DENSITIES AND POROSITIES OF ORDINARY CHONDRITES; DO HIGH POROSITY METEORITES REPRESENT REGOLITH MATERIALS?

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Introduction: Densities and porosities of meteorites provide information about the physical properties of their parent bodies (asteroids). Recent studies report the densities and porosities of ~40 ordinary chondrite (OC) meteorites [1,2]. In this study, we present 42 additional measurements of OC densities and porosities, and provide a rigorous analysis of the errors in the method. Additionally, we investigate potential controls on OC porosity, examine the range of heterogeneity among stones of a single fall, and consider if friable OCs could be potential analogs for low-density asteroids or secondary products from higher-density asteroids.

Background: The *bulk volume* of a meteorite consists of the volume of the mineral grains and the volume of the pore spaces. *Grain volume* is defined as only the volume of the mineral grains within the meteorite sample. *Microporosity* is the inherent porosity within the sample (on the same scale as the grain size). *Macroporosity* is large-scale porosity from fractures and voids caused by fracturing.

Methods: Bulk densities were measured using a modified Archimedian method [1,3], and grain densities were measured using a helium gas pycnometer [1,4]. We measured the accuracy of the pycnometer and show the grain volume measurements to be ~± 6 cm^3 independent of sample size. Smaller-sized samples are thus more affected by the grain volume error than larger-sized samples. The porosity of a sample is calculated using its bulk and grain volumes.

Results: We measured the grain densities, bulk densities, and porosities of 42 pieces of 30 ordinary chondrites. The average grain density of our OC samples was 3.51 g/cm^3. The mean value of sample porosities range from –12% to 27%, with 95% of samples below 20% porosity. Negative porosities are consistent with zero after taking into account the error in the measurement methods. Because measurements of smaller sized samples have greater errors associated with them, we calculate a weighted average that takes into account the uncertainties in the measurements. The weighted average porosity of all ordinary chondrite samples (n=42) was 6.4% ± 0.7%. The median porosity value of the dataset (n=42) was 3.7%. The (non-weighted) average of only those porosity measurements with less than ± 5% porosity error (n=18) is 6.2%.

Discussion: To investigate the key controls on our observed range of porosity (-12 to 27%), we compare our porosity results to ordinary chondrite chemical group, petrologic grade, mass, bulk and grain density, and shock level. We find that no significant correlation exists between porosity and chemical group, petrologic grade, sample mass, or shock level. As a first-order effect, bulk elemental composition controls the density of a meteorite (i.e. types of meteorites such as irons vs. stones). However, Wilkison and Robinson [3] showed that bulk density is independent of bulk chemical composition within the OC group of meteorites. Wilkison and Robinson [3] suggested that porosity was a main control of bulk density variations within the OC groups; our additional measurements support this hypothesis.

Shower stones. In order to investigate the range of heterogeneity in both porosity and density within a meteorite, we examined a suite of shower stones. Selecting samples from a single shower minimizes the potential differences in chemical group or petrologic grade seen between samples from different falls. Stones from the same shower should be nearly identical in composition and other physical properties. However, there is some evidence for heterogeneity in both bulk density and porosity among pieces of Pultusk [1,3]. We report the first data set on *both* porosity and density measured on individuals of a group of shower forming stones.

We measured only three pieces of Pultusk (due to lack of large enough pieces to be measured reliably), with resulting porosities of -3.8% ± 6.4%, -4.6% ± 5.7%, and 5.3 ± 3.8% (the weighted average porosity is 1.1% ± 2.8%). The grain densities of the pieces were 3.47 g/cm^3, 3.38 g/cm^3, and 3.76 g/cm^3. The porosity values of the three Pultusk stones are consistent within the experimental error.

We also examined stones of a fall (Holbrook) that had nine pieces large enough to be reliably measured in our pycnometer. The weighted average of the porosity was 2.7% ± 1.6%, ranging from 0% to 6.2%. The stones exhibited bulk densities that varied slightly beyond the analytical uncertainties, but the porosities were identical within analytical uncertainties. We can thus conclude that there are only slight differences in density and porosity among the pieces of Holbrook.

Examination of numerous pieces from two showers, Pultusk and Holbrook, indicate relative homogeneity in porosity and density between pieces from the same shower.

Porous and friable OCs. Porous meteorites have garnered more attention given the low-density measurements (1-2 g/cm^3) of many asteroids. These low bulk densities have been interpreted to indicate the presence of large-scale macroporosity within the asteroid [i.e. 1,3,5], or to indicate that the rare group of highly-friable, porous meteorites may be more representative of ordinary chondrite parent bodies with high microporosity [2]. We have undertaken a study of the densities and porosities of two particularly friable OCs (Bjurbole and Allegan) to investigate these possibilities.

The porosity of a 142 g piece of Bjurbole is 0.8% ± 12.7%; unlike most pieces of Bjurbole reported in the literature, our sample was not very friable. The samples of Bjurbole measured by Flynn et. al. [2] were described as being extremely crumbly and friable, and they determined the porosities of two pieces (29.31 g and 10.84 g) to be 20% and 23% porous, respectively. There is a substantial difference in porosity and friability between the pieces examined in this study and in [2].

We also measured the densities and porosities of two fusion-crusted fragments of Allegan. One piece has a porosity of 27%, a grain density of 4.29 ± 0.69 g/cm^3, and is more friable than the other piece, which has a porosity of 13% and a grain density of 3.54 ± 0.61 g/cm^3. Just as with Bjurbole, there are substantial differences in porosity and friability between the pieces of Allegan examined in this study.

Bjurbole and Allegan are complicated examples of a rare group of OCs, because they are equilibrated (and thus metamorphosed), yet some specimens retain remarkable friability and porosity compared to other ordinary chondrites. In addition, variability in both friability and porosity exists between pieces of the same fall. We speculate that these meteorites could have formed in two very different environments. First, the pieces may represent a unique OC parent body that accreted with a high microporosity. Second, the meteorites could be representative of a lithified rock that formed on the surface of the parent body, in a regolith or along a fault zone. We discuss each theory in the context of Eros below.

433 Eros. Can Eros be a unique parent body that accreted with a high microporosity? Eros's porosity, to the first order, appears to be uniform throughout [6]. If Eros had no macroporosity, its bulk density (2.67 g/cm^3) [7,8] should match that of its meteorite analog. Even though Bjurbole and Allegan have high microporosity and friability, we did not measure any pieces with anomalously low bulk densities (Bjurbole, 3.01 g/cm^3, and Allegan, 3.08 g/cm^3 and 3.13 g/cm^3) compared to that of Eros (2.67 g/cm^3). Flynn et al. [2] measured the bulk densities of two extremely friable OCs, Bjurbole (2.64 and 2.84 g/cm^3) and Saratov (2.98 g/cm^3), and a less friable ordinary chondrite, Mt. Tazerzait (3.01 g/cm^3). Although their bulk densities are low, the only sample that is anomalously low (and thus comparable to Eros) is the 2.64 g/cm^3 piece of Bjurbole. However, surface structural evidence [9,10] suggests that Eros has significant fracturing and thus a significant amount of macroporosity. We conclude that Eros did not accrete with a high microporosity.

Could friable, porous OCs be lithified rocks that formed in a regolith or fault zone of an asteroid, rather than representing the density and porosity of the asteroid as a whole? Results from NEAR Shoemaker show that Eros has a pervasive and complex regolith, typically tens of meters thick [11]. The regolith and/or the deep fractures seen on the surface of Eros are ideal locations to find low density/high porosity material to potentially form these friable meteorites. We thus conclude that these friable and porous OCs could be from the regolith of an asteroid. To test the validity of this theory, further investigation (to look for evidence of solar wind implantation, anomalous clasts, clasts with morphologies associated with fault action, etc.) of the bulk geochemistry and petrology of these meteorites is required.

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