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Reiners and Turchyn, 2018, Extraterrestrial dust, the marine lithologic record, and global biogeochemical cycles: Geology, https://doi.org/10.1130/G45040.1.

References and details for Figure 1.

Assumed surface areas for areal averaging: Global Ocean: 3.62×10^8 km^2; Southern Ocean: 2.033×10^7 km^2. For estimates from Raiswell and Canfield (2012) (see below), filterable iron includes all aqueous iron (<0.02 μm diameter), nanoparticulate iron (<0.1 μm or <0.2 μm (see their Fig. 1.3 and text for examples of both)), and colloidal iron (< 1 μm).

References in Figure 1:

1. Terrestrial aeolian dust flux of filterable iron, Raiswell and Canfield (2012). Upper point: Total filterable iron: 1530-3030 Gg/a. Lower point: Aqueous iron: 560-1870 Gg/a. Points are means and error bars upper and lower limits.
2. Terrestrial aeolian dust flux of soluble iron, Tagliabue et al. (2008): 450 Tg/a total, 3.5% Fe, solubility = 10%. Low and high error bars are 1% and 40% solubility.
3. Terrestrial aeolian dust flux of soluble iron, Gao et al. (2003): 0.62-4.4 Tg/a, dry + wet deposition.
4. Benthic flux of total filterable iron (not necessarily all bioavailable) from sediments on shelves, from Raiswell and Canfield (2012): Upper point: total global flux from shelves; Lower point: estimated 5% fraction transported to open ocean: 50-250 Gg/a.
5. Riverine flux of iron, from Raiswell and Canfield (2012). Upper point: Total filterable iron: 140 Gg/a. Lower point: Aqueous iron: 80 Gg/a.
6. Hydrothermal flux of total filterable iron, from Raiswell and Canfield (2012), who note that contribution to surface waters is uncertain: 50 Gg/a.
7. Terrestrial aeolian dust flux to the Southern Ocean. From top to bottom: Fung et al. (2000) assuming 1-10% solubility: 0.68-6.8 μmol/m^2/a; flux at last glacial maximum (LGM) from EPICA Dome Antarctic ice sheet, 26-21 ka (Conway et al., 2015): 0.36-5.0 μmol/m^2/a;

aeolian aqueous fraction (Raiswell and Canfield, 2012): 0.1-3.0 Gg/a; aeolian modern soluble iron (Conway et al., 2015 citing Watson et al., 2000): 0.2 μmol/m^2/a.

8. Bioavailable iron from filterable iron delivered in icebergs to Southern Ocean (Raiswell and Canfield, 2012), 3 Gg/a.
9. Lower point: Bioavailable iron dust flux from modern extraterrestrial dust (interplanetary dust) flux, assuming 25% iron (average of H and L chondrites that compose >70% of incoming meteoritic material), and 100% bioavailability, with incoming dust flux from Peucker-Ehrenbrink (2016) and references therein: $4 \pm 2 \times 10^7$ kg/a. Upper point (smaller light blue square): Same estimate but with estimated 10x increase for meteoritic smoke particle delivery focusing over Southern Ocean (Plane; 2012; Dhomse et al., 2013).
10. Five-fold increase over modern (globally averaged) rate of extraterrestrial iron flux estimated for 6-8 Ma Veritas event from ^{3}He records (Montanari et al., 2017; also see Farley et al., 2006). Upper point is 10x higher to represent potential atmospheric focusing to Late Miocene Southern Ocean as in 9.
11. 5.5-x increase over modern (globally averaged) rate of extraterrestrial iron flux estimated for Eocene-Oligocene event lasting ~2.5 Ma from ^{3}He records (Farley et al., 1998; 2009). Upper point is 10x higher to represent potential atmospheric focusing to high southern latitudes as in 9.
12. 10-x increase over modern (globally averaged) rate of extraterrestrial iron flux estimated for Eocene-Oligocene event lasting ~2.5 Ma from Os-isotope records (Dalai et al., 2006). Upper point is 10x higher to represent potential atmospheric focusing to high southern latitudes and in 9.

13. Late Cretaceous increases estimated from ^{3}He records: Lower: 4x increase over modern (globally averaged) rate of extraterrestrial iron flux estimated for the ~5-10-Ma K3 event from (Farley et al., 2012). Upper: 10x increase estimated for the ~3-Ma K1 event (Farley et al., 2017).

14. a. 10x (low-end) estimate for increase over modern (globally averaged) rate of extraterrestrial iron flux for early-mid Ordovician L-chondrite event, from fossil meteorite analysis (Schmitz et al., 1996). b. 100x estimate from meteorite and extraterrestrial chromite abundances in multiple locations (Schmitz et al., 2013). c. 69x and 173x estimates from fossil meteorite abundances (Schmitz et al., 2001).

Oolitic ironstones

Phanerozoic oolitic ironstones are relatively thin (typically tens of cm) accumulations of Fe-rich ooliths, concentrically laminated Fe-oxides/oxyhydroxides and/or Fe-rich clays and apatite or carbonate, in some cases with more massive/dense ironstone. Oolitic ironstones typically cut across local facies boundaries over large regions, and have been used as isochronous event markers. They are frequently associated with "condensed" or low sedimentation-rate sections, and iron-rich carbonates, microbial (sometimes "stromatolitic-like" iron-rich layers, and "hardgrounds," and are sometimes much more fossiliferous than adjacent strata (Ferretti, 2005; Ferretti et al., 2012; McLaughlin et al., 2012). Over million-year timescales oolitic ironstones are also closely associated with black shales (Van Houten and Arthur, 1989). Several studies have noted the stratigraphic coincidence of ironstone deposition and positive δ^{13}C excursions worldwide (McLaughlin et al., 2012; Sullivan et al., 2012). The formation and significance of ooidal ironstones are controversial (e.g., Van Houten and Bhattacharyya, 1982). A few studies have suggested that the iron minerals are late diagenetic replacements, but most consider them primary (Collin et al., 2005). As described in the text most researchers consider ooidal ironstone occurrences to be related to redox changes in shelf environments that promote higher iron flux from shelf sediments to the sediment-water interface (Cotter and Link, 1993; Witzke et al., 1997; McLaughlin et al., 2012; Sullivan et al., 2012). One instance of modern iron ooid formation is documented, in Indonesia (Heikoop et al., 1996; Sturresson et al., 2000), but its local volcanic origin cannot serve as a general analog for the diverse depositional settings of Phanerozoic occurrences.

Estimating Fe flux of incoming extraterrestrial dust

Most incoming extraterrestrial dust today probably comes from three main-belt asteroid families (Kortenkamp and Dermott, 1998) dominated by ordinary and carbonaceous chondrites with about 20-35% iron. The modern flux of macroscopic meteorites (>70% H and L chondrites) has similar iron concentrations: ~31-35% and 20-22% iron, respectively. Assuming the average iron concentration in H and L chondrites (25%) and the modern extraterrestrial dust flux leads to an estimated modern extraterrestrial iron influx of about 1.0×10^7 kg/a.

Jurassic sections reporting extraterrestrial material

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Asteroid family ages

Table DR1. Characteristics of asteroid families with Phanerozoic formation ages estimated in previous studies [or orbital characteristics permitting statistical estimation of Phanerozoic age as in Nesvorny et al. (2015)].

Family #	Family Name	a (AU)[+]	Tax. Type[¥]	pV[¥]	C_0 (10^{-4} AU)[¥]	ρ (g/cm^3)[¥]	Best Age[£] (Ma)	± Age (Ma)	Age Source*	# of Members[¥]
E-Belt										
434	Hungaria	1.944162	Xe				205	7	1	2965
Inner Main Belt, 2<a<2.5 AU										
298	Baptistina	2.263659	X	0.16	0.25	2.87	110	10	2	2500
20	Massalia	2.409175	S	0.22	0.25	2.66	176	6	1	6424
163	Erigone[@]	2.367006	CX	0.06	0.2	1.96	190	25	2	1776
302	Clarissa	2.405863	X	0.05	0.05	2.87	106	27	3	179
752	Sulamitis	2.463547	C	0.04	0.3	1.57	320	30	2	303
1892	Lucienne	2.461778	S	0.22	0.15	2.66	148	37	3	142
27	Euterpe	2.346281	S	0.26	0.5	2.66	411	103	3	474
1270	Datura	2.234483	S	0.21			0.53	0.02	4	6
21509	Lucascavin	2.281104	S				0.55	0.25	5	3
623	Chimaera	2.461276	CX	0.06	0.3	1.57	467	117	3	108
329	Svea	2.476531	CX	0.06	0.3	1.57	473	118	3	48
2076	Levin	2.274138					366	59	1	1145[#]
Central Main Belt, 2.5<a<2.82										
3	Juno	2.668531	S	0.25	0.5	2.66	483	87	1	1684
128	Nemesis	2.749259	C	0.05	0.25	1.57	440	20	2	1302
145	Adeona	2.673275	C	0.07	0.7	1.57	794	92	6	2236
363	Padua	2.747028	X	0.1	0.5	2.87	191	16	6	1087
396	Aeolia	2.741442	X	0.17	0.075	2.87	95	12	1	296
410	Chloris	2.723145	C	0.06	0.75	1.57	700	400	7	424
569	Misa	2.6565	C	0.03	0.5	1.57	700	140	2	702
606	Brangane	2.58851	S	0.1	0.04	2.66	47	3	1	195
668	Dora	2.793545	C	0.05		1.57	515	74	1	1259
808	Merxia	2.747927	S	0.23	0.3	2.66	328	18	1	1215
847	Agnia	2.781914	S	0.18	0.15	2.66	200	10	2	2125
1128	Astrid	2.787416	C	0.08	0.12	1.57	150	8	1	489
1272	Gefion	2.783999	S	0.2	0.8	2.66	485	25	8	2547
3815	Konig	2.569495	CX	0.04	0.06	1.57	51	4	1	354
1644	Rafita	2.548276	S	0.25	0.5	2.66	480	100	2	1295

1726	Hoffmeister	2.787673	Cb	0.04	0.2	1.88	270	10	1	1819
4652	Iannini	2.644493	S	0.32						150
173	Ino	2.742772	S	0.24	0.5	2.66	585	146	3	463
14627	Emilkowalski	2.599817	S	0.2			0.22	0.03	5	4
16598	1992 YC2	2.61965	S				0.15	0.1	5	10
2384	Schulhof	2.611387	S	0.27			0.78	0.1	9	6
5438	Lorre	2.744694	C	0.05			1.9	0.3	10	2
322	Phaeo	2.781263	X	0.06	0.3	2.87	778	195	3	146
1668	Hanna	2.807315	CX	0.05	0.2	1.57	240	20	2	280
3811	Karma	2.578541	CX	0.05	0.25	1.57	468	117	3	124
2732	Witt	2.759492	S	0.26	0.75	2.66	790	200	2	1816
2344	Xizang	2.752302		0.12	0.3	2.2	220	20	2	275
369	Aeria	2.651003	X	0.17	0.3	2.87	180	20	2	272
3152	Jones	2.626089	T	0.05						22
3395	Jitka	2.791523	S				143	15	11	50^
10955	Harig and Darcydiegel	2.720466					454	69	1	553#
1521	Seinajoki	2.85337					133	15	1	50^
569	Misa	2.6565	C				257	80	1	25
15124	2000 EZ39	2.65591					112	7	1	50^
1547	Nele	2.643194	TD				14	2	1	108#
3827	Zdenekhorsky	2.740393	C				154	14	1	671#
1658	Innes	2.558359	S				464	31	1	558#
5	Astraea	2.573285	S				395	44	6	2120#
148	Gallia	2.771037	S	0.17	0.5	2.66	650	60	2	182
945	Barcelona	2.635145	S	0.25	0.25	2.66	250	10	2	306
1222	Tina	2.794978	X	0.34	0.1	2.87	170	25	12	96
4203	Brucato	2.605565	CX	0.06	0.5	1.57	480	100	2	342
Outer Main Belt, 2.82<a<3.7										
283	Emma	3.051636	C	0.05	0.3	1.57	299	33	6	76
293	Brasilia	2.860626	X	0.18	0.2	2.87	160	10	2	579
490	Veritas	3.170541	CPD	0.07	0.2	1.57	8.3	0.5	13	1294
832	Karin	2.863564	S	0.21	0.03	2.66	5.8	0.2	13	541
845	Naema	2.939411	C	0.08	0.2	1.57	210	10	2	301
3556	Lixiaohua	3.173025	CX	0.04	0.25	1.57	155	36	14	756
18405	(1993) FY12	2.849028	CX	0.17	0.08	1.57	83	12	1	104
778	Theobalda	3.190516	CX	0.06			6.90	2.30	15	376

1189	Terentia	2.929774	C	0.07	0.13	1.57	190	47	3	79
10811	Lau	2.928006	S	0.27	0.075	2.66	94	24	3	56
656	Beagle	3.149017	C	0.09	0.07	1.57	104	26	3	148
158	Koronis(2)	2.868793	S	0.14	0.01	2.66	17	4	3	246
5614	Yakovlev	2.872906	C	0.05	0.15	1.57	249	62	3	67
15454	1998 YB3	2.869622	CX	0.05	0.1	1.57	232	58	3	38
36256	1999 XT17	2.941212	S	0.21	0.25	2.66	359	90	3	58
926	Imhilde	2.981506	CX	0.05	0.2	1.57	501	125	3	43
3330	Gantrisch	3.155707	X				458	82	1	600[#]
845	Naema	2.939411	C				161	7	1	253[#]

Notes:

Families in table without age picks (Jones; Iannini) are included because one or more reference suggested a loosely quantified Phanerozoic age or uncertainty overlapping an age younger than 540 Ma.

[+] *a* of principal member from http://www.minorplanetcenter.net/iau/mpc.html

[¥] From Nesvorny et al. (2015) Table 1.

[@] Includes Martes for Spoto et al. (2015)

[#] Number of members from Milani et al. (2014)

[^] Number of members not found; assumed to be 50 for plotting in Figure 2.

[£] Age pick procedure: 1. Highest available precision on uncertainties among references below (ages with in-and-out estimates [e.g., Spoto et al. (2015)] are calculated as weighted means and errors as standard error of in-and-out estimates), then 2. Nesvorny et al. (2015) statistical method (reference 4, below) with assumed 25% uncertainty, and densities taken from Carry et al. (2012) using taxonomic type in Nesvorny et al. (2015), or (in a small number of cases where Nesvorny taxonomic type was not referenced in Carry et al. (2012), a representative mean density of 2.2 g/cm^3 (e.g., Masiero et al. [2012] and references therein) was used.

*Sources for age picks:

1. Spoto et al. (2015).
2. Carruba and Nesvorny (2016).
3. Nesvorny et al. (2015) statistical method (Equation 1 and Table 1).
4. Vokrouhlicky et al. (2009).
5. Nesvorny and Vokrouhlicky (2006).
6. Milani et al. (2017).
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8. Nesvorny et al. (2009).
9. Vokrouhlicky and Nesvorny (2011).
10. Novakovik et al. (2012).
11. Milani et al. (2014).
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