The Tagish Lake Meteorite: A Possible Sample from a D-Type Asteroid

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A new type of carbonaceous chondrite, the Tagish Lake meteorite, exhibits a reflectance spectrum similar to spectra observed from the D-type asteroids, which are relatively abundant in the outer solar system beyond the main asteroid belt and have been inferred to be more primitive than any known meteorite. Until the Tagish Lake fall, these asteroids had no analog in the meteorite collections. The Tagish Lake meteorite is a carbon-rich (4 to 5 weight %), aqueously altered carbonaceous chondrite and contains high concentrations of presolar grains and carbonate minerals, which is consistent with the expectation that the D-type asteroids were originally made of primitive materials and did not experience any extensive heating.

Most meteorites are believed to come from asteroids or extinct comets. The possible parent asteroid of each meteorite class may be determined through reflectance spectroscopy along with considerations of a dynamical mechanism to deliver the meteorite to Earth. However, there are several spectral types of asteroids (*1*) whose meteorite counterparts have not been found. Among them are the P- and D-type asteroids, which are inferred by some to be made of "supercarbonaceous" chondrites (*2, 3*); that is, meteorites richer in carbon than any known carbonaceous chondrite meteorite. Here, we report on a meteorite that may be our first sample from a D-type asteroid: the Tagish Lake meteorite, a new ungrouped C2 chondrite (*4*) that fell to Earth in January 2000.

The Tagish Lake meteorite is a carbon-rich (4 to 5 wt.%), aqueously altered carbonaceous chondrite. It contains high concentrations of presolar grains and Ca-Fe-Mg carbonate minerals, but an unusually low amount of high-temperature nebular materials such as chondrules and calcium/aluminum-rich inclusions (CAI) (*4*). These characteristics are consistent with the expected composition of P- and D-type asteroids or extinct comets (*2, 3*).

Two chip samples of the Tagish Lake meteorite were ground separately and passed through a 125-μm sieve. Although both samples were collected months after the fall and may thus be somewhat degraded, one of them appeared to have remained relatively unaltered. Bidirectional ultraviolet–visible–near infrared reflectance spectra of the two samples were measured at 30° incidence and 0° emergence angles [expressed as (30, 0) below] in the wavelength range of 0.3 to 2.6 μm. Biconical Fourier transform infrared (FTIR) reflectance spectra were also measured in the wavelength range of 1 to 25 μm (*5*). These two samples exhibit the same properties in the 0.3- to 3.6-μm wavelength range, where comparisons with asteroid reflectance spectra are most often made. This suggests that terrestrial weathering has had little, if any, effect on the spectra of these meteorite samples.

The spectrum of the Tagish Lake meteorite sample that visually appears least weathered has been compared with average reflectance spectra of the C-, G-, B-, F-, T-, P-, and D-type asteroids taken from the Eight-Color Asteroid Survey (ECAS) (*6*) and the 52-Color Asteroid Survey (*7*), scaled to the Infrared Astronomical Satellite (IRAS) albedos (*8*) at the 0.55-μm band [Supplementary fig. 1 (*9*)]. Because the reflectivity of the Tagish Lake meteorite is very low (2 to 4%), we only compared its reflectance spectrum with low-albedo asteroid spectra. The spectrum of the Tagish Lake meteorite has a characteristic red slope typical of very fine-grained carbon-containing powdered materials. If we assume the laboratory bidirectional reflectance at 0.55 μm and the asteroid albedos are comparable measures of brightness, the fact that the typical C-, G-, B-, and F-type asteroids have brighter and flatter reflectance spectra than the Tagish Lake spectrum suggests that the Tagish Lake meteorite has a greater content of absorbing species, consistent with its carbon-rich mineralogy (*4*). The spectral shape distinguishes many of the low-albedo asteroids. In terms of the overall spectral slope [Supplementary fig. 1 (*9*)], the T-, P-, or D-type asteroids are good spectral analogs of the Tagish Lake meteorite. In contrast, comparison of the reflectance spectra of the Tagish Lake sample with all the available reflectance spectra of the C-, G-, B-, and F-type asteroids did not reveal any acceptable matches.

The scaled reflectance spectrum of the Tagish Lake meteorite is compared with each kind of spectral class of asteroid analogs (Fig. 1). Whereas most of the P-type asteroids spectrally match the Tagish Lake meteorite in the wavelength range longer than 0.9 μm, they are different in the shorter wavelength range. On the other hand, some of the T- and D-type asteroids spectrally match the Tagish Lake meteorite throughout the entire measured range. The visible reflectivity of the Tagish Lake powder sample prepared in this study, however, is much closer to the average albedo of the D-type asteroids than that of the T-type asteroids [Supplementary fig. 1 (*9*)]. The T asteroids are inferred to have compositions similar to troilite-rich iron meteorites (*10*), which is incompatible with the mineralogy of the Tagish Lake meteorite.

The extended visible spectral shape and albedo of the primitive asteroids are the most decisive factors for identifying the parent body of the Tagish Lake meteorite (Fig. 1) [Supplementary fig. 1 (*9*)]. We used a common spectral ratio to determine the spectral shape information for use with asteroid survey data. The redness is defined as R(853)/R(550), where R(λ) indicates reflectance through one of the ECAS (*6*) bandpass filters centering at λ nm in wavelength, and the brightness is defined as the albedo measured by the IRAS (*8*) or R(550). Reflectance spectra of two additional asteroids were also taken from (*11*),

Table 1. Albedo and diameter *D* (*8*), and semimajor axis *a*, eccentricity *e*, and sine inclination sin(*i*) (*21*) of the D-type asteroids and locations of the Kirkwood Gaps.

Number	Name	Albedo	*D* (km)	*a* (AU)	*e*	sin(*i*)
336	Lacadiera	0.042	72.0	2.252	0.091	0.110
	Gap 3:1			2.500		
	Gap 5:2			2.824		
773	Irmintraud	0.033	99.1	2.858	0.047	0.301
	Gap 7:3			2.956		
368	Haidea	0.032	74.5	3.070	0.170	0.163
	Gap 2:1			3.276		

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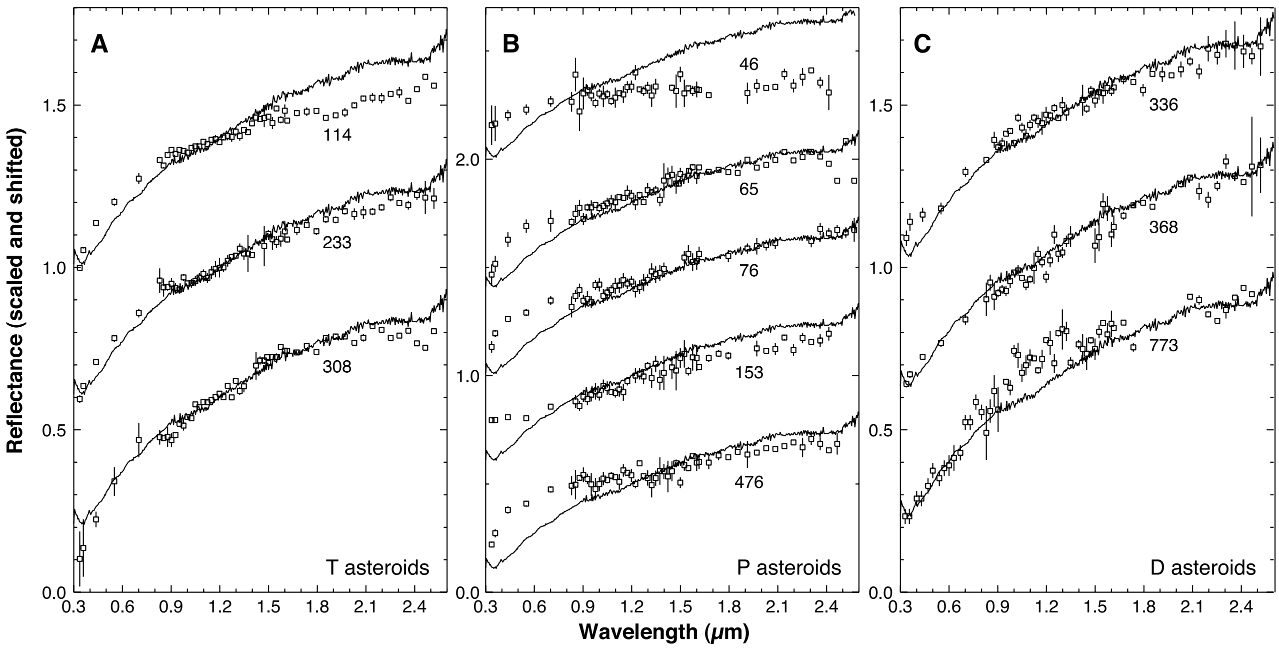

Fig. 1. (**A** to **C**) Comparison of reflectance spectra (*5*) of the Tagish Lake meteorite with individual reflectance spectra of the T-, P-, and D-type asteroids (*6, 7*). Each of the reflectance spectra of the asteroids (open squares) and that of the Tagish Lake meteorite (solid line) are scaled for the best fit with each other for spectral shape comparison. The asteroid-meteorite spectra are then offset from one another for clarity.

from which the R(853) and R(550) values were calculated by convolving the effective transmission curves of the bandpass filters used by the ECAS (*6*) with each of the asteroid spectra. Bidirectional reflectance values of the Tagish Lake sample were similarly converted (Fig. 2). In order to examine the viewing geometry dependence of brightness and redness of the Tagish Lake sample, measurements were also performed at viewing geometries of (11, 0), (6, –6), and (15, –15) because the ECAS measurements were typically at small phase angles (*6*) (Fig. 2). We compared the Tagish Lake spectra with the C-, G-, B-, F-, T-, P-, and D-type asteroid spectra and found that the meteorite is closest to the D-type asteroids in brightness and redness, whereas these measurements also show that varying viewing conditions may produce properties that bridge the spectral characteristics of the D- and P-type asteroids.

Although the redness and albedo of the D-type asteroids are similar to those of the Tagish Lake meteorite (Fig. 2), the case linking the two would be stronger if a common characteristic absorption band could be found, such as in the case of the V-type asteroids and howardite, eucrite, and diogenite (HED) meteorites [e.g., (*12, 13*)]. Most spectra for low-albedo asteroids have low signal-to-noise ratios and few spectral features [Supplementary fig. 1 (*9*)]. Perhaps the best spectral feature for comparison would be the strong hydrous (OH or H_2O) feature near 3 μm. There are four D-type asteroids whose 3-μm reflectance spectra (*14*) are publicly available, and they are compared with our FTIR reflectance spectrum of the Tagish Lake meteorite sample (Fig. 3). Because of the high level of noise of the asteroid 3-μm spectra, this comparison does not give us any conclusive information other than a hint that these D-type asteroids may have shallower spectral bands near 3 μm than the Tagish Lake meteorite. Even if the D-type asteroids have shallower 3-μm bands than the Tagish Lake sample, it may mean that the surface regoliths of the D-type asteroids have undergone dehydration due to space weathering processes such as micrometeorite bombardments or that minor terrestrial contamination has occurred in the Tagish Lake sample. For the former possibility, space weathering simulations (*15, 16*) on the Tagish Lake sample may be useful to evaluate band strength issues.

On the basis of the spectral shape and brightness discussed above, we suggest that the Tagish Lake meteorite is derived from a D-type asteroid. Assuming that the Tagish Lake meteorite came from a D-type asteroid, we can consider whether one of the D asteroids 368, 336, and 773 could be the parent body. Among these three, although 368 Haidea is spectrally closest to the Tagish Lake meteorite (Fig. 1), 773 Irmintraud is closest [<0.034 astronomic units (AU)] to a chaotic zone [e.g., (*17*)] associated with one of the Kirkwood Gaps (Table 1) [Supplementary fig. 2 (*9*)] due to the mean

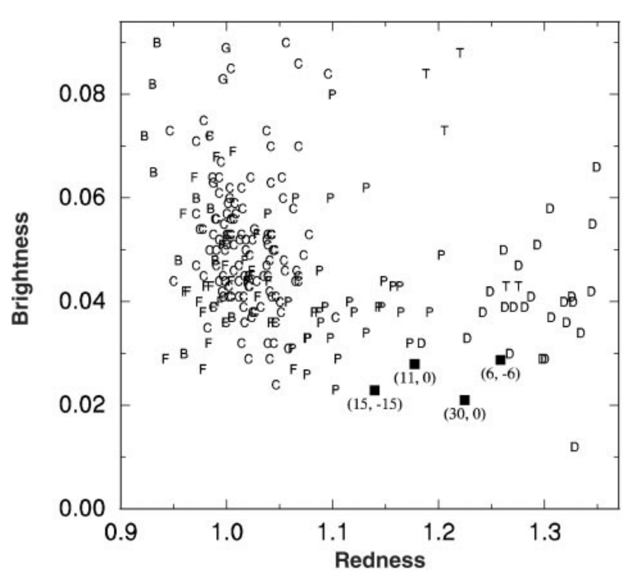

Fig. 2. A plot of the redness and brightness of the low-albedo C-, G-, B-, F-, T-, P-, and D-type asteroids (*6–8, 11*) and the Tagish Lake meteorite sample (filled squares). The redness is defined as R(853)/R(550), where R(λ) indicates reflectance through one of the ECAS (*6*) bandpass filters centered at λ nm in wavelength, and the brightness is defined as the IRAS albedo (*8*) or R(550). Tagish Lake meteorite viewing geometries are indicated as (incidence, emergence) angles in degrees.

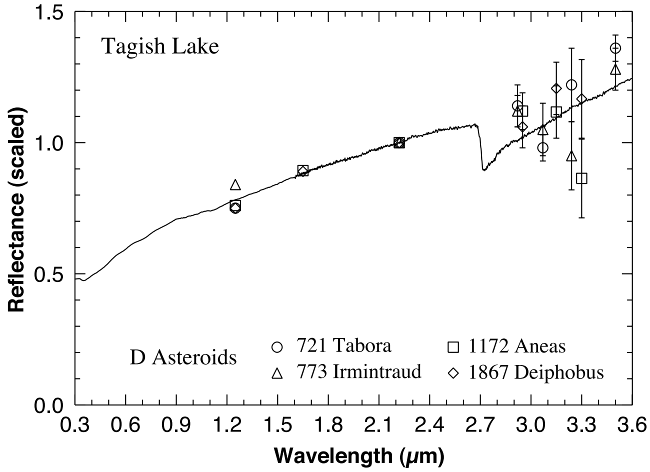

Fig. 3. The 3-μm reflectance spectra (*14*) of four D-type asteroids compared with visible and FT-IR spectrum of the Tagish Lake meteorite sample.

motion resonance with Jupiter. Their IRAS albedos (*8*) of 0.032 and 0.033 are both close to the reflectance of the Tagish Lake sample at 0.55 μm under a viewing geometry of (6, –6) (Fig. 2). More detailed analysis is needed to determine whether ejecta from this asteroid, or other D-type asteroids, can traverse the distance to the chaotic zones [Supplementary fig. 2 (*9*)] when driven by impact ejection energy and the Yarkovsky effect [e.g., (*19, 20*)]. In addition, more extensive telescopic observations are needed to determine whether the apparent spectral difference between 773 Irmintraud and the Tagish Lake meteorite is significant or whether there is a better candidate for the Tagish Lake parent body among other D-type asteroids. The launch efficiency from the Tagish Lake parent body may also be problematic to model because of the low density (1.7 g/cm^3) (*20*) and mechanical weakness of the Tagish Lake meteorite. The kinetic energy of impactors may be absorbed more efficiently on the Tagish Lake parent body than on stronger bodies, resulting in a smaller kinetic energy of the ejecta.

Linking asteroid types to well-studied meteorite classes is a difficult endeavor because extraterrestrial materials that fall to Earth are limited by physical conditions and form an inherently biased sample in time and space. Recovery of the Tagish Lake meteorite suggests that perhaps many more mechanically weak classes of meteorites are destroyed during atmospheric entry before they can be recovered.

References and Notes

1. D. J. Tholen, thesis, University of Arizona, Tuscon, AZ (1984).
2. F. Vilas, B. A. Smith, *Icarus* **64**, 503 (1985).
3. J. F. Bell, D. R. Davis, M. J. Gaffey, in *Asteroids II*, R. P. Binzel, T. Gehrels, M. S. Matthews, Eds. (Univ. of Arizona Press, Tuscon, AZ, 1989), pp. 921–945.
4. P. G. Brown *et al.*, *Science* **290**, 320 (2000).
5. Reflectance spectra of the meteorite samples were measured at RELAB, a multiuser facility supported by NASA grant NAG5-3871. The details of the facility can be found at www.planetary.brown.edu/relab/index.html.
6. B. Zellner, D. J. Tholen, E. F. Tedesco, *Icarus* **61**, 335 (1985).
7. J. F. Bell, P. D. Owensby, B. R. Hawke, M. J. Gaffey, *Lunar Planet. Sci.* **19**, 57 (1989).
8. E. F. Tedesco, in (*3*), pp. 1090–1138.
9. Supplementary figures are available at www.sciencemag.org/cgi/content/full/1063734/DC1.
10. M. J. Gaffey, T. H. Burbine, R. P. Binzel, *Meteoritics* **28**, 161 (1993).
11. S. Xu, R. P. Binzel, T. H. Burbine, S. J. Bus, *Icarus* **115**, 1 (1995).
12. R. P. Binzel, S. Xu, *Science* **260**, 186 (1993).
13. T. B. McCord, J. B. Adams, T. V. Johnson, *Science* **168**, 1445 (1970).
14. L. A. Lebofsky, T. D. Jones, P. D. Owensby, M. A. Feierberg, G. J. Consolmagno, *Icarus* **83**, 16 (1990).
15. M. Yamada *et al.*, *Earth Planets Space* **51**, 1255 (1999).
16. W. Cassidy, B. Hapke, *Icarus* **25**, 371 (1975).
17. A. M. Nobili, in (*3*), pp. 862–879.
18. E. J. Öpik, *Proc. R. Ir. Acad.* **54A**, 165 (1951).
19. D. Vokrouhlický, P. Farinella, *Nature* **407**, 606 (2000).
20. M. Gounelle, M. E. Zolensky, E. Tonui, T. Mikouchi, *Lunar Planet. Sci.* **32** (2001) [CD-ROM].
21. A. Milani, Z. Knezevic, *Icarus* **107**, 219 (1994).

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The Organic Content of the Tagish Lake Meteorite

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The Tagish Lake meteorite fell last year on a frozen lake in Canada and may provide the most pristine material of its kind. Analyses have now shown this carbonaceous chondrite to contain a suite of soluble organic compounds (∼100 parts per million) that includes mono- and dicarboxylic acids, dicarboximides, pyridine carboxylic acids, a sulfonic acid, and both aliphatic and aromatic hydrocarbons. The insoluble carbon exhibits exclusive aromatic character, deuterium enrichment, and fullerenes containing "planetary" helium and argon. The findings provide insight into an outcome of early solar chemical evolution that differs from any seen so far in meteorites.

The biogenic elements have a long cosmic history that spans their stellar nucleosynthesis through complex stages of interstellar, nebular, and planetary processes that preceded life. Some of this prebiotic chemical evolution is recorded in carbonaceous chondrites, a primitive type of meteorite containing organic carbon. Although a majority of this carbon is bound in a kerogenlike, insoluble material, CM and, to a lesser extent, CI chondrites also contain a large and complex suite of soluble organics (*1*). The presence of amino acids and other compounds having terrestrial counterparts has led to speculation that comets and meteorites could have seeded early Earth with bioprecursor molecules (*2*).

The Tagish Lake meteorite fell in January 2000 in Canada and is a carbonaceous chondrite of uncertain classification (*3*). Its fall, brief environmental exposure, and collection at subfreezing conditions were exceptional, raising expectations for a pristine sample. We report here the findings from analyses of the soluble and insoluble organic content of about half (4.5 g) of a pristine (*3*) stone surrounded by fusion crust. We conducted water and solvent extractions of interior powdered samples and nuclear magnetic resonance (NMR) analyses of the insoluble organic material obtained after dissolution of mineral phases. The analytical procedures followed closely those established for the study of similar carbonaceous meteorites (*4–7*).

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