Elastic Wave Velocity, Porosity, and Pore Geometry of Ordinary Chondrites

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Summary

Elastic wave velocity, bulk density, and derived elastic moduli of meteorites are used as analogues for meteorite parent bodies such as asteroids and assist in constraining parameters involved in the modelling of collisions on meteorite parent bodies. Meteorite physical and elastic properties are influenced by the presence of porosity and pore geometry; classification of pore geometries observed in meteorites and the effects of pore geometry on elastic and physical properties are examined. Elastic wave velocity trends in ordinary chondrites have been documented by Hons (2004) and additional meteorite physical property trends have been documented in the literature. Trends documented in the literature were confirmed in this study and five new bulk density, elastic wave velocity, and physical property trends were identified.

Introduction

Understanding the elastic wave velocities and elastic properties and related pore structures of meteorites provides information about meteorite parent bodies (e.g. asteroids) required for diverse purposes such as the development of asteroid diversion/sampling techniques. Data were collected from of a suite of meteorite samples from the Center for Meteorite Studies Collection at Arizona State University, the University of Calgary, and the private collection of Dr. David Gregory. This research was completed as part of a Master of Science program in Geology at the University of Calgary.

Objectives

The objectives of this project are: (1) confirm (or reject) previously identified elastic wave velocity/physical property trends in ordinary chondrites, (2) describe the pore geometries present in meteorites, and (3) test the hypothesis that variations in pore geometry associated with petrologic type result in reduced elastic wave velocities in meteorites of high petrologic type.

Previous Research

Elastic wave velocities in meteorites have been measured in several studies; Yomogida and Matsui (1983) and Hons (2004). Meteorite bulk density, grain density, and porosity values have been documented in detail in the literature (e.g. Consolmagno and Britt, 2003; Hons, 2004; Flynn *et al.*, 1999). Minimal research has been completed related to the mechanical properties of meteoritic material, despite knowledge of meteorite compressive and tensile strengths and elastic moduli being essential in predicting response to forces including impacts on meteorite parent bodies. Petrovic (2001) compiled and summarized the available mechanical property data from the literature for the primary mineral constituents of stony meteorites.

Five statistically significant elastic wave velocity trends in ordinary chondrites were documented by Hons (2004); (1) velocity increases/porosity decreases with increasing terrestrial weathering time, (2) velocity increases with meteorite bulk density, (3) velocity decreases with metamorphic grade/petrologic type in H-chondrite fresh falls, (4) velocity increases with meteorite darkness in ordinary chondrites, and (5) velocity decreases as total porosity increases. Yomogida and Matsui (1983) documented decreasing porosity in H-chondrites of high petrologic type.

Methods

Compressional and shear wave transducers borrowed from the CREWES project (University of Calgary) were used to measure elastic wave velocities through meteorite slabs. Meteorite bulk density measurements were collected via an Archimedean method employing glass beads as the fluid (described by Consolmagno and Britt, 1998, and later used by Hons, 2004), and in some cases through precise volume measurements using digital calipers and gridded paper. A correction factor was applied to the bulk density measurements to account for systematic uncertainty related to variance in sample shape and size; small samples tend to have higher uncertainties associated with measured bulk densities than their larger counterparts. Grain densities were measured in a He-pycnometer at the School of Earth and Space Exploration, Arizona State University. Elastic moduli were calculated from elastic wave velocity and bulk density data. Pore geometries and fracture characteristics for a representative suite of meteorites were observed in thin section using a petrographic microscope.

Sample Selection

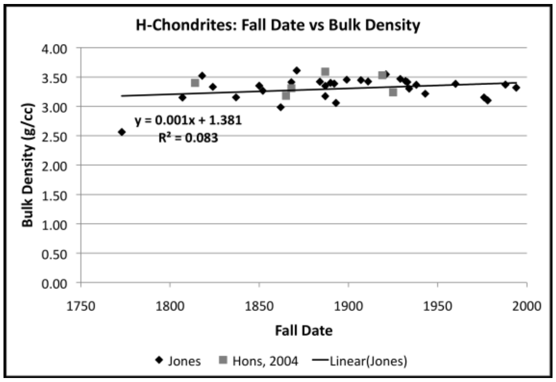
The meteorite samples are predominantly ordinary chondrites, although some carbonaceous chondrites, enstatite chondrites, and achondrites have been included. The use of meteorite falls, rather than finds, allows samples with minimal terrestrial alteration to be selected and allows the potential effects of terrestrial weathering to be recognized in samples with longer terrestrial residence times. Cut meteorite slabs allow the most efficient coupling of transducers during elastic wave velocity measurements, thus velocity data were collected predominantly from samples with flat sides to ensure reliable results.

Results

Results from this study in combination with data from the literature confirm trends documented by Hons (2004) and Yomogida and Matsui (1983) in H-chondrites, demonstrate that these trends exist in other chondrite sub-populations, and show that the derived shear, bulk, and Young's moduli exhibit analogous trends. Meteorite shear modulus, bulk modulus, and Young's modulus increase with increasing bulk density. This is a reflection of the previously defined relationship between bulk density and elastic wave velocity; elastic moduli are derived from elastic wave velocities, thus higher elastic wave velocities produce larger elastic moduli. Elastic moduli provide a quantitative method to assess rock strength; how a rock behaves under stress. The large range of meteorite bulk and shear moduli suggest that meteorite parent bodies also have a wide range and heterogeneous distribution of moduli; different ordinary chondrite parent bodies may respond differently to similar states of stress.

Five new trends were identified; bulk density decreases with increasing terrestrial residence time (Figure 1), bulk density increases with petrologic type in H-chondrites, total porosity decreases with increasing shock state in H- and L-chondrites (Figure 2), Poisson's ratio and Vp/Vs decrease with increasing petrologic type in H-chondrites, and Poisson's ratio and Vp/Vs may decrease with increasing porosity in H- and L-chondrites.

Pore geometries were classified and documented in a suite of ordinary chondrites to test the hypothesis that the decrease in mean elastic wave velocity in meteorites of high petrologic type is related to variation in pore shape. Three pore geometries were observed; equant to irregular voids greater than approximately 0.1mm in longest dimension (Figure 3), smaller equant to irregular pores less than approximately 0.1mm disseminated throughout the meteorite matrix, refered to as intragranular/intracrystalline pores (Figure 4), and fracture (or crack) porosity (Figure 5). These observations are consistent with Flynn *et al.* (1999) who documented three general pore shapes in meteorites.



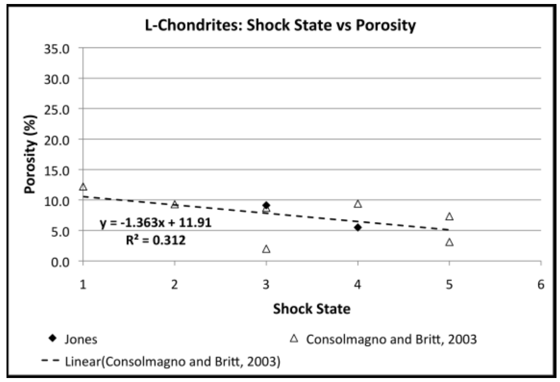
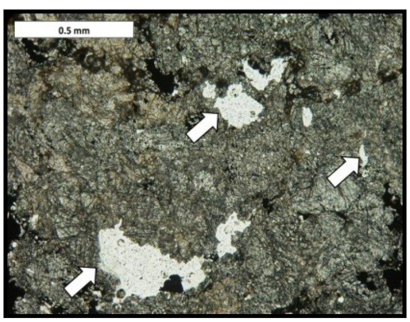
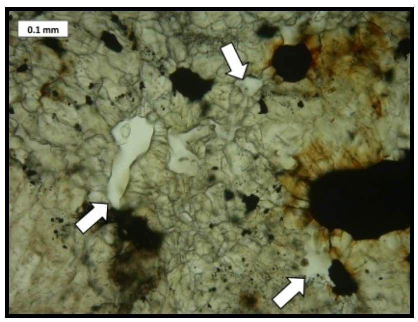


Figure 1: (Above Left) A possible correlation exists between meteorite fall date (terrestrial residence time) and meteorite bulk density. During terrestrial weathering the density of ordinary chondrites may initially increase as water and oxygen are added during oxidation. During later stages of weathering density may decrease as iron is removed. **Figure 2:** (Above Right) Results show a potential correlation between shock state and L-chondrite total porosity; high levels of shock correspond to low porosity values. Shock may contribute to total porosity thorough the formation of fractures and previous research suggests that 6-10% porosity is regularly maintained in ordinary chondrites regardless of shock and that only the most porous meteorites would show a significant reduction in porosity due to shock (Consolmagno *et al.*, 2008). Results are consistent with the literature, although more shock state data are required to confirm this relationship. If meteorite shock state correlates with porosity, brecciation related to shock events may also be expected to correlate with porosity. Porosity data collected in this study does not show any relationship with brecciation.





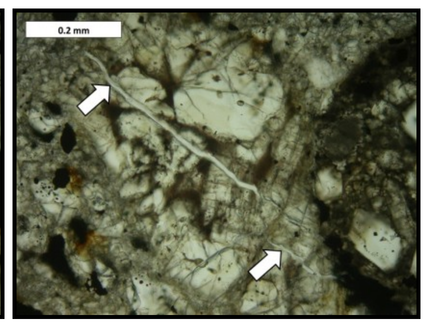
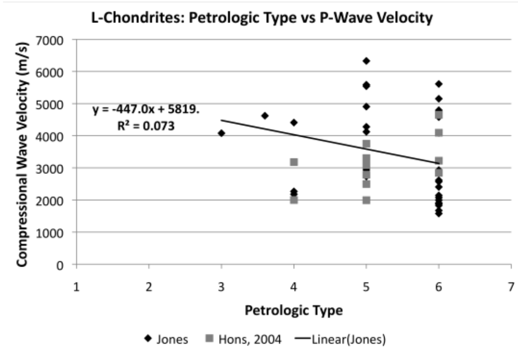


Figure 3: (Above Left) View of large equant to irregular pore spaces in the L5 chondrite Farmington (ASU 48.5 04) (PPL). **Figure 4:** (Above Center) High powered magnification of Chateau-Renard (ASU 333.2) reveal intragranular/intracrystalline porosity less than or equal to 10 μm (PPL). **Figure 5:** (Above Right) Microfractures magnified within a grain in the LL6 chondrite Jelica (ASU 64B.3) (PPL).

Numerous factors may contribute to the decrease in mean elastic wave velocity observed in ordinary chondrites of high petrologic type (Figure 6): total porosity, pore geometry, variation in mineral phases, and recrystallized matrix texture. Data from this study and Yomogida and Matsui (1983) demonstrates that total porosity decreases with increasing petrologic type in H- and L-chondrites; thus the decrease in mean elastic wave velocity at high petrologic type is not due to an increase in total porosity. Pore geometry does not correlate with petrologic type or chemical group in meteorites demonstrating that the decrease in the average elastic wave velocity from petrologic type 5 to 6 is not related to variations in pore geometry. This disproves the hypothesis that variations in meteorite elastic wave velocities and derived elastic moduli are primarily caused by variations in pore geometry. The presence of different pore shapes (in particular, fracture porosity) is shown to influence the elastic wave velocities of meteorites, but does not account for the decrease in average elastic wave velocity observed from petrologic



types 5 to 6. Textural and mineralogical changes are other potential causes for variation in elastic wave velocity that should be investigated in detail in future work.

Figure 6: (Left) Elastic wave velocity decreases in meteorites of high petrologic type. This trend was first documented by Hons (2004) in H-chondrites and has been confirmed in H-chondrites and demonstrated in L-chondrites in this study.

Conclusions

Results from this study confirm elastic wave velocity and porosity trends documented in the literature and demonstrate that derived elastic moduli show analogous trends. In addition, five new physical property, elastic wave velocity, and derived moduli trends in ordinary chondrites were identified. Three pore geometries were documented in meteorites and the occurrence of different pore shapes were compared with meteorite elastic wave velocities. The absence of a correlation between pore geometry, elastic wave velocity, and petrologic type disprove the hypothesis that the decrease in mean elastic wave velocity in meteorites of high petrologic type is related to variation in pore geometry. Future work should include investigation of the effects of mineralogical and textural changes associated with increasing metamorphism/petrologic type on elastic wave velocity in ordinary chondrites.

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