Paleocene-Eocene Thermal Maximum Meets The North Atlantic Igneous Province: Coincidence Or Global Environmental Conspiracy?

University of

(and some other thoughts on the meaning of carbon isotope changes in paleoclimate records)

Andy Ridgwell









IA																	
1 1s ¹ hydrogen 1.008	2A											3A	4A	5A	_6A	7A	2 He ^{15² helium 4.003}
3 L1 _{[He]2s¹ lithium}	4 Be											5 B [He]2s ² 2p ¹ boron	6 C [He]2s ² 2p ² carbon	7 N [He]2s ² 2p ³ nitrogen	B [Hej2 ² 2p ⁴ oxygen	9 [He]2 s²2p⁵ fluorine	10 Ne [He]2s ² 2p ⁶ neon
6.941 11 Na	9.012 12 Mg											10.81	12.01 14 Si	14.01 15 P	16.00 16 S	19.00 17 C1	20.18 18 Ar
[Ne]35' sodium 22.99	[Ne]3 s' magnesium 24.31	3B	4B	5B	6B	7B				11B	12B	aluminum 26.98	silicon 28.09	phosphorus 30.97	sulfur 32.07	chlorine 35.45	[Ne]3#3p ³ argon 39.95
19 K	20 Ca	21 Sc	Ti	23 V	\mathbf{Cr}^{24}	Mn	26 Fe	C0	28 Ni	²⁹ Cu	\mathbf{Zn}^{30}	Ga	Ge	As	Se	35 Br	36 Kr
[Ar]4s ¹ potassium 39.10	[Ar]4 s² calcium 40.08	[Ar]4 s²3d¹ scandium 44.96	[Ar]4s ² 3d ² titanium 47.88	[Ar]4s ² 3d ³ vanadium 50.94	[Ar]4s ¹ 3d ⁵ chromium 52.00	[Ar]4s ² 3d ⁵ manganese 54.94	[Ar]4s ² 3d ⁶ iron 55.85	[Ar]4s ² 3d ⁷ cobalt 58.93	[Ar]4s ² 3d ⁸ nickel 58.69	[Ar]4s ¹ 3d ¹⁰ copper 63.55	[Ar]4s ² 3d ¹⁰ zinc 65.39	^{[Ar]4s²3d¹⁰4p¹ gallium 69.72}	[Ar]4s ² 3d ¹⁰ 4p ² germanium 72.58	[Ar]4s ² 3d ¹⁰ 4p ³ arsenic 74.92	[Ar]4s ² 3d ¹⁰ 4p ⁴ selenium 78.96	[Ar]4s ² 3d ¹⁰ 4p ⁵ bromine 79.90	[Ar]4 ² 3d ¹⁰ 4p ⁶ krypton 83.80
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	Ru	45 Rh	⁴⁶ Pd	$\begin{bmatrix} 47 \\ Ag \end{bmatrix}$	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
^{[Kr]55¹ rubidium 85.47}	[Kr]5 5² strontium 87.62	[Kr]5 5²4d¹ yttrium 88.91	[Kr]5 s²4d² zirconium 91.22	[Kr]5s ¹ 4d ⁴ niobium 92.91	[Kr]5s ¹ 4d ⁵ molybdenum 95·94	[Kr]5s ² 4d ⁵ technetium (98)	[Kr]5s ¹ 4d ⁷ ruthenium 101.1	[Kr]5s ¹ 4d ⁸ rhodium 102.9	[Kr]4d ¹⁰ palladium 106.4	[Kr]5s ¹ 4d ¹⁰ silver 107.9	[Kr]5s ² 4d ¹⁰ cadmium 112.4	[Kr]5s ² 4d ¹⁰ 5p ¹ indium 114.8	[Kr]5s ² 4d ¹⁰ 5p ² tin 118.7	[Kr]5s ² 4d ¹⁰ 5p ³ antimony 121.8	[Kr]5s ² 4d ¹⁰ 5p ⁴ tellurium 127.6	[Kr]5s ² 4d ¹⁰ 5p ⁵ iodine 126.9	[Kr]5s ² 4d ¹⁰ 5p ⁶ xenon 131.3
55 Čs	56 Ba	57 La*	72 Hf	73 Ta	W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 H g	81 TI	⁸² Pb	83 Bi	84 Po	85 At	86 Rn
[Xe]6s ¹ cesium 132.9	[Xe]6 s² barium 137.3	[Xe]6 s²5d¹ lanthanum 138.9	[Xe]6s ² 4f ¹⁴ 5d ² hafnium 178.5	[Xe]6 s²4f¹⁴5d³ tantalum 180.9	[Xe]6s ² 4f ¹⁴ 5d ⁴ tungsten 183.9	[Xe]6 s²4f¹⁴5d⁵ rhenium 186.2	[Xe]6 ² 4f ¹⁴ 5d ⁶ osmium 190.2	[Xe]6 ² 4f ¹⁴ 5d ⁷ iridium 190.2	[Xe]6s ¹ 4f ¹⁴ 5d ⁹ platinum 195.1	[Xe]6s ¹ 4f ¹⁴ 5d ¹⁰ gold 197.0	[Xe]6 ² 4f ¹⁴ 5d ¹⁰ mercury 200.5	Xej6s ² 4f ¹⁴ 5d ¹⁰ 6p ¹ thallium 204.4	Xe]6s ² 4f ¹⁴ 5d ¹⁰ 6p ² lead 207.2	Xej6 ² 4f ¹⁴ 5d ¹⁰ 6p ³ bismuth 208.9	[Xe]6 ² 4f ¹⁴ 5d ¹⁰ 6p ⁴ polonium (209)	Xej6s ² 4f ¹⁴ 5d ¹⁰ 6p ⁵ astatine (210)	[Xe]65 ² 4f ¹⁴ 5d ¹⁰ 6p ⁶ radon (222)
87 Fr	⁸⁸ Ra	⁸⁹ Ac~	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Uuu	112 Uub						
[Rn]7s ¹ francium (222)	[Rn]7 s radium	[Rn]7 ² 6d ¹ actinium	[Rn]7s ² 5f ¹⁴ 6d ² rutherfordium (257)	[Rn]7 \$ 5f ¹⁴ 6d ³ dubnium (260)	[Rn]7s ² 5f ¹⁴ 6d ⁴ seaborgium	[Rn]7 ² 5f ¹⁴ 6d ⁵ bohrium	[Rn]7\$25f ¹⁴ 6d ⁶ hassium (265)	[Rn]7 ² 5f ¹⁴ 6d ⁷ meitnerium	[Rn]7 ¹ 5f ¹⁴ 6d ⁹ darmstadtium	(272)							





abundance ratio(sample): $R_{sample} = n_{heavy}/n_{light}$ abundance ratio(standard): $R_{stand.} = n_{heavy}/n_{light}$

 δ (sample) = (R_{sample}/R_{stand.} - 1) x 1000





lA																	
1 1s ¹ hydrogen 1.008	2A											3A	4A	5A	6A	7A	2 He ^{15² helium 4.003}
3 Li _{[He]25} 1 lithium 6.941	4 Be _{[He]2} beryllium 9.012											5 B [He]2s ² 2p ¹ boron 10.81	6 C [He]2s ² 2p ² carbon 12.01	7 N _{[He]25²2p³ nitrogen 14.01}	8 0 [He]2s ² 2p ⁴ oxygen 16.00	9 [He]2s ² 2p ⁵ fluorine 19.00	10 Ne [Hej2 ² 2p ⁶ neon 20.18
11 Na ^{[Ne]35¹ sodium 22.99}	12 Mg _{[Ne]35} magnesium 24.31	3B	4B	5B	6B	7B		—8B -		11B	12B	13 Al _{[Ne]3\$23p1} aluminum 26.98	14 Si ^{[Ne]3\$3p² silicon 28.09}	15 P [Ne]3 ² 3p ³ phosphorus 30.97	16 S [Ne]3 ² 3p ⁴ sulfur 32.07	17 Cl [Ne]3 ² 3p ⁵ chlorine 35:45	18 Art [Ne]3s ² 3p ⁶ argon 39.95
19 K [Ar]4s ¹ potassium 39.10	20 Ca [Ar]45 ² calcium 40.08	21 Sc [Ar]4s ² 3d ¹ scandium 44.96	22 Ti [Ar]4s ² 3d ² titanium 47.88	23 V [Ar]4s ² 3d ³ vanadium 50.94	24 Cr [Ar]4s ¹ 3d ⁵ chromium 52.00	25 Mn [Ar]4s ² 3d ⁵ manganese 54.94	26 Fe ^{[A148²3d⁶ iron 55.85}	27 Co [Ar]4 ² 3d ⁷ cobalt 58.93	28 Ni ^{[Ar]4s²3d⁸ nickel 58.69}	29 Cu [Arj4s ^{13d10} copper 63.55	30 Zn ^{[Ar]45²3d¹⁰ zinc 65.39}	$\underset{\substack{[Ar]4s^{2}3d^{10}4p^{1}\\gallium}\\69.72}{31}$	32 Ge [Ar]4s ² 3d ¹⁰ 4p ² germanium 72.58	33 AS ^{[Ar]4} ^{23d¹⁰4p³ arsenic 74.92}	34 Se _{[Ar]4s²3d¹⁰4p⁴ selenium 78.96}	35 Br ^{[Ar]4s²3d¹⁰4p⁵ bromine 79.90}	36 Kr [Ar]4s ² 3d ¹⁰ 4p ⁶ krypton 83.80
37 Rb rubidium	38 Sr strontium 87 62	39 Y Vtrium 88 01	40 Zr ^{Krj5s²4d²}	41 Nb Krj5s ¹ 4d ⁴ nobium	42 Mo Krj5s ¹ 4d ⁵ molybdenum	43 Tc	44 Ru ^{[Kr]5s¹4d⁷ ruthenium}	45 Rh Krj5s ¹ 4d ⁸ rhodium	46 Pd ^{[Kr]4d¹⁰ palladium}	47 Ag	48 Cd [Kr]5s ² 4d ¹⁰ cadmium	${\overset{49}{In}}_{{}^{[K_{7}]5^{g_{4d}}10_{5p^{1}}}_{indium}}$	50 Sn ^{[Kr]55²4d¹⁰5p²}	51 Sb _{[Kr]55²4d¹⁰5p³ antimony}	52 Te ^{[Krj55²4d¹⁰5p⁴} tellurum	53 I [Kr]55 ² 4d ¹⁰ 5p ⁵ iodine	54 Xeo [Kr]5 ² 4d ¹⁰ 5 ^{p6} xenon
55 CS [Xej6s ¹ cesium 132.9	56 Ba _{[Xe]65} ² barium 137-3	57 La* [Ke]6 ² 5d ¹ lanthanum 138.9	$\begin{array}{c} 72 \\ Hf \\ _{[Xe]6s^24t^{14}5d^2 \\ hafnium \\ 178.5 \end{array}}$	73 Ta [Xej6s ² 4f ¹⁴ 5d ³ tantalum 180.9	74 W [Xe]65 ² 4f ¹⁴ 5d ⁴ tungsten 183.9	(96) 75 Re ^{[Xe]66²4f¹⁴5d⁵} rhenium 186.2	76 OS [Xe]6 ² 4t ¹⁴ 5d ⁶ osmium 190.2	77 Ir [Xe]6#41 ¹⁴ 5d ⁷ iridium 190.2	78 Pt [Xe]6s ¹ 4f ¹⁴ 5d ⁹ platinum 195.1	79 Au (Xe)65 ¹ 4f ¹⁴ 5d ¹⁰ gold 197.0	80 Hg [Xej6 ² 4f ¹⁴ 5d ¹⁰ mercury 200.5	$\overset{\text{B1}}{\underset{x_{\text{e} 65^24f}^{145d}^{10}6p^1}{\text{mallium}}}$	82 Pb xej654f ¹⁴⁵ d ¹⁰ 6p ² lead 207.2	83 Bi xej6544 ¹⁴ 5d ¹⁰ 6p ³ bismuth 208.9	84 Po [Xe)65 ² 4f ¹⁴ 5d ¹⁰ 6p ⁴ polonium (209)	85 At xej6 ² 41 ⁴ 5d ¹⁰ 6p ⁵ astatine (210)	86 Rn _{[Xe)6²41¹⁴5d¹⁰6p⁶ radon (222)}
87 Fr Francium (223)	88 Ra (Rn)7 ² radium (226)	89 Ac~ [Rn]7 ² 6d ¹ actinium (227)	104 Rf (Rnj7 ² 51 ¹⁴ 6d ² nutherfordium (257)	105 Db [Rn]7\$5f ¹⁴ 6d ³ dubnium (260)	106 Sg [Rn]7 ² 51 ¹⁴ 6d ⁴ seaborgium (263)	107 Bh (Rn]7 ^{25f¹⁴8d⁵ bohrium (262)}	108 HS [Rn]75 ² 51 ^{146d⁶} hassium (265)	109 Mt _{[Rn]75} 251 ¹⁴ 8d ⁷ meitnerium (266)	110 Ds [Rn)7\$5f ¹⁴ 8d ⁹ darmstadtium (271)	111 Uuu ₍₂₇₂₎	112 Uub						





 $R_{sample} > R_{stand.}$ $\delta(sample) = (R_{sample}/R_{stand.} - 1) \times 1000$ $=> \delta(sample) \text{ is POSITIVE}$ ('isotopically enriched')



 $R_{sample} > R_{stand.}$ $\delta(sample) = (R_{sample}/R_{stand.} - 1) \times 1000$ $=> \delta(sample) is NEGATIVE$ ('isotopically depleted')



IA																	
1 1s ¹ hydrogen 1.008	2A											3A	4A	5A	6A	7A	2 He ^{1s²} helium 4.003
3 L1 _{[He]25¹ lithium 6.941}	4 Be [He]25 ² beryllium 9.012											5 B [He]2s ² 2p ¹ boron 10.81	6 C [He]2 ² 2p ² carbon 12.01	7 N _{[He]2s²2p³ nitrogen 14.01}	8 0 [He]2s ² 2p ⁴ oxygen 16.00	9 F [He]2s ² 2p ⁵ fluorine 19.00	10 Ne ^{[He]2\$2p6} neon 20.18
11 Na ^{[Ne]35¹ sodium 22.99}	12 Mg _{[Ne]35} magnesium 24.31	3B	4B	5B	6B	7B		—		11B	12B	13 Al _{[Ne]3²3p¹ aluminum 26.98}	14 Si ^{[Ne]3s²3p² silicon 28.09}	15 P [Ne]3s ² 3p ³ phosphorus 30.97	16 S [Ne]3\$ ² 3p ⁴ sulfur 32.07	17 C ^{[Ne]32²3p⁵ chlorine 35:45}	18 Ar [Nej3s ² 3p ⁶ argon 39.95
19 K _{[Ar]4s¹ potassium 39.10}	$\begin{array}{c} 20\\ Ca\\ {}_{[Ar]4s^2}\\ {}_{calcium}\\ 40.08\end{array}$	21 Sc [Ar]4s ² 3d ¹ scandium 44.96	22 Ti [Ar]4s ² 3d ² titanium 47.88	23 V [Ar]4s ² 3d ³ vanadium 50.94	24 Cr [Ar]4s ¹ 3d ⁵ chromium 52.00	25 Mn [Ar]4s ² 3d ⁵ manganese 54.94	26 Fe [A1/48 ² 3d ⁶ iron 55.85	27 Co [Ar]4 ² 3d ⁷ cobalt 58.93	28 Ni _{[Ar]45²3d⁸ nickel 58.69}	29 Cu [Ar]4s ^{13d10} copper 63.55	30 Zn ^{[Ar]42²3d¹⁰ zinc 65.39}	$\underset{\substack{[Ar]4s^{2}3d^{10}4p^{1}\\gallium}{69.72}}{31}$	32 Ge _{[Ar]4s²3d¹⁰4p² germanium 72.58}	33 AS [Ar]4s ² 3d ¹⁰ 4p ³ arsenic 74.92	34 Se [Ar]4s ² 3d ¹⁰ 4p ⁴ selenium 78.96	35 Br ^{[Ar]4s²3d¹⁰4p⁵ bromine 79.90}	36 Kr ^{[Ar]4s²3d¹⁰4p⁶ krypton 83.80}
37 Rb ^[Kn55] rubidium 85.47	38 Sr ^{[Kr]52} strontium 87.62	39 Y [Kr]5\$24d ¹ vitrium 88.91	40 Zr [Kr]5s ² 4d ² zirconium 91.22	41 Nb Krj5s ¹ 4d ⁴ niobium 92.91	42 Mo Krj5s ¹ 4d ⁵ molybdenum 95.94	43 Tc [Kr]5 ² 4d ⁵ technetium (98)	44 Ru [Krj55 ¹ 4d ⁷ ruthenium 101.1	45 Rh [Kr]55 ¹ 4d ⁸ rhodium 102.9	46 Pd ^{[Kr]4d¹⁰ palladium 106.4}	47 Ag [Krj5s ¹ 4d ¹⁰ silver 107.9	48 Cd [Kr]55 ² 4d ¹⁰ cadmium 112.4	49 In ^{[Kr]5s²4d¹⁰5p¹ indium 114.8}	50 Sn ^{[Kr]5s²4d¹⁰5p² tin 118.7}	51 Sb [Kr]5 ² 4d ¹⁰ 5p ³ antimony 121.8	52 Te ^{[Kr]55²4d¹⁰5p⁴ tellurium 127.6}	53 J [Kr]5 ² 4d ¹⁰ 5p ⁵ iodine 126.9	54 Xe [Kr]5 ² 4d ¹⁰ 5p ⁶ xenon 131.3
55 CS [Xef6 ⁴ cesium 132.9	56 Ba ^{[Xe]65² barium 137.3}	57 La* ^{[Xe]63²5d¹ lanthanum 138.9}	${ { Hf}\atop_{{}^{[Xe]6s^24t^{14}5d^2}\\{}^{hafnium}\\{}_{178.5}}}$	73 Ta ^{[Xe]65²41¹⁴50³ tantalum 180.9}	74 W [Xe]6 ² 4f ¹⁴ 5d ⁴ tungsten 183.9	75 Re ^{[Xe]65²4f¹⁴5d⁵ ^{rhenium} 186.2}	76 Os [Xej6\$24f ¹⁴ 5d ⁶ osmium 190.2	77 Ir _{[Xe]65²41¹⁴5d⁷ iridium 190.2}	78 Pt [Xej6: ^{14f145d9} platinum 195.1	79 Au (Xe)65 ¹ 4f ¹⁴ 5d ¹⁰ gold 197.0	80 Hg [Xe]65 ² 4f ¹⁴ 5d ¹⁰ mercury 200.5	81 T1 _{Xe)65²41¹⁴5d¹⁰6p¹ thallium 204.4}	82 Pb _{xej65²4f¹⁴5d¹⁰6p² lead 207.2}	83 B1 _{Xej6241} ⁴⁵ 51 ⁰ 6p ³ bismuth 208.9	84 Po _{[Xe]65²41¹⁴5d¹⁰6p⁴ polonium (209)}	85 At _{Xe)65} 241 ¹⁴ 5d ¹⁰ 6p ⁵ astatine (210)	86 Rn (xe)6 ² 41 ¹⁴ 51 ¹⁰ 5p ⁶ radon (222)
87 Fr Francium (223)	88 Ra ^{[Rn]75} radium (226)	89 Ac~ [Rn]7 ² 6d ¹ actinium (227)	104 Rf IRNJ75 ^{25/14} 8d ² rutherfordium (257)	105 Db ^{[Rn]72²5f¹⁴8d³ dubnium (260)}	106 Sg [Rn]7551 ¹⁴ 6d ⁴ seaborgium (263)	107 Bh [Rn]7 ² 5f ¹⁴ 6d ⁵ bohrium (262)	108 HS [Rn]75 ² 51 ¹⁴ 6d ⁶ hassium (265)	109 Mt _{[Rn]7} 251 ¹⁴ 6d ⁷ meitnerium (266)	110 DS [Rn)7 ⁴ 5f ¹⁴ 6d ⁹ darmstadtium (271)	111 Uuu ₍₂₇₂₎	112 Uub						







'lighter' isotope'heavier' isotope

1 1s ¹ hydrogen 1.008	2A											34	4A	5A	6A	7A	2 He ^{15²} helium 4.003
3 Li _{[He]25} 1 lithium 6.941	4 Be [He]2s ² beryllium 9.012											5 B [He]2s ² 2p ¹ boron 10.81	6 C [He]2 ² 2p ² carbon 12.01	7 N [He]2s ² 2p ³ nitrogen 14.01	8 (Hej2 ² 2p ⁴ oxygen 16.00	9 [He]2 ² 2p ⁵ fluorine 19.00	10 Ne ^{[He]2\$²2p⁶ neon 20.18}
11 Na _{[Nej3s1} sodium 22.99	12 Mg Mg Mej35 magnesium 24.31	3B	4B	5B	6B	7B		—8B -		11B	12B	13 Al ^{[Ne]3\$3p¹ aluminum 26.98}	14 Si ^{[Ne]3\$3p² silicon 28.09}	15 P [Ne]3s ² 3p ³ phosphorus 30.97	16 S [Ne]3 ² 3 ^{p4} sulfur 32.07	17 Cl ^{[Ne]3²3p⁵ chlorine 35:45}	18 Ar [Ne]3s ² 3p ⁶ argon 39.95
19 K _{[Ar]4s¹ potassium 39.10}	20 Ca [Ar]45 ² calcium 40.08	$\underset{\substack{[Ar]4s^23d^1\\scandium\\44.96}}{21}$	22 Ti ^{[Ar]4s²3d²} titanium 47.88	23 V [Ar]4 ² 3d ³ vanadium 50.94	24 Cr [Ar]4s ¹ 3d ⁵ chromium 52.00	25 Mn [Ar]4 ² 3d ⁵ manganese 54.94	26 Fe ^{[Ar]4s²3d⁶ iron 55.85}	27 Co [Ar]45 ² 3d ⁷ cobalt 58.93	28 Ni _{[Ar]45²3d⁸ nickel 58.69}	29 Cu [Ar]4s ¹³ d ¹⁰ copper 63.55	30 Zn ^{[Ar]4s²3d¹⁰ zinc 65.39}	$\underset{\substack{\text{[Ar]4s}^23d}^{31}}{31}\\ \textbf{Ga}\\ \underset{\substack{\text{gallium}\\ 69.72}}{31}$	32 Ge _{[Ar]4s²3d¹⁰4p² germanium 72.58}	33 AS [Ar]4s ² 3d ¹⁰ 4p ³ arsenic 74.92	34 Se [Ar]4s ² 3d ¹⁰ 4p ⁴ selenium 78.96	35 Br [Ar]4s ² 3d ¹⁰ 4p ⁵ bromine 79.90	36 Kr ^{[Ar]4s²3d¹⁰4p⁶ krypton 83.80}
37 Rb ^{[Kr]55[]] rubidium 85.47}	38 Sr strontium 87.62	39 Y ^{Krj52²4d¹} vtfrium 88.91	40 Zr ^{[Kr]5²4d² zirconium 91.22}	41 Nb [Kr]55 ¹ 40 ⁴ niobium 92.91	42 Mo [Krj5s ¹ 4d ⁵ molybdenum 95.94	43 Tc ^{[Kr]5s²4d⁵ tecinnetium (98)}	44 Ru ^{[Kr]55¹4d⁷ ruthenium 101.1}	45 Rh ^{[Kr]55¹4d⁸ rhodium 102.9}	46 Pd ^{Kr]4d¹⁰ palladium 106.4}	47 Ag ^{[Kr]55¹4d¹⁰ silver 107.9}	48 Cd [Kr]55 ² 4d ¹⁰ cadmium 112.4	$\underset{{}^{[Kr]5s^{2}4d^{10}5p^{1}}_{\text{indium}}}{49}_{{}^{[Kr]5s^{2}4d^{10}5p^{1}}_{\text{indium}}}$	${\underset{{}_{{_{{I}}}}}{50}}{50}\atop{{_{{I}}}{sn}}{55}}{{_{{I}}}{sn}}{10}}{{_{{I}}}{sn}}{10}$	51 Sb ^{[Kr]5s²4d¹⁰5p³ antimony 121.8}	52 Te ^{[Kr]5s²4d¹⁰5p⁴ tellurium 127.6}	53 I ^{[Kr]5s²4d¹⁰5p⁵ iodine 126.9}	54 Xe ^{[Kr]5s²4d¹⁰5p⁶} xenon 131.3
55 CS [Xej6s ⁴ cesium 132.9	56 Ba ^{[Xe]6² barium 137.3}	57 La* ^{[Xe]62²51¹ lanthanum 138.9}	72 Hf ^{[Xe]62²4f¹⁴5d² hafnium 178.5}	73 Ta ^{[Xe]6²4¹¹⁴50³ tantalum 180.9}	74 W ^{[Xe]65²4f¹⁴5d⁴ tungsten 183.9}	75 Re ^{[Xe]624f^{145d⁵} thenium 186.2}	76 Os _{[Xe]624f} ¹⁴ 5d ⁶ osmium 190.2	77 Ir _{[Xe]65²4f¹⁴5d⁷ iridium 190.2}	78 Pt ^{[Xe]65¹4f¹⁴5d⁹ platinum 195.1}	79 Au _{[Xe]65¹4f¹⁴5d¹⁰ gold 197.0}	80 Hg [X=j624f ¹⁴ 5d ¹⁰ mercury 200.5	81 Tl _{xej624f} ^{145d106p1} thallium 204.4	82 Pb _{xej6²4f¹⁴5d¹⁰6p² lead 207.2}	83 Bi _{Xej6241} ^{145d106p3} bismuth 208.9	84 Po _{[Xe]6²4f¹⁴5d¹⁰6p⁴ polonium (209)}	85 At xej634f ¹⁴ 5d ¹⁰ 6p ⁵ astatime (210)	86 Rn ^{[Xe]65²41¹⁴5d¹⁰6p⁶ radon (222)}
87 Fr ^{[Rn]7s¹ francium (223)}	88 Ra ^{[Ro]7² radium (226)}	89 Ac~ [Rn]7\$6d ¹ actinium (227)	104 Rf (Rn)7 ² 5 ¹⁴ 6d ² rutherfordium (257)	105 Db ^{[Rn]725f¹⁴6d³ dubnium (260)}	106 Sg [Rn]7 ² 51 ¹⁴ 6d ⁴ seaborgium (263)	107 Bh (Rn)7 2⁵/¹⁴8d⁵ bohrium (262)	108 HS [Rn]75 ² 51 ¹⁴ 6d ⁶ hassium (265)	109 Mt [Rn]7 ² 51 ¹⁴ 6d ⁷ meitnerium (266)	110 DS [Rn)7\$5f ¹⁴ 6d ⁹ darmstadtium (271)	111 Uuu (272)	112 Uub						



1A





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3 L1 _{[He]25} 1 lithium 6.941	4 Be [He]25 ² beryllium 9.012											5 B [He]2s ² 2p ¹ boron 10.81	6 C [He]2s ² 2p ² carbon 12.01	7 N _{[He]2s²2p³ nitrogen 14.01}	8 0 [He]2s ² 2p ⁴ oxygen 16.00	9 [He]2 ² 2p ⁵ fluorine 19.00	10 № _{[He]2²2p⁶ псоп 20.18}
11 Na ^{[Ne]35¹ sodium 22.99}	12 Mg Mg Mej35 magnesium 24.31	3B	4B	5B	6B	7B		—8B -		11B	12B	13 Al _{[Ne]3\$23p1} aluminum 26.98	14 Si ^{[Ne]3\$3p² silicon 28.09}	15 P [Ne]3 ² 3p ³ phosphorus 30.97	16 S [Ne]3 ² 3p ⁴ sulfur 32.07	17 Cl _{[Ne]3²3p⁵ chlorine 35-45}	18 Ar ^{[Ne]3s²3p⁶ argon 39.95}
19 K [Ar]4s ¹ potassium 39.10	20 Ca [Ar]45 ² calcium 40.08	21 Sc [Ar]4s ² 3d ¹ scandium 44.96	22 Ti [Ar]4s ² 3d ² titanium 47.88	23 V [Ar]45 ² 3d ³ vanadium 50.94	24 Cr [Ar]45 ¹ 3d ⁵ chromium 52.00	25 Mn [Ar]4s ² 3d ⁵ manganese 54.94	26 Fe (A1/4 s ² 3d ⁶ iron 55.85	27 Co [Ar]4 ² 3d ⁷ cobalt 58.93	28 Ni ^{[Ar]4s²3d⁸ nickel 58.69}	29 Cu [Ar]4s ^{13d¹⁰ copper 63.55}	30 Zn [Ar]4 ² 3d ¹⁰ zinc 65.39	$\underset{\substack{[Ar]4s^{2}3d^{10}4p^{1}\\gallium}{69.72}}{31}$	32 Ge [Ar]4 ² 3d ¹⁰ 4p ² germanium 72.58	33 As ^{[Ar]45²3d¹⁰4p³ arsenic 74.92}	34 Se [Ar]4 ² 3d ¹⁰ 4p ⁴ selenium 78.96	35 Br ^{[Ar]42²3d¹⁰4p⁵ bromine 79.90}	36 Kr ^{[Ar]4s²3d¹⁰4p⁶ krypton 83.80}
37 Rb ^[Kn55] rubidium 85.47	38 Sr strontum 87.62	39 Y ^{[Kr]5,24d¹ vttrium 88.91}	40 Zr [Kr]5s ² 4d ² zirconium 91.22	41 Nb ^{[Kr]5s¹4d⁴ niobium 92.91}	42 Mo Krj5s ¹ 4d ⁵ molybdenum 95.94	43 Tc [Kr]5\$445 technetium (98)	44 Ru [Kr]55 ¹ 4d ⁷ ruthenium 101.1	45 Rh [Kr]5s ¹ 4d ⁸ rhodium 102.9	46 Pd ^{[Kr]4d¹⁰ palladium 106.4}	47 Ag [Krj5s ¹ 4d ¹⁰ silver 107.9	48 Cd [Kr]5 ⁶ 24d ¹⁰ cadmium 112.4	$\begin{matrix} 49\\ In\\ _{[Kr]5e^24d^{10}5p^1\\ indium\\ 114.8}\end{matrix}$	50 Sn ^{[Kr]5s²4d¹⁰5p² in 118.7}	51 Sb [Kr]5 ² ² 4d ¹⁰ 5p ³ antimony 121.8	52 Te [Kr]5 ² 4d ¹⁰ 5 ⁹ 4 tellurium 127.6	53 I [Kr]5 ² 4d ¹⁰ 5p ⁵ iodine 126.9	54 Xe [Kr]5 ² 4d ¹⁰ 5p ⁶ xenon 131.3
55 CS [Xe]6 ⁵¹ cesium 132.9	56 Ba _{[Xe]6} ² barium 137.3	57 La* ^{[Xe]625d¹ lanthanum 138.9}	72 Hf ^{[Xe]6²4¹¹⁴5d² hafnium 178.5}	73 Ta _{[Xe]05²41¹⁴5d³ tantalum 180.9}	74 W [Xej6 ² 4f ¹⁴ 5d ⁴ tungsten 183.9	75 Re ^{[Xe]62³4f¹⁴5d⁵ rhenium 186.2}	76 Os ^{[Xe]6²4f¹⁴5d⁶ osmium 190.2}	77 Ir _{[Xe]65²41¹⁴5d⁷ iridium 190.2}	78 Pt ^{[Xe]6s¹4f¹⁴5d⁹ platinum 195.1}	$\begin{matrix} 79 \\ Au \\ {}_{[Xe]65^{1}4f^{14}5d^{10}} \\ {}_{gold} \\ 197.0 \end{matrix}$	80 Hg [Xe]6s ² 4f ¹⁴ 5d ¹⁰ mercury 200.5	81 1 _{Xe)624f} ¹⁴ 5d ^{106p1} thallium 204.4	82 Pb _{xej65²4f¹⁴5d¹⁰6p² lead 207.2}	83 Bi _{Xef6241} ⁴⁵ 51 ¹⁰ 6p ³ bismuth 208.9	84 Po ^{[Xe]624f¹⁴5d¹⁰6p⁴ polonium (209)}	85 At _{X=162} ^{241¹⁴5d¹⁰6p⁵ astatine (210)}	86 Rn _{[Xe]65²41¹⁴5d¹⁰6p⁶ radon (222)}
87 Fr ^{[Rn]7s¹ francium (223)}	88 Ra ^{[Ro]7² radium (226)}	89 Ac~ [Rn]7 ^s 6d ¹ actinium (227)	104 Rf (Rn]7 ² 5 ⁶¹⁴ 8d ² rutherfordium (257)	105 Db [Fn]7551 ¹⁴ 6d ³ dubnium (260)	106 Sg [Rn]7 ² 5f ¹⁴ 6d ⁴ seaborgium (263)	107 Bh (Rn)7 ² 5f ¹⁴ 6d ⁵ bohrium (262)	108 HS [Rn]75 ² 51 ¹⁴ 6d ⁶ hassium (265)	109 Mt [Rn]7\$51 ¹⁴ 6d ⁷ meitnerium (266)	110 Ds (Rn)7 ⁴ 5f ¹⁴ 6d ⁹ darmstadtium (271)	111 Uuu (272)	112 Uub						



bond breaking



IA																	
1 1s ¹ hydrogen																	He
1.008	2A											3A	4A	5A	6A	7A	4.003
3 L1 _{[He]2} s1 lithium 6.941	4 Be											5 B [He]2s ² 2p ¹ boron 10.81	6 C [He]2 ² 2p ² carbon	7 N [He]2s ² 2p ³ nitrogen	8 0 [He]2 ² 2p ⁴ oxygen 16.00	9 [He]2s ² 2p ⁵ fluorine	10 Ne (He)25 ² 2p ⁶ neon 20.18
	12											12	1/	15	16	17	18
Na	Μσ												Śi	D	S ID	Ċ	
I Ta	IVIS											INe13s ² 3p ¹	INe13s ² 3p ²	INe13s ² 3p ³	[Ne13s ² 3p ⁴	INe13s ² 3p ⁵	INe13s ² 3p ⁶
sodium	magnesium 2/1.31	3B	4B	5B	6B	7B		<u> </u>		11B	12B	aluminum 26.98	silicon 28.00	phosphorus	sulfur	chlorine 35.45	argon
19	20	21	22	22	21	25	26	27	28	20	30	31	32	33	34	35	36
ĬĬ			Ťi	τĭ	Ćr	М'n	É	\hat{C}_{α}	NI:		7 n	Č	Ğ	Ăc	Š	Ř.	Ŭ.
[Ar]4s ¹	Larias ²	IAri4s ² 3d ¹	[Ar14c ² 3d ²	IAr14s ² 3d ³	[Arl4s ¹ 3d ⁵	IVIII IArlac ² 3d ⁵	1°C	LA-14+22+47				Ua	1041221104-2	1 LO 14r22rd104rd3	14rl4r23rd104rd	10+14+22+104+5	IAr14r22rd104r
potassium 39.10	calcium	scandium	titanium	vanadium	chromium	manganese 54.04	iron 55.85	cobalt	nickel	copper 62.55	zinc 65.20	gallium 60.72	germanium 72.58	arsenic 74.92	selenium 78.96	bromine 79.90	krypton 83.80
37	38	30	40	41	42	43		45	46	47	48	49	50	51	52	53	54
Řh	Šr	ĬŸ	7r	Nh	M	Tc	Rii	Rĥ	Pd	Aσ	C Å	In	Šn	Šh	Ťe	ĬĬ	Хе
IKr15s ¹	1Kr15s ²	IKri5s ² 4d ¹	IKr15s ² 4d ²	[Kr]5s ¹ 4d ⁴	[Kr]5s ¹ 4d ⁵	[Kr15s ² 4d ⁵	[Kr]5s ¹ 4d ⁷	[Kr]5s ¹ 4d ⁸	[Kr]4d ¹⁰	Kr]5s ¹ 4d ¹⁰	[Kr]5s ² 4d ¹⁰	[Kr]5 ² 4d ¹⁰ 5p ¹	[Kr]5s ² 4d ¹⁰ 5p ²	[Kr]5s ² 4d ¹⁰ 5p ³	[Kr]5s ² 4d ¹⁰ 5p ⁴	[Kr]5s ² 4d ¹⁰ 5p ⁵	[Kr]5s ² 4d ¹⁰ 5p
rubidium 85.47	strontium 87.62	vttrium 88.91	zirconium 91.22	niobium 92.91	mòlýbdenum 95-94	technetium (98)	rùthenium 101.1	rhódium 102.9	palladium 106.4	silver 107.9	cadmium 112.4	indium 114.8	tin 118.7	antimony 121.8	tellurium 127.6	iodine 126.9	xenon 131.3
55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86
Cs	Ba	La*	Hf	Ta	Ŵ	Re	Os	Ir	Pt	Au	Ĥσ	T1	Ph	Bi	Po	At	Rn
[Xe]6s ¹	[Xe]6 s²	[Xe]6 ² 5d ¹	[Xe]6 ² 4f ¹⁴ 5d ²	[Xe]6 ² 4f ¹⁴ 5d ³	[Xe]6s ² 4f ¹⁴ 5d ⁴	[Xe]6s ² 4f ¹⁴ 5d ⁵	[Xe]6 ² 4f ¹⁴ 5d ⁶	[Xe]6 ² 4f ¹⁴ 5d ⁷	[Xe]6s ¹ 4f ¹⁴ 5d ⁹	[Xe]6s ¹ 4f ¹⁴ 5d ¹⁰	[Xe]6 ² 4f ¹⁴ 5d ¹⁰	Xe]6 ² 4f ¹⁴ 5d ¹⁰ 6p ¹	Xe]6s ² 4f ¹⁴ 5d ¹⁰ 6p ²	Xe]6 ² 4f ¹⁴ 5d ¹⁰ 6p ³	[Xe]6s ² 4f ¹⁴ 5d ¹⁰ 6p ⁴	Xe]6s ² 4f ¹⁴ 5d ¹⁰ 6p ⁵	[Xe]6 ² 4f ¹⁴ 5d ¹⁰ 6p
132.9	137.3	lanthanum 138.9	hafnrum 178.5	tantalum 180.9	183.9	rhenium 186.2	osmium 190.2	190.2	platinum 195.1	gold 197.0	mercury 200.5	thallium 204.4	lead 207.2	bismuth 208.9	polonium (209)	astatine (210)	radon (222)
87	88	.89	104	105	106	107	108	109	110	111	112						
Fr_	Ra_	Ac~		Db_	Sg_	Bh	Hs_	Mt	Ds_	Uuu	Uub						
[Rn]7s ¹ francium	[Rn]7 2	[Rn]7 \$ 6d ¹	[Rn]7 s 25f ¹⁴ 6d ²	[Rn]7\$25f ¹⁴ 6d ³	[Rn]7551146d4	[Rn]7s ² 5f ¹⁴ 6d ⁵	[Rn]7\$25f ¹⁴ 6d ⁶	[Rn]7s ² 5f ¹⁴ 6d ⁷	[Rn]7s ¹ 5f ¹⁴ 6d ⁹								
(223)	(226)	(227)	(257)	(260)	(263)	(262)	(265)	(266)	(271)	(₂₇₂)	(₂₇₇)						







IA																	
1 1s ¹ hydrogen 1.008	2A											3A	4A	5A	6A	7A	2 He ^{1s²} helium 4.003
3 Li ^{[He]2s¹ lithium 6.941}	4 Be [He]2 ² beryllium 9.012											5 B [He]2\$2p ¹ boron 10.81	6 C [He]2 ² 2p ² carbon 12.01	7 N _{[He]2s²2p³ nitrogen 14.01}	8 0 [He]2s ² 2p ⁴ oxygen 16.00	9 F [He]2 <i>s</i> ² 2p ⁵ fluorine 19.00	10 Ne _{[Hej2s²2p⁶ neon 20.18}
11 Na ^{[Ne]35¹ sodium 22.99}	12 Mg ^{Nej35} magnesium 24.31	3B	4B	5B	6B	7B		—		11B	12B	13 Al ^{[Ne]32²3p¹ aluminum 26.98}	14 Si ^{[Ne]3\$²3p² silicon 28.09}	15 P [Ne]3s ² 3p ³ phosphorus 30.97	16 S [Ne]3 ² 3p ⁴ sulfur 32.07	17 C _{[Ne]32²3p⁵ chlorine 35:45}	18 Ar _{[Ne]3s²3p⁶ argon 39.95}
19 K [Ar]45 ¹ potassium 39.10	$\begin{array}{c} 20\\ \textbf{Ca}\\ _{\text{[Ar]4s}^2\\ \text{calcium}\\ \textbf{40.08} \end{array}}$	21 Sc [Ar]4s ² 3d ¹ scandium 44.96	22 Ti [Ar]45 ² 3d ² titanium 47.88	23 V [Ar]4s ² 3d ³ vanadium 50.94	24 Cr [Ar]4s ¹ 3d ⁵ chromium 52.00	25 Mn [Ar]4s ² 3d ⁵ manganese 54.94	26 Fe (Ar/4s ^{23d⁶} iron 55.85	27 Co [Ar]4 ² 3d ⁷ cobalt 58.93	28 Ni _{[Ar]45²3d⁸ nickel 58.69}	29 Cu [Ar]4s ^{13d10} copper 63.55	30 Zn ^{[Ar]42²3d¹⁰ zinc 65.39}	$\underset{\substack{\text{[Ar]4s}^{2}3d^{10}4p^{1}\\gallium}{69.72}}{31}$	32 Ge [Ar]4 ² 3d ¹⁰ 4p ² germanium 72.58	33 AS [Ar]4s ² 3d ¹⁰ 4p ³ arsenic 74.92	34 Se [Ar]4s ² 3d ¹⁰ 4p ⁴ selenium 78.96	35 BT [Ar]4s ² 3d ¹⁰ 4p ⁵ bromine 79.90	36 Kr [Ar]4s ² 3d ¹⁰ 4p ⁶ krypton 83.80
37 Rb ^{K1551} rubidium 85.47	38 Sr strontium 87.62	39 Y Vitrium 88.91	40 Zr [Kr]5s ² 4d ² zirconium 91.22	41 Nb ^{[Kr]55¹4d⁴} niobium 92.91	42 Mo Krj55 ¹ 4d ⁵ molybdenum 95.94	43 Tc [Kr]5s ² 4d ⁵ technetium (98)	44 Ru [Kr]55 ¹ 4d ⁷ ruthenium 101.1	45 Rh ^{[Kr]5s¹4d⁸ rhodium 102.9}	46 Pd ^{[Kr]4d¹⁰ palladium 106.4}	47 Ag ^{[Kr]55¹4d¹⁰ silver 107.9}	48 Cd _{[K155²4d¹⁰ cadmium 112.4}	$\underset{\stackrel{[Kr]5s^24d^{10}5p^1}{\text{indium}}}{\overset{[Kr]5s^24d^{10}5p^1}{\text{indium}}}$	50 Sn ^{[Kr]55²4d¹⁰5p²} tin 118.7	51 Sb ^{[Kr]55²4d¹⁰5p³ antimony 121.8}	52 Te ^{[K1]55²4d¹⁰5p⁴ tellurium 127.6}	53 I ^{[Kr]52²4d¹⁰5p⁵ iodine 126.9}	54 Xe ^{[Kr]5s²4d¹⁰5p⁶ xenon 131.3}
55 Cs [Xe]65 ¹ cesium 132.9	56 Ba _{[Xe]65} ² barium 137.3	57 La* ^{[Xe]63²5d¹ lanthanum 138.9}	72 Hf ^{[Xe]6²4¹⁴5d² hafnium 178.5}	73 Ta ^{[Xe]65²41¹⁴50³ tantalum 180.9}	74 W [Xej6 ² 4f ¹⁴ 5d ⁴ tungsten 183.9	75 Re ^{[Xe]624f^{145d5} rhenium 186.2}	76 OS ^{[Xe]6²41¹⁴5d⁶ osmium 190.2}	77 Ir _{[Xe]65²41¹⁴5d⁷ iridium 190.2}	78 Pt ^{[Xe]65¹4f¹⁴5d⁹ platinum 195.1}	79 Au ^{[Xe]65¹4f¹⁴5d¹⁰ gold 197.0}	80 Hg [Xe]65 ² 4f ¹⁴ 5d ¹⁰ mercury 200.5	81 1 _{Xe)65²41¹⁴5d¹⁰6p¹ thallium 204.4}	82 Pb _{Xe)65241} ^{145d106p2} lead 207.2	83 Bi _{Xej6} 241 ¹⁴ 5d ¹⁰ 6p ³ bismuth 208.9	84 Po _{[Xe]6²41¹⁴5d¹⁰6p⁴ polonium (209)}	85 At _{Xe]65²41¹⁴5d¹⁰6p⁵ astatine (210)}	86 Rn _{[Xej6541¹⁴5d¹⁰6p radon (222)}
87 Fr [Rn]75 ¹ francium (223)	88 Ra ^{[Rn]75} radium (226)	89 Ac~ [Rn]75 ² 6d ¹ actinium (227)	104 Rf [Fn]7 ² 5f ¹⁴ 6d ² nutherfordium (257)	105 Db ^{[Rn]75²5f¹⁴6d³ dubnium (260)}	106 Sg [Rn]7551 ⁴ 6d ⁴ seaborgium (263)	107 Bh [Rn]7 ^{25f14} 6d ⁵ bohrium (262)	108 HS [Rn]7 ² 5f ¹⁴ 6d ⁶ hassium (265)	109 Mt [Rn]7\$51 ^{146d7} meitnerium (266)	$\underset{(271)}{\overset{110}{\text{Ds}}}$	${\overset{111}{Uuu}}_{{}_{^{(272)}}}$	112 Uub						

















Carbonate δ^{13} C variability through time





what exactly does it (temporal changes in $\delta^{13}C$) mean?

Re-partitioning of carbon within surficial reservoirs?



Re-partitioning of carbon **between** surficial reservoirs (cf. LGM)?



Injection (or removal) of isotopically light carbon?



Change in C_{org} and/or carbonate weathering and/or burial (at fixed carbonate and/or C_{org} weathering / burial)?



Carbonate diagenesis and loss of primary δ^{13} C signal, either marine sedimentary or subaerial.



what exactly does it (temporal changes in δ^{13} C) mean? Re-partitioning of carbon within surficial reservoirs?



what exactly does it (temporal changes in δ^{13} C) mean? Re-partitioning of carbon within surficial reservoirs?

Re-partitioning of carbon **between** surficial reservoirs (cf. LGM)?









Contours of carbon release vs. source isotopic signature for a global -4‰ carbon isotopic excursion. Contours differ according to the initial mean global δ^{13} C.



what exactly does it (temporal changes in δ^{13} C) mean?

Re-partitioning of carbon within surficial reservoirs?



Re-partitioning of carbon **between** surficial reservoirs (cf. LGM)?



Injection (or removal) of isotopically light carbon?



Change in C_{org} and/or carbonate weathering and/or burial (at fixed carbonate and/or C_{org} weathering / burial)?

One can write (*Kump and Arthur* [1999], *Chem. Geol.*):

$$F_{corg} / (F_{corg} + F_{caco3}) = \sum_{ratio}^{C \text{ burial ratio}} (\delta^{13}C_{obs} - \delta^{13}C_{input}) / (\delta^{13}C_{caco3} - \delta^{13}C_{corg})$$

$$M_{arbonate} \delta^{13}C_{-5.0} \qquad 25.0$$

observed (recorded) carbonate δ^{13} C -5



what exactly does it (temporal changes in $\delta^{13}C$) mean?

Re-partitioning of carbon within surficial reservoirs?



Re-partitioning of carbon between surficial reservoirs (cf. LGM)?



Injection (or removal) of isotopically light carbon?



Change in C_{org} and/or carbonate weathering and/or burial (at fixed carbonate and/or C_{org} weathering / burial)?



Carbonate δ^{13} C variability through time

8% $CO_{2(g)}$ $CO_{2(aq)}$ H^+ H +10% -3% H^+ H_2O 0 HCO₃ CO_3^2 H₂CO₃ 0% $CaCO_{3(s)}$ pH-driven re-partitioning of the Са Ca where the isotopic composition of Ca the mean surficial reservoir is held

dapted from: Barker and Ridgwell [2012]





























O₂

OM

CH₄



climate warming



Temperature



Westbrook et al. [2009]

Forcing

Orbital pacing of methane hydrate destabilisation during the Palaeogene?

Forcing

Orbital pacing of methane hydrate destabilisation during the Palaeogene?

Forcing

Orbital pacing of methane hydrate destabilisation during the Palaeogene?

Climate fedback with methane hydrates



Climate fedback with methane hydrates















time





Contours of carbon release vs. source isotopic signature for a global -4‰ carbon isotopic excursion. Contours differ according to the initial mean global δ^{13} C.

Ridgwell and Arndt [2014]





time









time



deep time shallow time atmospheric CO₂ concentration (ppm) 380 6.6 -6.8 370 atmospheric δ^{13} CO₂ (‰) -7.0 360 -7.2 350 release in 10 yr -7.4 340 330 -7.6 release in 1 yr 320 -7.8 310--8.0 300 -8.2 290 -8.4 280 - -8.6 1900 1920 1940 1960 2000 1980 time





























1 1s ¹ hydrogen 1.008	2A											34	4A	5A	6A	74	2 He ^{15²} helium 4.003
Li	Be											5 B	6 C	7 N	Ö	9 F	10 Ne
ithium 6.941	beryllium 9.012											[He]29 ⁻² p ⁺ boron 10.81	[He]2 5²2p² carbon 12.01	[He]2s ² 2p ³ nitrogen 14.01	[He]25 ² 2p* oxygen 16.00	[He]2s ² 2p ³ fluorine 19.00	[He]2s ² 2p ⁰ ncon 20.18
11 Na _{[Ne]35} ¹ sodium 22.99	12 Mg ^{[Ne]35} magnesium 24.31	3B	4B	5B	6B	7B		— 8B -		11B	12B	13 Al _{[Ne]3s²3p¹ aluminum 26.98}	14 Si ^{[Ne]3s²3p² silicon 28.09}	15 P [Ne]3s ² 3p ³ phosphorus 30.97	16 S [Ne]3 ² 3p ⁴ sulfur 32.07	17 Cl [Ne]3 ² 3p ⁵ chlorine 35-45	18 A 17 _{[Ne]3s²3p⁶ argon 39.95}
19 K	20 Ca	21 Sc	22 Ti	23 V	Cr	²⁵ Mn	26 Fe	27 Co	28 Ni	29 Cu	³⁰ Zn	³¹ Ga	Ge 32	33 As	34 Se	35 Br	36 Kr
[Ar]4s' potassium 39.10	[Ar]4 s² calcium 40.08	[Ar]4 s² 3d ¹ scandium 44.96	[Ar]4 s²3d² titanium 47.88	[Ar]4 s² 3d ³ vanadium 50.94	[Ar]4s ¹ 3d ⁵ chromium 52.00	[Ar]4s ² 3d ⁵ manganese 54.94	[Ar]4s ² 3d ⁶ iron 55.85	[Ar]4s ² 3d ⁷ cobalt 58.93	[Ar]4s ² 3d ⁸ nickel 58.69	[Ar]4s ¹ 3d ¹⁰ copper 63.55	[Ar]4s ² 3d ¹⁰ zinc 65.39	[Ar]4s ² 3d ¹⁰ 4p ¹ gallium 69.72	[Ar]4s ² 3d ¹⁰ 4p ² germanium 72.58	[Ar]4s ² 3d ¹⁰ 4p ³ arsenic 74.92	[Ar]4s ² 3d ¹⁰ 4p ⁴ selenium 78.96	[Ar]4s ² 3d ¹⁰ 4p ⁵ bromine 79.90	[Ar]4s ² 3d ¹⁰ 4p ⁶ krypton 83.80
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	A7 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
[Kr]5s ¹ rubidium 85.47	[Kr]5 5² strontium 87.62	[Kr]5 5²4d¹ yttrium 88.91	[Kr]5s ² 4d ² zirconium 91.22	[Kr]5s ¹ 4d ⁴ niobium 92.91	[Kr]5s ¹ 4d ⁵ molybdenum 95-94	[Kr]5s ² 4d ⁵ technetium (98)	[Kr]5s ¹ 4d ⁷ ruthenium 101.1	[Kr]5s ¹ 4d ⁸ rhodium 102.9	[Kr]4d ¹⁰ palladium 106.4	[Kr]5s ¹ 4d ¹⁰ silver 107.9	[Kr]55 ² 4d ¹⁰ cadmium 112.4	[Kr]5 5²4 d ¹⁰ 5p ¹ indium 114.8	[Kr]5s ² 4d ¹⁰ 5p ² tin 118.7	[Kr]5s ² 4d ¹⁰ 5p ³ antimony 121.8	[Kr]5s ² 4d ¹⁰ 5p ⁴ tellurium 127.6	[Kr]55 ² 4d ¹⁰ 5p ⁵ iodine 126.9	[Kr]5s ² 4d ¹⁰ 5p ⁶ xenon 131.3
Cs	56 Ba	57 La*	72 Hf	73 Ta	74 W	75 Re	76 Os	Ir	78 Pt	79 Au	80 H g	81 T 1	⁸² Pb	83 Bi	Po	85 At	86 Rn
[Xej65 ¹ cesium 132.9	[Xe]6 5² barium 137.3	[Xe]6 s²5d¹ lanthanum 138.9	[Xe]65 ² 4f ¹⁴ 5d ² hafnium 178.5	[Xe]6 ² 4f ¹⁴ 5d ³ tantalum 180.9	[Xe]6s ² 4f ¹⁴ 5d ⁴ tungsten 183.9	[Xe]6s ² 4f ¹⁴ 5d ⁵ rhenium 186.2	[Xe]6 ² 4f ¹⁴ 5d ⁶ osmium 190.2	[Xe]6 ² 4f ¹⁴ 5d ⁷ iridium 190.2	[Xe]6s ¹ 4f ¹⁴ 5d ⁹ platinum 195.1	[Xe]6s ¹ 4f ¹⁴ 5d ¹⁰ gold 197.0	[Xe]6 ² 4f ¹⁴ 5d ¹⁰ mercury 200.5	Xej6s ² 4f ¹⁴ 5d ¹⁰ 6p ¹ thallium 204.4	Xe]6s ² 4f ¹⁴ 5d ¹⁰ 6p ² lead 207.2	Xej6 ² 4f ¹⁴ 5d ¹⁰ 6p ³ bismuth 208.9	(Xe]6 ² 4f ¹⁴ 5d ¹⁰ 6p ⁴ polonium (209)	[Xe]6s ² 4f ¹⁴ 5d ¹⁰ 6p ⁵ astatine (210)	(Xe)6s ² 4f ¹⁴ 5d ¹⁰ 6p ⁶ radon (222)
87 Fr	88 Ra _	89 Ac~	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Uuu	112 Uub						
[Rn]75 ¹ francium (223)	[Rn]7 s² radium (226)	[Rn]7\$ ² 6d ¹ actinium (227)	[Rn]7 ² 5f ¹⁴ 6d ² nutherfordium (257)	[Rn]7 \$ 5f ¹⁴ 6d ³ dubnium (260)	[Rn]7 ² 5f ¹⁴ 6d ⁴ seaborgium (263)	[Rn]7 \$ 5f ¹⁴ 6d ⁵ bohrium (262)	[Rn]7 ² 5f ¹⁴ 6d ⁶ hassium (265)	[Rn]7 ² 5f ¹⁴ 6d ⁷ meitnerium (266)	[Rn}7\$ ¹ 5f ¹⁴ 6d ⁹ darmstadtium (271)	(272)	(277)						







































Time since PETM onset (ka)









Atm. pCO₂ (ppm)

sur. pH (pH_(sws))

4000

3000

2000

1000

7.8

7.6

7.4

7.2

CaCO₃





Total carbon release (PgC)





Conclusions

10,000-12,000 PgC was emitted over the PETM as a whole, with a mean isotopic signature of -11 to -17 per mil. This is largely independent of the assumed onset time-scale.

This can be explained entirely by volcanism + volcanic-related processes (e.g. thermogenic methane), or volcanism in combination with sufficial carbon cycle feedbacks.

A 'perfect' record could be assimilated in models to derive a time-resolved reconstruction of carbon emissions, and their specific sources.









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Osmium isotope records










PETM recovery characterized by long-lasting shift to radiogenic Os. Consistent with enhanced granitic weathering (silicate weathering feedback).

(Also, expulsion of fluids form organic rich sediments.)

Strong transient decline in ^{187/188}Os. Enhanced unradiogenic input from volcanism. (Also, extraterrestrial ...)

Dickson et al. [2015] (Palaeogeography, Palaeoclimatology, Palaeoecology **438**) (also see: Wieczorek et al. [2013] (GCA **119**))





60

120

180

0

-180

-120

-60









-

☆

180



L

р





1209 ☆

180

Sensitivity of total carbon release to onset time-scale



Assumed excursion on-set: 100 - 1,000 yr



Sensitivity of total carbon release to onset time-scale



Assumed excursion on-set: 2,000 - 20,000 yr

