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# Multi-technique investigation reveals new mineral, chemical, and textural heterogeneity in the Tagish Lake C2 chondrite

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ABSTRACT

The Tagish Lake meteorite, an ungrouped C2 chondrite that is related to CI and CM chondrites, is a heterogeneous accretionary breccia with several distinct lithologies that, in bulk, are thought to represent the first known sample of a primitive carbonaceous D-type asteroid. Textural and chemical zoning of clasts and matrix have been little studied and promise additional insight into early solar system processes in both the solar nebula and on the Tagish Lake parent asteroid. We have examined an intact 2.9 g fragment and two polished thin sections from the spring 2000 (non-pristine) Tagish Lake collection to ascertain the major mineralogy and textures of notable features such as chondrules, amoeboid olivine aggregates (AOAs), inclusions, clasts, matrix, and fusion crust. We designed three stages of analysis for this friable meteorite: an initial, non-destructive *in situ* reconnaissance by μXRD to document meteorite mineralogy and textures and to identify features of interest, followed by spatially correlated μXRD, SEM-EDX and colour SEM-CL analysis of polished thin sections to fully understand mineralogy and the record of texture development, and finally higher resolution SEM-BSE mapping to document smaller scale relationships.

Our analyses reveal several previously unreported or poorly characterized features: (1) distinctive colour cathodoluminescence (CL) zoning in relict CAI spinel, in chondrule and AOA forsterite, and in calcite nodules occurring throughout the Tagish Lake matrix. Forsterite frequently shows CL colour and intensity zonation that does not correspond with major or minor element differences resolvable with EPMA, indicating a trace element and/or structural CL-activation mechanism for the zonation that is likely of secondary origin; (2) an irregular inclusion dominated by magnesioaluminate spinel, dolomite, and phyllosilicates with traces of a Ca, Ti oxide phase (likely perovskite) interpreted to be a relict CAI; (3) variable preservation of mesostasis glass in porphyritic olivine chondrules. We anticipate that our multi-technique methodology, particularly non-destructive μXRD, can be successfully applied to other rare and friable materials such as the pristine Tagish Lake fragments.



## 1. Introduction: the Tagish Lake C2 chondrite

Carbonaceous (C) chondrites provide the most primitive solar system material accessible on Earth. They carry textural, mineralogical, and compositional clues to processes and environments in the earliest stages of solar system evolution, both in the solar nebula and on parent asteroids (Brearley and Jones, 1998; Scott and Krot, 2005). Carbonaceous chondrites are commonly friable and porous, and are prone to rapid contamination and alteration in the terrestrial environment. Carbonaceous chondrites are rarely recovered soon after they fall; therefore, the recovery of a freshly fallen and relatively unaltered C chondrite is a rare and scientifically valuable event.

The Tagish Lake carbonaceous chondrite fell in northern British Columbia, Canada, on 18 January 2000 (Brown et al., 2000). Fortuitously, a large quantity of fragments fell on the frozen surface of Tagish Lake. A small amount, ~1 kg was recovered within days of the fall event by local resident Jim Brook. In spring 2000, a recovery operation headed by the University of Western Ontario and the University of Calgary recovered ~10 kg of additional material. A comprehensive review of the fall and recovery of the Tagish Lake meteorite was provided by Hildebrand et al. (2006). Tagish Lake is among the most primitive and physically weak meteorites ever studied (Brown et al., 2000). It is also among the few meteorite falls for which pre-entry orbital elements have been determined through the use of a combination of eyewitness, video, photograph, infrasound, and satellite data (Brown et al., 2000, 2002). The orbital data suggest an association with the primitive, organic-rich C, D or P-type asteroids of the outer main belt (Brown et al., 2000; Hildebrand et al., 2006). Infrared spectroscopy also suggests a relationship with outer belt

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D and P-type asteroids (Hiroi et al., 2001; Hiroi and Hasegawa, 2003).

Tagish Lake is an ungrouped C2 chondrite with affinities to both CI and CM chondrites. It is an accretionary breccia consisting of at least two major lithologies, identified as carbonate-poor and carbonate-rich (Zolensky et al., 2002; Simon and Grossman, 2003; Bland et al., 2004). There may be some degree of gradation between these lithologies. The ratio of carbonate-poor to carbonate-rich lithology has been estimated as ~3:2 (Zolensky et al., 2002), but given the heterogeneity of the meteorite and the small fraction of the total amount of recovered material that has been examined thus far, such assessments may be non-representative of the main mass: the amount of material investigated in detail between 2000 and 2006 was no more than 18 g of the pristine material (Herd and Herd, 2007). Both lithologies are characterized by a dark, fine-grained opaque matrix consisting of complex intergrowths of the Fe-bearing phyllosilicate saponite with magnetite, Fe, Ca, Mg, Mn carbonates and Fe, Ni sulfides (Zolensky et al., 2002; Bland et al., 2004). Matrix sulfides consist primarily of pyrrhotite with rare pentlandite (Zolensky et al., 2002; Boctor et al., 2003). The phyllosilicates in the Tagish Lake matrix have previously been identified as saponite complexly intergrown with serpentine based on HR-TEM lattice fringes (Keller and Flynn, 2001; Mikouchi et al., 2001; Noguchi et al., 2002; Zega et al., 2005) and XRD (Bland et al., 2004; Russell, 2006). Matrix carbonate in the carbonate-poor lithology is predominantly siderite whereas the carbonate-rich lithology is dominated by calcite (Nakamura et al., 2003). The carbonate-rich lithology is also much lower in magnetite abundance. Izawa et al. (2010) reported two new possible lithologies: a magnetite- and sulfide-rich 'dark, dusty' material, and a carbonate-rich material dominated by siderite (up to ~25 wt%) rather than calcite (Izawa, 2008; Izawa et al., 2010). Blinova and Herd (2010) and Blinova et al. (2009) also reported new Tagish Lake lithologies including a highly friable, clast-poor and phyllosilicate-rich "dark, dusty" lithology.

Set within the matrix are a variety of clasts including sparse chondrules, amoeboid olivine aggregates (AOA), isolated grains of olivine, uncommon coarse-grained phyllosilicates and rare pyroxene, rare calcium–aluminium rich inclusions (CAI), and irregular carbonate nodules (Zolensky et al., 2002; Bland et al., 2004). Geochemical (Mittlefehldt, 2002; Nakamura et al., 2003), oxygen isotopic (Clayton and Mayeda, 2001; Baker et al., 2002; Russell, 2006; Russell et al., 2010), organic chemical (Pizzarello et al., 2001; Kminek et al., 2002; Binet et al., 2004), and petrologic (Zolensky et al., 2002) studies suggest a relationship between Tagish Lake and the CI and CM chondrites.

## 2. Rationale

Despite the comprehensive overview provided by Zolensky et al. (2002), much of the mass of the remarkably heterogeneous Tagish Lake meteorite remains unstudied and unknown. Here we report mineralogical and textural observations from new Tagish Lake fragments using a reconnaissance strategy that follows three successive stages: an initial, non-destructive *in situ* reconnaissance step using micro X-ray diffraction (μXRD) to document meteorite mineralogy and textures and to identify features of interest, followed by spatially correlated μXRD, scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX), and cathodoluminescence (CL) analysis of polished thin sections to fully understand their mineralogy and textures, and finally higher resolution SEM-BSE mapping to establish spatial context for textural variation.

Recent developments in micro X-ray diffraction (μXRD) have expanded the applicability of X-ray diffraction to *in situ* study of Earth and planetary materials (Flemming, 2007). Micro XRD extends X-ray diffractometry to the scale of 10 s of microns, enabling rapid, non-destructive, *in situ* measurements of crystal structure. This technique is valuable as a 'no-touch' first-pass reconnaissance, which may identify areas for further study, helping to minimize sample manipulation and loss. Furthermore, we demonstrate that micro XRD also provides point-by-point correlation of crystal structure data with other microscopic and microanalytical data, such as imaging and elemental mapping via SEM-EDX and quantitative chemical analysis by electron probe microanalysis (EPMA).

Micro XRD was applied in two ways in this study: to identify the major minerals in an intact fragment of the Tagish Lake C2 carbonaceous chondrite without sample preparation; and in Tagish Lake polished thin sections, in conjunction with SEM-EDX mapping, SEM-CL imagery, and EPMA chemical analysis, providing crystal structure data to complement these chemical analyses. Micro X-ray diffraction has also provided qualitative textural information using a two-dimensional detector, and provides an *in situ* probe of long range order.

## 3. Experimental methods

### 3.1. Micro X-ray diffraction (μXRD)

All μXRD measurements were made using a Bruker-AXS D8 Discover diffractometer using Cu Kα radiation ($\lambda = 1.5418$ Å) at 40 kV accelerating voltage and 40 mA beam current. Göbel mirror parallel beam optics removed Kβ radiation, and maximized diffracted beam intensity for non-flat samples. A nominal beam diameter of 500 μm or 50 μm was produced by an exchangeable pinhole collimator snout. Diffracted X-rays were detected with a two-dimensional general area diffraction detector system (GADDS). Two-dimensional detection also provides a measure of the texture and crystallinity of the sample, by examination of the distribution of diffracted ray intensity along the Debye rings (He, 2003; Helming et al., 2003; Tissot, 2003; Flemming, 2007). The integrated GADDS images were analysed using Bruker-AXS Diffrac Plus Evaluation software (BrukerAXS, 2005), and the International Center for Diffraction Data (ICDD) Powder Diffraction File (PDF-4) database (rev. 2006) for phase identification. Flemming (2007) presented a comprehensive description of μXRD instrumentation and techniques.

### 3.2. Secondary electron microscopy with multi-spectral cathodoluminescence (SEM-CL)

Backscatter electron (BSE), secondary electron (SE), and colour cathodoluminescence (CL) images of polished thin sections were collected with a tungsten-filament Hitachi S-2500C SEM at the Zircon and Accessory Phase Laboratory, University of Western Ontario using Robinson Backscatter and Gatan ChromaCL detectors. The carbon coated thin sections were analysed at high vacuum with an accelerating voltage of 15–20 kV and a working distance of ~10 mm. SEM-CL has the ability to reveal submicron scale variations in electron-stimulated light emissions from polished surfaces; these variations are a proxy for trace element and/or structural variations within several microns of the emitter surface. The electron beam was rastered using a Digiscan II beam controller and the dwell time per pixel was varied over the range of 80–500 μs, depending on the amount of long-lived infrared luminescence (commonly observed in carbonates). CL emission