Available online at www.sciencedirect.com
ScienceDirect
Planetary and Space Science 56 (2008) 895–900
Planetary and Space Science
www.elsevier.com/locate/pss

Rapid Communication

Pore size distribution in an uncompacted equilibrated ordinary chondrite

Jon M. Friedrich[a,b,*], Robert J. Macke[c], Douglas P. Wignarajah[a], Mark L. Rivers[d], Daniel T. Britt[c], Denton S. Ebel[b]

[a] *Department of Chemistry, Fordham University, 441 East Fordham Road, Bronx, NY 10458, USA*
[b] *Department of Earth and Planetary Sciences, American Museum of Natural History, New York, NY 10024, USA*
[c] *Department of Physics, University of Central Florida, Orlando, FL 32816, USA*
[d] *Consortium for Advanced Radiation Sources, University of Chicago, Argonne, IL 60439, USA*

Received 2 November 2007; received in revised form 28 January 2008; accepted 1 February 2008
Available online 13 February 2008

Abstract

The extraordinarily uncompacted nature of the ordinary L chondrite fall Baszkówka gives a unique opportunity to investigate the potentially pre-compaction pore size distribution in an equilibrated ordinary chondrite. Using X-ray microtomography and helium pycnometry on two samples of Baszkówka, we have found that on average, two-thirds of the 19.0% porosity resides in inter- and intra-granular voids with volumes between $\sim 3 \times 10^{-5}$ and $3\,mm^3$. We show the cumulative number density of pore volumes observable by X-ray microtomography obeys a power law distribution function in this equilibrated ordinary chondrite. We foresee these data adding to our understanding of the impact processing of chondrites and their parent asteroids, where porosity and pore size play significant roles in the parameterization of impact events.

Keywords: X-ray microtomography; Porosity; Density; Ordinary chondrite; Asteroid

1. Introduction

About 85% of meteorites are chondrites thought to originate in the inner asteroid belt. Most ordinary chondrites are equilibrated, in that the chemical composition of silicate minerals have been homogenized by thermal and aqueous alteration on their parent asteroids early in the solar system's history. Measurements of chondrite physical properties offer information on the structure of their asteroid parents. Although robotic and satellite co-orbital observations provide relatively precise estimates of asteroidal density (see Britt et al. (2002) and references therein) and insight into their macrostructure, laboratory investigations of chondrites are currently our only means of observing the mineralogical packing structures responsible for the observed properties. Measurements of chondrite bulk density, grain density, and porosity have set significant constraints on the structure of asteroids. Reconciliation of the data with astronomical observations strongly suggests a significant amount of macroporosity within asteroids (Britt et al., 2002).

General bulk properties of chondrites and asteroids are also important parameters for modeling impact-related phenomenon such as shock propagation, impact-related (re)heating, and the thermal diffusion in asteroids since the size and structure of the porosity is as important as the degree of porosity. For example, while it has become clear that deposited collisional energy varies with porosity (Love et al., 1993), this quantity also varies with the pore size distribution (Sarid et al., 2005; Wünnemann et al., 2006). It has been suggested that the majority of porosity in chondritic meteorites resides in micrometer-sized fractures and voids within a sample, and that the majority of the voids in ordinary chondrites are impact-related microcracks (Flynn et al., 1999). Given the minute size of these

*Corresponding author at: Department of Chemistry, Fordham University, 441 East Fordham Road, Bronx, NY 10458, USA.
Tel.: +1 718 817 4446; fax: +1 718 8174432.
E-mail address: friedrich@fordham.edu (J.M. Friedrich).

0032-0633/$ - see front matter
doi:10.1016/j.pss.2008.02.002

fractures, observational evidence for possible sources of porosity primarily arises from two-dimensional optical or instrumental thin-section inspection. The three-dimensional (3D) imaging technique synchrotron X-ray computed microtomography (XMT) offers the ability to reconstruct the spatial relationship of materials with differing X-ray attenuation properties in small ($<\sim 2.5\,cm^3$) samples at resolutions down to the single μm scale (Ebel and Rivers, 2007) in samples free of the sample preparation artifacts inherent to thin sectioning. Here, we have used XMT and the more traditional method of helium (He) pycnometry to examine the pore volume distribution in two samples of the unusually uncompacted Baszkówka L chondrite. Combining the data obtained from these two methods allows us to obtain a cumulative distribution portrait of pore volumes present in Baszkówka. We anticipate that these data will assist in the parameterization of impact processes involving chondritic asteroids and will increase our knowledge of asteroidal evolution.

2. Methods

2.1. Samples

Other than the abundance of large pore sizes, Baszkówka is a relatively typical equilibrated ordinary chondrite. Mineralogically, the Baszkówka chondrite exhibits evidence for only a mild (<5 GPa) amount of shock loading [S1 in the scheme of Stöffler et al., 1991], which is a relative rarity among the L chondrites (see Friedrich et al., 2004). Additionally, Baszkówka has been noted as possessing an unusually porous, grainy texture, a relatively low bulk density of $2.9\,g/cm^3$ (Stępniewski et al., 1996), and high thin-section-based porosity estimated at $\sim$20% (Siemiątkowski, 2001; Przylibski et al., 2003). As a rock in hand specimen, Baszkówka is physically indurated and only slightly friable. Chemically, Baszkówka is clearly an equilibrated L chondrite that experienced only mild shock (see Friedrich et al., 2004) and there is no evidence that it is a regolith breccia either chemically (Friedrich et al., 2004) or petrographically (Przylibski et al., 2003).

For comparison with the tomograms of the uncompacted Baszkówka, we also examined the relatively porous L chondrite Saratov (L4, S2) with XMT. Flynn et al. (1999) reported that Saratov possesses a porosity of $13\pm2\%$ based on He pycnometry, while Britt and Consolmagno's (2003) compilation of porosity data using He pycnometry gives 15.5%. In summary, porosity values for Baszkówka and Saratov are at least three times the L chondrite fall average of $5.8\pm4.7\%$ (Britt and Consolmagno, 2003).

2.2. X-ray microtomography and volumetric data extraction

For the collection of XMT data, we used routine procedures of the GeoSoilEnviroCARS bending magnet beamline (13-BM) located at the Advanced Photon Source of Argonne National Laboratory. Ebel and Rivers (2007) provide additional meteorite-specific data collection and post-processing details. We collected tomographic data on two chunks of the L chondrite Baszkówka—hereafter designated Sample 1 (580 mg) and Sample 2 (1004 mg)—and a single 840 mg portion of the mildly shocked (S2) L4 chondrite Saratov (AMNH 4908) all at 50 keV. To balance the competing demands of voxel resolution, collection time, and analyzable sample size we settled on a resolution of 16.8 μm/voxel for our XMT analyses. Sample 1 was imaged as three separate volumes while Saratov and Sample 2 were collected as four volumes. Each of the separate volumes was later reconstructed into a single continuous image stack, which was used in the computer-aided volumetric extractions described below. Fig. 1 shows typical XMT "slices" of each Baszkówka sample. In these representations, higher average atomic weight materials are brighter, with the air around and inside the chondrite being the darkest material. Silicates are generally a dark gray and sulfides appear in gray scale as darker than the higher-intensity (brighter) metal. When referring to 'metal' or 'sulfide' we are actually referring to chondrite components that have X-ray attenuations similar to that expected for chondritic metal (kamacite, taenite) or sulfide [Fe(Ni)S] phases: dense oxides such as chromite, much smaller in size [typically $\leqslant 50$ μm in size (Johnson and Prinz, 1991; Bunch et al., 1967)] than the largest metal grains will also likely be included in one of these categories because of the digital thresholding techniques used for the isolation of the components of interest. To extract quantitative data from volumetric representations, we used the BLOB3D software tool (Ketcham, 2005), which contains numerous options for the separation and segmentation of components of interest based on their grey-scale values. After applying a mild, single-voxel radius median smoothing, necessary to remove noise from our tomograms, we obtain a maximum resolution of $28{,}400\,\mu m^3$ ($2.84\times10^{-5}\,mm^3$) per volumetric unit. With user input, BLOB3D is able to isolate and count the number of voxels within a defined component yielding the volumes and shapes of individual isolated components. We separated materials in the following order: (1) external air (to obtain bulk meteorite volume), (2) Fe(Ni) metal, (3) Fe(Ni) sulfide and (4) internal pores. Based on replicate separation by multiple student investigators extracting metal and sulfide components on a variety of duplicate ordinary chondrite samples, we have found our BLOB3D extracted component volume errors to be $\leqslant 6\%$.

2.3. Helium pycnometry

We used standard He pycnometry procedures (e.g. Consolmagno et al. (2006) and references therein) to measure the total grain volume of our Baszkówka samples. Porosity is simply the difference between the bulk volume (measured in our case with XMT) and the grain volume. Given the grain volume and mass information, we can calculate the grain density, or the density of the minerals