BULK PHYSICAL PROPERTIES OF THE TAGISH LAKE METEORITE FROZEN PRISTINE FRAGMENTS.
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Introduction: The Tagish Lake meteorite is an ungrouped carbonaceous chondrite that fell in northern British Columbia, Canada, on 18 January 2000. Tagish Lake has been described as perhaps the most primitive meteorite ever discovered [1]. Frozen samples found eight days after the fall have retained volatile organic compounds (e.g. naphthalene); degraded samples were recovered several months later in the spring [1]. A large lithological variation in samples has led to Tagish Lake being described as a breccia composed of breccia [2], with clear evidence of a continuum of aqueous alteration [2,3]. The pristine fragments of Tagish Lake are chemically and physically unstable, and the majority of them are curated at the University of Alberta, in temperatures at or below -10°C. Given the limited amount of this unique material—approximately 820 g remain following initial sampling and thawing of material, and organic studies [3]—it is critical to use non-destructive methods to characterize these pristine samples as much as possible.

Research objectives: In this study, bulk density, grain density, and porosity were determined for a suite of frozen pristine Tagish Lake samples. Bulk and grain volumes were measured within the curation facility via 3D laser imaging and helium pycnometry, respectively. For most samples, a bulk volume and a grain volume were determined, allowing porosity to be derived. The literature values of approximately 1.6–1.7 g/cm³ for bulk density and 35–45% for porosity (from six published sources reported in [4]) are very unusual for meteorites. The main objective of this study is to expand the database of these measurements to include pristine Tagish Lake samples, enabling an evaluation of any frozen volatiles.

Methods: Bulk density is defined as the ratio of the mass to the total volume including the internal pore spaces. The accurate determination of mass is trivial, but measuring volume presents a challenge. A modified Archimedean method, where the fluid has been replaced by 40 µm glass beads, has been successfully used for a variety of meteorites [5]; however, the frozen Tagish Lake samples are too fragile for this method. Instead, 3D non-contact laser imaging was used to determine the bulk volume [6,7]. The Konica Minolta Vivid 9i is a visible light laser camera that generates a 3D point cloud representing the topology of the imaged surface in great detail. A library of images capturing the entire surface of a sample was created. Relevant images were edited and assembled into a watertight 3D model, whose bulk volume was calculated by software.

The Ultrapyc 1200e helium pycnometer was used to determine the grain volume. The pycnometer applies the ideal gas law to measure grain volume, which excludes the internal pore spaces. The Ultrapyc 1200e performs 15 runs per sample. The results of the last five runs are averaged to give the grain volume, which is then used to calculate the grain density and porosity. Porosity is the ratio of the bulk and grain volumes.

Data acquisition was done at a temperature of -10°C. This was not an issue for the helium pycnometer. The laser camera, because of its commercial grade electronics, could not cool below +10°C or the dewpoint. To allow for approximately two-hour imaging sessions in the cold room, a method of insulating the camera was devised, involving several layers of thermal blankets [4].

Results: The results for mass, bulk density, grain density, and porosity are listed in Table 1. In total, 13 samples were imaged with the laser camera. The same fragments were analyzed with the pycnometer except P-1 and P-10a, which were too big to fit into the instrument. The mass of each sample was measured to a precision of ± 0.002 g. The formal uncertainty on the mass, pycnometer, and camera measurements was propagated by quadrature (partial differentiation) to the final results for bulk density, grain density, and porosity. An estimate of the uncertainty for a single volume measurement made with the laser camera was attempted for the first time [4], based on inter-operator variability [7,8] and the alignment error among all of the points that constitute the model [8,9] from previous studies. The bulk volume results from laser imaging appear to be more precise than the results previously obtained by the modified Archimedean method [1,2,4,7]. The uncertainty on the grain volume is the standard deviation of the results from the last five runs.

Discussion: Most of the bulk density results cluster near 1.80 g/cm³. As seen in Figure 1, three samples (P-3a, P-5a, P-9a) were closer to 1.90 g/cm³; of these, two (P-3a, P-5a) appear similar to the dark, dusty lithology [3], interpreted to be more brecciated and altered relative to other specimens. The porosity results of the suite clustered near 30%. The major outlier at 36%, P-4, has an unusual fusion crust texture. Although its interior is not visible, the porosity and unusual crust suggest a different lithological character.

The results from this study differ significantly from the literature data compiled from six published sources [4]. The bulk density of pristine sample P-10a was reported as 1.66 ± 0.10 g/cm³ in [1], in contrast to the result of 1.80 ± 0.03 g/cm³ here. The discrepancy is explained by the use of 1 mm beads in [1], which may overestimate bulk volume, leading to the underestimation of bulk density. Overall, per Figure 1, the literature bulk density is lower and the porosity is higher. The difference likely results from most of the literature values coming from measurements of either degraded or thawed pristine Tagish Lake samples. For these samples, there has been a loss of volatiles. In the frozen pristine samples, some pore space may be occupied by a solid such as water ice, thus increasing bulk density and decreasing porosity. A numerical check can be done by comparing the average "degraded" values for bulk density (1.7 g/cm³) and porosity (40%) from the literature [4] with the average "pristine" values for bulk density (1.8 g/cm³) and porosity (30%) found in this study. If 10% of the solids are removed from the pristine material to increase the porosity to 40%, then the bulk density changes from 1.8 g/cm³ to 1.7 g/cm³ if the density of the solid was 1 g/cm³, *i.e.* that of water ice.

More investigations need to be done on the lithologies of Tagish Lake in order to explain variations in the experimental data. A cautionary note: Tagish Lake is very hygroscopic like many soils. If subjected to a humid environment, it will adsorb water, causing its mass to increase. This effect further complicates data analysis, especially when comparing measurements made by different studies in different environments. As the pristine samples have not been subject to temperatures above -10°C, adsorbed water should not be a factor in this study.

Conclusion: Laser imaging and helium pycnometry are excellent methods by which to systematically and non-destructively characterize fragile material. This study contributed high-precision results for the bulk density, grain density, and porosity of Tagish Lake. Further work—especially on the different lithologies—is needed to get further insight on the physical properties of this unique meteorite.

References: [1] Hildebrand A.R. et al. (2006) *M&PS*, 41, 407–431. [2] Zolensky M.E. et al. (2002) *M&PS*, 37, 737–761. [3] Herd C.D.K. et al. (2011) *Science*, 332, 1304–1307. [4] Ralchenko M. (2013) B.Sc. thesis. [5] Consolmagno G.J. et al. (2008) *Chem. Erde,* 68, 1–29. [6] Smith D.L. et al. (2006) *J. Geophys. Res.,* 111, E10002. [7] McCausland, P.J.A et al. (2011) *M&PS*, 46, 1079–1109. [8] Fry C. (2013) M.Sc. thesis. [9] Fry C. (2011) B.Sc. thesis.

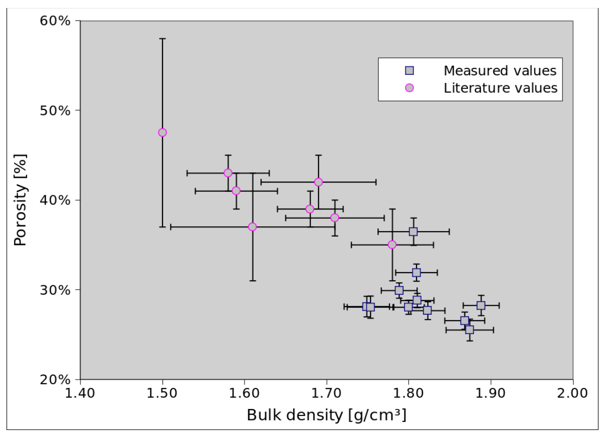

Figure 1: Comparison of bulk density and porosity results to literature values compiled in [4].

Sample ID	Mass [g]	Bulk density [g/cm³]	Grain density [g/cm³]	Porosity [ ]
P-1	157.760 ± 0.002	1.72 ± 0.02	*Fragments too large*	
P-10a	111.017 ± 0.002	1.80 ± 0.03		
P-4	59.957 ± 0.002	1.81 ± 0.04	2.84 ± 0.07	36 ± 2%
P-7	44.910 ± 0.002	1.81 ± 0.03	2.66 ± 0.04	32 ± 1%
P-6	33.548 ± 0.002	1.81 ± 0.02	2.54 ± 0.01	29 ± 1%
P-10b	24.889 ± 0.002	1.79 ± 0.02	2.55 ± 0.01	30 ± 1%
P-9b	20.778 ± 0.002	1.80 ± 0.02	2.50 ± 0.05	28 ± 1%
P-9a	18.314 ± 0.002	1.87 ± 0.02	2.54 ± 0.01	27 ± 1%
P-11b	12.520 ± 0.002	1.75 ± 0.03	2.43 ± 0.03	28 ± 1%
P-3a	11.471 ± 0.002	1.89 ± 0.02	2.63 ± 0.12	28 ± 1%
P-5a	9.450 ± 0.002	1.87 ± 0.03	2.52 ± 0.05	26 ± 1%
P-11r	8.892 ± 0.002	1.75 ± 0.03	2.44 ± 0.05	28 ± 1%
P-11c	8.340 ± 0.002	1.82 ± 0.02	2.52 ± 0.06	28 ± 1%

Table 1: Bulk density, porosity, and grain density for a suite of frozen pristine Tagish Lake samples.