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Report

X-ray computed tomography imaging: A not-so-nondestructive technique

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Abstract–X-ray computed tomography has become a popular means for examining the interiors of meteorites and has been advocated for routine curation and for the examination of samples returned by missions. Here, we report the results of a blind test that indicate that CT imaging deposits a considerable radiation dose in a meteorite and seriously compromises its natural radiation record. Ten vials of the Bruderheim L6 chondrite were placed in CT imager and exposed to radiation levels typical for meteorite studies. Half were retained as controls. Their thermoluminescence (TL) properties were then measured in a blind test. Five of the samples had TL data unaltered from their original (~10 cps) while five had very strong signals (~20,000 cps). It was therefore very clear which samples had been in the CT scanner. For comparison, the natural TL signal from Antarctic meteorites is ~5000–50,000 cps. Using the methods developed for Antarctic meteorites, the apparent dose absorbed by the five test samples was calculated to be 83 $\pm$ 5 krad, comparable with the highest doses observed in Antarctic meteorites and freshly fallen meteorites. While these results do not preclude the use of CT scanners when scientifically justified, it should be remembered that the record of radiation exposure to ionizing radiations for the sample will be destroyed and that TL, or the related optically stimulated luminescence, are the primary modern techniques for radiation dosimetry. This is particularly important with irreplaceable samples, such as meteorite main masses, returned samples, and samples destined for archive.

INTRODUCTION

Ketcham and Carlson (2001) succinctly describe the advantages of X-ray computer tomography (CT) by contrasting two methods for obtaining a 3-D image of the interior of a skull. Fourie (1974) took 2 years to make multiple sections, thereby destroying the skull, and prepare a series of sketches. Rowe et al. (1993) used X-ray CT to obtain 3-D images in a matter of days. In their reviews, Ketcham and Carlson (2001) and Cnudde et al. (2006) repeatedly used the term "nondestructive" to describe X-ray CT and compared to multiple slicing of the skull it was. The first suggestion to use this technique with meteorites was probably that of Arnold et al. (1983) who thought it would aid in the location of refractory inclusions. In the last decade the technique has become widespread in meteorite research, and a special issue of *Geochimica et Cosmochimica Acta* has been devoted to it (Hezel et al. 2013a). Two papers in the special issue advocated the use of the technique with samples returned by future space missions (Tsuchiyama et al. 2013; Uesugi et al. 2013).

Of course, the CT imager, initially known as the CAT scanner (for computed axial tomography, for example, Alfidi et al. 1974) was originally developed for medical applications. While the technique's power as a diagnostic technique in medicine is without question, there has always been concern in the literature over the radiation dose administered to the patient. In 2014, the United Kingdom government published a report expressing concern at the excessive use of X-ray CT scans pointing to a significant increase in risk of cancer (COMARE 2014).

Measuring the absorbed radiation dose using thermoluminescence or related techniques (optically stimulated luminescence and electron paramagnetic resonance, for example) utilize the distribution of electrons and ions in crystals, how many are in the ground state versus how many are in excited metastable states. The passage of ionizing radiations—α, β, γ, X-rays, solar and galactic radiation—through the crystal promotes electrons from the ground state to excited metastable sites. Personnel radiation monitoring by thermoluminescence dosimeters (more familiarly known as "TLDs") is commonplace (McKeever 1985). Archeological pottery dating is now as routine as radiocarbon dating (Aitken 1985). Dating of quaternary sediments or archeological structures by optical bleaching methods (OSL) is increasing in importance and each has dedicated conferences.

The relationship describing the natural TL levels of a sample is:

$$\phi = \phi_s / \{1 + [s/\alpha\ R \exp(-E/kT)]\} \qquad (1)$$

where ϕ is the level of natural TL, ϕ_s is the value of TL at saturation, dimensionless parameter s is the Arrhenius factor, α is the dose to fill $1/e$ of the excited states, R is the dose rate, E is the activation energy for restoring electrons to the ground state, k is Boltzmann's constant, and T is absolute temperature. Therefore, while there are several parameters that describe the solid state properties of the crystal, only two describe the environment, R and T. Thus, natural TL has been important in assessing the thermal and radiation history of meteorites, so much so that for 14 years natural TL measurements were part of the preliminary examination process for Antarctic meteorites (Sears et al. 2013).

The present paper reports the results of a blind test to explore the sensitivity of meteorites to the radiation experienced in a typical X-ray CT scan. We argue that if one technique is negatively impacted by placing a sample through this instrument, the technique should not be referred to as "nondestructive." Furthermore, CT scans should not be performed without knowledge of the detrimental effects. This is especially true of main masses of meteorites, unique and valuable returned samples of extraterrestrial material, or material intended for long-term archive.

METHODS

About 100 mg of nonmagnetic crushed powder from the Bruderheim L6 chondrite (residues from the Haq et al. [1988], study), ~200 μm in grain size, were divided into 10 aliquots and placed in 5 mm diameter, 2 mm deep, copper pans. These were then placed in the thermoluminescence apparatus and heated to 500 °C to remove their natural TL. After this treatment, their natural TL curve was run to ensure that any TL signal present was removed and to provide a background measurement. The TL apparatus consists of a modified Daybreak Nuclear and Medical, Inc., system that has frequently been described in the literature (Sears et al. 2013).

The 10 samples were then placed in vials (labeled A–J) and sent to the American Museum of Natural History. Five (B, E, F, G, I) were selected randomly and placed in a GE Phoenix VtomeX S240 computed microtomography instrument where they were given a controlled dose of radiation typical of that used for meteorite studies. A tungsten (W) filament 240 kV X-ray tube was used at 140 kV and 142 μA. Additional metallic filters (e.g., Cu, Al) between the X-ray tube and sample are often employed in CT imaging; however, we used no additional filters during the imaging experiments here. In order of increasing duration in minutes, the X-ray exposure times for each sample were as follows: B = 20, G = 40, I = 80, E = 120, F = 160. X-ray tubes such as that in the VtomeX instrument produce polychromatic bremsstrahlung X-rays with an additional peak at W characteristic energies. The X-rays produced by the X-ray tube under the above conditions given above range from about 20 to 140 keV, with a mean near 55 keV. Although the actual number must be determined empirically for each X-ray tube, an estimate for the X-ray flux produced by the tube across all energies is on the order of 10^8 to 10^9 photons s^{-1}.

After a delay period of about 3 months, which allowed short-term effects to dissipate (the induced TL signal due to shallow short-lived electron traps which decay on the time scale of the TL measurement), the 10 vials were returned to Ames with no indication as to which had been placed in the scanner. The thermoluminescence of the samples was then recorded. After each sample had been run, a black body, or background, curve was also recorded.

RESULTS

The thermoluminescence data are obtained as "glow curves," which are plots of the light emitted against the temperature to which the sample has been heated (Fig. 1). For half the samples (A, C, D, H, and J) there was no significant natural TL signal detectable above background, the upturn at high temperatures being entirely due to black body radiation. Noise on the curve reflects thermal noise in the detector. These results are identical to those obtained before sending the samples

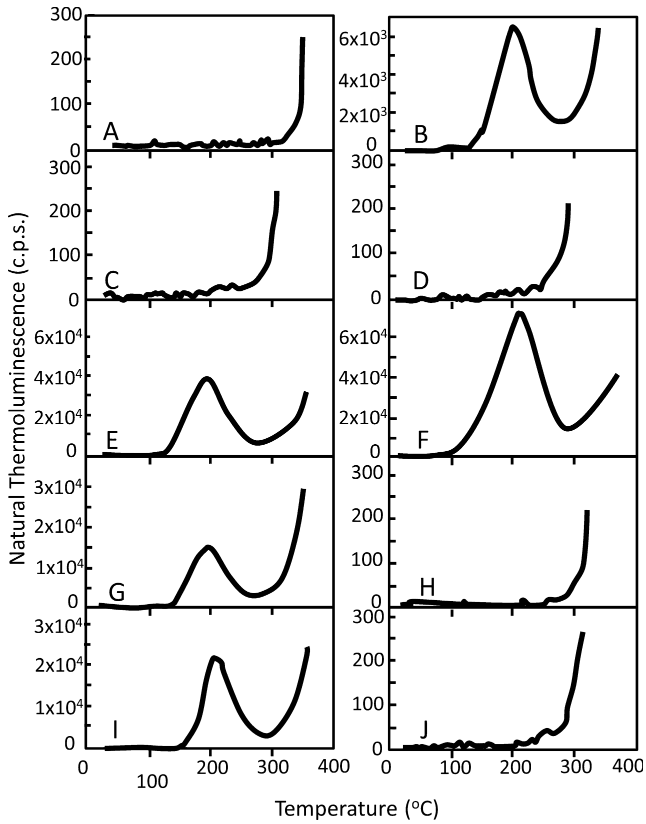

Fig. 1. Thermoluminescence data for 10 aliquots of the Bruderheim meteorite. The data are presented as plots of the light emitted (in counts per second) as a function of heating temperature in the apparatus, these curves are usually known as "glow curves." Before the experiment, all samples were drained of their natural TL by heating to 500 °C. Then five samples were placed in an X-ray CT scanner at the American Museum of Natural History, five were kept as controls. The samples were sent blind to Ames Research Center for TL measurement. For five samples, there is little or no measureable TL signal, the rise to the right corresponding to the onset of black body radiation. For five samples, there was a single peak at about 215 °C in the glow curve with intensities of 16,000–68,000 c.p.s. Clearly, aliquots B, E, F, H, and I were placed in the scanner and A, C, D, H, and I are the controls.

to the AMNH. Variations in the background reflect sample-to-sample variations (slight changes in albedo, how they filled the sample cup, or moved during the run, for example) and differences in settings. A typical signal was 10–40 cps, within a few sigma of background. The remaining samples (B, E, F, G, and I) produced a very strong TL signal and a glow curve characteristic of freshly fallen ordinary chondrites. The glow curves have fairly narrow peaks (by TL standards) at ~215 °C in the glow curve. Count rates at the peaks were 16,000–68,000 cps with a background of ~10 cps. The range in TL sensitivity reflects mostly the duration of irradiation; excluding the data for vial B there is a correlation where counts per minute = 360 × time (minutes). Normalizing to mass does reduce the scatter in the TL intensity values somewhat, but light level depends on many additional factors (such as surface area of the sample and light scattering properties of the grains) that the process is not very precise. In any event, the difference between irradiated and control samples is so marked it is not important for the present purposes. The peak temperatures, maximum count rates, and backgrounds are given in Table 1.

The preferred way of handling natural TL data, the method used for the survey of Antarctic meteorites and in most publications on the TL of Antarctic meteorites, is to measure the ratio of the low temperature TL (i.e., at the peak) to the TL of the high temperature peak (usually at ~400 °C). When signals in the high temperature region are weak, they can be obscured by "black body" radiation; this is the radiation produced by the sample by virtue of its temperature. In these cases we take the TL measurement at the dip of the glow curve as the signal from the low temperature peak drops with increasing temperature and before significant black body radiation becomes apparent as the sample is heated. With this approach, the low temperature TL is being used as the quantity of interest and the high temperature TL is being used for normalization to remove unwanted effects such as sample heterogeneity, sample albedo, and sample mass. These results are shown in Table 2. Because of the normalization, which removes factors affecting raw counts, such as sample mass and sample heterogeneity, they show less than ~10% spread. The TL peak height ratio (LT/HT) can be converted to an estimate of absorbed dose, the natural TL (NTL), by a relationship described by Hasan et al. (1987):

$$\log(\mathrm{NTL}) = [\log(\mathrm{LT/HT}) + 0.844]/0.775 \qquad (2)$$

and the NTL values are also shown in Table 2. The five aliquots of Bruderheim exposed in the X-ray CT scanner have a mean ± 1σ of 83 ± 5 krad (note 100 rad = 1 Gray, the SI unit for absorbed dose).

DISCUSSION

The largest database on natural TL values is for Antarctic meteorites. For 14 years (1987–2001), the natural TL level of every Antarctic meteorite larger than about 1 cm was measured as part of their preliminary examination. The results were published in the Antarctic Meteorite Newsletter along with petrographic descriptions (Sears et al. 2013). In terms of raw counts per second, the natural TL signal from Antarctic meteorites is ~5000–50,000 cps, compared to 16,000 to 68,000 cps for the present samples after being in the

Table 1. Peak temperatures (when present) and counts (with background) for the natural thermoluminescence of the present samples.

	Peak T (°C)	Intensity (c.p.s.)	Bgd (c.p.s.)
Bruderheim A	–	40	10
Bruderheim B	215	60,000	8
Bruderheim C	–	23	10
Bruderheim D	–	30	10
Bruderheim E	210	38,000	10
Bruderheim F	220	68,000	10
Bruderheim G	213	16,000	10
Bruderheim H	–	10	10
Bruderheim I	215	16,000	10
Bruderheim J	–	10	10

Table 2. Natural thermoluminescence peak height ratios and calculated doses (NTL).

Sample	LT/HT	NTL (krad)
Bruderheim B	4.28	80.2
Bruderheim E	4.22	78.7
Bruderheim F	4.25	79.5
Bruderheim G	4.66	89.5
Bruderheim I	4.57	87.3
Mean		83.0
Standard deviation		5.0

X-ray CT scanner. A more sophisticated comparison is to consider natural TL values as calculated from peak height ratios using Equation 2. A histogram of the data is shown in Fig. 2. Natural TL values for Antarctic meteorites range from <0.1 krad to just over 100 krad, with most between 5 krad and 50 krad. For comparison, Japanese Antarctic meteorites have a slightly greater spread and are skewed to slightly higher values (Sears et al. 2013). Non-Antarctic meteorites, with their shorter terrestrial ages, are skewed to even higher values (Haq et al. 1988; Benoit et al. 1992).

Superimposed on Fig. 2 is the mean $\pm$ 1σ (83 $\pm$ 5 krad) for the five samples of Bruderheim that were put in the X-ray CT imager. It is clear that a typical exposure in an X-ray CT scanner deposits a radiation dose to the meteorite comparable to the higher doses received by Antarctic meteorites and comparable to observed falls. Of course, the dose naturally present in a meteorite consists of that due to cosmic ray exposure and internal radioactivities. Back-of-the-envelope calculations indicate that the dose received from cosmic rays over a 10^6 year time scale is similar to the dose received from internal radioactivities over the lifetime of the solar system (Sears 1980), although it depends on shielding (e.g., Sears 1975) and target chemistry (Arnold et al. 1983).

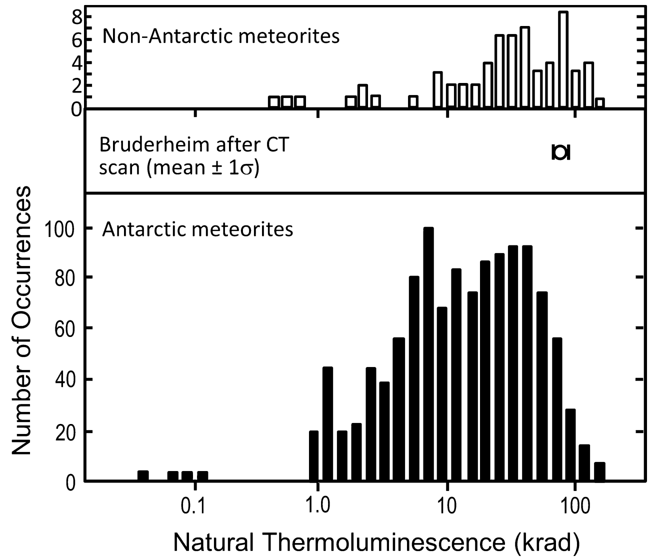

Fig. 2. Histogram of the natural thermoluminescence observed in Antarctic meteorites collected in Western Antarctica (from Sears et al. 2013) compared with the natural TL induced in the five samples of Bruderheim by a typical exposure in the X-ray CT scanner. Also shown are non-Antarctic observed falls (Haq et al. 1988), which tend to plot toward the top of the Antarctic meteorite range with a peak at ~100 krad.

A synchrotron CT apparatus imparted a dose of 1.1 and 1.3 kGy (110 and 130 krad) in two recent experiments using the microCT attached to the synchrotron beamline at the Advanced Photon Source at the Argonne National Laboratory, beamline and hutch 13-BM-D (Friedrich et al. 2016), which is similar to the values calculated here from the induced TL. According to government health reports (COMARE 2014), a typical X-ray CT scan deposits in the human body a dose of about 1000 mrem.

This is not to say that CT scans should never be performed on meteorites or other scientific samples, but that it should only be performed with knowledge of the changes being induced in the sample. This is particularly critical when irreplaceable main masses, or sole masses, of a given meteorite are placed in a CT scanner. Current techniques are easily capable of detecting the absorbed radiation; future techniques will be even more sensitive. The usual factors to be considered when handling meteorites are gain to science versus risk to the meteorite. Is the science gain sufficient to justify the risk to the sample? Can the same or equivalent data be gained by alterative techniques with lower risks, for example, does a cut and polished face provide a reasonable equivalent of the information sought? Is the three-dimensional data really necessary and so much superior to data from a cut face to justify losing the radiation history of the sample? Today's techniques are easily capable of detecting the radiation dose from a CT scan. Future techniques will almost certainly provide greater and better data than current techniques. If it is determined that the science gain justifies compromising the radiation history of the sample then an indication should be available for all eternity that this sample was irradiated in the laboratory, perhaps an indelible mark placed on the fusion crust of the sample. Paper or digital records may be lost, confused, or simply not consulted before the sample is taken. The stakes are much higher for main masses, or sole masses, samples returned by missions. More than half of the Apollo samples were put in long-term storage pending new generations of scientists and techniques.

While we are primarily concerned with meteorites here, we would like to point out that thermoluminescence dating of pottery is now used as a routine dating technique as radiocarbon dating (Aitken 1985). Samples of pottery subjected to X-ray CT scanning would almost certainly be useless for TL dating. Second, perhaps worse than X-ray CT scanning, neutron CT scanning (Winkler et al. 2002) seriously compromises the information that can be obtained from cosmogenic nuclides in meteorites (K. Nishiizumi, personal communication).

CONCLUSIONS

In a blind test, samples of a meteorite placed in a typical X-ray CT scanner were shown to absorb a radiation dose comparable to that observed by meteorites from cosmic rays, during their 10s to 100s million years of exposure, and from internal radioactivities during their lifetime. The increasing use of X-ray CT imaging is compromising the natural radiation record of meteorites. This is particularly problematic when unique samples are used, such as main masses of meteorites; samples returned by space missions; or samples intended for archive, pending the development of new and currently unimagined techniques. It needs to be demonstrated that any data obtained by X-ray CT imaging justify the loss of the sample's radiation record. We suggest that meteorite curators make an indelible mark on the meteorites or other samples when they have been placed in an X-ray CT imager as separate documentation may be lost, dissociated from the sample, or simply not consulted, when studies of radiation record are contemplated.

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REFERENCES

Aitken M. J. 1985. *Thermoluminescence dating (Studies in archaeological science)*. London: Academic Press. 359 p.

Alfidi R. J., MacIntyre W. J., Meaney T. F., Chernak E. S., Janicki P., Tarar R., and Levin H. 1974. Experimental studies to determine application of CAT scanning to the human body. Presented at the Seventy-fifth Annual Meeting of the American Roentgen Ray Society, San Francisco, California, September 24–27.

Arnold J. R., Testa J. P. Jr., Friedman P. J., and Kambic G. 1983. Computed tomographic analysis of meteorite inclusions. *Science* 219:383–384.

Benoit P. H., Sears H., and Sears D. W. G. 1992. The natural thermoluminescence of meteorites—IV: Ordinary chondrites at the Lewis Cliff ice field. *Journal of Geophysical Research* 97:4629–4647.

Cnudde V., Masschaele B., Dierick M., Vlassenbroeck J., Van Hoorebeke L., and Jacobs P. 2006. Recent progress in X-ray CT as a geosciences tool. *Applied Geochemistry* 21:826–832.

COMARE. 2014. Patient radiation dose issues resulting from the use of CT in the UK. Committee on Medical Aspects of Radiation in the Environment (COMARE), 16th report. London: Public Health England.

Fourie S. 1974. The cranial morphology of Thrinaxodon liorhinus Seeley. *Annals of the South African Museum* 65:337–400.

Friedrich J. M., Glavin D. P., Rivers M. L., and Dworkin J. P. 2016. Effect of a synchrotron x-ray microtomography imaging experiment on the amino acid content of a CM chondrite. *Meteoritics & Planetary Science*, doi:10.1111/maps.12595.

Haq M., Hasan F. A., and Sears D. W. G. 1988. Thermoluminescence and the shock and reheating history of meteorites—IV: The induced TL properties of type 4-6 ordinary chondrites. *Geochimica et Cosmochimica Acta* 52:1679–1689.

Hasan F. A., Haq M., and Sears D. W. G. 1987. Natural thermoluminescence levels in meteorites, I: 23 meteorites of known Al-26 content. Proceedings, 17th Lunar and Planetary Science Conference, Part 2. *Journal of Geophysical Research* 92:E703–E709.

Hezel D. C., Friedrich J. M., and Uesugi M. 2013a. Looking inside: 3D structures of meteorites (Editorial). *Geochimica et Cosmochimica Acta* 116:1–4.

Ketcham R. A. and Carlson W. D. 2001. Acquisition, optimization and interpretation of X-ray computed tomographic imagery: Applications to the geosciences. *Computers & Geosciences* 27:381–400.

McKeever S. W. S. 1985. *Thermoluminescence of solids*. Cambridge, UK: Cambridge University Press. 376 p.

Rowe T. B., Carlson W. D., and Bottdorf W. W. 1993. Thrinaxodon digital atlas of the skull. Austin, Texas: University of Texas Press. CD-ROM.

Sears D. W. 1975. Thermoluminescence studies and the preatmospheric shape and mass of the Estacado meteorite. *Earth and Planetary Science Letters* 26:97–104.

Sears D. W. 1980. Thermoluminescence of meteorites; relationships with their K-Ar age and their shock and reheating history. *Icarus* 44:190–206.

Sears D. W. G., Ninagawa K., and Singhvi A. K. 2013. Luminescence studies of extraterrestrial materials: Insights into their recent radiation and thermal histories and into their metamorphic history. *Chemie der Erde—Geochemistry* 73:1–37.

Tsuchiyama A., Nakano T., Uesugi K., Uesugi M., Takeuchi A., Suzuki Y., Noguchi R., Matsumoto T., Matsuno J., Nagano T., Imai Y., Nakamura T., Ogami T., Noguchi

T., Abe M., Yada T., and Fujimura A. 2013. Analytical dual-energy microtomography: A new method for obtaining three-dimensional mineral phase images and its application to Hayabusa samples. *Geochimica et Cosmochimica Acta* 116:5–16.
Uesugi M., Uesugi K., Takeuchi A., Suzuki Y., Hoshino M., and Tsuchiyama A. 2013. Three-dimensional observation of carbonaceous chondrites by synchrotron radiation X-ray CT—Quantitative analysis and developments for the future sample return missions. *Geochimica et Cosmochimica Acta* 116:17–32.
Winkler B., Knorr K., Kahle A., Vontobel P., Lehmann E., Hennion B., and Bayon G. 2002. Neutron imaging and neutron tomography as non-destructive tools to study bulk-rock samples. *European Journal of Mineralogy* 14:349–354.