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Stony meteorite porosities and densities: A review of the data through 2001

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Abstract–In this review, we summarize the data published up to December 2001 on the porosity and density of stony meteorites. These data were taken from 925 samples of 454 different meteorites by a variety of techniques. Most meteorites have densities on the order of 3 to 4 g/cm^3, with lower densities only for some volatile-rich carbonaceous meteorites and higher densities for stony irons. For the vast majority of stones, porosity data alone cannot distinguish between different meteorite compositions. Average porosities for most meteorite classes are around 10%, though individual samples can range as high as 30% porosity. Unbrecciated basaltic achondrites appear to be systematically less porous unless vesicles are present. The measured density of ordinary chondrites is strongly controlled by the amount of terrestrial weathering the sample has undergone with porosities steadily dropping with exposure to the terrestrial environment. A theoretical grain density based on composition can model "pre-weathered" porosities. The average model porosity for H and LL chondrites is 10%, while L chondrite model porosities average only 6%, a statistically significant difference.

INTRODUCTION

Meteorite densities and porosities are fundamental characteristics of these materials that can give significant clues to the physical environment in which the meteorite was lithified and evolved. These data are also important in interpreting a variety of other data ranging from cosmic ray exposure ages to magnetic properties to evaluating the structure of potential meteorite parent bodies (especially as our knowledge of asteroidal bulk densities grows).

Here, we provide a complete review of published and some unpublished meteoritic density and porosity data current up to the end of 2001. These data were obtained by many different, and at times uncalibrated, methods, which are also summarized. We hope this compilation is a virtually complete set of the porosity data. Density data are far more scattered through the literature; occasional density values for 1 or 2 meteorites will be listed by many authors in various contexts without a systematic explanation of how or where those data were obtained. We do not claim our compilation of density data is complete but hope that what we provide is representative of what is to be found in the literature.

Techniques

The porosity of a rock is the percent fraction of the volume of a sample that is empty space. Most simply, porosity can be represented as the volume of the rock plus pores (bulk volume, V_b) minus the volume of just the minerals in the rock (grain volume, V_g), normalized to the bulk volume. Equivalently, one can subtract the density of the sample plus pores (bulk density, ρ_b) from the density of the minerals alone (grain density, ρ_g), normalized to the grain density. Though some techniques exist for attempting to estimate porosity directly, the most robust measurements involve some measurement of the meteorite's bulk and grain densities.

$$\text{Bulk density } (\rho_b)\text{: } \rho_b = M_g / V_b \tag{1}$$

$$\text{Grain density } (\rho_g)\text{: } \rho_g = M_g / V_g \tag{2}$$

$$\text{Porosity } (\eta_t)\text{: } = (1 - \rho_b / \rho_g) \times 100 \tag{3}$$

All density measurements require a measure of the sample's mass (M_g) and volume. Measuring a mass can be accomplished trivially, but volume measurement of an irregularly shaped object is far more difficult.

Three possible volume measurement techniques are in use. The simplest is to measure only easily measured shapes, such as a cube or a thin slab. (The surface area of an irregular slab can be measured by, for instance, tracing the outline of the slab onto graph paper and then multiplying against the measured thickness to obtain a volume.) The most obvious of these techniques involve cutting the meteorite into the required shape and, thus, are destructive to some extent. Also, an unknown amount of stressing and cracking may occur during the preparation of the sample, resulting in new pore spaces not originally in the sample. Thus, this method can potentially result in an overestimation of the original porosity.

A variant of this method is to pack the sample into clay, which is then molded in an easily measured shape; the clay is then removed, repacked, and remeasured. The difference between the volumes is then, presumably, the volume of the sample. Contamination by the clay (some authors first wrap the sample in plastic) and inconsistencies in the packing and measuring of the clay volumes are obvious difficulties with this method.

The more common method of volume determination is a variation of the classical Archimedean method. The sample is inserted into a fluid of known volume, and the resulting volume of the fluid plus sample is then measured. Fluids that have been used include water and various organic liquids including toluene and carbon tetrachloride. All of these compounds, unfortunately, have the potential of altering or contaminating the sample. In addition, because of surface tension forces and air trapped in the pore space on one hand and penetration of the fluids into cracks and pores on the other, one can never be certain just how thoroughly these fluids have or have not penetrated into the meteorite. The resulting volume, thus, lies somewhere between the true bulk volume (rock plus pore space) and grain volume (volume of the rock alone) and can lead to an underestimation of the porosity.

To avoid these problems, powders such as microscopic glass beads, which can follow the shape of the sample without entering into smaller pores or chemically reacting with the material (Consolmagno and Britt 1998), are used for bulk density measurements. This technique can be quite accurate once the experimenter has gained proficiency in the techniques of settling and smoothing the powder in a repeatable manner (Wilkison and Robinson 1999).

The sample's grain density is measured using an inert gas such as helium, which easily penetrates cracks without chemical reaction. To avoid contamination, the residues of the bulk volume determination, either fluids or glass beads, must be completely removed from the sample. Also, the helium must be of laboratory grade to avoid the introduction of other noble gases. As a check, some of the samples that had been measured for porosity with the helium technique were measured for trapped noble gases by Tim Swindle of the University of Arizona. No evidence of terrestrial contamination was found.

A third method, to date used primarily for determining asteroid volumes, is to image the sample and then, through computer processing, calculate a shape model for the object. The shape model provides the bulk volume, and with sample mass, sample bulk density can be calculated easily. Tests to date by the authors in collaboration with Glenn MacPherson, using a sophisticated imaging system at the Smithsonian Institute, have shown that this technique, while promising, is not yet practical for small laboratory specimens.

A variation of this method that has been successfully used, however, is to actually image the cracks and pore spaces in SEM microscopy, calculating the porosity from a measure (usually automated via software such as NIH Image) of the relative areas of crack space to mineral grains. Obviously, this technique is limited to measuring the porosity on a scale visible to the SEM; pore spaces larger, or smaller, than a few microns will be missed. This technique also assumes both that porosity is not introduced into the sample during the process of making the thin section and that the porosity is essentially homogeneous throughout the sample. Both of these issues have been addressed in the literature (cf., Strait et al. 2001).

Finally, in industry, porosity is often estimated from the measurement of the sound speed within a sample. In terrestrial samples, one generally finds that increased porosity results in a decreased speed of sound; by calibrating the variation in sound speed against samples of known porosity, one can convert these sound speed measures into a porosity estimate. The calibration varies with rock type, but by assuming that a meteorite can be compared to an appropriate terrestrial analogue (basalts for achondrites or sandstones for chondrites, for example), a reasonably accurate estimation can be made. This method, however, demands that the sample is cut into a slab so that the two sawn surfaces can be mated against the sonic probe (Corrigan et al. 1997).

Sources

Roughly a dozen different papers and authors have addressed the subject of meteorite porosity over the past 50 years, using a variety of techniques. These data are collected in our list, and the following section provides brief descriptions of the techniques used.

Throughout the 19th century, density was regularly measured for newly fallen meteorites, usually using the technique of immersion into water. Unfortunately, one must rely often on the value of the density to infer whether it more closely resembles a bulk or a grain density. (A quick immersion produces a bulk volume, while lengthy saturation in the fluid provides the grain volume.) In our database, we include the values given in the compilation of North American meteorites by Farrington (1915), marked as "NA."

Modern porosity measurements began in the late 1950s. Work by Alexayeve (1958; hereafter "A") was cited in Keil (1962) and lists porosity data from 6 meteorites. Keil (1962; hereafter "K") himself measured the densities and porosities of 48 samples by immersion into water and carbon tetrachloride. His samples tend to be in the range of several tens of grams in mass. Stacy et al. (1961; hereafter "SLP"), in a paper on the magnetic properties of meteorites, list 8 measurements of meteorite porosities without explicitly describing how they were measured. The samples, however, were cylinders (of unknown size) drilled out of the meteorite. In the early 1960s, Brian Mason ("M") measured several dozen meteorite densities by immersion into carbon tetrachloride; most of these values were never published, but they have been graciously provided by Dr. Mason to the present authors. Unfortunately, again, the masses of the samples are unknown.

In the 1980s, porosity and density data for 40 meteorites at the National Institute for Polar Research in Japan were published by Matsui et al. (1980), Miyamoto et al. (1982), Yomogida and Takafumi (1983), and Yomogida and Matsui (1981). (These data are indicated below as "J.") These papers followed a number of different techniques. In some cases, to find a bulk density, the samples were cut into a regular shape then measured; the grain density was measured with a helium pycnometer; other samples were measured by packing in clay as described above. Yet other samples were immersed first in toluene and then in water: the toluene saturated the pores (providing a grain density) and then, being immiscible in water, was left in the pore spaces while the sample was immersed in water to provide a bulk density measure. Generally, these papers did not list the masses of the samples measured; the few given tend to indicate hand samples of a few tens of grams.

A group at the Geological Survey of Finland (Kukkonen and Pesonen 1983; Terho et al. 1993; and Pesonen et al. 1993) measured 489 samples of 368 meteorites, primarily bulk densities, by immersion into water. Though published and discussed in the papers referenced above, the data for these samples used here (indicated as "GSF") come from a complete compilation graciously provided to the authors by Mauri Terho. The masses of these samples are given and can range from less than a gram to several hundred grams.

Corrigan et al. (1997) and unpublished work by Zolensky and Consolmagno at the Johnson Space Center, Houston ("JSC") measured the porosity and permeability of chondritic meteorites and interplanetary dust particles; the Corrigan paper gave data for 31 samples, mostly using the SEM imaging technique with a cross-comparison from a commercial laboratory sound speed estimation. The unpublished Zolensky and Consolmagno work, using the sound speed method, included cross-comparisons with meteorites whose porosity had been measured at the Vatican (see below).

Consolmagno and Britt (1998, 2000; see also Soto et al. 1997) measured bulk densities and porosities at the Vatican Observatory ("VO") with an unusually large helium pycnometer and using the glass bead method for the first time. Since these original publications, many additional meteorites from the Vatican collection have had their bulk density measured via the glass bead method; including these previously unpublished data, nearly 100 meteorites, including 30 porosities are included in this compilation. The pycnometer, constructed by Geddis (Geddis 1994) and loaned to the authors by the University of Arizona's Department of Hydrology, allowed the first pycnometer measurements of samples of several kg in mass. (Commercial pycnometers are much smaller and generally can only handle sample volumes of a few tens of cubic centimeters.) Most of the samples they measured for porosity were at least 100 g in mass, ranging up to several kg.

The helium and glass bead methods were subsequently used by Flynn and collaborators ("F") with the results published in Flynn and Klock (1998), Moore and Flynn (1999), and Flynn et al. (1999); their pycnometer could only handle smaller samples (tens of grams). And finally, an extensive set of ordinary chondrite bulk density measurements using the glass bead method have also been reported by Wilkison and Robinson (2000; hereafter "WR"). At this writing, Wilkison is continuing the measurements of densities and porosities of meteorites from the Field Museum collection, and publication of these data are anticipated in the not-too-distant future.

AVERAGE DENSITIES AND POROSITIES OF THE STONY METEORITE CLASSES

The grain densities, bulk densities, and measured porosity, as averages of all individually reported measurements for stony meteorites are shown in Tables 1–5. The reported error represents the 1σ spread among those averages. No independent attempt was made by the authors to estimate the actual measurement errors (which are often unknown) of the widely varying methods reported in this compilation. Included in these data are the authors' estimates for model porosity, which assume a theoretical grain density based on the composition of the meteorite or meteorite type. The difference between this value and the actual measured porosity may indicate the degree to which terrestrial weathering has altered the original porosity. The average porosity is calculated from the difference between the average grain and average bulk densities. This value, when compared to measured porosity and model porosity, indicates heterogeneity in porosity or composition (or in the accuracy of the measurements) from sample to sample. Large differences between average, measured, and model porosities indicate either high degrees of heterogeneity or the need to improve the accuracy of some measurements. The group average grain density and model porosity are summarized in Fig. 1. This emphasizes that most stony meteorites cluster between 3 and 3.7 g/cm^3, with a wide range in model porosity. These grain densities are standard for common rock forming minerals. The deviations from this range come from meteorites with large iron components, such as mesosiderites, and those with significant components of low-density phyllosilicates.

Data for achondrite meteorites are shown in Table 1. Little work has been done on measuring the density or porosity of *basaltic achondrites*; most of what has appeared in the literature is from the Geological Survey of Finland work. A special problem exists for grain density and porosity measurements: certain basaltic minerals are known to be

Table 1. Achondrites.

	Average	Minimum	Maximum
Diogenites			
(Based on 8 pieces of 3 meteorites, 60.27 g total reported mass.)			
Grain density	3.39 ± 0.12	3.30	3.47
Bulk density	3.26 ± 0.17	3.11	3.44
Measured porosity	2.5% ± 2.2%	1.0%	4.1%
Model porosity	6.4% ± 4.8%	1.1%	10.6%
Average porosity	2.5%	–	–
Eucrites			
(Based on 18 pieces of 9 meteorites, 585.77 g total reported mass.)			
Grain density	3.12 ± 0.09	2.99	3.18
Bulk density	2.86 ± 0.07	2.74	2.95
Measured porosity	7.8% ± 6.8%	0%	14.8%
Model porosity	10.5% ± 2.0%	7.4%	14.1%
Average porosity	8.6% ± 4.6%	1.2%	13.6%
Howardites			
(Based on 8 pieces of 5 meteorites, 18.40 g total reported mass.)			
Grain density	3.25 ± 0.08	3.17	3.33
Bulk density	3.02 ± 0.19	2.80	3.16
Measured porosity	(none available)		
Model porosity	9.9% ± 5.7%	5.8%	16.4%
Average porosity	4.7% ± 0.5%	4.4%	5.1%
Shergottites			
(Based on 4 pieces of 2 meteorites, 4.43 g total reported mass.)			
Grain density	3.43	–	–
Bulk density	3.10 ± 0.04	3.07	3.12
Measured porosity	(none available)		
Model porosity	5.9% ± 0.3%	5.6%	6.1%
Average porosity	7.7% ± 4.0%	4.9%	10.6%
Chassigny			
(Based on 1 piece of 1 meteorite.)			
Bulk density	3.32	–	–
Model porosity	7.5%	–	–
Nahkla			
(Based on 3 pieces of 1 meteorite, 177.2 g total reported mass.)			
Grain density	3.29	–	–
Bulk density	3.15 ± 0.07	3.10	3.20
Measured porosity	5.7%	–	–
Model porosity	5.6%	–	–
Average porosity	4.2%	–	–
Ureilites			
(Based on 7 pieces of 3 meteorites, 35.46 g toal reported mass.)			
Grain density	3.35	–	–
Bulk density	3.05 ± 0.22	2.81	3.21
Measured porosity	6.0%	–	–
Model porosity	12.1% ± 6.7%	8.2%	19.8%
Average porosity	8.9%	–	–

Table 2. Carbonaceous meteorites.

	Average	Minimum	Maximum
CI			
(Based on 14 pieces of 4 meteorites, 63.5 g total reported mass.)			
Grain density	2.26 ± 0.08	2.20	2.38
Bulk density	2.11	–	–
Measured porosity	8.7% ± 9.1%	2.0%	19.0%
Average porosity	11.3%	–	–
CM			
(Based on 33 pieces of 18 meteorites, 3.16 kg total reported mass.)			
Grain density	2.71 ± 0.11	2.57	2.87
Bulk density	2.12 ± 0.26	1.79	2.40
Measured porosity	9.3% ± 6.9%	3.0%	20.0%
Average porosity	23.0% ± 7.5%	12.9%	30.3%
CR			
(Based on 7 pieces of 3 meteorites, 104.2 g total reported mass.)			
Grain density	3.23 ± 0.28	2.92	3.47
Bulk density	3.10	–	–
Measured porosity	6.4% ± 3.8%	3.5%	10.8%
CO			
(Based on 22 pieces of 8 meteorites, 402.98 g total reported mass.)			
Grain density	3.48 ± 0.27	3.00	3.78
Bulk density	2.95 ± 0.11	2.79	3.09
Measured porosity	8.5% ± 4.6%	4.0%	13.2%
Average porosity	19.8% ± 4.1%	15.2%	23.5%
CV			
(Based on 51 pieces of 10 meteorites, 2.08 kg total reported mass.)			
Grain density	3.48 ± 0.09	3.26	3.58
Bulk density	2.95 ± 0.26	2.69	3.25
Measured porosity	9.7% ± 9.2%	0.0%	24.1%
Average porosity	13.8% ± 9.1%	0.3%	20.9%
CH			
(Based on 1 piece of 1 meteorite.)			
Grain density	3.44	–	–
CK			
(Based on 4 pieces of 2 meteorites, 10.2 g total reported mass.)			
Grain density	3.47 ± 0.02	3.46	3.49

Table 3. Enstatite meteorites.

	Average	Minimum	Maximum
Aubrites			
(Based on 10 pieces of 6 meteorites, 455 g total reported mass.)			
Grain density	3.12	–	–
Bulk density	3.12 ± 0.15	2.97	3.33
Measured porosity	9.7% ± 7.6%	4.3%	15.1%
Model porosity	6.2% ± 4.4%	0.1%	11.0%
Average porosity	0.0%	–	–
EH			
(Based on 8 pieces of 5 meteorites, 125 g total reported mass.)			
Grain density	3.67 ± 0.07	3.56	3.75
Bulk density	3.72 ± 0.02	3.71	3.73
Model porosity	10.5% ± 2.6%	7.6%	13.0%
Average porosity	−1.2% ± 2.5%	–4.1%	−0.5%
EL			
(Based on 15 pieces of 7 meteorites, 229 g total reported mass.)			
Grain density	3.58 ± 0.05	3.51	3.66
Bulk density	3.55 ± 0.1	3.48	3.62
Model porosity	9.3% ± 3.9%	5.1%	14.3%
Average porosity	2.7%	–	–

Table 4. Ordinary chondrites.

	Average	Minimum	Maximum
H chondrites			
(Based on 265 pieces of 157 meteorites, 14.17 kg total reported mass.)			
Grain density	3.64 ± 0.12	3.23	3.84
Bulk density	3.40 ± 0.18	2.80	3.80
Measured porosity	6.0% ± 4.5%	–1.0%	18.1%
Model porosity	10.6% ± 4.8%	–0.1%	27.2%
Average porosity	6.4% ± 4.2%	–1.0%	16.7%
L chondrites			
(Based on 277 pieces of 160 meteorites, 20.24 kg total reported mass.)			
Grain density	3.51 ± 0.11	3.26	3.75
Bulk density	3.35 ± 0.16	2.50	3.96
Measured porosity	5.8% ± 4.7%	0.0%	19.5%
Model porosity	6.9% ± 4.6%	–9.9%	30.7%
Average porosity	4.5% ± 4.6%	–0.8%	19.5%
LL chondrites			
(Based on 149 pieces of 39 meteorites, 7.22 kg total reported mass.)			
Grain density	3.48 ± 0.08	3.38	3.69
Bulk density	3.21 ± 0.22	2.38	3.49
Measured porosity	9.3% ± 8.5%	1.0%	32.6%
Model porosity	10.0% ± 6.3%	2.1%	33.1%
Average porosity	7.9% ± 4.2%	1.6%	14.8%

Table 5. Stony-iron meteorites.

	Average	Minimum	Maximum
Pallasites			
(Based on 10 pieces of 5 meteorites, 1.54 kg total reported mass.)			
Grain density	4.49 ± 0.53	3.78	5.07
Bulk density	4.76 ± 0.10	4.64	4.89
Measured density	2.4% ± 5.3%	–3.7%	5.9%
Average porosity	0.0% ± 5.2%	–3.7%	5.9%
Mesosiderites			
(Based on 8 pieces of 3 meteorites, 5.54 kg total reported mass.)			
Grain density	4.40 ± 0.36	4.15	4.82
Bulk density	4.25 ± 0.02	4.23	4.27
Measured density	5.0% ± 6.9%	–0.2%	12.8%
Average porosity	3.0% ± 8.1%	–2.6%	12.2%
Steinbach			
(Based on 2 pieces of 84.7 g reported mass.)			
Grain density	4.56 ± 0.01	–	–
Bulk density	4.18 ± 0.10	–	–
Average porosity	8.2%	–	–

relatively impervious to gases, even helium, especially compared to highly fractured material such as ordinary chondrites. Some indication exists that, as a result, grain densities of intact basalts measured by pycnometry may lead to serious underestimates of the porosity (Lippolt and Weigel 1988; Trull et al. 1991; Graham et al. 1987). For example, we note that a sample of Juvinas measured by He pycnometry at the Vatican yields a grain density essentially equal to its bulk density, implying zero porosity, even though numerous voids are visible on the surface of this sample. The density, 2.95 g/cm^3, is, in fact, identical to that measured for Stannern, which Stacey et al. (1959) determined to have a porosity of 15%. The calculated grain density of a rock with Juvinas' composition is 3.19 g/cm^3 (Kitts and Lodders 1998), which, along with its measured bulk density, would suggest a porosity of 7.5%.

For meteorites such as these, the mineralogy of which is well understood, we can calculate what the grain density ought to be based on mineral grain densities. Using the values of Kitts and Lodders (1998) for specific meteorites, where available, or our own similar calculations and reasonable averages based on the calculated densities of similar meteorites, we are able to compare these model grain densities with the measured bulk densities to arrive at a model porosity, as given above and in Table 1 (Consolmagno et al. 1998).

Diogenites: The grain density calculated from the modal mineralogy for Tatahouine and Y-74013 is 3.48, which matches the measured grain density of Y-74013 but is significantly higher than Tatahouine's measured grain density of 3.3. Since diogenites do not have a significant metal content, seeing how this difference can be attributed to weathering is difficult. In addition, diogenites are essentially monomineralic, so attributing density variation to heterogeneity in the samples is difficult. Instead, we might conclude that the helium pycnometer used to measure the grain density failed to reach voids within Tatahouine's pyroxene given the problems noted above of helium penetrating through unfractured minerals. This discrepancy leads to the high model porosity.

Eurcites: Model grain densities have been calculated for a number of eucrites by Kitt and Lodders (1998), and they fall in a narrow range between 3.18 and 3.22; this agrees with the grain densities measured for Camel Donga and Millbillillie but, as noted above, is much larger than that seen for Juvinas. All 3 meteorites are listed as "brecciated," but in fact, the piece of Juvinas measured shows no signs of brecciation. Possibly, the scale of "breccia" is larger than the scale of thin sections. Eucrites have been known to show a significant number of vesicles, and voids are visible in the sample of Juvinas. As with the diogenite data, the discrepancy between model and measured grain densities and porosities is likely due to the difficulties of helium penetration in unfractured rock during the measurement process.

Howardites: This class of meteorite is a breccia composed of material from both eucrites and diogenites. No measurements of howardite porosities have been found. Three howardites have had grain densities reported, and 3 have had bulk density measurements. Only for Kapoeta are both reported, but they are not of the same sample. In this case, the bulk density was measured in Finland, the grain density in Washington. The best we can do is compare the averages of these densities, which is at best a questionable procedure. Since howardites are brecciated mixtures of diogenites and eucrites, not only does a noticeable variation in composition among different howardites exist, but heterogeneity could also exist, even within the same meteorite. Variation within a meteorite is an especially serious problem given the small sizes of the

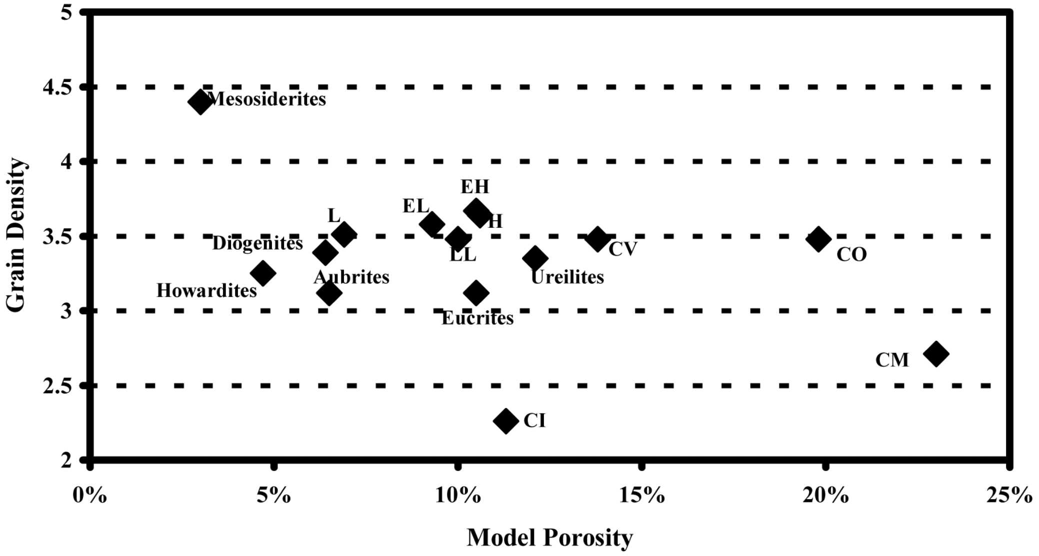

Fig. 1. Grain density versus model porosity for the major meteorite groups. This plot emphases how anomalous the CI and CM carbonaceous chondrites are relative to the vast majority of stony meteorites. Most stony meteorites are clustered between 3.0 and 3.7 g/cm^3, while CI and CM meteorites are much less dense. The mesosiderites are also outliers because of their high iron content.

samples measured in most of the reported data. In this case, the largest measured mass reported is only 10 g. Thus, the most reliable estimate for the porosity is probably found using the model grain densities of Kitt and Lodders (1998). The sparse data available suggest that howardites may be more porous, as a class, than either eucrites or diogenites. Additional data can put constraints on the lithification process of these breccias and characterize the physical differences between this class and the other 2 igneous classes in basaltic achondrites. This would be especially interesting compared to ordinary chondrites where the brecciation and relithification process appears to reduce porosity relative to the averages for that meteorite group (Consolmagno et al. 1998).

SNC Meteorites: Again, the data are sparse; only for Nahkla does a direct measurement of porosity exist, and the total mass of shergotities measured is extremely small. Surprisingly, however, all 4 SNCs measured show essentially the same porosity, about 6%. One suspects that this porosity may be due to cracks induced in the event that lifted these rocks from the surface of their parent body (presumably Mars). This could be confirmed quickly by an examination of SNC thin sections. If true, this puts an interesting limit on the origin of the cracking (and resultant microporosity) of ordinary chondrites, as will be discussed below.

Ureilites: All 3 meteorites show evidence of significant porosity. ALH A77257 is the only one to have a grain density and porosity directly measured. Compared to the other measured ureilites, this meteorite is more olivine-rich, but the literature chemical analysis (Jarosewich 1984) reports no metallic iron (other ureilites have 2%–3% metal and sulfide). From this analysis, we have calculated a mode and a model grain density of 3.43, which is higher than the reported grain density of 3.35. This difference, the extra FeO, and the lack of Fe metal could all be attributed to terrestrial weathering. While this meteorite has been given a weathering grade of “Ae” (minor rust but evaporite materials visible to the naked eye), the small amount of weathering required to oxidize metallic iron and fill pore space could be consistent with this grade. Novo-Urei and Haverö both have compositions yielding a model grain density of 3.5; the low measured bulk density of Haverö suggests that it must be nearly 20% porous.

Carbonaceous Chondrites: Figure 2 summarizes the grain density and measured porosity for the carbonaceous chondrite subgroups. Note that most *carbonaceous chondrites* cluster around 3.5 g/cm^3, which is common to other stony meteorites and to be expected from their mineralogy dominated by common rock-forming silicates. The higher proportions of low density hydrated phyllosilicates in CI and CM groups push their grain densities down substantially. However, both subgroups show approximately the same range of porosity as the higher density subgroups.

CI: The descriptions of CI meteorites contemporaneous with their recovery are often in marked contrast with the appearance of the meteorites today (Zolensky and Giunelle 2001). This point is emphasized by our experience with Tagish Lake, which (Grady, personal communication) emitted a sulfurous vapor when first thawed out to room temperature. Since even warming up the rocks to room temperature, not to mention exposure to terrestrial water and air, can apparently cause strong but, at times, poorly-

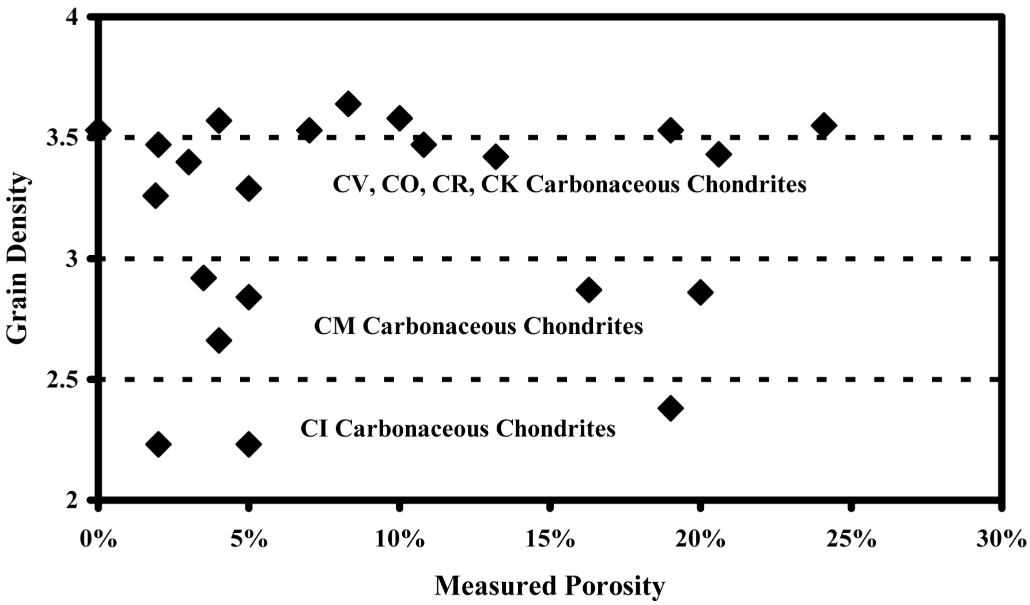

Fig. 2. Carbonaceous chondrite porosities and grain densities. Note that the vast majority of carbonaceous chondrites have grain densities clustering around 3.5 g/cm^3, similar to other stony meteorites such as ordinary chondrites. The exceptions are the CMs and CIs, which are rich in low-density hydrated silicates.

characterized changes in the rock (see Zolensky and Giunelle 2001), the physical state of the samples, when measured accurately, do not clearly reflect the state of these rocks while they were still in orbit. Most of the measurements reported, 9 of the 14, are on Orgueil, and considerable variability exists in the porosity and bulk density reported, even of this single meteorite. The helium pycnometer/glass bead method on the Vatican sample of Orgeuil reported a bulk density of 1.5 and a porosity of 35%, while the Finnish group reports a bulk density of 2.25, and Corrigan et al. (1997) found only 3% porosity in their point-counting of Orgueil thin section voids. Explanations for this variation include the fact that different samples may have experienced different terrestrial alterations and that the voids may be at a scale too large or too small to be seen in thin section. Likewise, no attempt is made to model grain densities, since the density of the material is clearly controlled by the volatile (water and sulfate) content, which probably alters rapidly in the terrestrial environment.

CM: The low bulk densities of CM meteorites are related to their volatile content, which is primarily OH bound in clays. The average grain density of CM meteorites is on par with the grain densities of common clays. As with the CI meteorites, how much this has been altered by terrestrial temperatures and conditions is not clear. Of the 11 meteorite porosity measurements reported, 7 are in the 4–6% range, 2 are 16%, and 2 are greater than 20%. Most of the mass measured is in the meteorites Murchison, Murray, and Nogoya; both measures for Murchison are high, both of those for Nogoya are low, and for Murray, Corrigan et al. (1997) report 4% porosity for their sample, while Moore and Flynn (1999) report 28.6% porosity. The difference, almost certainly, is due to the measurement technique; all the low porosity measurements are found using the point-counting technique of Corrigan et al. (1997). These authors do report other CM porosities in the 15–30% range, but one suspects that their low porosity values indicate that the thin sections they measured were not representative of the samples as a whole. This, in turn, suggests that the porosity in these meteorites is often in voids too large to be recognized, in a thin section, as integral to the meteorite itself. It also suggests that our large "average" porosity values in Table 2 are probably more representative of bulk CM meteorites.

CR: All but 1 of the measured porosities were done by the point-counting method of Corrigan et al. (1997), the results of which were all less than 5% porosity. Terho (1993), using more traditional techniques, found 10% porosity for Y-793495. Possibly, the same difficulties arise with the point-counting technique as are seen in the CM meteorites, but clearly, the data are too sparse to draw any strong conclusion. The relatively high bulk densities of these meteorites reflect a balance between their high metal and sulfide contents (which can be 20% or more) and the large OH and other volatile content (5% for Y-793495; over 10% for Al Rais).

CO: Again, the thin section point counting method of Corrigan et al. (1997) yields porosities of 5% or less, while the porosities measured on bulk samples average 10%, and the averaging of different bulk and grain density measurements can yield porosities of 20%. A systematic discrepancy appears to exist in grain densities; those measured by Mason (from immersion in carbon tetrachloride) are all in the range of 3.6–3.8, while many of the helium pycnometer measurements reported by Flynn and Klock (1999) are from 3.0 to 3.4. (These authors do report a 3.57 density for Isna, however.) The discrepancy is most marked in Kasinsaz, where Mason reports a density of 3.76 but Flynn and Klock (1999) report 3.15, while later work by Flynn and coworkers gives a value for 2 other pieces of Kasinsaz at 3.4. The Flynn work was constrained by their instrument to measure only small samples under 10 g. The size of the sample that Mason measured is unknown. Given this wide discrepancy, making any general statements about CO porosities is difficult based on these data.

CV: These meteorites appear to fall into "high porosity" and "low porosity" groups independent of the measuring technique. Allende, Axtell, and Mokoia are all found to be high (19% to 24%) in porosity in thin section point counts, by helium pycnometry, and by immersion techniques. Bali, Efremovka, Leoville, and Vigarano have porosities ranging from 0 to 10%. The Vigarano measurement is quite secure (point counting actually finding more porosity than pycnometry), while the measurements of the others rest on only one technique. Kaba presents a cautionary example; point counting suggests a porosity of only 3%, while the comparison of the bulk density of one sample with the grain density of different sample would imply a porosity of 20%. With the exception of Bali (measured only by point counting, at 10% porosity), the trend appears to be that the high porosity meteorites belong to the "oxidized" subgroup of CVs, while the low porosity examples are all "reduced." More and better data are needed to test this trend.

CH, CK: Clearly, more data are needed before any trends can be discussed.

Aubrites: Few of these meteorites have been measured for density, much less porosity. Their composition is essentially pure enstatite, so one can assume a "model" grain density of 3.3, equal to the density of enstatite, and from that deduce model porosities from the few bulk densities available. Doing so, we find a range from 0 to 11%. However, we note that the only grain density actually measured (by Flynn and Klock [1998] using a helium pycnometer) gives a density substantially lower than this grain density. Possibly, significant voids exist within this meteorite that are not readily accessible to the surface via cracks; however, as the sample volume was roughly 1 cubic cm, the majority of the volume lies within a quarter of a cm of the surface, and one might expect that helium would be quite capable of penetrating such distances, even through rock, in a relatively short time. The only measurements of aubrite porosities are more than 40 years old, (Alexayeve 1958; Stacey et al. 1961) and vary widely. Clearly, more work needs to be done.

EH and EL: The majority of the grain densities given for these samples were also measured by Flynn and Klock (1998) and they are all substantially lower than what one would calculate from the mineralogy of the meteorites in question. The enstatite chondrites in this data set have metal abundances ranging from 14% to 36% and sulfide abundances of 6% to 15%. Combined with enstatite, one would expect densities of 3.75 (for Khairpur) up to 4.27 (for Daniel's Kuil), which would be substantially greater than any reported. The fact that these reported grain densities are unrealistically low is also indicated by the "negative" porosities that result when comparing these data to measured bulk densities. Most of these measurements were done with immersion techniques using penetrating fluids. These methods typically underestimate the grain density and provide numbers closer to bulk density. If that is the case, then the reported grain densities might actually be proxies for bulk density, and the "model" porosities for these meteorites (marked with an asterisk in the main table) would range from 5% to 14%.

Ordinary Chondrites: A previous analysis of ordinary chondrite bulk densities appeared in Consolmagno et al. (1998), and the conclusions of that work still hold with the expanded data set given here. In particular, they noted that weathering controls the grain density and porosity of the ordinary chondrites in our collections today.

Bland et al. (1996) describe the weathering of ordinary chondrites as occurring in 2 stages: the first stage is a rapid oxidation of metal within the rock but without destruction of the overall rock fabric; the second, much slower stage leads to the eventual disintegration of the sample. Rocks that have undergone the second stage of weathering generally will not even be recognizable as meteorites; we can safely assume that virtually all ordinary chondrites in our collections are somewhere in the first stage of weathering.

The altering of metallic iron to iron oxides in an ordinary chondrite fills in the pore spaces. Typically, this converts metallic iron (density 7.3–7.9) to goethite FeOH (density 4.37) by a reaction with water, which increases the volume of the original iron by between 67–80%. This stage ends when all the pore spaces are filled with the oxide weathering products, which cuts the easy access of terrestrial moisture into the interior of the rock. One result of this process is that virtually all ordinary chondrite finds have zero porosity. The speed of this process also means that all but the freshest of falls have been altered to some degree, and almost all falls show reductions in their porosities that correlate with the length of terrestrial residence (Consolmagno et al. 1998).

The grain density of a sample changes as its pore space is filled with weathering products. But, the addition of terrestrial oxygen has only a minor effect on the rock's mass, and so long as the rock's gross structure is not compromised, its bulk volume will change very little during this first weathering stage. Thus, one can assume, to first order, that the bulk density stays constant during the first stage of weathering. If one can estimate the initial grain density, modeling the pristine unweathered density of the meteorite should then be possible.

As was done above with the enstatite and basaltic achondrites, one can use the average mineralogy of the ordinary chondrite classes to estimate this original grain density. In Consolmagno et al. (1998), the largest observed grain density was assumed to represent the freshest meteorite, and accordingly, they assumed a pristine grain density of 3.84 for H chondrites, 3.75 for L chondrites, and 3.54 for LL chondrites.

Another method, however, is to use the average normative mineralogy of each meteorite and the literature density value for each major mineral to calculate this typical grain density. (Or, one could use published oxide abundances for each meteorite to estimate its modal mineralogy before preceding as above.) Using the average modal compositions of McSween et al. (1991), we calculate that the grain density of an H chondrite should be 3.8, while that of an L is 3.6 and of an LL chondrite is 3.55. We also calculated grain densities for a number of individual meteorites, and with few exceptions, the spread within a class is less than 0.02 g/cm^3.

The LL value is essentially identical to that used by Consolmagno et al. (1998), so we have not changed those values here. The H value is only slightly lower, but nonetheless, we have recalculated our model porosities for the H meteorites. In fact, only 2 measured H chondrite grain densities are greater than 3.8, and both are for Antarctic meteorites for which only one measurement has been reported.

The modal grain density value for the L chondrites is significantly lower than the value used by Consolmagno et al. (1998), however. Looking to the actual meteorite data, we find that the measured grain densities of all but 6 of the 75 L chondrite meteorites for which grain densities are available are less than 3.6 (within measurement error), and only 4 of the 143 model porosities calculated with this value are significantly less than zero. The L chondrite Homestead has the grain density of 3.75 used by Consolmagno et al. (1998); it is in fact more iron-rich than a typical L, though its modal mineralogy suggests its grain density is probably closer to 3.65. Of the other 5 meteorites, the high densities are, in all but 1 case, based on only 1 measurement, and one might presume an error of 0.1 in any of these. For Kunashak, the density error between different measurements is, in fact, 0.14; one of the 3 reported grain density measurements is greater than 3.7, but the other 2 are less than 3.6.

Likewise, looking at the 4 meteorites for which the reported bulk densities are significantly greater than 3.6 (yielding negative values for the calculated model porosity), we find that these bulk densities are either highly uncertain (greater than 0.2 in 2 cases) or are based on a single measurement of a small sample; only the bulk density of Apt is not so easily explained away. If nothing else, this emphasizes the importance of multiple measurements of meteorite densities.

Using our revised grain density of 3.6, we find that L chondrites appear to be less porous on average than H or LL chondrites. Where the average porosity of the latter 2 groups is 10%, that for L chondrites is now only 6%. Assuming the spread in the data is due to random differences in the cracking histories of the ordinary chondrites, the actual statistical 1σ value for each type is on the order of 0.4% (the 1σ spread in the data for each group is 4%, and each group has a sample size greater than 100), so this difference appears to be significant. The difference between measured and model porosity is illustrated in Figs. 3 and 4. The measured porosity versus grain density for all the ordinary chondrites in our

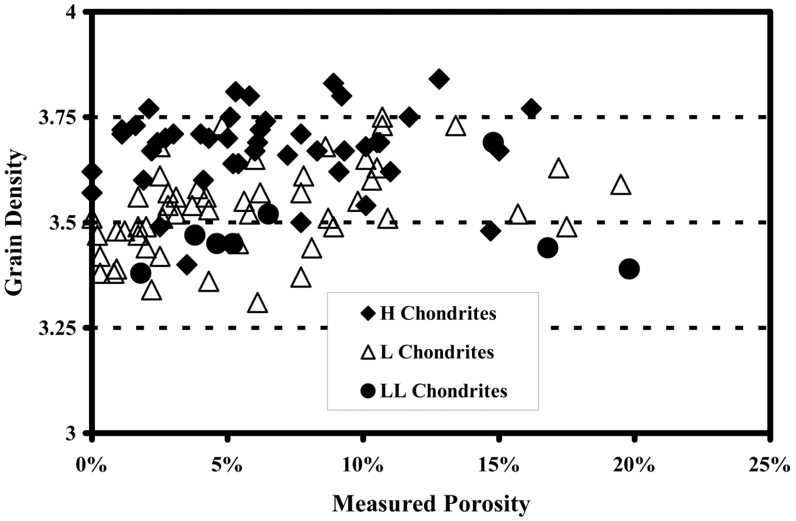

Fig. 3. The grain density and measured porosity of all ordinary chondrites in the database. Although is considerable scatter exists, the H chondrites have generally higher grain densities, while the L and LL chondrites overlap. All 3 subgroups overlap in measured porosity, and the distribution is skewed toward zero porosity.

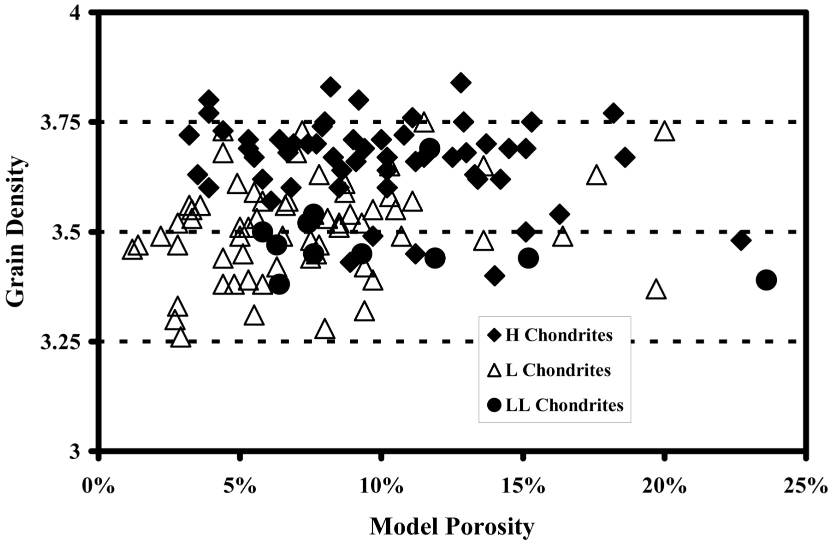

Fig. 4. The grain density and measured porosity of all ordinary chondrites in the database. Applying the model removes the low-porosity skew effect from terrestrial weathering and highlights an apparent difference between H and L chondrite porosities. L chondrites are systematically less porous than H chondrites.

database is shown in Fig. 3. Note that even with considerable scatter, H chondrite grain densities are generally higher, while L and LL grain densities overlap. Since the first stage of ordinary chondrite weathering tends to fill pore space, the porosity distribution is skewed toward zero porosity. Ordinary chondrite model porosities versus grain densities are shown in Fig. 4. The effect of adjusting porosities for terrestrial weathering removes the skew toward zero porosity and highlights the porosity differences between H and L chondrites.

Stony-Iron Meteorites: The density depends on the relative abundances of metal to silicate, which can vary across a meteorite as well as from meteorite to meteorite. The fact that so little variation exists in the literature data presented here merely testifies to how little data have been taken to date. The measured porosity is, within the error, essentially zero; the "negative" porosities reported here reflect the inherent measuring error for the small meteorite samples. The largest porosity measured is for the mesosiderite Crab Orchard, which is a heavily weathered find; the values are no doubt real but merely reflect the deterioration of the metal phase from metallic iron to less dense goethite. Brenham, a weathered pallasite, was measured to have a 5% porosity; likewise, this may be due to deterioration of the metal phase. The "porosity" of Steinbach (an anomalous meteorite that looks much like a pallasite but with pyroxene rather than olivine inclusions) may be an artifact of comparing bulk verses grain densities measured on different samples in different laboratories. In this case, heterogeneity between the samples, rather than actual porosity, could account for the difference between bulk and grain density without requiring porosity.

DISCUSSION

This paper should not be considered as the last word in meteorite densities and porosities. If anything, it is an introductory preface to work already begun to prepare a systematic synoptic collection of meteorite densities and porosities. Thus, the majority of our discussion will center on what we suggest might be interesting questions to ask given what we have seen so far.

However, even in the data seen so far, we can draw some interesting conclusions. First, porosities for most meteorite types seem to average around 10% percent with certain basaltic meteorites having closer to zero porosity, while some (but not all) carbonaceous meteorites may have porosities as high as 30%.

Second, the bulk densities of stony meteorites, regardless of group, tend to be in the range of 3 to 4 g/cm^3. The only exceptions are meteorites rich in volatiles (CI and CM classes), though even volatile-rich CR meteorites have densities around 3, and the stony-iron meteorites, with densities ranging from 4 to 6 g/cm^3. This means that density alone is not a good discriminant between different meteorite types; indeed, note that shock-blackened ordinary chondrites can match dry carbonaceous chondrites in both density and albedo. This is especially a challenge when attempting to compare asteroid densities to meteorite densities and is only compounded by the problem of the unknown degree of macroporosity in these small bodies.

We note 2 interesting divisions in the porosity data for similar meteorite groups: in the data to date, oxidized CV meteorites appear to have high porosities, on the order of 20%, while reduced CV meteorites appear to have porosities less than 10%. And the model porosities of L chondrites, at

6%, appear to be significantly different from the 10% model porosities found for H and LL chondrites. These differences may hold a clue to the formation history of the meteorites in question.

A number of questions are suggested by these data, which only further data can answer:

- Do brecciated meteorites, especially basaltic meteorites, have a systematically higher porosity than non-brecciated meteorites?
- What are the primordial porosities of carbonaceous material? How does weathering affect these porosities?
- Is it generally true that all reduced CV meteorites have low porosity?
- What is the porosity of enstatite meteorites? What does this say about the environment in which they were made?
- Are some mesosiderites actually porous? Is this porosity related to the brecciation and lithification history of these meteorites?
- Are any pallasites truly porous? Is such porosity consistent with our understanding of their formation processes?

Clearly, these and many other questions remain, and in all cases, more data is needed before further trends can be established or understood. The biggest problem to date is the lack of reliable, repeatable data. Hopefully, the surveys presently underway will help elucidate these issues.

Table 6a. Individual meteorite densities and porosities: Achondrites.

Sample name	Type	#	Grain ρ	Bulk ρ	Measured porosity	Model porosity	Average porosity	Reference
Shalka	Diog	4	–	3.11 ± 0.09	–	12.6%	–	GSF
Tatahouine	Diog	3	3.30 ± 0.04	3.22 ± 0.12	4.1% ± 4.5%	9.5% ± 0.3%	2.5%	GSF, F
Y-74013	Diog	1	–	3.44	1.0%	3.4%	–	J
ALH 76005	Euc	1	–	2.92	7.0%	9.3%	7.9%	J
Camel Donga	Euc	1	3.17	–	–	–	–	M
Jonzac	Euc	3	–	2.85 ± 0.18	–	11.0% ± 0.7%	–	GSF
Juvinas	Euc	2	2.99	2.95	–1.3%	7.4%	1.2%	GSF, VO
Millbillillie	Euc	2	3.18 ± 0.03	2.86	10.6%	10.4%	10.0%	F
Padvarninkai	Euc	4	–	2.83 ± 0.12	–	11.6% ± 0.5%	–	GSF
Pasamonte	Euc	1	–	2.85	–	11.0%	10.2%	GSF
Sioux County	Euc	1	–	2.74	–	14.1%	13.6%	GSF
Stannern	Euc	3	–	2.91 ± 0.12	14.8%	9.2% ± 0.4%	–	SLP, GSF
Bununu	How	1	3.17	–	–	–	–	M
Frankfort (stone)	How	1	3.33	–	–	–	–	M
Kapoeta	How	2	3.26	3.10	–	7.6%	5.1%	M, GSF
Le Teilleul	How	1	–	3.16	–	5.8% ± 1.5%	4.4%	VO
Luotolax	How	3	–	2.80 ± 0.05	–	16.4% ± 0.3%	–	GSF
Chassigny	SNC	1	–	3.32	–	7.5%	–	GSF
EET 79001	SNC	1	–	3.12	–	5.4% ± 0.1%	4.9%	GSF
Nakhla	SNC	3	3.29	3.15 ± 0.07	5.7%	5.6%	4.2%	VO, GSF
Zagami	SNC	3	3.43	3.07	–	6.1%	10.6%	F, GSF
ALH 77257	Urei	1	–	3.15	6.0%	8.2%	–	J
Novo-Urei	Urei	2	–	3.21 ± 0.13	–	8.4% ± 0.4%	–	GSF
Haverö	Urei	4	–	3.24 ± 0.08	–	19.8%	–	GSF[a]

[a] One discordant measure dropped.

Table 6b. Individual meteorite densities and porosities: Carbonaceous chondrites.

Sample name	Type	#	Grain ρ	Bulk ρ	Measured porosity	Model porosity	Average porosity	Reference
MAC 87300	C	1	–	–	25.0%	–	–	JSC
Coolidge	C	2	3.53	–	0.0%	–	–	M, JSC
Y-82162	C	1	–	–	2.0%	–	–	JSC
Kakangari	CH	1	3.44	–	–	–	–	M
Alais	CI	2	2.23	–	2.0%	–	–	M, J
Ivuna	CI	2	2.23	–	5.0%	–	–	M, JSC
Orgueil	CI	9	2.38 ± 0.08	2.11 ± 0.12	19.0% ± 22.7%	–	11.3%	VO, JSC, M, GSF, F
Tonk	CI	1	2.20	–	–	–	–	M
Karoonda	CK	2	3.49 ± 0.11	–	–	–	–	M, F
Maralinga	CK	2	3.46 ± 0.02	–	–	–	–	F
ALH 83100	CM	1	–	–	6.0%	–	–	JSC

Table 6b. Individual meteorite densities and porosities: Carbonaceous chondrites. *Continued.*

Sample name	Type	#	Grain ρ	Bulk ρ	Measured porosity	Model porosity	Average porosity	Reference
B-7904	CM	1	–	–	16.0%	–	–	JSC
Bells	CM	2	2.84	–	5.0%	–	–	M, JSC
Boriskino	CM	1	2.74	–	–	–	–	M
Cold Bokkeveld	CM	2	2.65	2.31	–	–	12.9%	M, GSF
Crescent	CM	1	2.82	–	–	–	–	M
EET 83226	CM	1	–	–	4.0%	–	–	JSC
EET 83334	CM	1	–	–	3.0%	–	–	JSC
Erakot	CM	1	2.66	–	–	–	–	M
Haripura	CM	1	2.72	–	–	–	–	M
Kivesvaara	CM	1	0.00	2.40	–	–	–	GSF
Mighei	CM	3	2.70	1.94 ± 0.03	–	–	28.2%	M, GSF
Murchison	CM	4	2.86 ± 0.03	2.37 ± 0.02	20.0% ± 4.3%	–	17.1%	JSC, M, F
Murray	CM	4	2.87 ± 0.06	–	16.3% ± 17.4%	–	–	M, F, JSC
Nawapali	CM	1	2.57	–	–	–	–	M
Nogoya	CM	5	2.66	1.96 ± 0.05	4.0% ± 0.0%	–	26.3%	M, JSC, VO, GSF
Pollen	CM	1	2.57	–	–	–	–	M
Santa Cruz	CM	2	2.57	1.79	–	–	30.3%	M, GSF
Colony	CO	1	3.00 ± 0.01	–	–	–	–	F
Dar Al Gani 005	CO	1	3.17 ± 0.03	–	–	–	–	F
Felix	CO	2	3.78	2.92	–	–	22.9%	M, GSF
Isna	CO	3	3.57 ± 0.03	–	4.0%	–	–	JSC, F
Kainsaz	CO	4	3.42 ± 0.15	2.96	13.2%	–	–	M, F
Lancé	CO	4	3.64	3.09 ± 0.13	8.3%	–	15.2%	M, JSC, VO GSF
Ornans	CO	5	3.61	2.98 ± 0.32	–	–	17.4%	VO, JSC, M, GSF
Warrenton	CO	2	3.64	2.79	–	–	23.5%	M, GSF
Al Rais	CR	3	2.92	–	3.5% ± 2.1%	–	–	M, JSC
Renazzo	CR	3	3.29	–	5.0% ± 4.2%	–	–	M, JSC
Y-793495	CR	1	3.47	3.10	10.8%	–	–	GSF
Allende	CV	23	3.53 ± 0.14	2.88 ± 0.05	19.0% ± 3.3%	–	18.5%	VO, JSC, M, GSF, F, J
Axtell	CV	3	3.43 ± 0.01	2.72 ± 0.03	20.6% ± 1.8%	–	20.7%	F
Bali	CV	2	3.58	–	10.0%	–	–	M, JSC
Efremovka	CV	2	3.53	–	7.0%	–	–	JSC, M
Grosnaja	CV	2	3.49	3.20	–	–	8.5%	M, GSF
Kaba	CV	3	3.40	2.69	3.0%	–	20.9%	JSC, M, GSF
Leoville	CV	4	3.47	–	2.0%	–	–	JSC, M, J, F
Mokoia	CV	3	3.55	–	24.1%	–	–	JSC, M, SLP
Vigarano	CV	7	3.26 ± 0.22	3.25 ± 0.06	1.9% ± 2.4%	–	0.3%	VO, JSC, M, GSF

Table 6c. Individual meteorite densities and porosities: Enstatite.

Sample name	Type	#	Grain ρ	Bulk ρ	Measured porosity	Model porosity	Average porosity	Reference	Model grain ρ
Bishopville	Aub	2	–	3.22 ± 0.16	–	3.4% ± 0.2%	–	GSF	–
Cumberland Falls	Aub	3	–	3.10 ± 0.00	4.3%	7.1% ± 0.0%	–	SLP, GSF	–
Norton County	Aub	2	–	2.97 ± 0.12	–	11.0% ± 0.4%	–	GSF	–
Peña Bl. Spring	Aub	1	3.12 ± 0.01	–	–	6.2%[a]	–	F	–
Pesyanoe	Aub	1	–	3.02	15.1%	9.3%	–	A	–
Shallowater	Aub	1	–	3.33	–	0.1%	–	GSF	–
Abee	EH	3	3.56	3.71 ± 0.01	–	8.1%	–4.1%	GSF, VO, M	4.03
Adhi Kot	EH	1	3.75	–	–	7.6%[a]	–	M	4.06
Indarch	EH	2	3.71	3.73	–	11.2%	–0.5%	M, GSF	4.2
Saint-Sauveur	EH	1	3.68	–	–	13.0%[a]	–	M	4.23
St. Mark's	EH	1	3.67	–	–	12.8%[a]	–	M	4.21
Atlanta	EL	1	3.58	–	–	9.8%[a]	–	M	3.97
Blithfield	EL	1	3.51	–	–	5.9%[a]	–	M	3.73
Daniel's Kuil	EL	1	3.66	–	–	14.3%[a]	–	M	4.27

Table 6c. Individual meteorite densities and porosities: Enstatite. *Continued.*

Sample name	Type	#	Grain ρ	Bulk ρ	Measured porosity	Model porosity	Average porosity	Reference	Model grain ρ
Hvittis	EL	2	3.58	3.48 ± 0.18	–	12.9%	2.7%	VO, M, GSF	4
Jajh deh Kat Lalu	EL	1	3.59	–	–	5.3%[a]	–	M	3.79
Khairpur	EL	1	3.56	–	–	5.1%[a]	–	M	3.75
Pillistfer	EL	8	–	3.62 ± 0.01	–	11.9%	–	GSF	4.11

[a] Assuming reported grain density is in fact a bulk density.

Table 6d. Individual meteorite densities and porosities: Stony irons.

Sample name	Type	#	Grain ρ	Bulk ρ	Measured porosity	Model porosity	Average porosity	Reference
Brenham	Pall	4	4.64 ± 0.07	4.74 ± 0.09	5.1% ± 2.8%	–	–2.3%	VO, F
Eagle Station	Pall	3	–	4.89 ± 0.33	–	–	–	VO
Finmarken	Pall	1	5.07 ± 0.18	4.77 ± 0.14	5.9% ± 4.5%	–	5.9%	VO
Huckitta	Pall	1	3.78 ± 0.02	–	–	–	–	F
Imilac	Pall	1	4.48 ± 0.05	4.64 ± 0.09	–3.7% ± 2.2%	–	–3.7%	F
Steinbach	Unique	2	4.56 ± 0.01	4.18 ± 0.10	–	–	8.2%	VO, F
Crab Orchard	Meso	3	4.24 ± 0.02	4.27 ± 0.15	2.3% ± 2.1%	–	–0.6%	VO
Mincy	Meso	2	4.82 ± 0.06	4.23 ± 0.07	12.8% ± 2.2%	–	12.2%	VO
Morristown	Meso	3	4.15 ± 0.02	4.26 ± 0.20	–0.2% ± 1.6%	–	–2.6%	VO

Table 6e. Individual meteorite densities and porosities. Ordinary chondrites: H chondrites.

Sample name	Type	#	Grain ρ	Bulk ρ	Measured porosity	Model porosity	Average porosity	Reference
Acfer 024	H	1	–	3.51	3.1%	8.7%	–	GSF
Acfer 025/1	H	1	–	3.72	4.0%	3.2%	–	GSF
Acfer 025/2	H	1	–	3.30	4.0%	14.0%	–	GSF
Acfer 046	H	1	–	3.16	1.4%	17.6%	–	GSF
Acfer 048	H	1	–	3.55	–	7.6%	–	GSF
Acfer 061	H	1	–	3.60	–	6.3%	–	GSF
Acfer 065	H	1	–	3.50	–	9.0%	–	GSF
Acfer 067	H	1	–	3.45	–	10.2%	–	GSF
Acfer 073/1	H	1	–	2.96	1.4%	23.0%	–	GSF
Acfer 073/2	H	1	–	3.32	2.5%	13.6%	–	GSF
Acfer 098	H	1	–	3.09	8.6%	19.6%	–	GSF
Acfer 132	H	1	3.60 ± 0.01	3.45 ± 0.06	4.1% ± 7.0%	10.2%	–	F
Acfer 308	H	1	–	3.64	–	5.2%	–	GSF
Acme	H	1	–	3.31	–	13.8%	–	GSF
Adrian	H	1	–	3.19	–	16.9%	–	GSF
Agen	H	5	3.67	3.36 ± 0.02	9.3%	12.5% ± 0.6%	8.5%	GSF, VO, WR
Akbarpur	H	1	3.73	3.67	1.6%	4.4%	–	K
Alamogordo	H	1	–	3.47	–	9.5%	–	GSF
ALH 77182	H	1	3.48	2.97	14.7%	22.7%	–	J
ALH 77233	H	1	3.64	3.45	5.2%	10.2%	–	J
ALH 77288	H	1	3.77	3.69	2.1%	3.9%	–	J
ALH 77294	H	1	3.84	3.35	12.8%	12.8%	–	J
Alessandria	H	1	–	3.74 ± 0.02	–	2.6%	–	WR
Allegan	H	7	3.77 ± 0.09	3.14 ± 0.09	16.2%	18.2% ± 2.4%	16.7%	NA, GSF, M, VO, WR
Ambapur Nagla	H	2	–	2.80 ± 0.10	–	27.2%	–	GSF, WR
Barbotan	H	1	–	3.36	–	12.4%	–	GSF
Bath	H	5	3.69 ± 0.04	3.44 ± 0.02	6.1% ± 0.1%	9.4% ± 0.4%	6.8%	GSF, VO, K, M
Beardsley	H	1	–	3.48	–	8.4%	–	GSF
Beaver Creek	H	2	–	3.14 ± 0.04	–	17.5%	–	GSF, WR
Belly River	H	1	3.64	–	–	–	–	M
Bielokrynitschie	H	3	3.70 ± 0.03	3.52 ± 0.10	5.0% ± 3.6%	7.4% ± 2.6%	5.0%	A, K, GSF
Big Rock Donga	H	1	3.67 ± 0.02	–	–	–	–	F

Table 6e. Individual meteorite densities and porosities. Ordinary chondrites: H chondrites. *Continued.*

Sample name	Type	#	Grain ρ	Bulk ρ	Measured porosity	Model porosity	Average porosity	Reference
Bremervörde	H	2	3.60	3.65	–	3.9%	–	M, WR
Bur-Gheluai	H	2	3.70 ± 0.09	3.54	2.7%	6.9%	4.4%	M, VO
Butsura	H	2	3.72	3.39 ± 0.14	6.2%	10.8%	–	K, WR
Cangas de Onis	H	2	–	3.73 ± 0.09	–	1.9%	–	GSF, WR
Cape Girardeau	H	3	3.67	3.41	–	10.2%	7.0%	NA, GSF, WR
Casilda	H	1	3.23 ± 0.03	–	–	–	–	F
Castalia	H	1	–	3.42	–	10.1%	–	GSF
Chamberlin	H	1	–	3.34	–	12.1%	–	GSF
Charsonville	H	1	–	3.41	–	10.2%	–	GSF
Chitado	H	1	–	3.25 ± 0.03	–	14.5%	–	WR
Clovis (1)	H	1	–	3.28	–	13.7%	–	GSF
Cobija	H	1	–	3.43	–	9.7%	–	GSF
Colby (Kansas)	H	1	–	3.36	–	11.6%	–	GSF
Coldwater (stone)	H	1	–	3.59	–	5.4%	–	GSF
Collescipoli	H	1	–	3.46	–	9.1%	–	GSF
Conquista	H	1	–	3.39 ± 0.06	–	10.8%	–	WR
Coonana	H	1	3.47 ± 0.04	–	–	–	–	F
Cope	H	1	–	3.46	–	9.1%	–	GSF
Covert	H	1	–	3.30	–	13.1%	–	GSF
Densmore (1950)	H	1	3.40 ± 0.04	–	–	–	–	F
Dhajala	H	1	–	3.24 ± 0.05	–	14.7%	–	WR
Dimmitt	H	1	3.41	–	–	–	–	F
Djati-Pengilon	H	1	–	3.69	–	2.8%	–	GSF
Dokachi	H	1	–	3.62 ± 0.05	–	4.7%	–	WR
Doroninsk	H	1	3.67	3.59	2.2%	5.5%	–	K
Erxleben	H	2	3.68	3.55	–	6.7%	3.5%	GSF, K
Estacado	H	6	3.63 ± 0.05	3.67 ± 0.04	−0.6% ± 2.8%	3.5% ± 1.0%	−1.0%	K, F, M, VO
Etter	H	2	–	3.40 ± 0.00	–	10.5% ± 0.0%	–	VO
Farley	H	1	–	3.33	–	12.3%	–	GSF
Favars	H	1	–	3.42 ± 0.03	–	10.0%	–	WR
Ferguson Switch	H	2	3.49	3.43 ± 0.04	2.5%	9.7% ± 1.0%	1.7%	GSF
Flandreau	H	1	3.49 ± 0.03	–	–	–	–	F
Fleming	H	2	–	3.44 ± 0.08	–	9.6% ± 2.2%	–	GSF
Forest City	H	4	3.76 ± 0.06	3.38 ± 0.08	–	11.1%	10.1%	NA, M, GSF, WA
Forest Vale	H	2	–	3.19	18.1%	16.1%	–	SLP, WR
Gao-Guenie	H	1	3.67 ± 0.02	–	–	–	–	F
Geidam	H	1	3.75	–	–	–	–	M
Gilgoin	H	2	3.81	3.80 ± 0.27	5.3%	−0.1%	0.2%	J, GSF[a]
Gladstone	H	2	3.75	3.50	5.1%	8.0% ± 2.3%	6.8%	J, GSF
Grady (1937)	H	2	3.49	3.43	–	9.7%	1.7%	GSF, F
Grüneberg	H	1	–	3.55 ± 0.04	–	6.6%	–	WR
Gruver	H	1	–	3.46	–	9.1%	–	GSF
Guareña	H	1	–	3.45 ± 0.05	–	9.2%	–	WR
Hainaut	H	1	–	3.55	–	6.5%	–	GSF
Hat Creek	H	1	–	3.52	–	7.3%	–	GSF
Hessle	H	1	–	3.27	–	13.9%	–	GSF
Howe	H	1	–	3.36	–	11.7%	–	GSF
Hugoton	H	1	–	3.30	–	13.2%	–	GSF
Itapicuru-Mirim	H	1	3.74	3.50	6.4%	7.9%	–	K
Jilin	H	2	–	3.53	–	7.0%	–	GSF, WR
Kerilis	H	1	3.69	3.60	2.4%	5.3%	–	K
Kernouve	H	2	–	3.60	–	5.3%	–	GSF, WR
Kesen	H	2	–	3.51	–	7.6%	–	GSF, J
Kiffa	H	1	–	2.90	–	23.7%	–	GSF
Laborel	H	1	–	3.33	2.4%	12.3%	–	GSF
Lancon	H	3	3.70	3.51 ± 0.08	4.3%	7.7% ± 2.1%	5.2%	K, GSF, WR

Table 6e. Individual meteorite densities and porosities. Ordinary chondrites: H chondrites. *Continued.*

Sample name	Type	#	Grain ρ	Bulk ρ	Measured porosity	Model porosity	Average porosity	Reference
LEW 86102	H	1	–	–	2.0%	–	–	JSC
Macau	H	1	–	3.37 ± 0.05	–	11.3%	–	WR
Marsland	H	1	–	3.39	–	10.9%	–	GSF
Menow	H	2	3.67	3.09 ± 0.04	15.0%	18.6% ± 0.9%	15.7%	K, GSF
Metsäkylä	H	5	3.40	3.27 ± 0.02	3.5%	14.0% ± 0.5%	4.0%	GSF
Miami	H	1	3.43 ± 0.01	3.46 ± 0.13	−1.0 ± 3.8%	8.9%	–	F
Miller (AR)	H	1	3.68	–	–	–	–	M
Mills	H	1	–	3.21	–	15.7%	–	GSF
Misshof	H	2	3.67 ± 0.09	3.36 ± 0.19	8.3% ± 3.0%	11.5% ± 35.8%	8.2%	A, K, GSF
Monroe	H	2	3.80	3.65	5.8%	3.9%	–	J, WR
Mooresfort	H	2	3.70	3.28	–	13.7%	11.4%	M, GSF
Morland	H	2	–	3.56 ± 0.01	–	6.4% ± 0.2%	–	GSF
Mount Browne	H	3	3.66	3.46 ± 0.11	7.2% ± 0.6%	9.1%	5.6%	SLP, GSF, WR
Mulga (north)	H	1	3.27 ± 0.02	–	–	–	–	F
Muslyumovo	H	1	3.54 ± 0.01	3.18 ± 0.07	10.1% ± 2.0%	16.3%	–	F
Nammianthal	H	3	3.67	3.49 ± 0.06	6.0%	8.3% ± 1.7%	5.0%	K, GSF, WR
Nanjemoy	H	2	3.66	3.38	–	11.2%	7.8%	NA, GSF
Nuevo Mercurio	H	1	–	3.06	–	19.5%	–	GSF
Ochansk	H	5	3.62	3.26 ± 0.03	11.0%	14.2 ± 0.9%	9.9%	GSF, VO, WR
Ogi	H	1	3.62	3.29	9.1%	13.4%	–	K
Orimattila	H	2	3.60	3.48 ± 0.08	1.9%	8.5% ± 2.1%	3.5%	GSF
Orvinio	H	1	–	3.46 ± 0.21	–	8.9%	–	GSF, VO
Ovid	H	1	–	3.40	–	10.5%	–	GSF
Ozona	H	1	3.50 ± 0.01	3.23 ± 0.04	7.7% ± 1.0%	15.1%	–	F
Pipe Creek	H	1	–	3.49	–	8.3%	–	GSF
Plainview (1917)	H	4	3.60	3.54 ± 0.00	–	6.8% ± 0.0%	1.6%	GSF, F
Prairie Dog Creek	H	1	–	3.41 ± 0.05	–	10.2%	–	VO
Pribram	H	2	3.57	3.57	0.0%	6.1%	0.0%	GSF
Pultusk	H	19	3.64 ± 0.04	3.47 ± 0.05	5.4%	8.6% ± 0.7%	4.6%	GSF, VO, F, WR
Quenggouk	H	1	–	3.00	–	21.2%	–	GSF
Ransom	H	1	–	3.57	–	6.1%	–	GSF
Richardton	H	2	3.75	3.22	–	15.3%	–	M, WR
Rose City	H	1	3.74	–	–	–	–	M
Salaices	H	1	3.62 ± 0.02	–	–	–	–	F
Saline	H	2	–	3.51 ± 0.03	–	7.5% ± 0.7%	–	GSF
San Carlos	H	1	–	3.46	–	8.9%	–	GSF
Selma	H	2	3.45	3.37	–	11.2%	2.2%	M, GSF
Seneca	H	1	–	3.29	–	13.4%	–	GSF
Seres	H	2	3.71	3.46 ± 0.30	1.1%	9.0% ± 7.8%	6.8%	K, GSF
St. Ger.-du-Pinel	H	1	3.75	3.31	11.7%	12.9%	–	K
Ställdalen	H	2	–	3.57 ± 0.04	–	6.1% ± 1.1%	–	GSF
Stonington	H	1	–	3.39	–	10.7%	–	GSF
Supuhee	H	1	3.72	3.68	1.1%	3.2%	–	K
Tabor	H	1	–	3.47	–	8.7%	–	GSF
Tell	H	1	3.52 ± 0.07	–	–	–	–	F
Texline	H	1	–	3.56	–	6.3%	–	GSF
Tieschitz	H/L	4	–	3.23 ± 0.08	–	15.0% ± 2.1%	–	GSF
Timochin	H	2	–	3.30 ± 0.08	–	13.1%	–	GSF, WR
Tjabe	H	1	–	3.32 ± 0.02	–	12.6%	–	WR
Tomhannock Ck	H	2	3.62 ± 0.05	3.58	0.0%	5.8%	1.0%	K, M
Torino	H	2	3.68	3.30 ± 0.01	10.1%	13.0% ± 0.2%	10.1%	VO
Travis County	H	2	–	3.48 ± 0.10	–	8.3% ± 2.5%	–	GSF, VO
Trenzano	H	2	3.69	3.23 ± 0.10	10.6%	15.1% ± 2.7%	12.6%	K, GSF
Tulia (a)	H	1	–	3.45	–	9.3%	–	GSF
Uberaba	H	2	–	3.42 ± 0.04	–	10.1% ± 1.1%	–	GSF, VO
Udipi	H	1	3.71	3.60	3.0%	5.3%	3.0%	K

Table 6e. Individual meteorite densities and porosities. Ordinary chondrites: H chondrites. *Continued.*

Sample name	Type	#	Grain ρ	Bulk ρ	Measured porosity	Model porosity	Average porosity	Reference
Ute Creek	H	1	–	3.34	–	12.1%	–	GSF
Vernon County	H	3	3.69 ± 0.04	3.25 ± 0.10	10.5%	14.5% ± 2.6%	11.8%	NA, K, GSF
Wellman (A)	H	2	3.71 ± 0.16	3.56 ± 0.03	4.0% ± 3.2%	6.4% ± 0.8%	4.1%	J, GSF
Weston	H	4	3.63 ± 0.04	3.30 ± 0.04	–	13.3% ± 1.8%	9.2%	NA, M, GSF, WR
Willaroy	H	1	3.54	–	–	–	–	M
Wilmot	H	1	–	3.00	–	21.2%	–	GSF
Y-74156	H	1	3.80	3.45	9.2%	9.2%	9.2%	J
Y-74647	H	1	3.83	3.49	8.9%	8.2%	8.9%	J
Y-791428	H	1	–	3.57	3.6%	6.1%	–	GSF
Y-791500	H	1	–	3.33	8.7%	12.4%	–	GSF
Yanchiang	H	2	3.71 ± 0.07	3.42 ± 0.06	7.7% ± 0.1%	10.0% ± 1.6%	7.7%	F
Zhovtnevyi	H	1	–	3.27	13.1%	13.9%	–	A

[a] Bulk density includes a GSF measure of a 0.4 g sample with an unusually large value of 4; probably not representative of whole rock.

Table 6f. Individual meteorite densities and porosities. Ordinary chondrites: L chondrites.

Sample name	Type	#	Grain ρ	Bulk ρ	Measured porosity	Model porosity	Average porosity	Reference
Aleppo	L	1	–	2.50	–	30.7%	–	GSF
Alfianello	L	6	3.55	3.29 ± 0.06	5.6% ± 2.3%	8.7% ± 1.7%	7.4%	K, GSF
ALH 76009	L	1	3.59	2.89	19.5%	19.7%	19.5%	J
ALH 77115	L	1	3.37	3.11	7.7%	13.6%	7.7%	J
ALH 77230	L	1	3.48	3.44	1.2%	4.4%	1.1%	J
ALH 77231	L	2	3.68 ± 0.14	3.37 ± 0.42	8.6% ± 8.0%	6.5% ± 11.6%	8.5%	J[a]
ALH 77254	L	1	3.49	2.88	17.5%	20.0%	17.5%	J
ALH 78103	L	1	3.73	3.23	13.4%	10.3%	13.4%	J
ALH 78105	L	1	3.58	3.44	3.9%	4.4%	3.9%	J
ALH 78251	L	1	3.73	3.33	10.7%	7.5%	10.7%	J
Apt	L	1	–	3.73 ± 0.04	10.7%	−3.6%	–	WR
Arapahoe	L	1	3.61	3.52	2.5%	2.2%	2.5%	J
Arriba	L	3	–	3.35 ± 0.03	2.2%	7.0% ± 0.7%	–	GSF
Asco	L	1	3.68	3.59	2.5%	0.3%	2.4%	K
Aumale	L	1	–	3.43	–	4.7%	–	WR
Aumieres	L	1	–	3.25 ± 0.04	–	9.7%	–	WR
Ausson	L	4	3.55	3.22 ± 0.03	9.8%	10.5% ± 0.7%	9.1%	GSF, F, WR
Bachmut	L	1	3.55	3.33 ± 0.03	–	7.5%	6.2%	K
Barratta	L	6	3.48	3.45 ± 0.01	0.9% ± 0.3%	4.2% ± 0.3%	0.9%	SLP, M, GSF
Bath Furnace	L	1	–	3.36	–	6.8%	–	GSF
Beaver	L	1	–	3.46	–	3.9%	–	GSF
Beenham	L	1	–	3.34	–	7.2%	–	GSF
Berlanguillas	L	1	3.73	3.55	4.8%	1.4%	4.8%	K
Bluff	L	2	3.47	3.39	–	5.8%	2.3%	M, GSF
Brandon	L	1	3.38 ± 0.01	3.37 ± 0.12	0.3% ± 3.6%	6.3%	0.3%	F
Brewster	L	1	–	3.44	–	4.4%	–	GSF
Bruderheim	L	3	3.44 ± 0.22	3.34 ± 0.04	8.1%	7.4% ± 1.0%	3.2%	J, GSF, F
Buschhof	L	2	–	3.20 ± 0.03	–	11.1% ± 0.8%	–	GSF, WR
Cabezo de Mayo	L/LL	2	3.57	3.29 ± 0.08	6.2%	8.5% ± 2.3%	7.8%	GSF, K
Calliham	L	1	–	3.56	–	1.2%	–	GSF
Carraweena	L	1	3.46	–	–	–	–	M
Castine	L	1	–	3.46	–	4.0%	–	J
Chandakapur	L	1	–	3.31 ± 0.13	–	8.1%	–	GSF, WR
Chandpur	L	1	3.53	3.38	4.3%	6.1%	4.2%	K
Chantonnay	L	2	–	3.57 ± 0.00	–	0.8%	–	GSF, WR
Colby (WI)	L	1	–	3.48 ± 0.03	–	3.3%	0.0%	WR
Chateâu-Renard	L	3	3.55	3.48 ± 0.07	–	3.3% ± 1.9%	1.9%	M, GSF, WR
Dalgety Downs	L	3	3.53	3.43	–	4.8%	2.8%	GSF, J, F

Table 6f. Individual meteorite densities and porosities. Ordinary chondrites: L chondrites. *Continued.*

Sample name	Type	#	Grain ρ	Bulk ρ	Measured porosity	Model porosity	Average porosity	Reference
Danville	L	1	–	3.40	–	5.4%	–	GSF
De Nova	L	1	–	3.29	–	8.6%	–	GSF
Densmore (1879)	L	1	–	3.42 ± 0.12	–	4.9%	–	VO
Drake Creek	L	1	–	3.49	–	3.2%	–	NA
Durala	L	2	3.56	3.32 ± 0.12	4.2%	7.7% ± 3.5%	6.7%	K, GSF
EET 90513	L	1	–	–	10.0%	–	–	JSC
EET 90628	L	1	–	–	6.0%	–	–	JSC
Elenovka	L	1	–	3.50	10.5%	2.8%	–	A
Ella Island	L	1	–	3.20	–	11.1%	–	GSF
Ergheo	L	2	–	3.32 ± 0.02	–	7.7% ± 0.6%	–	GSF, VO
Farmington	L	11	3.45 ± 0.19	3.39 ± 0.11	5.4% ± 1.9%	5.8% ± 3.1%	1.6%	NA, SLP, M, J, GSF, F, VO
Fisher	L	2	–	3.43 ± 0.02	–	4.8% ± 0.5%	–	NA, VO
Forrest 002	L	1	3.38 ± 0.02	–	–	–	–	F
Forsyth	L	1	–	3.52	–	2.2%	–	NA
Fukutomi	L	1	3.49	3.42	2.0%	5.0%	2.0%	K
Futtehpur	L	2	3.51	3.49 ± 0.10	2.6%	3.0% ± 2.9%	0.5%	K, GSF
Garraf	L	2	–	3.66 ± 0.21	–	–1.6% ± 5.9%	–	VO
Girgenti	L	2	–	3.33 ± 0.06	–	7.4%	–	GSF, WR
Goodland	L	1	–	3.51	–	2.4%	–	GSF
Grassland	L	1	–	3.08	–	14.3%	–	GSF
Grossliebenthal	L	2	–	3.25 ± 0.01	–	10%	–	GSF, WR
Hamilton (Q’lnd)	L	1	–	3.37	–	6.3%	–	GSF
H. al Hamra 071	L	1	3.42 ± 0.01	3.41 ± 0.02	0.3% ± 1.0%	5.3%	0.3%	F
H. al Hamra 136	L	1	3.39 ± 0.01	3.35 ± 0.03	0.9% ± 2.0%	6.8%	0.9%	F
Harrison County	L	1	–	3.47	–	3.8%	–	NA
Harrisonville	L	1	–	3.42	–	5.1%	–	GSF
Hermitage Plains	L	2	3.45 ± 0.21	3.29	–	8.5%	4.7%	VO, F
Holbrook	L	7	3.51 ± 0.05	3.19 ± 0.11	10.9%	11.5% ± 3.1%	9.1%	M, GSF, F, WR
Homestead	L	4	3.75	3.40 ± 0.10	10.7%	5.5% ± 2.8%	9.1%	NA, VO
Ilafegh 011	L	1	3.31 ± 0.01	3.11 ± 0.01	6.1% ± 0.4%	13.6%	6.1%	F
Jackalsfontein	L	2	–	3.13 ± 0.43	–	13.0% ± 12.0%	–	GSF
Julesburg	L	1	–	–	5.0%	–	–	JSC
Kermichel	L	4	3.34	3.28 ± 0.04	2.2% ± 0.3%	8.8% ± 1.2%	1.8%	GSF, VO, JSC
Kisvarsany	L	1	–	3.25	–	9.8%	–	GSF
Kramer Creek	L	1	–	3.21	–	11.0%	–	GSF
Kuleschovka	L	1	–	3.11 ± 0.05	–	13.6%	–	WR
Kunashak	L	3	3.65	3.50	6.0%	2.8% ± 3.5%	4.0%	A, J
Kybunga	L	1	3.33 ± 0.03	–	–	–	–	F
Kyushu	L	3	3.53	3.42 ± 0.23	–	5.0% ± 6.3%	3.1%	M, GSF, WR
L’Aigle	L	3	3.49	3.40 ± 0.04	–	5.6% ± 1.2%	2.7%	GSF, F, WR
La Bécasse	L	1	–	3.96 ± 0.21	–	–9.9%	–	VO
La Criolla	L	1	–	3.57 ± 0.03	–	0.8%	–	WR
La Lande	L	1	–	3.50	–	2.9%	–	GSF
Ladder Creek	L	1	–	3.33	–	7.5%	–	GSF
Laketon	L	1	–	3.33	–	7.4%	–	GSF
Lanzenkirchen	L	1	–	3.49	–	2.9%	–	GSF
Laundry West	L	1	3.26 ± 0.03	–	–	–	–	F
Le Pressoir	L	1	–	2.97	–	17.6%	–	GSF
Leedey	L	1	3.63	3.25	10.5%	9.7%	10.5%	J
Linum	L	1	–	3.25	–	9.7%	–	GSF
Lissa	L	3	–	3.30 ± 0.01	–	8.5% ± 0.2%	–	GSF, WR
Long Island	L	1	–	3.32	–	7.9%	–	GSF
Lumpkin	L	1	–	3.65	–	–1.4%	–	NA
Lundsgard	L	3	–	3.25 ± 0.15	–	9.7% ± 4.2%	–	GSF, VO, WR
Macy	L	1	3.39 ± 0.02	–	–	–	–	Moore
Marion (Iowa)	L	2	–	3.31 ± 0.09	–	8.0% ± 2.6%	–	GSF

Table 6f. Individual meteorite densities and porosities. Ordinary chondrites: L chondrites. *Continued.*

Sample name	Type	#	Grain ρ	Bulk ρ	Measured porosity	Model porosity	Average porosity	Reference
Marlow	L	1	3.28 ± 0.01	–	–	–	–	F
Mauerkirchen	L	2	–	3.29 ± 0.07	–	8.5% ± 1.9%	–	GSF, WR
Mbale	L	1	3.52 ± 0.01	3.32 ± 0.05	5.8% ± 1.0%	7.8%	5.8%	F
McKinney	L	12	3.47 ± 0.05	3.42 ± 0.13	0.2% ± 0.3%	4.9% ± 3.7%	1.3%	K, GSF, VO, JSC, F
META 78003	L	1	3.61	3.33	7.8%	7.5%	7.8%	J
Meuselbach	L	2	3.44	3.47	2.0%	3.6%	–0.8%	K, F
Mezö-Madaras	L	4	3.56	3.46 ± 0.15	1.7%	4.0% ± 4.3%	2.9%	K, GSF, WR
Milena	L	1	–	3.26	–	9.3%	–	GSF
Minas Gerais	L	1	3.52	3.41	3.1%	5.3%	3.1%	K
Mocs	L	10	3.51 ± 0.10	3.18 ± 0.08	8.7% ± 0.3%	11.6% ± 2.3%	9.3%	M, GSF, VO, WR
Modoc (1905)	L	3	3.58	3.45 ± 0.13	–	4.3% ± 3.7%	–	M, NA, WR
Monze	L	1	–	3.32	–	7.8%	–	GSF
Mount Tazerzait	L	1	3.63 ± 0.01	3.01 ± 0.05	17.2%	16.4%	17.2%	F
Nagy-Borové	L	2	3.49	3.40 ± 0.04	1.7%	5.6% ± 1.2%	2.6%	K, WR
Nakhon Pathom	L	1	3.53	–	–	–	–	M
Nashville (stone)	L	1	–	3.42	–	4.9%	–	GSF
Neenach	L	1	–	3.40	–	5.5%	–	GSF
Nejo	L	1	3.59	–	–	–	–	M
Nerft	L	3	3.56	3.44 ± 0.13	3.1%	4.4% ± 3.7%	3.3%	K, GSF, WR
Ness County (1894)	L	3	3.38 ± 0.05	3.36 ± 0.01	0.8% ± 1.4%	6.7% ± 0.2%	0.7%	K, GSF, VO
New Concord	L	7	3.57 ± 0.03	3.33 ± 0.05	7.7% ± 1.5%	7.6% ± 1.5%	6.7%	NA, K, M, GSF, J, F
Norcateur	L	1	–	3.26	–	9.4%	–	GSF
Oak	L	1	3.32 ± 0.01	–	–	–	–	F
Oesel	L	1	–	3.19	–	11.4%	–	GSF
Otis	L	1	–	3.34	–	7.1%	–	GSF
Ovambo	L	1	–	3.34	–	7.3%	–	GSF
Pacula	L	1	–	3.26	–	9.4%	–	GSF
Patrimonio	L	1	–	3.39 ± 0.05	–	5.8%	–	WR
Potter	L	2	–	3.26 ± 0.06	4.4%	9.5%	–	GSF
Putinga	L	2	–	3.39 ± 0.05	–	5.8% ± 1.5%	–	VO, WR
Reggane 002	l	1	3.55 ± 0.01	–	–	–	–	F
Roy (1933)	L	1	–	3.30	–	8.4%	–	GSF
Rush Creek	L	1	–	3.44	–	4.5%	–	GSF
Salla	L	2	–	3.39	–	5.8%	–	GSF
Santa Barbara	L	1	–	3.50 ± 0.04	–	2.8%	–	WR
Saratov	L	3	3.52	2.97	15.7%	17.4%	15.5%	A, F
Schönenberg	L	1	–	3.50 ± 0.05	–	2.8%	–	WR
Segowlie	L	1	3.47	3.41	1.7%	5.3%	1.7	K
Sevrukovo	L	2	3.51	3.50 ± 0.01	0.0%	2.7% ± 0.3%	0.2%	K, GSF
Shaw	L	1	3.30	–	–	–	–	M
Sleeper Camp	L	1	3.36 ± 0.04	3.21 ± 0.10	4.3 ± 3.4%	10.7%	4.3%	F
Slobodka	L	1	3.49	3.18	8.9%	11.7%	8.9%	K
Smith Center	L	1	–	3.47	–	3.8%	–	GSF
Springfield	L	1	–	3.29	–	8.7%	–	GSF
St. Chris.-la-Ch.	L	1	3.61	3.52	2.5%	2.2%	2.5%	K
St. Michel	L	1	–	3.39	–	5.8%	–	GSF
Stavropol	L	1	3.57	3.47	2.8%	3.6%	2.8%	K
Tadjera	L	1	3.56	–	–	–	–	M
Taiban	L	1	–	3.47	–	3.5%	–	GSF
Tenham	L	1	–	3.36	–	6.6%	–	GSF
Tennasilm	L	3	3.56	3.20 ± 0.15	–	11.0% ± 4.2%	10.0%	M, GSF
Tourinnes-la-gr.	L	2	–	3.23 ± 0.14	–	10.3% ± 3.9%	–	GSF, WR
Tryon	L	1	–	3.36	–	6.7%	–	GSF
Valkeala	L	1	–	3.34	–	7.2%	–	GSF
Varpaisjärvi	L	1	–	3.37	–	6.4%	–	GSF
Vera	L/LL	1	–	3.33	–	7.6%	–	GSF

Table 6f. Individual meteorite densities and porosities. Ordinary chondrites: L chondrites. *Continued.*

Sample name	Type	#	Grain ρ	Bulk ρ	Measured porosity	Model porosity	Average porosity	Reference
Vouillé	L	3	3.54	3.43 ± 0.04	2.8%	4.8% ± 1.1%	3.2%	K, GSF, WR
Waconda	L	1	–	3.26	–	9.4%	–	GSF
Waltman	L	1	3.42 ± 0.01	3.33 ± 0.08	2.5% ± 2.6%	7.5%	2.5%	F
Willard (a)	L	1	–	–	0.0%	–	–	JSC
Y-74191	L	1	3.60	3.23	10.3%	10.3%	10.3%	J
Y-75097	L	1	3.65	3.28	10.1%	8.9%	10.1%	J
Y-8410	L	1	–	3.37	2.2%	5.3%	–	GSF
Zaborzika	L	1	3.54	3.41	3.7%	5.3%	3.7%	K
Zavid	L	1	–	3.31	–	8.1%	–	GSF
Zemaitkiemis	L	1	–	3.55	–	1.4%	–	GSF

[a] One sample noted as uncertain by authors.

Table 6g. Individual meteorite densities and porosities. Ordinary chondrites: LL chondrites.

Sample Name	Type	#	Grain ρ	Bulk ρ	Measured porosity	Model porosity	Average porosity	Reference
Albareto	LL	1	3.45	3.29	4.6%	7.6%	–	K
ALH 78109	LL	1	3.39	2.72	19.8%	23.6%	–	J
Alta'ameem	LL	2	–	3.25 ± 0.06	–	8.8% ± 1.7%	–	GSF, WR
Arcadia	LL	2	–	3.22 ± 0.04	–	9.6% ± 1.1%	–	GSF
Bandong	LL	2	–	3.12 ± 0.08	–	12.5% ± 2.1%	–	VO, WR
Bjurböle	L/LL	74	3.44	3.02 ± 0.08	16.8% ± 1.7%	15.2%	12.3%	SLP, GSF, T
Chainpur	LL	1	3.40	–	–	–	–	M
Cynthiana	L/LL	3	3.44	3.14	–	11.9%	8.9%	NA, M, GSF
Dhurmsala	LL	5	3.47	3.34 ± 0.13	3.8%	6.3% ± 3.8%	3.9%	K, GSF, VO
Ensisheim	LL	7	–	3.49 ± 0.16	–	2.1% ± 1.8%	–	GSF, VO, WR
Guidder	LL	1	–	3.23	–	9.4%	–	GSF
Jelica	LL	4	–	3.19 ± 0.13	–	10.5% ± 3.6%	–	GSF, VO, WR
Krymka	LL	1	–	3.35	6.7%	–	–	A
Knyahinya	L/LL	5	3.50	3.35 ± 0.02	–	5.8% ± 0.6%	4.3%	M, GSF, VO
Lake Labyrinth	LL	1	–	3.29	–	7.7%	–	GSF
Manbhoom	LL	3	–	3.18 ± 0.24	–	10.6% ± 6.7%	–	GSF, WR
Mangwendi	LL	1	3.69	3.15	14.8%	11.7%	14.8%	VO
Manych	LL	1	–	–	1.0%	–	–	JSC
Ngawi	LL	1	3.56	–	–	–	–	M
Nyirábrany	LL	1	–	3.19	–	10.4%	–	GSF
Olivenza	LL	1	–	3.31 ± 0.04	–	7.0%	–	WR
Ottawa	LL	2	3.54	3.29	–	7.6%	7.1%	M, WR
Oubari	LL	1	–	3.19	–	10.4%	–	GSF
Paragould	LL	1	–	3.41	–	4.3%	–	GSF
Parnallee	LL	3	3.45	3.23 ± 0.05	5.2%	9.3% ± 1.3%	6.4%	K, GSF, VO
Richfield	LL	3	3.38 ± 0.01	3.33 ± 0.01	1.8% ± 0.6%	6.4% ± 0.4%	1.6%	F
Richmond	LL	3	3.52	3.30 ± 0.01	6.5%	7.4% ± 0.3%	6.3%	NA, K
Savtschenskoje	LL	2	–	3.40 ± 0.06	–	4.6% ± 1.8%	–	VO
Soko-Banja	LL	5	–	3.32 ± 0.14	–	6.5% ± 4.6%	–	GSF, VO, WR
Siena	LL	1	–	3.46 ± 0.03	–	2.8%	–	WR
Tuxtuac	LL	1	–	3.24	–	8.9%	–	GSF
Vavilovka	LL	2	–	3.09 ± 0.01	–	13.1% ± 0.4%	–	GSF, VO
Y-75258	LL	1	3.53	2.38	32.6%	33.1%	–	J
Y-790448	LL	1		3.18	2.7%	10.7%	–	GSF
Y-790519	LL	1	–	3.11	7.0%	12.6%	–	J
Y-790723	LL	1	–	3.03	8.0%	14.9%	–	J
Y-790964	LL	1	–	2.78	16.0%	21.9%	–	J

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