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A rain of ordinary chondritic meteorites in the early Ordovician

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Abstract

Forty fossil meteorites with a total original mass of ~7.7 kg have been recovered in the first systematic search for fossil meteorites, pursued in an active quarry in Lower Ordovician (480 Ma) marine limestone in southern Sweden. The meteorites represent at least 12 different falls over a seafloor area of ~6000 m^2 during ≤1.75 Myr, making the quarry one of the most meteorite dense areas known in the world. Geochemical analyses of relict chromite grains indicate that all or most of the meteorites are ordinary chondrites and probably L chondrites. Mechanisms for meteorite delivery from the asteroid belt to Earth were the same 480 Ma as today, however, the flux was one to two orders of magnitude higher, most likely reflecting the disruption of the L chondrite parent body at about that time. This is a major event in late solar-system history, which may also have led to an enhanced flux of asteroids to Earth during ~30 Myr.

Keywords: meteorites; ordinary chondrites; chromite; asteroids; Os-188/Os-187

1. Introduction

Modern influx rates and compositional variations of meteorites on Earth are well-constrained. Sky-watch camera networks and meteorite search programs in wind-eroded deserts indicate that on average between 36 and 116 meteorites >10 g accumulate annually per 10^6 km^2 of the Earth surface [1,2]. Meteorite fall statistics indicate that 80% of the meteorites are ordinary chondrites (H, L or LL), 7.9% achondrites, 4.8% iron meteorites, and 4.6% carbonaceous or anomalous chondrites [3]. Enstatite chondrites and stony irons make up only 1.6% and 1.1% of the falls, respectively. Among recent ordinary chondrites the H and L groups make up 45% each, with the remainder being LL chondrites. For the distant geological past we know hardly anything about the meteorite influx to Earth. Prior to the start of this project in 1992 only half a dozen fossil meteorites were known (see [4]). This is a very small number considering that during the last century billions of tons of coal and limestone were industrially quarried and vast areas of sedimenta-

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ry rocks have been inspected by field geologists. The rarity of fossil meteorites led authors in the mid-20th century to argue that meteorites did not fall before the late Quaternary [4]. Meteorite experts, like H.H. Nininger, counterargued that meteorites would not survive in recognizable form in older rocks and that no systematic attempt to recover fossil meteorites had been performed [5].

In a preliminary account of our systematic fossil meteorite search in the Thorsberg quarry (58°35′N, 13°26′E) at Kinnekulle, southern Sweden, we reported 17 meteorite finds [6]. Here we present the first detailed documentation and evaluation of our findings. With 40 meteorites found, from the end of 1992 to the end of 2000, our data base is now sufficiently large to make firm quantitative estimates of the meteorite abundance on the Ordovician seafloor. We also present a summary of the chemical analyses of relict chromite grains from 26 of the fossil meteorites, aimed at constraining the types of meteorites that fell 480 Ma. We discuss sedimentological and chemical approaches to the problem of pairing the fossil meteorites, critical for estimating fluxes. More detailed reports of the chromite analyses, the search process, and the meteorites found will be given elsewhere.

The active part of the Thorsberg quarry spans a section of 3.2 m of Lower Ordovician marine limestone (Figs. 1 and 2). Twelve prominent beds, 11–62 cm thick, can be discerned; each has a name traditionally used by the quarry workers. The beds occur in a horizontal position and have not been affected by tectonism. The lower ~80 cm and the upper ~1 m of the section consist of red limestone, separated by ~1.4 m gray limestone. The quarried Orthoceratite Limestone was deposited during the Arenigian to Llanvirnian in an epicontinental sea that covered several 100 000 km^2 of the Baltoscandian Shield [7,8]. This condensed limestone formed at an average rate of one to a few mm/kyr, however, deposition was variable, changing from long periods of non-deposition and hardground formation to more rapid pulses of sedimentation [7,8]. Biostratigraphically, the quarried section belongs to the *Amorphognatus variabilis–Microzarkodina flabellum* conodont subzone [9]. Based on an average sedimentation rate of ~2 mm/kyr for the Arenigian limestone at Kinnekulle the section is esti-

Fig. 1. The Thorsberg quarry in June 1999. Note water filled basin in front from which the Arkeologen bed has been recovered.

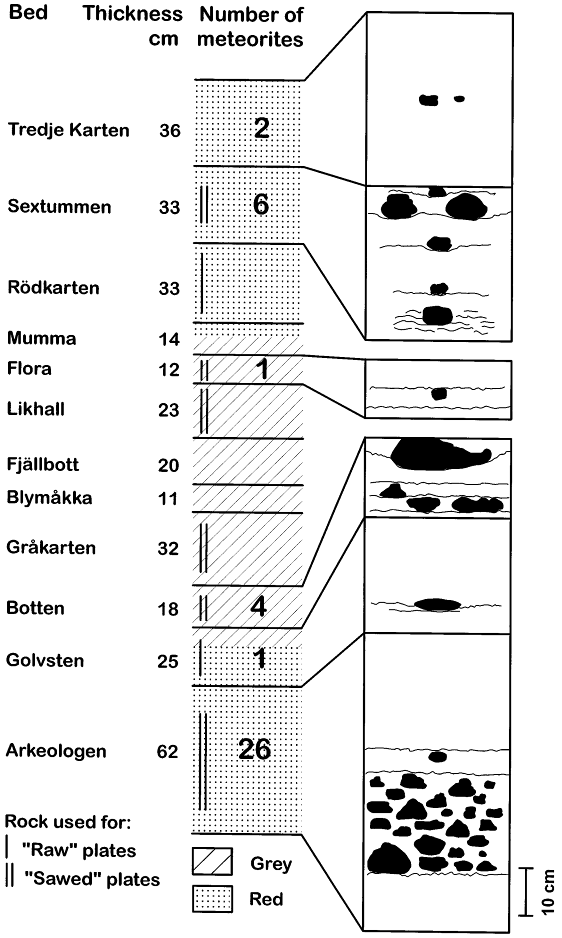

Fig. 2. Quarried beds and meteorite distribution in the Thorsberg quarry. Column at the right shows the intra-bed distribution of the meteorites. The exact positions of the meteorites from the Tredje Karten bed and most of the meteorites from the Arkeologen bed are not known (see main text). Only half of the section is used for production of plates, the rest being crushed and not searched for meteorites.

mated to represent a time span of ≤1.75 Myr [9].

According to traditional/regional stratigraphic nomenclature the section in the Thorsberg quarry belongs to the Lower Ordovician, however, we note that the International Commission on Ordovician Stratigraphy has suggested to revise the definition of the Lower/Middle Ordovician boundary [10], implying that the section would instead be in the Middle Ordovician series.

The different beds and sublayers in the Thorsberg quarry are of different industrial quality. A major part of the section consists of high-quality limestone used for the production of sawed plates sold as floor plates, window sills, stair cases etc. (Fig. 2). Some intervals of lower quality can occasionally yield sawed plates, but are primarily used as raw garden plates or crushed for production of cement or agricultural lime. Some intervals are only used for production of crushed rock. Blocks of limestone (ca. 1.25×2×0.5 m) are recovered and transported to the nearby sawing factory. The quarrying is performed in two steps: first the beds above the basal Arkeologen bed are removed and thereafter the Arkeologen bed, that is under the ground water table, is quarried in small basins from which the water has to be pumped (Fig. 1). From the end of 1992 to the end of 2000 an area of ~6000 m^2 of the beds overlying the Arkeologen bed and ~2700 m^2 of the Arkeologen bed were quarried. The workers and owners of the quarry and sawing factory have been trained by us to recognize meteorites, which are usually found during sawing, but are occasionally already discovered on exposed surfaces in the quarry. We visit the quarry and factory regularly in order to follow and document the industrial process and to collect the meteorites recovered.

The fossil meteorites can readily be identified by macroscopical examination (Figs. 3–5), despite being completely pseudomorphosed primarily by calcite, barite and phyllosilicates [9,11,12]. The only relict mineral phases are chromite and chromian spinel [11,12]. For all 14 meteorites from layers above the Arkeologen bed and for 16 of 26 meteorites from the Arkeologen bed visual identification was confirmed by bulk-meteorite platinum group element (PGE) [6,9] or osmium isotope analyses and/or element analyses of relict chromite grains ([6], this study).

2. Chemical and isotopic methods

The element analyses of chromite grains were performed using a LINK Oxford energy dispersive spectrometer with a Ge detector, mounted in a Zeiss DSM 940 scanning electron microscope. Chromite grains were polished to a flat surface using 1 μm diamond slurry. A cobalt standard,

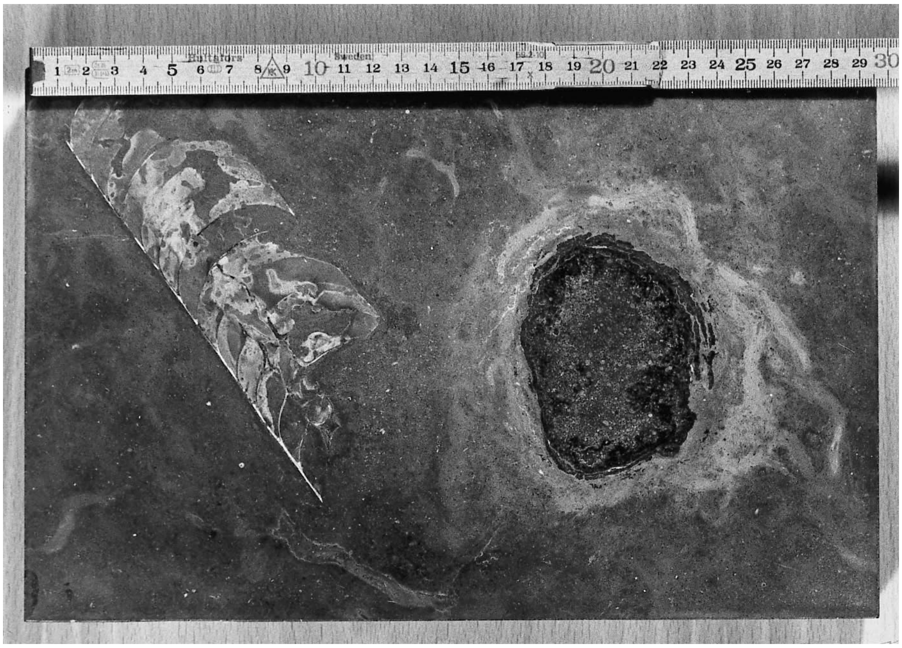

Fig. 3. The Österplana Sex 001 meteorite together with a nautiloid shell in a limestone plate sawed parallel to seafloor surface. Note relict chondrule structures and partly peeled-off fusion crust.

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 s 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 [13].

For Os isotopic analysis a 10–50 mg sample from respective meteorite was spiked with ^{190}Os, homogenized and mixed with a mixture of Ni, S, and borax. The mixture was fused at 1020°C for 90 min, cooled and the NiS bead separated and dissolved in hot 6.2 N HCl. The solution was passed through a 0.45 μm filter to capture the insoluble, PGE-containing particles [14]. The filter paper was dissolved in 1 ml concentrated HNO_3 at about 100°C overnight. Osmium was extracted from this solution using the sparging technique [15] and analyzed by magnetic sector inductively coupled plasma-mass spectrometry (ICP-MS) (Finnigan Element). Rhenium concentrations were measured on separate 25–95 mg powdered sample splits. After spiking with ^{185}Re and dissolution with mineral acids, Re was separated and purified on a column of 1 ml of AG1X8 (200–400 mesh) in 0.5 N HNO_3 and eluted with 8 N HNO_3. Subsequently Re was measured by ICP-MS using conventional liquid uptake. Total Re blanks of ~0.5 pg are negligible compared to the amount of sample Re (300 pg–18 ng).

3. Distribution and sizes of fossil meteorites

The 40 meteorites vary in cross-section from 0.7×1 cm to 15×20 cm (Fig. 2). Cross-sections of the 26 meteorites from the basal, red Arkeologen bed range from 0.7×1 cm to 7.5×9 cm. A single large meteorite, 6×9×2 cm, has been found in the overlying Golvsten bed. In the gray interval only the Botten and Flora beds have yielded meteorites. From the Botten bed four meteorites have been recovered, one with a a size of ~15×20×6.5 cm, representing the largest meteorite of the project. From this bed derive also another large, 5.5×9×3 cm, and two medium-

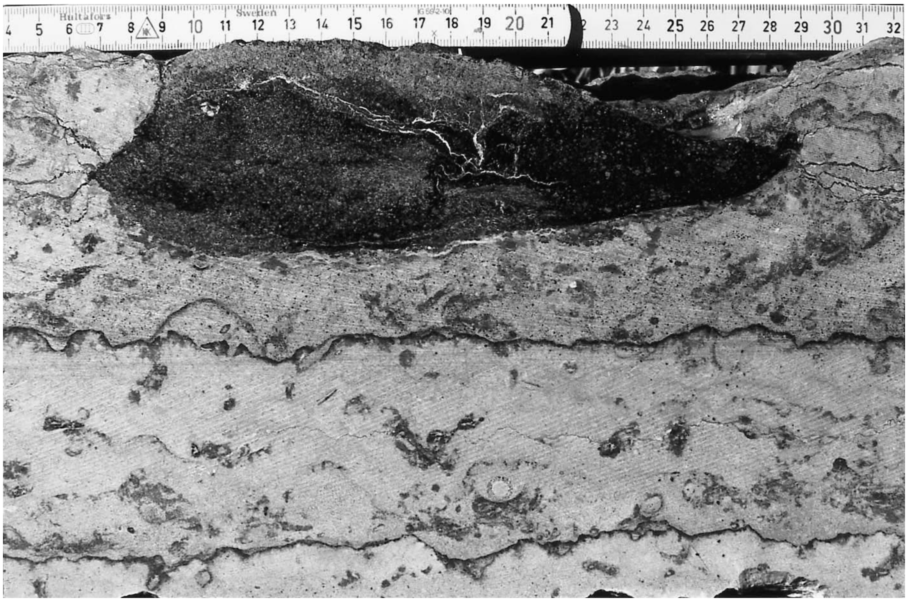

Fig. 4. The Österplana Bot 003 meteorite in a limestone plate sawed perpendicularly to seafloor surface. This is the largest meteorite found with an original mass of 3.4 kg. Note relict chondrule structures in meteorite and two prominent hardground surfaces below the meteorite.

sized meteorites, 4×5 cm and 3.3×6.5 cm. The Flora bed has yielded one small meteorite, 2×2.5 cm. In the upper red interval six meteorites, from 1.4×3 cm to 6.5×8 cm, have been found in the Sextummen bed and two small meteorites, 1.3×2 cm and 3×3.4 cm, were recovered from the Tredje Karten bed. As the volume of limestone quarried per year and the rate of finds have remained relatively constant over the past 8 yr we infer that meteorites were distributed relatively evenly throughout the quarry.

Most of the meteorites originate from intervals used for production of sawed plates, which may primarily reflect that the sawing procedure requires much more visual inspection of the rock than other production methods. Comparing the number of meteorites recovered from each bed with the total amount of rock area of respective bed through which the saw in the factory has penetrated gives some indications about real variations in the abundance of meteorites through the section (Table 1). The quarry owners record

Table 1
Fossil meteorite abundance and areas of sawed plates from the Thorsberg quarry

Bed	Sawed plates 1993–2000		Meteorites 1992–2000	
	(m^2)	(rel.%)	(n)	(rel.%)
Tredje Karten	0	0.0	2	5.0
Sextummen	6260	7.7	6	15.0
Rödkarten	5596	6.9	0	0
Flora	7842	9.6	1	2.5
Likhall	16800	20.6	0	0
Gråkarten	13314	16.3	0	0
Botten	11280	13.9	4	10.0
Golvsten	3750	4.6	1	2.5
Arkeologen	16616	20.4	26	65.0
Total	81458	100.0	40	100.0

Fig. 5. Large plate (70×110 cm) of limestone sawed parallel to seafloor surface. Several nautiloid shells accumulated on a hardground surface in the vicinity of the Österplana Ark 023 meteorite (3.5×4.5 cm). The iron in the red limestone around the meteorite has been reduced, therefore a halo of lighter gray limestone has formed.

sawed-area data to determine the lifetime of the saw blades. Therefore, these data can only give information about the density of meteorites per rock surface exposed by sawing. The data show that the Arkeologen bed is significantly richer in meteorites than the other sawed beds. It has

Table 2
Os, Re and $^{187}Os/^{188}Os$ in fossil meteorites[a]

Meteorite	Os (ng/g)	Re (ng/g)	$^{187}Os/^{188}Os$
Österplana Ark 003	385 ± 0.7	7.2	0.1269 ± 0.0003
Österplana Ark 008	733 ± 2	46.9	0.1288 ± 0.0003
Österplana Ark 019	169 ± 0.4		0.1262 ± 0.0004
Österplana Ark 027	72 ± 0.7		0.1275 ± 0.0010
Österplana Gol 001	651 ± 3	4.2	0.1255 ± 0.0005
Österplana Bot 002	852 ± 8	737	0.1534 ± 0.0006
Österplana Bot 003	1031 ± 5		0.1751 ± 0.0003
Österplana Flo 001	94 ± 1		0.1264 ± 0.0009
Österplana Sex 001	74 ± 0.2		0.1290 ± 0.0008
Österplana Sex 003	1280 ± 5		0.1263 ± 0.0002
Österplana Tre 002	163 ± 0.3		0.1270 ± 0.0004

[a] 2σ uncertainties are listed for $^{187}Os/^{188}Os$ and Os based on counting statistics. In-run precision of the Re analyses was 2–3%.

yielded 65% of the meteorites but represents only 20.4% of the total sawed rock area. No meteorites have been recovered from the Likhall and Gråkarten beds in the middle of the gray interval, although they represent as much as 36.9% of the sawed rock area. These differences reflect variations in meteorite influx and/or sedimentation rate, however, the small differences between other beds may not be statistically significant. The fact that some of the meteorites, such as the two in the Tredje Karten bed, have been found in situ in the quarry adds uncertainty to the comparisons in Table 2.

Meteorites typically lie on hardgrounds, where they accumulated together with other large objects such as abundant nautiloid shells (Figs. 3–5). This indicates that meteorites were concentrated due to sediment winnowing by bottom currents, analogous to the process that leads to meteorite-enriched surfaces in wind-eroded deserts. Fragile nautiloid shells show no preferred orientation and are commonly well-preserved, ruling out that meteorites were transported to this area by strong bottom currents (Fig. 5). Sometimes the meteorites are associated with marl layers (Fig. 4). We have established a detailed understanding of the succession of hardgrounds and marl layers within the different beds. In many cases it has been possible to identify the specific horizon at which individual meteorites deposited. The Botten bed, for example, shows several prominent hardground surfaces, and there is firm evidence that the four meteorites in that bed occur at three distinctively different surfaces (Figs. 2 and 4). The red meteorite-yielding beds (Arkeologen, Sextummen and Tredje Karten) show lateral intra-bed variations and complex layering which makes it more difficult to assign meteorites to specific horizons. In the Arkeologen bed all except one of the 26 meteorites appear to derive from a 25 cm thick interval extensively used for sawing (Fig. 2). While some of these meteorites definitely come from different levels within this interval, detailed positions for the majority of the meteorites are not known. The meteorites in the Sextummen bed come from at least four and possibly five different horizons. The exact positions of the Tredje Karten meteorites are not known.

We estimate that individual meteorites from the Arkeologen bed had original masses between ~1 and ~760 g. The total meteorite mass from this bed is ~2.2 kg (Fig. 6). The meteorites from the overlying beds weighed between ~5 and ~500 g, except the largest meteorite recovered, that weighed ~3.4 kg (Fig. 4). The total meteorite mass from beds above the Arkeologen bed is ~5.5 kg. Masses have been calculated from cross-section data, assuming an ellipsoidal shape, and using a meteorite density of 3.6 g/cm^3. The height of the meteorites (when not known) is assumed to be 75% of the shortest cross-section in the bedding plane.

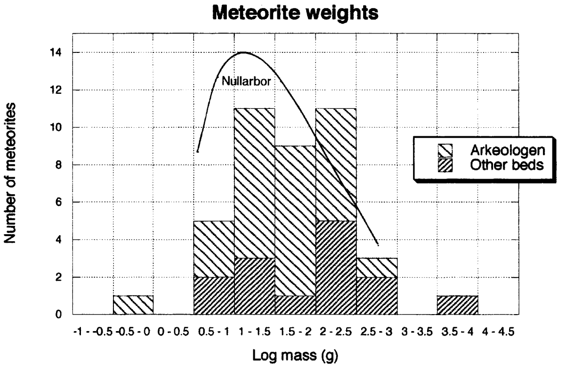

Fig. 6. Mass distribution of fossil meteorites. A schematic illustration of the shape of the size distribution curve for 578 paired meteorites from the Nullarbor region is also shown [3].

Most meteorites found today in search programs in Antarctica and wind-eroded hot deserts weigh less than 100 g and have a peak in the mass distribution at about 10–20 g (Fig. 6) [3,16,17]. The median weight for all the fossil meteorites is ~40 g, and there are significantly more large (≥100 g) than small (10–20 g) meteorites compared to meteorite collections from recent hot deserts and Antarctica (Fig. 6). This indicates that our search is biased towards larger meteorites. The 14 meteorites from the beds that overlie the Arkeologen bed have a median mass of ~100 g, reflecting that most of these beds are not searched for meteorites with as much scrutiny as the Arkeologen bed.

4. Os, ^{187}Os/^{188}Os, and Re results

Ordinary chondrites that fell on Earth recently typically have Os concentrations in the range 420–1050 ng/g and ^{187}Os/^{188}Os ratios of 0.1265–0.1305 [18]. The 12 fossil meteorites analyzed in this study show Os concentrations in the range 72–1280 ng/g and ^{187}Os/^{188}Os ratios of 0.1255–0.1751 (Table 2). Seven of the meteorites have Os concentrations as high as recent meteorites, 385–1280 ng/g, whereas five have lower concentrations, 74–169 ng/g, most likely reflecting loss of PGEs during diagenesis. Ten of the fossil meteorites, all from red limestone or in the red–gray transition interval, have ^{187}Os/^{188}Os ratios in the range 0.1255–0.1290, very similar to recent meteorites. Two meteorites from the Botten bed, in the gray limestone interval, have ^{187}Os/^{188}Os ratios of 0.1534 and 0.1751, significantly higher than for recent chondrites. This enrichment in ^{187}Os can be explained by diagenetic accumulation of Re from pore solutions in the reducing environment of the gray sediments, followed by decay of ^{187}Re to ^{187}Os. This is supported by a substantially higher Re concentration, 737 ng/g, in one analyzed meteorite from the Botten bed, compared to three meteorites from the red or reddish gray intervals, showing Re concentrations in the range 4.2–46.9 ng/g (Table 2). This is consistent with previous findings that the gray limestone is strongly enriched in Re and ^{187}Os compared to the surrounding red limestone [6]. 'Initial' ^{187}Os/^{188}Os ratios for the fossil meteorites at 480 Ma are difficult to calculate because of uncertainties about the timing and amount of diagenetic loss or gain of Re. Our estimates of 'initial' ^{187}Os/^{188}Os based on realistic assumptions about Re mobility support that the Os is of chondritic origin.

5. Meteoritic chromite and its composition

Studies of the two fossil meteorites Brunflo and Österplana, found in Ordovician limestone in Sweden before our project started, have shown that the chemical composition of relict chromite can be used to classify the meteorites [11,12]. We have performed elemental analyses of chromite grains from 15 of the largest meteorites from the Arkeologen bed and 11 of the meteorites from overlying beds. In addition, chromite grains from a variety of recent ordinary chondrites were analyzed using identical methods in order to obtain optimally comparable data. For each meteorite a total of 10–40 analyses were performed on typically 10–20 'coarse chromite' grains (0.05–0.3 mm; see [19]). The recent chondrites ($n = 33$) analyzed constitute a representative sample of groups (H, L and LL) and petrologic types (3–6). In most ordinary chondrites chromite is a common trace mineral (0.05–0.5 wt%), whereas it is rare or absent in carbonaceous and enstatite chondrites as well as iron meteorites [19–23].

In all fossil meteorites inspected, chromite grains are common and have chemical compositions indicative of ordinary chondrites (Fig. 7; Table 3). Chromites from carbonaceous chondrites, achondrites, pallasites, mesosiderites and iron meteorites have compositions markedly different than chromites from ordinary chondrites [24–29]. The fossil chromite grains show, with a few exceptions, only little variation in MgO, TiO_2, Al_2O_3 and V_2O_5 within a meteorite and between different meteorites. Chromite FeO, MnO and ZnO concentrations are also quite uniform in most fossil meteorites, but in some meteorites concentrations are anomalous and variable, reflecting most likely diagenetic effects. There is no

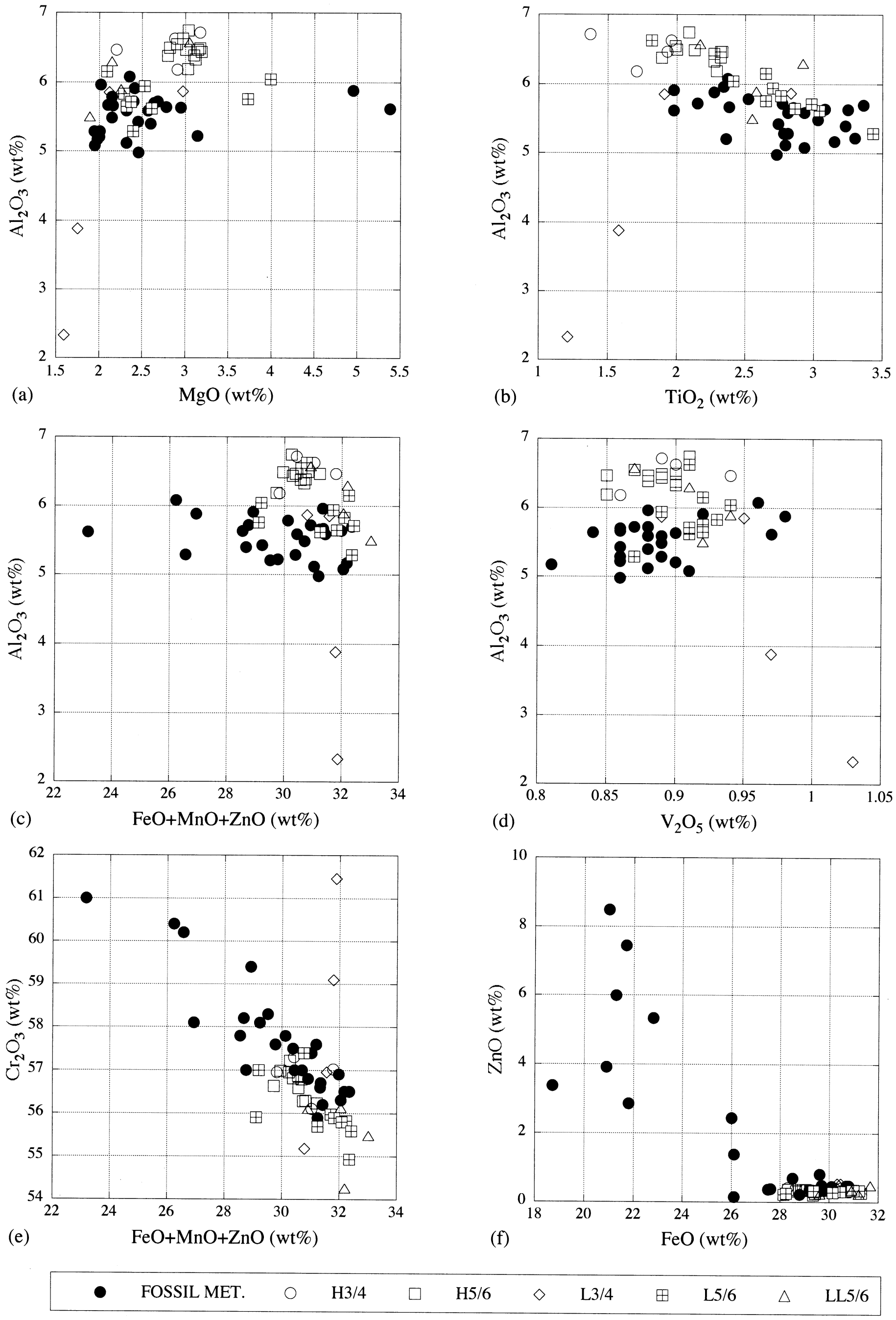

Fig. 7. Chemical composition (averages) of chromite grains from 26 fossil and 33 recent meteorites. The following recent ordinary chondrites were analyzed. H3: Brownfield 1937; H4: Bath, Dimmitt, Kesen; H5: Abajo, Forest City, Hessle, Jilin, Pultusk; H6: Archie, Benoni, Estacado, Kernouve, Ozona, Mills; L3: Julesburg; L4: Barratta, Saratov, Waltman; L5: Ausson, Elenovka, Etter, Tsarev; L6: Baroti, Holbrook, Mbale (L5/6), Modoc 1905, New Concord, Walters; LL5: Altameen; LL6: Beeler, Bison, Dhurmsala.

Table 3

Average element concentration (wt%) in chromite from fossil and recent meteorites[a]

	Mets/anal[b]	Cr_2O_3	Al_2O_3	MgO	TiO_2	V_2O_5	FeO	MnO	ZnO	Total
Recent H5/6 group	11/261	56.7 ± 0.3	6.45 ± 0.14	3.03 ± 0.14	2.17 ± 0.16	0.88 ± 0.02	29.12 ± 0.42	1.02 ± 0.04	0.33 ± 0.05	99.70
Recent L5/6 group	10/209	56.0 ± 0.7	5.86 ± 0.36	2.73 ± 0.64	2.73 ± 0.42	0.91 ± 0.02	30.16 ± 1.18	0.84 ± 0.10	0.31 ± 0.04	99.54
All fossil meteorites	26/594	57.6 ± 1.3	5.53 ± 0.29	2.57 ± 0.83	2.73 ± 0.40	0.89 ± 0.04	26.94 ± 3.89	1.01 ± 0.33	1.86 ± 2.43	99.13
Arkeologen bed	15/332	57.2 ± 1.2	5.55 ± 0.26	2.35 ± 0.37	2.79 ± 0.42	0.88 ± 0.03	26.97 ± 4.13	1.05 ± 0.38	2.33 ± 3.01	99.12
Other beds	11/262	58.2 ± 1.3	5.51 ± 0.34	2.87 ± 1.16	2.64 ± 0.38	0.91 ± 0.05	26.89 ± 3.73	0.96 ± 0.25	1.21 ± 1.15	99.19
USNM 117075 standard	($n = 5$)	61.6 ± 0.7	9.68 ± 0.10	15.2 ± 0.37	0.11 ± 0.03	n.a.	13.04 ± 0.55	n.a.	n.a.	99.63

n.a. = not analyzed.

[a] Data given are averages (with S.D.) of averages of composition of typically 10–20 chromite grains in each meteorite.

[b] Number of meteorites from which chromite was analyzed/total number of analyses of chromite grains.

significant difference in composition between chromites from the Arkeologen meteorites and those from the overlying layers.

Previous work has shown that there are differences in chromite composition between recent H, L and LL chondrites of petrologic types 5 and 6, however, the compositional ranges between the groups overlap [24,25]. Chromites from ordinary chondrites of lower petrologic types show larger compositional variability. Our analyses of chromite in recent chondrites confirm trends shown in earlier work, such as generally higher FeO and TiO_2 and lower MgO and Al_2O_3 in L and LL than H type 5/6 chondrites [24,25]. Fig. 7 shows that the majority of the fossil meteorites plot in the low MgO and Al_2O_3 and high TiO_2 fields indicative of recent L and LL chondrites. For FeO, ZnO and MnO the situation is more complicated. Some fossil meteorites have chromite grains with (on average) much lower FeO (as low as 18.7 wt%) and much higher ZnO (up to 8.5 wt%) and MnO (up to 1.8 wt%) concentrations than in recent ordinary chondrites (Table 3; Fig. 7). The negative correlation between FeO and ZnO (as well as MnO) in some relict chromites (Fig. 7f) and the similarity of the FeO+MnO+ZnO content in recent and fossil chromite (Fig. 7c) indicates that FeO can be replaced by ZnO and MnO during diagenesis. Some relict chromites have higher Cr_2O_3 and lower FeO+MnO+ZnO concentrations than recent chromite, which may also be a diagenetic effect (Fig. 7e). The chromites in all fossil meteorites have the same narrow range in V_2O_5 concentrations as in recent ordinary chondrites (Fig. 7d).

Schmitz et al. [6] suggested that the abundance of meteorites in the Thorsberg quarry may be related to a high meteorite influx following the disruption of the L chondrite parent body ~500 Ma [30–32]. The chromite data presented here support, but do not unequivocally prove, that all or a large majority of the fossil meteorites are indeed L chondrites. Due to some overlap in chromite composition between different ordinary chondrite groups and the possibility that diagenetic processes have affected relict chromites, a mixed origin from three ordinary chondritic parent bodies as observed today cannot be ruled out.

Moreover, the existence of currently unproductive or no longer existing parent bodies resembling H, L and LL parent bodies in composition cannot be excluded either. Oxygen isotopic analyses of relict chromite are in progress and may help better constraining the origin of the fossil meteorites.

6. Early Ordovician meteorite influx rates

The major difficulty in estimating the flux of meteorites in the early Ordovician from our data is the pairing problem. A meteorite may break up during flight, producing several fragments on the ground. In reconstructions of present influx rates, e.g. in the Nullarbor desert, textural features, cosmic-ray exposure ages, terrestrial residence ages, and spatial distribution of meteorites can be used to determine which fragments belong to the same fall [3], but the Ordovician meteorites are too altered to be paired in this way. Fossil meteorites on different hardgrounds, however, must represent different falls, because post-depositional vertical migration across hardgrounds is very unlikely. Upward migration due to shake-sorting [33], for instance, would result in unrealistically long exposure times on the seafloor. In dry terrestrial environments meteorites disintegrate already within 20–30 kyr [2,3], however, the rate at which meteorites decay on the seafloor is not known. The well-preserved, often angular, shapes of most of our meteorites indicate that they have not spent any substantial time drifting across the seafloor (Figs. 3–5). The 40 meteorites were recovered from at least 12 different surfaces and thus represent at least 12 falls (Fig. 2). The main uncertainty in the number of independent surfaces is the difficulty associated with laterally correlating hardgrounds in the meteorite-rich Arkeologen bed.

Our data yield a reliable minimum estimate of the flux of meteorites to Earth at 480 Ma. We know that at least 40 meteorites with a mass of 7.7 kg representing at least 12 falls with individual masses ranging from 14 to 3400 g fell within a seafloor area of ~ 6000 m^2 during ≤ 1.75 Myr. It could be argued that uncertainties in the average sedimentation rate (~ 2 mm/kyr) pose a problem for the flux estimates. However, biological evolutionary changes over the quarried interval, e.g. for conodonts and trilobites [34,35], are small and rule out a significantly longer period of deposition than the 1.75 Myr postulated here. The best estimate for the present meteorite flux to Earth is 80 ± 40 meteorites > 10 g per 10^6 km^2 of the Earth's surface per year [1,2], which corresponds to only 0.8 ± 0.4 meteorites per 6000 m^2 per 1.75 Myr. Our search, however, is biased towards finding mainly the larger meteorites. Therefore a comparison with recent flux in the corresponding size range is more meaningful. Based on estimates of the recent flux 0.28 meteorite > 100 g including 0.12 meteorite > 700 g should have been recovered from the quarried area [1,36]. Assuming that fossil meteorites on the same hardground represent fragments of a single fall implies that at least seven meteorites > 100 g including three > 700 g fell in the quarried area. These data indicate that the meteorite flux was at least 25 times higher in the Ordovician than today.

The pairing problem can be circumvented by comparing total meteorite mass rather than number of falls. Bland [2] calculated that today 5.7–14.3 kg of meteoritic material in the mass range 10^1–10^3 g accumulates per 10^6 km^2 per year, which is equivalent to 0.06–0.15 kg per 6000 m^2 per 1.75 Myr. Correcting our mass estimate for the fact that the Arkeologen bed has only been searched for meteorites over 2700 m^2 and assuming that the remaining 3300 m^2 of this bed is as rich in meteorites as the searched part gives a total mass of 10.4 kg (7.7 kg+2.7 kg). A comparison with recent mass estimates implies a factor of 69–173 higher meteorite flux during the Ordovician.

We consider these minimum estimates for the following reasons. The 40 meteorites recovered represent only a fraction of the meteorites that fell within the area quarried. Only half of the limestone section is being used for sawed plates and hence carefully examined for meteorites (Fig. 2). Even for the beds suitable for production of sawed slabs not all of the material removed has been inspected for meteorites. Some material may be sold to other sawing factories or, if there is no demand for material from a particular bed, the quarried blocks are crushed or stored. Even in the fraction of rock handled in an optimal way for meteorite recovery, a large fraction of the small meteorites are not recovered as indicated by the size distribution data. Many stone products from the quarry are thicker than the typical thickness of meteorites and it is a matter of chance whether the saw cuts through a meteorite so that a sufficiently large area is exposed for recognition. It is also possible that only a fraction of meteorites that fell on the seafloor remain preserved in a recognizable state. Seafloor destruction of meteorites most likely occurred at hardgrounds exposed to corrosive bottom waters for long times.

The extremely high meteorite density in the Arkeologen bed (one meteorite per 100 m^2) remains puzzling. Such densities have only been reported for a few, extremely fragment-rich strewn fields, such as that of the Pultusk meteorite shower [37]. The available data do not allow us to differentiate whether the Arkeologen meteorites reflect a strewn field or several distinct falls during a period of particularly high meteorite influx. Studies of coeval strata worldwide may give an answer to this.

7. Delivery of meteorites from the asteroid belt

Systematic searches for fossil meteorites from different geological periods can be used to test proposed models for meteorite delivery to Earth. For example, the predominance of ordinary chondritic material (80% of recent falls) among present meteorites is in marked contrast to its rarity ($\leq$1%) in micrometeorite and stratospheric extraterrestrial dust samples, believed to be more representative of the dust-producing asteroid population [38–41]. This discrepancy led to the hypothesis that asteroids of ordinary chondritic composition were never abundant in the main asteroid belt and that, historically, carbonaceous material has dominated the entire main belt [41]. Our findings do not support this hypothesis, and instead indicate that the flux of ordinary chondritic meteorites was even more important 480 Ma than today.

It has been known for a long time that among the ordinary chondrites that reach Earth today a large fraction of L chondrites show ^{39}Ar–^{40}Ar gas retention ages of $\sim$500 Ma [30–32]. This indicates that one of the major asteroid break-up events in late solar-system history occurred at about that time. There is a significant uncertainty in the proposed break-up age, and ^{87}Rb–^{87}Sr analyses and a laser-heating Ar dating yield ages of 450–465 Ma [42–44]. Considering the large age uncertainties, the meteorite-rich sediments in the Thorsberg quarry may well have formed just after the disruption event. Zappala et al. [45] have shown that the flux of asteroids to Earth may increase substantially after major asteroid break-up events. More than 80% of the impacts on Earth related to such an event should take place during a 2–30 Myr period. The cratering rate during this period could be enhanced by one to two orders of magnitude. Depending on the type of orbital resonances involved, there may be a time lag of up to ca. 100 Myr between the break-up event and the resulting asteroid shower, but in most situations the lag is less than one or a few million years [45]. Major break-up events can similarly be expected to lead to a surge of meteorites to Earth on time scales of 1–10 Myr [45,46].

The correspondence between the age of the L chondrite parent-body disruption and the many fossil meteorites (probably L chondrites) in the Thorsberg quarry prompted us to scrutinize the terrestrial cratering record for further evidence for such a disruption event. In Fig. 8 all dated impact craters ($\leq$630 Ma) on Earth are plotted as a histogram with 30 Myr bins [47–49]. The 450–480 Ma bin shows a factor of three to four more craters than any other 30 Myr bin from 180 to 630 Ma. We note also that of 17 known craters on the Baltoscandian Shield four have been unequivocally dated by chitinozoan stratigraphy to the 450–480 Ma period (the Tvären, Kärdla, Lockne and Granby craters) [48,49]. The peak in crater ages at 480–450 Ma could be a reflection of the L chondrite disruption event, however, we realize that the terrestrial crater record is very incomplete, representing only a fraction of a percent of all the craters that have formed on Earth [47]. The assigned ages of many craters also have large uncertainties. The observed peak in the

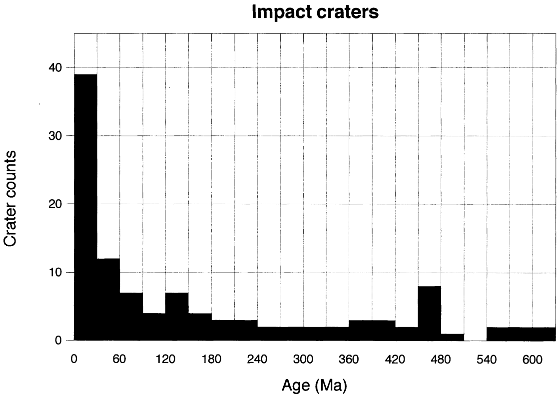

Fig. 8. Histogram of ages of all dated craters in crater compilation of [47] complemented by information on ages of two craters (Lockne and Tvären) in [48,49]. Note the small peak in crater ages in 450–480 Ma bin.

abundance of craters with ages 450–480 Ma may thus be purely coincidental. Even if this observation is an artifact, the existing data do not preclude that a major asteroid disruption occurred. A break-up event in the asteroid belt may lead to a larger relative increase in the flux of meteorite-sized than asteroid-sized objects to Earth. Asteroids of the L chondrite type may normally represent a smaller fraction of the total large-body flux to Earth than the fraction of L chondrite meteorites in the total flux of meteorite-sized objects. For example, it is likely that the ratio of comet to asteroid particles impacting the top of the atmosphere increases with particle size, but cometary material may have a higher entry speed, causing the smaller comet objects to preferentially disintegrate to dust during atmospheric passage [38]. In essence, an order of magnitude increase in the influx of L chondritic asteroids following a break-up event may not manifest itself clearly in the imperfect cratering record. The distribution of known impact crater ages hence does not contradict a one to two orders of magnitude increase in meteorite flux as indicated by the fossil meteorite data, particularly if the peak increase in meteorite flux was restricted to a period of a few million years. Our search for fossil meteorites in condensed limestone from other time intervals of the Ordovician has so far been unsuccesful, suggesting tentatively that the culmination of the meteorite influx coincided with the deposition of the Orthoceratite Limestone exposed in the Thorsberg quarry.

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