Supplementary Information for

Asteroid break-ups and meteorite delivery to Earth the past 500 million years

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Dataset S1
Supplementary Text

Geological setting

The mid-to-late Cambrian of Scandinavia. The Drumian and Guzhangian stages in Scandinavia are part of the Alum Shale Formation, dominated by kerogen-rich black shales with a few organic-rich limestone beds. The condensed alum shales and limestone beds formed ~506 – 478 Ma ago when Scandinavia was covered by a shallow epicontinental sea on a peneplained passive margin of the Baltic shield (1-4). As such, sedimentation rates were extremely low and Scandinavia was tectonically undisturbed for a substantial amount of time. The Hypagnostus Limestone bed of the Drumian Stage is developed as an approximately 60 cm thick, organic-rich, massive limestone succession in Västergötland, south-central Sweden. It belongs to the uppermost part of the Ptychagnostus atavus global agnostoid Zone correlating to the uppermost Hypagnostus parvifrons regional agnostoid Zone in Scandinavia. In Scania, southernmost Sweden, the corresponding level is developed as shale (4). The Andrarum Limestone bed of the Guzhangian Stage is developed as an approximately 1 meter thick, massive limestone bed in Scania, southernmost Sweden. It belongs to the Lejopyge laevigata global agnostoid Zone and correlates to the Solenopleura brachymetopa regional polymerid Zone in Scandinavia. In Västergötland, the corresponding level is developed as a conglomerate (the Exporrecta Conglomerate) (4).

The Middle Jurassic of north-eastern Italy. The upper Bajocian to the Tithonian of the Altipiano de Asiago area is represented by red pelagic limestones colloquially referred to as the Rosso Ammonitico Veronese (5). This succession is divided into three units; the lower, middle and upper Ammonitico Rosso. The lower Ammonitico Rosso comprises upper Bajocian to lower Callovian strata and our samples derive from the lower Bathonian part of this succession in the Asiago section, outside the city of Asiago.

The mid-to-late Jurassic of southern Spain. The middle to early Jurassic in southern Spain is represented by a shallow inner shelf carbonate platform situated at the South Iberian paleomargin. The platform underwent emersion, erosion and a subsequent formation of hydromorphic soils (6). As such, a discontinuity surface representing Late Bathonian to Middle Oxfordian strata, sits at the base of Middle Oxfordian limestones (6). Following drowning in Middle Oxfordian times, sponge meadows thrived, which resulted in spongiolithic limestones in the Middle–Upper Oxfordian (6).

The samples processed in this study consist of red-coloured limestones from the transition zone just below the erosion surface below the middle Oxfordian strata at the Carcabuey section, province of Córdoba. Consequently, our sampled 0.4 m of strata represents 2.5-5.5 million years.

Variables affecting the flux of extraterrestrial chrome spinel

In our first-order reconstruction of the extraterrestrial flux in the Phanerozoic, three parameters are constants (the density of limestone, the area of deposition and the time), whereas the other two (grain concentration and sedimentation rate) are variables. The density of limestone differs somewhat depending on porosity and impurities in the range of 2.3-2.7 g/cm³ in different settings (7). In this study, the average value of 2.5 g/cm³ is used throughout. Many uncertainties are associated with sedimentation rate estimates in deep time. Non-deposition and erosion are two examples of these uncertainties. Thus, the sedimentation rate is the most uncertain parameter in our flux estimates, however, even large errors in the published rate estimates would not affect the outcome of our results (See Table S2 for an overview of flux variables).
**Fig. S1.** a, Early Paleocene (66-61 Ma ago, Danian Stage), Bottaccione section, Umbrian Apennines, central Italy. b, Late Cretaceous (92-91 Ma ago, Turonian Stage), Bottaccione section, Umbrian Apennines, central Italy. c, Late Cretaceous (94-92 Ma ago, Cenomanian-Turonian stages), Bottaccione section, Umbrian Apennines, central Italy. d, Early Cretaceous (117-103 Ma ago, Aptian-Albian stages), Pacifica section, California, USA. e, Early Cretaceous (145-133 Ma ago, Berriasian-Hauterivian stages), Monte Acuto and Bosso sections, Apennines, central Italy. f, Middle Jurassic (166-164 Ma ago, Callovian Stage), Carcabuey section, Betic Cordillera, southern Spain. g, Middle Jurassic (168-166 Ma ago, Bathonian Stage), Altopiano de Asiago, northeastern Italy. h, Late Devonian (374-372 Ma ago, Frasnian-Famennian stages), Coumiac section, Montagne Noir, southern France. i, Late Silurian (426-424 Ma ago, Gorstian-Ludfordian stages), Cellon section, Central Carnic Alps, southern Austria. j, Middle Ordovician (463-462 Ma ago, Darriwilian Stage), Gärde Quarry, Jämtland, central Sweden. k, Middle Ordovician (466-465 Ma ago, Darriwilian Stage), Komstad quarry, Scania, southernmost Sweden. l, Middle Ordovician (467-466 Ma ago, Darriwilian Stage), Lynna river section, western Russia. m, Middle Ordovician (467-466 Ma ago, Darriwilian Stage), Hällekis section, Västergötland, southern Sweden. n, Late Cambrian (500-499 Ma ago, Guzhangian Stage), Andrarum quarry and Baskemölla sections, Scania, southernmost Sweden. o, Late Cambrian (503-502 Ma ago, Drumian Stage), Gudhem quarry, Västergötland, southern Sweden. p, Middle Ordovician (467-465 Ma ago, Darriwilian Stage), Puxi river section, Hubei province, China [this window is not included in the flux calculations, but is a crucial data set showing the reproducibility of the chrome-spinel approach (8)].
Fig. S2. Sampled localities, stratigraphy and outcrops for the Cambrian windows. A, Map over southern Sweden showing the three localities sampled for this study. The *Hypagnostus* Limestone was sampled from the Gudhem quarry outside the city of Falköping. The Andrarum Limestone was sampled from the Andrarum quarry outside the village of Andrarum and from the Baskemölla beach section at the village of Baskemölla. B, Stratigraphy and composite lithological succession of the Cambrian chrome-spinel yielding units. Encircled A = Andrarum Limestone; encircled H = *Hypagnostus* Limestone. C, Cored sample from the Andrarum Limestone, Andrarum. D, The Andrarum Limestone in the Baskemölla beach section. Note the 90 degrees overturn of the unit as compared to the same unit in Andrarum. E, Outcrop of the *Hypagnostus* Limestone (between the dotted lines) in the Gudhem quarry. See SI Supplementary Text for more information.
Fig. S3. Sampled locality, stratigraphy and outcrops for the Bathonian Stage, Italy. A. Map over northeastern Italy showing the location of the Asiago section sampled for this study. B. Stratigraphy and lithologic succession of the Asiago section. C. Overview of the Asiago Quarry. D. Close up of sampled lower-middle portion of the Bathonian Stage in the Asiago section. See SI Supplementary Text for more information.
**Fig. S4.** Sampled locality, stratigraphy and outcrop for the Callovian Stage, Spain. 

**A.** Map over southern Spain showing the location of the Carcabuey section sampled for this study. 

**B.** Stratigraphy and lithologic succession for the Carcabuey section. 

**C.** Hammer resting on top of the Bathonian-Callovian hardground. 

**D.** Preserved ammonite in the hardground. See SI Supplementary Text for more information.
Fig. S5. K-Ar ages of recently fallen ordinary chondrites. A. K-Ar ages of recent H chondrites (9). B. K-Ar ages of recent L chondrites (9). The plots show individual probability distribution for ages of individual meteorites (dashed line) and a combined probability distribution (solid line) for all of the data. The diagrams take in account the uncertainties in the individual data points in a graphical way by giving each data point equal area; see further reference (9). Regarding the more precise timings of impacts on the H-chondrite parent body, see also discussion in reference (10).
Table S1. Phanerozoic flux variation of the groups of ordinary chondrites based on chrome spinel

<table>
<thead>
<tr>
<th>Time window</th>
<th>Ma ago</th>
<th>n</th>
<th>H (%)</th>
<th>L (%)</th>
<th>LL (%)</th>
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<tr>
<td>Today (11)</td>
<td>0</td>
<td>926</td>
<td>41.1</td>
<td>47.4</td>
<td>11.5</td>
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<tr>
<td>Early Paleocene (12)</td>
<td>~66-61</td>
<td>86</td>
<td>69.0</td>
<td>22.0</td>
<td>9.0</td>
</tr>
<tr>
<td>Late Cretaceous (13)*</td>
<td>~92-91</td>
<td>113</td>
<td>62.3</td>
<td>28.0</td>
<td>9.7</td>
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<tr>
<td>Late Cretaceous (13)</td>
<td>~94-92</td>
<td>59</td>
<td>49.8</td>
<td>45.1</td>
<td>5.1</td>
</tr>
<tr>
<td>Early Cretaceous (14)</td>
<td>~117-103</td>
<td>227</td>
<td>57.4</td>
<td>31.2</td>
<td>11.4</td>
</tr>
<tr>
<td>Early Cretaceous (15)</td>
<td>~145-133</td>
<td>81</td>
<td>44.7</td>
<td>44.6</td>
<td>10.7</td>
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<tr>
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<td>142</td>
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<tr>
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<td>129</td>
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<td>32.3</td>
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<tr>
<td>Late Devonian (16)</td>
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<tr>
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<td>29.8</td>
<td>65.3</td>
<td>4.9</td>
</tr>
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<td>Middle Ordovician (18)</td>
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<td>108.7</td>
<td>-4.3</td>
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<tr>
<td>Middle Ordovician (19)</td>
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<td>Middle Ordovician (15)</td>
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<td>215</td>
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<td>Middle Ordovician (20)</td>
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<td>71.3</td>
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<td>147</td>
<td>62.0</td>
<td>20.1</td>
<td>17.9</td>
</tr>
</tbody>
</table>

*Based on TiO₂ content. Percentages presented with correction for 10% overlap in TiO₂ content between groups (see Material and Methods). §Values for today based on observed meteorite falls, not chrome spinel. *This study.
Table S2. Overview of variables affecting the micrometeorite flux estimates

<table>
<thead>
<tr>
<th>Time window (Ma ago)</th>
<th>Sed. rate (cm kyr⁻¹)</th>
<th>EC³² (grains kg⁻¹)</th>
<th>EC³³ (grains kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early Paleocene (~66-61)</td>
<td>0.43 (12)</td>
<td>0.1169</td>
<td>0.0142</td>
</tr>
<tr>
<td>Late Cretaceous (~92-91)</td>
<td>1.00 (13)</td>
<td>0.1144</td>
<td>0.0053</td>
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<tr>
<td>Late Cretaceous (~94-92)</td>
<td>1.00 (13)</td>
<td>0.1157</td>
<td>0.0208</td>
</tr>
<tr>
<td>Early Cretaceous (~117-103)</td>
<td>0.34 (14)</td>
<td>0.3149</td>
<td>0.0145</td>
</tr>
<tr>
<td>Early Cretaceous (~145-133)</td>
<td>2.50 (15)</td>
<td>0.0478</td>
<td>0.0012</td>
</tr>
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<td>#0.01 (6)</td>
<td>n/a</td>
<td>0.6636</td>
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<td>0.30 (5)</td>
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<td>0.0512</td>
</tr>
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<td>Late Silurian (~426-424)</td>
<td>0.40 (17)</td>
<td>0.4798</td>
<td>0.0311</td>
</tr>
<tr>
<td>Middle Ordovician (~463-462)</td>
<td>0.34 (18)</td>
<td>n/a</td>
<td>0.4510</td>
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<tr>
<td>Middle Ordovician (~466-465)</td>
<td>0.25 (17)</td>
<td>&gt;68.6274</td>
<td>4.6471</td>
</tr>
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<td>#0.07 (22, 23)</td>
<td>0.6632</td>
<td>0.0912</td>
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<td>0.34 (20)</td>
<td>0.2882</td>
<td>0.0190</td>
</tr>
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<td>Late Cambrian (~500-499)</td>
<td>0.16 (24)</td>
<td>0.7327</td>
<td>0.1202</td>
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<tr>
<td>Late Cambrian (~503-502)</td>
<td>0.16 (24)</td>
<td>0.4135</td>
<td>0.0577</td>
</tr>
</tbody>
</table>

EC³² = EC grains 32-63 µm large. EC³³ = EC grains 63-355 µm large. *Based on a representation of our sample of 2.5-5.5 Ma (see Fig. S4 and SI Supplementary Text). #Based on a comparison of the thickness of the *Megistaspis polyphemus* Trilobite Zone in the Hälleksis and Lynna sections.
Dataset S1 (separate file). Element analyses of chrome-spinel grains from the Cambrian (Sweden), the Jurassic (Italy and Spain) and Cretaceous (Italy) periods.

S1 References


