**Supplementary Information**

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| **SIZE** | **EVENT** | **AGE (Ma)** | **REFERENCE and notes** | **ERROR (Myr)** |
| **Diameter (km)** | **Impact craters** |  | Diameters are from *Earth Impact Database (2015)* |  |
| 160 | Vredefort | 2023 | *Jourdan (2012)* | 4 |
| 150 | Chicxulub | 66.04 | *Renne et al. 2013*. Average of Chicxulub and Boltysh impacts used in analysis | 0.025/0.049 |
| 130 | Sudbury | 1849.3 | *Jourdan (2012)* | 0.3 |
| 90 | Popigai | 35.7 | *Earth Impact Database (2015)*. Average of Popigai and Chesapeake ages used in analysis | 0.2 |
| 85 | Manicouagan | 214.56 | *Jourdan (2012)* | 0.05 |
| 70 | Morokweng | 145.2 | *Jourdan (2012)* | 0.8 |
| 65 | Kara | 70.3 | *Earth Impact Database (2015)* | 2.2 |
| 55 | Tookoonooka | 125 | *Gorter and Glikson (2012), Bron and Gostin (2012)*. Overlap with Ontong Java LIP. Tookoonooka age used in analysis | 1 |
| 52 | Kara-Kul | <5 | *Earth Impact Database (2015)*. 2.5 Ma used in analysis | [2.5] |
| 52 | Siljan | 380.9 | *Jourdan (2012)* | 4.6 |
| 45 | Montagnais | 50.5 | *Earth Impact Database (2015)* | 0.76 |
| 40 | Chesapeake | 35.67 | *Jourdan (2012)* | 0.28 |
| 40 | Araguainha | 254.7 | *Tohver et al. (2012)* | 2.5 |
| 40 | Mjolnir | 142 | *Earth Impact Database (2015)* Average of Mjolnir and Gosses Bluff used in analysis | 2.6 |
| 40 | Puchezh-Katunki | 167 | *Earth Impact Database (2015)* | 3 |
| 40 | Lake Saint Martin | 227.8 | *Schmieder et al. (2014)* | 1.1 |
| 36 | West Clearwater | 286.2 | *Schmieder et al. (2015)* | 2.6 |
| 25 | Kamensk | 50.37 | *Jourdan (2012)* | 0.4 |
| 24 | Boltysh | 65.82 | *Jourdan (2012)* | 0.74 |
| 24 | Ries | 14.6 | *Schwartz and Lippolt (2014)*. Average of Ries and Monterey excursion used in analysis | 0.15 |
| 23 | Lappajärvi | 76.2 | *Earth Impact Database (2015)* | 0.29 |
| 23 | Rochechouart | 202.7 | *Jourdan (2012)*. Average of Rochechouart and extinction at 201.4 Ma used in analysis | 2.2 |
| 22 | Gosses Bluff | 142.5 | *Earth Impact Database (2015)* | 0.8 |

Table 1a. Impact craters, see legend for Tables 1a-d below.

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| --- | --- | --- | --- | --- |
| **SIZE** | **EVENT** | **AGE (Ma)** | **REFERENCE and notes** | **ERROR (Myr)** |
| **Area (million km2)** | **Large igneous provinces** |  |  |  |
| 7 | CAMP | 201.5 | *Blackburn et al. (2013)* | various within ± 0.6 Myr |
| 2.71 | Mackenzie | 1267 | *Ernst et al (2008)*; 1263 Ma *Day et al. (2013)*; 1269 Ma *Mackie et al. (2009)* | 2 |
| 2.225 | Franklin | 716.33 | *MacDonald et al. (2010)*. Average of Sturtian ages used in analysis | 0.54 |
| 2.1 | Kalkarindji | 510.7 | *Jourdan et al. (2014)* | 0.6 |
| 2.08 | Umkondo | 1110 | *de Kock et al. (2014)* | 2 |
| 2 | Afar | 31 | *Bryan and Ferrari (2013); Prokoph et al. (2013)* state 30 ± 0.5 Ma | <2 |
| 2 | Parana-Edentaka | 134.3 | *Bryan and Ferrari (2013)*; 134.7 ± 0.3 - 133.9 ± 0.7 Ma *Florisbal et al. (2014)* | 1.8 |
| 1.9 | Ontong Java-Manihiki-Hikurangi | 125-120 | *Bryan and Ferrari (2013), Tejada et al. (2013), Timm et al. (2011)* 124.6 ± 1.6. See Tookoonooka | <4 |
| 1.8 | Deccan Traps | 67-66 | *Bryan and Ferrari (2013), Schöbel et al. (2014)* 67.12 ± 0.44 Ma*.* See Chicxulub and Boltysh | <1.5 |
| 1.6 | Madagascar | 92 | *Cucciniello et al. (2013),* 92.3 ± 2.0, 91.5 ± 1.3 Ma | <4.5 |
| 1.55 | Warakurna | 1076 | *Ernst et al. (2008)* | 3 |
| 1.5 | Siberian Traps | 252 | *Bryan and Ferrari (2013)*; *Ivanov et al. (2013)* give 7 MKm2 and note pulse around 252 Ma with various errors less than 1 Myr (their Table 4). Extinction age used in analysis | <2 |
| 1.34 | Guibei | 825 | *Wang et al. (2010),* 823 ± 4, peak at 825 Ma | 5-10 |
| 1.3 | NAVP | 61-62 | *Bryan and Ferrari (2013); Ganerød et al. (2010)* emplacement over 3 Myr ± 0.6 | <4 |
| 1 | Karoo-Ferrar | 183.2 | *Sell et al. (2014),* main volume of LIP may have been 4-5 Myr,CIE/Toarcian OAE between ash beds of 183.22 ± 0.26 and 181.99 ± 0.13 Ma; *Svensen et al. (2012)*. Average of 183.2 and extinction at 183.5 Ma used in analysis | <3 |

Table 1b. Large igneous provinces, see legend for Tables 1a-d below.

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| --- | --- | --- | --- | --- |
| **SIZE** | **EVENT** | **AGE (Ma)** | **REFERENCE and notes** | **ERROR (Myr)** |
|  | **Neoproterozoic glaciations** |  |  |  |
| n/a | Gaskiers | 582.4 | *Hoffman and Li (2009)*, depositional age for glacigenic strata | 0.5 |
| n/a | Marinoan | 635.6 |
| n/a | Sturtian | 713.7  715.9 716.5 | *Bowring et al. (2007), Lan et al. (2014), MacDonald et al. (2010)* respectively. Average of all three used in analysis | 0.5,2.8,0.2 |

Table 1c. Neoproterozoic glaciations, see legend for Tables 1a-d below.

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| --- | --- | --- | --- | --- |
| **SIZE** | **EVENT** | **AGE (Ma)** | **REFERENCE and notes** | **ERROR (Myr)** |
| Ecological severity ranking, *McGhee et al. (2013)* | **Most severe extinctions** |  |  |  |
| 1 | end-Permian | 251.9 | *Burgess et al. (2014)*, 251.94 ± 0.037 - 251.88 ± 0.031 Ma | <0.2 |
| 2 | end-Cretaceous | 66.04 | *Renne et al. (2013)* | 0.043 |
| 3 | end-Triassic | 201.4 | *Wotzlaw et al. (2014), Ikeda and Tada (2014)* | 0.2 |
| 4 | Frasnian | 373.9 | *De Vleeschouwer and Parnell (2014).* 372.2 ± 1.6 Ma is GSSP | <3 |
| 5 | Capitanian | 260.3 | The main extinction was estimated at approximately 0.5 Myr before the end of the Capitanian (259.8 ± 0.4 Ma), *Groves and Wang (2013)* | <1 |
| 6 | Serpukhovian | 323.2 | 323.2 ± 0.4 is GSSP, the main extinction may have been earlier, *Pointon et al. (2012)* | <0.5 |
| 7= | Famennian | 358.9 | 358.97 ± 0.11, 358.89 ± 0.2 with earlier 359.97 ± 0.46 Ma, *Myrow et al. (2014)* | <2 |
| 7= | end-Ordovician | 445.0 | Two phases, starting with glaciation at beginning of Hirnantian 445.2 ± 1.4 - 443.8 ± 1.5 Ma, *Melchin et al. (2013)* | <2 |

Table 1d. Most severe extinctions.

Supplementary Tables 1a-d. Event sizes, names, ages, references and errors for four event types. All events included in the analysis, with the possible exception of one or two LIPs, have errors of less than five Myr. Stated errors may be based on one or more samples. Events listed in decreasing order of size/severity within each event type. References not in the main text are given at the end of the Supplementary Information.

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| --- | --- | --- | --- | --- | --- |
| Cluster equivalent age range (Ma) | Impacts | LIPs | Extinctions | Glaciations | Probability (null model of Poisson distribution) |
| 1.3 to 2.9 | Kara-kul (<5), Chicxulub & Boltysh (2.6 average),  Araguainha (1.6), Siljan (1.3) | Guibei (2.5), Mackenzie (1.6), Deccan (counted with Chicxulub & Boltysh) | end-Ordovician (2.1), end-Cretaceous (counted with Chicxulub & Boltysh) | Marinoan glaciation (2.9) | eight events in 2.6 Myr window, exclude Kara-kul (P=0.000943 for 7 events) |
| -1.2 to  -1.8 | Tookoonooka (-1.5), Vredefort (-1.6) | NAVP (-1.8), Ontong Java (counted with Tookoonooka), Siberian Traps (counted with end-Permian) | end-Permian  (-1.2) |  | four events in 1.6 Myr, P=0.0136 |
| 6.9 to 7.8 | Kara (7.0) | Parana-Edentaka  (7.8) | end-Capitanian (7.2), end-Serpukhovian (6.9) |  | four events in 1.9 Myr, P=0.023 |
| 12.2 to 15.7 | Ries (14.2 average with Monterey),  Lappajärvi (12.9), Mjolnir and Gosses Bluff (average 15.7),  Rochechouart  (average 12.2 with extinction), Sudbury (14.5) | CAMP (counted with Rochechouart and end-Triassic) | end-Triassic (12.2 average with Rochechouart) | Gaskiers (13.0), (Monterey climate shift also used with Ries age) | six events in 4.5 Myr, P=0.036; alternatively 12.2 to 14.5 Ma giving five events in 3.3 Myr, P=0.035 |

Supplementary Table 2. Significant clusters of events. Event name is followed by equivalent age on 63.27 Myr cycle (rounded to 0.1 Myr). Minimum of four events in cluster from different 63 Myr repeats. Size or severity of events given in Supplementary Table 1. Probability is determined from time window of observed age-range + (2 x 0.5) Myr.

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