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ScienceDirect

Chemie der Erde 68 (2008) 1–29

CHEMIE der ERDE GEOCHEMISTRY

www.elsevier.de/chemer

INVITED REVIEW

The significance of meteorite density and porosity

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Received 3 December 2007; accepted 15 January 2008

Abstract

Non-destructive, non-contaminating, and relatively simple procedures can be used to measure the bulk density, grain density, and porosity of meteorites. Most stony meteorites show a relatively narrow range of densities, but differences within this range can be useful indicators of the abundance and oxidation state of iron and the presence or absence of volatiles. Typically, ordinary chondrites have a porosity of just under 10%, while most carbonaceous chondrites (with notable exceptions) are more than 20% porous. Such measurements provide important clues to the nature of the physical processes that formed and evolved both the meteorites themselves and their parent bodies. When compared with the densities of small solar system bodies, one can deduce the nature of asteroid and comet interiors, which in turn reflect the accretional and collisional environment of the early solar system.

Keywords: Asteroids; Density; Meteorites; Porosity; Solar nebula; Trans-Neptunian objects

1. The study of meteorite density and porosity

1.1. Introduction

On Earth, a geologist can take samples *in situ*, recognizing the stratigraphic relationship between neighboring samples, and then measure the chemical and physical properties of those samples in the lab. For studying the solar system, an analog of a stratigraphic sequence can be found in the compositions and orbital locations of small solar system bodies, which represent the relatively unprocessed material from which the major planets were formed. There are two major sources of information on the compositional diversity of the small bodies of the solar system: remote information from telescopic observations of asteroid, comet, and Trans-Neptunian object (TNO) mineralogy, and direct samples of meteorites that have fallen from the asteroid belt onto Earth, and into our labs.

The 44 compositional types, subtypes, and metamorphic grades of meteorites represent an invaluable resource of "free" geological material from asteroids that sample their mineralogy, geochemistry, and small-scale structure as well as textural and isotopic evidence of their origin and evolution. Their chemical study has been going on with a remarkable intensity since the Apollo era, coinciding with the development of highly precise devices such as scanning electron microscopes (SEMs)/microprobes and mass spectrometers, which have allowed ever finer measurements of chemical and isotopic compositions to be made at ever higher resolution on ever tinier samples. But until recently, the measurement of the physical properties of these samples has not been pursued with the same vigor. Here

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0009-2819/$ - see front matter © 2008 Elsevier GmbH. All rights reserved.
doi:10.1016/j.chemer.2008.01.003

we review recent efforts to correct that imbalance, and show how these meteorite physical properties, in particular density and porosity, can be tied to recently determined asteroid physical properties. This study can lead us to a deeper insight into the structure of the early-forming solar system itself.

1.2. Density and porosity

Density, mass per unit volume, is one of the fundamental properties of matter. Only a limited number of parameters control a rock's density: its mass is determined by the atomic masses of the elements that make up a rock, while its volume is a function of the physical arrangement of those elements into crystalline forms, as modified by whatever flaws exist in that arrangement of elements that could cause the rock's density to deviate from a theoretical value. These flaws can include dislocations within the minerals (which in practice have a negligible effect on density), the incomplete compaction of the individual crystals in the rock, or disruptions of the fabric of the material by events such as thermal stresses or the passage of shock waves. All such voids and cracks are generally referred to as *porosity*.

The common way to determine the porosity of an object is by measuring its bulk volume V_b and grain volume V_g. Grain volume measures only the volume of solid matter in the sample, while bulk volume is based on overall dimensions and includes volume contributions from any cracks or voids that are present within the sample. Porosity is then calculated as follows:

$$P = \left(1 - \frac{V_g}{V_b}\right) \times 100\%.$$

Alternatively, if bulk density $\rho_b = M_m/V_b$ (where M_m is the mass of the meteorite) and grain density $\rho_g = M_m/V_g$ are determined, porosity can be calculated by

$$P = \left(1 - \frac{\rho_b}{\rho_g}\right) \times 100\%.$$

Like density, mineralogy is also a function of the composition and arrangement of atoms within a substance. But while mineralogy and density both depend on the same variables, there is not a unique mapping between them. Different minerals can have the same densities, while a given mineral can be a solid solution of different cations (such as Fe and Mg) and thus exhibit a range of different densities. Still, most meteorites have a relatively simple mineralogy, fixed by the equilibrium chemistry of elements whose relative abundances are usually not too different from solar abundances, formed at relatively uniform (and low) pressures and temperatures. Thus one might expect that a meteorite's density could provide at least a zeroth-order indication of its mineral composition.

Britt and Consolmagno (2003) reviewed the measurement of meteorite densities that had been measured through the year 2001. Until the 1950s, most meteorite density values were found casually as a part of the description of individual falls. In most of those cases, the authors did not outline the method used to make the measurement, presumably using the standard geological technique of weighing the sample first in air and then suspended in water. This method gives a quick estimate of the bulk density of the sample, but does not take into account any penetration of the water into the pore space and, of course, carries with it the risk of contamination and weathering that can result from dipping meteorites into water.

The first systematic study of meteorite porosity was presented by Keil (1962), although earlier papers by Alexayeve (1958) and Stacy et al. (1961) had published porosities for six and eight meteorites, respectively. Keil measured 48 meteorites with the uniform technique of immersion into water to find a bulk density, and into carbon tetrachloride (taking steps to insure that it saturated the pore spaces) to find the grain density. In 1960s Brian Mason also measured the grain densities of 70 meteorites with carbon tetrachloride, but most of these were not published until the Britt and Consolmagno (2003) compilation.

After a gap of 20 years, a new series of density and porosity measurements were conducted in the 1980s. At the National Institute for Polar Research in Japan, 40 meteorites from their Antarctic collection were measured for density and porosity (Matsui et al., 1980; Miyamoto et al., 1982; Yomogida and Matsui, 1981, 1983), while researchers at the Geological Survey of Finland measured bulk densities (and, in some cases grain densities and porosities) for the largest sample set up to that time, 489 pieces (most of them only a few grams) of 368 different meteorites (Kukkonen and Pesonen, 1983; Terho et al., 1993; Pesonen et al., 1993); a similar, if smaller, study was carried out in Leningrad (Guskova, 1985).

The first measurements of meteorite bulk densities using glass beads instead of water (see below) were reported by Consolmagno and Britt (1998). Since then, a combination of glass bead (or digital imaging) and gas pycnometry methods have been used by us and a number of other workers (Flynn and Klock, 1998; Moore et al., 1999; Flynn et al., 1999; Wilkison and Robinson, 2000; Kohout et al., 2006; Smith et al., 2006; McCausland et al., 2007) to measure meteorite densities and porosities.

Besides volume measurements, other techniques for determining porosity directly include point-counting void spaces visible in SEM backscatter images or inferring porosity from the measurement of sound