Traces in Earth's geological record of the break-up of the L-chondrite parent body 470 Ma

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Abstract

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Key words

L chondrite, Middle Ordovician, extraterrestrial material, meteorite flux, Sweden

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Contents

Abstract

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Populärvetenskaplig sammanfattning

Popular summary in Swedish

Varje år faller cirka 30 000 ton utomjordiskt material ner på jorden. Den stora merparten av detta material har sitt ursprung i asteroidbältet, vilket är beläget mellan Mars och Jupiters banor. Detta består av miljontals oregelbundna stenblock i storleksordningen 10 meter till 1000 kilometer i diameter, så kallade asteroider. Det stora antalet asteroider i bältet gör att kollisioner dem emellan är relativt vanliga. Kollisionerna får till följd att asteroiderna fragmenteras och material slungas ut ur sin omloppsbana. På grund av solens starka gravitation, dras en del av detta material in mot de inre delarna av solsystemet, och träffar jorden. Om en stor asteroid splittras upp, innebär detta att enorma mängder material slungas ut och således mer material kan träffa jorden. Detta var precis vad som inträffade för cirka 470 miljoner år sedan då den L-kondritiska (en typ av stenmeteorit) föräldrakroppen splittrades upp, vilket resulterade i ett kraftigt ökat inflöde av utomjordiskt material till jorden. Fynd av mer än 80 fossila L-kondritiska meteoriter (1-20 cm i diameter) i mellanordovicisk kalksten från Kinnekulle i södra Sverige visar på att inflödet av meteoriter ökade med en faktor hundra under de påföljande cirka tre miljoner åren efter uppbrytningen av föräldrakroppen. Ökningen kan även ses i de höga halterna av sedimentspridda extraterrestriska kromitkorn (en järn/krom oxid) från nedbrutna L kondriter, i likåldriga kalkstenar. Tidpunkten för det förhöjda inflödet sammanfaller med starten på den stora ordoviciska biodiversitetsökningen. Detta är den period då livet på jorden på allvar började ta fart, med mängder av nya arter och släkten som följd. Det har spekulerats huruvida diversifieringsprocessen på något sätt accelererades av det kosmiska bombardemanget. Ett annat kännetecken för denna period är den rikliga mängden av megabreccior. En breccia är en bergart som består av stora kantiga bitar i en mer finkornig mellanmassa. Detta har också kopplats samman med det ökade inflödet av kosmiskt material, då man menar att de rikliga nedslagen av stora asteroider har destabiliserat sediment längs de dåvarande kustlinjerna, vilket då skulle ha utlöst stora skred och följaktligen bildat enorma breccior. Båda dessa hypoteser, kopplingen mellan det ökade inflödet och diversifieringen respektive megabrecciorna, kräver dock att det förhöjda inflödet även innefattade större kroppar, 100 meter i diameter eller större. Även om modelleringsstudier tyder på att så borde vara fallet, saknas det än så länge empiriska bevis för sådana nedslag. Ett av syftena med denna avhandling är därför att undersöka om det ökade inflödet av extraterrestriskt material, som följde den L-kondritiska uppsplittringen, även innefattade större kroppar. Studien syftar även till att utveckla nya metoder för att identifiera och klassificera fossilt extraterrestriskt material på jorden.

Eftersom extraterrestriskt material inte överlever någon längre tid på vår fuktiga och syrerika planet, är det inte helt lätt att finna spår efter ~470 miljoner år gamla nedslag. Dessutom förgasas större delen av en stor kropp redan vid själva nedslaget på grund av den enorma hettan som utvecklas. Trots den dåliga bevaringspotentialen visar undersökningarna i den här avhandlingen, samt en del tidigare studier, att det går att finna spår av bombardemanget som följde den L-kondritiska uppsprickningen. Det handlar bara om att veta vad man skall leta efter och därefter leta noggrant.

Det material som undersökts inom ramen för denna avhandling härstammar från mellan- och senordoviciska sedimentära bergarter från olika lokaler i Sverige och, i ett fall, från Estland. De spår som påträffats och studerats innefattar extraterrestriska kromitkorn, mineralinklusioner i extraterrestriska kromitkorn, omvandlade kondruler (runda mineralkorn typiska för kondriter) i fossila meteoriter och chockmetamorfa strukturer i kvartskorn som bildats i samband med nedslag. Nedan följer en sammanfattning av de upptäckter som gjorts och de slutsatser som dragits utifrån studierna i denna avhandling.

Undersökningar av extraterrestriska kromitkorn i lager från Locknekratern (458 Myr) i Mellansverige samt i Osmussaar Breccian (466 Myr) i Estland visar på att de båda har bildats av L-kondritiska projektiler, vilket tyder på att större kroppar ingick i det ökade inflödet till jorden, strax efter uppsprickningen av den L-kondritiska föräldrakroppen.

Fynd av chockmetamorfa strukturer i kvartskorn i material från Granbykratern i södra Sverige bekräftar att strukturen är ett resultat av ett nedslag. Vilken typ av projektil som skapade strukturen är visserligen okänt, dock är tidpunkten för nedslaget, ca 467 miljoner år sedan, en stark indikation för att det rör sig om en L kondrit.

Fyndet av höga halter av sedimentspridda extraterrestriska kromitkorn med L-kondritisk sammansättning i mellanordovicisk kalksten från Gärdebrottet i centrala Sverige, tyder på att det L-kondritiska inflödet fortfarande var förhöjt när Brunflometeoriten föll ner, det vill säga cirka 5 miljoner år efter det att de fossila meteoriterna från Kinnekulle föll. Dessutom visar nya undersökningar av Brunflometeoriten, med bland annat mätningar av kondrul- och kromitstorlek, att meteoriten är en L kondrit.

Förekomsten av kromit med extraterrestriskt ursprung i material från nedslagskratrar tyder på att fysiska bitar av större kroppar som träffar jorden kan klara sig. Kemiska analyser av kromit visar att den till största delen behållit sin ursprungliga sammansättning, vilket därmed möjliggör klassificering av projektiler, eftersom kromitsammansättningen varierar med typ av meteorit.

Fynd av inklusioner, av bland annat mineralen olivin och pyroxen, i extraterrestrisk kromit, visar på att andra meteoritmineral utöver kromit kan överleva hundratals miljoner år på jorden om de skyddats inkapslade i ett annat mer resistent mineral. Den ursprungliga sammansättningen av mineralen kan dessutom användas till att klassificera dess ursprung.

Introduction

This thesis is the result of seven papers (I to VII), all dealing with traces in sediments on Earth of extraterrestrial projectiles related to the break-up of the L-chondrite parent body at 470 Ma. The focus of the thesis is on mineralogy and chemistry of extraterrestrial material, as well as shock metamorphic features in terrestrial target rocks. The main aim of this thesis is to investigate if the increased flux of extraterrestrial material to Earth, following the disruption of the L-chondrite parent body also included larger asteroid-sized bodies. With this follows the objective to try and develop new methods and tools for finding and classifying relict cosmic material. The thesis is compiled to meet the formal requirements set for academic dissertations at Swedish universities.

Summary of papers

Paper I: Alwmark, C. and Schmitz, B. (2007). Extraterrestrial chromite in the resurge deposits of the early Late Ordovician Lockne crater, central Sweden. *Earth and Planetary Science Letters* 253, 291–303.

Summary: In this paper we show that the resurge deposits of the early Late Ordovician (458 Ma) Lockne impact structure in central Sweden are locally extremely rich in extraterrestrial chromite grains (>75 grains kg^{-1}) originating from the impactor. Analyses of the chemical composition of the chromite grains reveal that they have been subdued to post-depositional alteration, primarily due to the hydrothermal system that was induced by the impact. The dominating alteration effect is the incorporation of Zn in the grains, mainly on behalf of Mg and Fe^{2+}. However, the composition of the best preserved grains indicates that the impactor was an ordinary chondrite of the L group, i.e. part of the increased influx during the late Middle and early Late Ordovician due to the disruption of the L-chondrite parent body at ca. 470 Ma. Furthermore, the study also shows that physical pieces of a celestial body can survive at larger craters (>1.5 km).

Paper II: Schmitz, B., Harper, D. A. T., Peucker-Ehrenbrink, B., Stouge, S., Alwmark, C., Cronholm, A., Bergström, S. M., Tassinari, M., and Wang, X. (2008). Asteroid breakup linked to the Great Ordovician Biodiversification Event. *Nature Geoscience* 1, 49–53.

Summary: Here we show that the onset of the Great Ordovician Biodiversification Event coincides with the disruption in the asteroid belt of the L-chondrite parent body at ca. 470 Ma. The precise coincidence between these two events is established by bed-by-bed records of extraterrestrial chromite, osmium isotopes and invertebrate fossils in Middle Ordovician strata in Baltoscandia and China. The simultaneous timing of two such major events made us speculate in whether they were linked in some way. We concluded that the best explanation is that frequent impacts on Earth of large asteroids, i.e., fragments of the L-chondrite parent body, generated changes in the biota, and thus accelerated the biodiversification process.

Paper III: Alwmark, C. and Schmitz, B. (2009). The origin of the Brunflo meteorite and extraterrestrial chromite in mid-Ordovician limestone from the Gärde quarry (Jämtland, central Sweden). *Meteoritics & Planetary Science* 44, 95–106.

Summary: In this paper we show that the mid-Ordovician Brunflo fossil meteorite, found in marine limestone ca. 5 million years younger than similar limestone that has yielded >80 fossil meteorites in the Thorsberg quarry at Kinnekulle, is an L4 chondrite, and not, as previously suggested, an H chondrite. The new classification is based on chondrule-size measurements, chromite maximum diameters, the well-defined chondrule structures and the low TiO_2 contents of the relict chromites. Furthermore, a search of the limestone from which the meteorite originates reveals that it is relatively rich (about 0.45 grain kg^{-1}) in sediment-dispersed extraterrestrial chromite grains with chemical composition similar to those in L chondrites. This suggests that the enhanced flux of L chondrites prevailed, although somewhat diminished, at the time when the Brunflo meteorite fell.

Paper IV: Alwmark, C. and Schmitz, B. (2009). Relict silicate inclusions in extraterrestrial chromite and their use in the classification of fossil chondritic material. *Geochimica et Cosmochimica Acta* 73, 1472–1486.

Summary: In this paper we have identified primary inclusions of olivine, pyroxene, merrillite and plagioclase in chromite in recent and fossil meteorites as well as in sediment-dispersed extraterrestrial chromite grains. Analyses of the chemical composition of the inclusions reveal that when encapsulated in relict chromite the minerals can survive for hundreds of millions of years maintaining their primary composition. In the case of olivine and pyroxene, sub-solidus reequilibration between inclusion and host chromite during entrapment has altered the composition with an increase in chromium and in olivine also magnesium. The systematic compositional difference in Fa content (with an average 14% lower) in the chromite hosted olivine and the more or less analogous

Fs content in Ca-poor pyroxene compared to matrix phases, makes it possible to establish ranges for inclusions analogous to the well established classification system based on Fa in olivine and Fs in Ca-poor pyroxene, for ordinary equilibrated chondrites. Analyses of olivine and Ca-poor pyroxene inclusions in chromite from fossil meteorites from the Thorsberg quarry in southern Sweden (the Österplana meteorites), the Brunflo fossil meteorite from the Gärde quarry in central Sweden and in sediment-dispersed extraterrestrial chromite grains from four different limestone samples from the Thorsberg and Gullhögen quarries in southern Sweden, all plot within the L-chondritic field using the newly defined ranges, which is in agreement with previous classifications. Thus, the accuracy makes this a good tool in classification of fossil meteorites as well as in determining the origin of sediment-dispersed chromite grains from decomposed meteorites and larger impacts, where no other matrix minerals have survived or are present.

Paper V: Schmitz, B., Reza-Heck, P., Alwmark, C., Kita, N., Peucker-Ehrenbrink, B., Ushikubo, T., and Valley, J. (2009). Determining the impactor of the Ordovician Lockne crater: Oxygen isotopes in chromite versus sedimentary PGE signatures. *40th Lunar and Planetary Science Conference*, abstract #1161.

Summary: Here we confirm, by O isotope analysis, that the chromite grains in the resurge deposits of the early Late Ordovician (458 Ma) Lockne impact structure in central Sweden, have an L-chondritic origin. Thus, the impactor that created the Lockne impact structure was indeed related to the L chondrite parent body break-up at 470 Ma. We also demonstrate that meteoritic elemental ratios in ancient sedimentary environments are altered to an extent that they can not be used for detailed assessment of precursor meteorite group.

Paper VI: Alwmark, C., Schmitz, B., and Kirsimäe, K. (submitted). The mid-Ordovician Osmussaar Breccia in Estonia linked to the disruption of the L-chondrite parent body in the asteroid belt. *Geological Society of America Bulletin*.

Summary: In this paper we show that the Middle Ordovician (466 Ma) Osmussaar Breccia, situated along the north-western coast of Estonia is rich in angular chromite grains of extraterrestrial origin (>13 grains kg^{-1}). The angularity of the chromite grains imply that they have not been transported or reworked to any large extent, connoting that the brecciation is the result of a contemporary impactor. Analyses of the chemical composition of the extraterrestrial chromite indicate that the impactor was an ordinary chondrite of L-type. This concurs well with the hypothesis that the influx of large bodies to Earth increased during this period, due to the break-up of the L-chondrite parent body, which in turn supports the suggestion that the abundant coeval megabreccias of the time, are the result of this bombardment. The study also strengthens the fact that physical pieces of a large celestial body can survive upon impact with Earth.

Paper VII: Alwmark, C. (submitted). Shocked quartz in the sediments of the Granby structure, Sweden – Verification of an impact. *Meteoritics & Planetary Science*.

Summary: Here I present the finding of shock metamorphic features, in the form of multiple sets of decorated planar deformation features (PDFs) in quartz grains from the in-fill breccia of the Middle Ordovician Granby structure in Sweden. Measurements of the PDFs show that they have an orientation pattern characteristic for that of impact craters, i.e. the Granby structure is the result of an impact. I also show that the shocked quartz grains originate from two different lithologies; rounded grains from mature sandstone and angular grains derived from crystalline basement rocks. The rounded quartz grains display a heterogeneous distribution of shock effects and several PDF poles oriented at high angles to the c-axis. The PDFs in the basement quartz are exclusively oriented in crystallographic plane ω. This discrepancy in frequency of orientation is interpreted as a reflection of the two lithologies different behavior to shock pressure rather than variation in shock pressure *per se*.

Background

The largest documented asteroid break-up event during the past few billion years occurred at ~470 Ma, when the L-chondrite parent body disrupted in the asteroid belt. (Anders 1964; Heymann 1967; Keil et al. 1994; Korochantseva et al. 2007) The break-up resulted in a large increase in the delivery of extraterrestrial material to Earth. The finding of more than 80 fossil L-chondritic meteorites (1–20 cm in diameter) in Middle Ordovician limestone in southern Sweden show that the meteorite flux was enhanced by two orders of magnitude for at least a few million years after the disruption event (Schmitz et al. 1997, 2001, unpublished; Bridges et al. 2007). This enhancement was corroborated by the finding of anomalously large quantities of sediment-dispersed extraterrestrial chromite grains (EC) from decomposed L-chondritic meteorites in contemporary limestones (Schmitz et al. 2003; Schmitz and Häggström 2006; Cronholm and Schmitz 2007; Häggström and Schmitz 2007; Heck et al. 2008).

The enhanced influx coincides in time with the Great Ordovician Biodiversification Event (GOBE; Harper 2006) which made us speculate in whether the diversification process was in some way accelerated by an increased asteroid bombardment (Paper II). Another characteristic for this period is the abundance of megabreccias. Parnell (2009) showed that the time between 460 and 470 Ma saw a widespread distribution of megabreccias along the contemporaneous continental margins, and suggested a link between the two anomalies, i.e. common asteroid impacts destabilized sediment slopes and triggered mass wasting on a global scale. Both these hypotheses, however, suppose that the influx of larger bodies was increased as well. Although modeling studies suggest that the enhanced flux of extraterrestrial matter, after major asteroid disruption events include large asteroids (Zappalà et al. 1998), empirical evidence in the case of the L chondrite parent body disruption is lacking.

Material and methods

The majority of the material studied originates from Middle and Late Ordovician sedimentary rocks from different localities within Sweden and in one case from Estonia (Fig. 1). For detailed information of the material and the specific methods used, see the individual papers included in this thesis.

Trace evidence

Because meteoritic material generally does not survive for a very long time in the wet and oxidizing environment of our planet, the search for traces of extraterrestrial material that is ~470 Ma old can be difficult, and trying to classify it, even more so. Furthermore, larger projectiles (>100 meters in diameter) are believed to be totally vaporized upon impact with Earth (Melosh 1981; Grieve 1997; Koeberl 1998), leaving only a small amount of recondensed projectile vapor mixed-in with the target rocks (e.g., Muñoz-Espadas et al. 2003). Despite the low survival rate, previous studies as well as some of the research included in this thesis demonstrate that traces are to be found, it is just a matter of knowing what to search for and then search carefully. The main traces found and dealt with, of the break-up event, within the scope of this thesis are summarized below.

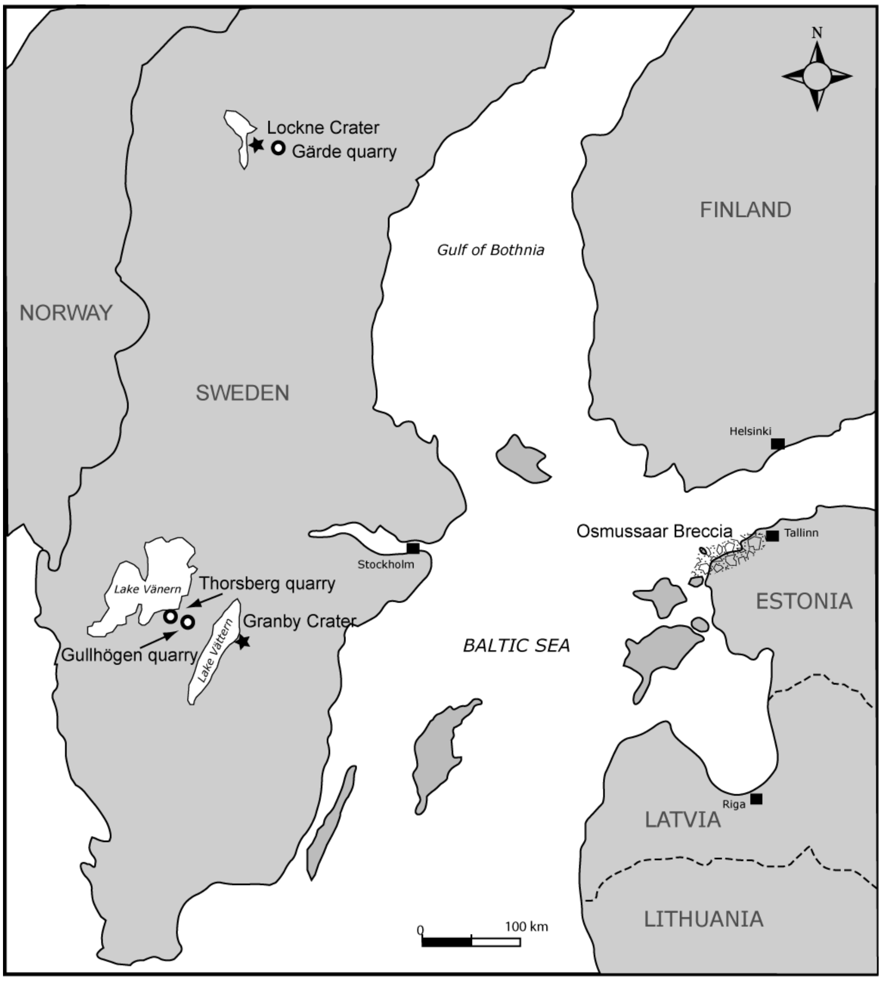

Fig. 1. Map of southern Scandinavia with the location of the studied areas.

Chromite

Chromite ($FeCr_2O_4$) is a common accessory mineral in many meteorites, constituting 0.05–0.5 wt% of recent chondrites (Keil 1962). It has a high resistance against weathering and diagenesis and is often the only surviving mineral in chondritic fossil meteorites (Fig. 2; Thorslund et al. 1984; Schmitz and Häggström 2006). Chromite is also a good petrogenetic indicator; extraterrestrial (chondritic) chromite (EC) has a characteristic composition that differs from the terrestrial ditto, with typically higher TiO_2 content (2.0–3.5 wt%) and Cr/(Cr+Al) ratio (>0.8) and a narrow span of V_2O_3 (0.6–0.9 wt%) (Table 1; Nyström et al. 1988; Schmitz et al. 2001; Schmitz and Häggström 2006). Furthermore, the compositions of EC varies slightly with both group and petrographic type of the host meteorite it originates from (Bunch et al. 1967; Schmitz et al. 2001; Wlotzka 2005; Paper III), thus allowing classification of decomposed meteorites as well as larger impacts, where no other matrix minerals have survived or are present (Table 1). The size of the chromite grains can in some cases also be used to discriminate between different petrographic types, due to the fact that the grain diameter (D_{max}) increases with type (Bridges et al. 2007).

The whole-rock oxygen isotopic composition of recent ordinary chondrites varies with group, with a progressive increase in both $\delta^{18}O$ and $\Delta^{17}O$ from H through L to LL (Clayton et al. 1991). Greenwood et al. (2007) showed that the relationship between oxygen isotopes and meteorite group is valid even when analyzing chromite alone, and that fossil chromite grains have retained their primary oxygen isotopic composition. Thus, oxygen isotope analyses of relict chromite becomes a reliable alternative method of classifying fossil meteoritic material.

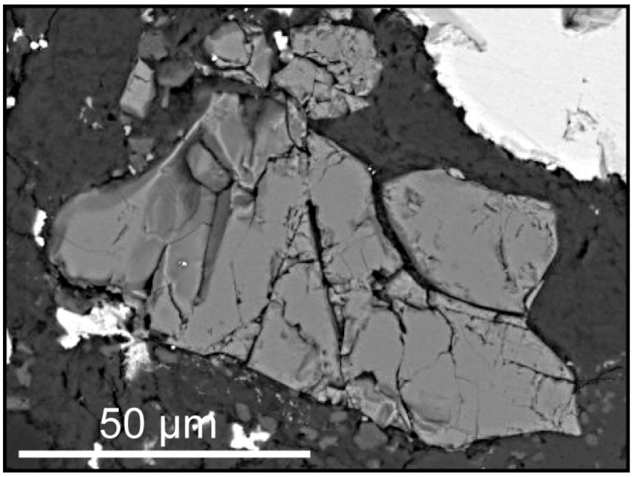

Fig. 2. Backscatter image of chromite grain in the Brunflo meteorite.

Inclusions in chromite

In Paper IV we show that, when encapsulated in relict chromite, other meteoritic minerals, e.g., olivine and pyroxene, can survive for hundreds of millions of years maintaining their primary composition (Fig. 3). By studying recent chondrites where both matrix and chromite-enclosed olivine and pyroxene are present it becomes clear that, apart from a slight modification due to sub-solidus re-equilibration, the olivine and pyroxene inclusions in the chromite grains of the recent chondrites have a composition analogous to the olivine and pyroxene of the matrix, respectively. This makes it possible to establish an analogue to the well established classification system for ordinary chondrites, founded on the fact that olivine and Ca-poor pyroxene in equilibrated (type 4–6) ordinary

Table 1. The average element concentration (wt% and standard deviation 1σ) of EC grains from studies presented in this thesis, in comparison with other studies.

	Cr_2O_3	Al_2O_3	MgO	TiO_2	V_2O_3	FeO	MnO	ZnO	Fe#[1]	Cr#[2]
EC grains from sample FF2 of the Loftar stone, 73 grains (Paper I)	57.87 ±1.1	5.74 ±0.8	1.59 ±1.5	2.48 ±0.38	0.72 ±0.05	26.83 ±1.8	1.44 ±0.47	2.35 ±2.10	90.4 ±8.1	87.1 ±1.5
EC grains from the Brunflo chondrite, 36 grains (Paper III)	56.40 ±0.6	6.81 ±0.3	2.21 ±0.2	1.88 ±0.15	0.73 ±0.08	29.20 ±0.5	0.78 ±0.24	0.86 ±0.57	88.1 ±0.8	84.8 ±0.6
Sediment disp. EC grains from Gärde quarry, 8 grains (Paper III)	57.59 ±1.4	5.65 ±0.4	2.25 ±0.6	3.09 ±0.37	0.72 ±0.03	28.42 ±1.7	0.91 ±0.18	0.74 ±0.93	85.2 ± 3.2	86.7 ± 0.8
EC grains from sample OS1 of the Osmussaar Breccia, 39 grains (Paper VI)	56.71 ±0.5	6.08 ±0.3	2.54 ±0.2	3.00 ±0.26	0.73 ±0.05	29.20 ±0.5	0.79 ±0.19	0.08 ±0.21	86.6 ± 1.1	86.2 ±0.5
Sediment disp. EC grains from Thorsberg quarry, Kinnekulle, 276 grains (Schmitz and Häggström 2006)	57.61 ±1.6	6.07 ±0.8	2.58 ±0.8	3.09 ±0.33	0.75 ±0.07	27.36 ±2.6	0.78 ±0.20	0.53 ±0.50	85.6 ±3.9	86.5 ±1.4
EC grains from 26 meteorites from Thorsberg quarry, Kinnekulle, 594 grains (Schmitz et al. 2001)	57.60 ±1.3	5.53 ±0.3	2.57 ±0.8	2.73 ±0.40	0.73 ±0.03	26.94 ±3.9	1.01 ±0.33	1.86 ±2.43	85.3 ±5.0	87.5 ±0.6
Chromite from 13 recent H4-6 group chondrites (Wlotzka 2005)	57.10 ±1.1	6.64 ±0.4	3.40 ±0.2	1.96 ±0.29	0.65 ±0.03	28.90 ±0.6	0.88 ±0.07	0.28 ±0.14	82.7 ±1.0	85.2 ±1.0
Chromite from 6 recent L4-6 group chondrites (Wlotzka 2005)	56.10 ±0.8	5.90 ±0.2	2.52 ±0.2	2.67 ±0.44	0.70 ±0.06	30.90 ±0.6	0.63 ±0.08	0.34 ±0.06	87.3 ±1.0	86.5 ±0.3
Chromite from 4 recent LL3-7 group chondrites (Wlotzka 2005)	55.80 ±0.6	5.52 ±0.2	1.85 ±0.1	3.40 ±0.60	0.67 ±0.10	31.60 ±0.6	0.51 ±0.04	-	90.5 ±0.9	87.2 ±0.2

[1]Fe#: mole% Fe/(Fe+Mg); [2]Cr#: mole% Cr/(Cr+Al)

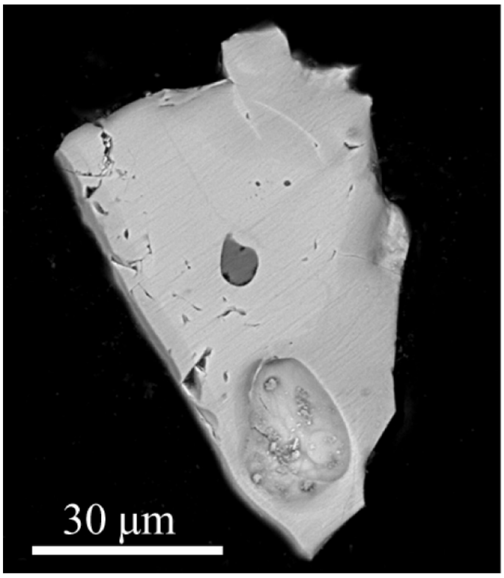

Fig. 3. Backscattered electron image of a solitary olivine inclusion in a sediment-dispersed extraterrestrial chromite grain from the Gullhögen quarry.

chondrites have specific ranges of chemical composition depending on group (H, L, LL; e.g., Mason 1963; Keil and Fredriksson 1964; Gomes and Keil 1980; Rubin 1990), based on the inclusions (Fig. 4). Thus creating an independent tool in the classification of fossil chondrites and sediment-dispersed extraterrestrial chromite grains originating from decomposed micrometeorites (Heck et al. 2008) and chondritic fragments related to impact events, when no matrix silicates are preserved or present.

Chondrules

Chondrules are rounded grains of primarily olivine or pyroxene, believed to have formed as molten, or partially molten, droplets in space before being accreted to their parent asteroids. Despite the pervasive alteration generally seen in fossil meteorites, the original texture is often very well preserved, including the chondrules (Fig. 5). Because mean chondrule diameter varies with chondrite group (Grossman et al. 1988; Rubin 2000; Bridges et al. 2007), it is possible to asses meteorite group by measuring the diameter of the chondrule pseudomorphs in fossil meteorites. Furthermore, the definition of the chondrules can give an impression of what petrographic type the meteorite belongs to, since definition decreases with increase in type (Van Schmus and Wood 1967).

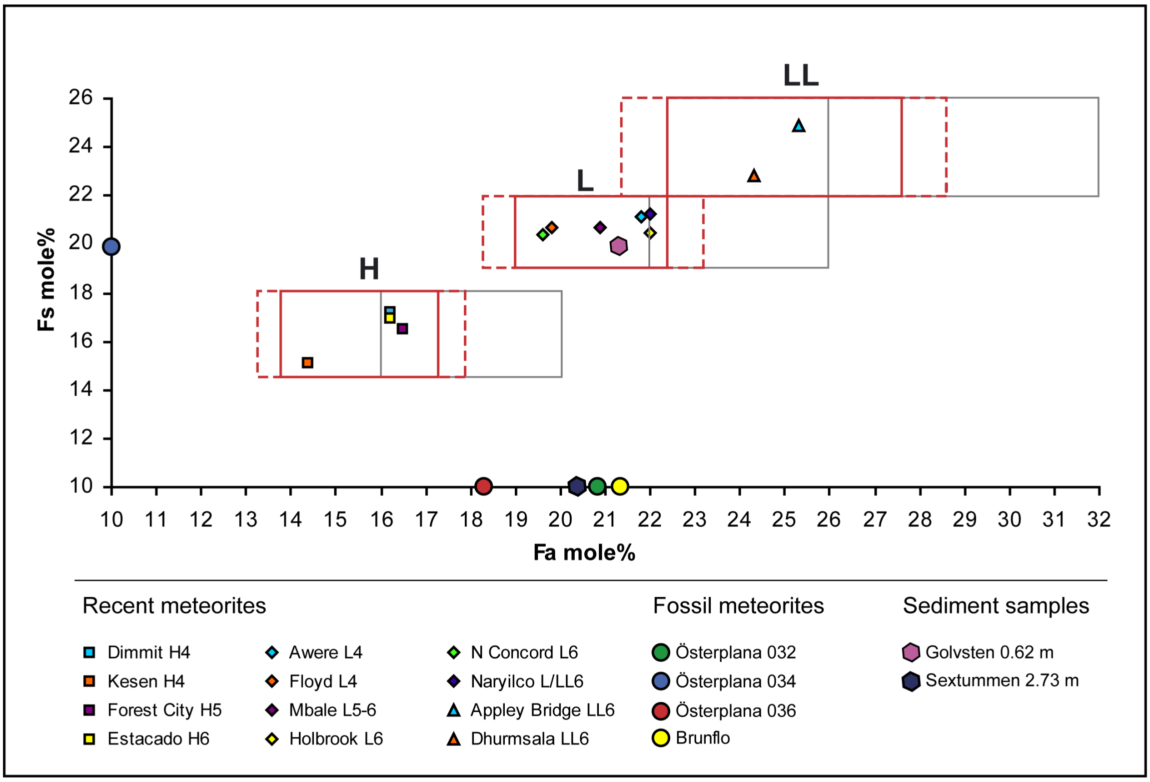

Fig. 4. Fa content in olivine and Fs content in Ca-poor pyroxene of inclusions in chromite of recent and fossil meteorites and sediment samples. The red boxes represent the newly defined ranges of Fa and Fs in Ca-poor pyroxene and olivine, respectively, of inclusions in chromite, with the red dotted lines being the standard deviation (1σ). The gray boxes represent the established ranges of Fs and Fa in Ca-poor pyroxene and olivine, respectively, determined for the three groups (H, L, LL) of ordinary equilibrated chondrites (Brearley and Jones, 1998, and references therein).

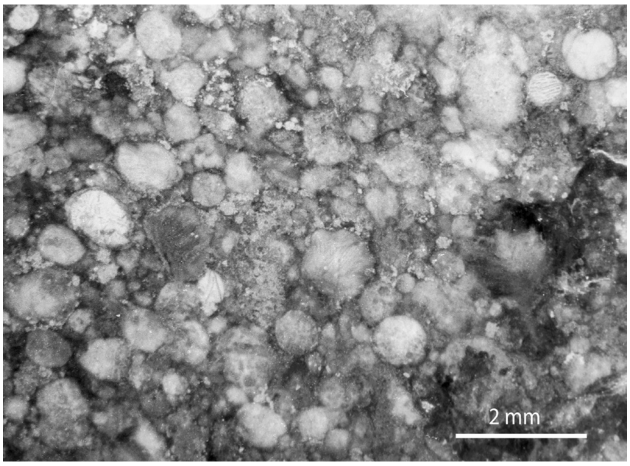

Fig. 5. Well-defined relict chondrules in the Brunflo meteorite; reflected light. The photo was taken for the paper by Thorslund et al. (1984)

Shock effects
When a large celestial body hits Earth, vast amounts of energy are released under an extremely short time interval, creating a number of characteristic shock-metamorphic effects in the minerals of the target rocks. One of the most studied of these shock effects are planar deformation features (PDFs) in quartz (e.g. French and Short 1968; von Engelhardt and Bertsch 1969; Stöffler and Langenhorst 1994; Grieve et al. 1996). PDFs are extremely fine planar lamellae, consisting of highly deformed or amorphous quartz, that occur in parallel multiple sets oriented along specific crystallographic planes of the quartz crystal (Fig. 6). PDFs form in quartz at pressures between 7-35 GPa, making them a unique feature of impacts (with the exception of nuclear explosions) and a very good diagnostic tool in identifying them. Furthermore, the PDFs vary in appearance and orientation with pressure, thus they can be used as a shock barometer (Hörz 1968; Robertson et al. 1968; Robertson and Grieve 1977; Stöffler and Langenhorst 1994; Dressler et al. 1996).

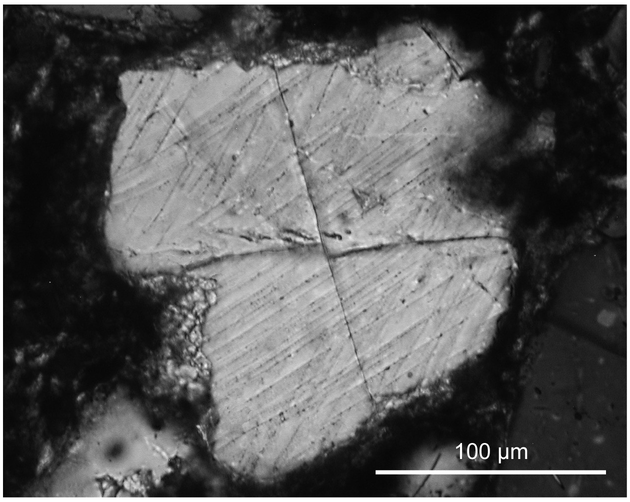

Fig. 7. Microphotograph of quartz grain from the Granby structure showing two sets of partially decorated PDFs.

Conclusions

The L-chondritic origin of the 458 Ma Lockne crater impactor and the vast amount of chromite with an L-chondritic composition in the 466 Ma Osmussaar Breccia, suggesting yet another L-chondritic impact event, imply that the increased flux of extraterrestrial material to Earth, following the disruption of the L chondrite parent body included larger asteroid-sized bodies. This in turn gives support to the suggestion that the megabreccias of the time are a result of impacts, as well as the hypothesis that the Great Ordovician Biodiversification Event was accelerated due to the bombardment.

That the increased flux included larger projectiles is further corroborated by the verification of the Granby structure as being impact derived. Although the projectile type is unknown, the timing of the impact (467 Ma) raises the suspicion that it too originates form the L chondrite parent body.

New chondrule-size measurements for the Brunflo meteorite show that it is an L chondrite, and thus related to the L-parent body break-up. Furthermore, the low TiO_2 (1.8 wt%) and the D_{max} of relict chromite and the relatively sharp chondrule definition imply that Brunflo is of petrographic type 4. The limestone in the Gärde quarry is relatively rich (~0.45 grain kg^{-1}) in sediment-dispersed extraterrestrial chromite grains with an L-chondritic composition, suggesting that the enhanced flux of L chondrites prevailed, although somewhat diminished, at the time when the Brunflo meteorite fell, i.e. ca 5 Ma after the meteorites from the Thorsberg quarry.

The finding of extraterrestrial chromite grains in impact related material shows that physical pieces of larger projectiles can survive the impact process. Chemical analyses of chromite show that the majority of the recovered grains have retained their primary composition and that they thus can be used to classify the impacting projectile.

Primary inclusions of olivine, pyroxene, merrillite and plagioclase have been identified in chromite of extraterrestrial origin, both in recent and fossil meteorites, as well as in sediment-dispersed EC grains. The systematic compositional difference in Fa in the chromite-hosted olivine and the more or less analogous Fs-content in Ca-poor pyroxene, compared to matrix phases, makes it possible to establish ranges for inclusions analogous to the well established classification system based on Fa in olivine and Fs in Ca-poor pyroxene, for ordinary equilibrated chondrites. Thus, making this a good tool in classification of fossil meteorites, as well as the origin of sediment-dispersed chromite grains from decomposed meteorites and larger impacts, where no other matrix minerals have survived, or are present.

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