WHAT DENSITY AND POROSITY TELL US ABOUT METEORITES G.J. Consolmagno[1], D.T. Britt[2], and R.J. Macke[2], [1]Specola Vaticana, V-00120, Vatican City State, gjc@specola.va, [2]Department of Physics, University of Central Florida, Orlando, FL 32816-2385, USA

Introduction: Density and porosity are our primary tools to understand the physical history of meteorites. We and others [1] have been systematically measuring meteorite density and porosity for the past ten years. Previously, a lack of data had forced us to infer some meteorite density and porosity trends from data taken with inconsistent or unreliable methods. Our combined database has density measurements on more than 1200 different samples, but reliable porosities (using bulk and grain densities of the same sample) are available for only about half of these: 171 ordinary chondrites, 17 carbonaceous chondrites, 9 enstatite chondrites, and 25 achondrites. Still, enough of these meteorites have now been measured in a common, uniform, and reliable way that we can begin to draw some robust conclusions about trends in the data.

Ordinary Chondrites: The H, L, and LL chondrites have essentially indistinguishable porosities, averaging 8.6% ± 5.4%. We conclude that they all experienced very similar physical processes, which occurred after the compositional nature of these classes were determined. Furthermore, since their porosities show no correlation with either petrographic grade or shock state, one is led to the rather startling conclusion that their porosity must have been fixed independently of whenever their petrographic/metamorphic and shock states were set. Given that metamorphism would presumably alter porosity, one can only conclude that the pore-forming events for in the ordinary chondrites must have occurred after the metamorphic events. Shock events may produce (or at least contribute to) the observed porosity; but if so, the resulting porosity must be independent of the shock strength.

Primitive Achondrites: Only five meteorites of this group have been measured for porosity, two brachianites and three winonaites. Not surprisingly, given the chemical similarities, their densities and porosities closely resemble ordinary chondrites: average grain density of 3.63 ± 0.17 g/cm^3, average bulk density 3.23 ± 0.18 g/cm^3, average porosity 11.5% ± 3.6%.

Enstatite Chondrites: The enstatite chondrite data in hand are consistent with the possibility that they participated in the same physical history as the ordinary chondrites and primitive achondrites, obtaining their porosity after their compositional, metamorphic, and shock states had been fixed. The measured porosities cluster into two groups, with six meteorites having low porosities (0.3% to 6.4%) and three others with 11.7%, 12.3%, and 12.6% porosity. Both groups include falls and finds; both include samples from the EL and EH subclasses. These subclasses were originally defined [2] in terms of high (EH) and low (EL) iron and siderophile contents, though later work has suggested that the differences in iron content may not be as characteristic of the groups as first thought. We do find a slightly higher grain density (3.70 ± 0.03 g/cm^3) for EH meteorites compared to EL samples (averaging 3.61 ± 0.07 g/cm^3) but the difference is small, and given the sparse data set it may not be significant.

Basaltic Achondrites: Aubrite, Ureilite, HED and SNC porosites are similar to the ordinary and enstatite chondrites, in spite of the obvious difference in their physical histories and greater physical strength. Their igneous nature points to an origin very different from the OC's: perhaps a larger parent body, a physically different location from the chondrites, or a different time in solar nebula history when radioactive or other heat sources were more prevalent. But this difference does not appear to extend to their porosity histories.

Carbonaceous Chondrites: CMs and CIs are significantly lower in density than any other meteorites, with grain densities well below 3 g/cm^3 and bulk densities near 2 g/cm^3. Murchison's porosity is 22 ± 2%; Murray's is 28%. Five of the six CO meteorites with measured porosities are under 15% porous, but all five (along with the one reliably measured CR, Acfer 097 – porosity 14%) are finds; the one measured CO fall, Warrenton, has a porosity of 26%. Five of the seven CV and CK meteorites (the two classes are thought to be closely related) measured in hand sample are more than 20% porous. The lower porosity CVs are Leoville (13%), a find, and Vigarano (6%), a fall; the other CVs measured are Allende (fall, 23.0% ± 5% based on 48 measurements) and Axtell (find, 21% ± 2% based on 2 measurements). The three measured CK meteorites range in porosity from 21% to 24%; two are falls, one a find. The CV class can be divided into oxidized and reduced subgroups [3]; the two high porosity CVs. Allende and Axtell, are also members of the oxidized group, while the two low porosity CVs, Leoville and Vigarano, belong to the reduced subgroup. This supports the suggestion [4] that reduced CV's porosities should be lower than those of the oxidized group.

While most carbonaceous meteorites' porosities are > 20%, nonetheless these samples are typically well-lithfied rocks. Notable exceptions include the highly friable volatile-rich meteorites Orgueil (CI) and Tagish Lake (CM), which still were able to survive passage through our atmosphere and be recognizably solid, individual samples. The contrast between the densities of these meteorites and the ordinary chondrites argues that carbonaceous chondrites are in a very different physical state and likely have undergone a very different physical history than the other meteorites, both chondrites and achondrites, presumably from having been formed in a very different part of the solar nebula.

Implications for Parent Bodies: This variation in porosity between carbonaceous meteorites and the other major meteorite groups directly addresses issues of formation of these bodies, and their parent bodies, in the solar nebula. If each meteorite's compositional type was formed in its own distinct area of nebular space, then this could show up as significant differences in their physical states, beyond the obvious differences in chemistry and mineralogy. Different nebular conditions may lead to differences in accretional timing, accretional energy, lithification, and compaction, resulting in differences in microporosity. From our data, we conclude that most carbonaceous chondrites are significantly less compacted and less completely lithified than the other meteorite types. Any hypothesis for the lithification of meteorites must account for this difference. In addition, the high porosity of some carbonaceous chondrites may be indicative of a lower overall crushing strength, giving us an important clues to the structure of their putative parent bodies (the dark asteroids) and their survivability in atmospheric entry.

Differences in porosity with the "scale" of the object would have a direct bearing on how meteorites lithify and also how they break apart upon atmospheric entry [5]. For ordinary chondrites there is no correlation with either the value or the spread of porosities for samples ranging in size from a few grams to several tens of kilograms, and the evidence of the point-counting method (which can reproduce hand-sample porosity for ordinary chondrites) [6] indicates that this uniformity extends down to the scale of a meteorite thin section. More data on other meteorite types can show whether this generalization can be extended beyond the ordinary chondrite case.

Part of the issue of how asteroid materials respond to regolith processes is to determine the relationship between meteorite shock state and porosity; we found no correlation, though the sparse data for the highest shock states cannot rule out the possibility that unusually severe shocking may somewhat reduce porosity. Breccias are fragmental collections of shattered rock that have been re-lithified by shock, usually by grain-boundary melting under high pressures [7]; this led us to ask if breccias were less porous than non-breccia meteorites. In fact, however, we have found that the average porosity (corrected for weathering effects) of 22 H chondrite breccias in our sample is actually 2.28 percentage points higher than the H chondrite average (10.3% compared to 8.02%); the porosity of breccias in the L group (based on 19 samples) is within 0.25 points of the group average; and the average porosity of the 12 LL breccias measured is 1.05 percentage points lower than the whole group average.

Weathering: The final stage in meteorite evolution is its processing after accretion to the Earth. Terrestrial weathering in ordinary chondrites increases the content of low density clay minerals and iron oxides [8] and may result in the formation of carbonates in CO meteorites. This process continually lowers the porosity as internal voids and cracks are filled with lower-density weathering products, which lowers the grain density (by increasing the volume of solid material present) but tends to keep the bulk densities essentially fixed: so long as only pore spaces are filled, the bulk volume stays unchanged and the added mass of the terrestrial oxidizers is generally negligible. However, weathering effects in other meteorite types, particularly oxidized carbonaceous chondrites, are largely unknown. Terrestrial weathering significantly alters the carbon isotopes in CO meteorites, which is attribute to the presence of carbonates formed by the evaporation of carbonate-rich terrestrial water that has been taken up by the meteorite [9]. Presumably these carbonates are filling void spaces in the meteorite, lowering its porosity. However, there is no distinction between the porosity of falls and finds among the CV and CK class. The mechanism of weathering in Antarctic meteorites is distinctly different. Antarctic meteorite grain densities are, on average, comparable to those for falls, not finds. However, certain Antarctic meteorites have porosities that are remarkably high (above 30%) compared to other ordinary chondrites; this may be the result of freeze-thaw cycles within the meteorite during its stay on the Antarctic ice. In a similar vein, sulfides in CI meteorites formed by reactions with terrestrial water may play a role in increasing the porosity of some samples.

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References: [1] Britt, D. T. and Consolmagno, G. J. (2003) *Meteoritics & Planet. Sci., 38,* 1161-1180. [2] Sears, D. W., Kallemeyn, G. W., and Wasson, J. T. (1982) *Geochim. Cosmochim. Acta. 46*, 597-608. [3] Krot, A. N., Scott, E. R. D., and Zolensky, M. E. (1995) *Meteoritics 30,* 748-775. [4] MacPherson, G. J., and Krot, A. N. (2002) *Meteoritics & Planet. Sci., 37*, A91. [5] Flynn, G. J., Moore, L. B., and Klock, W. (1999) *Icarus 142,* 97-105. [6] Strait M. M. and Consolmagno G. J. (2002) *Lunar Planet. Sci. XXXIII*, Absract #1711. [7] Bischoff, A., Rubin, A. E., Keil, and K., Stöffler, D. (1983) *Earth Planet. Sci. Lett. 66*, 1-10. [8] Bland, P. A., Sexton, A. S., Jull, A. J. T., Bevan, A. W. R., Berry, F. J., Thornley, D. M., Astin T. R., Britt, D. T., and Pillinger, C. T. (1998) *Geochim. Cosmochim. Acta 62,* 3169-3184. [9] Ash, R. D. and Pillinger, C. T. (1995) *Meteoritics 30,* 85-92.