The Tsarev Meteorite: Petrology and Bidirectional Reflectance Spectra of a Shock-Blackened L Chondrite

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The Tsarev meteorite is a highly shocked black L5 ordinary chondrite. Meteorites of this class may have been subjected to regolith processes on or near the surface of ordinary chondrite bodies. The study of their optical alteration can provide valuable support in the spectral search for ordinary chondrite parent bodies. Although Tsarev is very dark in a cut surface hand sample, it is characterized by subtle variations in apparent darkness, called in this work grey and black areas. Both areas are substantially optically altered from normal ordinary chondrites and are characterized by a much lower albedo and strongly suppressed absorption features. Although both areas are altered, they show differences in albedo and the strength of absorption features. Particulate samples from the black area have a slightly higher albedo and stronger absorption features, while the particulate samples from the grey area show a systematic suppression of spectral features and albedo. Chemical, mineralogical, and spectral analyses suggest that the spectral differences can be the result of one or a combination of several factors, including shock effects on the crystallographic structure of the minerals and differences in the size, distribution, and amount of metal and troilite grains.

INTRODUCTION

One of the major goals of bidirectional reflectance spectroscopy is the remote determination of the surface composition of distant solar system bodies. Asteroids are of particular interest because of their numbers, diversity, and relevance to the earliest period of solar system condensation and accretion. Over the last 20 yrs workers have used laboratory spectra of meteorites and remotely obtained spectra of asteroids to establish a connection between some of the major meteorite types and possible asteroidal parent bodies (McCord et al., 1970; Chapman, 1976; Gaffey and McCord, 1978; McFadden, 1983; Pieters, 1984; Cruikshank and Hartmann, 1984; Bell, 1986). However, there is an apparent disparity between the proportions of meteorite types falling to Earth (Wasson, 1974; Graham et al., 1985) and the proportions of asteroid types suggested as parent bodies (Zellner, 1979). In particular, ordinary chondrites account for 78.3% of meteorite falls (Wasson, 1974), but so far no main belt parent bodies have been identified for this meteorite type. In contrast, carbonaceous chondrites account for only 4.5% of falls (Wasson, 1974), but their compositional analog based on spectra, the C-type asteroids, account for about 70% of asteroids (Zellner, 1979). This apparent dominance of ordinary chondrite falls is not an artifact of the short time (<200 yrs) or limited area over which meteorites have been actively observed and collected. Statistics from the Antarctic meteorite collection suggest that the dominance of ordinary chondrite falls has continued for at least the last 10^7-10^8 yrs and evidence from the few "fossil" meteorites found in sediments suggests that the dominance of ordinary chondrite falls may have extended throughout the phanerozoic (Graham et al., 1985; Lipschutz and Cassidy, 1986; Pellas, 1988).

One possible explanation for the disparity between the abundant ordinary chondrite falls and the absence of spectrally observed parent bodies is that regolith processes on parent body surfaces may have altered the spectral signature of ordinary chondrite regolith material (Britt and Pieters, 1987). On atmosphereless bodies the regolith environment includes processes such as gas implantation by the solar wind, cosmic irradiation, and meteoritic bombardment. Characteristics such as solar wind-implanted gases, brecciation, shock effects, and unequilibrated exotic clasts suggest that a substantial portion of ordinary chondrites may have been involved in regolith or near-surface processes (Heymann, 1967; Taylor and Heymann, 1971; Ashworth and Barber, 1976; Bischoff et al., 1983; Pellas, 1988).

One class of optically altered ordinary chondrites are the black chondrites, which are substantially darker in hand sample than normal ordinary chondrites. Although the spectral properties of only a few altered ordinary chondrites have been measured (Gaffey, 1976; Bell and Keil, 1988), black chondrites tend to exhibit low albedo and subdued absorption features and are more similar spectrally to some carbonaceous chondrites than to normal ordinary chondrites. Black chondrites generally display pervasive shock features including evidence of strong shock-heating, they tend to have young 40Ar gas-retention ages, indicating relatively recent shock events, and their metallographic cooling rates often point to burial after shock, perhaps in the megaregolith of an ordinary chondrite parent body (Heymann, 1967; Taylor and Heymann, 1971). These meteorites may represent a class of material that has been exposed to the shock, thermal, and chemical processes that would occur during the impact process on an ordinary chondrite parent body. Black
chondrites are probably derived from a number of parent bodies and reflect diverse collisional, thermal, and shock histories (Taylor and Hefman, 1971; Bischoff et al., 1983; Rubin et al., 1983; Taylor et al., 1987). However diverse their origins, the black chondrites may provide critical information on the chemical, petrological, and spectral effects of regolith processes on asteroidal surfaces.

The study presented here is part of a larger program to study the spectral, petrographic, and chemical properties of ordinary chondrites that may have been involved in regolith processes. The highly shocked, L5e-f black ordinary chondrite, Tsarev is the focus of this initial detailed study. The Tsarev meteorite was found in 1968 in an agricultural area southeast of the city of Volograd (48°42'N, 45°42'E), Volograd district, Russian Federative SSR, USSR. However, the samples were recognized as meteorites only in 1979 when the first chunk was received by the Meteorite Committee of the USSR Academy of Sciences (Krotinok, 1982). A total of 69 individuals and fragments have been collected with a total mass of 1325 kg. The masses of separate samples vary from 0.002 kg to 283.8 kg (Zotkin, 1982; Zotkin and Tsvelev, 1984; Zotkin et al., 1987). Analysis of evidence from witnesses, newspaper and magazine reports, and Meteorite Committee Archives reveals that on December 6, 1922, between 0600 and 0700 hrs local time, a violent fireball was observed in the region of the Tsarev find (Zotkin, 1982). The evidence from witnesses on the direction of the bolide's movement agrees with the direction estimated based on the scattering of the Tsarev fragments (Zotkin, 1982; Zotkin and Tsvelev, 1984). This fireball was seen in neighboring towns and villages at distances of some hundreds of kilometers from the location of the Tsarev find. Since no recent violent fireballs have been reported in this region, these facts suggest that the Tsarev meteorite fell December 6, 1922 (Zotkin, 1982).

**PETROLOGY AND MINERALOGY**

The first detailed mineralogical-petrological description of three individual samples of Tsarev was done by Migasova et al. (1982a,b). The textures and structures of the three samples are similar, but they do vary in the degree of terrestrial weathering. The samples for this coordinated study of compositional and optical properties were taken from sample number 15384, the least weathered sample. Most of the following petrographic description is based on the results of the Migasova et al. (1982) analysis.

In cut-surface hand sample the Tsarev meteorite is very dark throughout but shows a well-defined mottled structure of dark grey areas with well-preserved chondritic texture and darker areas with a very fine-grained texture. For convenience we will refer to these areas as the grey and black areas, respectively. Since these two types of areas exhibited apparent differences in optical properties, they were treated separately in the spectroscopic analysis. The volume of the black areas varies between individual samples over a range of 30 vol.% to 56 vol.%. For sample 15384 the amount of black area was estimated at 50 vol.% by point count using a 750 cm² grid. The grey areas vary in size from a few millimeters to 12 cm across with the predominant size being about 7 cm. The black areas occur as thin veins with multiple branches or large branched zones up to 4-5 cm across dividing the grey areas.

Some samples of Tsarev contain curved vugs as large as 60-80 mm in length and about 5 mm in width. Numerous small vugs are present in all samples and some vugs are closely related to elongate veins of metal. Vugs are common in shocked ordinary chondrites and are thought to form due to inhomogeneities in shock wave patterns that cause local superheating and vaporization (Olsen, 1981). No detailed study of the vugs in Tsarev has been performed.

In polished thin section the Tsarev meteorite shows a shocked structure similar to the L5 ordinary chondrite Farmington. The boundaries between grey and black areas, as shown in Fig. 1, are clear but not sharp. Chondrules in the grey areas are often cracked and vary in shape from rounded to angular. The grey areas can show differences in petrological type that vary from type 4 to type 6. The grey area matrix is a crystalline-granular aggregate, often with centric structure. Sometimes the structure of the grey areas is crystalloloblastic. The characteristic feature of the grey area is the presence of large, sometime subhedral-shaped crystals of olivine and pyroxene and their intergrowths. The matrix between large crystals is filled with a dense, fine-grained aggregate of silicates and irregular grains of opaque minerals. Some areas of matrix contain many thin cracks filled by opaque minerals or black veinlets of cryptocrystalline material with fine-grained dispersed metal and troilite.
The black areas are the most shocked zones of the meteorite and are saturated by fine-grained dispersed metal and troilite. The major component of the black areas is black cryptocrystalline silicate material enclosing relics of olivine and pyroxene crystals, rare chondrules, and fragments of chondrules. Shown on the right side of Fig. 1 is an example of a black area dominated by cryptocrystalline material with a few chondrule fragments. The cryptocrystalline silicate material is weakly translucent in transmitted light.

The pervasive shock features of this meteorite include maskelynitization of plagioclase, cracking of silicates, planar features and recrystallization of olivine, and the presence of melt veinlets and pockets. A substantial part of the metal and troilite, especially in the black areas, occurs as fine, dispersed grains in silicates. Figure 2a shows a reflected light photomicrograph of the dispersed metal and troilite in a black area, and Fig. 2b shows that area in transmitted light. For comparison, Fig. 2c shows a reflected light photomicrograph of the metal and troilite in a grey area, and Fig. 2d shows the same grey area in transmitted light. While the metal and troilite is finely and evenly dispersed in the black areas, the metal and troilite distribution in the grey areas is characterized by much larger, irregular clumps of material sometimes distributed in a roughly linear pattern along grain boundaries. The shock features suggest a shock facies of "e-f" on the Dodd and Jarosewich (1979) criteria of shock intensity. This implies a peak shock pressure of >600 kb and a reheating event to ≥ 1200°C (Migdisova et al., 1982b, 1984). Analysis of the 40Ar-39Ar system suggests a gas-retention age of 650 ± 50 m.y. associated with a major thermal and shock event (Minb et al., 1984). The similarity of this gas-release age with the age of the samples studied by Heymann (1967) implies that Tsrev
TABLE 1. Microprobe results (in wt.%).

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
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<tbody>
<tr>
<td>SiO₂</td>
<td>38.3</td>
<td>38.5</td>
<td>55.4</td>
<td>58.3</td>
<td>57.2</td>
<td>0.31</td>
<td>0.49</td>
<td>0.3</td>
<td>47.2</td>
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<tr>
<td>Al₂O₃</td>
<td>0.02</td>
<td>0.07</td>
<td>0.2</td>
<td>8.2</td>
<td>6.2</td>
<td>0.00</td>
<td>0.04</td>
<td>5.8</td>
<td>1.9</td>
</tr>
<tr>
<td>CaO</td>
<td>n.d.</td>
<td>0.11</td>
<td>0.22</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.03</td>
<td>0.05</td>
<td>58.1</td>
<td>n.d.</td>
</tr>
<tr>
<td>FeO</td>
<td>22.7</td>
<td>21.6</td>
<td>13.4</td>
<td>6.0</td>
<td>6.7</td>
<td>0.73</td>
<td>0.50</td>
<td>28.5</td>
<td>17.7</td>
</tr>
<tr>
<td>MnO</td>
<td>n.d.</td>
<td>0.53</td>
<td>0.52</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.06</td>
<td>0.09</td>
<td>0.67</td>
<td>n.d.</td>
</tr>
<tr>
<td>MgO</td>
<td>39.1</td>
<td>38.6</td>
<td>28.8</td>
<td>12.0</td>
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<td>4.7</td>
<td>0.19</td>
<td>4.9</td>
<td>28.7</td>
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<tr>
<td>CaO</td>
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<td>0.11</td>
<td>0.85</td>
<td>14.1</td>
<td>15.4</td>
<td>45.7</td>
<td>52.9</td>
<td>n.d.</td>
<td>0.96</td>
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<tr>
<td>Na₂O</td>
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<td>0.05</td>
<td>0.10</td>
<td>3.6</td>
<td>3.1</td>
<td>2.9</td>
<td>0.48</td>
<td>n.d.</td>
<td>0.87</td>
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<tr>
<td>K₂O</td>
<td>n.d.</td>
<td>0.10</td>
<td>0.06</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.01</td>
<td>0.00</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>45.0</td>
<td>42.7</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>Total</td>
<td>100.23</td>
<td>99.67</td>
<td>99.55</td>
<td>102.2</td>
<td>102.9</td>
<td>99.44</td>
<td>97.44</td>
<td>100.77</td>
<td>97.33</td>
</tr>
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</table>

Columns: 1—Olivine (4 grains) from black area; 2—olivine (7) of chondrules from grey area; 3—orthopyroxene (7) of chondrules from grey area; 4—clinopyroxene (4) of chondrules from grey area; 5—clinopyroxene (4) of chondrules from black area; 6—whiteclite (2); 7—fluorapatite (4); 8—chromite (5) from matrix; 9—cryptocrystalline from black area.

TABLE 2. Point count analysis of several parts of Tsarev sample 15384.3 (in wt.%).

<table>
<thead>
<tr>
<th>Section numbers:</th>
<th>15384.3-2,2b</th>
<th>15384.3-2,1</th>
<th>15384.3-3</th>
<th>15384.3-1,2</th>
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</thead>
<tbody>
<tr>
<td>Section area, cm²</td>
<td>2.9</td>
<td>2.9</td>
<td>0.8</td>
<td>6.4</td>
</tr>
<tr>
<td>Metal</td>
<td>6.7</td>
<td>9.0</td>
<td>4.1</td>
<td>7.9</td>
</tr>
<tr>
<td>Troilite</td>
<td>1.3</td>
<td>1.5</td>
<td>4.3</td>
<td>2.1</td>
</tr>
<tr>
<td>Chromite</td>
<td>0.4</td>
<td>0.5</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Oxides</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>—</td>
</tr>
<tr>
<td>Silicates and phosphates</td>
<td>91.5</td>
<td>88.9</td>
<td>91.0</td>
<td>89.6</td>
</tr>
</tbody>
</table>

was included in a major shock event that produced a number of other L5 black chondrites (Heymann, 1967; Minb et al., 1984).

The mineral composition of Tsarev is typical for ordinary chondrites. Major minerals include olivine, pyroxenes, metal, troilite, plagioclase, chromite, and phosphates (whiteclite and apatite), with many of the plagioclase grains converted into maskelymite. Rare ilmenite and rutile grains are associated with some chromite grains. The composition of major mineral phases in sample 15384 were analyzed using an Hitachi XMA-5B microprobe, and the results are summarized in Table 1. The mineral components of the grey and black areas, although different in texture and albedo, are almost identical in composition.

The opaque fractions are very heterogeneous distributed throughout the meteorite. Listed in Table 2 are the results of a point count analysis of opaques vs. silicates for several areas of Tsarev sample 15384.3, showing compositional variations of between 4.1-9.0 wt.% for metal and 1.3-4.3 wt.% for troilite. The average content of metal in the largest section (column 4 of Table 2) agrees with the bulk chemical value of 7.65 wt.% (Barsukova et al., 1982), suggesting that the variations of metal tend to be local. The average content of troilite, however, is lower than the chemical value of 5.28 wt.%, suggesting that a substantial part of the troilite occurs as dispersed grains that are too small to be observed under point count analysis.

SAMPLE DESCRIPTION

For spectral investigations three samples totaling 6.05 g were selected from adjoining portions of Tsarev slab number 15384.3-2.1. Shown in Fig. 3 is a general view of the three portions of the Tsarev meteorite used for spectroscopic analysis. The largest portion, sample 1a/B, contains both grey and black areas of the meteorite, sample 1a/C is predominantly grey material, and sample 1a/T is predominantly black material. To minimize weathering effects, these samples are from an interior portion of number 15384. The study of thin sections from other areas of slab sample 15384.3 suggest that the content of terrestrial oxides was less than 0.2 wt.%. Examination of a polished thin section of sample 1a/B and microscopic examination of hand samples and the crushed powders of the same sample revealed no evidence of rust or other terrestrial alteration. As discussed in the spectroscopy section, a spectral measure for terrestrial alteration (Salehy and Hunt, 1974) showed the samples to be very fresh and unweathered.

The primary difference in hand sample between the grey and black areas is the preservation of the chondrite texture in the grey areas. As a result, the grey areas appear much coarser grained than the black areas. Although grey and black areas can be described separately in terms of texture and apparent albedo, both areas are mixed throughout the meteorite on a millimeter to centimeter scale. The black areas are not completely homogeneous but, as shown in Fig. 1, contain more
of the cryptocrystalline silicates and fewer chondrules than the grey areas.

**BIDIRECTIONAL REFLECTANCE SPECTRA**

**Ordinary and Black Chondrites**

Spectrally, ordinary chondrites are characterized by a reddish spectrum in the visible, a maximum at 0.7 μm, and absorption bands due to mafic minerals (largely orthopyroxene and olivine) centered approximately at 0.95 μm and 1.9 μm (Gaffey, 1976). Albedos vary with petrologic type and metamorphic grade, but for L5 chondrites albedos are commonly in the 17% to 25% range (Gaffey, 1976). Black chondrites are a subset of ordinary chondrites. Although chemically indistinguishable from the range of normal ordinary chondrites, they are characterized spectrally by lowered albedos and subdued absorption features (Gaffey, 1976). Shown in Fig. 4 are spectra of several normal ordinary chondrites and black chondrites. For comparison, the spectrum of a particulate sample of the Tsarév black area sample 1a/T is included. The albedo, absorption features, and spectral contrast of all the black chondrites are reduced relative to the normal ordinary chondrites. For example, the Tsarév sample has an albedo of 0.12 at 0.56 μm, which is about half the albedo of normal ordinary chondrites of similar petrologic type (Gaffey, 1976). The low albedo and low spectral contrast of several black chondrites make them appear more similar to other low-albedo meteorites, such as carbonaceous chondrites and ureilites than to normal ordinary chondrites. Although the proportion of black chondrites is not accurately known, Britt and Pieters (1987) estimated the percentage of black chondrites in the U.S. National Museum collection at approximately 6% of ordinary chondrites.

**Spectra of Tsarév**

A series of bidirectional reflectance spectra was obtained using the RELAB spectrometer (Pieters, 1983), over a wavelength range of 0.3 μm to 2.5 μm, for portions of Tsarév sample 15384.3-2.1 containing both grey and black areas. The portions of the meteorite included in the spectral analysis are outlined in Fig. 3. The grey area studied spectrally, outlined by a dashed line, is from sample 1a/C and the black area, outlined by a solid line, is from sample 1a/T. The samples were ground to a particle size of <500 μm, and bidirectional reflectance spectra of bulk samples were measured directly from the powder. Viewing geometry of the bidirectional reflectance measurements was \( \theta = 30^\circ, \phi = 0^\circ \).

Shown in Fig. 5 are reflectance spectra of Tsarév bulk particulate material (particle size <500 μm) taken from the predominantly black area in sample 1a/T (solid line) and from the predominantly grey area in sample 1a/C (dashed line). In both samples the spectrum below 0.6 μm displays typical charge transfer absorptions. Two weak absorption features are observed near 0.92 μm and 1.95 μm. These features imply that low-calcium pyroxene is a major mafic mineral, whereas the long wavelength broadening of the 0.92-μm feature and the relative weakness of the 1.95-μm feature indicate the presence of significant olivine. Surprisingly, the particulate sample of the black area, although appearing darker in hand sample, exhibits a spectrum with a higher albedo and has better developed absorption features than the spectrum of the particulate material from the grey area.

Microscopic examination of the bulk particulate samples showed no visible evidence of terrestrial weathering. A spectral test for terrestrial weathering is the criterion of Salisbury and Hunt (1974) that the 0.5-μm/0.6-μm ratio of a sample’s spectrum should be ≥ 0.94 for that sample to be considered unweathered. The 0.5-μm/0.6-μm ratio for both grey and black bulk powders were calculated as 0.955 for the grey area and

![Spectra of normal and black L5 ordinary chondrites. The spectra of normal ordinary chondrites are shown as dashed lines, and the spectra of black chondrites are shown as solid lines.](image_url)

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a few percent clinopyroxene (Cloutis et al., 1986). Using bulk chemical analysis, the normative composition of Tsariev is calculated to be 71.27 wt.% orthopyroxene and olivine, with only 3.57 wt.% clinopyroxene (Migdisova et al., 1982a), which makes band ratio analysis appropriate for this meteorite. The normative opx/(opx + olv) ratio for Tsariev is 0.445 (Migdisova et al., 1982a). Using the spectrum of the bulk sample of the black area, the band ratio method predicts an opx/(opx + olv) ratio of 0.45, in good agreement with the normative silicate composition. Analysis of spectra of particle-size separates from the black area material show values that cluster tightly around a ratio of 0.45, supporting the similarity of the black area to the normative mineralogy of the bulk meteorite. However, for the grey area, which exhibits more subdued absorption features, the band ratio method for the bulk particulate sample predicts a higher orthopyroxene proportion with an opx/(opx + olv) ratio of 0.56. Band ratio analysis of particle-size separates of the material from the grey area show much greater variance than the results from the black area material, with ratios varying between 0.27 and 0.64. Only for the three finest particle-size fractions of the grey area material, which have the highest albedo and the best developed absorption features of any of the grey area material, were the ratios consistent with the meteorite's bulk normative composition. The variation in predicted opx/(opx + olv) ratios suggests that for low-albedo materials with low band contrast, such as the grey area, this type of empirical analysis may be subject to large errors and should be used with care.

The higher albedo and relatively well-developed absorption features of the black area bulk powder was unexpected, since this area appears darker than the grey area in cut-surface hand sample. Shown in Fig. 6 are the spectra of cut-surface slabs of the grey and black areas. Although any interpretation of slab spectra must be used with caution, these spectra do confirm that in hand sample, the black area has a significantly lower albedo than the grey area. Crushing these samples to a powder changes the relative albedo of the two samples and tends to enhance the spectral features of mineral components in the black area more than those in the grey area.

To examine the spectral differences between the grey and black areas in more detail, six particle-size separates from both areas were prepared. Particle-size separates were wet sieved with ethanol into size bins of <25 μm, 25-45 μm, 45-63 μm, 63-125 μm, and 250-500 μm, and bidirectional reflectance spectra were obtained for each separate. Spectra of these particulate samples, shown in Figs. 7 and 8, confirm that the powder from the black area exhibits more prominent absorption features than the powder from the grey area. This is clearly shown in Fig. 9, which presents the spectra of the three finest fractions of the powders from the grey and black areas scaled to unity at 0.6 microns. Spectra of powders from the black area are indicated by the solid lines, and the spectra of the powder from the grey area are indicated by the dashed lines. After differences in albedo are removed, the powder from the grey area generally shows weaker absorption features than the powder from the black area for all size fractions. Shown in Fig. 10 are the spectra of powders from both areas for the 25-45-μm and 45-75-μm particle sizes after they have been
rescaled by an automatic linear continuum removal in wavelength space and stretched in scaled reflectance to fit the depth of the 1-μm absorption band. The similar spectral shape of the 1-μm and 2-μm bands for both the black and grey areas provides evidence that the mafic mineralogy of the material from the two areas is very similar.

**DISCUSSION AND CONCLUSIONS**

Black chondrites such as Tsarev are thought to have been formed during major impact and brecciation events that take place on ordinary chondrite parent bodies. As such, they represent samples of the shock, thermal, and chemical environment that can occur in an atmosphereless body and perhaps in the regoliths of ordinary chondrite parent bodies. The overall spectral properties of black chondrites are characterized by an optical alteration that results in a much lower albedo and more subdued absorption features than is normal for ordinary chondrites. The Tsarev samples also show that some of the detailed optical effects of regolith processes can be enigmatic. In a cut-surface hand sample Tsarev's grey area exhibits a slightly higher albedo than the black area, but the same sample has a lower albedo than the black area when both samples are prepared as particulates. The powder from the black area has well-developed spectral absorption features that imply a mineralogy consistent with the meteorite’s normative composition, while the powder from the grey area shows suppressed spectral features that make compositional interpretations more difficult. Although the petrological evidence suggests there are no major composition differences between the grey and black areas, subtle spectroscopic differences occur between the samples.
The cause of the subtle spectral differences between grey and black areas are currently unknown, but in principle could be a result of a higher proportion of mafic minerals in the black area, a difference in the form and particle size of opaque minerals between the grey and black areas, a difference in the amount of opaque phases in each area, a difference in the degree of crystallinity in the two areas, or a combination of these factors. Since the proportion of silicates is roughly constant in the areas of the meteorite studied (Table 2), a higher proportion of mafic minerals in the black area would imply that plagioclase was a more significant component in the grey than in the black area. However, the amount of additional plagioclase required to dilute the 1-μm absorption band would be inconsistent with the lower reflectance of the grey material. Also, the similarity between Tsarev's bulk normative composition and the black area's opx/(opx + ol) ratio argues against any major differences in the content of mafic minerals. On the other hand, differences in crystallinity between the grey and black areas due to shock effects, resulting in variations in glass and maskelynite abundance, would produce differences in the spectral characteristics of the two areas, but this cannot be readily assessed due to the fine-grained nature of the black areas.

The presence of finely disseminated metal and troilite has long been considered the major cause of the suppressed optical characteristics of black chondrites (e.g., Fredriksson et al., 1963; Heymann, 1967; Gaffey, 1976), and differences in the amount or the distribution of this opaque phase may also account for the subtle spectral differences observed between the grey and black areas of Tsarev. The black area is characterized by abundant small, finely dispersed grains of metal and troilite distributed throughout the cryptocrystalline silicates. The metal and troilite in grey areas tend to be distributed in larger, more irregularly arranged grains. Point count analysis shows that the amount of these phases varies throughout the meteorite, but the extreme particle size differences between grey and black areas make direct comparisons of the abundance of opaque phases very difficult. While the absolute amount of the opaque phase for the grey and black areas is unknown, the grain size and form of the metal and troilite are clearly different in the two areas. For Tsarev, the particulate material from the area with the finely dispersed opaques (black areas) exhibited stronger absorptions and slightly higher albedo than the particulate material from the area with the larger grains of opaques (grey areas). This relation between the particle size of opaques and the spectral characteristics of silicates is opposite that observed for laboratory experiments with fine- and coarse-grained carbon physically mixed with silicate grains (Clark, 1983). In the laboratory the fine-grained carbon had the stronger effect on lowering albedo and subduing absorption features, most likely by physically coating the larger silicate grains. The appropriate experimental data thus do not currently exist to develop an accurate model to describe the effects that the physical form of the opaque phase has on the spectral properties of the mafic silicate minerals. It is anticipated, however, that as more spectroscopic and petrographic data become available for a variety of naturally occurring altered meteorites, a more refined description of the spectral effects of opaque phases on the expected spectral character of regoliths on meteorite parent bodies will emerge.

The form and distribution of opaque minerals can clearly have a powerful effect on the spectral characteristics of ordinary chondritic material both on albedo as well as on the strength of absorption features. Black chondrites are black probably because of the presence of micron to submicron grains of metal and troilite in optically critical areas such as the grain boundaries of the cryptocrystalline silicates. Subtle variations in the form or the distribution of these opaque phases may cause the subtle spectral variations observed in Tsarev. Interpretation of the spectra of any low-albedo material must take into account the form and distribution of the opaque component, which is a function of both the original composition and any subsequent alteration processes.

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