Extraterrestrial chromite in Middle Ordovician marine limestone
at Kinnekulle, southern Sweden—Traces of a major asteroid breakup event

Birger SCHMITZ\(^1\)* and Therese HÄGGSTRÖM\(^2\)

\(^1\)Department of Geology, Lund University, SE-22362 Lund, Sweden
\(^2\)Department of Marine Geology, Earth Sciences Center, Göteborg University, SE-40530 Göteborg, Sweden
*Corresponding author. E-mail: birger.schmitz@geol.lu.se

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Abstract–The distribution of sediment-dispersed extraterrestrial chromite grains and other Cr-rich spinels (>63 \(\mu\)m) has been studied in Middle Ordovician Orthoceratite Limestone from two quarries at Kinnekulle, southern Sweden. In the Thorsberg quarry, an ~3.2 m thick sequence of beds previously shown to be rich in fossil meteorites is also rich in sediment-dispersed extraterrestrial chromite grains. Typically, 1–3 grains are found per kilogram of limestone. In the nearby Hälleklis quarry, the same beds show similarly high concentrations of extraterrestrial chromite grains, but in samples representing the 9 m downward continuation of the section exposed at this site, only 5 such grains were found in a total of 379 kg of limestone. The extraterrestrial (equilibrated ordinary chondritic) chromite grains can be readily distinguished by a homogeneous and characteristic major element chemistry, including 2.0–3.5 wt% TiO\(_2\) and stable V\(_2\)O\(_3\) concentrations close to 0.7 wt%.

Terrestrial Cr-rich spinels have a wide compositional range and co-exist with extraterrestrial chromite in some beds. These grains may be derived, for example, from mafic dykes exposed and weathered at the sea floor.

Considering lithologic and stratigraphic aspects variations in sedimentation rate cannot explain the dramatic increase in extraterrestrial chromite seen in the upper part of the composite section studied. Instead, the difference may be primarily related to an increase in the ancient flux of extraterrestrial matter to Earth in connection with the disruption of the L chondrite parent body at about this time. The coexistence in some beds of high concentrations of chondritic chromite and terrestrial Cr-rich spinels, however, indicates that redistribution of heavy minerals on the sea floor, related to changes in sea level and sea-floor erosion and currents, must also be considered.

INTRODUCTION

A systematic search for fossil meteorites has been conducted since 1992 in mid-Ordovician marine limestone in the Thorsberg quarry at Kinnekulle, southern Sweden (Schmitz et al. 2001). Within the project, more than fifty fossil meteorites, 1–20 cm in diameter, have been found during quarrying of the ancient, lithified sea floor. The number of fossil meteorites found compared to the area quarried is far too high to be explained by a meteorite flux to Earth similar to that of the present. There is no indication that the meteorites have been concentrated into a small area of the sea floor after impacting on Earth. Schmitz et al. (1996, 2001) therefore suggested that accretion rates of meteorites were one to two orders of magnitude higher during a part of the Middle Ordovician than at the present. This idea is consistent with argon isotope gas retention ages of recent meteorites showing that a major collision/disruption event affected the L chondrite parent body 450–500 Myr ago (McConville et al. 1988; Keil et al. 1994; Bogard 1995). The major and trace element composition of relict chromite grains from the fossil meteorites in the Thorsberg quarry indicate that all or almost all meteorites found are L chondrites (or possibly LL chondrites) (Schmitz et al. 2001). The amount of cosmic ray produced noble gases in the chromite grains increases the higher up in the strata a meteorite is found (Heck et al. 2004). This is consistent with an origin of all the meteorites from one major asteroid breakup event.

The search for fossil meteorites is time-consuming and tedious, hence we have tested using the distribution of
sediment-dispersed extraterrestrial chromite grains for reconstructing the ancient meteorite flux to Earth (Schmitz et al. 2003). Recent ordinary chondrites contain 0.05–0.5 wt% chromite (Keil 1962). Chromite is very resistant and endures most acid treatments, weathering exposure, and diagenesis relatively unaffected. If a meteorite lands on the sea floor and decomposes due to weathering, chromite grains are left as a remnant of the original meteorite. The approach can best be applied for ordinary equilibrated chondritic meteorites in which chromite is the dominant oxide (Rubin 1997). The “coarse” chromite of such chondrites (Ramdohr 1973) can be readily distinguished from terrestrial chromite, for example, by high TiO2 concentrations (2–3.5 wt%) and a narrow range of V2O3 (0.6–0.8 wt%) concentrations (Bunch et al. 1967; Nyström et al. 1988; Schmitz et al. 2001). The differences in composition are further treated in the Results section.

In this report, we present the detailed results of a search for extraterrestrial chromite in limestone in the Thorsberg and Hälleks quarries at Kinnekulle, southern Sweden (Figs. 1 and 2). A preliminary summary of some of the results was given by Schmitz et al. (2003). The quarried section at the Thorsberg quarry spans ~3.2 m of mid-Ordovician, condensed marine Orthoceratite Limestone. In this quarry, the distribution of sediment-dispersed extraterrestrial chromite can be compared with the distribution of the fossil meteorites found (Schmitz et al. 2001). In the abandoned Hälleks quarry, which is four kilometers northwest of the Thorsberg quarry, we studied a more extended Orthoceratite Limestone section spanning ~20 m of the Middle Ordovician. Studies of the extraterrestrial chromite distribution throughout the sections in the Hälleks and Thorsberg quarries can give a better understanding of the extent of the stratigraphic interval rich in fossil meteorites.

GEOLOGICAL SETTING

Kinnekulle and the Orthoceratite Limestone

Kinnekulle, situated southeast of Lake Vänern, is a 306 m high table mountain, mainly made up by sedimentary rocks of Cambrian to Silurian age. Altogether, fourteen table mountains occur as isolated “islands” of lower Paleozoic sedimentary rock in the dominantly metamorphic and igneous Precambrian terrain of the province of Västergötland. The characteristic flat top of the table mountains is typically related to a horizontal diabase intrusion that has protected the underlying sedimentary rocks from erosion. TheOrdovician part of the sedimentary record at Kinnekulle is dominated by the Orthoceratite Limestone, which was deposited mainly during the Arenigian and Llanvirnian in a vast epicontinental sea, covering large parts of the Baltoscandian Shield (Lindström 1971, 1979). The limestone is generally very condensed, having formed at average sedimentation rates of one to a few millimeters per thousand years (Lindström 1971, 1979). Hard grounds are common and represent long periods (1–10 kyr) of nondeposition. The color of the limestone alternates in shades between red to brown-red and light-gray to darker gray and depends on the oxidation state when pore water circulation came to an end (Lindström 1979). The Orthoceratite Limestone is one of the most popular building stones in Sweden and fossil meteorites have been found when the limestone is industrially sawed into plates (Thorslund et al. 1984; Schmitz et al. 2001). The meteorites often occur on hard ground surfaces together with cephalopod shells. Apparently, winnowing processes by currents in the water column, analogous to wind-winnowing of sand leading to meteorite accumulation in deserts, prevented more fine-grained debris from settling on the sea floor. A distal position relative to the shore may also explain the condensed nature of the limestone. Delicate cephalopod shells are preserved unbroken and show no preferred orientation, indicating a quiet environment on the sea floor (Schmitz et al. 2001). Possibly winnowing may have acted higher up in the water column or occurred only episodically at the sea floor.

The Thorsberg and Hälleks Quarries

The two localities studied are the Thorsberg quarry (58°35′N, 13°26′E) close to the Österplana church and the Hälleks quarry (58°37′N, 13°24′E) near the town of Hälleks.

Fig. 1. The location of the Thorsberg and Hälleks quarries. The quarries are situated 4 km from each other on the small table mountain Kinnekulle.
Extraterrestrial chromite in Middle Ordovician marine limestone at Kinnekulle, southern Sweden

Fig. 1. The Thorsberg quarry is still active, but exposes only ~6 m of the mid-Ordovician rock record; of this, only 3.2 m are quarried, mainly for the production of building stones (Schmitz et al. 2001) (Fig. 2). The middle part of the quarried interval is represented by a 1.4 m thick band of gray limestone of which the middle part is rich in marl layers and was probably deposited at a faster rate than the condensed, hard-ground rich gray limestone that grades into the enclosing red limestone. The lower 0.8 m and the upper 1 m of the quarried interval at Thorsberg is typical red condensed limestone with hard grounds.

The abandoned Häleks quarry used to be one of the largest limestone quarries in Sweden, and exposes an ~50 m thick section of Orthoceratite Limestone. Considered here is only the lower ~20 m of this section, of which the middle part is identical with the shorter section exposed in the Thorsberg quarry (Fig. 2). The studied Häleks section is represented by macrolithologically monotonous red Orthoceratite Limestone (Tinn and Meidla 2001), except for the 1.4 m thick gray band in the middle part that can be traced to the Thorsberg quarry. This prominent gray band can be traced further to Billingen and southern Öland, 35 and 300 km southeast of Kinnekulle, respectively (Schmitz et al. 2003). According to conodont stratigraphy the studied Häleks section spans, from base to top, the following zones and subzones: Paroistodus originalis, Lenodus variabilis, Yangtzeplacognathus crassus, Microzarkodina hagetiana and M. ozarkodella (Zhang 1998; A. Löfgren, personal communication). The interval corresponds to the Arenigian-Llanvirnian series in British stratigraphy, with the boundary between the two series approximately at the gray band in the middle of the section. In the global stratigraphic framework the upper three-quarters of the section studied belong to the Darrwilian stage and the lower quarter belongs to the presently unnamed first stage of the Middle Ordovician.

The quarried interval in the Thorsberg quarry spans the L. variabilis and Y. crassus conodont zones (Fig. 2). The interval is made up of 12 horizontally piled beds, each with a...
traditional name from the quarrying industry. The succession of beds over the interval is identical in the Hälleks and
Thorsberg quarries. In the lowermost bed, Arkeologen, as
many as 26 fossil meteorites had been found over an area of
2700 m² by the end of year 2000 (Schmitz et al. 2001). In the
overlying beds, 24 meteorites had been found over an area of
6000 m². Additionally, more than ten meteorites have been
found in the Thorsberg quarry after year 2000 (B. Schmitz,
unpublished data).

MATERIALS AND METHODS

For chromite searches, large samples (typically 10–
30 kg) of Orthoceratite Limestone were collected. In the
Thorsberg quarry, we searched for chromite in eight
limestone samples from the Arkeologen, Golvsten, Botten,
and Sextummen beds. The weight of each sample ranged
from 10.7 to 26 kg and the total mass analyzed was 148 kg.
We avoided collecting samples close to spots where fossil
meteorites had been recovered. From the Hälleks section,
two samples, 7.3 and 18.7 kg, were collected from the
Arkeologen bed, one sample of 28 kg from 8.5 m above this
bed, and fourteen samples with a total mass of 379 kg
spanning the 9 m interval below the Arkeologen bed.

The samples were split with a sledgehammer into pieces
smaller than 8 cm and then further crushed to a fragment size
of 5 mm using a Retsch Jaw Crusher BB 200. The crushed
material was decalcified in 6 M hydrochloric acid at room
temperature. After sieving the residue at 32 µm, the
remaining fraction was leached with 18 M hydrofluoric acid
at room temperature with occasional stirring. The residue
was recovered with a 32 µm sieve. In a few cases, further mineral
separation was performed with LST Fastfloat (sodium
heteropolytungstate) heavy liquid into material with a density
higher or lower than 2.8 g cm⁻³. The acid-insoluble fraction in
the size range 63–355 µm was searched for opaque minerals
under the binocular microscope and grains were picked with a
fine brush for element analyses. The grains were mounted in
epoxy resin and polished to a flat surface using 1 µm diamond
slurry. The element analyses were performed with a LINK
Oxford energy dispersive spectrometer with a Ge detector,
mounted in a Zeiss DSM 940 scanning electron microscope.
A cobalt standard linked to simple oxide and metal standards
was used to monitor drift of the instrument. Accelerating
voltage of 25 kV, sample current about 1 nA and counting
live-time of 100 sec were used. Precision (reproducibility) of
analyses was typically better than 1–4%. Analytical accuracy
was controlled by repeated analyses of the USNM 117075
(Smithsonian) chromite reference standard (Jarosewich et al.
1980).

RESULTS

Distribution of Cr-Rich Spinel

The distribution of Cr-rich spinels through the composite
section studied is shown in Fig. 3 and Table 1. The grains are
divided into two groups: those that we consider to be
“typical” extraterrestrial chromite (EC) grains and those that
we refer to as “other” Cr-rich spinel (OC) grains. The EC
grains have a chemical composition very similar to common
chromite grains in the fossil meteorites from the Thorsberg
quarry and similar to chromite in recent ordinary chondritic
meteorites of higher petrographic types (4–6) (Schmitz et al.
2001). Under the light microscope, the OC grains cannot be
distinguished from the EC grains, but they differ in chemical
composition and show a wide compositional range. The
chemistry of the two groups of grains is further dealt with in
the next section.

All the samples from the meteorite-yielding interval in
the Thorsberg quarry show high concentrations of EC in the
range of 0.9–3.3 grains per kg of whole-rock (Fig. 3). The
highest concentration of EC, 3.3 grains per kg, occurs in the
lower middle part of the meteorite-rich Arkeologen bed at the
base of the studied section. There is no clear trend upward
through the sequence. Instead, the EC content varies between 0.9 and 2.1 grains per kg throughout the interval. The lower red and the upper gray part of the Golvsten bed contain 1.7 and 2.1 grains, respectively, per kg of rock. The gray Botten bed that has yielded some of the largest fossil meteorites shows the lowest concentrations of EC at 0.9 grain per kg. Three intervals of the Sextummen bed in the upper red interval show between 1.4 and 1.9 grains per kg. In total, 276 EC grains were found in 148 kg of limestone from the meteorite-yielding interval of the Thorsberg quarry.

Four beds in the middle part of the gray limestone interval (the Gråkarten, Blymåkka, Fjällbott, and Likhall beds) have never yielded any fossil meteorites, although some parts of this interval are used extensively for the production of sawed slabs (Schmitz et al. 2001). The acid-insoluble residues of these beds are very rich in various authigenic heavy minerals such as pyrite and barite. Searches for chromite in these beds were considered to be too time-consuming and were therefore abandoned.

In the Hälleks quarry, the lower and middle part of the Arkeologen bed is as rich in EC grains as in the Thorsberg quarry. However, the fourteen samples from the stratigraphic interval between 0.8 and 9.2 m below the Arkeologen bed, weighing 379 kg in total, contained only 5 EC grains distributed over four samples. The sample from 8.5 m above the base of the Arkeologen bed contained 11 EC grains per 28 kg of limestone, i.e., 0.4 grain per kg. This represents a substantial enrichment in EC grains compared to the 9 m interval below the Arkeologen bed, but a significant decline from the high EC concentrations in the meteorite-yielding beds.

Chromium-rich spinels other than the typical chondritic chromite grains are rare (0–0.4 grains per kg) throughout the composite section studied except at three levels in the interval that is also rich in EC grains. The highest concentration of OC, 1.8–2.0 grains per kg, occurs in the lower middle part of the Arkeologen bed, which is also the interval with the highest concentrations of EC grains. The upper and lowermost part of the Arkeologen bed contain only rare OC grains, but high concentrations of EC at 1.7–1.8 grains per kg. Two other samples rich in OC grains, the middle Sextummen sample with 1.3 grains per kg, and the Botten bed with 1.4 grains

### Table 1. The distribution of extraterrestrial chromite (EC) and other Cr-rich spinel (OC) grains in mid-Ordovician limestone. Depths are relative to the base of the Arkeologen bed.

<table>
<thead>
<tr>
<th>Bed</th>
<th>Depth (m)</th>
<th>Sample size (kg)</th>
<th>No. EC grains</th>
<th>EC grains (kg⁻¹)</th>
<th>No. OC grains</th>
<th>OC grains (kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thorsberg quarry, Kinnekulle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sextummen</td>
<td>+2.73 to +2.83</td>
<td>12.6</td>
<td>21</td>
<td>1.7</td>
<td>5</td>
<td>0.4</td>
</tr>
<tr>
<td>Sextummen</td>
<td>+2.58 to +2.73</td>
<td>19.0</td>
<td>26</td>
<td>1.4</td>
<td>25</td>
<td>1.3</td>
</tr>
<tr>
<td>Sextummen</td>
<td>+2.50 to +2.58</td>
<td>10.7</td>
<td>20</td>
<td>1.9</td>
<td>2</td>
<td>0.2</td>
</tr>
<tr>
<td>Botten</td>
<td>+0.87 to +1.05</td>
<td>24.6</td>
<td>23</td>
<td>0.9</td>
<td>34</td>
<td>1.4</td>
</tr>
<tr>
<td>Golvsten</td>
<td>+0.77 to +0.87</td>
<td>13.3</td>
<td>28</td>
<td>2.1</td>
<td>4</td>
<td>0.3</td>
</tr>
<tr>
<td>Golvsten</td>
<td>+0.62 to +0.77</td>
<td>17.7</td>
<td>30</td>
<td>1.7</td>
<td>1</td>
<td>0.06</td>
</tr>
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<td>Arkeologen</td>
<td>+0.32 to +0.56</td>
<td>24.0</td>
<td>41</td>
<td>1.7</td>
<td>3</td>
<td>0.1</td>
</tr>
<tr>
<td>Arkeologen</td>
<td>+0.08 to +0.32</td>
<td>26.0</td>
<td>87</td>
<td>3.3</td>
<td>51</td>
<td>2.0</td>
</tr>
<tr>
<td>Hälleks quarry, Kinnekulle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+8.50 to +8.65</td>
<td>28.0</td>
<td>11</td>
<td>0.4</td>
<td>1</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Arkeologen</td>
<td>+0.14 to +0.31</td>
<td>7.3</td>
<td>22</td>
<td>3.0</td>
<td>13</td>
<td>1.8</td>
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<tr>
<td>Arkeologen</td>
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<td>18.7</td>
<td>34</td>
<td>1.8</td>
<td>4</td>
<td>0.2</td>
</tr>
<tr>
<td>−0.82 to −0.97</td>
<td>25.4</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0.04</td>
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<tr>
<td>−1.47 to −1.69</td>
<td>28.0</td>
<td>1</td>
<td>0.04</td>
<td>6</td>
<td>0.21</td>
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<td>−2.35 to −2.60</td>
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<tr>
<td>−2.60 to −2.85</td>
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<td>−3.12 to −3.27</td>
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<td>1</td>
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<td>2</td>
<td>0.07</td>
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<tr>
<td>−3.27 to −3.45</td>
<td>27.7</td>
<td>1</td>
<td>0.04</td>
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<td>−3.45 to −3.95</td>
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<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>−4.30 to −4.50</td>
<td>28.1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>−4.50 to −4.58</td>
<td>20.6</td>
<td>2</td>
<td>0.1</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>−5.00 to −5.25</td>
<td>30.5</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td></td>
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<tr>
<td>−5.45 to −5.70</td>
<td>28.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>−5.88 to −6.08</td>
<td>23.1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>−6.08 to −6.18</td>
<td>20.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>−9.05 to −9.15</td>
<td>26.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tr>
</tbody>
</table>
Chemical Composition of Extraterrestrial Chromite

The sediment-dispersed EC grains are very similar in composition to the relict chromite grains that are abundant in the fossil meteorites recovered in the Thorsberg quarry (Tables 2, 3, and 4; Fig. 4) (Tables 3 and 4 are available online at http://meteoritics.org/Online%20Supplements.htm). The grains are characterized in the first hand by high Cr₂O₃ contents of ∼55–60 wt%, FeO concentrations in the range of ∼25–30 wt%, low Al₂O₃ at ∼5–8 wt%, and MgO concentrations of ∼1.5–4 wt%. The most discriminative feature, however, is that they plot in narrow ranges of V₂O₃, ∼0.6–0.9 wt%, and TiO₂, ∼2.0–3.5 wt%, concentrations. We stress that for a grain to be classified as an EC grain, it has to have a composition within the defined ranges for all the elements listed above. For example, a grain with TiO₂ and V₂O₃ concentrations within the defined EC ranges but with an Al₂O₃ concentration significantly outside this range is classified as an OC grain. The only differences in composition for the sediment-dispersed EC grains compared to chromite from the fossil meteorites are for ZnO, which is on average 1.3 wt% lower in the sediment-dispersed grains, and TiO₂ and Al₂O₃ that are on average 0.36 wt% and 0.54 wt% higher, respectively, in the sediment-dispersed grains (Fig. 4). However, for TiO₂ and Al₂O₃, the differences are smaller than the standard deviations for the average values and may not be significant. The only significant systematic difference between sediment-dispersed grains from different beds is a few percent higher FeO content in grains from the Botten and upper Golvsten beds, both in the lower part of the gray interval.

The EC grains from the Arkeologen bed in the Hällelekis section show an almost identical average composition to all the EC grains from the Thorsberg quarry (Table 2). However, the five grains classified as EC grains from the 9 m interval below the base of the Arkeologen bed are on average 2.6 wt% higher in Cr₂O₃, 3.4 wt% lower in FeO, and most notably 0.8 wt% lower in TiO₂ than the average for all the other EC grains. Some increase of Cr₂O₃ at the expense of FeO may occur during diagenesis of EC grains (Fig. 7 in Schmitz et al. 2001), but diagenesis does not appear to generally affect the TiO₂ content. Of the five EC grains from the 9 m interval below the Arkeologen bed four lie in the range 1.4–2.4 wt% TiO₂, with the fifth grain yielding 3.3 wt% TiO₂ (Table 4). Only 4% of the 343 EC grains from above the base of the Arkeologen bed in this study show TiO₂ concentrations of 2.4 wt% or lower, with the lowest value at 1.9 wt% (Tables 3 and 4). The eleven EC grains at 8.50 m above the base of the Arkeologen bed show a “normal” average TiO₂ concentration of 3.1 wt%.

Chemical Composition of “Other” Cr-Rich Spinels

For three samples that contain both abundant EC and OC grains, elemental cross plots illustrate the relations between the two categories of grains (Fig. 5). Whereas the abundant EC grains cluster within narrow ranges for all elements, OC grains show a very large compositional spread: the Cr₂O₃ concentrations vary between ∼20 and 62 wt%, FeO varies between 15 and 52 wt%, MgO between 2.4 and 16 wt%, and Al₂O₃ between 3.8 and 43 wt% (Tables 3 and 4). The OC grains generally show V₂O₃ concentrations lower than 0.4 wt% and TiO₂ concentrations lower than 1 wt%. The OC grains have Cr/(Cr + Al) ratios in the range ∼0.3–0.9, with most values below 0.7, compared with a narrow range of 0.8–0.9 for the EC grains. There are some significant differences in the average composition of OC grains between the beds. The Cr/(Cr + Al) ratio is generally significantly higher in OC grains from the Sextummen bed, compared to the Arkeologen bed (Fig. 6). The Botten bed also shows many OC grains with higher Cr/(Cr + Al) ratios than those in the Arkeologen bed.

DISCUSSION

EC Grains

In the 9 m interval of Orthoceratite Limestone below the Arkeologen bed at Kinnekulle, sediment-dispersed EC grains are extremely rare (5 grains per 379 kg of rock), whereas they are common (332 grains per 174 kg of rock) in the meteorite-yielding interval above the base of this bed. The section studied is lithologically relatively homogeneous, with condensed limestone dominating throughout, implying that major changes in sedimentation rates cannot explain the difference in EC abundance. The extensions of trilobite and conodont zones in the section (Fig. 2) also speaks against any major changes in long-term averaged sedimentation rates, although individual beds may have formed at significantly different rates. The OC grains are also more abundant above the base of the Arkeologen bed (142 grains per 174 kg), than below (11 grains per 379 kg), but whereas EC grains appear to be relatively evenly distributed throughout the meteorite-rich interval, the OC grains are mainly confined to three of nine levels studied. There may be a connection between the coeval increase in OC and EC grains above the base of the Arkeologen bed, but the issue may be complex.

The two orders of magnitude increase in EC grains starting at the Arkeologen bed was interpreted by Schmitz et al. (2003) as evidence of an enhanced flux of meteorites to
Table 2. The average element concentration (wt% and standard deviation) of sediment-dispersed extraterrestrial chromite (EC) grains.

<table>
<thead>
<tr>
<th>Locality and depth relative to base of Arkeologen bed</th>
<th>No. EC grains</th>
<th>Cr$_2$O$_3$</th>
<th>Al$_2$O$_3$</th>
<th>MgO</th>
<th>TiO$_2$</th>
<th>V$_2$O$_3$</th>
<th>FeO</th>
<th>MnO</th>
<th>ZnO</th>
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<tbody>
<tr>
<td><strong>Thorsberg quarry, Kinnekulle</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Sextummen +2.73 to +2.83 m</td>
<td>21</td>
<td>57.44 ± 1.59</td>
<td>5.89 ± 0.76</td>
<td>2.54 ± 1.50</td>
<td>3.06 ± 0.28</td>
<td>0.75 ± 0.07</td>
<td>26.67 ± 2.83</td>
<td>0.74 ± 0.16</td>
<td>0.42 ± 0.42</td>
<td>97.51</td>
</tr>
<tr>
<td>Sextummen +2.58 to +2.73 m</td>
<td>26</td>
<td>58.18 ± 2.05</td>
<td>6.36 ± 1.13</td>
<td>2.07 ± 0.83</td>
<td>2.99 ± 0.29</td>
<td>0.71 ± 0.08</td>
<td>26.68 ± 3.99</td>
<td>0.61 ± 0.12</td>
<td>0.35 ± 0.22</td>
<td>97.95</td>
</tr>
<tr>
<td>Sextummen +2.50 to +2.58 m</td>
<td>20</td>
<td>56.74 ± 2.11</td>
<td>5.95 ± 0.93</td>
<td>2.48 ± 0.92</td>
<td>3.06 ± 0.39</td>
<td>0.74 ± 0.08</td>
<td>26.36 ± 2.13</td>
<td>0.79 ± 0.16</td>
<td>0.52 ± 0.22</td>
<td>96.64</td>
</tr>
<tr>
<td>Botten +0.87 to +1.05 m</td>
<td>23</td>
<td>56.42 ± 0.94</td>
<td>5.93 ± 0.59</td>
<td>2.53 ± 0.38</td>
<td>3.13 ± 0.16</td>
<td>0.73 ± 0.06</td>
<td>30.05 ± 0.91</td>
<td>0.79 ± 0.09</td>
<td>0.31 ± 0.08</td>
<td>99.89</td>
</tr>
<tr>
<td>Golvssten +0.77 to +0.87 m</td>
<td>28</td>
<td>57.52 ± 1.34</td>
<td>5.80 ± 0.62</td>
<td>2.63 ± 0.52</td>
<td>3.06 ± 0.38</td>
<td>0.74 ± 0.05</td>
<td>28.61 ± 1.27</td>
<td>0.85 ± 0.08</td>
<td>0.37 ± 0.14</td>
<td>99.57</td>
</tr>
<tr>
<td>Golvssten +0.62 to +0.77 m</td>
<td>30</td>
<td>57.96 ± 1.50</td>
<td>6.04 ± 0.76</td>
<td>2.61 ± 0.55</td>
<td>2.97 ± 0.42</td>
<td>0.78 ± 0.09</td>
<td>27.01 ± 2.36</td>
<td>0.95 ± 0.34</td>
<td>0.74 ± 0.62</td>
<td>99.06</td>
</tr>
<tr>
<td>Arkeologen +0.32 to +0.56 m</td>
<td>41</td>
<td>57.49 ± 1.52</td>
<td>6.26 ± 0.77</td>
<td>2.77 ± 0.66</td>
<td>3.12 ± 0.28</td>
<td>0.76 ± 0.07</td>
<td>27.01 ± 2.80</td>
<td>0.77 ± 0.20</td>
<td>0.57 ± 0.52</td>
<td>98.73</td>
</tr>
<tr>
<td>Arkeologen +0.08 to +0.32 m</td>
<td>87</td>
<td>57.99 ± 1.26</td>
<td>6.09 ± 0.59</td>
<td>2.68 ± 0.73</td>
<td>3.18 ± 0.31</td>
<td>0.75 ± 0.07</td>
<td>27.11 ± 2.27</td>
<td>0.77 ± 0.17</td>
<td>0.63 ± 0.66</td>
<td>99.20</td>
</tr>
<tr>
<td><strong>Total no. of grains and average composition</strong></td>
<td>276</td>
<td>57.61 ± 1.58</td>
<td>6.07 ± 0.76</td>
<td>2.58 ± 0.79</td>
<td>3.09 ± 0.33</td>
<td>0.75 ± 0.07</td>
<td>27.36 ± 2.63</td>
<td>0.78 ± 0.20</td>
<td>0.53 ± 0.50</td>
<td>98.77</td>
</tr>
<tr>
<td><strong>Hällekleis quarry, Kinnekulle</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>+8.50 to +8.65 m</td>
<td>11</td>
<td>60.35 ± 1.07</td>
<td>6.12 ± 0.29</td>
<td>2.76 ± 0.82</td>
<td>3.09 ± 0.28</td>
<td>0.75 ± 0.05</td>
<td>25.11 ± 1.45</td>
<td>0.95 ± 0.08</td>
<td>0.40 ± 0.13</td>
<td>99.53</td>
</tr>
<tr>
<td>Arkeologen +0.14 to +0.31 m</td>
<td>22</td>
<td>57.59 ± 1.59</td>
<td>6.15 ± 0.87</td>
<td>2.52 ± 0.71</td>
<td>3.16 ± 0.19</td>
<td>0.80 ± 0.06</td>
<td>26.65 ± 2.91</td>
<td>0.86 ± 0.17</td>
<td>1.51 ± 1.44</td>
<td>99.24</td>
</tr>
<tr>
<td>Arkeologen 0.00 to +0.14 m</td>
<td>34</td>
<td>57.95 ± 1.09</td>
<td>5.93 ± 0.52</td>
<td>2.69 ± 0.46</td>
<td>3.18 ± 0.23</td>
<td>0.77 ± 0.06</td>
<td>27.26 ± 2.11</td>
<td>0.86 ± 0.21</td>
<td>0.58 ± 0.49</td>
<td>99.22</td>
</tr>
<tr>
<td>−0.82 to −9.15 m</td>
<td>5</td>
<td>60.16 ± 1.02</td>
<td>6.01 ± 0.37</td>
<td>3.96 ± 0.63</td>
<td>2.32 ± 0.69</td>
<td>0.71 ± 0.04</td>
<td>23.96 ± 0.77</td>
<td>1.20 ± 0.17</td>
<td>0.72 ± 0.29</td>
<td>99.04</td>
</tr>
<tr>
<td><strong>Fossil meteorites, weighted average of EC grains from 26 meteorites from Thorsberg quarry (Schmitz et al. 2001).</strong></td>
<td>594</td>
<td>57.6 ± 1.3</td>
<td>5.53 ± 0.29</td>
<td>2.57 ± 0.83</td>
<td>2.73 ± 0.40</td>
<td>0.73 ± 0.03</td>
<td>26.94 ± 3.89</td>
<td>1.01 ± 0.33</td>
<td>1.86 ± 2.43</td>
<td>98.97</td>
</tr>
</tbody>
</table>
Earth during a part of the Ordovician. The same beds that are rich in EC grains are also enriched in fossil meteorites by about two orders of magnitude compared to the expected abundance if the meteorite flux had been similar to that of the present (Schmitz et al. 2001). A dramatically enhanced meteorite flux may be related to the disruption of the L chondrite parent body 450–500 Myr ago (see the Introduction). The cosmogenic nuclide $^{21}\text{Ne}$ measured in chromite grains from nine of the fossil meteorites yield very young ($\sim 0.1–0.2$ Myr) cosmic-ray exposure ages for meteorites from the Arkeologen bed, with successively older (up to $\sim 1$ Myr) exposure ages for meteorites upward through the section (Heck et al. 2004). The ages are consistent with the estimated sedimentation rates and suggest that all meteorites derive from one catastrophic disruption event shortly before the formation of the Arkeologen bed. The longer a fragment from this disruption spent in space the higher its content of cosmogenic nuclides. The dispersed EC grains most likely represent the remains of primarily small meteorites, in the size range of 0.1 to 1 cm in diameter, that

Fig. 4. The chemical composition of individual sediment-dispersed extraterrestrial chromite grains from the Thorsberg quarry section (results from Table 3). Shown is also the average composition (including standard deviations) of chromite grains from 11 recent H5/6 meteorites, respectively 10 recent L5/6 meteorites, and 26 fossil meteorites from the Thorsberg quarry (data from Schmitz et al. 2001). a) Results for the Arkeologen +0.08–0.32 m and Sextummen +2.50–2.58 m samples. b) Results for the Golsten and Botten beds.
weathered and decomposed at the sea floor. Schmitz et al. (2003) estimated that approximately as much as 85–90% of the total mass of meteorites larger than ∼0.1 cm that fell on the Middle Ordovician sea floor decomposed and is today represented only by dispersed EC grains. More fine-grained (<200 μm) extraterrestrial dust may not have settled on the sea floor because of prevailing currents in the water column. High concentrations of EC grains have also been found in beds corresponding to the Arkeologen bed in quarries 35 and 300 km southeast of Kinnekulle (Schmitz et al. 2003). During the formation of the Arkeologen bed, about 3000 EC grains (>63 μm) accumulated per square meter over at least entire southern Sweden, an area of more than 250,000 square kilometers (Schmitz et al. 2003). High concentrations of EC grains prevail through the 3.2 m thick meteorite-rich interval above the Arkeologen bed (except probably the middle part of the gray band). In the sample at 8.5 m above the base of the Arkeologen bed, the concentrations of EC grains have declined, but are still a factor of ∼30 more abundant than below the Arkeologen bed.

Chromite in recent equilibrated meteorites of the three groups of ordinary chondrites show small differences in compositions, with Fe and Ti contents increasing from H to L to LL chondrites. However, the Fe content of relict chromites in fossil meteorites may not be indicative since it is susceptible to some diagenetic alteration (Bunch et al. 1967; Schmitz et al. 2001). TiO₂ may be more useful, and homogeneous high TiO₂ concentrations, 3.1 wt% on average (Table 2), in the sediment-dispersed EC grains at Kinnekulle suggest that the grains predominantly derive from an L or LL chondritic precursor, similarly to the chromites preserved within the fossil meteorites from the Thorsberg quarry. Large chondrule sizes (on average ∼0.5 mm) in texturally well-preserved fossil meteorites confirm an L or LL chondritic origin (B. Schmitz, unpublished data). It is notable that four of five EC grains in the interval below the Arkeologen bed have low TiO₂ concentrations (1.4–2.4 wt%), which is more indicative of H chondritic chromite (Bunch et al. 1967; Schmitz et al. 2001). Above the base of the Arkeologen bed, such grains only represent a few percent of the EC grains. This may indicate that the proportions between L and H chondrites reaching Earth was relatively similar to the present prior to the L chondrite parent-body disruption event, whereas L chondrites overshadowed the H chondrites after the event. Some EC grains with low TiO₂ (1.5–2 wt%) in the Kinnekulle sections may represent unequilibrated L or H chondrites.

OC Grains

The abundant OC grains in three samples and rare such grains in other samples primarily represent terrestrial material, but probably also represent some extraterrestrial precursor materials. The proportions between these sources may also vary between the samples. Barnes and Roeder (2001) have made extensive compilations of the major element composition of terrestrial chrome spinels. The majority of the OC grains from the lower Arkeologen bed plot within the compositional density contour fields where 50% or 90% of spinels from continental mafic intrusions plot according to Barnes and Roeder. A comparison with other types of terrestrial spinels, such as from ophiolites also show a good fit, whereas there is less similarity with spinels from, for example, greenschists, basalts, and komatiites. The majority of the OC grains from the Sextummen and Botten...
beds plot in the same compositional field as the Arkeologen OC grains, but many of the Sextummen OC grains, and also some from the Botten bed, plot outside these fields (Fig. 6). A large fraction of the OC grains from the Sextummen bed have higher Cr/(Cr + Al) ratios and are lower in Fe$^{3+}$(Fe$^{3+}$ + Cr + Al) than those from the Arkeologen beds, and could have an extraterrestrial origin (see plots for meteorites in Roeder 1994).

It must be noted that even in the limestone samples with the highest concentrations of terrestrial OC (∼1–2 grains per kg), the concentrations are very low compared to many types of sediments. In most of our HF-leached residues, any clastic minerals larger than 63 µm are very rare and in some of the residues the EC grains dominate the clastic fraction. The clastic fractions of the limestone do not represent density-separated lag deposits such as, for example, beach sands. The bedrock in southern Sweden is dominated by granite and gneiss, and mafic rock represents a subordinate fraction of the exposed rock. If the OC grains derive from weathering of the bedrock on the surrounding land masses ilmenites from granites would be far more abundant in our acid residues than OC grains. One possibility is that the OC grains derive from mafic dykes exposed at the sea floor. Today, mafic continental intrusions of Permian age are common in the region, like on the top of Kinnekulle and other table mountains in the region. Older mafic intrusions may have injected sea floor sediments and became subject to submarine weathering during the Ordovician. In contrast to the EC grains, the OC grains appear to have been brought to the sea floor in pulses rather than as a continuous flow, which could reflect that OC sources successively became buried by sediments or were rejuvenated in other regions by sea floor erosion or intrusions of new dykes.

Some of the OC grains may represent rare types of extraterrestrial materials. The fossil meteorites at Kinnekulle contain rare chrome spinel grains with varying Cr, Al, and Mg concentrations (B. Schmitz, unpublished data). However, such chrome spinel grains do not make up more than 1–2% of the total assemblage of Cr-rich opaque minerals in the fossil meteorites, and therefore should be rare in the sediments. Chromite from unequilibrated ordinary chondrites can show a large compositional range well beyond the EC grain composition defined here (Bunch et al. 1967). However, these chondrites contain significantly less chromite than equilibrated chondrites. We have considered the possibility that the OC grains derive from weathered fusion crusts, but although abundant spinels form in fusion crusts, Cr-rich spinels do only form at very low oxygen fugacity (Genge and Grady 1999; Toppani and Libourel 2003). The atmosphere was most likely oxygen-rich during the Ordovician, which rules out a fusion-crust origin. Moreover, if a majority of the OC grains derive from melted meteoritic matter, they would have been equally abundant in all the EC rich samples.

**Increased Flux of Meteorites or a Terrestrial Concentration Mechanism?**

Could the abundant fossil meteorites and EC grains reflect primarily a terrestrial concentration mechanism rather than an increased flux of meteorites to Earth? One argument against this is that if a “normal” population of meteorites, i.e., one with a meteorite diversity similar to that of the present population, had been concentrated by, for example, transport and concentration of meteorites by strong bottom current or because old meteorite-rich icebergs drifted and melted over southern Sweden, then the composition of chromite grains in the fossil meteorites and textures of fossil meteorites would have shown a large variability. Instead, all meteorites appear to represent L (or possibly LL) chondrites. Neither have we ever encountered any terrestrial drop stones during the search for fossil meteorites in the limestones.

The reason why OC grains are common only in samples...
from the meteorite-rich interval above the base of the Arkeologen bed may be related to the fact that all over Baltoscandia, this is an interval characterized by unusual and prominent sea-level changes and associated water movements (e.g., Tinn and Meidla 2001; Dronov 2004). The anomalous gray, clay-rich band in the middle of this interval contains a peculiar and anomalous fauna. At some levels cystoids make up the bulk of the rock and the sea floor may have been more or less covered by these animals over entire southern Sweden. Shallow-water ostracode assemblages, and high-energy sediments, including clayey horizons and coarser limestones in the gray interval at Hällelekis attest to the shallowing (Tinn and Meidla 2001). The gray color of the bed is probably related to restricted water circulation in the basin following the sea-level fall. Dronov et al. (2001) place the onset of sea-level changes already at ~2 m below the Arkeologen bed. The occurrence of OC-rich levels starting in the Arkeologen bed may reflect exposure of soil-weathered mafic rocks to erosion because of sea-level change and seaward transport of the eroded material. Sea-level changes may also possibly be related to mafic volcanism in the region, including injection of mafic dykes on the sea floor. Environmental perturbations may even be related to a major L chondritic asteroid impacting on the Baltic continental shield. Impact craters of mid-Ordovician age are overrepresented in the Baltoscandian crater record (see discussion and references in Schmitz et al. 2001), suggesting that not only meteorites but also asteroids struck the Earth at higher rates than usual.

Although there is a coincidental increase of OC and EC grains in a few samples, the EC/OC ratio in general is far too high to be explained by any other process than a substantial increase in the influx of meteorites to Earth. Some sorting and reworking of heavy minerals, including EC grains, did occur on the sea floor and the abundance of EC grains may not always be directly related to the meteorite flux rate. However, in the Kinnekulle sections, results from a broad size spectrum of meteoritic materials, from dispersed microscopic chromite grains to large kg-size fossil meteorites, indicate a two orders of magnitude increase in the flux of meteoritic materials to Earth during a part of the mid-Ordovician. It would be difficult to explain the observed high abundance of meteoritic materials in all size fractions by any known sea-floor hydrodynamic sorting or reworking process. Further studies of the distribution of Cr-rich spinel grains in condensed sections in southern Sweden and central China are ongoing and will give further perspectives on whether the EC and OC grain distribution patterns seen at Kinnekulle reflect local processes or globally reproducible trends.

CONCLUSIONS AND FUTURE WORK

The distribution of EC grains in condensed sediments can be used to reconstruct variations in the flux of ordinary chondritic meteorites to Earth. A two orders of magnitude increase in EC grains in mid-Ordovician limestone from Kinnekulle probably reflects a dramatic increase in the influx of extraterrestrial material to Earth in connection with the disruption of the L chondrite parent body. Locating this event in the stratigraphic record on Earth opens up the possibility of further study of the effects on the terrestrial environment of an enhanced influx of meteorites and asteroids, and also to reconstruct in detail how extraterrestrial matter is transported to Earth after major asteroid disruption events.

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Editorial Handling—Dr. Timothy Swindle

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