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Enstatite chondrite density, magnetic susceptibility, and porosity

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Abstract–As part of our continuing survey of meteorite physical properties, we measured grain and bulk density, porosity, and magnetic susceptibility for 41 stones from 23 enstatite chondrites (ECs), all with masses greater than 10 g, representing the majority of falls and a significant percentage of all available non-Antarctic EC meteorites. Our sampling included a mix of falls and finds. For falls, grain densities range from 3.45 to 4.17 g cm^{-3}, averaging 3.66 g cm^{-3}; bulk densities range from 3.15 to 4.10 g cm^{-3}, averaging 3.55 g cm^{-3}; porosities range from 0 to 12% with the majority less than 7%, and magnetic susceptibilities (in log units of 10^{-9} m^3 kg^{-1}) from 5.30 to 5.64, with an average of 5.47. For finds, weathering reduces both grain and bulk densities as well as magnetic susceptibilities. On average, finds have much higher porosity than falls. The two EC subgroups EH and EL, nominally distinguished by total iron content, exhibit similar values for all of the properties measured, indicating similar metallic iron content in the bulk stones of both subgroups. We also observed considerable intra-meteorite variation, with inhomogeneities in bulk and grain densities at scales up to approximately 40 g (approximately 12 cm^3).

INTRODUCTION

Enstatite chondrites (ECs), characterized in part by an abundance of nearly FeO-free enstatite, are relatively rare among known meteorites, with only 17 recorded falls (a little over 1% of all meteorite falls) and about 400 finds, mostly Antarctic with only 110 non-Antarctic finds known (Grossman 2009). Most of the iron in ECs is contained within metal grains (Dodd 1981). By analogy of the H-L-LL nomenclature adopted for groups of ordinary chondrites which differ in total iron content, the two groups of ECs were named EH and EL for high-Fe and low-Fe by Sears et al. (1982), though differences between the two groups in chemistry, mineralogy and texture were understood at least as early as the 1960s (Anders 1964; Keil 1968), and the two groups exhibit sufficient differences to establish their origins on separate parent bodies (Keil 1989). The two groups also differ in degree of thermal metamorphism, with most EHs being type 4 or 5 on the petrographic type scheme of Van Schmus and Wood (1967) and most ELs type 6, though representatives for both groups covering the range from type 3 to type 6 are known (e.g., Prinz et al. 1984; Sears et al. 1984; Zhang et al. 1993).

Though many studies on chemistry and mineralogy of ECs have been conducted, there have been relatively few studies of their physical properties, such as density and porosity. To date the only systematic studies have been Guskova (1985) and Rochette et al. (2008). Guskova (1985) measured density and magnetic properties for 21 stones from 10 meteorites in the collections of the Soviet Union, many of which were small and one less than 1 g. Rochette et al. (2008) measured magnetic susceptibilities of approximately 150 stones from 72 meteorites, including many Antarctic finds. No study of porosity conducted under a consistent methodology for a statistically meaningful number of ECs has been conducted before now.

Physical properties, generally measured on bulk samples of greater than 10 g, yield information about the whole rock at scales generally not studied in more detailed chemical analyses. Grain density, the density of the solid component of the meteorite, is effectively a mass-weighted average of the mineral species composing the sample. Porosity is the percentage of the sample occupied by pore space (cracks, voids, and intergranular spaces), and is determined by comparison of grain density with bulk density (the density determined by the total volume enclosed by the sample). Physical properties such as porosity are informative of physical conditions under which the meteorite parent bodies formed and under which they were physically altered, as well as providing information about large-scale structure of analogous asteroids. Magnetic susceptibility, the degree to which a sample exposed to a magnetic field will respond to that field, is also an important physical property. It depends primarily on the quantity of paramagnetic and ferromagnetic materials in the sample, so serves as a good first-order indicator of metallic iron quantity. It is not a perfect indicator, as nonmetallic materials, including phosphides such as schreibersite, may contribute to magnetic susceptibility. Nevertheless, these phases constitute less than 1 wt% of the typical EC (Keil 1968) and so are negligible compared to the contribution of metallic iron. In the case of ordinary chondrites, magnetic susceptibility in conjunction with grain density (also largely dependent on the quantity of dense iron metal relative to less-dense silicates and other phases) has been shown to serve as a viable tool for rapid classification of stones into H, L, and LL subgroups (Consolmagno et al. 2006). The same should occur for EH and EL if the difference in their iron content is significant.

The dearth of studies of EC physical properties is due in part to their relative rarity and to the lack until recently of methods for measuring bulk density that would avoid contaminating or destroying specimens, as would be the case with typical fluid immersion. Consolmagno and Britt (1998) developed a fast, nondestructive, and noncontaminating method for performing these studies on hand-sized stones using small glass beads that collectively behave as an Archimedean fluid. The development of this technique, in conjunction with other fast, nondestructive and noncontaminating techniques for measuring grain density and magnetic susceptibility, has enabled large surveys of many hand-sized stones in major meteorite collections.

With this goal in mind, to date we have visited seven major meteorite collections: the Natural History Museum in London, the Vatican meteorite collection in Italy, the Smithsonian Institution in Washington DC, the American Museum of Natural History in New York, and three university collections at Arizona State University, the University of New Mexico, and Texas Christian University. We have performed physical property measurements on over 1200 stones from over 650 individual meteorites, of which 41 stones were from ECs. All of the stones from ECs exceeded 10 g. Twenty-three distinct EC meteorites were sampled, including 11 of the 17 known falls and a large percentage of the non-Antarctic finds with >10 g stones available for study. Our measurements included 16 stones from nine EH meteorites (five falls, four finds) as well as 25 stones from 14 EL meteorites (six falls, eight finds). This data set provides sufficient statistics of EC physical properties to establish trends caused by weathering and to study whether the EH/EL distinction is manifest in grain density and magnetic susceptibility.

MEASUREMENT

For our density and porosity work, we use the methods developed by Consolmagno and Britt (1998) and outlined in detail in Consolmagno et al. (2008). All of our measurements were performed on-site at various meteorite collections, with the majority of ECs measured at the American Museum of Natural History in New York, the National Museum of Natural History in Washington DC, and the Natural History Museum in London. Because our methods are fast, nondestructive and noncontaminating, we were able to work with numerous hand-sized samples in rapid sequence at minimal risk to existing collections. We measured grain density with helium ideal-gas pycnometry, using a Quantachrome Ultrapycnometer 1000, and bulk density using the glass bead method developed by Consolmagno and Britt (1998) and widely used for meteorite research (cf. Flynn et al. 1999; Wilkison and Robinson 2000; Kohout et al. 2006; Smith et al. 2006). We applied a small bias adjustment to bulk density measurements according to the findings of Macke et al. (2010). Porosity is calculated from bulk and grain densities:

$$\eta = 1 - (\rho_{\mathrm{bulk}}/\rho_{\mathrm{grain}}) \tag{1}$$

Magnetic susceptibility was measured using a ZH-Instruments SM-30 meter, a model that has been calibrated by Gattacceca et al. (2004) and field-tested in Antarctica (Folco et al. 2006) for characterization of meteorites. A geometrical correction using bulk volume and density for small samples was applied to each measurement (Gattacceca et al. 2004).

RESULTS

Grain Density

A summary of all data can be seen in Table 1 and Fig. 1. Grain density ranged from 3.17 to 4.46 g cm^{-3}, with the majority of stones falling between 3.5 and 3.8 g cm^{-3}. This is slightly lower than found in H chondrite falls (3.6 to 3.9 g cm^{-3}) and roughly

Table 1. Enstatite chondrite data.

Meteorite name	Type[a]	Fall?	Collection	Catalog no.	Mass (g)	Bulk density (g cm^{-3})	Grain density (g cm^{-3})	Porosity (%)	Magnetic susceptibility (log χ)
Abee	EH 4[b]	Fall	NMNH	2096	138.65	3.48 ± 0.05	3.63 ± 0.01	4.0 ± 1.5	5.47 ± 0.08
Abee	EH 4[b]	Fall	NMNH	2096	30.497	3.45 ± 0.06	3.52 ± 0.02	1.9 ± 1.7	5.50 ± 0.09
Abee	EH 4[b]	Fall	Vatican	1129	66.88	3.58 ± 0.04	3.67 ± 0.04	2.6 ± 1.4	5.30 ± 0.09
Adhi Kot	EH 4[b]	Fall	AMNH	3993	56.94	3.58 ± 0.14	3.76 ± 0.04	4.7 ± 3.8	5.62 ± 0.09
Adhi Kot	EH 4[b]	Fall	NMNH	2156	16.017	3.65 ± 0.09	3.71 ± 0.03	1.6 ± 2.5	5.51 ± 0.08
Indarch	EH 4	Fall	AMNH	2237	13.44	3.25 ± 0.13	3.67 ± 0.05	11.7 ± 3.7	5.34 ± 0.08
Indarch	EH 4	Fall	LNHM	BM1921,23	77.89	3.55 ± 0.03	3.64 ± 0.01	2.4 ± 0.9	5.47 ± 0.09
Indarch	EH 4	Fall	Monnig	M 731.1	51.50	3.58 ± 0.03	3.65 ± 0.02	1.9 ± 1.0	5.50 ± 0.09
Indarch	EH 4	Fall	NMNH	3482	44.481	3.62 ± 0.05	3.62 ± 0.02	−0.1 ± 1.5	5.63 ± 0.09
Saint-Sauveur	EH 5	Fall	NMNH	7213	31.172	3.62 ± 0.04	3.66 ± 0.03	0.8 ± 1.4	5.47 ± 0.08
St. Mark's	EH 5	Fall	LNHM	BM1916,59	86.46	3.56 ± 0.03	3.74 ± 0.01	4.7 ± 0.9	5.50 ± 0.09
Bethune	EH 4/5	Find	AMNH	4201	12.23	3.14 ± 0.07	3.33 ± 0.04	5.7 ± 2.5	4.53 ± 0.08
Bethune	EH 4/5	Find	LNHM	BM1959,847	26.35	2.89 ± 0.05	3.17 ± 0.02	8.7 ± 1.5	4.43 ± 0.08
Kota-Kota	EH 3	Find	NMNH	7048	16.454	3.53 ± 0.06	3.55 ± 0.03	0.6 ± 2.0	5.35 ± 0.08
Sahara 97096	EH 3	Find	AMNH	4940	44.80	3.24 ± 0.05	3.73 ± 0.04	13.2 ± 1.7	5.61 ± 0.09
Sahara 97158	EH 3	Find	LNHM	BM1997,M8	123.83	3.55 ± 0.06	3.66 ± 0.01	2.9 ± 1.7	5.53 ± 0.09
Daniel's Kuil	EL 6	Fall	AMNH	4241	23.87	3.78 ± 0.04	3.73 ± 0.02	−1.2 ± 1.3	5.48 ± 0.08
Daniel's Kuil	EL 6	Fall	LNHM	BM1985,M143	62.67	3.47 ± 0.03	3.70 ± 0.01	6.4 ± 0.9	5.33 ± 0.09
Eagle	EL 6	Fall	AMNH	4739	14.31	3.50 ± 0.06	3.45 ± 0.03	−1.6 ± 2.1	5.35 ± 0.08
Hvittis	EL 6[c]	Fall	AMNH	4067	36.50	3.35 ± 0.06	3.59 ± 0.04	6.6 ± 1.8	5.55 ± 0.09
Hvittis	EL 6[c]	Fall	Monnig	M 753.1a	48.92	3.50 ± 0.07	3.54 ± 0.01	1.3 ± 1.9	5.41 ± 0.09
Hvittis	EL 6[c]	Fall	NMNH	400	68.182	3.61 ± 0.03	3.58 ± 0.01	−0.7 ± 0.9	5.49 ± 0.09
Hvittis	EL 6[c]	Fall	Vatican	443	51.17	3.36 ± 0.08	3.58 ± 0.04	6.0 ± 2.3	n.d.
Jajh deh Kot Lalu	EL 6	Fall	AMNH	3954	13.80	3.15 ± 0.12	3.57 ± 0.04	11.7 ± 3.6	5.44 ± 0.08
Jajh deh Kot Lalu	EL 6	Fall	LNHM	BM1928,479	31.91	3.36 ± 0.04	3.53 ± 0.02	4.7 ± 1.2	5.36 ± 0.08
Jajh deh Kot Lalu	EL 6	Fall	NMNH	1260	14.913	3.61 ± 0.05	3.53 ± 0.03	−2.2 ± 1.8	5.33 ± 0.08
Khairpur	EL 6	Fall	LNHM	BM51366	29.62	3.63 ± 0.05	3.80 ± 0.02	4.5 ± 1.3	5.57 ± 0.08
Khairpur	EL 6	Fall	NMNH	1055	24.934	4.10 ± 0.06	4.17 ± 0.03	1.5 ± 1.7	5.64 ± 0.08
Pillistfer	EL 6	Fall	AMNH	526	42.60	3.54 ± 0.13	3.74 ± 0.04	5.2 ± 3.7	5.55 ± 0.09
Pillistfer	EL 6	Fall	Monnig	M 544.1	44.14	3.59 ± 0.06	3.65 ± 0.02	1.7 ± 1.6	5.57 ± 0.09
Pillistfer	EL 6	Fall	NMNH	2993	25.571	3.75 ± 0.05	3.66 ± 0.02	−2.4 ± 1.6	5.45 ± 0.08
Atlanta	EL 6[c]	Find	LNHM	BM1959,1001	30.77	3.41 ± 0.09	3.63 ± 0.03	6.2 ± 2.6	5.52 ± 0.08
Atlanta	EL 6[c]	Find	Monnig	M 863.1	27.27	3.43 ± 0.06	3.51 ± 0.02	2.2 ± 1.7	5.33 ± 0.08
Blithfield	EL 6[c]	Find	AMNH	646	111.8	3.48 ± 0.06	3.50 ± 0.04	0.4 ± 1.9	5.09 ± 0.09
Blithfield	EL 6[c]	Find	NMNH	534	37.259	4.50 ± 0.09	4.46 ± 0.03	−0.9 ± 2.2	5.64 ± 0.08
Happy Canyon	EL 6/7[b]	Find	NMNH	5820	10.593	3.11 ± 0.06	3.32 ± 0.04	6.2 ± 2.2	4.64 ± 0.08
Ilafegh 009	EL	Find	AMNH	4757	35.30	3.54 ± 0.06	3.68 ± 0.04	3.8 ± 1.9	5.58 ± 0.09
North West Forrest	EL 6	Find	LNHM	BM1989,M27	78.47	2.89 ± 0.05	3.28 ± 0.01	12.0 ± 1.5	4.10 ± 0.09
NWA 2965	EL 6/7	Find	Monnig	M1326.1	40.98	3.07 ± 0.04	3.33 ± 0.02	7.9 ± 1.2	4.47 ± 0.09

Table 1. *Continued*. Enstatite chondrite data.

Meteorite name	Type[a]	Fall?	Collection	Catalog no.	Mass (g)	Bulk density ($g\ cm^{-3}$)	Grain density ($g\ cm^{-3}$)	Porosity (%)	Magnetic susceptibility ($\log \chi$)
NWA 3132	EL 3	Find	CMS	1506	21.26	2.93 ± 0.05	3.23 ± 0.02	9.2 ± 1.5	4.67 ± 0.08
Yilmia	EL 6	Find	IOM	C 89.2	72.21	3.14 ± 0.06	3.31 ± 0.01	5.0 ± 1.7	4.99 ± 0.09

Enstatite chondrite data from samples in this survey. Where porosities have negative values, they are effectively zero. Abbreviations for meteorite collections are as follows: AMNH = American Museum of Natural History, New York NY; CMS = Center for Meteorite Studies, Arizona State University, Tempe AZ; IOM = Institute of Meteoritics, University of New Mexico, Albuquerque NM; LNHM = The Natural History Museum, London UK; Monnig = Monnig Meteorite Collection, Texas Christian University, Fort Worth TX; NMNH = Smithsonian Institution—National Museum of Natural History, Washington DC; Vatican = Vatican Meteorite Collection, Specola Vaticana, Vatican City State.

[a]Petrologic types are based on the Meteoritical Bulletin Database (Grossman 2009).

[b]Impact melt breccia (Rubin et al. 1997).

[c]Breccia.

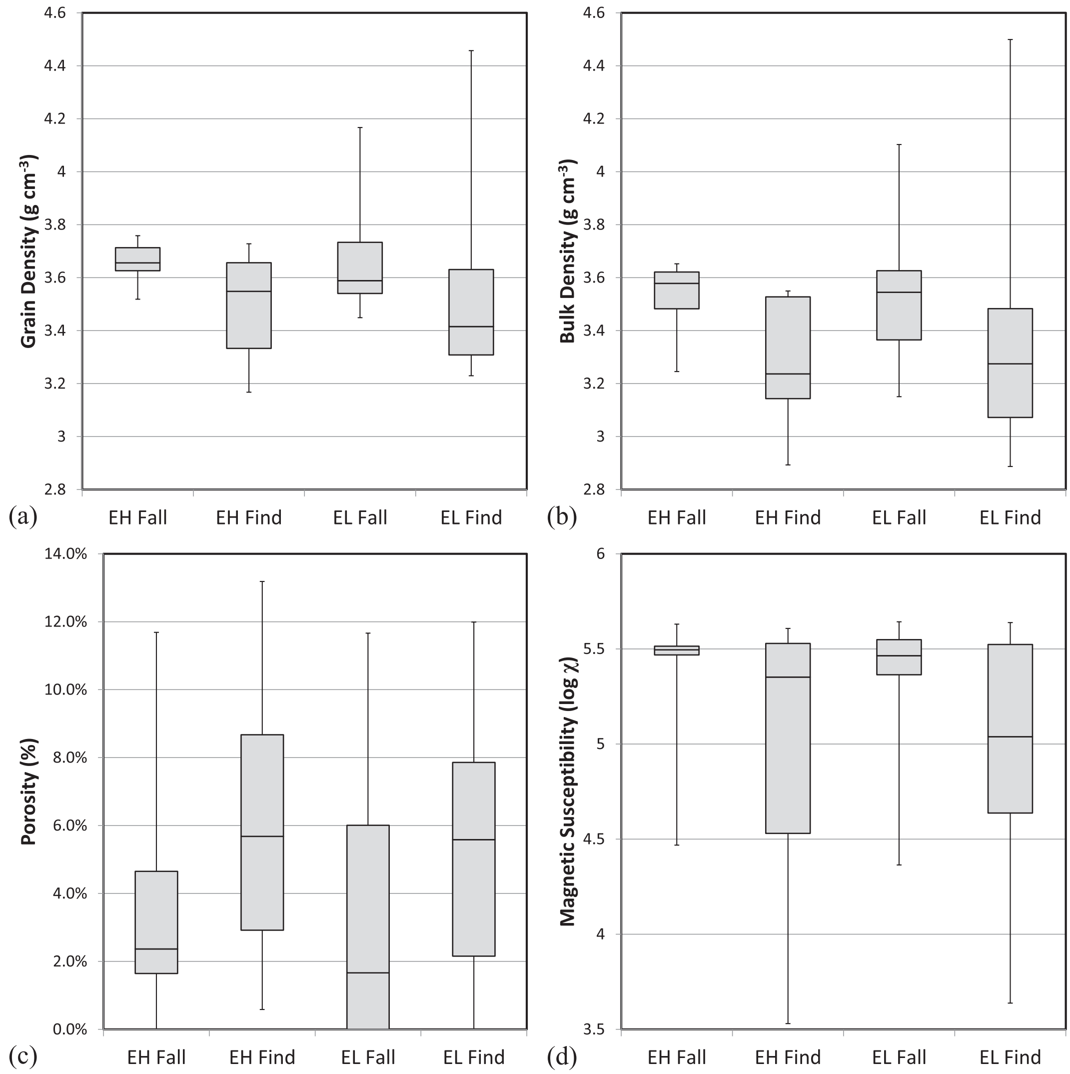

Fig. 1. Results for individual stones in the survey: (a) grain density results, (b) bulk density, (c) porosity, and (d) magnetic susceptibility. The grey box represents 50% of the sample population, and the central bar is the median value. The vertical lines above and below each box represent the full range of the sample population.

comparable to L falls (3.5 to 3.9 g cm^{-3}). Enstatite chondrite finds exhibit significantly reduced grain density compared with falls (Fig. 1a). The average grain density for finds is 3.51 g cm^{-3}, which is significantly lower than the average for falls at 3.66 g cm^{-3}. That being said, one stone of the EL find Blithfield had an anomalously high grain density of 4.46 g cm^{-3}. This drop in grain density in finds has not previously been observed in ECs due to low statistics (Consolmagno et al. 2008). Nevertheless, it is generally well-understood as the result of weathering of iron which expands as it oxidizes and has been well-studied in ordinary chondrites (Bland et al. 1998, 2006; Consolmagno et al. 1999).

Since our data indicate that finds are no longer representative of the original densities of the meteorites, we restrict further discussion of grain density to falls. EH and EL grain densities, while not identical, are quite similar and exhibit substantial overlap (Fig. 1a). The average grain density for EH falls was 3.66 g cm^{-3}, with a standard deviation of 0.06 g cm^{-3}, while for EL falls it was 3.65 g cm^{-3} with a standard deviation of 0.17 g cm^{-3}. Even eliminating the somewhat anomalous sample of Khairpur (4.17 g cm^{-3}), the average EL fall is 3.62 g cm^{-3} with a standard deviation of 0.10 g cm^{-3}. The range for EH falls is from 3.52 g cm^{-3} to 3.76 g cm^{-3}, and for EL falls (not counting the aforementioned sample of Khairpur) is 3.45 g cm^{-3} to 3.80 g cm^{-3}.

Bulk Density

Bulk density results follow the same trends established under grain density. Bulk density for the entire population ranged from 2.85 g cm^{-3} to 4.50 g cm^{-3}, with the majority of stones falling between 3.35 g cm^{-3} and 3.65 g cm^{-3}. As with grain density, EC finds exhibit a significant reduction in bulk density as compared with falls (Fig. 1b), with the average bulk density for all falls being 3.55 g cm^{-3}, and the average for finds 3.32 g cm^{-3} (including the anomalously high bulk density of the aforementioned Blithfield stone). This is unlike comparable results for ordinary chondrites, where no substantial change in bulk density is anticipated or observed as a result of weathering (Consolmagno et al. 1998).

Again, EH and EL falls do not exhibit strong differences in this property. The average bulk density for EH falls is 3.54 ± 0.11 g cm^{-3} (with "±" representing one standard deviation of sample values), and for all EL falls it is 3.55 ± 0.22 g cm^{-3}. Eliminating the high value for the same Khairpur stone as before, it is 3.51 ± 0.17 g cm^{-3}. The range for EH falls is 3.25 g cm^{-3} to 3.65 g cm^{-3}, and for EL falls (minus Khairpur) it is 3.15 g cm^{-3} to 3.78 g cm^{-3}.

Porosity

Porosities for ECs are on the low end for the chondrite group. Measured porosities in this survey ranged from effectively 0 to 13%, with most stones falling below 7%. By comparison, ordinary chondrites average about 9% porosity with a range that exceeds 20%, and carbonaceous chondrites tend to much higher porosities. Consolmagno et al. (2008) noted the possibility of two populations of ECs; one with relatively high porosity (above 10%) and one with low (below approximately 6%), but cited the need for more statistics. We do not see such a trend in these data. Only four stones exceeded 10%, two of which belong to meteorites with multiple stones included in the survey, but are the only members of their group to have high porosity. We do, however, see an unexpected trend with regard to finds. Rather than a reduction in porosity, finds exhibit on average an enhanced porosity (Fig. 1c). The average EC fall has a porosity of 3%, with a range from 0 to 11.7%. The average find has a porosity of 5.5%, with a range from 0 to 13.2%, and with most stones exhibiting porosities greater than 2%. Finds include the two stones (Sahara 97096 and North West Forrest) with the highest porosity measured in this survey. Porosity enhancement in finds correlates well with the reduction in bulk density mentioned above.

The EH and EL fall populations have very similar porosities. Both range between 0 and 11.7%, with an average value of about 3% All but one of the EH falls in this study exhibit porosities below 5%, while all but one of EL falls lies below 7%, with four stones between 5% and 7%. Given measurement uncertainties typically exceeding 1%, we do not recommend reading too much into this small discrepancy.

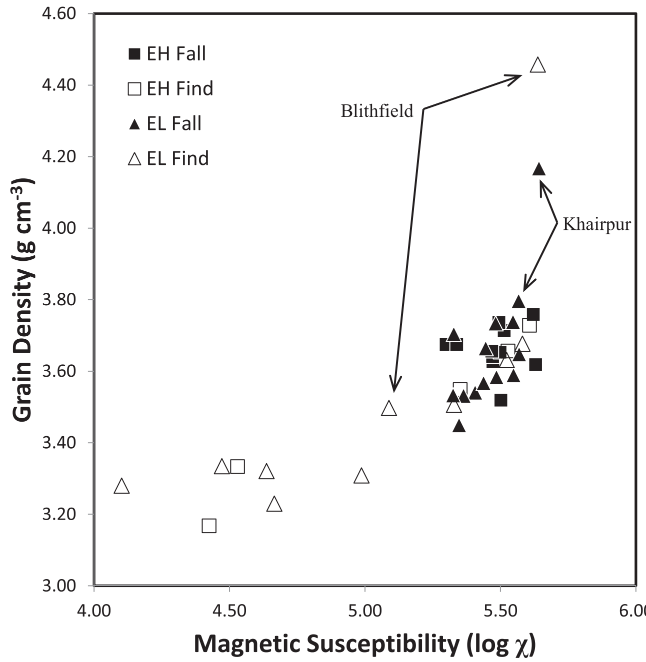

Fig. 2. Grain density vs. magnetic susceptibility results for the samples in the survey. The effects of weathering on iron reduce both grain density and magnetic susceptibility, thus resulting in the large population of finds occupying the lower left region of the plot.

Magnetic Susceptibility

Magnetic susceptibilities are reported in log units of 10^{-9} kg^3 m^{-1}. Values ranged from 4.10 to 5.64, with most stones between 5.3 and 5.6. The effect of weathering on finds is most observable in magnetic susceptibility as a severe reduction (Fig. 1d), due to the loss of magnetic components in the material. In a plot of grain density against magnetic susceptibility (Fig. 2), both of which vary with metallic iron content, it is apparent that the reduction in magnetic susceptibility correlates with that of grain density, though the effect is much more pronounced in magnetic susceptibility. Falls averaged 5.47, with a range from 5.30 to 5.64, while finds averaged 5.03, with a range from 4.10 to 5.64. EH and EL falls are again quite similar. EH fall magnetic susceptibilities averaged 5.48, ranging from 5.3 to 5.63, and EL fall values averaged 5.46, ranging from 5.33 to 5.64. The averages for the two groups of falls are the same as those reported by Rochette et al. (2008) for falls in their survey. Eliminating the previously discussed Khairpur stone, the EL range goes from 5.33 to 5.57, averaging 5.45.

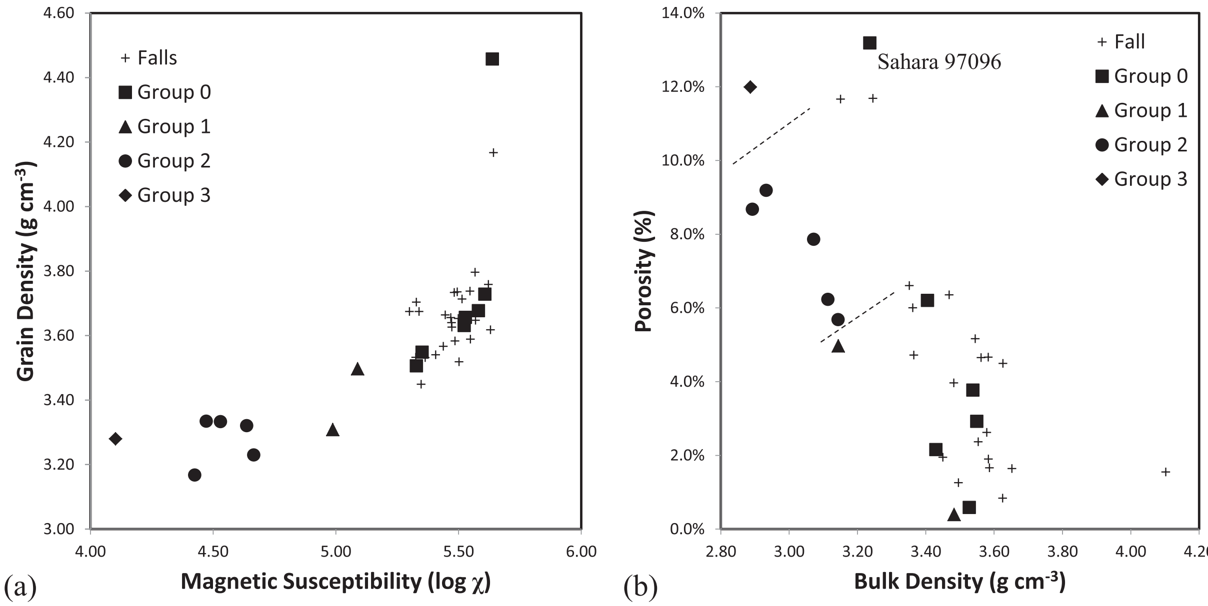

Fig. 3. Weathering results for EC finds. (a) Arbitrary subdivision of EC finds into four groups, based on magnetic susceptibility (an indicator of degree of weathering). Group zero is comparable to EC falls, and groups 1 through 3 are numbered according to relative degree of weathering. The group numbers are not intended to match published weathering states. (b) Porosity and bulk density for the four weathering groups of EC finds. The groups correlate well with observed trends of increased porosity and decreased bulk density for more weathered stones. Dashed lines have been included to separate groups 1, 2, and 3. Oddly, one group-zero find (Sahara 97096, from the AMNH collection) exhibits high porosity comparable to two stones from the falls. Only one stone of Sahara 97096 was measured in this survey. It is likely that other stones from that meteorite would probably lie among the main population, as is the case with additional stones from the two neighboring falls.

DISCUSSION

Weathering Effects on Finds

As noted, weathered finds exhibit on average a reduced grain density, bulk density and magnetic susceptibility, and an increased porosity. It is difficult to correlate these effects to established weathering states, for a number of reasons. First, only a few meteorites from this set have had determinations of weathering states made. Even in those cases, weathering determinations were made for stones other than those measured in this survey, and weathering effects can differ for stones of differing volumes. In addition, criteria for determining weathering states are not well-established and rely to some degree on the personal judgment of the investigator.

Though we cannot easily link our data to established weathering states, we can determine a rough degree of weathering for all stones, and establish how the degree of weathering affects trends in physical properties. Because the weathering effect on magnetic susceptibility due to oxidation of metallic iron in iron-rich meteorites is well understood (Consolmagno et al. 2006) and is the most pronounced of the four effects, we arbitrarily subdivided the EC finds into four groups based on that property, as in Fig. 3a. Group 0 exhibits minimal alteration, and group 3 is the most severely altered. By coincidence of the data, there are recognizable gaps between each of the groups. The three meteorites with recorded weathering states are in the following groups: Ilafegh 009 (W0/1) and Sahara 97096 (W1) are in group 0, and Northwest Africa (NWA) 3132 (W4) is in group 2.

The weathering effects of all four properties in this survey correlate with each other. Grain density correlates somewhat with magnetic susceptibility (Fig. 3a), though the effect on grain density is clearly less pronounced that that of magnetic susceptibility. This is quite reasonable if the primary effect of weathering is oxidation of metals. As iron oxidizes (reducing magnetic susceptibility), it expands, thus increasing grain volume without significantly affecting total mass, and so grain density is reduced.

Trends in bulk density and porosity are also related to degree of weathering (Fig. 3b). Group 0, as expected, aligns with falls. Groups 1 through 3 are clearly distinguished on the bulk density/porosity plot, and progress along a trend toward decreased bulk density and increased porosity as weathering state increases. This is the first time such a trend has been observed, because it is the first time enough statistics have been gathered to make the trend visible.

The results for bulk density and porosity, unlike those for grain density and magnetic susceptibility, are somewhat unexpected. To first order, oxidized metals should expand into available pore space, reducing porosity while not substantially affecting bulk density, as is observed in ordinary chondrites (Bland et al. 1998; Consolmagno et al. 1998). Two possible explanations exist for the observed trends in ECs. The first is an extension of the standard model for weathering. Enstatite chondrites begin with very low porosity, so that even minor weathering would fill what pore space exists. With further weathering, the expanding iron oxides would force apart the meteorite, cracking it and introducing new pore space while at the same time increasing the bulk volume and hence decreasing bulk density. The question here is how much of this expansion can take place before the structural integrity of the stone is compromised and the stone disintegrates. None of the samples in this survey were excessively friable, and so this explanation begs the question of why that would be the case. The second possibility is that materials are leached out during weathering. One obvious candidate mineral is oldhamite (CaS), which is so water soluble that samples of the EH4 fall Parsa exhibited signs of oldhamite loss due simply to moisture in the environment where it was stored (Bhandari et al. 1980). "Pits" left over from oldhamite leaching were observed in Yilmia (Buseck and Holdsworth 1972). Oldhamite alone is insufficient to account for the observed effects, however. First, it is not so abundant to account for the excess porosity; literature values place its abundance in falls between 0 and 2 wt% (Keil 1968; Bhandari et al. 1980; Rubin 1983a,c; Rubin and Keil 1983; Rubin et al. 1997). Assuming the maximum 2% original abundance and total loss, this can account for less than 3% porosity. This also assumes that oxidation products from metals do not fill in the new cavities, which is not a reasonable assumption as oxidation products have been observed even in mildly weathered falls (cf. Bhandari et al. 1980). Second, oldhamite is a low-density phase compared to the average EC grain density, so its loss would actually increase grain density. Finally, it would not be able to account for the considerable drop in magnetic susceptibility of more than 1.5 orders of magnitude. To account for all of the observed effects through leaching, it is necessary that metals rather than merely accessory phases are leached out during weathering. These two possibilities (cracking versus leaching) can be resolved by further studies aimed at characterizing the amount of oxides present in weathered finds.

Heterogeneity

Where multiple stones from an individual meteorite have been measured, results have varied widely, much more than is typical in other chondrites. For those meteorites with multiple stones measured, the bulk density range was on average 0.3 g cm^{-3}, grain density range was 0.2 g cm^{-3}, porosity 6%, and magnetic susceptibility 0.17, all of which exceed individual measurement uncertainties. The range is exaggerated among finds compared to falls, not a surprising result given the variable effect of weathering on different sized stones, though weathering is not the only source of heterogeneity.

For particular meteorites, variability is even more extreme than described above. The most extreme example, Blithfield, ranges about 1 g cm^{-3} in both bulk density and grain density, and ranges in magnetic susceptibility by about 0.55 (a factor of about 3.5). This inhomogeneity is not atypical for Blithfield, which is an impact-melt breccia with large troilite-rich clasts (Rubin 1984); one small sample studied by Keil (1968) had an anomalously low iron content of 12.9 wt%, much lower than the approximately 25 wt% average for the other type IIs in his study. This has been attributed to the fact that the sample studied by Keil was one of these troilite-rich clasts (Rubin 1984). For a truly representative sample of Blithfield, as much as 200 g may be required (Rubin, personal communication). While Blithfield may be the most inhomogeneous meteorite in this study, it is not the only one to exhibit large variability. Many other ECs are breccias, including Abee (Dawson et al. 1960; Rubin and Keil 1983), Adhi Kot (Rubin 1983a), Atlanta (Rubin 1983b), Hvittis (Rubin 1983c), and Happy Canyon (Rubin et al. 1997), which may account for much of the inhomogeneity, though nonbrecciated ECs also exhibit considerable variability between stones. Khairpur is not listed as a breccia, but of the two stones measured, one 24.9 g stone is anomalously high in both grain density and magnetic susceptibility, as described in preceding sections of this paper.

Hutson (1996) compiled literature data from seven separate studies of EC elemental abundances and observed a large degree of intra-meteorite variability in bulk chemical abundances, in particular in iron and sulfur. These were attributed to the fact that all of the analyses had been performed on samples below 8 g. Jarosewich (1990) observed in the context of ordinary chondrites that for meteorites with coarse iron grains the inclusion or exclusion of individual iron grains may skew results, and recommended a minimum mass of 10 g for homogeneity. Many ECs have very coarse metal grains, with EL grains much coarser than EH

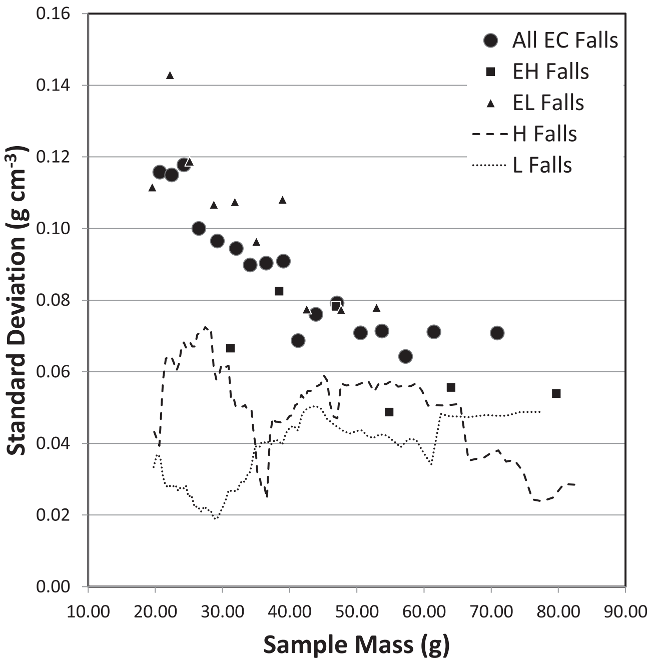

Fig. 4. Variability of EC grain densities by mass. For comparison purposes, H and L ordinary chondrite data are overlaid. Data were ordered by mass, and running bins created (ten stones per bin for EC, five for EH and EL, and twenty each for H and L, with bin sizes based on total number of stones per group), from which the standard deviation of grain densities was calculated. The sample mass is the average mass per bin. While OC standard deviations are relatively flat, indicating no increased inhomogeneities among smaller masses, EC standard deviations (particularly influenced by EL) do vary by mass, indicating inhomogeneities for masses below ~40 g.

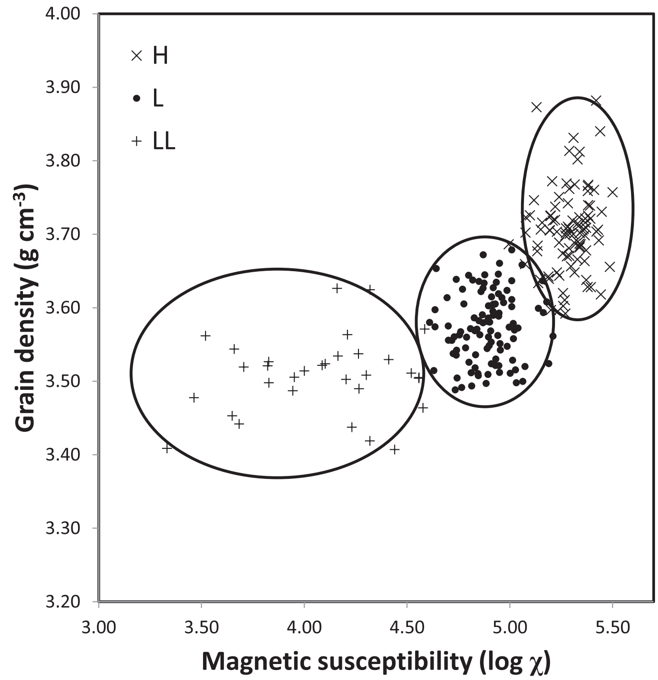

Fig. 5. Grain density and magnetic susceptibility for ordinary chondrite falls. Due to clear differences in metallic iron content, H, L, and LL groups are distinguished in three regions of the plot, each encircled.

(Easton 1983), and so this effect must be taken into consideration. (Easton's work expresses a difference due to petrographic type, since all ELs in the work were type 6 and all EHs were type 4–5, but this does not invalidate the statement, since as a population ELs are dominated by type 6 and EHs are dominated by lower petrographic types, and the "definitive" studies of the chemical and mineralogical differences between EH and EL were performed on EL6 and EH4-5 stones. In addition, there are indications that the size difference may not be solely due to petrologic type and even EL3 metal grains are larger than EH3 grains [Schneider et al. 1998].) Nevertheless, all the stones in our survey exceeded 10 g, some by an order of magnitude, and so we conclude that the variability we observe is due to larger-scale causes.

We have compared the variation in grain density with sample mass for EC falls (Fig. 4), and find not only that the standard deviation of grain density results increases with decreasing mass, but that it exceeds similar results for H and L falls. The data exhibit scale-dependent variability that levels out above approximately 40 g. This indicates that the samples exhibit scale-dependent inhomogeneities at low masses, and we consider the minimum mass for a representative homogeneous sample to be 40 g. Also plotted in Fig. 4 are EH and EL fall data, from which it is apparent that EL falls are considerably more inhomogeneous than EH falls. We observe a similar effect in bulk density, for masses up to approximately 60 g, though that physical property may be strongly influenced by porosity variations as well as mineralogical differences and so is not included here. Curiously, we do not see any scale-dependent effects in magnetic susceptibility, and Rochette et al. (2008) only observed heterogeneity below 1 g. The reason for the discrepancy eludes us, though grain density data alone are sufficient to establish that EC falls are heterogeneous below 40 g.

Grain Density, Magnetic Susceptibility, and Metallic Iron Content

Since both grain density and magnetic susceptibility vary with the amount of metallic iron present in a sample, together they give a respectable first-order indicator of relative amounts of iron metal present in various meteorites. In the case of ordinary chondrites, the difference in metal between H, L, and LL falls results in three distinct populations on a grain density – magnetic susceptibility plot (Fig. 5). If the EH-EL

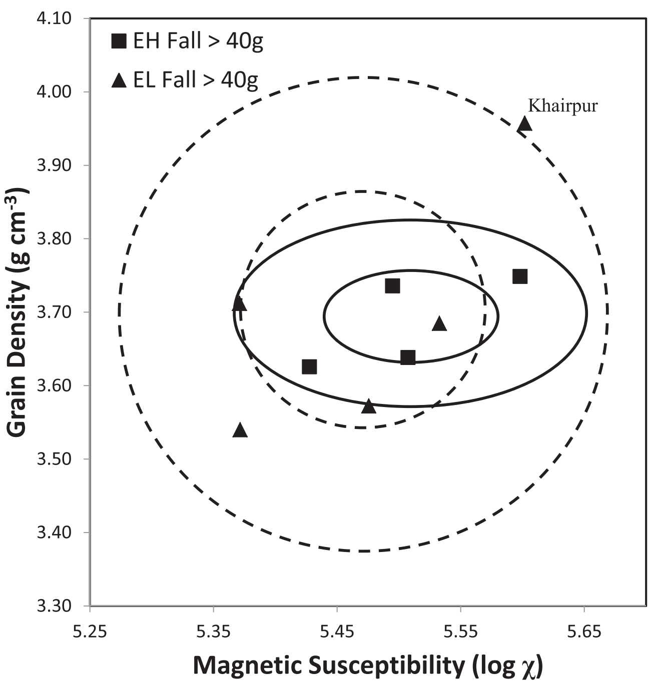

Fig. 6. Mass-weighted average grain density vs. magnetic susceptibility for falls exceeding total mass of 40 g. The ovals represent 1-σ and 2-σ from the mean for (solid) EH and (dashed) EL.

distinction is truly analogous to the H-L-LL distinction among ordinary chondrites, then they too should group in two distinct populations. We do not observe this, as can be seen in Fig. 6. For that figure, we used mass-weighted meteorite averages (Table 2) of only those meteorites for which we measured more than 40 g. This has the disadvantage of considerably reduced statistics over the use of individual stones (there are only four EH and five EL data points), but it resolves doubts that may arise from the inherent variability among stones. The basic result does not change if individual stones are included. The two populations overlap so closely as to be unable to distinguish whether the small observed difference in population averages is real or a result of statistics of small numbers. They do not spread into distinct groups.

Taking our results to be representative, we see a slight difference between EH and EL populations, with EH slightly higher in both grain density and magnetic susceptibility, but a substantial overlap between the two. Grain density averaged (by meteorite, not by stone) 3.69 g cm^{-3} for EH, with one standard deviation of 0.06 g cm^{-3}, and averaged 3.69 g cm^{-3} with standard deviation of 0.16 g cm^{-3} for EL. Magnetic susceptibility averaged 5.51 ± 0.07 for EH and 5.47 ± 0.10 for EL. We note that the EL population contains Khairpur,

Table 2. Weighted-average properties for enstatite chondrites in this survey.

Meteorite name	Type	Fall?	Number stones	Total mass (g)	Bulk density (g cm^{-3})	Grain density (g cm^{-3})	Porosity (%)	Magnetic susceptibility (log χ)
Abee	EH 4	Fall	3	236.03	3.50	3.63	3.3	5.43
Adhi Kot	EH 4	Fall	2	72.957	3.60	3.75	4.0	5.60
Indarch	EH 4	Fall	4	173.87	3.58	3.64	1.6	5.51
Saint-Sauveur	EH 5	Fall	1	31.172	3.62	3.66	0.8	5.47
St. Mark's	EH 5	Fall	1	86.46	3.56	3.74	4.7	5.50
Daniel's Kuil	EL 6	Fall	2	86.54	3.55	3.71	4.4	5.37
Eagle	EL 6	Fall	1	14.31	3.50	3.45	−1.6	5.35
Hvittis	EL 6	Fall	4	204.77	3.47	3.57	2.8	5.48[a]
Jajh deh Kot Lalu	EL 6	Fall	3	60.623	3.37	3.54	4.8	5.37
Khairpur	EL 6	Fall	2	54.554	3.83	3.96	3.2	5.60
Pillistfer	EL 6	Fall	3	112.31	3.61	3.68	2.1	5.53
Bethune	EH 4/5	Find	2	111.54	3.35	3.55	5.5	4.46
Kota-Kota	EH 3	Find	1	16.454	3.53	3.55	0.6	5.35
Sahara 97096	EH 3	Find	1	44.8	3.24	3.73	13.2	5.61
Sahara 97158	EH 3	Find	1	123.83	3.55	3.66	2.9	5.53
Atlanta	EL 6	Find	2	144.5	3.50	3.67	4.5	5.43
Blithfield	EL 6	Find	2	149.06	3.69	3.70	0.1	5.23
Happy Canyon	EL 6/7	Find	1	10.593	3.11	3.32	6.2	4.64
Ilafegh 009	EL 7	Find	1	35.3	3.54	3.68	3.8	5.58
North West Forrest	EL 6	Find	1	78.47	2.89	3.28	12.0	4.10
NWA 2965	EL 6/7	Find	1	40.98	3.07	3.33	7.9	4.47
NWA 3132	EL 3	Find	1	21.26	2.93	3.23	9.2	4.67
Yilmia	EL 6	Find	1	72.21	3.14	3.31	5.0	4.99

[a]Magnetic susceptibility for Hvittis is based on three stones, total mass 154 g.

which lies outside the 2-sigma radius (Fig. 6). Omitting it, the average EL grain density drops to 3.63 ± 0.08 g cm^{-3} and the average EL magnetic susceptibility becomes 5.44 ± 0.08. The similarities between EH and EL in both magnetic susceptibilities and grain densities implies no substantial difference in metallic iron quantities. We point out also that some ELs have grain density and magnetic susceptibility values that exceed that of some EHs, indicating that in those instances the ELs actually have more metallic iron than the EHs.

Using individual stones of all available masses rather than average meteorite values, the difference on average between populations is even less. In this case, the average grain densities are 3.66 g cm^{-3} (EH) and 3.65 g cm^{-3} (EL), and average magnetic susceptibilities are 5.48 (EH) and 5.46 (EL), with slightly larger standard deviations than the >40 g populations.

Rochette et al. (2008) were the first to note the almost identical magnetic susceptibility values for EH and EL populations and to infer from the data that the groups do not differ in quantity of iron metal. They did not question the literature with regard to the total iron quantity of the two populations, and they posited that the reported differences in iron were likely due to nonmetallic sulfide-bearing phases such as troilite (FeS). They also cited the similarities in grain density between the two groups (based on literature data) as confirmation of this. However, given the fact the density of troilite at 4.9 g cm^{-3} is higher than the average EC density of approximately 3.65 g cm^{-3}, any sizeable difference in the quantity of the mineral should appear as a recognizable difference in meteorite grain density.

In order to better understand how grain density and iron content vary with mineralogy in ECs, we constructed a simple model based on a mixture of nearly pure enstatite at 3.1 g cm^{-3}, pure kamacite (7.9 g cm^{-3}) to represent the metal, troilite (4.9 g cm^{-3}), and 8 wt% plagioclase (2.7 g cm^{-3}), based on abundances given in Mason (1966). We varied the kamacite and troilite percentages, leaving enstatite as the dependent quantity. We chose to use the same metallic iron quantity (21.5%, close to values determined by Keil 1968) to represent both EH and EL, and varied the amount of troilite. In this case, a 3.5 wt% difference in the abundance of troilite (from 7.5% to 11%) accounted for the difference between the average values of the two groups of 3.69 and 3.63 g cm^{-3}. This difference corresponds to a difference of only 2.2 wt% in total Fe between the two groups (26.2% and 24.0%, respectively). (If we consider the averages among individual stones instead of whole meteorites, the differences between the populations fall to less than 1% for troilite and less than 0.7% for total Fe.) This model is relatively insensitive to the abundance values chosen; for a specified metallic abundance, the observed difference in grain densities can be achieved by varying the troilite abundance by approximately 3.5–4%.

This model is not perfect, as it omits a number of less-abundant mineral phases. To exemplify this, the sulfur abundances according to the models are 4% (EH) and 2.7% (EL), while values from the literature (compiled in Hutson 1996) average 5.3% and 3.1%, respectively. Some of this difference can be accounted for with the incorporation of varying amounts of other sulfide-bearing phases such as oldhamite (CaS). Nevertheless, a few important conclusions can still be drawn from the model. First, if the observed difference in average grain density is to be achieved by iron metal alone, the difference in metal quantity must be very small (about 2%). Also, in that case the troilite variation between the two groups must also be very small (much less than 3.5%) which is not consistent with the literature (cf. Mason 1966). Second, even keeping the metallic iron quantities the same, the variation in troilite is not very dramatic, and the resulting difference total iron abundance of just over 2% is nowhere near as pronounced as some researchers have implied.

We would like to point out also that the meteorite-to-meteorite variation implies a considerable range of iron abundances within both EC subgroups. Based on grain densities alone, the range in total Fe abundance between EH falls for which we measured more than 40 g is anywhere from 4% to 5%, depending whether it is metal or troilite that varies, and for EL falls the range is anywhere from 6% to 7% (omitting Khairpur). With smaller stones taken into account, EH falls vary by as much as 8–9% Fe and EL falls vary by as much as 12–13%. Much of this variation is likely due to differences in metal between individual meteorites, as exemplified by the corresponding range of magnetic susceptibilities, though some of the variation is also likely due to troilite.

Our results here are consistent with some other findings as well. Most notably, Keil (1968) performed a study of chemical abundances in ECs using electron microprobe X-ray analysis of meteorite thin sections. He analyzed 3 "type I" (EH) meteorites, and 7 "type II" (EL). He found an average 25.3 wt% Fe for type I, and 23.3 wt% Fe for type II, with substantial variation among the two groups—with standard deviations of 3.6 wt% for type I and 6.0 wt% for type II. His data include finds as well as falls, and one sample of Blithfield is clearly anomalous, with only 12.9 wt% Fe and a total metal abundance an order of magnitude lower than all other samples in the study. Eliminating this, the average iron in Keil's type II group increases to 25.1 wt% (standard deviation 4.4%). We also note that the sample in Keil's study with the highest measured iron content belonged to an EL, not an EH. Using Keil's (1968) mineral abundances with fresh averages calculated for the EH and EL falls, we modified our simple model to include other minor phases. This produced average grain densities of 3.63 g cm^{-3} for EL and 3.68 g cm^{-3} for EH and total Fe abundances at 24.1 wt% and 26.0 wt% for EL and EH, respectively, with a standard deviation among individual meteorites of 5 wt% and 3 wt%, respectively. This indicates both that Keil's data are consistent with our own and that our model produces Fe abundances that are reasonably consistent with the modal analysis. In addition, Hutson (1996) measured elemental abundances in large-area thin-sections of an EH (Qingzhen) and an EL (MacAlpine Hills 88136), each of petrographic type 3 and with minimal weathering, and found iron abundances within measurement uncertainties of each other.

This of course raises the question of why some earlier studies have exhibited more pronounced differences in iron quantity. In one of the definitive studies of chemical abundances in ECs, Kallemeyn and Wasson (1986) observe a notable hiatus in Fe/Mg ratios between EH and EL, which differ from each other by a factor of almost 2. Fe/Si ratios also differ at 0.9 and 0.6, respectively. We note that the magnesium-normalized abundances are in part influenced not only by absolute Fe, but by absolute Mg as well which exaggerates the difference. Wasson and Kallemeyn (1988) list individual element abundances, and Mg is more abundant in EL than EH by a factor of 1.3 on average. Si abundances follow a similar trend. They still observed a difference in absolute Fe between the groups (290 mg g^{-1} for EH and 220 mg g^{-1} for EL). This is a difference of 7 wt% in absolute abundance, and a relative difference between the two of about 30%. This discrepancy is still large enough to beg for an explanation.

We do not question the instrumental accuracy of the neutron activation analysis that they and other researchers performed. One possible explanation is that the excess Fe is hidden in nonmetallic phases that do not significantly affect grain density or magnetic susceptibility, though the studies by Keil (1968) and Hutson (1996) should then testify to the difference if it is present, which they do not. Another possibility that must be seriously considered is that of sample bias when preparing small quantities of material for analysis. We remind the reader that Jarosewich (1990) observed in studies of ordinary chondrites the need for representative samples of 10 g or more to properly accommodate metal grain sizes. We present one possible scenario in which biases could be introduced in sample preparation. The instrumental neutron activation analysis techniques employed by Kallemeyn and Wasson, which are described in detail in Kallemeyn et al. (1989), make use of 250–300 mg sample sizes. They note that, due to inclusion or omission of metal grains, Fe and siderophile abundances in ordinary chondrites may vary by 10% (Kallemeyn et al. 1989). Given large metal grains in ECs and the fact that Fe and siderophiles are more depleted in EC silicate phases than in those of OCs, this may influence results of ECs to an even greater extent. Hutson (1996) posits that in studies performed on small EC samples, coarse metal grains are biased against in the sampling. In describing their method for sample preparation, Kallemeyn and Wasson (1986) note that on the unsawn surfaces of their 250–300 mg chunks, they removed any visible "rusty patches." These rusty patches may have originally been metal grains, and their removal (coupled with natural removal of surface metal grains due to weathering) may negatively influence total Fe. Since EL6 metal grains are larger than EH4-5, it is at least conceivable that more Fe was removed from EL than EH, exaggerating the difference.

The question of the true degree of Fe difference and where the difference resides can be better resolved through modal abundance studies utilizing large thin sections of representative sizes. None of these results should be taken to imply that there is no difference between the two groups of enstatite meteorites classified as EH and EL. That there are two distinct populations of ECs was recognized by Anders (1964) long before the EH/EL nomenclature was adopted. Given their significant systematic trace element differences, it is almost certain that they even come from different parent bodies (Keil 1989). However, the density and magnetic susceptibility trends now indicate that these differences are not related to a systematic difference in Fe or metal content.

CONCLUSIONS

Enstatite chondrites have not yet divulged all they have to tell us. We see in this study intriguing trends that call for further study of this class of meteorite. The counterintuitive weathering trend in bulk density and porosity of finds itself raises important questions, such as the underlying cause of the trend of increasing porosity with weathering and how, if the weathering is due to expansion of oxidized iron to form new cracks, the stone maintains its structural integrity and how far the process can continue before disintegration.

The similarity we observe in these properties, especially grain density and magnetic susceptibility, between EH and EL subgroups at the scale of bulk stones also calls for further study of iron as well. If there is a genuine difference in iron, why do we not see it? Is it fully accounted for by the presence of nonmetallic iron-bearing minerals such as troilite? Or is the discrepancy between our work and the literature due to sample bias for small fragments used in many of the past analyses?

Our homogeneity results present a word of caution for investigators. Many forms of analysis, such as neutron-activation analysis, provide high-precision results for very small samples, and so have become favored for such analyses, but when the meteorite in question exhibits variability at decagram scales, the possibility for bias in small samples cannot be ignored. We consider the need for representative sizes for future studies. One viable method is scanning electron microscope analysis of thin sections of surface area comparable to the cross section of a typical decagram stone or larger.

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REFERENCES

Anders E. 1964. Origin, age and composition of meteorites. *Space Science Review* 3:583–714.

Bhandari N., Shah V. B., and Wasson J. T. 1980. The Parsa enstatite chondrite. *Meteoritics* 15:225–233.

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. Climate and rock weathering: A study of terrestrial age dated ordinary chondritic meteorites from hot desert regions. *Geochimica et Cosmochimica Acta* 62:3169–3184.

Bland P. A., Zolensky M. E., Benedix G. K., and Sephton M. A. 2006. Weathering of chondritic meteorites. In *Meteorites and the early solar system II*, edited by Lauretta D. S. and McSween H. Y. Tucson, AZ: The University of Arizona Press. pp. 853–867.

Buseck P. R. and Holdsworth E. F. 1972. Mineralogy and petrology of the Yilmia enstatite chondrite. *Meteoritics* 7:429–447.

Consolmagno G. J. and Britt D. T. 1998. The density and porosity of meteorites from the Vatican collection. *Meteoritics & Planetary Science* 33:1231–1241.

Consolmagno G. J., Britt D. T., and Stoll C. P. 1998. The porosities of ordinary chondrites: Models and interpretations. *Meteoritics & Planetary Science* 33:1221–1230.

Consolmagno G. J., Bland P. A., and Strait M. M. 1999. Weathering and porosity: A preliminary SEM study of weathered meteorites (abstract #1158). 30th Lunar and Planetary Science Conference. CD-ROM.

Consolmagno G. J., Macke R. J., Rochette P., Britt D. T., and Gattacceca J. 2006. Density, magnetic susceptibility, and the characterization of ordinary chondrite falls and showers. *Meteoritics & Planetary Science* 41:331–342.

Consolmagno G. J., Britt D. T., and Macke R. J. 2008. The significance of meteorite density and porosity. *Chemie der Erde—Geochemistry* 68:1–29.

Dawson K. R., Maxwell J. A., and Parsons D. E. 1960. A description of the meteorite which fell near Abee, Alberta, Canada. *Geochimica et Cosmochimica Acta* 21: 127–144.

Dodd R. T. 1981. *Meteorites: A petrologic-chemical synthesis*. Cambridge, UK: Cambridge University Press. 368 p.

Easton A. J. 1983. Grain-size distribution and morphology of metal in E-chondrites. *Meteoritics* 18:19–27.

Flynn G. J., Moore L. B., and Klock W. 1999. Density and porosity of stone meteorites: Implications for the density, porosity, cratering, and collisional disruption of asteroids. *Icarus* 142:97–105.

Folco L., Rochette P., Gattacceca J., and Perchiazzi N. 2006. In situ identification, pairing, and classification of meteorites from Antarctica through magnetic susceptibility measurements. *Meteoritics & Planetary Science* 41:343–353.

Gattacceca J., Eisenlohr P., and Rochette P. 2004. Calibration of in situ magnetic susceptibility measurements. *Geophysical Journal International* 158:42–49.

Grossman J., ed. Meteoritical Bulletin Database [internet]. http://tin.er.usgs.gov/meteor/metbull.php. Accessed September 21, 2009.

Guskova E. G. 1985. Mangetic properties of enstatite chondrites. *Meteoritika* 44:111–118. In Russian.

Hutson M. L. 1996. Chemical studies of enstatite chondrites. Ph.D. thesis, The University of Arizona, Tucson, AZ, USA.

Jarosewich E. 1990. Chemical analysis of meteorites: A compilation of stony and iron meteorite analyses. *Meteoritics* 25:323–337.

Kallemeyn G. W. and Wasson J. T. 1986. Compositions of enstatite (EH3, EH4,5 and EL6) chondrites: Implications regarding their formation. *Geochimica et Cosmochimica Acta* 50:2153–2164.

Kallemeyn G. W., Rubin A. E., Wang D., and Wasson J. T. 1989. Ordinary chondrites: Bulk compositions, classification, lithophile element fractionations, and composition-petrographic type relationships. *Geochimica et Cosmochimica Acta* 53:2747–2767.

Keil K. 1968. Mineralogical and chemical relationships among enstatite chondrites. *Journal of Geophysical Research* 73:6945–6976.

Keil K. 1989. Enstatite meteorites and their parent bodies. *Meteoritics* 24:195–208.

Kohout T., Elbra T., Pesonen L. J., Schnable P., and Slechta S. 2006. Study of the physical properties of meteorites using mobile laboratory facility (abstract #1607). 37th Lunar and Planetary Science Conference. CD-ROM.

Macke R. J., Britt D. T., and Consolmagno G. J. 2010. Analysis of systematic error in "bead method" measurements of meteorite bulk volume and density. *Planetary and Space Science* 58:421–426.

Mason B. 1966. The enstatite chondrites. *Geochimica et Cosmochimica Acta* 30:23–26.

Prinz M., Nehru C. E., Weisberg M. K., and Delaney J. S. 1984. Type 3 enstatite chondrites: A newly recognized group of unequilibrated enstatite chondrites (uec's) (abstract #1331). 15th Lunar and Planetary Science Conference. pp. 653–654.

Rochette P., Gattacceca J., Bonal L., Bourot-Denise M., Chevrier V., Clerc J.-P., Consolmagno G., Folco L., Gounelle M., Kohout T., Pesonen L., Quirico E., Sagnotti L., and Skripnik A. 2008. Magnetic classification of stony meteorites: 2. Non-ordinary chondrites. *Meteoritics & Planetary Science* 43:959–980.

Rubin A. E. 1983a. The Adhi Kot breccias and implications for the origin of chondrules and silica-rich clasts in enstatite chondrites. *Earth and Planetary Science Letters* 64:201–212.

Rubin A. E. 1983b. The Atlanta enstatite chondrite breccias. *Meteoritics* 18:113–121.

Rubin A. E. 1983c. Impact melt-rock clasts in the Hvittis enstatite chondrite breccias: Implications for a genetic relationship between EL chondrites and Aubrites. Proceedings, 14th Lunar and Planetary Science Conference. *Journal of Geophysical Research* 88(Suppl.):B293–B300.

Rubin A. E. 1984. The Blithfield meteorite and the origin of sulfide-rich, metal-poor clasts and inclusions in brecciated enstatite chondrites. *Earth and Planetary Science Letters* 67:273–283.

Rubin A. E. and Keil K. 1983. Mineralogy and petrology of the Abee enstatite chondrite breccias and its dark inclusions. *Earth and Planetary Science Letters* 62:118–131.

Rubin A. E., Scott E. R. D., and Keil K. 1997. Shock metamorphism of enstatite chondrites. *Geochimica et Cosmochimica Acta* 61:847–858.

Schneider D. M., Akridge D. G., and Sears D. W. G. 1998. Size distribution of metal grains and chondrules in enstatite chondrites (abstract). *Meteoritics & Planetary Science* 36(Suppl.):A136.

Sears D. W., Kallemeyn G. W., and Wasson J. T. 1982. The compositional classification of chondrites: II The enstatite chondrite groups. *Geochimica et Cosmochimica Acta* 46:597–608.

Sears D. W. G., Weeks K. S., and Rubin A. E. 1984. First known EL5 chondrite—Evidence for dual genetic sequence for enstatite chondrites. *Nature* 308:257–259.

Smith D. L., Samson C., Herd R., Deslauriers A., Sink J.-E., Christie I., and Ernst R. E. 2006. Measuring the bulk density of meteorites nondestructively using three-dimensional laser imaging. *Journal of Geophysical Research* 111:E10002.

Van Schmus W. R. and Wood J. A. 1967. A chemical-petrologic classification for the chondritic meteorites. *Geochimica et Cosmochimica Acta* 31:747–765.

Wasson J. T. and Kallemeyn G. W. 1988. Compositions of chondrites. *Philosophical Transactions of the Royal Society of London A* 325:535–544.

Wilkison S. L. and Robinson M. S. 2000. Bulk density of ordinary chondrite meteorites and implications for asteroidal internal structure. *Meteoritics & Planetary Science* 35:1203–1213.

Zhang Y., Benoit P. H., and Sears D. W. G. 1993. LEW 88180, LEW 87119, and ALH 85119: New EH6, EL7, and EL4 enstatite chondrites. *Meteoritics* 28:468.