Fine-grained dust rims in the Tagish Lake carbonaceous chondrite: Evidence for parent body alteration

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Abstract–The Tagish Lake carbonaceous chondrite consists of heavily aqueously altered chondrules, CAIs, and larger mineral fragments in a fine-grained, phyllosilicate-dominated matrix. The vast majority of the coarse-grained components in this meteorite are surrounded by continuous, 1.5 to >200 μm wide, fine-grained, accretionary rims, which are well known from meteorites belonging to petrological types 2 and 3 and whose origin and modification is still a matter of debate. Texturally, the fine-grained rims in Tagish Lake are very similar throughout the entire meteorite and independent of the nature of the enclosed object. They typically display sharp boundaries to the core object and more gradational contacts to the meteorite matrix. Compared to the matrix, the rims are much more fine-grained and characterized by a significantly lower porosity. The rims consist of an unequilibrated assemblage of phyllosilicates, Fe,Ni sulfides, magnetites, low-Ca pyroxenes, and forsteritic olivines, and are, except for a much lower abundance of carbonates, very similar to the Tagish Lake matrix. Electron microprobe and synchrotron X-ray microprobe analyses show that matrix and rims are also very similar in composition and that the rims differ significantly from matrix and bulk meteorite only by being depleted in Ca. X-ray elemental mapping and mineralogical observations indicate that Ca was lost during aqueous alteration from the enclosed objects and preferentially crystallized as carbonates in the porous matrix. The analyses also show that Ca is strongly fractionated from Al in the rims, whereas there is no fractionation of the Ti/Al-ratios. Our data suggest that the fine-grained rims in Tagish Lake initially formed by accretion in the solar nebula and were subsequently modified by in situ alteration on the parent body. This pervasive alteration removed any potential evidence for pre-accretionary alteration but did not change the overall texture of the Tagish Lake meteorite.

INTRODUCTION

The Tagish Lake meteorite, which fell on January 18, 2000 in the Yukon Territory, Canada, is a type 2 carbonaceous chondrite with both similarities and differences to CI and CM chondrite groups (Brown et al. 2000). While its high proportion of matrix and high amount of volatile elements suggest a close relationship to CI chondrites, the presence and mineral chemistry of chondrules and refractory inclusions, the sulfide mineralogy, and the bulk chemistry are more like CM and different from CI carbonaceous chondrites. As summarized by Simon and Grossman (2003), several previous studies of Tagish Lake’s bulk chemistry, oxygen isotopic composition, bulk organic carbon, and other organic compounds found that the meteorite is different from both CM and CI chondrites, yet in some properties it is intermediate between the two classes. Based on their mineralogical investigations, Zolensky et al. (2002) argued that Tagish Lake is distinct from all known C1- and C2-type carbonaceous chondrites and represents an entirely new type of C2 meteorite. As the reflectance spectrum of Tagish Lake is similar to spectra of D-type asteroids, it was suggested that this meteorite may represent the first material available on Earth from such very primitive and thermally unprocessed asteroids (Hiroi et al. 2001), although some ~10 μm IDPs exhibit reflection spectra similar to P- and D-type asteroids as well (Bradley et al. 1996).

One of the striking similarities of Tagish Lake with CM carbonaceous chondrites is the presence of fine-grained, matrix-like rims around coarse-grained components, such as Ca, Al-rich inclusions (CAIs), chondrules, and mineral fragments. Fine-grained rims around different kinds of
objects are found in many meteorites belonging to the unequilibrated petrological types 2 and 3 in various chondrite groups (see e.g., Metzler and Bischoff 1996 and references therein). The formation of such rims has been controversial since their first detailed description by Kurat (1970) in the H3 chondrite Tieschitz. The different formation mechanisms now proposed include: 1) condensation of fine-grained material from an impact-produced hot gas (Kurat 1970); 2) accretion of dust onto the surfaces of coarse-grained core objects in the solar nebula (e.g., Allen et al. 1980; Bunch and Chang 1980; King and King 1981; Scott et al. 1984; Rubin 1984; MacPherson et al. 1985; Rubin and Wasson 1987; Brearley and Geiger 1991; Tomeoka et al. 1991; Nakamura et al. 1991; Metzler et al. 1992; Brearley 1993; Metzler and Bischoff 1996; Hua et al. 1996, 2002); 3) formation by “regolith gardening” during multiple stages of aqueous alteration and brecciation of the enclosed objects on the parent body (Sears et al. 1993; Tomeoka and Tanimura 2000); 4) alteration of the enclosed objects (e.g., Richardson 1981; Sears et al. 1991, 1993); 5) shock melting caused by impacts into the regolith (Bunch et al. 1991); and 6) devitrification of quenched chondrule melts (Hutchison and Bevan 1983). Browning et al. (2000) studied rim textures surrounding individual silicate grains in CM chondrites and concluded that these rims formed by in situ alteration on the parent body. However, it should be pointed out that such rims are texturally quite different from the fine-grained dust mantles found in Tagish Lake and CM chondrites and thus require a distinct formation mechanism.

In order to address the origin of fine-grained, matrix-like rims and their relation to the meteorite matrix material, we performed a detailed study of the petrography and chemical compositions of the fine-grained rims in Tagish Lake.

SAMPLES AND ANALYTICAL METHODS

The Tagish Lake samples provided for this study were collected in spring 2000 and, although not disaggregated, may have been in contact with liquid lake water and snow melt for several months (Zolensky et al. 2002). To quantify potential changes of the meteorite’s bulk chemistry due to terrestrial alteration, Friedrich et al. (2003) and Dreibus et al. (2004) analyzed pristine and altered samples of the Tagish Lake meteorite. They found that the altered samples had suffered losses of the volatile halogens Cl, Br, and I as well as of the moderately volatile elements Na, K, and P, most likely due to dissolution of halogen salts in the ice water (Friedrich et al. 2003; Dreibus et al. 2004). In contrast, the studies showed that Ca, S, and Se abundances are almost identical in both the pristine and the altered samples, indicating that carbonates, sulfides, and sulfates remained unaffected during residence in the lake water and snow melt (Friedrich et al. 2003; Dreibus et al. 2004). This observation is also supported by the total absence of carbonate and sulfate veins and fillings, which would be indicative of leaching of Ca and S (e.g., Barrat et al. 1998; Gounelle and Zolensky 2001). A significant influence of terrestrial alteration on the distribution of especially calcium in the Tagish Lake samples studied here can thus be excluded.

Two demountable polished thin sections of Tagish Lake were studied in transmitted and reflected light by optical microscopy, backscattered electrons (BSE) by scanning electron microscopy (SEM), electron microprobe analysis (EPMA), transmission electron microscopy (TEM), and synchrotron X-ray fluorescence (SXRFL) analysis. BSE images were obtained using JEOL JSM-6300, -5900LV, and Zeiss DSM-962 scanning electron microscopes. Quantitative mineral analyses were performed with a JEOL JXA-8800L electron microprobe operated at 15 kV, a probe current of 15 nA, and a beam size of 1–2 μm. Major and minor element bulk compositions of the rims and the matrix were determined by electron microprobe analysis applying a defocused 25 and 50 μm electron beam, respectively. For analyses of phyllosilicates in rims and matrix, a defocused beam of 5–10 μm was used to avoid beam damage. Suitable mineral standards including anorthoclase, basaltic glass, chromite, chromium augite, diopside, ilmenite, microcline, and plagioclase, all certified by the United States National Museum as reference samples for electron microprobe analysis (Jarosewich et al. 1980), were applied to calculate the mineral compositions. The X-ray elemental maps were acquired on the same electron microprobe and on a Cameca SX-50 electron microprobe at 15 kV accelerating voltage, 50–100 nA beam current, and a beam size of approximately 1–2 μm.

After detailed petrographic studies, slotted Cu grids were glued on areas of interest of the thin section, removed and ion-thinned using a GATAN duo ion beam mill. During thinning, the samples were cooled by liquid nitrogen to avoid ion beam damage. TEM studies were carried out with a Philips CM20 analytical TEM operated at 200 kV and equipped with a Tracor Northern energy dispersive X-ray detector.

For trace element analyses, the samples were removed from the glass slide and mounted on Kapton film with a small drop of silicon oil. Trace element concentrations were measured in fragments from four rims, five matrix areas, and two chondrules using the X-ray microprobe at the National Synchrotron Light Source (Brookhaven National Laboratory). Depending on the size of the individual fragment, up to four analyses were carried out on each sample using a synchrotron X-ray beam of about 15 × 15 μm in size. Average compositions were calculated for matrix, chondrules, and each rim analyzed. The analytical errors of the SXRF analyses are on the order of ±10% for each value.

RESULTS

Petrography and Mineralogy of Rimmed Objects

Texturally, Tagish Lake is a porous breccia composed of
carbonate-poor and carbonate-rich lithologies distinguished mainly by different abundances of carbonates, magnetites, and sulfides (Zolensky et al. 2002). All sections investigated in this study belong to the more abundant carbonate-poor lithology (Figs. 1 and 2). According to the olivine and pyroxene textures, the meteorite shock stage is S1 (unshocked) (Scott et al. 1992; Zolensky et al. 2002).

In the sections studied, four different kinds of coarse-grained anhydrous components were found that are rimmed by fine-grained material: 1) chondrules; 2) CAIs; 3) mineral fragments; and 4) magnetite-rich aggregates (Fig. 3).

Chondrules occur in the size range of a few μm up to 1 mm and are dominantly FeO-poor porphyritic olivine (type IA; Fig. 3a) and olivine-pyroxene chondrules (type IAB; Fig. 2b). In such chondrules, the constituent olivines are nearly pure forsterites (Fa0.3–1.8) that contain considerable amounts of MnO (up to 0.43 wt%), CaO (up to 0.28 wt%), and Cr2O3 (up to 0.53 wt%; Table 1). Frequently, small Fe,Ni metal inclusions are present in the olivines. Pyroxene in type IAB chondrules is orthopyroxene (Fs0.7–1.6Wo0.3–1.1) with up to 0.78 wt% Al2O3 and 0.49 wt% Cr2O3 (Table 1).
Fig. 3. BSE images of various rimmed objects in Tagish Lake. a) Magnesian porphyritic olivine chondrule (type IA). b) Ferrous porphyritic olivine chondrule (type IIA) with compositionally zoned olivine grains. Parts of the formerly glassy mesostasis are still Al- and P-rich. c) Magnesian barred olivine chondrule. The mesostasis has been completely replaced by phyllosilicates. d) Magnesian olivine chondrule with dendritic texture. e) Porphyritic olivine chondrule with Fe,Ni-sulfide layer at the chondrule-rim interface. f) Two individually rimmed type IA chondrules attached to each other. FGR = fine-grained rim; mes = mesostasis; ol = olivine; phy = phyllosilicates; sf = sulfide.
Fine-grained dust rims in the Tagish Lake carbonaceous chondrite

In all chondrules of these two types, the high-Ca pyroxenes and the entire mesostasis have been aqueously altered to dominantly Mg-rich phyllosilicates, which are much more coarse-grained than the rim material (Figs. 2b and 3; Tables 2–3); also, no augite overgrowths on pyroxene phenocrysts were found. While several Fe,Ni metal inclusions in the forsteritic olivine have been replaced by alteration products (Table 4), their host olivines and also the constituent orthopyroxenes generally show only few signs of alteration. Occasionally, entire chondrules are almost completely altered to hydrous phases, leaving only rare relict forsterites (“chd psd” in Figs. 1 and 3). Two IA chondrules were found to be surrounded by a broad (up to 35 μm wide) Fe,Ni-sulfide band located between the silicate portion of the chondrule and the fine-grained rim (Fig. 3e).

Less abundant chondrule types with pronounced fine-grained rims include FeO-poor barred olivine chondrules (Fig. 3c), FeO-poor olivine chondrules with dendritic textures (Fig. 3d), and FeO-rich porphyritic olivine chondrules (type IIA; Fig. 3b). Again, the mesostasis of such chondrules has been replaced by phyllosilicates, whereas even the FeO-rich olivines appear almost unaffected by alteration. In some IIA type chondrules, relict olivines that display chemical zoning from Fa0.8 in the core to Fa35 at the rim are present (Fig. 3b; Table 1). In one of these chondrules, an exceptional case was found: parts of the formerly glassy Al- and P-rich mesostasis retained their primary compositional signature (Fig. 3b).

Independent of size, mineralogy, and chemical composition, several chondrules display ellipsoidal shapes most likely caused by deformation during mild shock metamorphism (Figs. 2a, 3b, and 3d). Such chondrule flattening was observed for samples of the Murchison CM2 chondrite experimentally shocked to only 4 GPa (Tomeoka
Table 1. Representative electron microprobe analyses of primary phases in various chondrule types and of unaltered mineral fragments.

<table>
<thead>
<tr>
<th>Chd. type</th>
<th>Min. frag.</th>
<th>ol 42.4</th>
<th>&lt;0.04</th>
<th>0.13</th>
<th>0.17</th>
<th>0.17</th>
<th>&lt;0.03</th>
<th>0.14</th>
<th>&lt;0.03</th>
<th>&lt;0.02</th>
<th>&lt;0.05</th>
<th>100.0</th>
<th>0.3</th>
</tr>
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<tbody>
<tr>
<td>IA</td>
<td>ol 42.3</td>
<td>&lt;0.04</td>
<td>0.14</td>
<td>0.17</td>
<td>0.41</td>
<td>&lt;0.03</td>
<td>0.41</td>
<td>0.14</td>
<td>&lt;0.03</td>
<td>&lt;0.02</td>
<td>&lt;0.05</td>
<td>100.0</td>
<td>0.4</td>
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<tr>
<td>&quot;-&quot;</td>
<td>ol 42.1</td>
<td>&lt;0.04</td>
<td>0.07</td>
<td>0.09</td>
<td>0.42</td>
<td>0.10</td>
<td>0.42</td>
<td>0.13</td>
<td>&lt;0.03</td>
<td>&lt;0.02</td>
<td>&lt;0.05</td>
<td>100.2</td>
<td>0.4</td>
</tr>
<tr>
<td>&quot;-&quot;</td>
<td>ol 42.5</td>
<td>&lt;0.04</td>
<td>0.14</td>
<td>0.25</td>
<td>0.10</td>
<td>0.10</td>
<td>0.25</td>
<td>0.13</td>
<td>&lt;0.03</td>
<td>&lt;0.02</td>
<td>&lt;0.05</td>
<td>100.8</td>
<td>0.2</td>
</tr>
<tr>
<td>&quot;-&quot;</td>
<td>ol 41.9</td>
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<td>0.08</td>
<td>0.53</td>
<td>1.7</td>
<td>0.19</td>
<td>1.7</td>
<td>0.06</td>
<td>&lt;0.03</td>
<td>&lt;0.02</td>
<td>0.13</td>
<td>100.6</td>
<td>1.7</td>
</tr>
<tr>
<td>IAB</td>
<td>ol 41.4</td>
<td>&lt;0.04</td>
<td>0.03</td>
<td>0.47</td>
<td>0.80</td>
<td>0.43</td>
<td>0.8</td>
<td>0.24</td>
<td>&lt;0.03</td>
<td>&lt;0.02</td>
<td>0.05</td>
<td>98.8</td>
<td>0.8</td>
</tr>
<tr>
<td>&quot;-&quot;</td>
<td>ol 41.9</td>
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<td>0.03</td>
<td>0.40</td>
<td>0.61</td>
<td>0.24</td>
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<td>0.26</td>
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<td>&lt;0.05</td>
<td>100.2</td>
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<tr>
<td>&quot;-&quot;</td>
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<td>0.33</td>
<td>0.64</td>
<td>0.22</td>
<td>0.6</td>
<td>0.22</td>
<td>&lt;0.03</td>
<td>&lt;0.02</td>
<td>&lt;0.05</td>
<td>99.2</td>
<td>0.7</td>
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<tr>
<td>&quot;-&quot;</td>
<td>px 58.6</td>
<td>&lt;0.04</td>
<td>0.78</td>
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<td>&lt;0.05</td>
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<tr>
<td>&quot;-&quot;</td>
<td>px 59.3</td>
<td>&lt;0.04</td>
<td>0.46</td>
<td>0.49</td>
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<td>&lt;0.03</td>
<td>1.2</td>
<td>0.30</td>
<td>&lt;0.03</td>
<td>&lt;0.02</td>
<td>&lt;0.05</td>
<td>100.9</td>
<td>1.6</td>
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<td>0.01</td>
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<td>0.81</td>
<td>0.29</td>
<td>0.8</td>
<td>0.23</td>
<td>&lt;0.03</td>
<td>&lt;0.02</td>
<td>&lt;0.05</td>
<td>99.6</td>
<td>0.8</td>
</tr>
<tr>
<td>&quot;-&quot;</td>
<td>ol 38.4</td>
<td>&lt;0.04</td>
<td>0.02</td>
<td>0.34</td>
<td>21.6</td>
<td>0.29</td>
<td>2.1</td>
<td>0.15</td>
<td>&lt;0.03</td>
<td>&lt;0.02</td>
<td>0.06</td>
<td>99.9</td>
<td>23.8</td>
</tr>
<tr>
<td>&quot;-&quot;</td>
<td>ol 36.6</td>
<td>&lt;0.04</td>
<td>0.01</td>
<td>0.20</td>
<td>32.7</td>
<td>0.37</td>
<td>3.2</td>
<td>0.46</td>
<td>&lt;0.03</td>
<td>&lt;0.02</td>
<td>0.06</td>
<td>100.7</td>
<td>37.8</td>
</tr>
<tr>
<td>&quot;-&quot;</td>
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<td>&lt;0.04</td>
<td>0.02</td>
<td>0.18</td>
<td>37.8</td>
<td>0.51</td>
<td>3.8</td>
<td>0.46</td>
<td>&lt;0.03</td>
<td>&lt;0.02</td>
<td>0.07</td>
<td>99.4</td>
<td>46.3</td>
</tr>
<tr>
<td>I, BO</td>
<td>ol 42.2</td>
<td>0.24</td>
<td>&lt;0.01</td>
<td>0.50</td>
<td>1.2</td>
<td>0.12</td>
<td>1.2</td>
<td>0.20</td>
<td>&lt;0.03</td>
<td>&lt;0.02</td>
<td>&lt;0.05</td>
<td>100.0*</td>
<td>0.9</td>
</tr>
<tr>
<td>Min. frag.</td>
<td>ol 42.4</td>
<td>&lt;0.04</td>
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<td>0.17</td>
<td>0.34</td>
<td>&lt;0.03</td>
<td>0.3</td>
<td>0.79</td>
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<td>&lt;0.05</td>
<td>100.2</td>
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<tr>
<td>Min. frag.</td>
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<td>0.05</td>
<td>0.53</td>
<td>36.5</td>
<td>0.55</td>
<td>3.6</td>
<td>0.28</td>
<td>&lt;0.03</td>
<td>&lt;0.02</td>
<td>&lt;0.05</td>
<td>100.8</td>
<td>43.2</td>
</tr>
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Data in wt%; chd. = chondrule; min. frag. = mineral fragment; ol = olivine; px = low-Ca pyroxene.

Table 2. Representative electron microprobe analyses of alteration products replacing olivine and pyroxene in various chondrule types and in mineral fragments.

<table>
<thead>
<tr>
<th>Chd. type</th>
<th>SiO2</th>
<th>TiO2</th>
<th>Al2O3</th>
<th>Cr2O3</th>
<th>FeO</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na2O</th>
<th>K2O</th>
<th>NiO</th>
<th>Total</th>
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<tr>
<td>IA</td>
<td>39.9</td>
<td>0.16</td>
<td>3.9</td>
<td>3.3</td>
<td>17.2</td>
<td>0.22</td>
<td>20.1</td>
<td>0.44</td>
<td>0.18</td>
<td>&lt;0.02</td>
<td>0.33</td>
<td>86.2</td>
</tr>
<tr>
<td>&quot;-&quot;</td>
<td>39.1</td>
<td>0.11</td>
<td>3.5</td>
<td>2.7</td>
<td>16.2</td>
<td>0.17</td>
<td>20.9</td>
<td>0.34</td>
<td>0.33</td>
<td>0.14</td>
<td>0.55</td>
<td>84.4</td>
</tr>
<tr>
<td>Type IAB</td>
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<td>0.13</td>
<td>4.6</td>
<td>4.1</td>
<td>19.6</td>
<td>0.31</td>
<td>21.5</td>
<td>0.44</td>
<td>0.47</td>
<td>0.11</td>
<td>0.38</td>
<td>90.2</td>
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<tr>
<td>I, BO</td>
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<td>4.3</td>
<td>4.0</td>
<td>18.1</td>
<td>0.15</td>
<td>22.1</td>
<td>0.31</td>
<td>0.36</td>
<td>0.13</td>
<td>0.44</td>
<td>91.0</td>
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<td>Min. frag.</td>
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<td>6.8</td>
<td>3.1</td>
<td>19.0</td>
<td>0.13</td>
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<td>0.49</td>
<td>0.12</td>
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<tr>
<td>Min. frag.</td>
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<td>4.3</td>
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<td>8.0</td>
<td>&lt;0.03</td>
<td>25.3</td>
<td>0.32</td>
<td>0.27</td>
<td>0.16</td>
<td>0.23</td>
<td>84.0</td>
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</table>

Data in wt%; chd. = chondrule; min. frag. = mineral fragment; ol = olivine; px = low-Ca pyroxene.
et al. 1999), a pressure corresponding to the shock class S1 assigned to the Tagish Lake chondrite (Stöffler et al. 1991; Scott et al. 1992; Zolensky et al. 2002).

Ca, Al-rich inclusions and other refractory objects in Tagish Lake are also strongly affected by alteration, as are the chondrules (Fig. 3g). Typically, the primary phases are extensively replaced by coarse-grained, FeO-poor phyllosilicates and dolomite with up to 5.2 wt% FeO and 3.9 wt% MnO. While other authors reported hibonite-rich inclusions and small grains of perovskite (e.g., Zolensky et al. 2002; Simon and Grossman 2003), in this study, only spinel (0.14 TiO₂, 69.0 Al₂O₃, 0.18 Cr₂O₃, 1.4 FeO, <0.03 MnO, 29.1 MgO, <0.02 CaO, 0.06 Na₂O, <0.02 K₂O, 0.13 NiO; data in wt%; normalized to 100% and corrected assuming that all SiO₂ comes from the surrounding material) was identified as an unaltered refractory phase. Also, olivine-rich objects largely consisting of refractory forsterite and lacking any (altered) mesostasis were only rarely found in the thin sections studied.

Mineral fragments rimmed by fine-grained material include forsteritic olivine, FeO-rich and sometimes compositionally zoned olivine, and FeO-poor low-Ca pyroxene (Fig. 3h). Similar to chondrules, all high-Ca pyroxenes are almost entirely altered to Mg-rich phyllosilicates, whereas olivine and orthopyroxene show no or only minor degrees of alteration along fractures and around Fe,Ni-metal inclusions (Fig. 3h, Tables 2 and 4).

Magnetite occurs as large single spherules, clusters of tiny euhedral or also rounded crystals, stacked platelets-plaquettes, and as framboids (Fig. 4). All these morphologies have been observed in various types of carbonaceous chondrites (e.g., Hua and Buseck 1998). The magnetite clusters are often found to be pseudomorphs after hexagonal pyrrhotite grains (Fig. 4a; Zolensky et al. 2002). Several of the 45 μm to 1 mm-sized clusters composed of ~50 to several hundred magnetites of different morphologies are surrounded by fine-grained rims (Fig. 3i).

**Table 3. Representative electron microprobe analyses of alteration products replacing mesostasis in various chondrule types.**

<table>
<thead>
<tr>
<th>Chd. type</th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>Cr₂O₃</th>
<th>FeO</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>NiO</th>
<th>S</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA</td>
<td>42.6</td>
<td>0.11</td>
<td>3.5</td>
<td>0.88</td>
<td>9.6</td>
<td>0.13</td>
<td>26.0</td>
<td>0.26</td>
<td>0.31</td>
<td>0.04</td>
<td>0.60</td>
<td>0.10</td>
<td>84.1</td>
</tr>
<tr>
<td>&quot;-&quot;-</td>
<td>43.5</td>
<td>0.29</td>
<td>3.1</td>
<td>0.63</td>
<td>11.4</td>
<td>0.06</td>
<td>26.8</td>
<td>0.32</td>
<td>0.22</td>
<td>0.11</td>
<td>1.1</td>
<td>0.17</td>
<td>87.7</td>
</tr>
<tr>
<td>&quot;-&quot;-</td>
<td>43.0</td>
<td>0.22</td>
<td>3.7</td>
<td>0.96</td>
<td>8.7</td>
<td>0.10</td>
<td>30.7</td>
<td>0.18</td>
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<td>0.03</td>
<td>0.57</td>
<td>0.06</td>
<td>88.5</td>
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<tr>
<td>IAB</td>
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<td>3.1</td>
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<td>0.08</td>
<td>26.5</td>
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<td>5.0</td>
<td>1.1</td>
<td>12.6</td>
<td>0.13</td>
<td>25.9</td>
<td>0.19</td>
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<td>0.13</td>
<td>0.51</td>
<td>0.06</td>
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<td>90.1</td>
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<tr>
<td>IIA</td>
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<td>10.3</td>
<td>0.16</td>
<td>25.1</td>
<td>0.11</td>
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<td>0.62</td>
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<td>0.29</td>
<td>0.09</td>
<td>0.73</td>
<td>0.21</td>
<td>87.9</td>
</tr>
</tbody>
</table>

Data in wt%; chd. = chondrule.

**Table 4. Representative electron microprobe analyses of typical metal alteration products in IAB chondrules and forsteritic olivine fragments.**

<table>
<thead>
<tr>
<th>Chd. type</th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>Cr₂O₃</th>
<th>FeO</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>NiO</th>
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<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>IAB</td>
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<td>&lt;0.04</td>
<td>4.8</td>
<td>2.1</td>
<td>18.2</td>
<td>0.15</td>
<td>23.6</td>
<td>0.37</td>
<td>0.53</td>
<td>0.06</td>
<td>2.3</td>
<td>0.51</td>
<td>90.5</td>
</tr>
<tr>
<td>Min. frag., ol</td>
<td>28.2</td>
<td>&lt;0.04</td>
<td>2.6</td>
<td>1.5</td>
<td>17.9</td>
<td>0.22</td>
<td>19.0</td>
<td>0.40</td>
<td>0.31</td>
<td>0.03</td>
<td>2.9</td>
<td>0.98</td>
<td>74.1</td>
</tr>
<tr>
<td>&quot;-&quot;-</td>
<td>37.9</td>
<td>&lt;0.04</td>
<td>6.9</td>
<td>1.2</td>
<td>16.7</td>
<td>&lt;0.03</td>
<td>22.1</td>
<td>0.14</td>
<td>0.94</td>
<td>0.11</td>
<td>0.29</td>
<td>0.44</td>
<td>86.8</td>
</tr>
</tbody>
</table>

Data in wt%; chd. = chondrule; min. frag. = mineral fragment; ol = olivine.

Mineralogy and Petrography of Fine-Grained Rims

Most chondrules, mineral fragments and refractory objects in Tagish Lake are surrounded by continuous, phyllosilicate-dominated, fine-grained rims, which can clearly be distinguished from the enclosed objects and the meteorite matrix (Figs. 1–3).

Texturally, the fine-grained rims exhibit very similar characteristics throughout the entire meteorite that are independent from the nature of the enclosed object (Fig. 5). The thicknesses of the rims vary between 1.5 and >200 μm and are positively correlated with the diameters of the enclosed objects, i.e., large objects are surrounded by broad rims and small constituents by thin layers (Fig. 6). Most rims contain radial cracks extending from the object-rim to the rim-matrix boundary and typically do not continue into the matrix or the core objects (Figs. 2 and 3). The rims generally exhibit sharp boundaries with the enclosed objects and show a clearly recognizable but more diffuse transition to the matrix of the meteorite (Figs. 2, 3, and 5a). The rims are much finer-grained and less porous than the chondrule, CAI, and mineral fragment alteration products and the meteorite matrix (Figs. 3 and 5b). The rim-chondrule boundaries are occasionally decorated by opaque layers of either Fe,Ni sulfides or magnetites, which clearly belong to the enclosed object (Fig. 3e). One type IA chondrule was found in which the
alteration products (phyllosilicates) of the primary chondrule phases seem to crosscut the rim into the meteorite matrix (Fig. 5c). Some rims show a pronounced internal layering with two layers of different compositions (Figs. 5a and 5b). In these cases, the layer appearing bright in BSE images is more fine-grained and enriched in magnetite and sulfides. Usually, the FeO-rich layer forms the outer and the FeO-poor layer the inner part of the dust rim (Fig. 5a). However, an opposite case was also observed (Fig. 5b).

Mineralogically, the rims consist of unequilibrated assemblages of dominant phyllosilicates, Fe,Ni sulfides of mostly intermediate pyrrhotite-pentlandite composition (Zolensky and Di Valentin 1998; Zolensky et al. 2002), as well as pentlandite, Fe,Ni metal, magnetites, low-Ca pyroxenes, and forsteritic olivines with sometimes high MnO contents (Figs. 5e and 5f). Magnetites in the rims exhibit very similar morphologies (rounded crystals, plaquettes, and framboids) to those observed in the Tagish Lake matrix (Fig. 5d), supporting this conclusion. Carbonates are less abundant in the rims compared to the matrix. Grain sizes of the different components vary from <1 to 25 μm, and, except for the much lower abundance of carbonates, the rims are mineralogically very similar to the matrix of Tagish Lake.

TEM investigations of several rims reveal the presence of both fine-grained phyllosilicates with entangled ribbon-like structures and more coarse-grained phyllosilicate flakes (Fig. 7a). These differently shaped aggregates are found as mostly distinct regions adjacent to each other on a sub-μm scale (Fig. 7a). While the ribbon-like aggregates consist of intimately intergrown saponite (1.0–1.2 nm lattice fringes) and serpentine (0.7 nm lattice fringes), the coarse-grained clumps and flakes are clearly dominated by curved saponite crystals with only minor amounts of serpentine (Figs. 7a and
Fig. 5. BSE images illustrating the characteristic features of fine-grained rims in Tagish Lake. a) Layered rim with FeO-poor portion at the chondrule-rim interface. Note the sharp rim-chondrule and the more gradual rim-matrix boundaries. b) Layered rim with FeO-rich portion at the chondrule-rim interface. c) Chondrule phyllosilicates crosscutting the fine-grained rim into the meteorite matrix. d) Magnetites of various morphologies (rounded crystals, framboids, and platelets) in a fine-grained rim. e) Large magnetite, sulfide, and Mg-rich olivine in a compact fine-grained rim matrix. f) Coarse phyllosilicates and tiny sulfides in a fine-grained rim. chd = chondrule; chd phy = chondrule phyllosilicates; cph = coarse phyllosilicates; FGR = fine-grained rim; mt = magnetite; ol = olivine; sf = sulfide.
7d). The anhydrous rim components, i.e., tiny, mostly rounded magnetites, lath shaped to euhedral Fe,Ni sulfides, and often randomly corroded silicates in the size range of several tens of nm to about 1 μm, are interspersed within the phyllosilicate dominated groundmass of the rims (Figs. 7a–c). These observations indicate that the fine-grained rims are also on the TEM scale very similar to the matrix of the carbonate-poor lithology of Tagish Lake (Keller and Flynn 2001; Mikouchi et al. 2001; Zolensky et al. 2002).

Chemical Composition of Matrix and Fine-Grained Rims

The major and minor element compositions of Tagish Lake matrix and fine-grained rims, as determined by defocused beam electron microprobe analysis, are given in Table 5 and illustrated in Fig. 9; the compositions of the rim and matrix phyllosilicates were also determined by electron microprobe analysis and are shown in Fig. 8. For analyses, only areas without carbonate grains and pits were selected. The microprobe analyses yield low average totals of 63.1 wt% for the matrix and of 76.2 wt% for the rims, indicating the presence of water-bearing phyllosilicates and an amount of porosity that is significantly higher in the matrix than in the rims (Table 5). Additionally, the low average totals may be caused by a higher percentage of saponite relative to serpentine in the matrix. The analyses also suggest that the fine-grained rims are chemically homogeneous at the 25 μm scale. As illustrated in a ternary Mg-Fe-Al + Si plot (Fig. 8), the phyllosilicates occurring in rims and matrix exhibit a striking compositional similarity. Both matrix and rim phyllosilicates show a comparable spread from Mg-rich compositions resulting from abundant Mg-rich phyllosilicates to more Fe-rich compositions caused by heterogeneous distributions of small magnetites, sulfides and more rarely Fe-rich phyllosilicates. This heterogeneous distribution of the opaque phases most likely also accounts for the slightly different molar Fe/(Mg + Fe) ratios that average at 0.35 for the matrix and at 0.41 for the rims. Compared to fine-grained rims in CM chondrites (Metzler et al. 1992; Zolensky et al. 1993), the rims in Tagish Lake show a broad compositional overlap with CM rims both extending to Mg-rich compositions (Zolensky et al. 1993).

By normalizing the compositions of matrix and rims to the bulk composition of the Tagish Lake meteorite, it is confirmed that matrix and rims are very similar in composition and differ from the bulk meteorite by being slightly depleted in Na and slightly enriched in S (Fig. 9). Most notably, the rims are strongly depleted in Ca and slightly enriched in Ti compared to bulk Tagish Lake. The only bulk compositional differences between matrix and rims are a significant depletion of Ca and a small enrichment of Ti in the rim material relative to the matrix (Fig. 9). This remarkable depletion of Ca in the rims and the core objects compared to the matrix is illustrated by X-ray elemental mapping of a single rimmed chondrule and of a larger area of Tagish Lake (Figs. 1 and 10).

The microprobe analyses also show that Ca is strongly fractionated from Al in the rims, whereas in the matrix the Ca/Al ratios scatter over a wide range (Fig. 11). The average Ca/Al ratios of the rims of 0.26 and the matrix of 0.71 are, however, both clearly below the ratio of 1.0 for the Tagish Lake bulk composition. In contrast to calcium, the geochemically less mobile Ti is significantly less fractionated in rims and matrix (Fig. 12). The only small variability in the Ti/Al ratios averages at 0.07 for the rims and 0.04 for the matrix compared to 0.05 for the bulk meteorite.

The results of synchrotron X-ray microprobe analyses indicate that, within analytical errors, there is only slightly variation for moderately volatile element concentrations from rim to rim (Fig. 13). Average matrix and rims have almost identical contents of Ni, Zn, Ga, and Se. Only Cu, and Ge may be slightly enriched in the rims. Relative to the mean Tagish Lake composition, rims and matrix are, on average, enriched in Ni, Cu, Ge, Se, and Zn. These results are in good agreement with data obtained from fine-grained rims of the CO3.0 chondrite ALH A77307 (Brearley et al. 1995). No correlation between element concentrations and the degree of volatility has been observed. The averaged concentrations of moderately volatile elements in the two chondrules analyzed differ significantly from those in matrix and rims. While Ni, Cu, Se, and Zn are depleted, Ga and Ge are enriched compared with the rims, the matrix, and the Tagish Lake mean (Fig. 13). In the chondrules, decreasing concentrations are found for Ga, Ge, Se, and Zn in the order of their decreasing condensation temperatures.
Fine-grained dust rims in the Tagish Lake carbonaceous chondrite

Fig. 7. Transmission electron microscope images of fine-grained rims in Tagish Lake. a) Bright field image showing the typical microtexture of the rims. Coarse- and fine-grained phyllosilicates are present in distinct, adjacent regions and serve as groundmass to small anhydrous mineral phases including magnetite, olivine and Fe,Ni sulfides; the latter are present as lath-shaped and euhedral crystals. b) Bright field image of a randomly corroded olivine embedded into coarse phyllosilicates. c) Bright field image of a euhedral sulfide and a rounded magnetite crystal. d) High-resolution TEM image of saponite displaying 1.2 nm interlayer spacings. cph = coarse phyllosilicates; fph = fine phyllosilicates; mt = magnetite; ol = olivine; sap = saponite; sf = sulfide.
DISCUSSION

Several of the observed mineralogical and chemical rim characteristics allow one to constrain the origin of the rims around anhydrous components in Tagish Lake. In the discussion, we will focus on the three main mechanisms proposed for the formation of fine-grained rims: regolith gardening, in situ alteration of the enclosed objects, and accretion onto the enclosed objects.

Formation of the Fine-Grained Rims

Regolith gardening for the origin of the fine-grained rims has been proposed by a number of investigators (e.g., Sears et al. 1993; Tomeoka and Tanimura 2000). However, the fine-grained rims in Tagish Lake completely surround the coarse-grained objects (CAIs, chondrules, and mineral fragments) and show no evidence for fragmentation. These observations strongly argue against formation of the rims by regolith gardening. Such highly disruptive processes should have produced abundant fragments of partly rimmed objects, completely rimmed lithic clasts composed of chondrules, CAIs, and/or mineral fragments, and also pervasive cracks not restricted to specific constituents (e.g., Metzler et al. 1992; Metzler and Bischoff 1996; Hua et al. 2002). Compared observations in many even strongly brecciated and/or metamorphosed CM chondrites, the fine-grained rims in Tagish Lake often contain radial cracks which do not extend into the meteorite matrix (e.g., Metzler et al. 1992, Brearley 1993; Hua et al. 2002). However, because none of the cracked rims is fragmented, it seems highly unlikely that the cracks formed by collision of the rimmed objects prior or during the aggregation of Tagish Lake. Instead, we suggest that these cracks formed during in situ aqueous alteration due to volume change (e.g., oxidation of metal to magnetite), as previously reported from the ungrouped carbonaceous chondrite MAC 88107 (Krot et al. 2000). The presence of different lithologies (carbonate-rich and poor) together with the restriction of cracks to only the fine-grained rims may further indicate that Tagish Lake is not brecciated on the chondrule but only on larger scale.

In situ alteration of the enclosed objects (e.g., Sears et al. 1991) is also unlikely for the origin of the fine-grained rims, based on convincing textural and compositional evidence: 1) the fine-grained rims exhibit very similar mineralogical characteristics independent of the nature of the enclosed object; 2) no replacement of any chondrule or CAI mineral by fine-grained rim material has been observed; 3) alteration products of mesostasis and high-Ca pyroxene in the rimmed chondrules and of refractory phases in CAIs are

Table 5. Defocused beam electron microprobe analyses of matrix and rims in Tagish Lake.

<table>
<thead>
<tr>
<th></th>
<th>Matrix n = 79</th>
<th>Rims* n = 80</th>
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<th>lo</th>
<th>2i</th>
<th>2o</th>
<th>3i</th>
<th>3o</th>
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<td>K₂O</td>
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<td>80.4</td>
<td>81.3</td>
<td>75.3</td>
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</table>

Data in wt%; *non-layered rims; i = inner rim; o = outer rim. 1–3: Fe/Mg(inner) < Fe/Mg(outer); 4: Fe/Mg(inner) > Fe/Mg(outer); n = number of analyses.
mineralogically and texturally different from the rim material; 4) the positive correlation of rim thickness with the diameter of the core object contradicts rim formation by in situ alteration (e.g., Metzler et al. 1992; Metzler and Bischoff 1996); 5) SXRF and EMP analyses show that the rims are compositionally very similar throughout the entire meteorite and significantly different from the enclosed objects.

Accretion onto the enclosed rims in the solar nebula for the formation of the fine-grained rims appears to us, in agreement with earlier investigators, to be the only viable mechanism for their origin. According to Metzler et al. (1991, 1992), the observed positive correlation between rim thickness and core object diameter indicates that the rims formed—depending on the dust/gas ratio—within several thousand years in a turbulent protoplanetary disk. Although chemically very similar, the layering of some fine-grained rims makes sampling from compositionally different reservoirs in the solar nebula very likely (e.g., Metzler et al. 1991, 1992; Metzler and Bischoff 1996).

Alteration and Modification of Fine-Grained Rims

Fine-grained rims dominantly consist of secondary minerals formed by aqueous alteration of anhydrous precursor phases, and there is still considerable debate about whether this alteration predates accretion of the rims (e.g., Ikeda 1983; Metzler et al. 1992; Bischoff 1998) or took place after rim formation on the parent body (e.g., Zolensky and McSween 1988; Krot et al. 1995, 1998a; Hanowski and Brearley 2000).

As discussed in a detailed review by Bischoff (1998), there are textural, mineralogical, and chemical characteristics of fine-grained rims and rimmed objects, especially in CM chondrites, which strongly indicate a pre-accretionary alteration of the rim material (see also Ciesla et al. 2003). The evidence listed includes: 1) the presence of unaltered chondrule mesostasis in direct contact with rim phyllosilicates, indicating that the rim phases must have been altered before accreting onto the chondrule; 2) the presence of a rimmed chondrule fragment where olivine displays both fresh and serpentinized surfaces but no alteration at the rim-chondrule interface, indicating that the olivine was altered before the rims accreted; 3) the presence of heterogeneous disequilibrium mineral assemblages in the rims, disproving homogeneous in situ parent body alteration; and 4) the presence of altered chondrules surrounded by rims containing numerous anhydrous minerals. All these observations can only be sufficiently explained by pre-accretionary alteration of the rim and/or chondrule minerals, but not by in situ parent body alteration, which should have led to a more homogeneous degree of alteration of all involved phases (Bischoff 1998 and references therein). It is further suggested that such pre-accretionary alteration occurred on small, uncompacted precursor planetesimals that were later disrupted, which produced large amounts of fine-grained chondritic material altered to different degrees (Metzler et al. 1992; Bischoff 1998; Wilson et al. 1998).

In contrast to this scenario, several observations have been made in carbonaceous chondrites which seem to contradict pre-accretionary alteration and are instead more compatible with in situ parent body alteration. For example, matrix and fine-grained rims within any particular meteorite are found to be mineralogically, but not always compositionally, identical to one another (Rubin 1984; Scott et al. 1984; Brearley and Geiger 1991; Zolensky et al. 1993). By assuming that the composition of the material was determined by the initial mineralogy, whereas the current mineralogy is determined by secondary modification processes, it is concluded that the observed identical mineralogy of rims and matrix was caused by post-accretional aqueous alteration on the parent body (Zolensky et al. 1993). This model seems to be supported by local correlations between mineralogy and composition of fine-grained rims, indicating that aqueous alteration occurred in situ and that the resulting secondary mineral assemblage is controlled by the rim’s bulk chemistry (Brearley and Geiger 1991). In addition, Hanowski and Brearley (2000) found Fe-rich aureoles around numerous components in CM chondrites, the origin of which is incompatible with pre-accretional alteration. Their mass balance calculations show that, during aqueous alteration, Fe was mobilized from metal grains and is now quantitatively present in the aureoles. Excluding any significant Fe loss due to previous pre-accretional alteration, thus, the aureoles strongly suggest in situ parent body alteration (Hanowski and Brearley 2000). Finally, a similar degree of alteration of rims and matrix, as well as a systematic Mg enrichment of serpentines in chondrules and rims with increasing degree of alteration, are taken as arguments for in situ parent body alteration (Hanowski and Brearley 2001).
The Tagish Lake meteorite shows strong compositional and mineralogical evidence for extensive in situ parent body aqueous alteration that affected all lithologies, including the fine-grained rims.

Chemically, this alteration resulted in the fractionation of the refractory lithophile Ca from Al in the rims and in their general depletion in Ca compared to the bulk meteorite (Figs. 1, 10, and 11). In contrast, the less mobile Ti remained unfractionated. A similar behavior of Ca was previously reported from fine-grained rims in various CM chondrites (e.g., Metzler et al. 1992; Brearley 1996; Hanowski and Brearley 2001; Hua et al. 2002). Our petrographic observations suggest that Ca was lost from the rimmed objects as a result of the replacement of Ca-rich phases, i.e., Ca-rich pyroxene, chondrule mesostasis, and melilite, by Ca-free/poor phyllosilicates. Because Ca and Al are refractory lithophile elements of similar volatility, the observed fractionation of Ca from Al and mobilization of Ca suggests
that Ca was transported via an aqueous fluid through the fine-grained rims and precipitated as Ca carbonates in the meteorite’s matrix. This preferential precipitation may have resulted either from the higher porosity of the matrix or was controlled by a chemical gradient between enclosed object, rim, and matrix. The fact that fractionation and redistribution of Ca is commonly observed in the aqueously altered CM, CR, and CV carbonaceous chondrites (e.g., Brearley 1996; Krot et al. 1998a, 1998b) strongly suggests that mobilization of Ca from chondrules and CAIs into the meteorite matrix is a general process during aqueous alteration of carbonaceous chondrites that may serve as an indicator for the degree of alteration (e.g., Brearley 1996; Krot et al. 1998a, 2003). Accordingly, the different degrees of Ca mobilization found in Tagish Lake and Murchison (Figs. 1 and 14) convincingly indicate that Tagish Lake is more pervasively altered than this rather weakly altered CM2 chondrite. This conclusion is supported by the extreme alteration of CAIs in Tagish Lake pointing to a more progressive alteration than in any other CAI-bearing CM2 chondrite (Zolensky et al. 2002).

With the exception of Ca and Ti, Tagish Lake matrix and rims show almost identical concentrations for all elements measured. However, as aqueous alteration may have also lead to a redistribution of, especially, the chalcophile elements Zn and Se, whose hosts pyrrhotite and pentlandite are often replaced by magnetite, a possible primary compositional difference between matrix and rims may have been erased.

Mineralogically, rims and matrix in Tagish Lake consist of saponite, serpentine, sulfides, and magnetites, in textures that are typical for CI1 chondrites but completely unlike those of CM2 chondrites (see also Keller and Flynn 2001; Mikouchi et al. 2001; Zolensky et al. 2002). Also, the molar Fe/(Fe + Mg) ratios of phyllosilicates in Tagish Lake matrix (fe = 0.3–0.35) and rims (fe = 0.41) are more similar to the phyllosilicate compositions of the CI1 chondrite Ivuna (fe ~0.3) rather than to those of rim and matrix phyllosilicates in CM2 chondrites averaging at fe ~0.7 (e.g., Zolensky et al. 1993; Brearley 1997; Zolensky et al. 2002). As suggested by several studies, there is a strong correlation between the degree of alteration and the MgO content of phyllosilicates replacing primary phases, i.e., the MgO content increases with increasing degree of alteration (e.g., Browning et al.
the high modal abundance of magnetite in Tagish Lake clearly shows that the meteorite is much more oxidized than CM2 chondrites, suggesting that the Mg-rich compositions observed for phyllosilicates in Tagish Lake are more likely due to fractionation of Fe from fine-grained phyllosilicates (Fe-rich serpentinite) into magnetite and not indicative for advanced alteration (e.g., Brearley 1997). In addition, recent studies of iron-nickel sulfides in CM chondrites showed that the alteration index based on the MgO content of phyllosilicates may not be valid for the most thoroughly altered CMs (Chokai et al. 2004).

There is, however, also strong mineralogical evidence for progressive in situ aqueous alteration of Tagish Lake. Systematic studies of sulfides in differently altered CM chondrites have shown that the amount of intermediate sulfides is directly related to the degree of alteration, i.e., pure pyrrhotite is the dominant sulfide in weakly altered CM chondrites, whereas intermediate sulfides become increasingly abundant in strongly altered CMs (Zolensky et al. 2002; Chokai et al. 2004). In Tagish Lake, the presence of both pure pyrrhotite and intermediate sulfides indicates incomplete transformation and a degree of aqueous alteration intermediate within the CM2 range (Zolensky et al. 2002).

Additionally, the very similar composition of phyllosilicates in matrix and rims, the survival of dominantly very Mg-rich anhydrous silicates in chondrules, matrix, and rims, as well as the presence of clusters of frambooidal magnetites in rims and matrix, prove a similar degree of alteration in all lithologies and strongly suggest in situ alteration of the rim material. However, the presence of anhydrous relict phases in matrix and rims confirm that aqueous alteration did not proceed to completion.

The rare occurrence of both entirely altered chondrule pseudomorphs (Fig. 3j) and chondrules with intact Fe-rich olivines (Fig. 3b) may either reflect mixing of differently altered material during brecciation or document that aqueous alteration was locally heterogeneous. Since the meteorite matrix, the vast majority of rimmed objects, and all rims show an almost identical degree of alteration, local heterogeneities during the alteration process seem much more likely (Fig. 1). Such different degrees of in situ chondrule alteration were previously found in dark inclusions from the Efremovka CV3 chondrite (Krot et al. 1999).

The evidence presented above strongly indicates that, apart from small localized heterogeneities, progressive parent body alteration pervasively affected all Tagish Lake lithologies and removed any potential evidence for pre-accretionary alteration. However, despite such strong alteration, the overall texture of Tagish Lake remained unchanged. Similar features were previously reported from the CM2 chondrites Nogoya (Metzler 1995) and ALH 81002 (Hanowski and Brearley 2000, 2001), and the ungrouped carbonaceous chondrite MacAlpine Hills (MAC) 88107 (Krot et al. 2000), where the mantled objects were also altered in situ on the parent body, but the primary accretionary texture is still preserved.
CONCLUSIONS

These observations on fine-grained rims in the Tagish Lake carbonaceous chondrite allow us to draw the following conclusions:
1. Fine-grained rims are not genetically linked to the enclosed objects, excluding their formation by alteration of the core object.
2. Fine-grained rims show no evidence of fragmentation, indicating that they formed prior to accretion of the meteorite parent body.
3. Formation of the rims by accretion in the solar nebula most convincingly accounts for all textural, mineralogical, and compositional characteristics of the fine-grained rims.
4. Fine-grained, enclosed objects, and the meteorite matrix contain abundant H2O-bearing phases, indicating that all lithologies experienced strong aqueous alteration of comparable intensity. Chondrule pseudomorphs and chondrules with intact Fe-rich olivines indicate local heterogeneities during the alteration process. Overall, the observed degree of alteration is intermediate within the CM2 range.
5. The very similar degree of alteration of all lithologies and the mobilization of Ca from the core objects (CAIs, Ca-rich pyroxenes, chondrule mesostasis) to the matrix can best be explained by alteration that took place in situ on the parent body. The similar behavior of Ca observed in the aqueously altered CM, oxidized CV chondrites, and ungrouped carbonaceous chondrite MAC 88107 suggests that mobilization of Ca from chondrules and CAIs into the meteorite matrix is a general process during aqueous alteration of carbonaceous chondrites and may be used as an indicator for the degree of alteration.
6. The pervasive alteration removed any potential evidence for pre-accretionary alteration, but did not affect the overall texture of the meteorite.

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