed to the A1g mode, and is inherent in the graphite lattice. It becomes observable when symmetry is broken by a crystallite edge (i.e., in-plane defects). Therefore, the D band is not present in perfectly stacked graphite or OM without aromatic structure (Wang et al. 1990; Ferrari and Robertson 2004), and thus the D band parameters are strong tracers of the maturity of OM that are directly correlated to the presence of defects. The ΓD value is a function of the distribution of the sizes of crystalline domains; therefore, as the Tagish Lake meteorite is heated, the annealed OM is dominated by larger crystalline domains, which leads to a narrower D band width due to reduced defects. The ID/IG ratio increases with heating (Fig. 3b), which indicates that graphitization has not been completed, as large-scale graphitization would have significantly reduced ID/IG (Ferrari and Robertson 2000). Despite the reduction in the heteroatoms and aliphatic contents, the OM is still present as amorphous C and not graphitized. The rapid changes in the D band parameters and the ID/IG ratio in response to heating up to 900 °C, and the insignificant variation between the 1 h and 96 h experiments suggest that the IOM maturation gradient strongly depends on the time/temperature history, and that the Raman C parameters are sensitive to short-term heating. Our observation agrees with Cody et al. (2008b) in that the kinetics could be described by a log-linear behavior in response to a rapid pyrolytic reaction.

Our experimental data also indicate that the heating experiments have led to significant widening of ΓG, and that the ΓG value first increases and then decreases. However, this trend runs counter to that for typical meteoritic organics, where decreasing ΓG is associated with increasing metamorphism (e.g., Busemann et al. 2007) (Figs. 3c and 3d). Although a decrease in ΓG (7–10 cm−1) was associated with samples that were exposed to a longer heating duration (96 h), the ΓG values are still at least 14 cm−1 wider than the unheated samples. The challenge with Raman analysis is that there is no clear functional group-level correlation with Raman parameters, unlike XANES analysis which can directly attribute the absorption features to a certain chemical moiety. Therefore, the present data underscore the fact that the trend observed for different Raman parameters of chondritic IOM is not rigorously tied to one specific molecular structural characteristic.

Despite the complicated influences of varying molecular structures to the Raman parameters, we can appreciate that a certain structural variation can lead to the development of several trends. One confident link is that higher degrees of crystallinity (ordering) favor the development of sharper bands. The G band is attributed to the second E2g double degenerate in-plane vibration modes, which corresponds to the C–C stretching vibration. Complete graphitic ordering into a perfectly stacked graphite results in a sharp narrow G band that corresponds to the sp2 carbons of the graphene network, with the nonbonding π-orbitals only giving rise to weak Van der Waals forces with minimal influences to the parallel carbon layers. Therefore, a prolonged heating event, such as long-term parent body metamorphism, could lead to a reduction in ΓG via graphitic ordering, which could ultimately result in very low ΓG values once graphitization is complete. As a result, given that the OM structure is well characterized, such as by determining the OM graphitization extent and the abundances of oxygenated moieties, the ΓG
values can be used to distinguish between short-term heating and conventional thermal metamorphism.

Our heating experiments provide a clear explanation for the $\Gamma_G$ values observed for TMCCs—their OM maturation does not strictly follow the general trend observed for meteoritic IOM. For instance, with a clear dehydration history indicated by the D band parameters, the G band parameter of the heated ($\geq 700 \degree C$) TMCC Y-86720 plots in the zone of primitive meteorites (Busemann et al. 2007; Quirico et al. 2014), which required an extensive but brief heating episode following aqueous alteration. The $\omega_D$ (1349 cm$^{-1}$) and $\Gamma_D$ (245 cm$^{-1}$) of Y-86720 (Busemann et al. 2007) would roughly place it between the 600 and 900 $\degree C$ experiments on the $\omega_D$ versus $\Gamma_D$ plot of experimentally heated Tagish Lake (Fig. 3a). Other than the disparity between the parameters of the OM heated under laboratory and natural processes elucidates variations in their heating conditions, such as the abovementioned heating kinetics and confining pressure. IOM metamorphosed naturally at depth on a chondritic parent body up to kilometers in radius is exposed to an overburden pressure that is significantly higher than that of our heating experiments (Asphaug et al. 2002). High pressure can enhance the thermal transformation of organic C by reducing the temperature of graphite formation and accelerating the graphitization process, leading to the formation of graphite through gradual loss of hydrogen and other heteroatoms and annealing of structural defects (Davydov et al. 2004). This justifies that short-duration heating at atmospheric pressure is not as favorable for the onset of OM graphitization as metamorphism under high confining pressure.

Absence of High Order Graphitic Component Despite Heating at Elevated Temperatures

Fourier transform infrared (FTIR) spectroscopic analysis indicated that the OM in the Tagish Lake meteorite has a significant contribution from long aliphatic chains (higher CH$_2$/CH$_3$ abundance ratio) compared to other primitive meteorites (Nakamura et al. 2002; Matrajt et al. 2004; Quirico et al. 2014), with a high aromatic to aliphatic intensity ratio (Kebukawa et al. 2011; Alexander et al. 2014). Raman, C-XANES, and nuclear magnetic resonance (NMR) analyses suggested a dominant aromatic constituent (Pizzarello et al. 2001; Matrajt et al. 2004; Cody and Alexander 2005; Busemann et al. 2007; Quirico et al. 2014).

No appreciable change in the aliphatic (CH$_3$ at $\sim$287.5 eV) moieties was observed after the Tagish Lake meteorite samples were treated with experimental heating. Note that aliphatic moieties are present in the Tagish Lake meteorite at a small abundance and are susceptible to heating. As the aqueously altered lithology of the Tagish Lake meteorite has a small initial abundance of aliphatic hydrocarbons, any further change to the aliphatic material in response to heating would be unrecognizable. The aromatic moieties were progressively enriched by the loss of the CO (and/or CH$_4$) moieties. Cleavage of hydrocarbon at elevated temperatures via decomposition of CO intermediaries can form organic acids through partial oxidation, which likely elucidates the high abundance of mono- and dicarboxylic acid content in the Tagish Lake meteorite (Pizzarello et al. 2001). Further loss of aliphatic hydrocarbon and carboxylic acids under prolonged heating would lead to total oxidation, carboxylation, and decarboxylation of the hydrocarbon skeleton into CO$_2$.

While C-XANES analysis of the experimentally heated Tagish Lake is influenced by sample heterogeneity (Fig. 5), our Raman data suggest that the OM in the heated Tagish Lake meteorite samples exhibits lower Raman intensity and fluorescence background, indicating the formation of polyaromatic structures by the loss of hydrogen and heteroatoms (Fig. 3). The widening of $\Gamma_G$ in the experimentally heated samples indicates an increase in development in the sizes of crystalline domains but graphitic ordering did not take place, which would otherwise have reduced the $\Gamma_G$ value. This interpretation is consistent with the C-XANES observation due to the absence of the graphene structure ($\sim$291.6 eV) that corresponds to a 1s--$\sigma^*$ exciton in the heated samples (Cody et al. 2008b). Although Cody et al. (2008b) observed a good correlation between the intensity of the 1s--$\sigma^*$ exciton and Raman spectra parameter, the C-XANES data of the experimentally heated IOM samples were compared with previously published Raman data ($\Gamma_D$ and $\Gamma_G$) of chondritic IOM (Busemann et al. 2007). Therefore, it could be possible that by comparing both the C-XANES and Raman data of the same laboratory-heated IOM would give the same trend we observed in this study.

As noted by Cody et al. (2008b), Murchison IOM samples flash heated for up to 2 s at 600, 1000, and 1400 $\degree C$ in helium, and up to 6 h at 600, 800, and 1000 $\degree C$ in argon; all exhibited a systematic increase in the intensity of the 1s--$\sigma^*$ exciton at $\sim$291.6 eV. In addition to the sharp peak around 291.6 eV, a pronounced broader peak at $\sim$292.3 eV and graphene-like oscillations spanning out to 390 eV in extended X-Ray absorption fine structure (EXAFS) are also indicative of the development of graphene when
studying with X-ray absorption spectroscopy (XAS) (Cody, personal communication). Although our Tagish Lake meteorite samples were heated to temperatures and durations comparable to those outlined in the experiments conducted by Cody et al. (2008b), the C-XANES spectra of the heated Tagish Lake samples showed that OM alteration was not accompanied by the development of the $1s-\sigma^*$ exciton and the OM did not transform into highly conjugated $sp^2$ bonded carbon domains as was clearly shown in the case of Murchison IOM (Cody et al. 2008b) (Fig. 5). Cody et al. (2008b) also recognized that the heated CM Y86720 and other TMCCs were outliers based on a similar concern—Y-86720 does not exhibit any significant evidence of a $1s-\sigma^*$ exciton even though it had been proposed that it was heated to as high as 850 °C (Akai 1992), which suggests that these meteorites have experienced short-term duration heating such as impact (Rubin 1995). The inconsistency between the actual metamorphic temperature and the occurrence of the $1s-\sigma^*$ exciton marries well with the Raman spectral features: parent body metamorphism leads to the reduction in $\Gamma_G$ via graphic ordering of the OM in the chondritic meteorites; however, short-term heating leads to the widening of $\Gamma_G$ of the OM in the Tagish Lake meteorite, probably by increasing the abundance of carboxyl moieties, but not graphic ordering (Fig. 3d). The C=O stretching vibration for carboxylic acids has a strong Raman band at 1640–1685 cm$^{-1}$ (Socrates 2001). Therefore, the presence of carboxylic acids would have widened the $\Gamma_G$ of the OM in the heated Tagish Lake samples.

We discuss here the two possible explanations for the Tagish Lake IOM to behave so differently than Murchison IOM. First, the capacity for the highly altered and aromatic-rich IOM in the Tagish Lake sample (comparable to Tagish Lake specimens 11v and 11i) to further transform into graphene-like material is limited as there is a lack of aliphatic C to begin with (Figs. 5 and 6). Second, while the Tagish Lake IOM is composed predominately of aromatic material, its solvent soluble organic matter (SOM) is dominated by carboxyl and dicarboxyl compounds and a low amino acid abundance (Pizzarello et al. 2001). In contrast, the IOM of Murchison is composed of both aromatic and aliphatic components, but it is more enriched in amino compounds in the soluble fraction (Pizzarello et al. 2001; Martins et al. 2006). Therefore, heating of the OM in the Tagish Lake meteorite significantly enhances the formation of oxygenated moieties, while heating of OM in the Murchison meteorite mainly reduces the abundance of the aliphatic components. With a lower O/C content in Murchison, the total loss of the aliphatic components and their conversion into aromatics far exceeds the formation of carbonyl, which is accompanied by the loss of electrons as H$_2$ (Alexander et al. 2014). Extensive dehydrogenation induces ordering of the aromatic moieties, leading to the development of the $1s-\sigma^*$ exciton in the heated Murchison sample observed by C-XANES (Cody et al. 2008b).

**Implications for Upcoming Missions Visiting C-Complex Asteroids**

Small bodies are often loosely bound rubble-pile objects that were disrupted into fragments before being re-accreted, and further compacted by subsequent impact events (Okada et al. 2017b). One of the main rationales for the landing site selection of the Hayabusa2 mission is to determine the presence of hydrated minerals by measuring the 3 μm absorption feature with the near-IR spectrometer (NIRS) (1.8–3.2 μm) (Iwata et al. 2013; Okada et al. 2017a). This 3 μm feature gradually diminishes when meteorite samples were heated to 500 °C and disappears at ~700 °C in response to the dehydration of phyllosilicates (Miyamoto and Zolensky 1994; Zolensky et al. 1994). One of the existing visible and near-infrared (VNIR) reflectance spectra (0.5–2.5 μm) of the Cg-type (Binzel et al. 2001), near-Earth asteroid 162173 Ryugu shows an absorption feature centered ~0.7 μm ascribed to Fe$^{2+}$-$Fe^{3+}$ charge transfer in iron-bearing phyllosilicates and/or hydroxylated or oxidized iron-bearing minerals (Vilas 2008). However, the 0.7 μm feature is evident only in this occurrence, while the heating experiment indicated that this feature disappears when Murchison was heated >400 °C (Hiroi et al. 1994; Zolensky et al. 1994). Mid-IR spectra (5–25 μm) of Ryugu have a weak feature in the 11.4–12.5 μm region (McAdam et al. 2015) that can be attributed to absorption bands seen from olivine in TMCCs which indicates dehydroxylation and dehydration of phyllosilicates (King et al. 2015a). The inconsistent occurrence of the 0.7 μm phyllosilicate feature suggests that the surface of Ryugu is heterogeneous, and contains both hydrated and thermally dehydrated indigenous materials (Vilas 2008; Lazzaro et al. 2013). Such heterogeneity is a common property of Main Belt C-complex asteroids (Rivkin et al. 2002); therefore, it is imperative to understand the nature of organic matter and the extent of organics lost in response to thermal processing on these C-complex asteroids, which are the target asteroids of the OSIRIS-REx and Hayabusa2 sample return missions.

Understanding the mineral/organic correlation on TMCCs helps to provide guidance to the spacecraft sampling site selection in order to enhance the chances of a successful collection of the targeted organic group.
The heterogeneity of Ryugu is best described by TMCCs, as they represent hydrated asteroids that were subsequently heated and dehydrated. The conditions of thermal metamorphism experienced by these meteorites are highly variable, as the heating and associated dehydration occurred in situ (Nakamura 2005). Thermal metamorphism, impact heating, and solar radiation have been proposed to be the possible heat sources, but short-term, high-temperature impact is a more likely pathway for the Belgica group meteorites as they appear to show no evidence of prolonged heating (Kimura and Ikeda 1992).

The chemical and bulk O isotopic compositions (Clayton and Mayeda 2001; Engrand et al. 2001; Zolensky et al. 2002) of the matrix of the carbonate-poor lithology of the Tagish Lake meteorite bears significant similarities to the TMCCs. The reflectance spectrum of the Tagish Lake meteorite resembles that observed from P- or D-type asteroids in the outer region of the main asteroid belt to a greater degree than any other meteorite (Brown et al. 2000; Hiroi et al. 2001). The D-type asteroids are expected to contain OM that did not experience any extensive heating and is more primitive than those contained in any known meteorites. The Tagish Lake meteorite has a low amino acid content (Kminek et al. 2002; Glavin et al. 2012), an extensive suite of soluble OM that includes mono- and dicarboxylic acids, pyridine carboxylic acids, and both aliphatic and aromatic hydrocarbons (Pizzarello et al. 2001). Its IOM is enriched in D and 15N, and both aliphatic and aromatic hydrocarbons (Pizzarello and dicarboxylic acids, pyridine carboxylic acids, and an extensive suite of soluble OM that includes mono-

CONCLUSIONS

We explore the effects of short-term heating on the OM in the carbonate-poor, aqueously altered lithology of the Tagish Lake meteorite with Raman spectroscopy,
C-XANES, and UPLC-FD/QToF-MS. OM maturity and graphitization is dependent on the nature of the OM precursor, the heating duration, and temperature; therefore, the Raman and C-XANES spectral features of the OM in the experimentally heated Tagish Lake meteorite samples significantly differ from that of the chondritic OM such as that in Murchison which has a lower abundance of oxygenated moieties, and other meteorite samples which were altered by prolonged metamorphism. Typical cosmothermometers cannot be used to interpret the peak heating temperature of meteorites that were altered by transient heating processes such as impact heating and/or solar radiation. Nevertheless, the effect of short-term heating on the OM in the Tagish Lake meteorite is well demonstrated by the distinctive Raman G band width, and can be used as a guide when typical cosmothermometers cannot be applied.

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REFERENCES


SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article.

**Fig. S1.** EDX X-ray maps of the carbonate-poor lithology. Scale bar is 100 µm.

**Fig. S2.** Peak-fitting results obtained with LBWF curve-fitting model in the first-order region (1000–1800 cm\(^{-1}\)) of the unheated Tagish Lake meteorite sample showing (top) the linear-background-corrected data (○), the fitted spectrum (black smooth solid line) and the decomposed D (green dashed line) and G (red dashed line) bands, (middle) the raw spectrum, and (bottom) the spectral fitting residue.

**Fig. S3.** Comparison of the Raman band parameters of the unheated and experimentally heated Tagish Lake samples obtained by LBWF and 2-Lorentzian (2L) peak-fitting models.

**Fig. S4.** C-XANES spectrum and the spectral fitting procedure of the Tagish Lake meteorite sample (600 °C 96h heating experiment) obtained from the FIB section prepared and analyzed on 2016 Feb. The top subplot shows various Gaussian functions used to model the absorption of known functional groups and their set and actual fitted peak center locations. The middle subplot shows the arctangent function used to model the absorption edge. The bottom subplot shows the spectral fitting residue.

**Fig. S5.** Comparison of the signal intensity between the raw Raman spectra of the unheated and heated Tagish Lake meteorite samples.

**Table S1.** Comparison between the Raman peak parameters of the Tagish Lake meteorite between different studies.

**Movie S1.** Stack of the two-dimensional (2D) axial images of the Tagish Lake meteorite sample (#11).

**Movie S2.** 3D volumetric reconstruction of the Tagish Lake meteorite sample (#11).