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Petrography and mineral chemistry of the anhydrous component of the Tagish Lake carbonaceous chondrite

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Abstract–Most studies of Tagish Lake have considered features that were either strongly affected by or formed during the extensive hydrous alteration experienced by this meteorite. This has led to some ambiguity as to whether Tagish Lake should be classified a CI, a CM, or something else. Unlike previous workers, we have focused upon the primary, anhydrous component of Tagish Lake, recovered through freeze-thaw disaggregation and density separation and located by thin section mapping. We found many features in common with CMs that are not observed in CIs. In addition to the presence of chondrules and refractory forsterite (which distinguish Tagish Lake from the CIs), we found hibonite-bearing refractory inclusions, spinel-rich inclusions, forsterite aggregates, Cr-, Al-rich spinel, and accretionary mantles on many clasts, which clearly establishes a strong link between Tagish Lake and the CM chondrites. The compositions of isolated olivine crystals in Tagish Lake are also like those found in CMs. We conclude that the anhydrous inclusion population of Tagish Lake was, originally, very much like that of the known CM chondrites and that the inclusions in Tagish Lake are heavily altered, more so than even those in Mighei, which are more heavily altered than those in Murchison.

INTRODUCTION

The Tagish Lake carbonaceous chondrite fell in the Yukon Territory, Canada on January 18, 2000. One week later, ~1 kg of the meteorite was collected from the frozen lake surface, placed in plastic bags, and kept frozen. Additional stones and naturally disaggregated material were collected during the spring thaw in May. Tagish Lake is one of the freshest, most volatile-rich meteorites available for study because the meteorite was initially volatile-rich, fell onto snow and ice, was collected soon after falling and was kept cold. It has provided a unique opportunity for detailed study of easily lost volatile, soluble, and low-temperature components.

Preliminary studies of Tagish Lake (e.g., Brown et al. 2000) showed that it is petrologically unique, with textural, isotopic, and bulk chemical features intermediate between those of CI and CM carbonaceous chondrites. It is matrix- and volatile-rich like CIs, yet contains chondrules and inclusions like CMs. Most studies of Tagish Lake have compared it to these chondrite types on the basis of organic chemistry, bulk composition, or matrix mineralogy and have reached varying conclusions. Studies that considered oxygen isotopes (Clayton and Mayeda 2001; Leshin et al. 2001), bulk organic carbon (Grady et al. 2002), bulk chemistry (Friedrich et al. 2002), and organic compounds (Pizzarello and Huang 2002) concluded that it is different from both CMs and CIs. Based on its bulk density, chondrule and inclusion types, and general mineralogy, Zolensky et al. (2002) concluded that Tagish Lake is distinct from the known CIs, CRs, and CMs and suggested that it is a new kind of type 2 carbonaceous chondrite, while studies of the sulfides (Bullock et al. 2002) and bulk chemistry (Mittlefehldt 2002) showed ways in which Tagish Lake is similar to CMs. Thus, a good understanding of Tagish Lake has remained elusive, and classification of Tagish Lake remains somewhat ambiguous.

In contrast to these previous studies, in the present paper, we focus upon the primary, anhydrous components (olivine crystals, chondrules, and inclusions) that formed at high temperatures and are present in Tagish Lake. In addition to being important recorders of early solar system history, these components can help us determine which, if any, of the previously recognized meteorite types are most closely related to Tagish Lake. The CI chondrites do not contain refractory inclusions (Ca-, Al-rich inclusions, or CAIs), and different types of carbonaceous chondrites have different refractory inclusion populations. Refractory inclusions in the

CM2 chondrites are typically dominated by spinel and/or hibonite, which are oxides, while those in C3s are dominated by melilite and, in some cases, fassaite, which are silicates. In CR2 chondrites, melilite-rich and spinel-pyroxene inclusions are the most abundant (Krot et al. 2002). The CAI population of Tagish Lake, therefore, can help us determine to which clan Tagish Lake is most closely related. In addition, the populations of isolated olivine grains in various types of carbonaceous chondrites, including CIs, have been characterized (Steele 1986, 1990), and analysis of such grains in Tagish Lake provides another means of comparison with recognized meteorite types. Preliminary results of this work have been reported by Simon and Grossman (2001a, 2001b) and by Grossman and Simon (2001).

ANALYTICAL METHODS

We received two allocations (1.15 and 9.68 g) of powder and small (mostly 0.5–1 cm width) chips of the meteorite (previously frozen and thawed material, not from the never-thawed, "pristine" sample). Each chip was examined under a binocular microscope, and fusion crust-bearing chips were separated from chips that were fusion crust-free. Through weighing followed by submersion in distilled water, we obtained a density of 1.8 ± 0.5 g cm^{-3} for a small sampling of fusion crust-free chips, in agreement with the value of 1.66 ± 0.08 reported by Zolensky et al. (2002). A total of 9.1 g of powder and fusion crust-free chips were placed in distilled water and subjected to alternating freeze-thaw cycles until they were completely disaggregated. This required 2–7 cycles, much fewer than the 15–20 required for the disaggregation of the Murchison CM2 chondrite, implying a much higher proportion of phyllosilicate and porosity in Tagish Lake. The lowest-density material (which floated or remained suspended in the water) was decanted. The remaining material was placed into a mixture of methylene iodide and acetone (henceforth, MI, having a bulk $\rho = 3.17$) and was centrifuged to separate the densest material. From the first aliquot (1.15 g), 0.215 g was decanted, 0.788 g floated in MI, and 0.147 g (12.8% of the starting material) was recovered in the dense fraction. From the second aliquot (9.68 g), after removal of chips for polishing and removal of those with fusion crust, 7.97 g was disaggregated; 0.629 g was decanted, 7.19 g floated in MI, and only 0.155 g (1.9%) was recovered in the dense fraction despite repeated stirring and centrifuging. After rinsing and drying, the dense fraction was examined under a binocular microscope. Olivine grains, inclusions, and spherical objects were hand-picked for petrographic study, along with a random "scoop" sample of dense material. In addition, a sampling of objects that floated in MI was taken for study. Samples were studied with a JEOL JSM-5800LV scanning electron microscope (SEM) equipped with an Oxford/Link ISIS-300 energy-dispersive X-ray analysis system. Each hand-picked object was examined in the SEM. We obtained X-ray maps of the polished chips and the scoop sample, and all Al-rich objects were investigated. Quantitative wavelength-dispersive analyses were obtained with a Cameca SX-50 electron microprobe operated at 15 kV with a beam current of 25 nA. The data were reduced via the modified ZAF correction procedure PAP (Pouchou and Pichoir 1984).

RESULTS

Petrography

Refractory Inclusions

We found 4 hibonite-bearing refractory inclusions: three were found in situ and one was in the scoop sample of the dense fraction. Backscattered electron images of these are shown in Fig. 1. The inclusions are spinel-rich, with somewhat sparse hibonite laths, 5–10 μm across, occurring between equant spinel grains that are typically ~5 μm across. Other phases found in these inclusions are perovskite, magnetite, and calcium carbonate. The 3 inclusions found in situ (Figs. 1a–1c) are partially to completely enclosed in phyllosilicate and occur in the carbonate-poor lithology recognized by Zolensky et al. (2002). The fragment from the scoop sample (Fig. 1d) contains the largest hibonite crystal we found, appears to be adjacent to matrix, and has no distinguishable phyllosilicate mantle.

Also present are spinel-rich spherules (Fig. 2a), which have no hibonite, and contain small grains of perovskite enclosed in spinel. Phyllosilicate occurs between spinel grains, and a partial magnetite rim exists. Such spherules are a small but important component of Tagish Lake.

Irregularly-shaped, altered remnants of CAIs containing hibonite, spinel, perovskite, calcite, and phyllosilicate, like those in Tagish Lake, as well as rare, spinel-rich spherules are also found in the altered CM2 chondrites Mighei (MacPherson and Davis 1994) and Cold Bokkeveld (Greenwood et al. 1994). In contrast, Murchison (CM2) contains blue spherules consisting of spinel + hibonite + perovskite ± melilite (MacPherson et al. 1983) with no secondary alteration products. The rare melilite-rich inclusions in Murchison, however, show evidence of alteration of melilite to calcite (MacPherson et al. 1983). In comparing the hibonite-bearing inclusions in Tagish Lake with those in Murchison, we can infer that at least some of the calcium carbonate seen in the Tagish Lake and Mighei inclusions was originally melilite and that the observed phyllosilicate could have been derived from hibonite. We consider, therefore, that the blue spherules found in Murchison (the "BB" type of MacPherson et al. [1983]) exemplify the progenitors of spherules and hibonite-bearing inclusions found in Tagish Lake, Mighei, and Cold Bokkeveld.

A more common inclusion type in Tagish Lake, is the irregularly-shaped spinel aggregates. The aggregates consist of equant, fine-grained (2–10 μm) spinel with or without

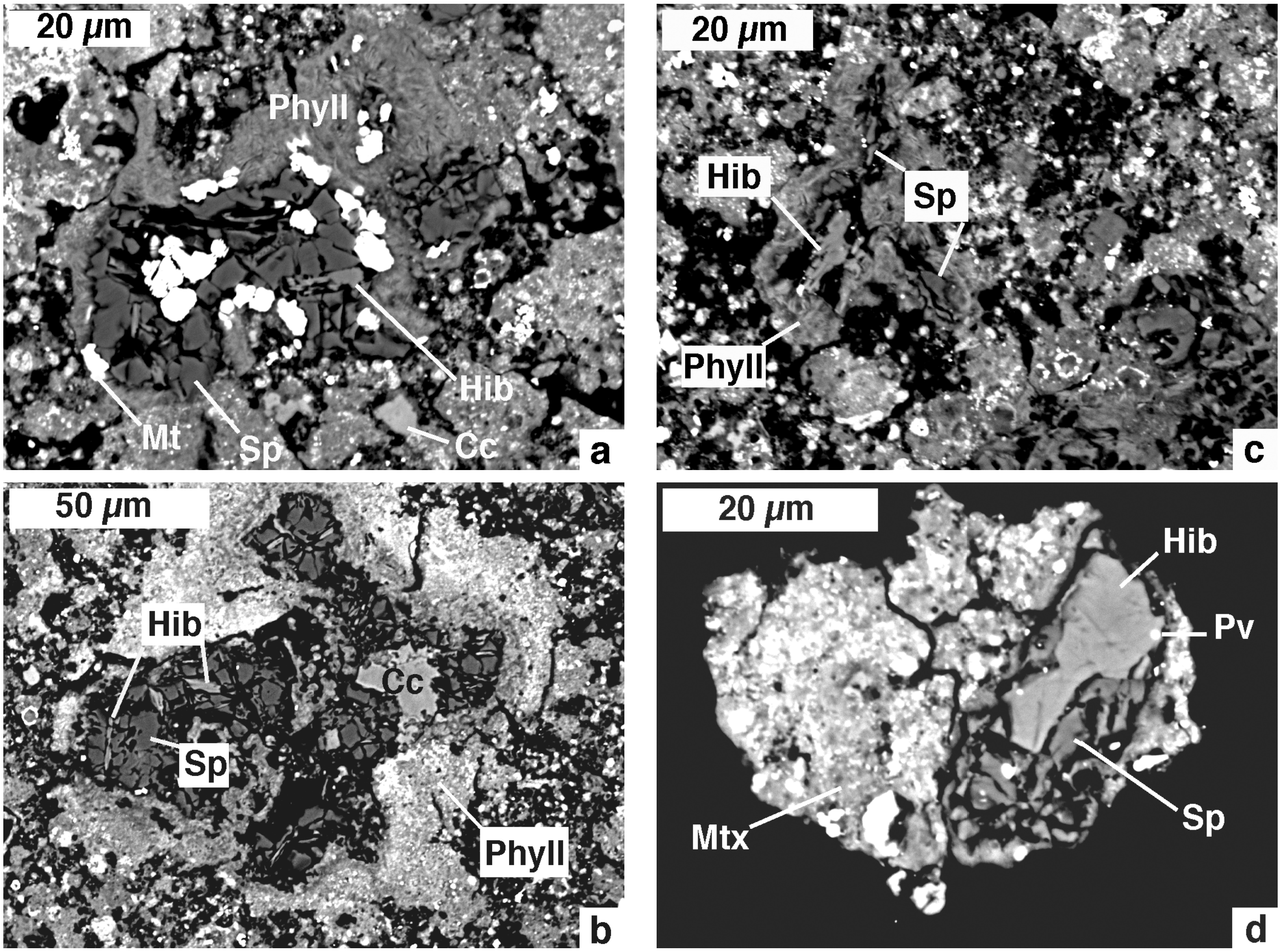


Fig. 1. Backscattered electron images of hibonite-bearing inclusions in Tagish Lake: a) CA2–15; b) CA4–21; c) PB3–27; d) TLDF32. (a)–(c) are in situ and (d) is from the dense fraction. The void spaces and epoxy are black. Cc = calcite; Hib = hibonite; Mt = magnetite; Mtx = matrix; Phyll = phyllosilicate; Pv = perovskite; Sp = spinel.

perovskite, clinopyroxene, Pt-metal nuggets, and magnetite. The spinel is commonly anhedral. Textures of the inclusions range from compact (as in the one shown in Fig. 2b) to rather fluffy and apparently very loosely aggregated (Fig. 2c). The latter type is probably broken up by the freeze-thaw process and was only found in situ and in the scoop sample. Spinel aggregates range in size from small clusters of ~20 µm width (and containing few crystals) to larger objects of ~100 µm width; most are ~60 µm across. The compact aggregates are probably altered fragments of another previously recognized inclusion type: the spinel-perovskite-pyroxene inclusions found in Murchison (the "OC" type of MacPherson et al. [1983, 1984]), Mighei (MacPherson and Davis 1994), and other CMs.

Olivine-Rich Objects

There are 3 major types of olivine-rich objects in Tagish Lake: 1) chondrules; 2) a group of objects which we have termed "polycrystalline olivine inclusions;" and 3) a group we call "forsterite aggregates."

Chondrules are rounded objects, or fragments thereof, consisting of olivine with or without pyroxene or spinel, with glass or its alteration products between some or all of the grains. Most of the spherical objects hand-picked from the density separates, including the material that floated in methylene iodide, turned out to be chondrules. Chondrules were also found in situ. Two examples are shown in Fig. 3. Note the completely altered mesostasis. Among Tagish Lake chondrules, we found that the most common textural type is porphyritic olivine followed by barred olivine. Both types were also observed by Zolensky et al. (2002). Some chondrules have experienced mild deformation and are slightly flattened, but most are still spherical.

Polycrystalline olivine inclusions (Fig. 4a), as the name implies, consist of multiple olivine crystals. They are irregularly shaped and have no mesostasis or phyllosilicate between the olivine grains, which distinguishes them from chondrule fragments. Grains may be immediately adjacent to each other, may have sulfide (pentlandite and/or FeS) between grains, or there may be void space. The olivine

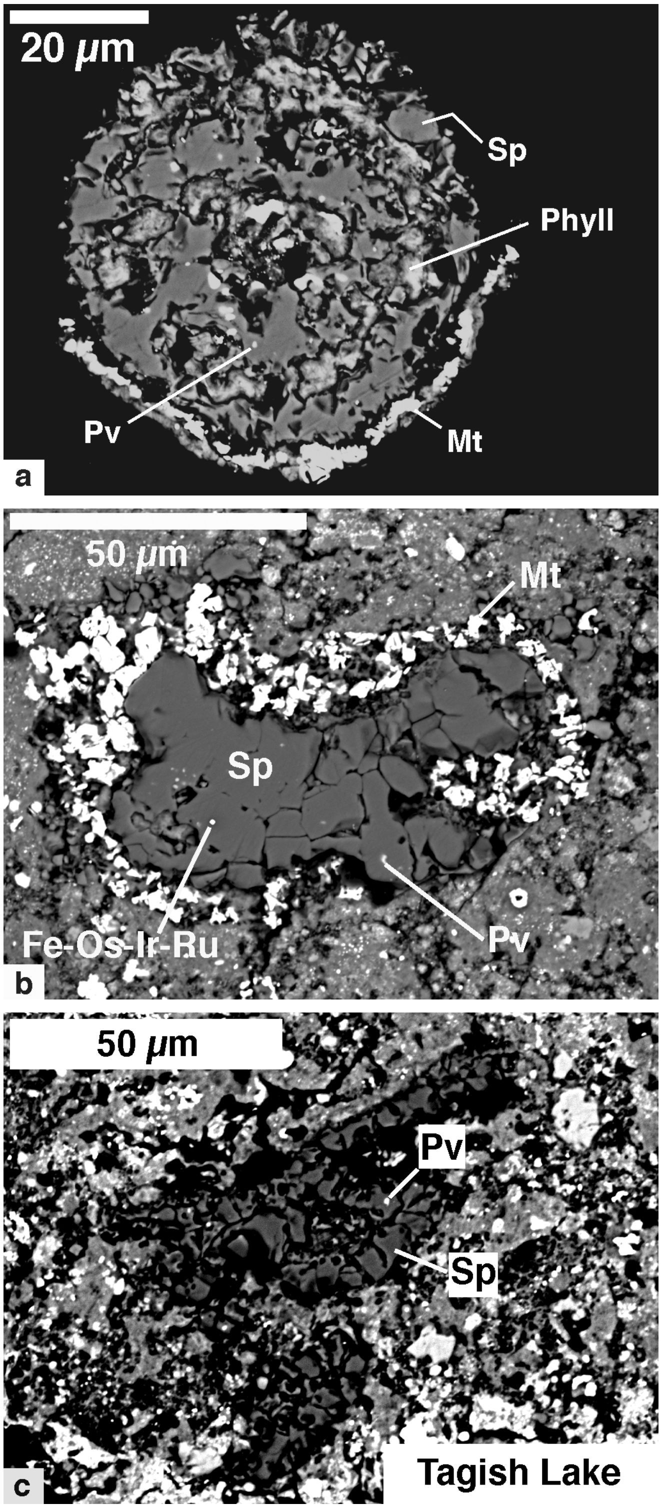


Fig. 2. Backscattered electron images of spinel-rich inclusions in Tagish Lake. Note the fine-grained perovskite enclosed in spinel in all samples: a) a spinel-rich spherule, TL4–29. Note the spherical shape; b) a compact spinel-rich inclusion, CA3–13; c) a fluffy spinel aggregate, CA6–65.

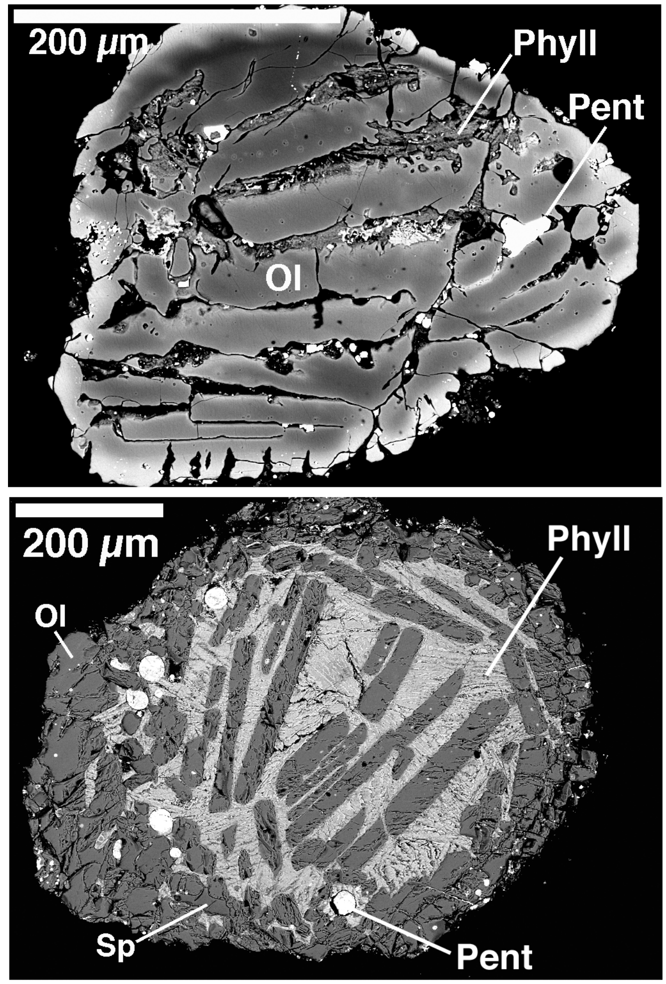


Fig. 3. Backscattered electron images of barred olivine chondrules from Tagish Lake. Note the deformation of the chondrules and complete conversion of mesostasis to phyllosilicate. Ol = olivine; Pent = pentlandite; Phyll = phyllosilicate; Sp = spinel.

grains are typically subhedral, and grain sizes ranging from ~10 μm to ~50 μm are common within individual inclusions. Olivine in these inclusions ranges from Fo_{60} to pure forsterite.

Forsterite aggregates (Fig. 4b) are irregularly-shaped objects that, unlike the polycrystalline olivine inclusions, consist almost entirely of fine-grained (~10 μm), pure forsterite. Minor amounts of magnetite, pentlandite, or troilite may also be present. Although they are generally quite porous, they are coherent enough to survive disaggregation of the meteorite. Neither these objects nor the polycrystalline olivine inclusions are analogous to the friable, white inclusions found in Murchison (Fuchs et al. 1973; Grossman and Olsen 1974). We only needed to examine one thin section of Murchison, however, to confirm that polycrystalline olivine inclusions and forsterite aggregates are also present in that meteorite.

Single, isolated crystals of olivine are found in all types of carbonaceous chondrites. In Tagish Lake, they are

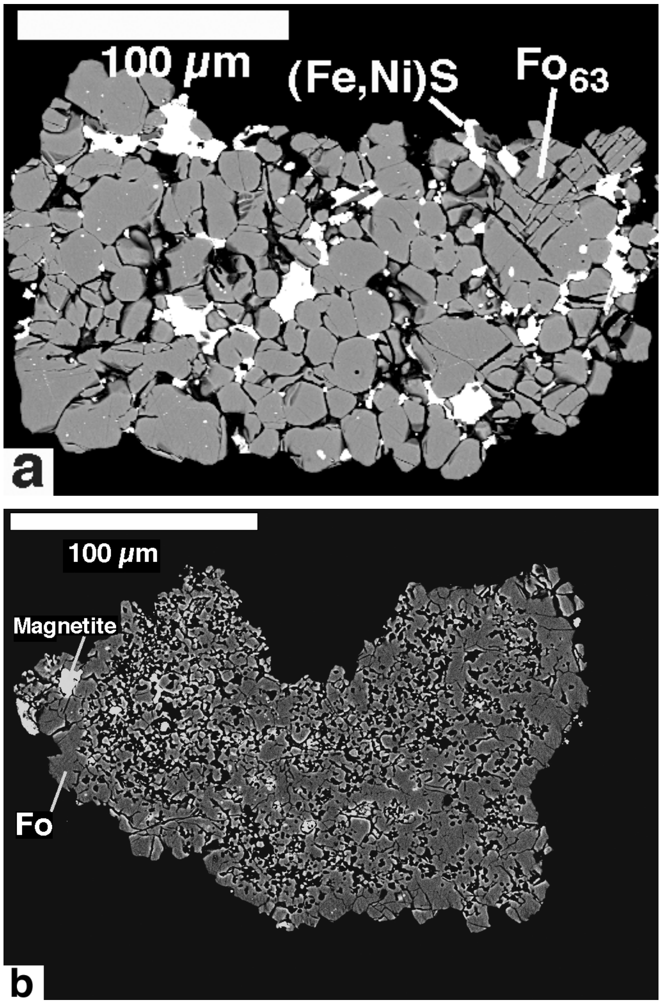


Fig. 4. Backscattered electron images of olivine-rich objects in Tagish Lake. Both are mounted in epoxy: a) a polycrystalline olivine inclusion, TL2–19. Note the irregular shape and lack of mesostasis between grains; b) a forsterite aggregate, TL3–4. Note the porous texture and uniform composition of olivine grains. Fo = forsterite.

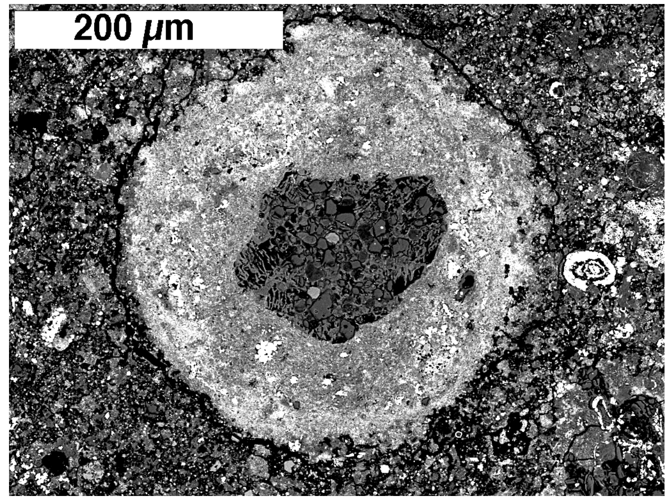


Fig. 5. Backscattered electron image of a porphyritic olivine chondrule fragment enclosed in a thick accretionary rim. Note the heterogeneity of the rim and its sharp contact with the chondrule fragment and with the meteorite matrix.

commonly subhedral. Single grains separated from the meteorite range in width from ~50 μm to ~1 mm. Round inclusions of metallic FeNi ≤5 μm are common. Some forsterite grains contain small, euhedral crystals of Mg-Al spinel, and some contain inclusions of aluminous diopside.

Coarse Cr-, Al-rich spinel (not reported from CI chondrites but easily found in the dense fraction of Murchison separates [Simon et al. 1994]) is present but rare in Tagish Lake. It occurs intergrown with, and as inclusions in, olivine.

Accretionary Mantles

All types of clasts and inclusions in this meteorite occur enclosed in fine-grained, accretionary mantles. As shown in Fig. 5, the thicknesses of some mantles approach the diameters of the objects they enclose, and the mantles commonly have sharp contacts with the matrix of the meteorite. Although they are not part of the high-temperature, anhydrous component, the mantles are included in this study because they provide an additional basis for the classification of Tagish Lake. The textures and mineralogy of the mantles (consisting of fine-grained phyllosilicate with clasts of olivine, calcium carbonate, magnetite, FeS, pentlandite and metal) are quite similar to those found in CM2 chondrites (Metzler et al. 1992). In contrast, the rare mineral clasts found in CI chondrites are not rimmed.

Proportion of the Dense Fraction and Relative Abundances of Inclusions

From the weights of the dense fractions, we can estimate the bulk abundance of anhydrous inclusions in Tagish Lake. The dense fraction from our first disaggregation represents ~13% of the starting material. In the second experiment, only ~2% was recovered in the dense fraction. This latter result is clearly an underestimate of the weight proportion of the anhydrous component of the meteorite, as chondrules and even single crystals of olivine were found among the materials that floated in methylene iodide. Despite stirring, some dense objects may have been physically blocked from sinking by the abundant phyllosilicates adhering to them in the centrifuge tube. In addition, many chondrules are so thoroughly altered that they contain more phyllosilicate than olivine. Our first experiment probably did not have the blocking problem because a small amount of material was used. We conclude from these results that Tagish Lake has an anhydrous fraction of ~13 wt%, a much smaller fraction than typical CM2 chondrites. Grossman and Olsen (1974) studied five CMs and found an average anhydrous component (chondrules, inclusions, and single grains) of 48 wt%, with a range of 39–56%. Tagish Lake is well outside of that range.

Chondrules are a minor petrographic component of CM chondrites (Grossman and Olsen 1974), so, not surprisingly, Zolensky et al. (2002) reported that chondrules are very sparse in Tagish Lake, with only ~1 cm^{-2}. We found them to be a significant component of the material hand-picked for study from the density separates, however, illustrating the effectiveness of the freeze-thaw technique in concentrating certain components of the meteorite, even if they are very minor. In contrast, many spinel-rich inclusions were found in situ and in the mount of the scoop sample but not among the hand-picked objects. The freeze-thaw process breaks the loosely aggregated spinel-rich inclusions down to smaller sizes but does not destroy the chondrules and forsterite aggregates. Also, some spinel aggregates are very small and, even if not broken further, would be unlikely to be sampled by hand-picking. Thus, both thin section mapping and freeze-thaw disaggregation are needed for thorough petrologic investigation of Tagish Lake and of CMs in general.

Due to a combination of their resistance to disaggregation and our interest in spherical objects, chondrules dominate the population of hand-picked objects. Excluding single crystals of olivine (which can be identified prior to picking and sectioning), 40% of 164 objects hand-picked from the density separates are chondrules, 21% are forsterite aggregates, 11% are polycrystalline olivine aggregates, 5% are matrix fragments, 2% are refractory inclusions, 2% are phosphate-rich objects, and 1% are olivine plus Cr-spinel assemblages. The remaining 18% of the objects do not fall into any of these categories. Many are phyllosilicate-rich and are too heavily altered to allow classification based on their primary features.

Mineral Chemistry

Refractory Inclusions

Endmember hibonite is $CaAl_{12}O_{19}$. In meteoritic hibonite, 1 Mg^{2+} cation commonly substitutes, along with 1 Ti^{4+} or Si^{4+} cation, for 2 Al^{3+} cations, giving rise to a strong positive correlation between Mg and Ti + Si abundances in hibonite. Representative analyses of hibonite in Tagish Lake inclusions are given in Table 1. Unlike that in Murchison, hibonite in Tagish Lake contains FeO, which we assume partially replaced MgO. MacPherson and Davis (1994) found that CAIs in Mighei are more altered than those in Murchison, and they also found that hibonite in Mighei, like that in Tagish Lake, is FeO-bearing, generally with >0.5 wt% FeO. In Fig. 6, for hibonite from Tagish Lake, Mighei, and Murchison, we have plotted Mg + Fe versus Ti + Si cations, which should exhibit a 1:1 correlation due to the coupled substitution mentioned above. We observe, however, that most of the analyses of Tagish Lake hibonite plot on the high-Mg side of the 1:1 line. This may be due to slight contamination of analyses of narrow hibonite laths by adjacent spinel. Analyses of the coarsest hibonite, that in TLDF32, are not contaminated by adjacent phases, and plot on the line.

Table 1. Electron microprobe analyses of hibonite in Tagish Lake inclusions.[a]

	1	2	3
MgO	0.82	0.84	3.23
Al_2O_3	88.36	88.76	80.85
SiO_2	0.04	0.10	0.36
CaO	8.55	8.47	8.02
TiO_2	1.66	1.67	5.82
V_2O_3	BDL[b]	BDL[b]	0.44
FeO	0.15	0.16	0.93
Total	99.58	100.00	99.65
Cations per 19 oxygen anions			
Mg	0.138	0.140	0.548
Al	11.688	11.685	10.850
Si	0.004	0.011	0.041
Ca	1.028	1.014	0.979
Ti	0.140	0.141	0.499
V	0	0	0.020
Fe	0.014	0.015	0.089
Total cations	13.012	13.006	13.026

[a]Columns 1 and 2: TLDF32 (Fig. 1d); column 3: PB3–27 (Fig. 1c).
[b]BDL = Below detection limit of 0.031 wt% V_2O_3.

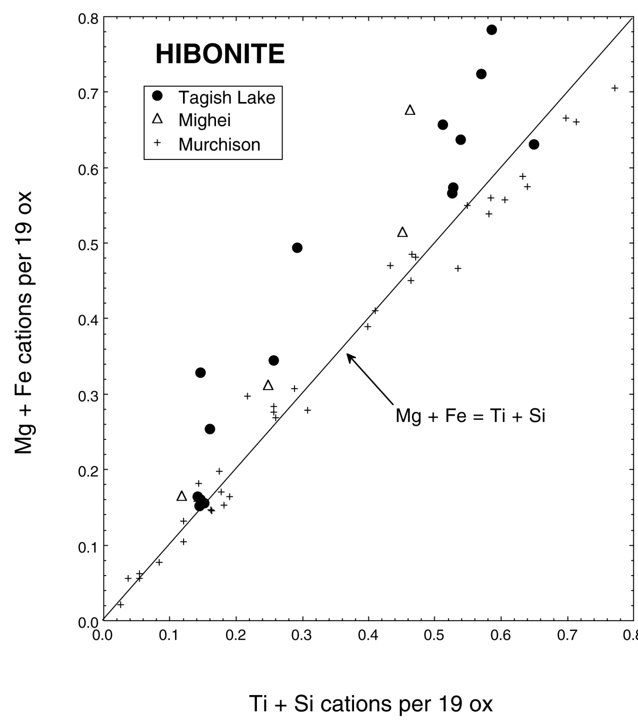


Fig. 6. Electron microprobe analyses of hibonite from the Tagish Lake, Mighei, and Murchison carbonaceous chondrites. The data scatter about the 1:1 correlation line for Mg + Fe versus Ti + Si cations, which is shown for reference. Analyses plotting on the (Mg + Fe)-rich side of the line, especially those from Tagish Lake and Mighei, probably reflect contributions from spinel adjacent to fine-grained hibonite. The Mighei data are from MacPherson and Davis (1994).

Table 2. Representative electron microprobe analyses of spinel in Tagish Lake inclusions.[a]

	1	2	3	4	5	6	7
MgO	27.86	28.12	28.43	28.41	28.38	28.32	28.58
Al_2O_3	70.56	70.58	70.81	71.68	70.35	70.30	70.35
SiO_2	0.10	0.06	0.30	0.27	0.03	0.03	0.03
CaO	0.02	0.03	0.02	0.09	BDL[b]	BDL[b]	0.02
TiO_2	0.06	0.25	0.07	0.26	0.71	0.35	0.17
V_2O_3	0.08	0.50	0.58	0.05	0.16	0.32	0.20
Cr_2O_3	0.15	0.12	0.11	0.18	0.55	0.08	0.18
MnO	BDL[b]	BDL[b]	0.04	0.03	BDL[b]	BDL[b]	BDL[b]
FeO	1.00	0.65	0.80	0.29	0.24	0.87	0.65
Total	99.83	100.31	101.16	101.26	100.42	100.27	100.18
Cations per 4 oxygen anions							
Mg	0.990	0.994	0.997	0.992	1.002	1.003	1.012
Al	1.984	1.974	1.965	1.980	1.964	1.969	1.970
Si	0.002	0.001	0.007	0.006	0.001	0.001	0.001
Ca	0.001	0.001	0	0.002	0	0	0.001
Ti	0.001	0.004	0.001	0.005	0.013	0.006	0.003
V	0.002	0.010	0.011	0.001	0.003	0.006	0.004
Cr	0.003	0.002	0.002	0.003	0.010	0.002	0.003
Mn	0	0	0.001	0.001	0	0	0
Fe	0.020	0.013	0.016	0.006	0.005	0.017	0.013
Total	3.003	2.999	3.000	2.996	2.998	3.004	3.007

[a]Column 1: CA2–15 (Fig. 1a); 2: CA4–21 (Fig. 1b); 3: PB3–27 (Fig. 1c); 4: TLDF32 (Fig. 1d); 5: TL4–29 (Fig. 2a); 6: CA3–13 (Fig. 2b); 7: CA6–65 (Fig. 2c).
[b]BDL = Below detection limit of the electron microprobe of 0.011 wt% CaO or 0.029 wt% MnO.

Analyses of Ti-rich hibonite from Tagish Lake and from Murchison may plot on the high-Ti side of the line due to direct substitution of Ti^{3+} for Al^{3+}.

Representative analyses of spinel from various types of inclusions found in Tagish Lake are given in Table 2. Minor element contents of spinel from hibonite-bearing inclusions in Tagish Lake are compared with those from Murchison and Mighei in Fig. 7. The spinels in all three meteorites have similar ranges in V_2O_3 contents (~0.06–0.6 wt%), but the TiO_2 contents of Murchison spinels extend to slightly higher values than those of the Tagish Lake spinels. Spinel in Tagish Lake inclusion CA2–15 (Fig. 1a) has very low TiO_2 and V_2O_3 contents. Spinel from the other inclusions tends to be richer in either one or both of these oxides than that in CA2–15.

Compositions of spinel in hibonite-free, spinel-rich inclusions are illustrated in Fig. 8. Spinel in the aggregates found in Tagish Lake generally has low TiO_2 contents (Fig. 8a), similar to those of Mighei spinel (MacPherson and Davis 1994). But, spinel in the Tagish Lake spherules has high TiO_2 contents. Either Tagish Lake sampled unusual spherules, or this small sample is not representative. Some aggregates have spinel with very low FeO contents, but most analyses have 0.5–1 wt% FeO and are more FeO-rich than most spinels from Mighei and Murchison. Spinel from hibonite-free inclusions from the 3 meteorites exhibits similar ranges in V_2O_3 contents (Fig. 8b), with most analyses being between 0.05 and 0.5 wt% V_2O_3. The data in Fig. 8 show that if the Tagish Lake spinel were less enriched in FeO, its compositions would closely overlap those of Murchison and Mighei spinels.

Olivine-Rich Inclusions

Compositions of olivine in chondrules and in polycrystalline olivine inclusions from Tagish Lake are compared to each other and to suites of isolated olivines from CM and CI chondrites and Tagish Lake in Fig. 9. Not a great deal of overlap exists between olivine in the polycrystalline inclusions and chondrule olivine, especially on a plot of Cr_2O_3 versus FeO (Fig. 9a), supporting the classification based on petrography. The polycrystalline olivine inclusions contain FeO-rich (27–33 wt%), Cr_2O_3-poor (0–0.2 wt%) compositions that are very rare among the isolated grains and are not seen in the chondrules. Some chondrules contain olivine with FeO contents between 8 and 18 wt%, rare among the isolated grains and the polycrystalline inclusions. We found relatively FeO-, MnO-rich olivine (15–20 and 0.5–0.9 wt%, respectively) in chondrules, which is not found elsewhere (Fig. 9b). The data suggest that the isolated olivine population in Tagish Lake was not simply derived from chondrules and polycrystalline olivine inclusions.

Compositions of olivine in the forsterite aggregates are compared to those of forsteritic isolated olivine crystals from Tagish Lake, CM, and CI chondrites in Fig. 10. The forsterite in the aggregates has very low contents of FeO, CaO, and other minor elements, though MnO contents are similar to those seen in some isolated forsterite crystals. Very little overlap exists between forsterite aggregates and the Tagish Lake single crystals, indicating that very few of the isolated grains were derived from forsterite aggregates and vice versa.

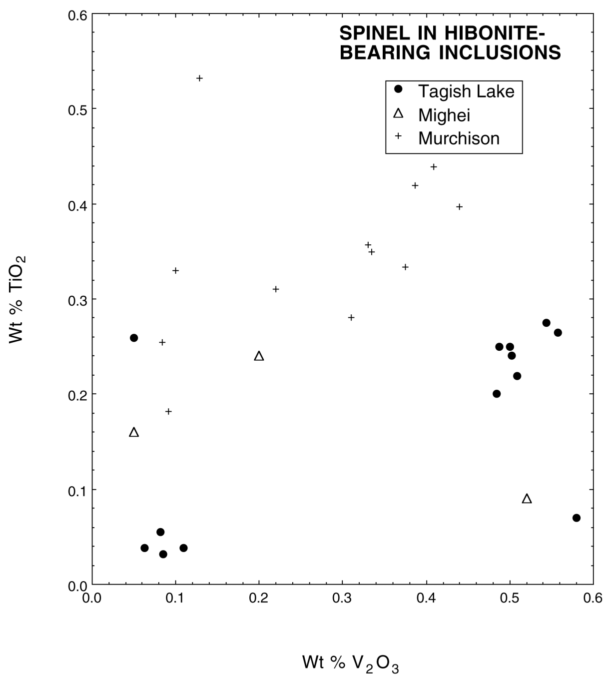


Fig. 7. Abundances of TiO_2 and V_2O_3 in spinel in hibonite-bearing inclusions. Spinel in Murchison inclusions tends to have higher TiO_2 contents than that in Tagish Lake inclusions. The Mighei data are from MacPherson and Davis (1994).

Among the analyses of isolated grains, a high degree of overlap exists between the CM, CI, and Tagish Lake data sets. All are dominated by forsterite. Among the forsteritic olivine, the Tagish Lake compositions closely follow the CM-CI trend, with sharply increasing Cr_2O_3 contents with increasing FeO (Fig. 9a). They do not follow the CV trend in which olivine with ≤6 wt% FeO has Cr_2O_3 contents that are between 0.1 and 0.3 wt% and do not increase with increasing FeO contents (Steele and Smith 1986). Olivine with FeO contents that are >30 wt% are found in Tagish Lake and the CMs but not in the CIs. This FeO-rich olivine from Tagish Lake has Cr_2O_3 contents of 0.2–0.5 wt%, as does the FeO-rich olivine from the CMs (Fig. 9a), and the variation of MnO with FeO contents (Fig. 9b) is also similar to that of the CMs.

An important component of most unequilibrated chondrites is so-called refractory forsterite (e.g., Steele 1986; Weinbruch et al. 2000), which is very low in FeO (<1 wt%) and high in CaO (0.5–0.8 wt%). While well-documented in CM and CV chondrites, refractory forsterite is either absent from or very rare in CI chondrites (Steele 1990). As illustrated in Fig. 10a, refractory forsterite (plotting in the field labelled "RF") is clearly present in Tagish Lake, providing another link between Tagish Lake and the CMs. Another difference between the isolated grain populations in CM and CI chondrites is that MnO-rich (>0.4 wt%) forsterite is more abundant in the latter than in the former (Steele 1990). The CI data set is smaller than those for the CMs and Tagish

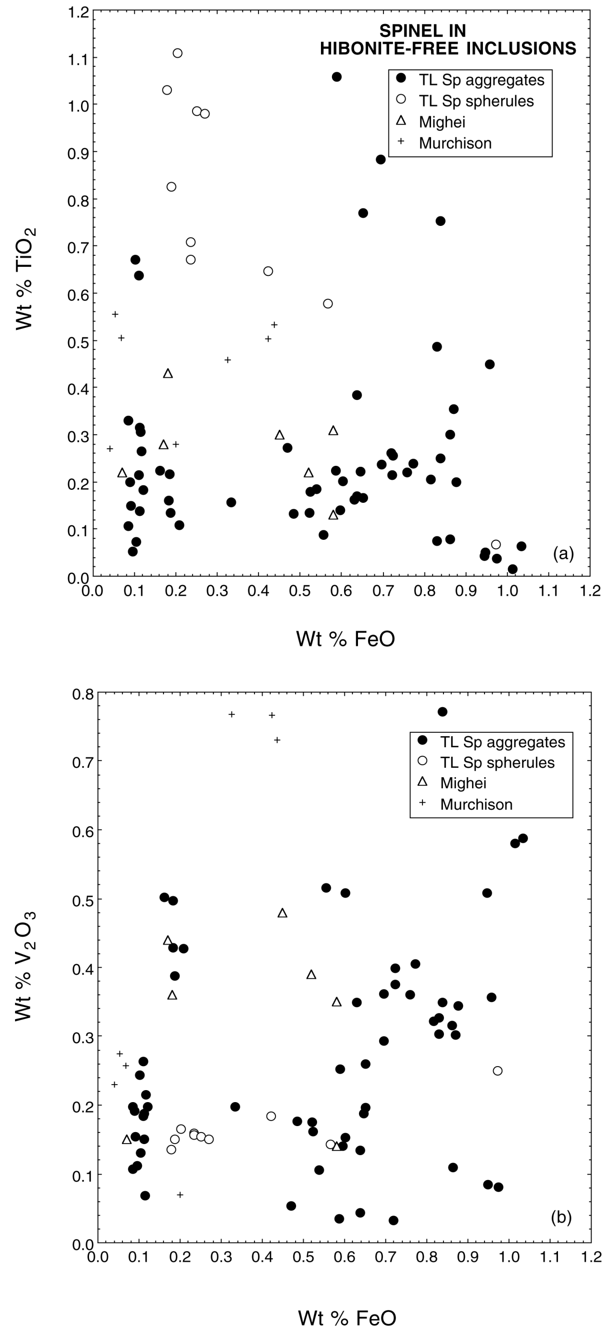
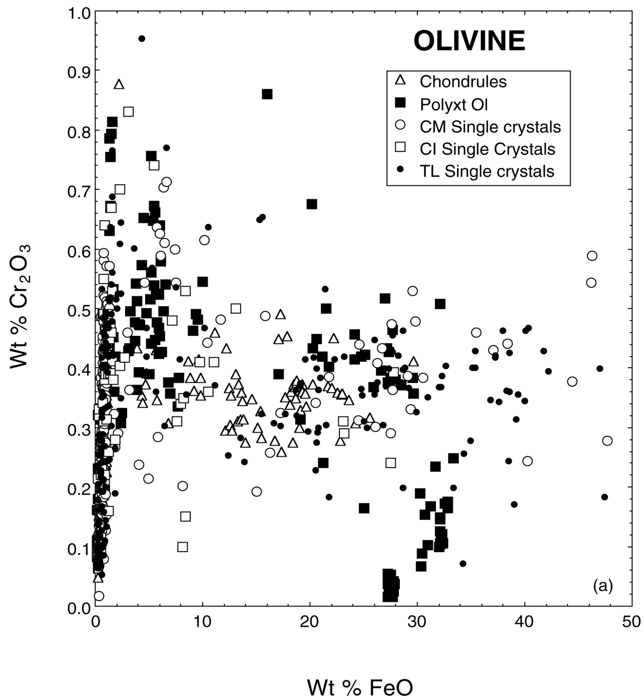


Fig. 8. Compositions of spinel in hibonite-free, spinel-rich inclusions. The range of FeO contents extends to higher values in Tagish Lake spinel than in spinel from Murchison or Mighei. Mighei data are from MacPherson and Davis (1994): a) TiO_2 versus FeO; b) V_2O_3 versus FeO.

Lake, but, as seen in Fig. 10b, several analyses of MnO-rich forsterite are present in each of the data sets.

Accretionary Rims

Many objects in Tagish Lake are enclosed in well-developed, phyllosilicate-rich rims. We analyzed these rims



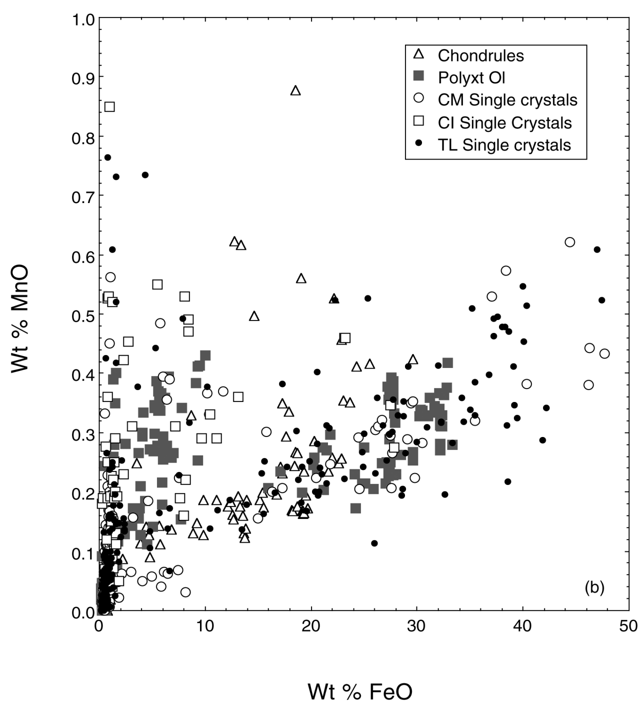
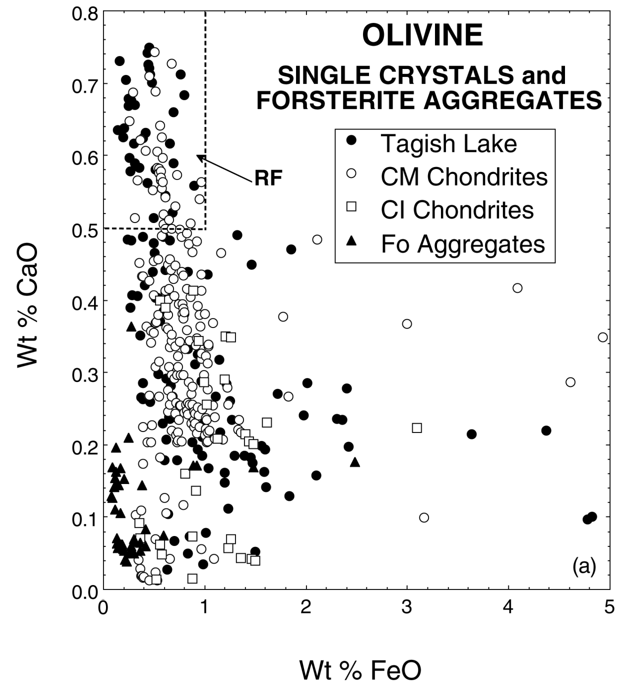


Fig. 9. Compositions of olivine in chondrules and polycrystalline olivine inclusions (Polyxt Ol) from Tagish Lake and of single crystals from Tagish Lake (TL), CM chondrites, and CI chondrites. Much overlap exists among the single crystal populations, which are all dominated by FeO-poor compositions: a) Cr_2O_3 versus FeO; b) MnO versus FeO.



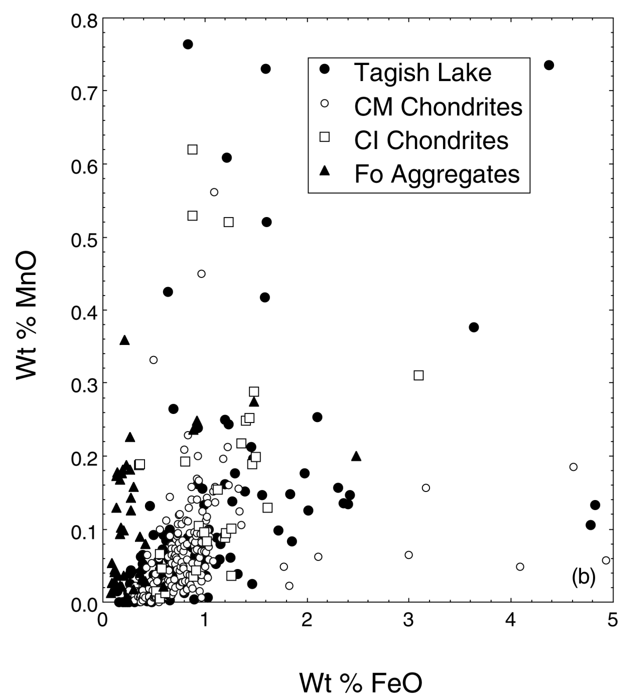


Fig. 10. Compositions of forsteritic olivine occurring as single grains in CMs, CIs, and Tagish Lake and in forsterite aggregates in Tagish Lake. Olivines plotting in the field labelled "RF" can be classified as refractory forsterites. Note the limited overlap between forsterite aggregates and single grain compositions, the absence of refractory forsterite in CI chondrites, and the presence of it in both CMs and Tagish Lake.

using an electron probe with a defocussed beam. The results are summarized in Fig. 11, a plot of normalized wt% Fe versus Mg/Si (wt ratio). Metzler et al. (1992) showed that bulk compositions of accretionary rims found in CM chondrites plot within the triangular field devised by McSween (1987) for analysis of carbonaceous chondrite matrices. This field is defined by the compositions of: a) Mg-rich serpentine; b) Fe-rich serpentine; and c) a mixture of 25% tochilinite and 75% cronstedtite normalized to 100 wt% Mg + Fe + Si. This field is shown for reference, along with average rim compositions from 22 CM chondrites (Metzler et al. 1992; Zolensky et al. 1993). Many of the analyses of Tagish Lake rims plot in or near the triangular field and overlap the range of average CM rim compositions. In addition, some relatively Fe-poor phyllosilicates occurring in Tagish Lake were analyzed, and their compositions are also plotted. These Fe-poor phases dominate some of the rims in Tagish Lake, giving Tagish Lake rims a composition range that extends to lower Fe contents than the range of CM rim averages. Some rims in Tagish Lake are, however, quite similar to those in previously studied CMs. The average of the Tagish Lake rim compositions plots within the triangular field, very close to the average rim compositions of several CM chondrites, with a typical Mg/Si ratio and an Fe content lower than most of the CM rim averages.

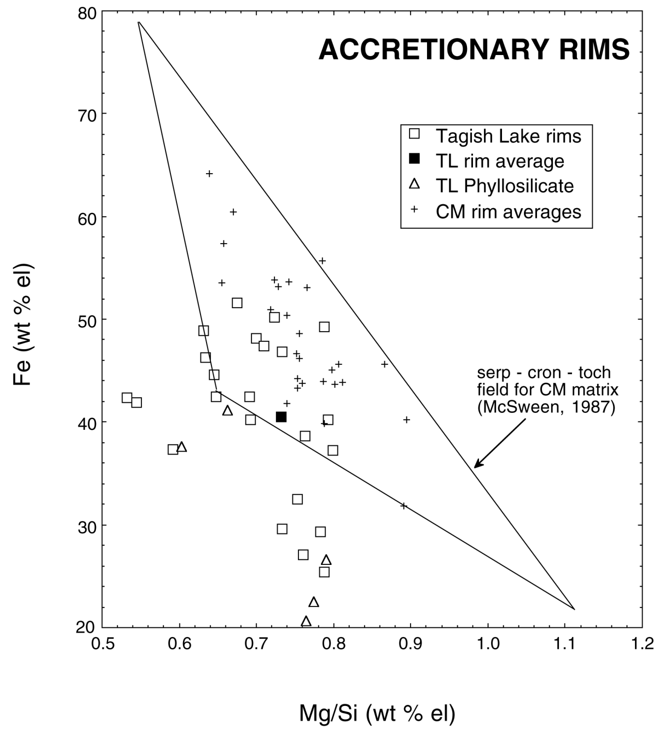


Fig. 11. Compositions of accretionary rims on objects in CM chondrites and Tagish Lake and analyses of phyllosilicates in Tagish Lake. Data are normalized to 100 wt% Fe + Mg + Si. Data for CM chondrites are average rim compositions from Metzler et al. (1992) and Zolensky et al. (1993).

DISCUSSION

We will base our comparison of the refractory inclusion population of Tagish Lake to that of the known CMs on 4 well-studied CM chondrites: Murchison (MacPherson et al. 1983, 1984) and Murray (Simon et al. 1993; Lee and Greenwood 1994), two lightly altered ones; and Mighei (MacPherson and Davis 1994) and Cold Bokkeveld (Greenwood et al. 1994), two more heavily altered ones. The inclusions in Tagish Lake resemble those in Cold Bokkeveld and are more heavily altered than those in Mighei in the sense that Tagish Lake inclusions have higher phyllosilicate contents, and their spinel has higher FeO contents.

Despite the differing degrees of alteration, we conclude that the refractory inclusion types found in Tagish Lake are also found in the other 4 meteorites, and therefore, this component of Tagish Lake is like that of the CM chondrites. All 5 meteorites contain spinel-, hibonite-bearing spherules. As shown by MacPherson et al. (1983), they are virtually unaltered in Murchison, with FeO-free spinel and no secondary alteration products. Unaltered spinel-hibonite spherules can be found in Mighei by freeze-thaw disaggregation (unpublished data of the authors), but MacPherson and Davis (1994) found only altered ones in the thin sections they studied. In Tagish Lake, we found only heavily altered remnants of this inclusion type, like those in Cold Bokkeveld (Greenwood et al. 1994). Spinel-rich, hibonite-bearing inclusions are virtually absent from other chondrite types, so the presence of such objects in Tagish Lake is an important feature that this meteorite has in common with typical CMs.

The compact, irregularly-shaped, spinel-rich inclusions in Tagish Lake are probably altered versions of the spinel-pyroxene inclusions found in Murchison and the other CMs. In Tagish Lake, they are enclosed in phyllosilicate, however, and not by fresh, intact clinopyroxene rims.

In addition to the spinel-pyroxene inclusions, MacPherson and Davis (1994) reported finding small, poorly aggregated, porous clusters of spinel grains in Mighei, as we found in Tagish Lake. MacPherson and Davis (1994) inferred that such objects are present in, but have not been reported from, Murchison because they are broken into smaller pieces by the freeze-thaw process and are not recovered by subsequent hand-picking. Our examination of thin sections of Murchison confirms that they are present in that meteorite as well. Porous spinel aggregates are, thus, another feature that Murchison, Mighei, and Tagish Lake have in common.

Forsterite aggregates are present in Tagish Lake and in Murchison. They were not reported by MacPherson and Davis (1994) in their study of Mighei, but these workers only looked for and described Al-rich inclusions. These objects have not been previously studied, probably because they are neither chondrules nor refractory inclusions. Forsterite aggregates contain no pyroxene and are quite coherent, allowing them to survive freeze-thaw disaggregation, but they are not chondrule fragments. They have irregular shapes, and most do not even have any smooth edges, as would be expected from chondrule fragments. In most cases, the forsterite grains are immediately adjacent to each other or have void space between them. Chondrules, however, tend to contain mesostasis, and in Tagish Lake chondrules, the mesostasis has been converted to phyllosilicates. The forsterite aggregates are unlikely to have once contained mesostasis or phyllosilicates between grains that dissolved away because this did not happen in the Tagish Lake chondrules.

Further evidence that forsterite aggregates are distinct from chondrules can be seen in a comparison of olivine compositions. A plot of CaO versus FeO in forsterite aggregates and Tagish Lake chondrules (Fig. 12) shows very little overlap of olivine compositions in these 2 types of objects. The forsterite aggregates contain very pure forsterite with less FeO than most chondrule olivines. This forsterite also has very low CaO contents, unlike the olivine found in chondrules or as single grains (Fig. 10a) in which the most forsteritic olivine tends to be refractory forsterite, with relatively high CaO contents.

For these reasons, we believe that it is unlikely that the forsterite aggregates were ever molten. Forsterite is predicted to be an equilibrium condensate from a gas of solar composition (Yoneda and Grossman 1995); forsterite aggregates are probably clusters of condensate grains that were sintered together to make coherent objects. If so, this implies that condensate forsterite can be very pure, with very low FeO and minor element contents, although refractory forsterites are also thought to be condensates (Weinbruch et al. 1993, 2000).

Despite much overlap among analyses of isolated olivine grains from the CM, CI, and Tagish Lake chondrites, there are some differences, and the compositions of those in Tagish Lake more closely match the CM population than the CI population. Olivine with FeO contents of 30–50 wt%, Cr_2O_3 contents of 0.2–0.5 wt% (Fig. 9a), and MnO contents of 0.2–0.6 wt% (Fig. 9b) are fairly common in both Tagish Lake and the CMs but are not found in the CIs. One possible explanation for the differences in populations is a difference in sources. Any chondrules or inclusions that have contributed to the single grain population in CMs are not present in CIs. The presence of refractory forsterite in CMs and Tagish Lake and its absence from CIs is also suggestive of a difference in sources. Such differences may have been magnified by the high degree of hydrous alteration experienced by the CIs, which could have led to preferential destruction of Fe-rich olivine in those meteorites (Zolensky, personal communication).

By weight, Tagish Lake has a smaller dense fraction than typical CMs. From its bulk oxygen isotopic composition, Clayton and Mayeda (2001) inferred that Tagish Lake was exposed to a high water/rock ratio, consistent with our observation of a relatively small anhydrous fraction. In CMs, this component is dominated by olivine (Grossman and Olsen 1974), so the smaller dense fraction should not necessarily be interpreted as a smaller refractory component; Tagish Lake is not depleted in bulk refractory trace elements relative to the CM chondrite average (Mittlefehldt 2002). Either Tagish Lake has a refractory inclusion content that is typical of CMs, or it originally had an abundance of refractory inclusions that was normal for a CM chondrite, and despite hydrous alteration, the elemental signature of this component was retained.

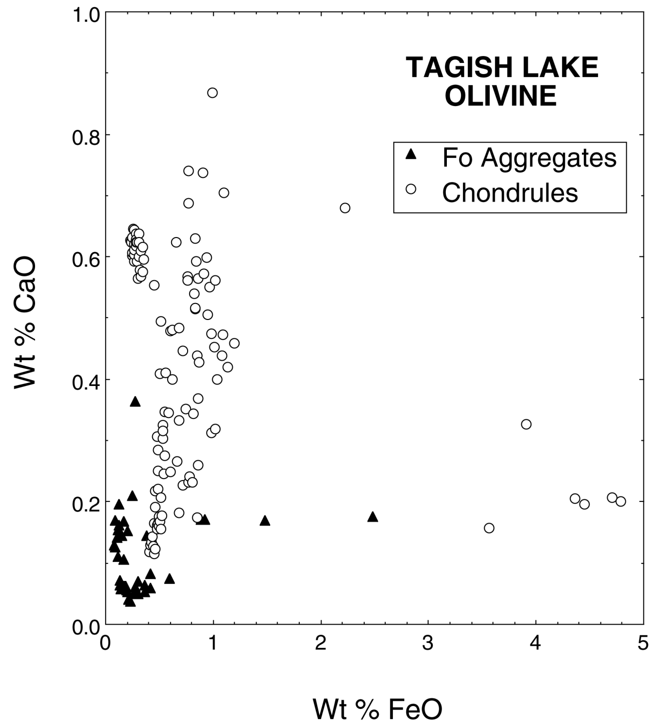


Fig. 12. CaO and FeO contents in forsteritic olivine in forsterite aggregates and in chondrules from Tagish Lake. Little overlap exists between the data sets, as the olivine in the aggregates generally has lower FeO and CaO contents than the olivine in chondrules.

CONCLUSIONS

Studies of Tagish Lake that have been mainly based on bulk analyses or components that were formed in (or severely modified by) low-temperature events have led to differing conclusions as to whether it is predominantly CM-like (e.g., Mittlefehldt 2002; Bullock et al. 2002) or intermediate between CIs and CMs (e.g., Brown et al. 2000; Leshin et al. 2001; Clayton and Mayeda 2001; Zolensky et al. 2002). The present study of the anhydrous component of Tagish Lake, however, reveals many features in common with CM chondrites that are not observed in CI chondrites, namely: hibonite-bearing refractory inclusions; spinel-rich refractory inclusions; chondrules; Cr-, Al-rich spinel; forsterite aggregates; refractory forsterite; compositions of isolated olivines; and thick, phyllosilicate-rich accretionary dust mantles enclosing all types of clasts. We conclude that Tagish Lake has (or at least originally had) an anhydrous inclusion population very much like that of CM chondrites. Tagish Lake experienced an alteration history that was somewhat different from that experienced by typical CIs and CMs (including more pervasive hydration of phases), leading to some uncertainty regarding this meteorite's classification.

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REFERENCES

Brown P. G., Hildebrand A. R., Zolensky M. E., Grady M., Clayton R. N., Mayeda T. K., Tagliaferri E., Spalding R., MacRae N. D., Hoffman E. L., Mittlefehldt D. W., Wacker J. F., Bird J. A., Campbell M. D., Carpenter R., Gingerich H., Glatiotis M., Greiner E., Mazur M. J., McCausland P. J., Plotkin H., and Rubak Mazur T. 2000. The fall, recovery, orbit, and composition of the Tagish Lake meteorite: A new type of carbonaceous chondrite. *Science* 290:320–325.

Bullock E. S., Gounelle M., Grady M. M., and Russell S. S. 2002. Fe-Ni sulphides in Tagish Lake and CI1 and CM2 carbonaceous chondrites (abstract). *Meteoritics & Planetary Science* 37:A27.

Clayton R. N. and Mayeda T. K. 2001. Oxygen isotopic composition of the Tagish Lake carbonaceous chondrite (abstract #1885). 32nd Lunar and Planetary Science Conference. CD-ROM.

Friedrich J. M., Wang M-S., and Lipschutz M. E. 2002. Comparison of the trace element composition of Tagish Lake with other primitive carbonaceous chondrites. *Meteoritics & Planetary Science* 37:677–686.

Fuchs L. H., Olsen E., and Jensen K. J. 1973. Mineralogy, mineral-chemistry, and composition of the Murchison (C2) meteorite. *Smithsonian Contributions to the Earth Sciences* 10:1–39.

Grady M. M., Verchovsky A. B., Franchi I. A., Wright I. P., and Pillinger C. T. 2002. Light element geochemistry of the Tagish Lake CI2 chondrite: Comparison with CI1 and CM2 meteorites. *Meteoritics & Planetary Science* 37:713–735.

Greenwood R. C., Lee M. R., Hutchison R., and Barber D. J. 1994. Formation and alteration of CAIs in Cold Bokkeveld (CM2). *Geochimica et Cosmochimica Acta* 58:1913–1935.

Grossman L. and Olsen E. 1974. Origin of the high-temperature fraction of C2 chondrites. *Geochimica et Cosmochimica Acta* 38: 173–187.

Grossman L. and Simon S. B. 2001. Refractory inclusions in Tagish Lake: A strong link to the CMs. *Meteoritics & Planetary Science* 36:A73–A74.

Krot A. N., Meibom A., Weisberg M. K., and Keil K. 2002. The CR chondrite clan: Implications for early solar system processes. *Meteoritics & Planetary Science* 37:1451–1490.

Lee M. R. and Greenwood R. C. 1994. Alteration of calcium- and aluminium-rich inclusions in the Murray (CM2) carbonaceous chondrite. *Meteoritics* 29:780–790.

Leshin L. A., Farquhar J., Guan Y., Pizzarello S., Jackson T. L., and Thiemens M. H. 2001. Oxygen isotope anatomy of Tagish Lake: Relationship to primary and secondary minerals in CI and CM chondrites (abstract #1843). 32nd Lunar and Planetary Science Conference. CD-ROM.

MacPherson G. J. and Davis A. M. 1994. Refractory inclusions in the prototypical CM chondrite, Mighei. *Geochimica et Cosmochimica Acta* 58:5599–5625.

MacPherson G. J., Bar-Matthews M., Tanaka T., Olsen E., and Grossman L. 1983. Refractory inclusions in the Murchison meteorite. *Geochimica et Cosmochimica Acta* 47:823–839.

MacPherson G. J., Grossman L., Hashimoto A., Bar-Matthews M., and Tanaka T. 1984. Petrographic studies of refractory inclusions from the Murchison meteorite. Proceedings, 15th Lunar and Planetary Science Conference. *Journal of Geophysical Research* 89:C299–C312.

McSween H. Y. 1987. Aqueous alteration in carbonaceous chondrites: Mass balance constraints on matrix mineralogy. *Geochimica et Cosmochimica Acta* 51:2469–2477.

Metzler K., Bischoff A., and Stöffler D. 1992. Accretionary dust mantles in CM chondrites: Evidence for solar nebula processes. *Geochimica et Cosmochimica Acta* 56:2873–2897.

Mittlefehldt D. W. 2002. Geochemistry of the ungrouped carbonaceous chondrite Tagish Lake, the anomalous CM chondrite Bells, and comparison with CI and CM chondrites. *Meteoritics & Planetary Science* 37:703–712.

Pizzarello S. and Huang Y. 2002. Molecular and isotopic analyses of Tagish Lake alkyl dicarboxylic acids. *Meteoritics & Planetary Science* 37:687–696.

Pouchou J. L. and Pichoir F. 1984. A new model for quantitative X-ray microanalysis. Part I: Application to the analysis of homogeneous samples. *Recherche Aerospatiale* 3:13–38.

Simon S. B. and Grossman L. 2001a. Petrography and mineral chemistry of the chondrule, inclusion, and olivine populations in the Tagish Lake carbonaceous chondrite (abstract #1240). 32nd Lunar and Planetary Science Conference. CD-ROM.

Simon S. B. and Grossman L. 2001b. The isolated grain population and accretionary rims observed in Tagish Lake (abstract). *Meteoritics & Planetary Science* 36:A189–A190.

Simon S. B., Grossman L., and Hsu A. 1993. Petrography and origin of refractory inclusions from the Murrray and Murchison C2 chondrites (abstract). 24th Lunar and Planetary Science Conference. pp. 1309–1310.

Simon S. B., Grossman L., Podosek F. A., Zinner E., and Prombo C. A. 1994. Petrography, composition, and origin of large, chromian spinels from the Murchison meteorite. *Geochimica et Cosmochimica Acta* 58:1313–1334.

Steele I. M. 1986. Compositions and textures of relic forsterite in carbonaceous and unequilibrated ordinary chondrites. *Geochimica et Cosmochimica Acta* 50:1379–1395.

Steele I. M. 1990. Minor elements in forsterites of Orgueil (C1), Alais (C1) and two interplanetary dust particles compared to C2-C3-UOC forsterites. *Meteoritics* 25:301–307.

Steele I. M. and Smith J. V. 1986. Contrasting forsterite compositions for C2, C3, and UOC meteorites: Evidence for divergence from common parent (abstract). 17th Lunar and Planetary Science Conference. pp. 822–823.

Weinbruch S., Zinner E. K., El Goresy A., Steele I. M., and Palme H. 1993. Oxygen isotopic composition of individual olivine grains from the Allende meteorite. *Geochimica et Cosmochimica Acta* 57:2649–2661.

Weinbruch S., Palme H., and Spettel B. 2000. Refractory forsterite in primitive meteorites: Condensates from the solar nebula? *Meteoritics & Planetary Science* 35:161–171.

Yoneda S. and Grossman L. 1995. Condensation of CaO-MgO-Al_2O_3-SiO_2 liquids from cosmic gases. *Geochimica et Cosmochimica Acta* 59:3413–3444.

Zolensky M., Barrett R., and Browning L. 1993. Mineralogy and composition of matrix and chondrule rims in carbonaceous chondrites. *Geochimica et Cosmochimica Acta* 57:3123–3148.

Zolensky M. E., Nakamura K., Gounelle M., Mikouchi T., Kasama T., Tachikawa O., and Tonui E. 2002. Mineralogy of Tagish Lake: An ungrouped type 2 carbonaceous chondrite. *Meteoritics & Planetary Science* 37:737–761.