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Petrographic classification of Middle Ordovician fossil meteorites from Sweden

J. C. BRIDGES[1*], B. SCHMITZ[2], R. HUTCHISON[3§], R. C. GREENWOOD[4], M. TASSINARI[2], and I. A. FRANCHI[4]

[1]Space Research Centre, Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK
[2]Department of Geology, Lund University, SE-22362 Lund, Sweden
[3]Department of Mineralogy, Natural History Museum, Cromwell Road, London, SW7 5BD, UK
[4]Planetary and Space Sciences Research Institute, Open University, Milton Keynes MK7 6AA, UK
[§]Deceased
[*]Corresponding author. E-mail: j.bridges@leicester.ac.uk

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Abstract–The maximum diameter of chromite ($FeCr_2O_4$) grains within L chondrites reflects the petrographic type of the sample. On the basis of our measurements of nine recent L chondrites, L3 chromite D_{max} = 34–50 μm, L4 = 87–150 μm, L5 = 76–158 μm, and L6 = 253–638 μm. This variation reflects the crystallization of the chromite grains during parent body thermal metamorphism.We use this calibration to classify six fossil meteorites from the Middle Ordovician in Sweden as type 3 (or 4) to 6. The high flux of L chondrites at 470 Ma contained a range of petrographic types and may have had a higher proportion of lower petrographic type meteorites than are found in recent L chondrite falls. The fossil meteorites have in places preserved recognizable chondrule textures, including porphyritic olivine, barred olivine, and radiating pyroxene. A large relict clast and fusion crust have also been tentatively identified in one fossil meteorite. Apart from chromite, all of the original meteorite minerals have been replaced by carbonate (and sheet silicate and sulfate) during diagenesis within the limestone host. The preservation of chondrule definition has allowed us to measure the mean diameters of relict chondrules. The range (0.4–0.6 mm) is consistent with measurements made in the same way on recent L chondrites.

INTRODUCTION

Chondrites are classified chemically and petrographically (Van Schmus and Wood 1967). They are normally assigned to chemical groups and petrographic types using mineral compositions and textures. This does not apply, however, to fossil meteorites in Swedish Middle Ordovician limestone, because the primary, mainly silicate, minerals have been replaced during diagenesis by low-temperature secondary minerals, particularly carbonates, sulfates, and phyllosilicates. The only common surviving mineral is chromite (Thorslund et al. 1984; Nyström et al. 1988; Schmitz et al. 1996). Many meteorites with chondrule structures have been found in the 470 Ma Middle Ordovician marine limestone in the Thorsberg Quarry, southern Sweden. Using the chemical compositions of their chromites, Schmitz et al. (2001) showed that these fossil meteorites most probably are L, or possibly LL, chondrites.

The petrographic classification of chondrites is based on diagnostic mineralogical and textural criteria (Van Schmus and Wood 1967). These include the common presence of twinned pyroxene (types 3 and 4), feldspar grains in recrystallized matrix clearly visible with a petrologic microscope (type 6 chondrites show this), and a progressive decrease in chondrule definition from type 3 to type 6. Type 3 chondrites are distinguished from type 4 primarily on the homogeneity of minerals rather than texture. In the absence of most primary minerals, the normal mineralogical criteria cannot be applied to the classification of fossil meteorites. Chromite, however, is chemically and texturally preserved. We explore the relationship between maximum diameter of chromite grains identified within L-chondrite falls and finds with petrographic type in order to determine whether the size range of chromite grains can be used to assign a petrographic type to a fossil meteorite. As further support for an L-chondrite classification, we present mean apparent diameters of chondrules. We also document the survival of original textures in chondrules in many of the samples whose primary minerals have gone.

Schmitz et al. (2001) analyzed chromites in 33 chondrite

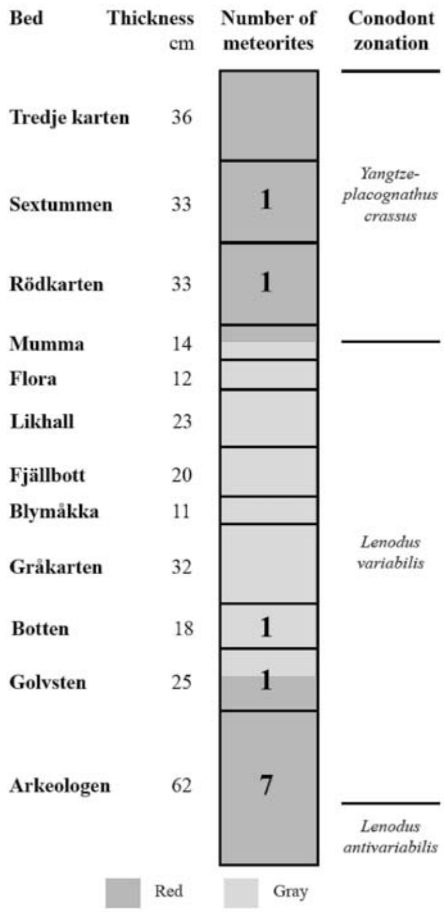

Fig. 1. Limestone beds in the Thorsberg quarry in southern Sweden where the fossil meteorites were deposited in the Ordovician (at 470 Ma). Total sedimentation time was 1–2 Myr (Schmitz et al. 1996). The number of meteorites analyzed per quarry bed is indicated. The fossil meteorites have sizes between 1 and 21 cm. Reddish-brown limestones are shown shaded dark gray, and gray sediments are shaded light gray. Samples used in this study for petrographic classification and chondrule measurements are from the Arkeologen (Ark), Golvsten (Gol), Botten (Bot), Rödkarten (Röd), and Sextummen (Sex) horizons. These are also the synonym names used in this paper for the Österplana relict meteorites.

falls and finds and showed by comparison that the chromites in the fossil meteorites most probably are from L, or possibly LL, chondrites. Moreover, Schmitz et al. (2001) and Wlotzka (2005), following Bunch et al. (1967) and Ramdohr (1967), demonstrated that chromite compositions can be used to distinguish between chondrite groups and to reveal information on the heating and cooling histories of their parent bodies. Chromite textures and chemistry are thus of particular importance in identifying the components in the flux of meteorite material preserved within the fossil record. As an extension of this work, Schmitz and Häggström (2006) were able to identify an extraterrestrial contribution to dispersed chromite grains in the limestone at Thorsberg and at Hällekis, 4 km to the north. Greenwood et al. (2007) used oxygen isotopes to confirm the L-group chemical classification of one of the Thorsberg meteorites (Golvsten 001), which were delivered rapidly (e.g., $<10^5$ yr) to Earth via Kirkwood gaps after parent body breakup in the asteroid belt (Heck et al. 2004). Chromite's resistance to low-temperature chemical change in sedimentary diagenesis means that it is also resistant to weathering. That is the basis for being able to use it as a petrogenetic marker in meteorite finds to compare with fossil meteorites.

Here we attempt to determine whether the enhanced flux in the Middle Ordovician included the range of petrographic types in the modern L-chondrite flux. If so, this would indicate that the L-chondrite body, whose breakup caused the Middle Ordovician "spike," is similar or identical to the body contributing meteorites to the modern flux. To do this, we aim to identify the petrographic types of the fossil meteorites.

TECHNIQUES AND SAMPLES

The naming of fossil meteorites (or "relict materials") has now been decided upon by the Nomenclature Committee of the Meteoritical Society. The revised, formal names of the samples referred to in this publication are as follows:

- Ark 003 = Österplana 003
- Ark 010 = Österplana 010
- Ark 011 = Österplana 011
- Ark 018 = Österplana 018
- Ark 019 = Österplana 019
- Ark 027 = Österplana 027
- Ark 032 = Österplana 046
- Gol 001 = Österplana 029
- Bot 001 = Österplana 030
- Röd 001 = Österplana 047
- Sex 001 = Österplana 035

In this publication's main text, we refer to the synonym names given above, e.g., Gol 001. These are abbreviations of the beds from which the relict meteorites originate (Fig. 1).

To assign a petrographic type to a fossil meteorite on the basis of the grain-size of its chromites, a calibration scale had to be established. For this we measured the diameters of chromite grains in nine classified L3 to L6 finds and falls. The results (particularly maximum diameter, D_{max}) from chromite grain searches in six of the fossil meteorites were compared with our calibration. Polished sections (or in the case of the fossil meteorites five unpolished blocks and one polished block of Gol 001—the same sample that was used for oxygen isotope analyses) (Greenwood et al. 2007) were examined using backscattered electrons and energy dispersive X-ray analyses (EDS) in order to locate, photograph, and measure the chromite grains. This was done using an SEM at the Open University (Quanta 200 3D) and the Department of Mineralogy, Natural History Museum (Jeol 5900LV and Leo 1455VP). Low-vacuum conditions were used for the fossil meteorite blocks. The polished section for SEM studies of

Gol 001 was prepared in a resin block with vacuum impregnation and without water. Chromite identity and other minerals were checked with qualitative EDS spectra. Between 12 and 154 mm^2 areas on the fossil and recent meteorites were surveyed systematically. The relative ease with which chromite can be distinguished through its backscatter and EDS characteristics means that we are confident an accurate chromite grain distribution was obtained in each case.

Any chemical changes associated with diagenesis of the fossil samples or weathering in the comparison recent meteorite finds would create chemical zonation visible in the SEM. For instance, this is seen in more extreme alteration, notably that occurring at up to 500 °C associated with serpentinization where Fe-rich rims are found around chromite grains (Bridges et al. 1995). The absence of zonation or alteration in the chromite of the meteorite finds in this study supports their use in a scale for petrographic type determination. Greenwood et al. (2007) also demonstrate with oxygen isotope analyses that the chromite grains have escaped chemical change during diagenesis.

The rarity of the fossil meteorite samples and the need to preserve intact the cut surfaces that have chondrite textures meant that we were not able to make polished sections of most samples.

For textural study, planar surfaces of eight representative fossil meteorites were photographed. Prints were scanned and integrated to produce montages of surfaces that include areas of good textural preservation. Photomontages of six of the meteorites were selected as suitable for measuring chondrule diameters on the basis of the total survival of a high density of chondrule pseudomorphs with sharp outlines. There is thus a bias in favor of low petrographic type chondrites in the samples selected for chondrule measurements. For fragmented chondrules or those with noncircular outlines, the maximum diameter was measured. As a check, chondrule sizes were similarly measured on a digital image of a polished surface of Barratta, L3.8. In only one meteorite, Österplana 035 (Sex 001), were chromite grain size and chondrule diameters measured.

The horizons and associated sedimentary log of the fossil meteorites we have studied are shown in Fig. 1. Using the synonym names as described above, Ark 011, 018, 019, 027, Bot 001, and Sex 001 were used for chondrule measurements; Ark 003, 010, 032, Sex 001, Röd 001, and Gol 001 were used for petrographic classification using chromite grain measurements.

RESULTS

Relict Chondrite Textures

Gol 001 was found to be dominated by $CaCO_3$ and phyllosilicate with lesser amounts of chlorapatite and chromite. This is consistent with studies of secondary minerals in other fossil meteorites, e.g., Thorslund et al. (1984). However, sulfides and sulfates (particularly barites), which are also typical of fossil meteorites, have not been identified in Gol 001. No relict chondrule textures were identified in this sample.

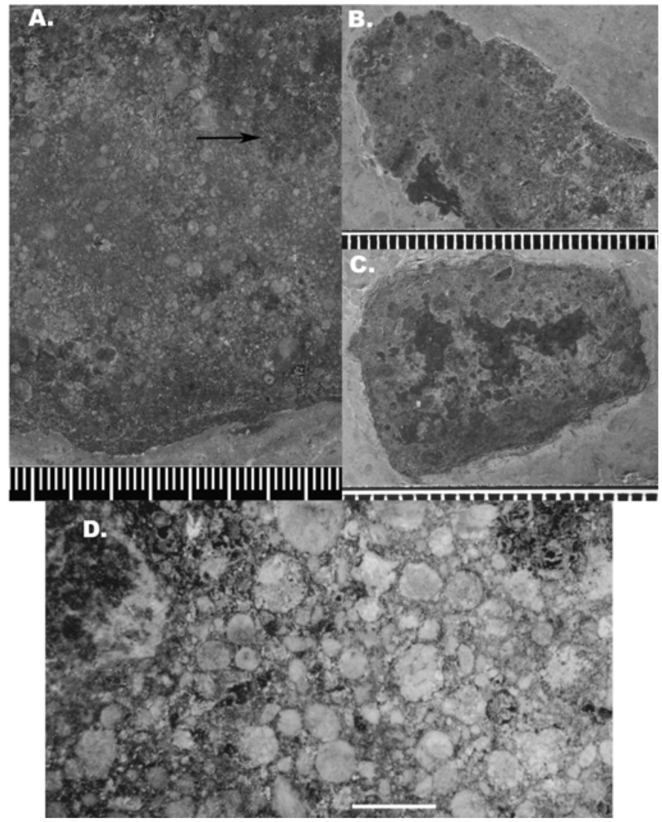

Fig. 2. a) Sex 001 fossil meteorite L4 (5). Chondrules are well defined, which is consistent with the probable low petrographic type 4 (Table 1) calculated on the basis of chromite grain size and relatively good chondrule definition. The black arrow indicates a possible relict chondrite clast within the fossil meteorite 1.3 cm in size, indicating that this meteorite may be a breccia. The thickness and even width of the 1 to 2 mm thick band at the margin of the fossil meteorite may be relict fusion crust. This sample has a mean chondrule diameter measured in thin section of 0.55 mm (Table 2). b) Ark 010 fossil meteorite L3 (4) showing clearly defined chondrules. c) Ark 032 fossil meteorite L4 or 5. The chondrules are less well defined in this sample than in Sex 001, although still visible. d) Magnified view of chondrules in Sex 001. Mutually indented chondrules are visible (arrowed). Scale bar is 2 mm (mm scales in a–c).

However, some of the fossil meteorites show relict chondrule textures on planar surfaces of hand specimens (Figs. 2a–d) and in thin section (Fig. 3). The proportion of chondrules is >65%, e.g., Figs. 2a, 2b, and 2d; this is typical of ordinary chondrites. Chondrule textures are also typical of ordinary chondrites with barred olivine, porphyritic olivine pyroxene, and radiating pyroxene pseudomorphs all present, together with some mutually indented chondrules. Figure 3b shows opaque minerals around the margin of a relict

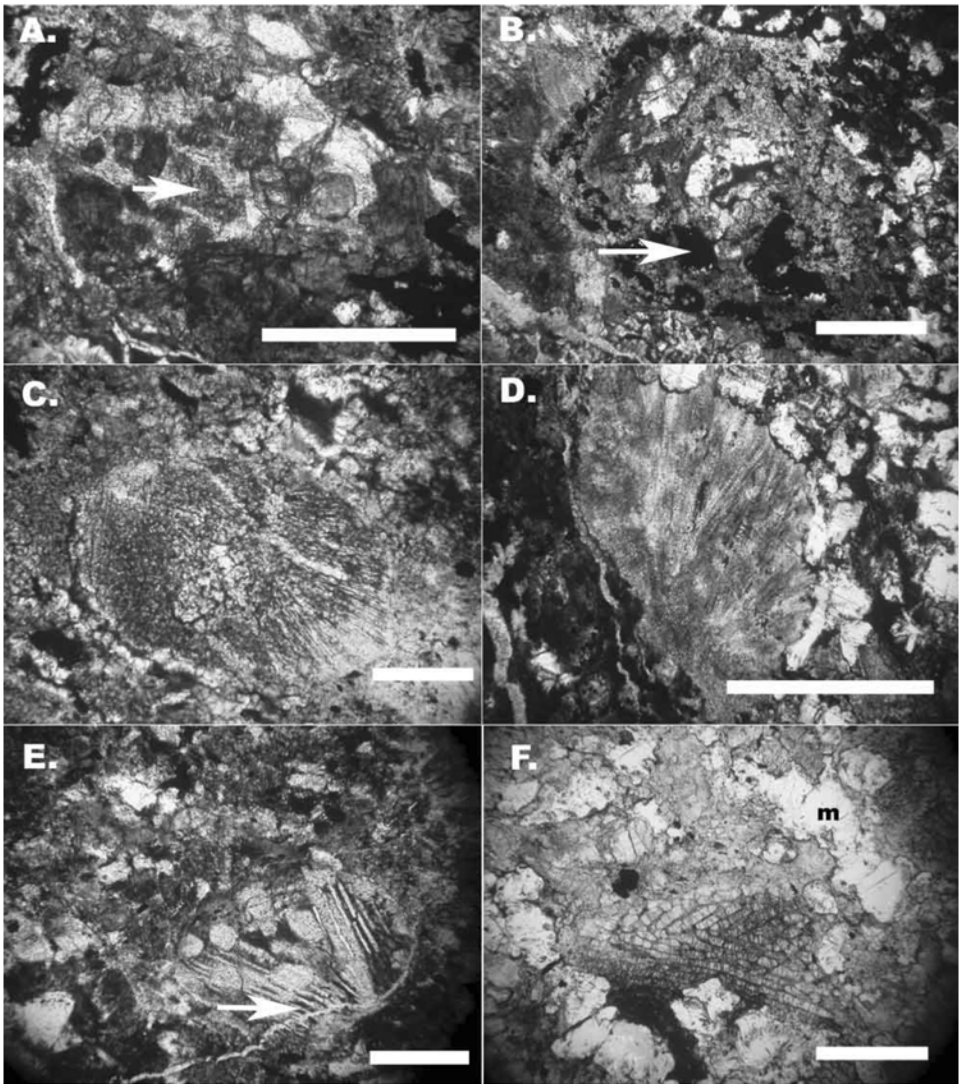

Fig. 3. Plane-polarized, transmitted light photos of chondrule textures from Ark 003 L4 (or 5). a) Relict porphyritic olivine pyroxene chondrule. The arrowed phase is carbonate, which probably has pseudomorphed olivine. The lighter phase within the relict chondrule is replaced pyroxene. b) This relict chondrule shows oxide that has replaced an iron metal-rich rim—a texture typical of many chondrules. c) Fine texture (probably replaced olivine bars) that have been pseudomorphed. d) Radiating pyroxene chondrule (probably a fragment that was broken in half on the parent body) replaced by carbonate. e) Relict chondrule containing replaced phenocrysts and bars (arrowed) of olivine. f) Relict barred olivine chondrule (olivine replaced by Ca carbonate). The colorless phase (m) is mica. Scale bars 1 mm.

chondrule in a texture, suggesting that they are a replaced metal-rich chondrule rim. The primary minerals (apart from chromite) have been precisely replaced by carbonates with lesser amounts of sheet silicate, sulfate, and phosphate forming during the meteorites' 470 Myr residence within the limestone. The diagenetic minerals in the fossil meteorites have been described by Schmitz et al. 1996, 2001, and Nyström et al. 1988.

Further possible relict chondrite texture is shown in Fig. 2a where a relict chondrite clast 1.3 cm in size is seen. This suggests that the sample Sex 001 may be a breccia or have accreted in the L-group parent body with large clasts (Bridges and Hutchison 1997). The 1–2 mm wide band at the margin of the fossil meteorite may be relict fusion crust.

Chromite Grain Measurements

Figure 4 shows a large chromite grain from Gol 001 and, for comparison, one from the recent fall Kyushu (L6). These grains show the typical anhedral outlines of chromite grains. There is an absence of any zonation in the chromite grains that reflects their intragrain compositional homogeneity. Such an absence of zonation or rims is inconsistent with an origin or alteration during diagenesis.

Our chromite grain measurements are summarized in Table 1 and Fig. 5. The clearest trend in the recent meteorites is the presence of chromite grains larger (>250 μm) in diameter (D_{max}) in L6 chondrites with smaller D_{max} in L3 chondrites. The D_{max} (μm) of L3 chondrites lies

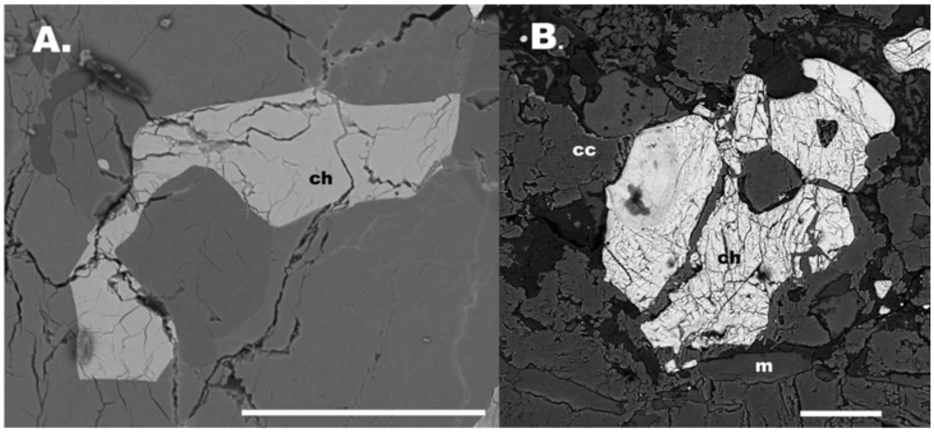

Fig. 4. a) Backscattered electron images of chromite (ch) grain in Kyushu (L6) recent meteorite. The (darker) gray minerals surrounding the chromite grain are Mg-Fe silicates. This 230 μm grain is typical of the relatively large chromite grains present in L6 chondrites. Scale bar 100 μm. b) Chromite grain (ch) in polished section of Gol 001 L6 fossil meteorite. This grain has D_{max} = 473 μm. Large, anhedral chromite grains like this formed through solid state reaction during thermal metamorphism on the chondrite parent bodies. Alone among the other common meteorite minerals, they are resistant to the diagenesis that led to the recrystallization of the silicate mineralogy. The surrounding and included phases (gray) are Ca-carbonate (cc) and muscovite (m). Scale bar is 100 μm.

Table 1. Chromite grain measurements in recent and fossil meteorites.

	Type	Area (mm^2)	No. of grains	No of grains >5 μm	D_{max} μm	Mean D >5 μm	Grains >5 μm/mm^2
Recent							
FRO 95048	L3	40	8	8	34	25	0.2
Julesburg	L3	52	69	38	50	13	0.7
Floyd	L4	144	26	26	150	47	0.2
FRO 90039,001	L4	31	52	51	95	28	1.6
FRO 90045	L4	50	304	215	87	18	4.3
FRO 90044,001	L5	19	59	53	76	28	2.8
Homestead	L5	40	153	131	158	24	3.3
FRO 90100,001	L6	14	105	79	253	26	5.6
Kyushu	L6	50	138	138	638	38	2.8
Fossil							
Sex 001	L4 (5)	154	77	77	110	41	0.5
Röd 001	L4 or 5	73	122	177	150	38	2.4
Ark 032	L4 or 5	59	23	23	110	43	0.4
Ark 010	L3 (4)	571	7	7	40	20	0.1
Ark 003	L6 (5)	102	41	41	300	92	0.4
Gol 001	L6	12	352	151	645	44	12.6

Fossil petrographic types in brackets are not ruled out on the basis of chromite grain measurements, but are less likely than the unbracketed figure when chondrule definition is also considered. L4 or 5 means that either of these petrographic types is considered equally likely and cannot be distinguished. Number of grains logged is given for all diameters and for >5 μm, as the latter figure is regarded as more reliable due to variation in polish or roughness of the samples hindering identification of chromite grains (e.g., for Ark 001). The chromite in some samples of Gol 001 has been separated and used for oxygen isotope analyses (Greenwood et al. 2007). D_{max} is chromite grain maximum diameter.

in the range of 34–50, L4 of 87–150, L5 of 76–158, and L6 of 253–638. Figure 5 plots part of the frequency percent of the larger grains for L3, L4, L5, and L6 recent chondrite samples. These lines also show that the proportion of large chromite grains is a general discriminate of petrographic type. The chromite grain size relationships in recent L chondrites also show that thermal metamorphism on the parent body is the cause, not diagenesis, e.g., within the Ordovician limestone.

We regard this as a more reliable way of distinguishing petrographic type than using, for instance, mean chromite grain diameter, because smaller chromite grains (e.g., <10 μm) can be difficult to identify in a thin section. In the case of the fossil meteorite blocks, lack of polish means that the smaller grains are particularly difficult to log accurately.

Thus although there appears to be a trend of increasing mean chromite grain diameter from L3 to L6 chondrites in Table 1 of 13 to 47 μm (for grains >5 μm), this is not duplicated in the fossil meteorites that have mean diameters of 38 to 92 μm. The higher range of calculated mean

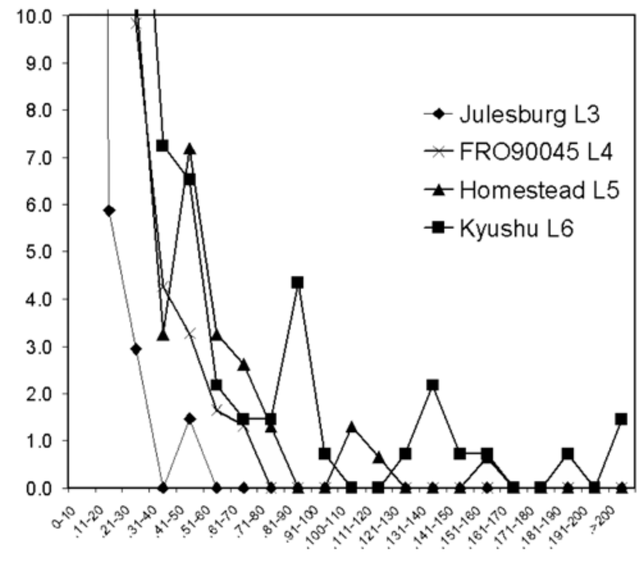

Fig. 5. Part of the frequency distribution (from 0–10%) of chromite grain sizes (μm) measured in recent meteorites. The results demonstrate that lower petrographic type L chondrites contain a higher proportion of smaller chromite grains, e.g., <30 μm. Higher petrographic type meteorites have a progressively higher proportion of the largest grains compared to lower petrographic types. This is consistent with Table 1 and the petrographic classifications based on maximum chromite grain size.

diameters in the fossil meteorites is due to the nondetection of the smallest grains on the relatively rough surfaces of the fossil meteorite unpolished blocks rather than through loss of smaller chromite grains during diagenesis of the meteorites. In the one fossil meteorite sample where we examined a polished block (Gol 001), many smaller chromite grains were detected.

On the basis of our D_{max} measurements, we classify the petrographic type of the fossil meteorites (Table 1). However, there is some overlap between the size ranges of different petrographic types, showing that chromite grain size alone cannot be a perfect discriminate. Specifically, it may not be possible through this technique to distinguish between type 4 and type 5 as they have overlapping D_{max} ranges and similar proportions of the largest chromite grains (Fig. 5).

There is a large variation in the concentrations of chromite grains between different recent or fossil meteorite samples. For instance, Frontier Mountain (FRO) 90045 has 4.3 grains (>5 μm in diameter) per mm^2, whereas the other L4 recent meteorites (Floyd and FRO 90039,001) have 0.2 and 1.6 chromite grains >5 μm per mm^2, respectively. Apart from this sample, types 5 and 6 recent L chondrites appear to have a higher concentration of chromite grains. This variation does not appear to affect the D_{max} and our petrographic classifications. Gol 001 (the sample used for oxygen isotope analyses on separated chromite grains by Greenwood et al. 2007), classified here as type 6, is particularly rich in chromite grains.

Table 2. Chondrule diameter measurements.

Meteorite	No. of chondrules	Mean D (mm)
Ark 011	132	0.49
Ark 018	89	0.38
Ark 019	67	0.52
Ark 027	169	0.42
Bot 001	238	0.41
Sex 001	397	0.55
Barratta L3.8	437	0.42
Average H, L, LL group		0.3, 0.5, 0.6

Measurements were made on photomontages using the same way for the recent meteorite (Barratta L3.8) and the fossil meteorites. See text for details. The average H, L, and LL group values are from Rubin (2000).

Chondrule Diameter Measurements

The mean apparent diameters and numbers of chondrule outlines measured in six fossil meteorites are shown in Table 2. The means range from 0.38–0.55 mm. Barratta (L3.8) has a mean chondrule diameter of 0.42 mm, which is within the range of the fossil chondrites. However, the mean diameters are also similar to those calculated by Rubin (2000) for L chondrites, ~0.5 mm. Rubin also reported H and LL mean chondrule diameters as 0.3 and 0.6 mm. The small discrepancy between our results for recent L chondrites and those of Rubin may be explained by the bias against encountering maximum diameters on a random planar surface or in thin section (e.g., Eisenhour 1996). Hughes (1978) suggested that measurements in thin section underestimate true mean chondrule diameters by ~22%, which would partially account for the lower values in our measurements. Benoit et al. (1999) showed a range of mean chondrule diameters taken on thin sections without correction procedures. Their mean L-group chondrule diameter, 0.4 mm, is at the lower end of our range in the fossil meteorites and close to the Barratta mean. We are confident that our measurements of chondrule diameters are a reliable confirmation of an L-group identity for the fossil chondrites.

In order to test this further, we have plotted the 397 chondrule measurements for Sex 001 as frequency plot in phi ($-\log_2 d$) units (Fig. 6). Phi units are typically used in studies of sedimentary grain or chondrule size distributions to reveal patterns of size sorting. Our results show a near log-normal size distribution typical of chondrule size distributions in recent chondrites (e.g., see Eisenhour 1996; Benoit et al. 1999). This gives us confidence that our chondrule measurement technique produced accurate results.

Because the samples measured have reasonable chondrule definition, it is unlikely that they are petrographic type 6. Sex 001 (Fig. 2a), on which we were also able to make chromite grain size measurements, is classified by us as L4 or 5 (Table 1), which is consistent with sufficient chondrule definition to make the chondrule measurements.

DISCUSSION

The chromite grains within the equilibrated L4–6 recent or fossil meteorites formed through solid state recrystallization in the matrix of the chondrites during parent body thermal metamorphism. This is reflected in their anhedral outlines (e.g., Fig. 4). In a study of ordinary chondrite chromite, Wlotzka (2005) determined equilibration temperatures of up to 820 °C for types 4, 5, and 6. Other processes, i.e., parent body shock, are not associated with formation of such relatively large chromite grains (Stöffler et al. 1991). Chromite in every petrographic type from type 4 to 6 also contained a range of average equilibration temperatures of 752–775 °C. Wlotzka (2005) suggested this could be explained by the chromite grains and their parent meteorites having formed within rubble pile environments where rocks of different types were stored and mixed together. However, the larger D_{max} chromite sizes in type 6 chondrites measured here are consistent with a longer history of heating and slow cooling than for the lower petrographic types even though no correlation between chromite grain size and maximum equilibration temperature was identified in recent meteorites by Wlotzka.

In our calibration scheme based on chromite D_{max} we are unable to firmly distinguish between types 4 and 5. This may be because the crystallization of chromite grains under the conditions associated with type 4 and 5 chondrites both create the same type of chromite grain sizes. We suggest that classification based on maximum chromite grain size is generally accurate to +/– 1 petrographic unit. However type 6 (e.g., Gol 001) can sometimes be clearly distinguished.

The relict chondrule textures are less diagnostic of petrographic type as chondrule textures can be preserved up to petrographic type 5. However, their presence in another five of our samples suggests that these samples are unlikely to be fossilized type 6 chondrites. When chromite measurements alone cannot distinguish between two petrographic types, chondrule definition can be used to help indicate which number is more likely (Table 1).

Origin on an L-Group Parent Body

L chondrites in our collections have cosmic ray exposure ages of <70 Ma (Patzer and Schultz 2001). Many of these meteorites are probably derived from a body (or bodies) that formed as a rubble pile by gravitational reassembly of the fragments produced in the catastrophic disruption of a pre-existing L-chondrite body. Blackening among L chondrites was recognized by Heymann (1967) as the result of shock, which was implicated in loss of radiogenic ^{4}He. There is a strong peak in L-chondrite ages, mainly by the ^{40}Ar-^{39}Ar method, at ~0.5 Ga (Turner et al. 1966; see review of Bogard 1995). McConville et al. (1988), however, found in vacuum experiments that heating an L chondrite resulted in the retention of some radiogenic ^{40}Ar, even when some melting occurred. Thus the measured ^{40}Ar-^{39}Ar ages of shocked meteorites will be overestimates of the true age of the shock event. Indeed, Korochantseva et al. (2007) measured the effect of inherited ^{40}Ar and suggested that the shock event that affected many L chondrites occurred 470 ± 6 Ma ago and within error of the age of the sediments surrounding the fossil meteorites (467.3 ± 1.6 Ma) based on conodont zones. This is consistent with the major breakup of an L-chondrite planetesimal leading to a high flux of material delivered to Earth within ~10^5 years via the Kirkwood resonance gaps. The short transit time is based on ^{21}Ne exposure ages recorded in chromites of the fossil meteorites (Heck et al. 2004). In a review of L chondrites ages, Bogard (1995) suggested that events at ~470 Ma have affected at least five out of eight recent L chondrites. Some of the fragments from the 470 Ma collision reaccreted to form the Flora family of asteroidal bodies (Nesvorný et al. 2002).

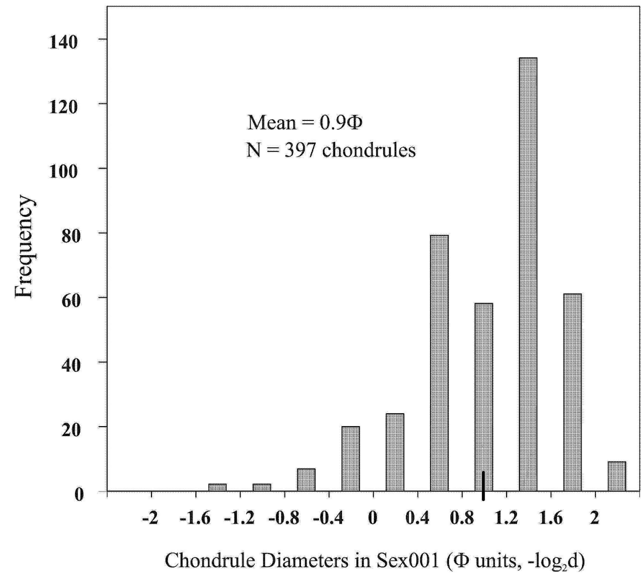

Fig. 6. Chondrule diameter frequency in Sex 001. N = 397 measurements, mean diameter = 0.9 phi units ($-\log_2 d$, where d is the diameter in mm). The approximately log-normal size distribution is typical of chondrules within recent chondrites and suggests that our measurements are reasonably accurate. The average recent L chondrite mean chondrule diameter (=1.0; Rubin 2000) is shown for comparison (black vertical line).

Our dataset of six petrographic type classifications is relatively small. However, on the basis of our knowledge of the locality and its samples, we believe that they are representative of the Österplana fossil meteorite materials. One-third of our classified samples are probably type 6, but for recent L chondrites falls, this figure is about two-thirds (Graham et al. 1985). Therefore our work raises the possibility that a different part of the L chondrite parent was sampled 470 Ma ago, having a higher proportion of low petrographic type material than recent meteorites.

CONCLUSIONS

1. Some of the fossil meteorites have pseudomorphed the original chondrite textures. For instance, porphyritic, poikilitic, radiating, and barred chondrule textures have been identified. In addition, the chromite (formed through solid state recrystallization on the L-group parent body) is preserved and allows petrographic classification.
2. The maximum diameter (D_{max}) of chromite grains within L chondrites can be used to determine the petrographic type accurate to ±1 petrographic type, or in the case of type 6 may sometimes be firmly identified. This is useful in fossil meteorites where the petrographic markers normally used for classification are absent or material for microbeam analyses is not available.
3. We use chromite grain size measurements to provide petrographic types for 6 L-group fossil meteorites from the Middle Ordovician in Sweden (Sex 001, Röd 001, Ark 003, Ark 010, Ark 032). The petrographic types range from 3 (or 4) to 6. One-third of our classified samples are probably type 6, but for recent L chondrites falls, this figure is about two-thirds. This suggests that the flux of petrographic type material from L chondrites that reached the Earth after the breakup of a parent body at 470 Ma varies from that seen today.
4. Chondrule mean diameters (0.4–0.6 mm) in six fossil meteorites are consistent with thin section-based measurements taken in the same way on a recent L chondrite. This supports previous conclusions for an L-group origin of these fossil meteorites. Because chondrule definition exists, these extra five samples (Ark 011, 018, 019, 027, and Bot 001) are unlikely to be fossil petrographic type 6. One of the samples (Sex 001) is also classified with chromite grain measurements as probably L4. This sample's chondrules have a log-normal frequency pattern, suggesting that the chondrule measurements give a reliable size distribution.

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Editorial Handling—Dr. Christine Floss

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