The Meteoritical Society

Meteoritics & Planetary Science 44, Nr 5, 643–652 (2009)
Abstract available online at http://meteoritics.org

The fine-grained matrix of the Semarkona LL3.0 ordinary chondrite: An induced thermoluminescence study

Jonathan P. CRAIG[1*], and Derek W. G. SEARS[1, 2]

[1]Arkansas Center for Space and Planetary Sciences, MUSE 202, University of Arkansas, Fayetteville, Arkansas 72701, USA
[2]Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, Arkansas 72701, USA
[*]Corresponding author. E-mail: jpc05@uark.edu

(Received 30 September 2008; revision accepted 25 January 2009)

Abstract–To investigate the nature, origin, and history of the fine-grained matrix in Semarkona and develop techniques suitable for small samples, we have measured the induced thermoluminescence properties of six matrix samples 10 µm to 400 µm in size. The samples had TL sensitivities comparable with 4 mg of bulk samples of type 3.2–3.4 ordinary chondrites, which is very high relative to bulk Semarkona. The other induced TL properties of these samples, TL peak temperatures, and TL peak widths distinguish them from other ordinary chondrite samples where the TL is caused by feldspar. Cathodoluminescence images and other data suggest that the cause of the luminescence in the Semarkona fine-grained matrix is forsterite. In some respects the matrix TL data resemble that of Semarkona chondrules, in which the phosphor is forsterite and terrestrial forsterites from a variety of igneous and metamorphic environments. However, differences in the TL peak temperature versus TL peak width relationship between the matrix samples and the other forsterites suggest a fundamentally different formation mechanism. We also note that forsterite appears to be a major component in many primitive materials, such as nebulae, cometary dust, and Stardust particles.

INTRODUCTION

The fine-grained matrix of type 3 ordinary chondrites, and in particular the fine-grained matrix of Semarkona, the least metamorphosed type 3 ordinary chondrite, has been the subject of considerable interest (Ashworth 1977; Huss et al. 1981; Ikeda et al. 1981; Rambaldi et al. 1981; Nagahara 1984; Brearley et al. 1989, 1996; Brearley 1993). It is unlike any other major component of ordinary chondrites and its origin is controversial. Because it is so fine-grained, most authors assume it is a condensate of some kind, with an occasional fragment produced by comminution of other major components in the meteorite (Ashworth 1977; Nagahara 1984; Alexander et al. 1989), presumably during working in a parent body regolith. There are traces of aqueous alteration in the matrix, such as fine lines of calcite (Hutchison et al. 1987), which has also affected the chondrules to produce smectite in the mesostasis and bleached zones (Hutchison et al. 1987; Grossman et al. 2000). Whether this condensate was produced from nebular gases (Nagahara 1984) or gases produced from local processes such as during chondrule formation (Sears and Akridge 1998) is not clear. It is not only present as a smoke-like material that permeates Semarkona, apparently cementing the components together, it also forms rims on chondrules where it may also be associated with fine-grained sulfides that appear to have formed by the condensation of volatiles released during chondrule formation (Alexander et al. 1989; Huang et al. 1996).

Thermoluminescence studies have proved valuable in understanding the metamorphic history of type 3 ordinary chondrites and identifying the particularly primitive members (Sears et al. 1980). The technique provides information of a sort not available by complementary techniques, such as insight into the composition and structural state of the minerals responsible for the luminescence (Sears 1988) and it has a sensitivity not matched by other bulk techniques (Sears et al. 1980). However, to date TL studies have been limited mostly to bulk powders, with a mass of 4 mg (Sears et al. 1980), and separated chondrules with masses ranging from 0.03 to 3.0 mg (Sears et al. 1995). We have now conducted a study of fragments of Semarkona matrix that go down to ~10 µm in size, with some fragments at ~100 µm, and one at ~400 µm that is chondrule sized. Our purpose was not only to demonstrate our ability to make measurements on such small particles, but also to see if TL could shed new light on the nature, origin, and history of the Semarkona fine-grained matrix. Preliminary reports of our study were made at conferences (Craig et al. 2007; Craig and Sears 2008; Sears et al. 2008; Sedaghatpour et al. 2008).

EXPERIMENTAL

Fragments of Semarkona matrix obtained during prior research and discussed by Craig et al. (2007; Craig and Sears 2008) were further crushed into six particles ranging in size from ~10 µm to 400 µm and designated SM-1 through SM-8 (SM-4 and SM-7 were lost during handling). Samples were selected on the basis of optical petrography under low intensity reflected light in a manner that early work on meteorites showed would not affect induced TL properties. The induced TL properties of the samples were then measured (Sears 1980). Characterization of the samples by SEM and EDX was performed afterwards.

Thermoluminescence measurements were performed under red light using the modified Daybreak Nuclear and Medical systems apparatus. The TL oven in this unit provides a linear heating cycle from 0–500 °C maximum with an adjustable rate which we set at 7.5 °C/s. These settings conform to all previous TL studies performed on meteoritic materials from this laboratory. Single matrix fragments were placed in a copper pan at the center of the heating strip and drained of any natural TL by subjecting each to the programmed heating ramp described above. The TL signal induced by a three-minute exposure to a 141 mCi ^{90}Sr beta radiation source (absorbed dose 125 gray/min) was then measured. The induced TL measurements were repeated three times to ensure reproducibility with a time delay between irradiation and TL measurement of ~180 s for each measurement. We are confident that thermal lag between the heating strip and the samples is not significant, because we obtain the same results with our forsterites regardless of sample size; neither do we think the optical depth of the samples is important because our applied radiation has minimal penetration.

Corning 7-59 and 4-69 heat filters were placed in front of the sample assemblage to minimize interference from black-body radiation. The TL signal was detected with an EMI 9635QB photomultiplier tube, which has a wavelength range of 320–600 nm and peak sensitivity around 400 nm. Photon-counting electronics were used and the system produced a signal-to-noise ratio in excess of 10 for glow curve temperatures ranging from room temperature to 500 °C. As with previous studies, we measured the maximum light produced (which is normalized to 4 mg of the H3.9 ordinary chondrite Dhajala and termed "TL sensitivity"), the temperature at which TL production is a maximum (the "peak temperature"), and the temperature range of the full-width at half-maximum of the TL peak (the "peak width"). Measurements were made directly from the TL glow curves and reduced by hand. Unlike previous work, Dhajala was not used as a day-to-day standard because of the danger of contamination, but careful monitoring of black body curves enabled us to ensure the stability of the equipment.

After completion of the TL measurements, images and chemical compositions of the fragments were determined by a Philips Model XL30 ESEM with EDX attachment using an accelerating voltage of 20kV and a 3 mm spot size. All samples showed the expected structure of blocky coherent angular fragments consisting of sub-µm grains (Fig. 1), with no obvious chondrules or chondrule fragments, metal/sulfide grains, or other discrete components. Our elemental analyses, normalized to bulk Semarkona composition, are shown in Fig. 2. Within the limitations of the analytical technique, these matrix fragments have Semarkona composition, although Al is high, S is low, and SM-2 is high in Ni and Mn. SM-1 is not only high in Al, but Ca is also elevated. These results are broadly in agreement with previous analyses of Semarkona and other low type UOC matrix by a variety of techniques (Huss et al. 1981; Ikeda et al. 1981; Scott et al. 1984; Taylor et al. 1984).

RESULTS

Our TL sensitivity (Dhajala-normalized peak height), induced TL peak temperature, and peak width data for the Semarkona matrix fragments are shown in Table 1.

The TL sensitivity values range from 0.014 to 0.091 with a 1σ uncertainty of ~0.005 calculated from three repeat measurements. As a point of reference, these values are at the upper end of the Semarkona chondrule range and about an order of magnitude higher than the bulk Semarkona value (Fig. 3). In fact, they resemble the TL sensitivity of 4 mg samples of 3.2–3.4 type 3 ordinary chondrites (Sears et al. 1980). There is no relationship between TL sensitivity and sample mass, which we suspect is due to the presence of large amounts of nonluminescent material.

Induced TL peak temperatures range from 179 °C to 199 °C, with peak widths of 79 °C to 150 °C. Again as a point of reference we compare these data with a recent compilation of data for type 3 ordinary chondrites in Fig. 4a. Peak widths and peak temperatures for UOCs show two clusters; a "low" cluster centering on ~95 °C and ~110 °C (consisting of type 3.0 to 3.4 ordinary chondrites), and a "high" cluster centering on ~150 °C and ~175 °C (consisting of type 3.5 to 3.9 ordinary chondrites). We have drawn ellipses with cross hairs on these clusters, the ellipses representing 1 and 2 variances and the cross hairs representing averages. Fig. 4b compares our matrix samples with these data. The matrix samples show a significantly different distribution with several plotting to the left of the upper cluster and above the lower cluster.

DISCUSSION

We will discuss our current understandings of the TL properties of type 3 ordinary chondrites as a necessary background to understanding the present data. Then we will compare the TL sensitivities of the present samples with similar data for chondrules from Semarkona and the bulk value for Semarkona. We will then discuss peak temperatures and widths for the present data, compare them with similar

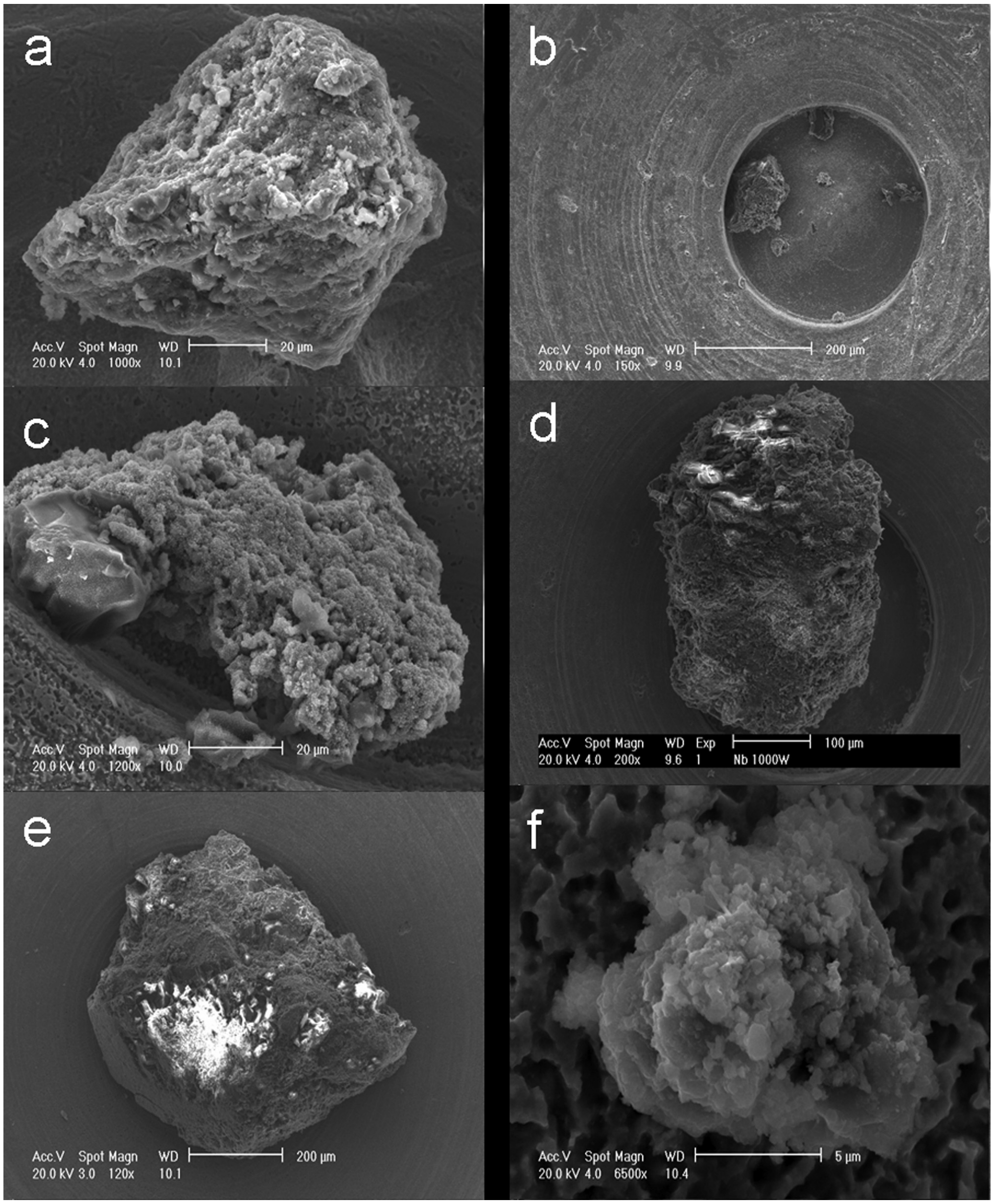

Fig. 1. Scanning electron microscope images of the six Semarkona matrix fragments in the present study. a) SM-1, b) SM-2, c) SM-3, d) SM-5, e) SM-6, f) SM-8. All show the expected structure of blocky coherent fragments with fractures and grains. The smallest fragment is about 20 µm and the largest is about 600 µm, most are about 150 µm.

Table 1. Induced TL of Semarkona matrix fragments.[a]

Sample #	Size (µm)	Peak height (Dhajala = 1)	Peak temperature (°C)	Peak width (°C FWHM)
SM-1	105 × 90 × 100	0.091	193	92
SM-2	140 × 70 × 25	0.014	173	150
SM-3	105 × 50 × 5	0.024	179	124
SM-5	390 × 275 × 275	0.045	199	116
SM-6	670 × 570 × 570	0.016	177	79
SM-8	20 × 15 × 5	0.014	181	138

[a]Typical 1σ uncertainties for peak height, peak temperature and peak width, respectively, are = 0.005 (Dhajala = 1), 9 °C, and 24 °C.

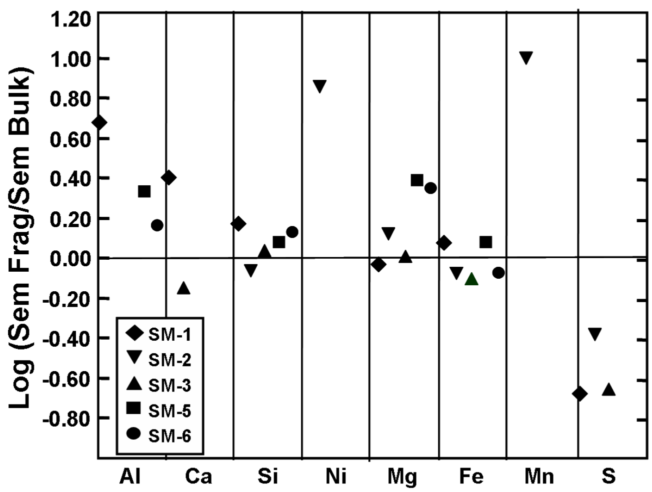

Fig. 2. Elemental abundances from five of the six particles extracted from the Semarkona meteorite, normalized to Semarkona bulk abundances. The mean Semarkona bulk matrix data are based on six 10 μm beam EMPA analyses in the literature. Within the limitations of our analyses, the present fragments have similar composition to bulk Semarkona, although Ca and Al are sometimes high and S is low. SM-2 has high Ni and Mn, the Fe presumably reflecting high metal, but the cause of high Mn is unknown.

data for UOCs. We then compare our data with data for separated chondrules and terrestrial forsterites.

Meteorite Mineralogy and Crystallography, TL and CL

The TL shown by virtually all ordinary chondrites (and most other meteorite classes) is produced by feldspar, a mineral that is absent in the lowest petrographic types, which instead contain a glass of feldspathic composition, and present in the highest types at ~5 vol% (Dodd et al. 1967). Thermoluminescence is so sensitive to the amount of crystalline feldspar, and the detection limits are so low, that it shows a 10^5-fold range in the ordinary chondrites as a whole and 10^3-fold range within the UOCs. This has led to TL being the basis for a petrographic subdivision into types 3.0–3.9 (Sears et al. 1980). Type 3.0 UOCs are extremely rare, Semarkona being the best known, and the absence of crystalline feldspar means that the TL signal observed must come from other minerals or phases. The CL mosaics of Akridge et al. (2004) suggest that while feldspar is the dominant phosphor in most ordinary chondrites, forsterite and calcic glass are important phosphors in the least metamorphosed meteorites. It is also possible that enstatite could be a luminescent component. For the matrix of Semarkona, we suggest that forsterite is the main candidate, since it is ubiquitous in the samples and known to be luminescent (Steele 1986). However, it will quickly lose its TL during even the mildest levels of metamorphism as Fe diffuses into the crystal structure and quenches the luminescence (Dodd et al. 1967; Steele 1986). While most studies have been performed on bulk samples, Ninagawa et al. (1992) report TL studies on individual chondrules that confirm interpretations based on bulk samples.

In addition to the TL sensitivity of a sample, which is a reflection of the amount of the luminescent mineral or phase present, the peak temperature and peak width reflects the crystalline and lattice defect structure (Guimon et al. 1984; 1985; 1988). Doping feldspar with various transition metal ions has shown that the impurity centers typically cause the TL in feldspars (Geake et al. 1973), while the ordering in the Al-Si backbone in feldspar affects the peak temperature and peak width of the TL signal (Pasternak 1978; Guimon et al. 1985). Up to type 3.4, any crystalline feldspar that is present is the low-temperature (ordered) form, while in the higher types the feldspar is in the high-temperature (disordered) form. This characteristic produces the two clusters in the peak temperature versus peak width plot for UOCs shown in Fig. 4a. Heating experiments and XRD measurements with terrestrial feldspars and ordinary chondrites have demonstrated these relationships (Guimon et al. 1985; Hartmetz and Sears 1987).

Cathodoluminescence, the luminescence produced by bombarding a sample with electrons, enables the activation of the luminescence centers under a microscope, so it is possible to identify the phases and minerals producing the TL which can then be subjected to petrographic examination and EMPA analysis (Sears et al. 1992; Akridge et al. 2004). Thus CL observations provide an independent means of obtaining similar and complementary information confirming the TL interpretations (Akridge et al. 2004).

TL Sensitivity of the Semarkona Matrix Fragments, Semarkona Chondrules and the Bulk Semarkona Value

Sears et al. (1995) reported TL data for chondrules removed from the Semarkona meteorite, the present matrix fragments have values at the high end of that range (Fig. 3). Sears et al. (1992) divided Semarkona chondrules into group A (bright CL) and group B (dull or no CL) chondrules as observed in CL mosaics (Akridge et al. 2004), which are loosely equivalent to low-FeO olivine, high refractory chondrules and high-FeO olivine, volatile-rich chondrules (Sears et al. 1992). There are fine details that confuse this picture, but essentially one expects group A chondrules to more frequently have high TL sensitivity and group B chondrules to include many with low TL sensitivity, which is essentially what we observe. Luminescence phases in the brightest group A chondrules are the anorthositic glass with yellow CL and forsteritic olivine with red CL (Sears et al. 1992). The high TL sensitivity of the fine-grained matrix samples suggests that they either contain feldspar—which is unlikely in a meteorite of type 3.0—or forsterite. In any event, it seems reasonable that the bulk TL sensitivity value should be

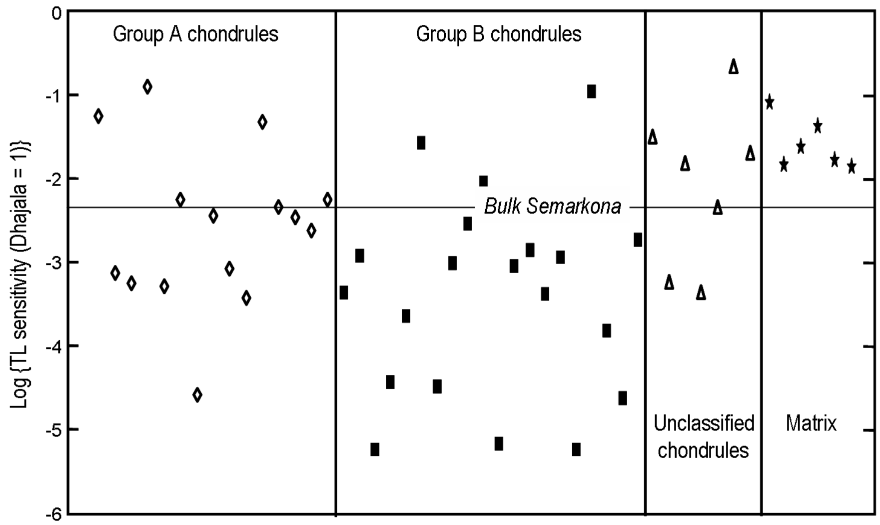

Fig. 3.Thermoluminescence sensitivity of Semarkona matrix fragments compared with data for Semarkona chondrules from Sears et al. (1995). The horizontal line at −2.3 represents the TL sensitivity of bulk Semarkona (Sears et al. 1980). Semarkona matrix fragments, shown at the right of the figure, display about an order of magnitude higher TL sensitivity than the bulk Semarkona and several orders of magnitude higher than most of the chondrules. This reflects the presence of an important TL phosphor in the matrix. Most of the chondrules (more so for group B chondrules than the group A chondrules) and the bulk meteorite are non-luminescent. (Group A refer to FeO-poor olivine, refractory, chondrules, while group B refer to FeO-rich olivine, volatile-rich, chondrules; Sears et al. 1992).

intermediate between its main luminescent components, the chondrules and matrix.

Comparison of Present Data with UOCs

A clear indication that the TL shown by the matrix fragments is not being produced by feldspar is illustrated by the fact that so many fragments plot outside the fields occupied by UOCs (Fig. 4b). The high refractory element abundance in some of these fragments, especially SM-1, might indicate the presence of refractory inclusions, which contain several thermoluminescent phases (Guimon et al. 1995). Similarly, the matrix fragments plotting in the high cluster in Fig. 4b could conceivably contain feldspar as a phosphor, but—as observed above—the low petrographic type indicates that this should not be the case. We suggest that these arguments are consistent with, if not necessarily proof that, the major TL producing phase in these fragments is forsterite.

Comparison of Present Data with Semarkona Chondrules

The plot of peak temperature versus peak width for the chondrules separated from Semarkona and published by Sears et al. (1995) is shown in Fig. 5. While the data show considerable spread, they occupy a region of the diagram reminiscent of that shown by the matrix fragments; namely, some plot above the low UOC field and to the left of the high UOC field, and some plot in the high UOC field. The group A and group B chondrules are not clearly segregated in this plot, suggesting that the relatively rare yellow luminescence of the group A anorthositic glass is not dominating these trends. Rather it is probably forsterite, the dominant silicate phase in the chondrules that is responsible for the major TL properties displayed. It should be mentioned that group A and B chondrules are further subdivided into A1-5 and B1-3, reflecting diversity in CL properties and that many of these chondrules are weakly cathodoluminescent (see Sears et al. 1992; 1995; Akridge et al. 2004, for a detailed discussion).

Comparison of Present Data with Terrestrial Forsterites

Suspecting that the luminescence of these matrix fragments was being produced by forsterite, we obtained seven samples of terrestrial forsterite from the Smithsonian Institution, six from purely volcanic regions and three from regions with a significant metamorphic overprint. Details of these samples, their TL measurement, and their TL properties, will be reported elsewhere (Craig and Sears 2008), but to compare them with the present data their peak temperature versus peak width plot is shown in Fig. 6. Regardless of whether purely volcanic or metamorphic, the data plot in the same region as Semarkona chondrules and matrix, namely above and to the left of the two UOC fields and overlapping the upper field. This is consistent with the TL properties of our matrix samples being caused by forsterite.

There have been several studies of the optical luminescence properties of forsterite, some of which are summarized by Benstock et al. (1997). They suggest that the CL at 700–800 nm is associated with Cr in the olivine lattice, while a peak at 640 nm is associated with Mn (Fig. 7a). The Cr^{3+} ions, probably substituted for Mg^{2+} ions in octahedral

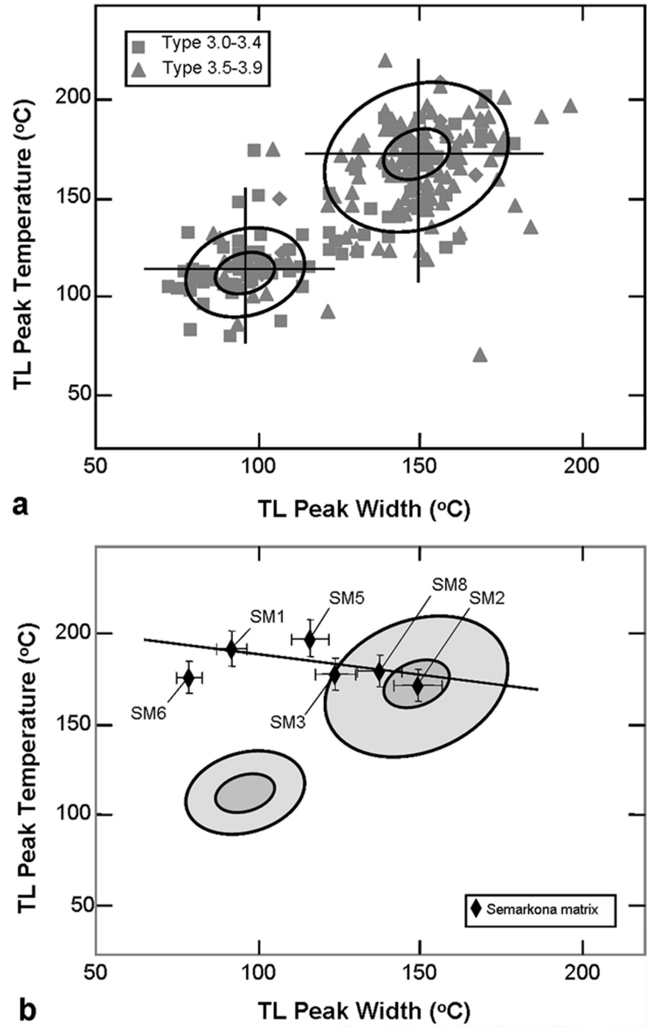

Fig. 4. a) Induced TL peak temperature versus peak width for Type 3 unequilibrated ordinary chondrites from an unpublished compilation by Jeff Grossman. The two ellipses refer to fields occupied by type 3.0–3.4 (lower) and type 3.5–3.9 (upper) ordinary chondrites, respectively. b) Induced TL peak temperature vs. peak width for the present Semarkona micrometer-sized matrix fragments compared with the Type 3 chondrite groups shown in Figure 4a. Half of the Semarkona fragments plot above the field for type 3.0–3.4 ordinary chondrites and to the left of the 3.5–3.9 ordinary chondrite field while the other half plot in the same field as the 3.5–3.9 ordinary chondrites, reflecting different structural states for the feldspar. Since feldspar is responsible for the TL observed in the Type 3 ordinary chondrites, the matrix fragments, which contain a dense distribution of forsteritic olivines, plot apart from the chondrites.

M1 and M2 sites, which form medium-field systems giving rise to $^2E \rightarrow {}^4T_2$ sharp line emissions at low temperatures and $^4T_2$, $^2E \rightarrow {}^4A_2$ thermalized broad bands at high temperatures between about 690 and 750 nm. (Moncorgé et al. 1991). The Mn^{2+} ions prefer the M2 site and luminesce from the lowest split component of the 4T1(G) above the ground state (Green and Walker 1985). A blue peak (420 nm) is of uncertain origin but readily removed by mechanical deformation. DeHart et al.

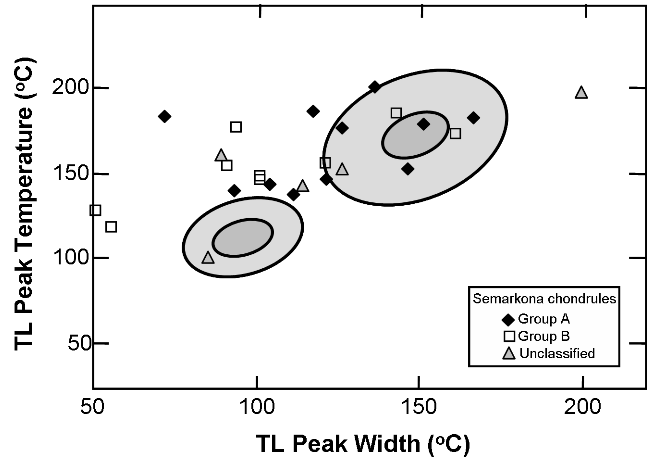

Fig. 5.Induced TL peak temperature vs. peak width of Semarkona chondrules compared with the Type 3 ordinary chondrite groups. The majority of these materials tend to plot apart from the chondrite groups and in the same general region as the Semarkona fragments. The different chondrule types are not clearly segregated in this plot, which suggests that the relatively rare yellow luminescence of the group A anorthositic glass is not dominating these trends. Rather it is probably forsterite, the dominant silicate phase in the chondrules that is responsible for the major TL properties displayed. It should also be mentioned that group A and B chondrules are further subdivided into A1-5 and B1-3, reflecting their diversity in CL properties and that many of these chondrules are weakly cathodoluminescent (see Sears et al. 1992; 1995; Akridge et al. 2004, for a detailed discussion).

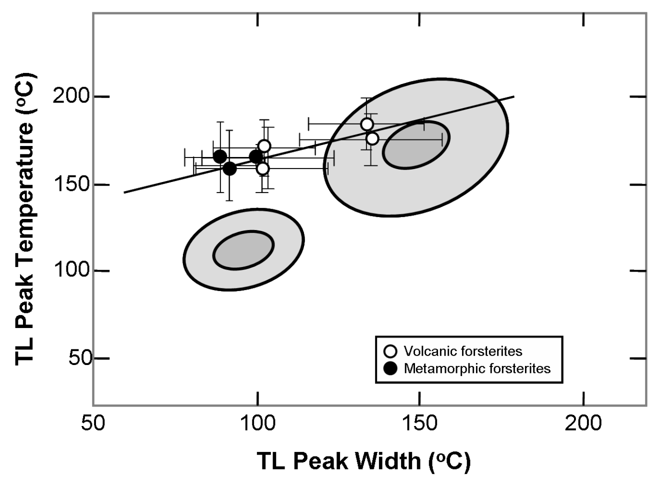

Fig. 6. Induced TL peak temperature versus peak width for terrestrial forsterites compared with the ordinary chondrite groups. Again, it is seen that these materials plot above and to the left of the chondrite groups and in the same general region as the Semarkona chondrules and micrometer-sized fragments. Since all of the materials in Figs. 4b, 5, and 6 represent olivines, it is reasonable that these materials tend to plot in the same general region and separated from the Type 3 chondrite groups.

(1992) have reported analyses of the luminescent olivines in Semarkona. The olivines with red CL have higher Mn and Cr (0.15 wt% MnO, 0.31 wt% Cr_2O_3) than those with blue CL (0.02 wt% MnO, 0.11 wt% Cr_2O_3), while both had low FeO

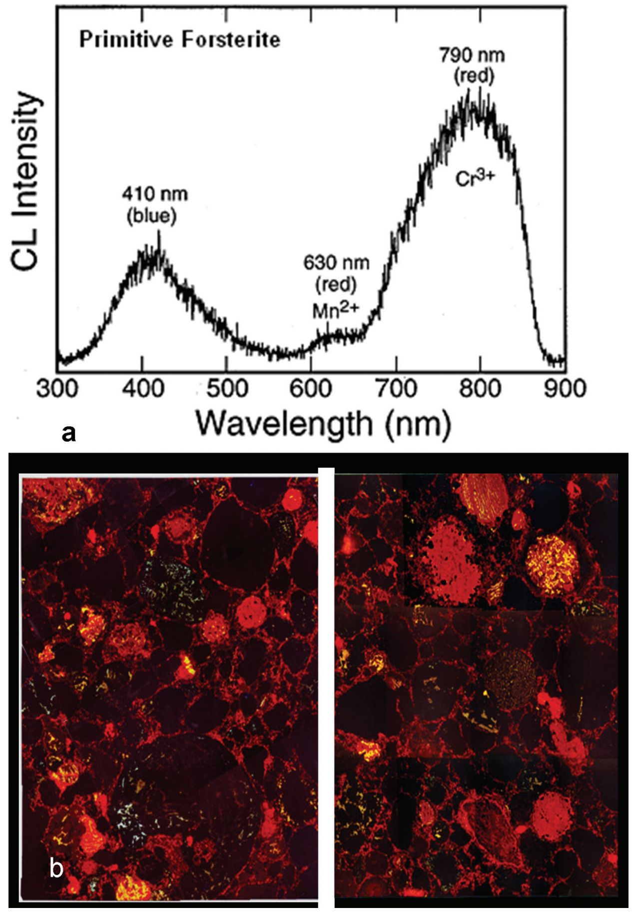

Fig. 7. a) Spectroscopic analysis of the CL intensity of primitive forsterite has shown that the red color of the CL is due to the presence of Cr^{3+} and Mn^{2+} incorporated in the forsterite crystal structure (Benstock et al. 1997). Reporting on primitive "Stardust" forsterite grains (Zolensky et al. 2006) noted the presence of enriched levels of Cr and Mn which according to Benstock would presumably display the red CL as seen by Akridge. b) CL image of Semarkona fine grained matrix (Akridge et al. 2004) displays a predominant red color. The images are about 1 cm across.

(1.38 wt% and 1.16 wt%). These data are consistent with the CL being attributed to the various impurity centers discussed by Benstock et al. (1997). In contrast, non-luminescent olivines, while containing MnO (0.05 wt%) and Cr_2O_3 (0.48 wt%), also contain relatively high FeO (4.28 wt%), Fe^{2+} being known to quench luminescence when present in greater than a few weight percent (Geake et al. 1973). It is thus clear that, for TL as well as CL, the luminescence of forsterite will be determined by its formation environment and the subsequent history of the grains.

We do not have spectra for our thermoluminescence data, but Akridge et al. (2004) have produced images, taken through a low-powered microscope, of the CL of a large number of extraterrestrial samples, including Semarkona. Two of these images are reproduced here (Fig. 7b). Semarkona is highly unusual in that it is one of a very few low

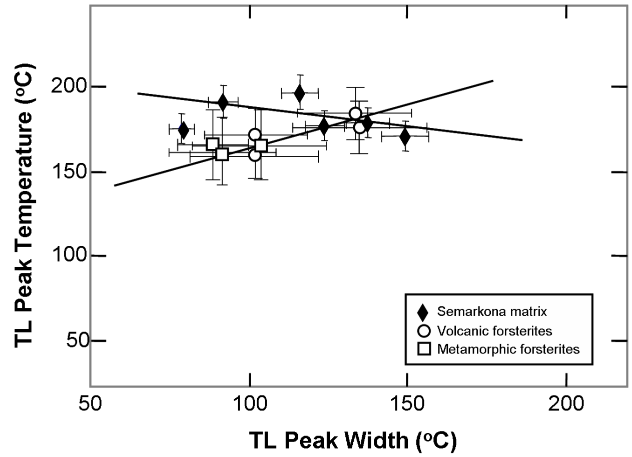

Fig. 8. Induced TL peak temperature and peak width of Semarkona fragments compared to terrestrial forsterites. The terrestrial forsterites tend to plot on a positive slope whereas the Semarkona fragments almost plot with a horizontal slope. Since TL peak temperature and peak width reflect crystal defect structure and impurity content, these trends could be indicative of differences in the initial formation processes and/or environments.

petrographic type chondrites that are essentially red under a CL microscope, most being blue, blue-green, or, if low type, non-luminescent. Semarkona is a spectacular mixture of a number of discrete components with a variety of CL properties, but important for our purposes is the abundant fine-grain matrix which permeates the meteorite and appears to "cement" the components together. This matrix is rich in μm-sized grains with red CL which appear (from EMPA analysis of a few of the larger grains) to be forsterite (DeHart et al. 1992). Thus our current knowledge of the CL properties of forsterite and the CL properties of Semarkona are consistent with the TL of the fine-grained matrix being due to forsterite.

However, we may be seeing an important difference in the forsterite of the matrix and terrestrial forsterite; namely the difference in slope of the peak temperature versus peak width plot (Fig. 8). More data are required to confirm the reality of our interpretation, but if real, might signal a major difference in the formation and history of these two types of material.

Implications for Primitive Olivine in the Solar System

Many types of primitive solar system material contain forsterite, the origin of which is often unclear. The matrices of many chondrites, particularly CM chondrites, contain isolated olivine grains whose origin is disputed (McSween 1977; Olsen and Grossman 1978; Steele et al. 1985a; Steele 1986; Jones 1992). Rival interpretations are that these isolated olivine grains are either primordial condensates from the presolar nebula or that they are grains formed in reduced chondrules and released by fragmentation in the parent body regolith. Forsterite is also thought to be present in astronomical nebula, as suggested by Koike et al. (2002) in the extended red emission of the spectrum of the Red Rectangle Nebula. Many astronomers have found evidence for olivine in comet dust tails, for instance Crovisier et al. (1997) reported evidence for olivine in the IR spectra of Hale Bopp's dust tail. Kloeck et al. (1989) compared olivine in UOC matrix with olivine in IDPs, and Steele et al. (1985b) compared olivine in C2 chondrites with olivine in deep-sea particles. Most recently, Zolensky et al. (2006) reported forsterite grains in the Wild 2 dust returned by the Stardust spacecraft, and these grains had elevated levels of Cr and Mn.

It seems unlikely that these astronomical sources of olivine have experienced the kind of geological processing experienced by terrestrial forsterite, although there might be analogies between chondrule olivines and terrestrial igneous forsterite. Material formed in the nebula or in the impact gas clouds will be formed by vapor phase deposition. The differences in the slope of the terrestrial forsterites and Semarkona matrix in Fig. 8, if real, might reflect a formation mechanism for the matrix forsterite which is more analogous to the vapor phase processes normally assumed for the forsterite and other components in a nebular or cometary dust environment. Forsterite is one of the first major minerals to condense from a gas of cosmic composition and it is the last to evaporate in a heating event (setting aside the relatively rare refractory phases of Ca and Al). Therefore, it seems reasonable that it would be an important constituent of a wide variety of solar system and extra solar system materials.

CONCLUSIONS

We have succeeded in obtaining TL data for six 10–400 µm sized fragments of Semarkona matrix, these samples being two or three orders of magnitude smaller than those of previous TL studies of extraterrestrial material. The TL sensitivity we measured for these fragments was surprisingly high, comparable with bulk samples of a type 3.2–3.4 ordinary chondrite. The TL peak parameters we obtained were unlike those of other type 3 ordinary chondrites, or even bulk samples from Semarkona, but resemble Semarkona chondrules and terrestrial forsterite in their general features but not in their peak temperature and peak width relationships. We note that olivine has been observed in nebula, cometary dust, and Stardust particles, and it appears that forsterite is a major component of most primitive materials. Cathodoluminescence observations suggest that the matrix of Semarkona contains abundant, uniformly dispersed, fine-grained forsterite. Assuming the temperature-width relationship for the matrix samples is real, and not an artifact of small numbers, it suggests a fundamental difference in the nature of Semarkona fine-grained forsterite and the forsterites found in chondrules and terrestrially.

Acknowledgments–We are grateful to Fatameh Sedaghatpour for help with the initial phases of this work, Walter Graupner for his help in maintaining the equipment, Jeff Grossman for supplying a database of TL measurements, the Smithsonian Institution for the terrestrial forsterites, and the NASA Discovery Data Analysis Program for support. We are grateful to Hazel Sears for reviewing and proofing this paper prior to submission.

Editorial Handling—Dr. A. J. Timothy Jull

REFERENCES

Akridge D. G., Akridge J. M. C., Batchelor J. D., Benoit P. H., Brewer J., DeHart J. M., Keck B. D., Jie L., Meier A., Penrose M., Schneider D. M., Sears D. W. G., Symes S. J. K., Yanhong Z. 2004. Photomosaics of the cathodoluminescence of 60 sections of meteorites and lunar samples. *Journal of Geophysical Research* 109:E07S03.

Alexander C. M. O'D., Barber D. J., Hutchison R. 1989. The microstructure of Semarkona and Bishunpur. *Geochimica et Cosmochimica Acta* 53:3045–3057.

Alexander C. M. O'D., Hutchison R., Barber D. J. 1989. Origin of chondrule rims and interchondrule matrices in unequilibrated ordinary chondrites. *Earth and Planetary Science Letters* 95: 187–207.

Ashworth J. R. 1977. Matrix textures in unequilibrated ordinary chondrites. *Earth and Planetary Science Letters* 35:25–34.

Benstock E. J., Buseck P. R., Steele I. M. 1997. Cathodoluminescence of meteoritic and synthetic forsterite at 296 and 77 K using TEM. *American Mineralogist* 82:310–315.

Brearley A. J. 1993. Matrix and fine-grained rims in the unequilibrated CO3 chondrite, ALHA77307: Origins and evidence for diverse, primitive nebular dust components. *Geochimica et Cosmochimica Acta* 57:1521–1550.

Brearley A. J. 1996. Nature of matrix in unequilibrated chondrites and its possible relationship to chondrules. In *Chondrules and the protoplanetary disk*, edited by R. H. Hewins, R. H. Jones, and E. R. D. Scott. Cambridge: Cambridge University Press. pp. 137–151.

Brearley A. J., Scott E. R. D., Keil K., Clayton R. N., Mayeda T. K., Boynton W. V., Hill D. H. 1989. Chemical, isotopic and mineralogical evidence for the origin of matrix in ordinary chondrites. *Geochimica et Cosmochimica Acta* 53:2081–2093.

Craig J., Sedaghatpour F., Gucsik A., Sears D. W. G. 2007. Fragments of separated opaque matrix from the Semarkona unequilibrated ordinary chondrite (abstract #1095). 38th Lunar and Planetary Science Conference. CD-ROM.

Craig J. P. and Sears D. W. G. 2008. The nature and origin of Semarkona fine-grained matrix: An induced thermoluminescence study (abstract #1081). 39th Lunar and Planetary Science Conference. CD-ROM.

Crovisier J., Leech K., Bockelée-Morvan D., Brooke T. Y., Hanner M. S., Altieri B., Keller H. U., and Lellouch E. 1997. The spectrum of comet Hale-Bopp (C/1995 01) observed with the Infrared Space Observatory at 2.9 astronomical units from the Sun. *Science* 275:1904–1907.

Dehart John M., Lofgren Gary E., Jie L. Benoit P. H., Sears D. W. G. 1992. Chemical and physical studies of chondrites. X—Cathodoluminescence and phase composition studies of metamorphism and nebular processes in chondrules of type 3

ordinary chondrites. *Geochimica et Cosmochimica Acta* 56: 3791–3807.
Dodd R. T., Van Schmus W. R., and Koffman D. M. 1967. A survey of the unequilibrated ordinary chondrites. *Geochimica et Cosmochimica Acta* 31:921–951.
Geake J. E., Walker G., Telfer D. J., Mills A. A., Garlick G. F. J. 1973. Luminescence of lunar, terrestrial, and synthesized plagioclase caused by Mn^{2+} and Fe^{3+}. Proceedings, 4th Lunar Science Conference. pp. 3181–3189.
Green G. R. and Walker G. 1985. Luminescence excitation spectra of Mn^{2+} in synthetic forsterites. *Physics and Chemistry of Minerals* 12:271–278.
Grossman J. N., Alexander C. M. O'D., Wang J., Brearley A. J. 2000. Bleached chondrules: Evidence for widespread aqueous processes on the parent asteroids of ordinary chondrites. *Meteoritics & Planetary Science* 35:467–486.
Guimon R. K., Weeks K. S., Keck B. D., Sears D. W. G. 1984. Thermoluminescence as a paleothermometer. *Nature* 311:363–365.
Guimon R. K., Keck B. D., and Sears D. W. G. 1985. Chemical and physical studies of type 3 chondrites—IV: Annealing studies of a type 3.4 ordinary chondrite and the metamorphic history of meteorites. *Geochimica et Cosmochimica Acta* 19:1515–1524.
Guimon R. K., Lofgren G. E., and Sears D. W. G. 1988. Chemical and physical studies of type 3 chondrites, IX: Thermoluminescence and hydrothermal annealing experiments and their relationship to metamorphism and aqueous alteration in type <3.3 ordinary chondrites. *Geochimica et Cosmochimica Acta* 52:119–127.
Guimon R. K., Symes S. P., Sears D. W. G., and Benoit P. H. 1995. Chemical and physical studies of type 3 chondrites XII: The metamorphic history of CV chondrites and their components. *Meteoritics* 30:707–714.
Hartmetz C. P. and Sears D. W. G. 1987. Thermoluminescence and X-ray diffraction studies of annealed oligoclase. 18th Lunar and Planetary Science Conference. pp. 395–396.
Huang S., Lu J., Prinz M., Weisberg M. K., Benoit P. H., Sears D. W. G. 1996. Chondrules: Their diversity and the role of open-system processes during their formation. *Icarus* 122:316–346.
Huss G. R., Keil K., Taylor G. J. 1981. The matrices of unequilibrated ordinary chondrites: Implications for the origin and history of chondrites. *Geochimica et Cosmochimica Acta* 45:33–51.
Hutchison R., Alexander C. M. O'D., Barber D. J. 1987. The Semarkona meteorite: First recorded occurrence of smectite in an ordinary chondrite and its implications. *Geochimica et Cosmochimica Acta* 51:1875–1882.
Ikeda Y., Kimura M., Mori H., Takeda H. 1981. Chemical compositions of matrices of unequilibrated ordinary chondrites. Proceedings of the Sixth Symposium on Antarctic Meteorites. *Memoirs of the National Institute of Polar Research* (Special Issue) 20:124.
Jones R. H. 1992. On the relationship between isolated and chondrule olivine grains in the carbonaceous chondrite ALHA77307. *Geochimica et Cosmochimica Acta* 56:467–482.
Kloeck W., Thomas K. L., McKay D. S., Palme H. 1989. Unusual olivine and pyroxene composition in interplanetary dust and unequilibrated ordinary chondrites. *Nature* 339:126–128.
Koike C., Chihara H., Koike K., Nakagawa M., Okada M., Tsuchiyama A., Aoki M., Awata T., Atobe K. 2002. Thermoluminescence of forsterite and fused quartz as a candidate for the extended red emission. *Meteoritics & Planetary Science* 37:1591–1598.
McSween H. Y., Jr. 1977. On the nature and origin of isolated olivine grains in carbonaceous chondrites. *Geochimica et Cosmochimica Acta* 41:411–418.
Moncorgé R., Cormier G., Simkin D. J., and Capobianco J. A. 1991. Fluorescence analysis of chromium-doped forsterite. IEEE *Journal of Quantum Electronics* 27:114–120.
Nagahara H. 1984. Matrices of type 3 ordinary chondrites-primitive nebular records. *Geochimica et Cosmochimica Acta* 48:2581–2595.
Ninagawa K., Nishimura S., Kubono N., Yamamoto I., Kohata M., Wada T., Yamashita Y., Lu J., Sears D. W. G., Matsunami S., Nishimura H. 1992. Thermoluminescence of chondrules in primitive ordinary chondrites Semarkona and Bishunpur. *Proceedings of the NIPR Symposium on Antarctic Meteorites* 5: 281.
Olsen E. and Grossman L. 1978. On the origin of isolated olivine grains in type 2 carbonaceous chondrites. *Earth and Planetary Science Letters* 41:111–127.
Pasternak E. S. 1978. Thermoluminescence of ordered and disordered albites. Ph.D. thesis, University of Pennsylvania, USA.
Rambaldi E. R., Fredriksson B. J., Fredriksson K. 1981. Primitive ultrafine matrix in ordinary chondrites. *Earth and Planetary Science Letters* 56:107–126.
Scott E. R. D., Rubin A. E., Taylor G. J., Keil K. 1984. Matrix material in type 3 chondrites-occurrence, heterogeneity and relationship with chondrules. *Geochimica et Cosmochimica Acta* 48:1741–1757.
Sears D. W. G. 1980. Thermoluminescence of meteorites; relationships with their K-Ar age and their shock and reheating history. *Icarus* 44:190–206.
Sears D. W. G. 1988. Thermoluminescence of meteorites: Shedding light on the cosmos. *Nuclear Tracks and Radiation Measurements/International Journal of Radiation and Applied Instrumentation D* 14:5–17.
Sears D. W. G., Grossman J. N., Melcher C. L., Ross L. M., Mills A. A. 1980. Measuring metamorphic history of unequilibrated ordinary chondrites. *Nature* 287:791–795.
Sears Derek W. G., Jie L., Benoit P. H., Dehart J. M., Lofgren G. E. 1992. A compositional classification scheme for meteoritic chondrules. *Nature* 357:207–210.
Sears D. W. G., Morse A. D., Hutchison R. Guimon R. K., Jie L., Alexander C. M. O'D., Benoit P. H., Wright I., Pillinger C., Xie T., Lipschutz M. E. 1995. Metamorphism and aqueous alteration in low petrographic type ordinary chondrites. *Meteoritics* 30:169–181.
Sears D. W. G. and Akridge G. 1998. Nebular or parent body alteration of chondritic material: Neither or both? *Meteoritics & Planetary Science* 33:1157–67.
Sedaghatpour F., Craig J. P., Sears D. W. G. 2008. A Study of the thermal history of Antarctic micrometeorites by thermoluminescence: A first look (abstract #1161). 39th Lunar and Planetary Science Conference. CD-ROM.
Sears D. W. G., Sedaghatpour F., and Craig J. 2008. Thermoluminescence as a technique for determining the nature and history of small particles (abstract #5241). *Meteoritics & Planetary Science* 43:A142.
Steele I. M., Smith J. V., Skirius C. 1985a. Cathodoluminescence zoning and minor elements in forsterites from the Murchison (C2) and Allende (C3V) carbonaceous chondrites. *Nature* 313: 294–297.
Steele I. M., Smith J. V., Brownlee D. E. 1985b. Minor-element signature of relic olivine grains in deep-sea particles—A match with forsterites from C2 meteorites. *Nature* 313:297–299.
Steele I. M. 1986. Compositions and textures of relic forsterite in carbonaceous and unequilibrated ordinary chondrites. *Geochimica et Cosmochimica Acta* 50:1379–1395.
Taylor G. J., Scott E. R. D., Keil K., Boynton W. V., Hill D. H., Mayeda T. K., Clayton R. N. 1984. Primitive nature of ordinary

chondrite matrix materials. 15th Lunar and Planetary Science Conference. pp. 848–849.

Zolensky M. E., Zega T. J., Yano H., Wirick S., Westphal A. J., Welsberg M. K., Weber I., Warren J. L., Velbel M. A., Tsuchiyama A., Tsou P., Toppani A., Tomioka N., Kazuchige T., Teslich N., Taheri M., Susini J., Stroud R., Stephan T., Staderman F. J., Snead C. J., Simon S. B., Simionovici A., See T. H., Robert F., Rietmeijer F. J., Rao W., Perronnet M. C., Nakamura-Messenger K., Nakamura T., Mostefaoui S., Mikouchi T., Melbom A., Matrajt G., Marcus M. A., Leroux H., Lemelle L., Le L., Lanzirotti A., Langenhorst F., Krot A. N., Keller L. P., Kearsley A.T., Joswiak D., Jacob D., Ishii H., Harvey R., Hagiya K., Grossman L., Grossman J. N., Graham G. A., Gounelle M., Gillet P., Genge M. J., Flynn G., Ferroir T., Fallon S., Ebel D. S., Dai Z.R., Cordier P., Clark B., Chi M., Butterworth A. L., Brownlee D. E., Bridges J. C., Brennan S., Brearley A., Bradley J. P., Bleuet P., Bland P. A., and Bastien R. 2006. Mineralogy and petrology of comet 81P/Wild 2 nucleus samples. *Science* 314:1735–1739.