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

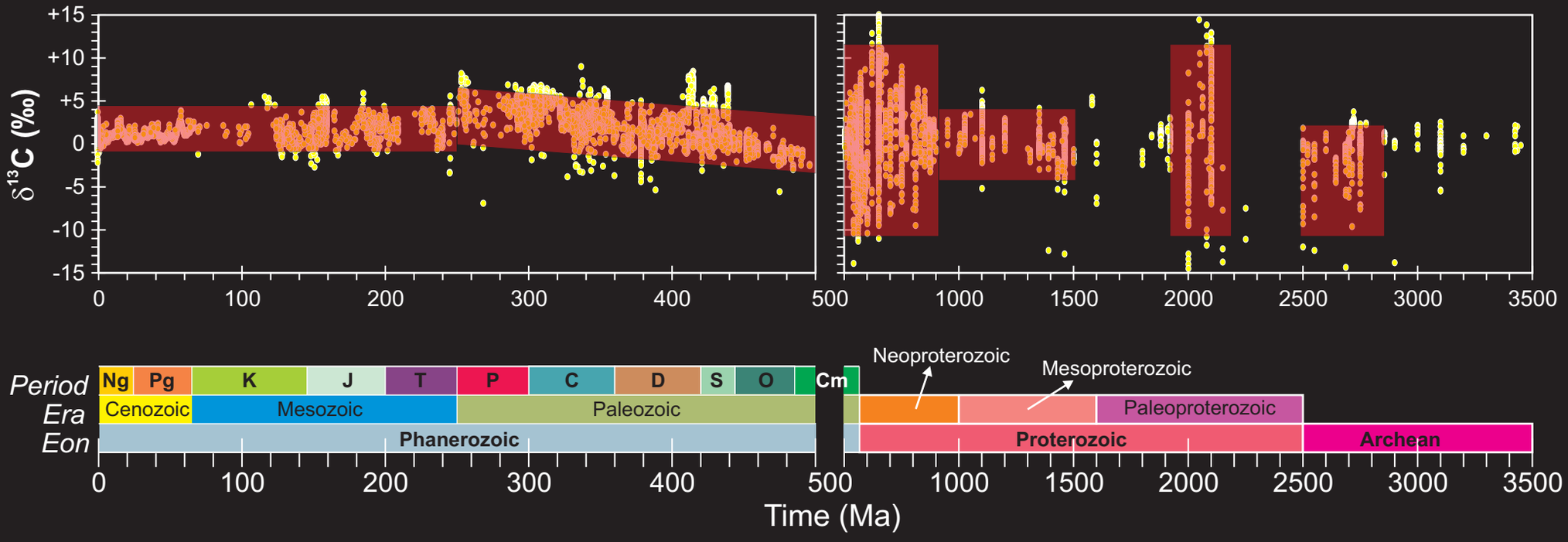
(and some other thoughts on the meaning of carbon isotope changes in paleoclimate records)

Andy Ridgwell

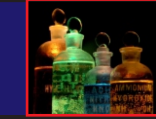

vs.

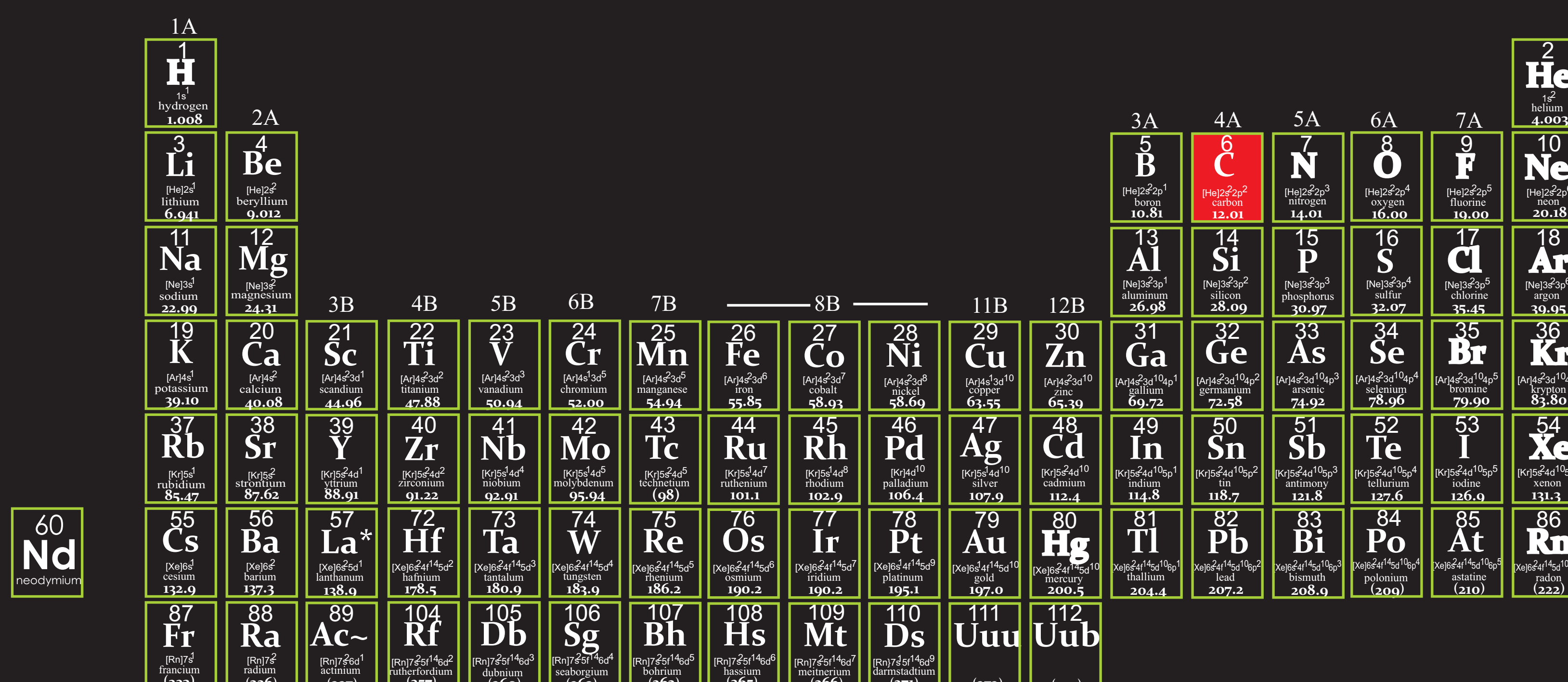

Carbon isotopes as a tracer of ... what?

Ridgwell and Arndt [2014]



Carbon isotopes as a tracer of ... what?





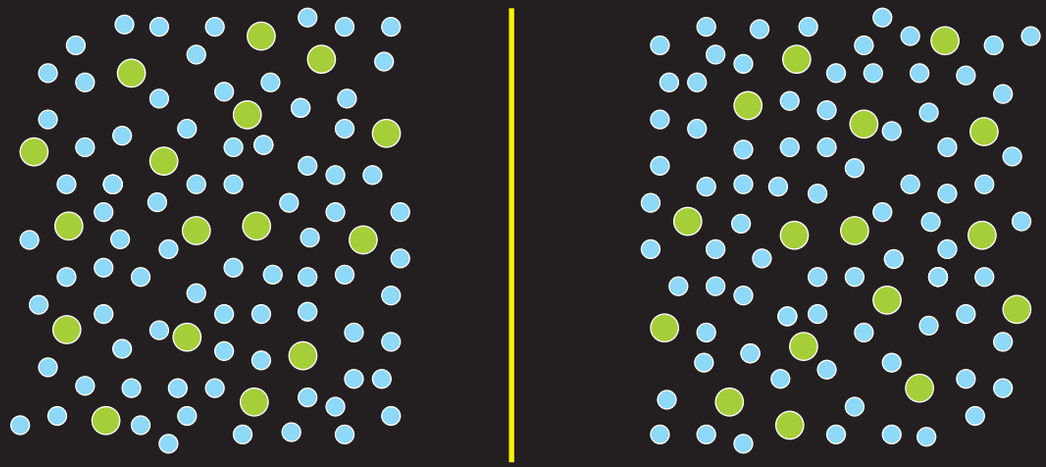
Carbon isotopes as a tracer of ... what?

abundance ratio(sample):
$R_{Sample} = n_{heavy}/n_{light}$

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

$\delta(sample) = (R_{Sample}/R_{Stand.} - 1) \times 1000$

- 'lighter' isotope
- 'heavier' isotope



1A																	2A
1 H hydrogen 1.008																	2 He helium 4.003
3 Li lithium 6.941	4 Be beryllium 9.012											5 B boron 10.81	6 C carbon 12.01	7 N nitrogen 14.01	8 O oxygen 16.00	9 F fluorine 19.00	10 Ne neon 20.18
11 Na sodium 22.99	12 Mg magnesium 24.31	3B	4B	5B	6B	7B	8B	8B	8B	11B	12B	13 Al aluminum 26.98	14 Si silicon 28.09	15 P phosphorus 30.97	16 S sulfur 32.07	17 Cl chlorine 35.45	18 Ar argon 39.95
19 K potassium 39.10	20 Ca calcium 40.08	21 Sc scandium 44.96	22 Ti titanium 47.88	23 V vanadium 50.94	24 Cr chromium 52.00	25 Mn manganese 54.94	26 Fe iron 55.85	27 Co cobalt 58.93	28 Ni nickel 58.69	29 Cu copper 63.55	30 Zn zinc 65.39	31 Ga gallium 69.72	32 Ge germanium 72.58	33 As arsenic 74.92	34 Se selenium 78.96	35 Br bromine 79.90	36 Kr krypton 83.80
37 Rb rubidium 85.47	38 Sr strontium 87.62	39 Y yttrium 88.91	40 Zr zirconium 91.22	41 Nb niobium 92.91	42 Mo molybdenum 95.94	43 Tc technetium (98)	44 Ru ruthenium 101.1	45 Rh rhodium 102.9	46 Pd palladium 106.4	47 Ag silver 107.9	48 Cd cadmium 112.4	49 In indium 114.8	50 Sn tin 118.7	51 Sb antimony 121.8	52 Te tellurium 127.6	53 I iodine 126.9	54 Xe xenon 131.3
55 Cs cesium 132.9	56 Ba barium 137.3	57 La* lanthanum 138.9	72 Hf hafnium 178.5	73 Ta tantalum 180.9	74 W tungsten 183.9	75 Re rhenium 186.2	76 Os osmium 190.2	77 Ir iridium 190.2	78 Pt platinum 195.1	79 Au gold 197.0	80 Hg mercury 200.5	81 Tl thallium 204.4	82 Pb lead 207.2	83 Bi bismuth 208.9	84 Po polonium (209)	85 At astatine (210)	86 Rn radon (222)
87 Fr francium (223)	88 Ra radium (226)	89 Ac~ actinium (227)	104 Rf rutherfordium (257)	105 Db dubnium (260)	106 Sg seaborgium (263)	107 Bh bohrium (262)	108 Hs hassium (265)	109 Mt meitnerium (266)	110 Ds darmstadium (271)	111 Uuu (272)	112 Uub (277)						

60 Nd neodymium

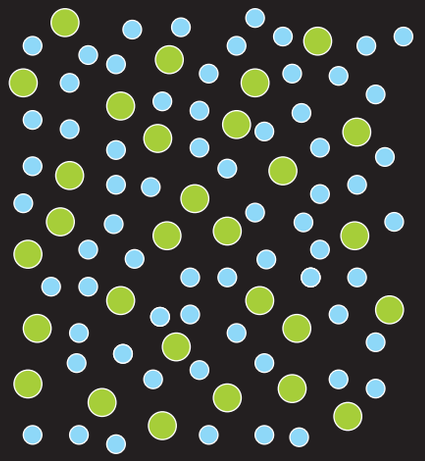
Carbon isotopes as a tracer of ... what?

$R_{Sample} > R_{Stand.}$

$\delta(sample) = (R_{Sample}/R_{Stand.} - 1) \times 1000$

=> δ(sample) is POSITIVE

('isotopically enriched')

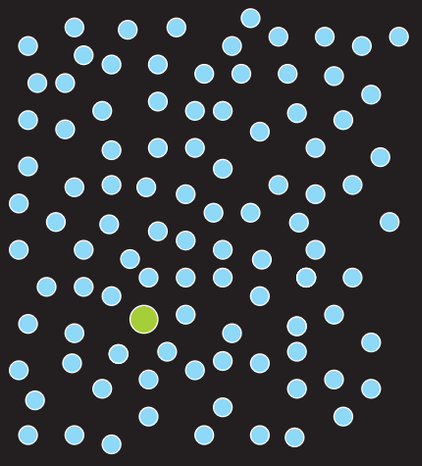


$R_{Sample} > R_{Stand.}$

$\delta(sample) = (R_{Sample}/R_{Stand.} - 1) \times 1000$

=> δ(sample) is NEGATIVE

('isotopically depleted')



- 'lighter' isotope
- 'heavier' isotope

1A																	2 He $1s^2$ helium 4.003
1 H $1s^1$ hydrogen 1.008	2A											3A	4A	5A	6A	7A	10 Ne $[He]2s^22p^6$ neon 20.18
3 Li $[He]2s^1$ lithium 6.941	4 Be $[He]2s^2$ beryllium 9.012											5 B $[He]2s^22p^1$ boron 10.81	6 C $[He]2s^22p^2$ carbon 12.01	7 N $[He]2s^22p^3$ nitrogen 14.01	8 O $[He]2s^22p^4$ oxygen 16.00	9 F $[He]2s^22p^5$ fluorine 19.00	18 Ar $[Ne]3s^23p^6$ argon 39.95
11 Na $[Ne]3s^1$ sodium 22.99	12 Mg $[Ne]3s^2$ magnesium 24.31	3B	4B	5B	6B	7B	8B	8B	8B	11B	12B	13 Al $[Ne]3s^23p^1$ aluminum 26.98	14 Si $[Ne]3s^23p^2$ silicon 28.09	15 P $[Ne]3s^23p^3$ phosphorus 30.97	16 S $[Ne]3s^23p^4$ sulfur 32.07	17 Cl $[Ne]3s^23p^5$ chlorine 35.45	36 Kr $[Ar]4s^23d^{10}4p^6$ krypton 83.80
19 K $[Ar]4s^1$ potassium 39.10	20 Ca $[Ar]4s^2$ calcium 40.08	21 Sc $[Ar]4s^23d^1$ scandium 44.96	22 Ti $[Ar]4s^23d^2$ titanium 47.88	23 V $[Ar]4s^23d^3$ vanadium 50.94	24 Cr $[Ar]4s^13d^5$ chromium 52.00	25 Mn $[Ar]4s^23d^5$ manganese 54.94	26 Fe $[Ar]4s^23d^6$ iron 55.85	27 Co $[Ar]4s^23d^7$ cobalt 58.93	28 Ni $[Ar]4s^23d^8$ nickel 58.69	29 Cu $[Ar]4s^13d^{10}$ copper 63.55	30 Zn $[Ar]4s^23d^{10}$ zinc 65.39	31 Ga $[Ar]4s^23d^{10}4p^1$ gallium 69.72	32 Ge $[Ar]4s^23d^{10}4p^2$ germanium 72.58	33 As $[Ar]4s^23d^{10}4p^3$ arsenic 74.92	34 Se $[Ar]4s^23d^{10}4p^4$ selenium 78.96	35 Br $[Ar]4s^23d^{10}4p^5$ bromine 79.90	54 Xe $[Kr]5s^24d^{10}5p^6$ xenon 131.3
37 Rb $[Kr]5s^1$ rubidium 85.47	38 Sr $[Kr]5s^2$ strontium 87.62	39 Y $[Kr]5s^24d^1$ yttrium 88.91	40 Zr $[Kr]5s^24d^2$ zirconium 91.22	41 Nb $[Kr]5s^14d^4$ niobium 92.91	42 Mo $[Kr]5s^14d^5$ molybdenum 95.94	43 Tc $[Kr]5s^24d^5$ technetium (98)	44 Ru $[Kr]5s^14d^7$ ruthenium 101.1	45 Rh $[Kr]5s^14d^8$ rhodium 102.9	46 Pd $[Kr]4d^{10}$ palladium 106.4	47 Ag $[Kr]5s^14d^{10}$ silver 107.9	48 Cd $[Kr]5s^24d^{10}$ cadmium 112.4	49 In $[Kr]5s^24d^{10}5p^1$ indium 114.8	50 Sn $[Kr]5s^24d^{10}5p^2$ tin 118.7	51 Sb $[Kr]5s^24d^{10}5p^3$ antimony 121.8	52 Te $[Kr]5s^24d^{10}5p^4$ tellurium 127.6	53 I $[Kr]5s^24d^{10}5p^5$ iodine 126.9	86 Rn $[Xe]6s^24f^{14}5d^{10}6p^6$ radon (222)
55 Cs $[Xe]6s^1$ cesium 132.9	56 Ba $[Xe]6s^2$ barium 137.3	57 La* $[Xe]6s^25d^1$ lanthanum 138.9	72 Hf $[Xe]6s^24f^{14}5d^2$ hafnium 178.5	73 Ta $[Xe]6s^24f^{14}5d^3$ tantalum 180.9	74 W $[Xe]6s^24f^{14}5d^4$ tungsten 183.9	75 Re $[Xe]6s^24f^{14}5d^5$ rhenium 186.2	76 Os $[Xe]6s^24f^{14}5d^6$ osmium 190.2	77 Ir $[Xe]6s^24f^{14}5d^7$ iridium 190.2	78 Pt $[Xe]6s^14f^{14}5d^9$ platinum 195.1	79 Au $[Xe]6s^14f^{14}5d^{10}$ gold 197.0	80 Hg $[Xe]6s^24f^{14}5d^{10}$ mercury 200.5	81 Tl $Xe]6s^24f^{14}5d^{10}6p^1$ thallium 204.4	82 Pb $Xe]6s^24f^{14}5d^{10}6p^2$ lead 207.2	83 Bi $Xe]6s^24f^{14}5d^{10}6p^3$ bismuth 208.9	84 Po $[Xe]6s^24f^{14}5d^{10}6p^4$ polonium (209)	85 At $Xe]6s^24f^{14}5d^{10}6p^5$ astatine (210)	
87 Fr $[Rn]7s^1$ francium (223)	88 Ra $[Rn]7s^2$ radium (226)	89 Ac~ $[Rn]7s^26d^1$ actinium (227)	104 Rf $[Rn]7s^25f^{14}6d^2$ rutherfordium (257)	105 Db $[Rn]7s^25f^{14}6d^3$ dubnium (260)	106 Sg $[Rn]7s^25f^{14}6d^4$ seaborgium (263)	107 Bh $[Rn]7s^25f^{14}6d^5$ bohrium (262)	108 Hs $[Rn]7s^25f^{14}6d^6$ hassium (265)	109 Mt $[Rn]7s^25f^{14}6d^7$ meitnerium (266)	110 Ds $[Rn]7s^25f^{14}6d^9$ darmstadium (271)	111 Uuu (272)	112 Uub (277)						

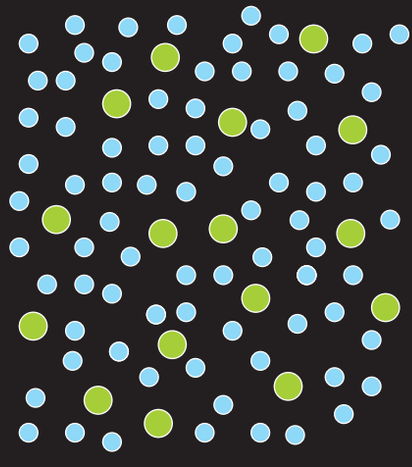
60 Nd neodymium

Carbon isotopes as a tracer of … what?

'lighter' isotope

'heavier' isotope

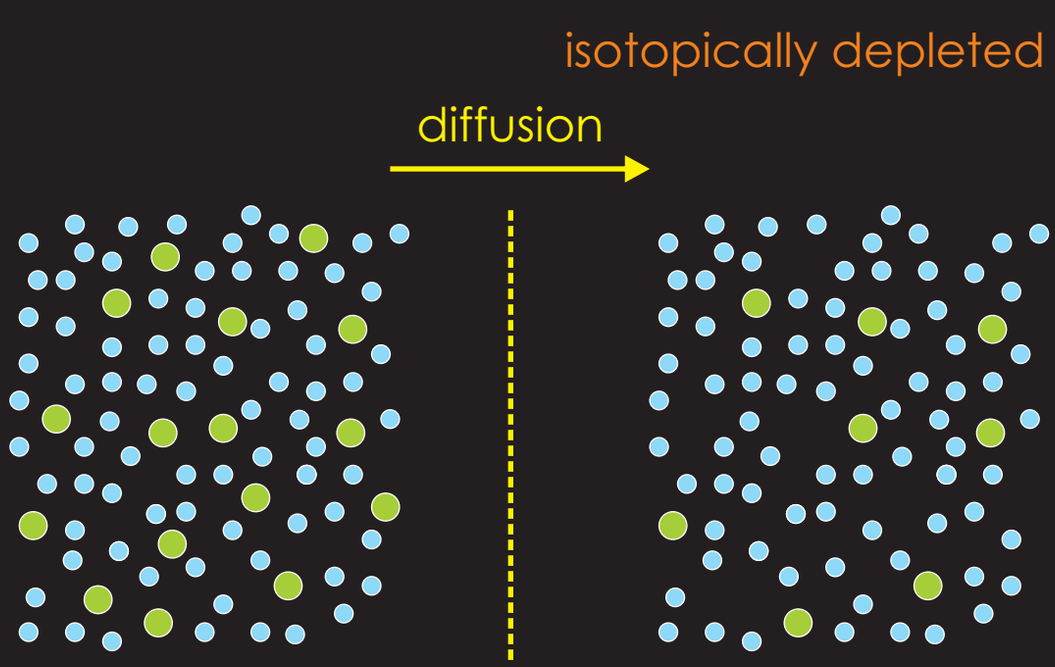
diffusion



1A													3A	4A	5A	6A	7A	
1 H hydrogen 1.008	2A																	2 He helium 4.003
3 Li lithium 6.941	4 Be beryllium 9.012												5 B boron 10.81	6 C carbon 12.01	7 N nitrogen 14.01	8 O oxygen 16.00	9 F fluorine 19.00	10 Ne neon 20.18
11 Na sodium 22.99	12 Mg magnesium 24.31	3B	4B	5B	6B	7B	8B			11B	12B		13 Al aluminum 26.98	14 Si silicon 28.09	15 P phosphorus 30.97	16 S sulfur 32.07	17 Cl chlorine 35.45	18 Ar argon 39.95
19 K potassium 39.10	20 Ca calcium 40.08	21 Sc scandium 44.96	22 Ti titanium 47.88	23 V vanadium 50.94	24 Cr chromium 52.00	25 Mn manganese 54.94	26 Fe iron 55.85	27 Co cobalt 58.93	28 Ni nickel 58.69	29 Cu copper 63.55	30 Zn zinc 65.39		31 Ga gallium 69.72	32 Ge germanium 72.58	33 As arsenic 74.92	34 Se selenium 78.96	35 Br bromine 79.90	36 Kr krypton 83.80
37 Rb rubidium 85.47	38 Sr strontium 87.62	39 Y yttrium 88.91	40 Zr zirconium 91.22	41 Nb niobium 92.91	42 Mo molybdenum 95.94	43 Tc technetium (98)	44 Ru ruthenium 101.1	45 Rh rhodium 102.9	46 Pd palladium 106.4	47 Ag silver 107.9	48 Cd cadmium 112.4		49 In indium 114.8	50 Sn tin 118.7	51 Sb antimony 121.8	52 Te tellurium 127.6	53 I iodine 126.9	54 Xe xenon 131.3
55 Cs cesium 132.9	56 Ba barium 137.3	57 La* lanthanum 138.9	72 Hf hafnium 178.5	73 Ta tantalum 180.9	74 W tungsten 183.9	75 Re rhenium 186.2	76 Os osmium 190.2	77 Ir iridium 190.2	78 Pt platinum 195.1	79 Au gold 197.0	80 Hg mercury 200.5		81 Tl thallium 204.4	82 Pb lead 207.2	83 Bi bismuth 208.9	84 Po polonium (209)	85 At astatine (210)	86 Rn radon (222)
87 Fr francium (223)	88 Ra radium (226)	89 Ac~ actinium (227)	104 Rf rutherfordium (257)	105 Db dubnium (260)	106 Sg seaborgium (263)	107 Bh bohrium (262)	108 Hs hassium (265)	109 Mt meitnerium (266)	110 Ds darmstadium (271)	111 Uuu (272)	112 Uub (277)							

60 Nd neodymium

Carbon isotopes as a tracer of ... what?



1A																	2A	3A	4A	5A	6A	7A	
1 H hydrogen 1.008																							2 He helium 4.003
3 Li lithium 6.941	4 Be beryllium 9.012																	5 B boron 10.81	6 C carbon 12.01	7 N nitrogen 14.01	8 O oxygen 16.00	9 F fluorine 19.00	10 Ne neon 20.18
11 Na sodium 22.99	12 Mg magnesium 24.31																	13 Al aluminum 26.98	14 Si silicon 28.09	15 P phosphorus 30.97	16 S sulfur 32.07	17 Cl chlorine 35.45	18 Ar argon 39.95
19 K potassium 39.10	20 Ca calcium 40.08	3B 21 Sc scandium 44.96	4B 22 Ti titanium 47.88	5B 23 V vanadium 50.94	6B 24 Cr chromium 52.00	7B 25 Mn manganese 54.94	8B 26 Fe iron 55.85	8B 27 Co cobalt 58.93	8B 28 Ni nickel 58.69	11B 29 Cu copper 63.55	12B 30 Zn zinc 65.39	31 Ga gallium 69.72	32 Ge germanium 72.58	33 As arsenic 74.92	34 Se selenium 78.96	35 Br bromine 79.90	36 Kr krypton 83.80
37 Rb rubidium 85.47	38 Sr strontium 87.62	39 Y yttrium 88.91	40 Zr zirconium 91.22	41 Nb niobium 92.91	42 Mo molybdenum 95.94	43 Tc technetium (98)	44 Ru ruthenium 101.1	45 Rh rhodium 102.9	46 Pd palladium 106.4	47 Ag silver 107.9	48 Cd cadmium 112.4	49 In indium 114.8	50 Sn tin 118.7	51 Sb antimony 121.8	52 Te tellurium 127.6	53 I iodine 126.9	54 Xe xenon 131.3
55 Cs cesium 132.9	56 Ba barium 137.3	57 La* lanthanum 138.9	72 Hf hafnium 178.5	73 Ta tantalum 180.9	74 W tungsten 183.9	75 Re rhenium 186.2	76 Os osmium 190.2	77 Ir iridium 190.2	78 Pt platinum 195.1	79 Au gold 197.0	80 Hg mercury 200.5	81 Tl thallium 204.4	82 Pb lead 207.2	83 Bi bismuth 208.9	84 Po polonium (209)	85 At astatine (210)	86 Rn radon (222)
87 Fr francium (223)	88 Ra radium (226)	89 Ac~ actinium (227)	104 Rf rutherfordium (257)	105 Db dubnium (260)	106 Sg seaborgium (263)	107 Bh bohrium (262)	108 Hs hassium (265)	109 Mt meitnerium (266)	110 Ds darmstadium (271)	111 Uuu (272)	112 Uub (277)						

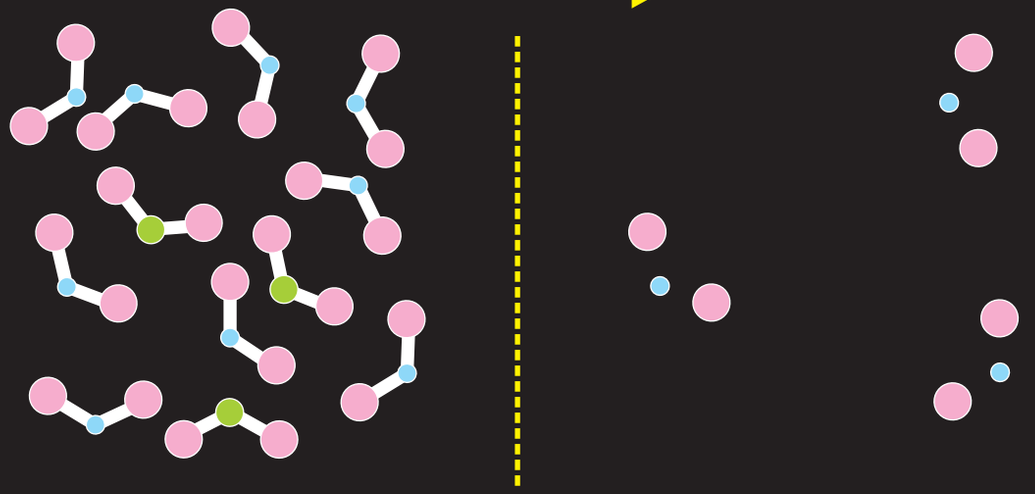
60 Nd neodymium

Carbon isotopes as a tracer of … what?

'lighter' isotope

'heavier' isotope

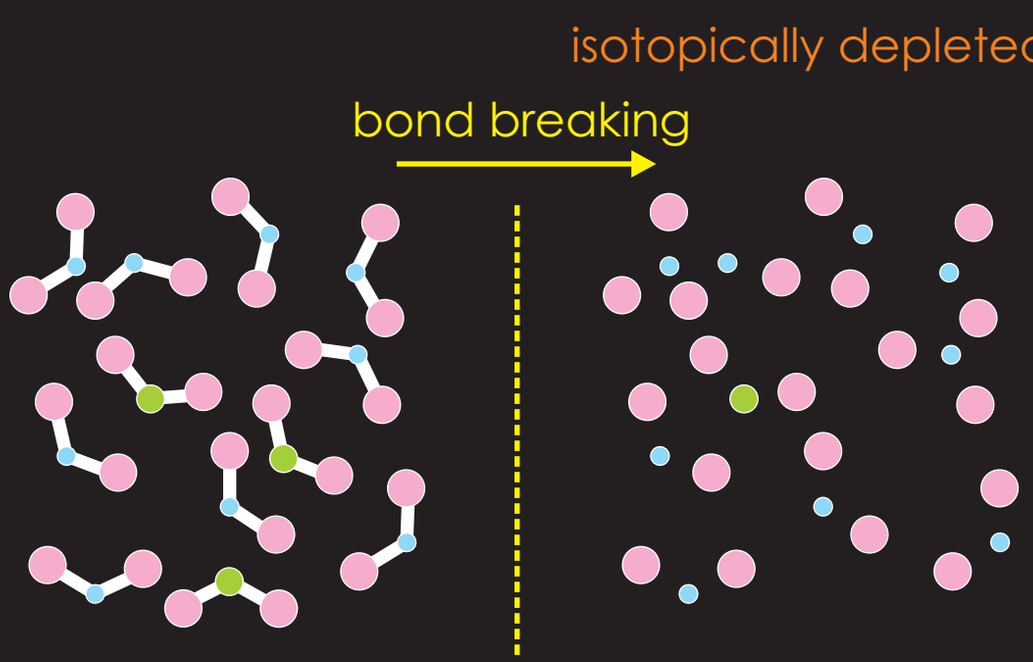
bond breaking



1A												3A	4A	5A	6A	7A	
1 H hydrogen 1.008	2A																2 He helium 4.003
3 Li lithium 6.941	4 Be beryllium 9.012											5 B boron 10.81	6 C carbon 12.01	7 N nitrogen 14.01	8 O oxygen 16.00	9 F fluorine 19.00	10 Ne neon 20.18
11 Na sodium 22.99	12 Mg magnesium 24.31	3B	4B	5B	6B	7B	8B			11B	12B	13 Al aluminum 26.98	14 Si silicon 28.09	15 P phosphorus 30.97	16 S sulfur 32.07	17 Cl chlorine 35.45	18 Ar argon 39.95
19 K potassium 39.10	20 Ca calcium 40.08	21 Sc scandium 44.96	22 Ti titanium 47.88	23 V vanadium 50.94	24 Cr chromium 52.00	25 Mn manganese 54.94	26 Fe iron 55.85	27 Co cobalt 58.93	28 Ni nickel 58.69	29 Cu copper 63.55	30 Zn zinc 65.39	31 Ga gallium 69.72	32 Ge germanium 72.58	33 As arsenic 74.92	34 Se selenium 78.96	35 Br bromine 79.90	36 Kr krypton 83.80
37 Rb rubidium 85.47	38 Sr strontium 87.62	39 Y yttrium 88.91	40 Zr zirconium 91.22	41 Nb niobium 92.91	42 Mo molybdenum 95.94	43 Tc technetium (98)	44 Ru ruthenium 101.1	45 Rh rhodium 102.9	46 Pd palladium 106.4	47 Ag silver 107.9	48 Cd cadmium 112.4	49 In indium 114.8	50 Sn tin 118.7	51 Sb antimony 121.8	52 Te tellurium 127.6	53 I iodine 126.9	54 Xe xenon 131.3
55 Cs cesium 132.9	56 Ba barium 137.3	57 La* lanthanum 138.9	72 Hf hafnium 178.5	73 Ta tantalum 180.9	74 W tungsten 183.9	75 Re rhenium 186.2	76 Os osmium 190.2	77 Ir iridium 190.2	78 Pt platinum 195.1	79 Au gold 197.0	80 Hg mercury 200.5	81 Tl thallium 204.4	82 Pb lead 207.2	83 Bi bismuth 208.9	84 Po polonium (209)	85 At astatine (210)	86 Rn radon (222)
87 Fr francium (223)	88 Ra radium (226)	89 Ac~ actinium (227)	104 Rf rutherfordium (257)	105 Db dubnium (260)	106 Sg seaborgium (263)	107 Bh bohrium (262)	108 Hs hassium (265)	109 Mt meitnerium (266)	110 Ds darmstadium (271)	111 Uuu (272)	112 Uub (277)						

60 Nd neodymium

Carbon isotopes as a tracer of … what?

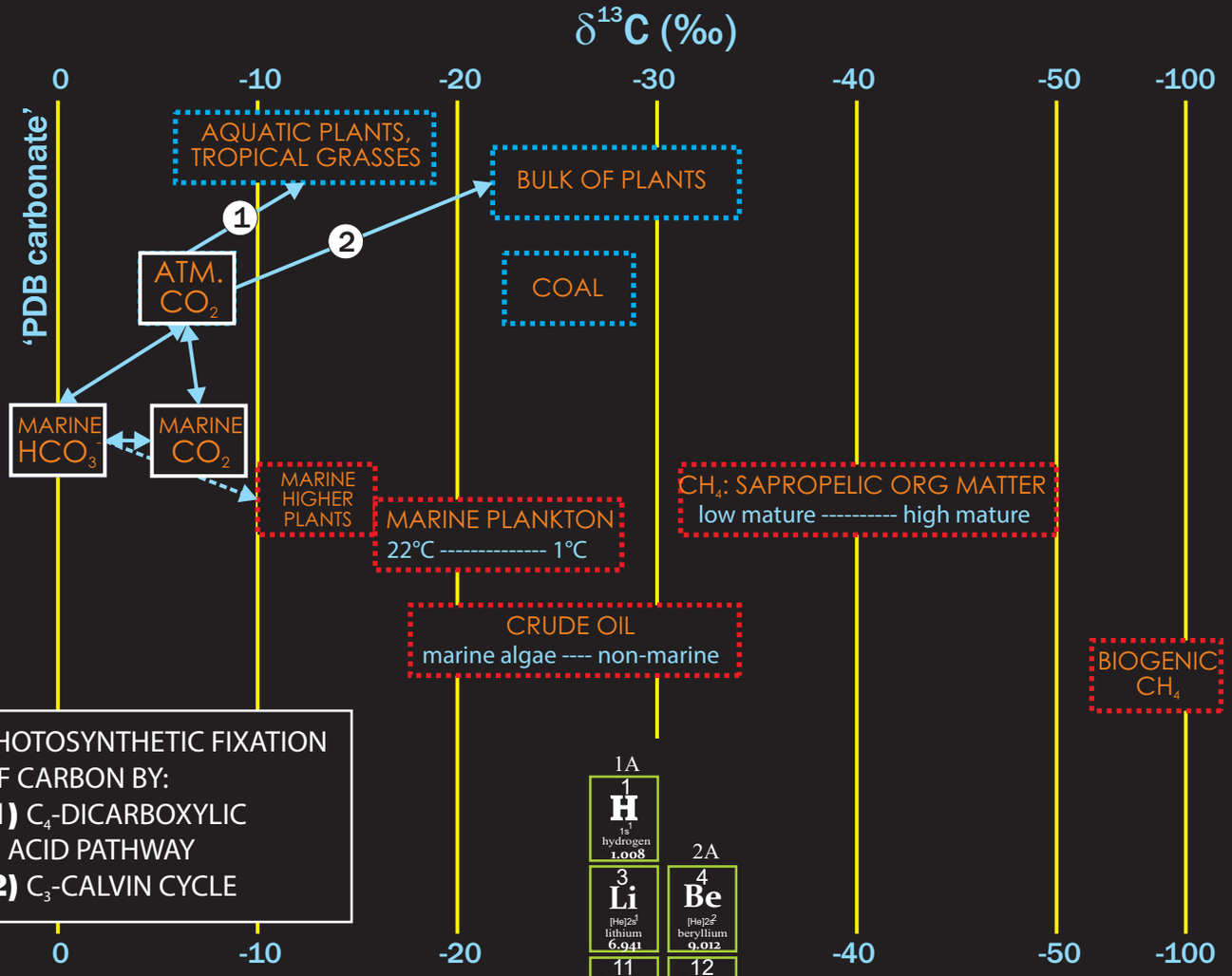


- 'lighter' isotope
- 'heavier' isotope

1A												3A	4A	5A	6A	7A	
1 H hydrogen 1.008	2A																2 He helium 4.003
3 Li lithium 6.941	4 Be beryllium 9.012											5 B boron 10.81	6 C carbon 12.01	7 N nitrogen 14.01	8 O oxygen 16.00	9 F fluorine 19.00	10 Ne neon 20.18
11 Na sodium 22.99	12 Mg magnesium 24.31	3B	4B	5B	6B	7B	8B	8B	8B	11B	12B	13 Al aluminum 26.98	14 Si silicon 28.09	15 P phosphorus 30.97	16 S sulfur 32.07	17 Cl chlorine 35.45	18 Ar argon 39.95
19 K potassium 39.10	20 Ca calcium 40.08	21 Sc scandium 44.96	22 Ti titanium 47.88	23 V vanadium 50.94	24 Cr chromium 52.00	25 Mn manganese 54.94	26 Fe iron 55.85	27 Co cobalt 58.93	28 Ni nickel 58.69	29 Cu copper 63.55	30 Zn zinc 65.39	31 Ga gallium 69.72	32 Ge germanium 72.58	33 As arsenic 74.92	34 Se selenium 78.96	35 Br bromine 79.90	36 Kr krypton 83.80
37 Rb rubidium 85.47	38 Sr strontium 87.62	39 Y yttrium 88.91	40 Zr zirconium 91.22	41 Nb niobium 92.91	42 Mo molybdenum 95.94	43 Tc technetium (98)	44 Ru ruthenium 101.1	45 Rh rhodium 102.9	46 Pd palladium 106.4	47 Ag silver 107.9	48 Cd cadmium 112.4	49 In indium 114.8	50 Sn tin 118.7	51 Sb antimony 121.8	52 Te tellurium 127.6	53 I iodine 126.9	54 Xe xenon 131.3
55 Cs cesium 132.9	56 Ba barium 137.3	57 La* lanthanum 138.9	72 Hf hafnium 178.5	73 Ta tantalum 180.9	74 W tungsten 183.9	75 Re rhenium 186.2	76 Os osmium 190.2	77 Ir iridium 190.2	78 Pt platinum 195.1	79 Au gold 197.0	80 Hg mercury 200.5	81 Tl thallium 204.4	82 Pb lead 207.2	83 Bi bismuth 208.9	84 Po polonium (209)	85 At astatine (210)	86 Rn radon (222)
87 Fr francium (223)	88 Ra radium (226)	89 Ac~ actinium (227)	104 Rf rutherfordium (257)	105 Db dubnium (260)	106 Sg seaborgium (263)	107 Bh bohrium (262)	108 Hs hassium (265)	109 Mt meitnerium (266)	110 Ds darmstadium (271)	111 Uuu (272)	112 Uub (277)						

60 Nd neodymium

Carbon isotopes as a tracer of … what?



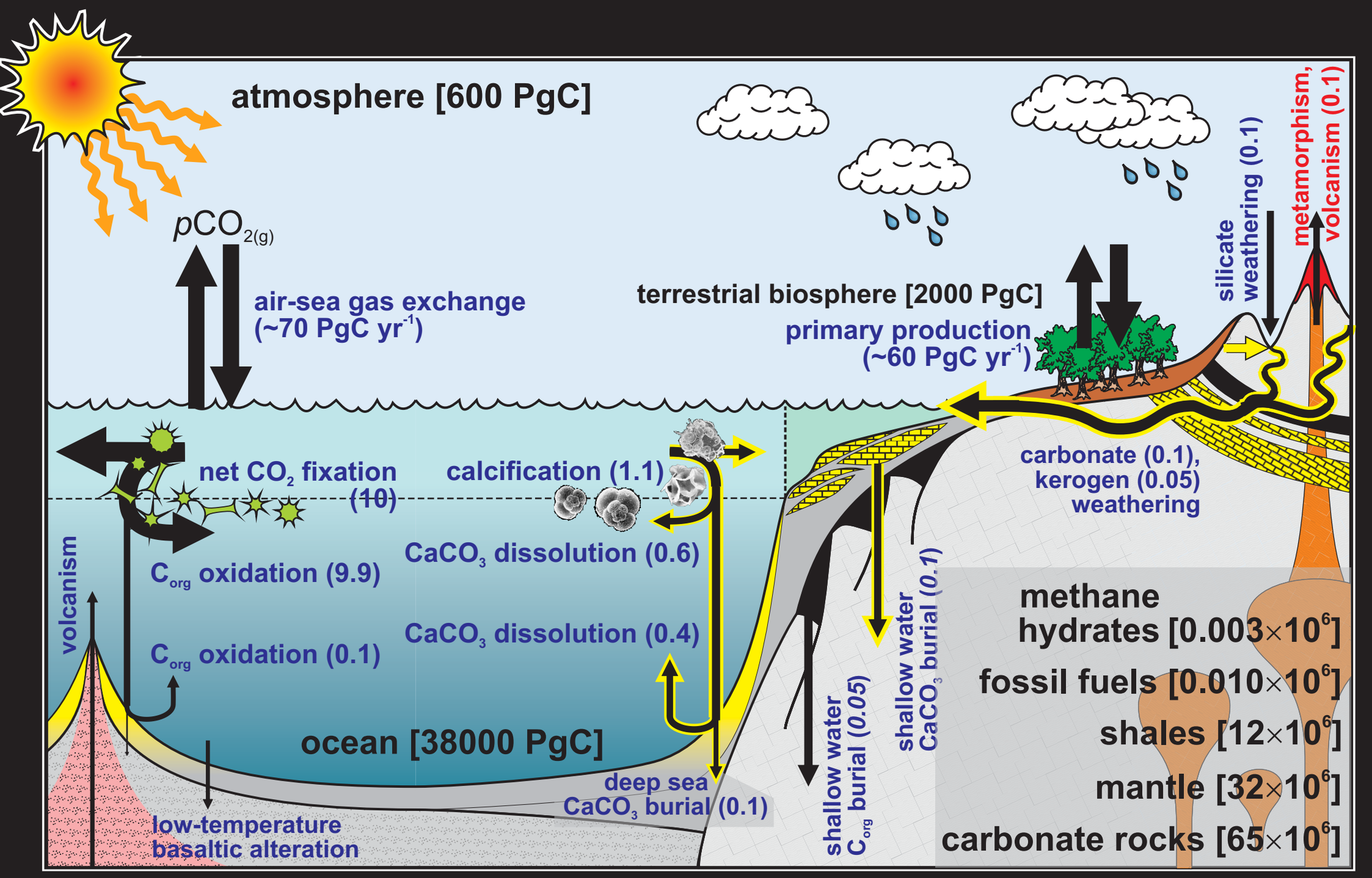
notation: $\delta^{13}C$

Maslin and Thomas [2003]

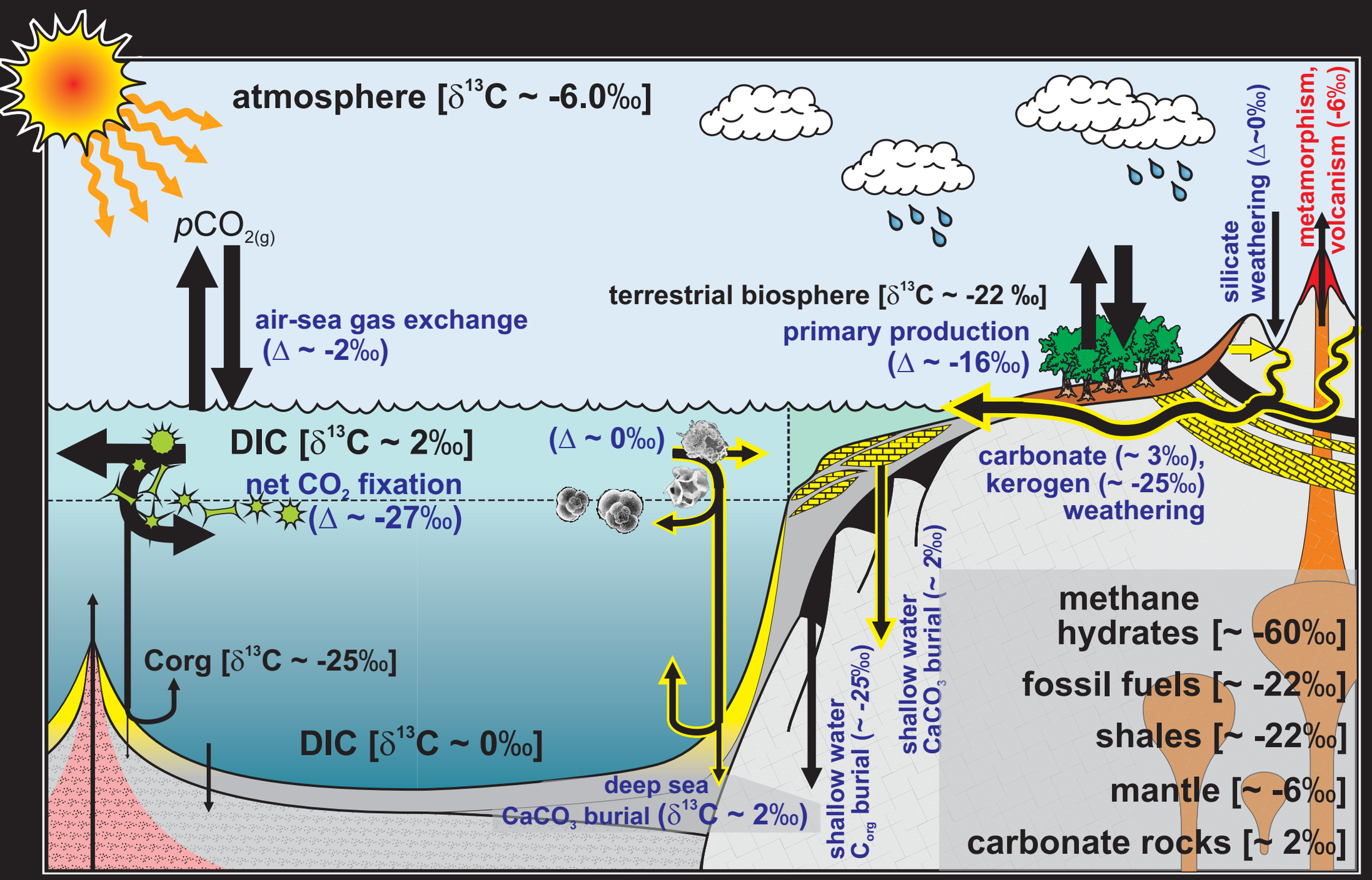
1A													3A	4A	5A	6A	7A	2A
1 H hydrogen 1.008	2A																	2 He helium 4.003
3 Li lithium 6.941	4 Be beryllium 9.012	3B	4B	5B	6B	7B		8B			11B	12B	5 B boron 10.81	6 C carbon 12.01	7 N nitrogen 14.01	8 O oxygen 16.00	9 F fluorine 19.00	10 Ne neon 20.18
11 Na sodium 22.99	12 Mg magnesium 24.31												13 Al aluminum 26.98	14 Si silicon 28.09	15 P phosphorus 30.97	16 S sulfur 32.07	17 Cl chlorine 35.45	18 Ar argon 39.95
19 K potassium 39.10	20 Ca calcium 40.08	21 Sc scandium 44.96	22 Ti titanium 47.88	23 V vanadium 50.94	24 Cr chromium 52.00	25 Mn manganese 54.94	26 Fe iron 55.85	27 Co cobalt 58.93	28 Ni nickel 58.69	29 Cu copper 63.55	30 Zn zinc 65.39	31 Ga gallium 69.72	32 Ge germanium 72.58	33 As arsenic 74.92	34 Se selenium 78.96	35 Br bromine 79.90	36 Kr krypton 83.80
37 Rb rubidium 85.47	38 Sr strontium 87.62	39 Y yttrium 88.91	40 Zr zirconium 91.22	41 Nb niobium 92.91	42 Mo molybdenum 95.94	43 Tc technetium (98)	44 Ru ruthenium 101.1	45 Rh rhodium 102.9	46 Pd palladium 106.4	47 Ag silver 107.9	48 Cd cadmium 112.4	49 In indium 114.8	50 Sn tin 118.7	51 Sb antimony 121.8	52 Te tellurium 127.6	53 I iodine 126.9	54 Xe xenon 131.3
55 Cs cesium 132.9	56 Ba barium 137.3	57 La* lanthanum 138.9	72 Hf hafnium 178.5	73 Ta tantalum 180.9	74 W tungsten 183.9	75 Re rhenium 186.2	76 Os osmium 190.2	77 Ir iridium 190.2	78 Pt platinum 195.1	79 Au gold 197.0	80 Hg mercury 200.5	81 Tl thallium 204.4	82 Pb lead 207.2	83 Bi bismuth 208.9	84 Po polonium (209)	85 At astatine (210)	86 Rn radon (222)
87 Fr francium (223)	88 Ra radium (226)	89 Ac~ actinium (227)	104 Rf rutherfordium (257)	105 Db dubnium (260)	106 Sg seaborgium (263)	107 Bh bohrium (262)	108 Hs hassium (265)	109 Mt meitnerium (266)	110 Ds darmstadium (271)	111 Uuu (272)	112 Uub (277)						

60 Nd neodymium

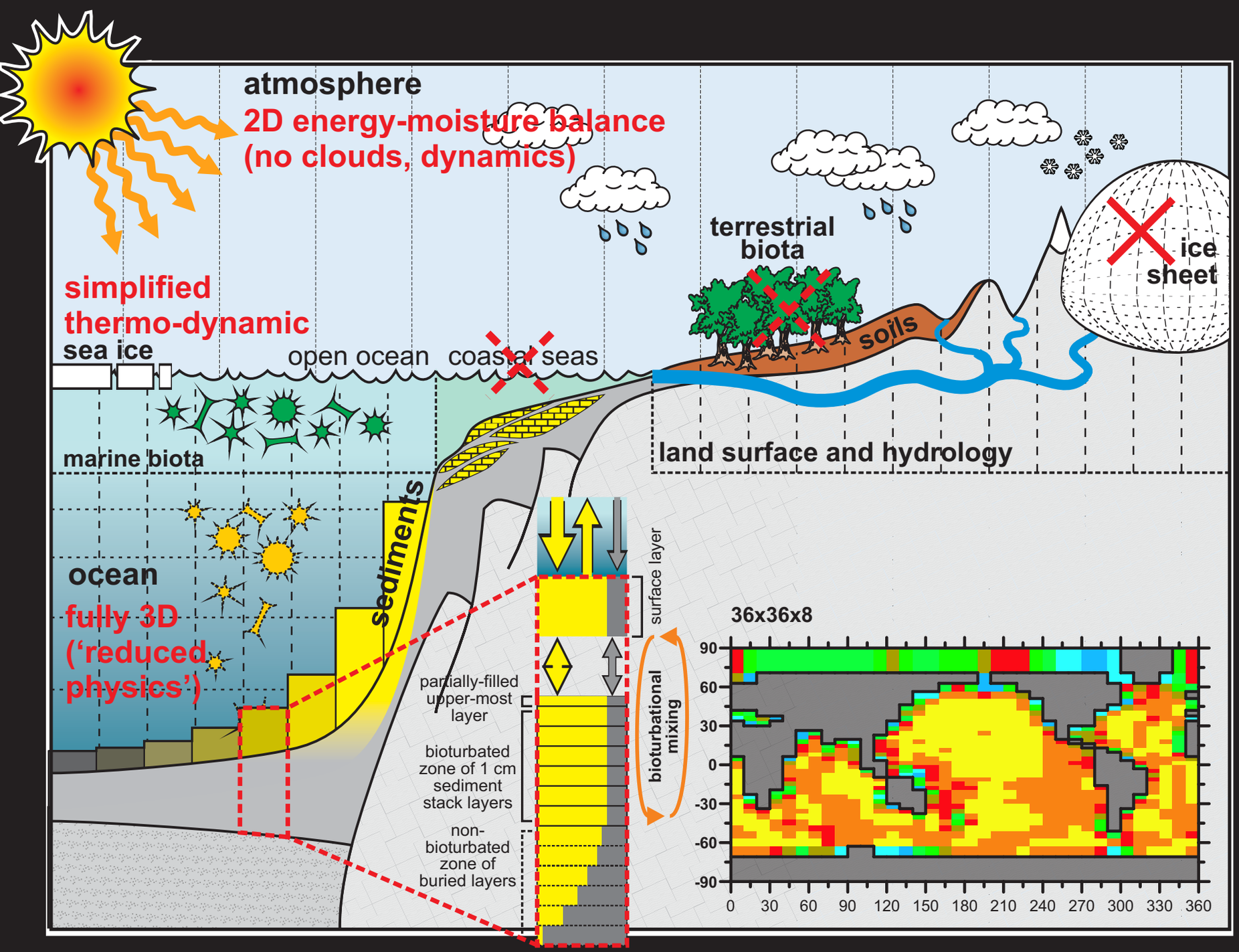
Carbon isotopes as a tracer of ... what?



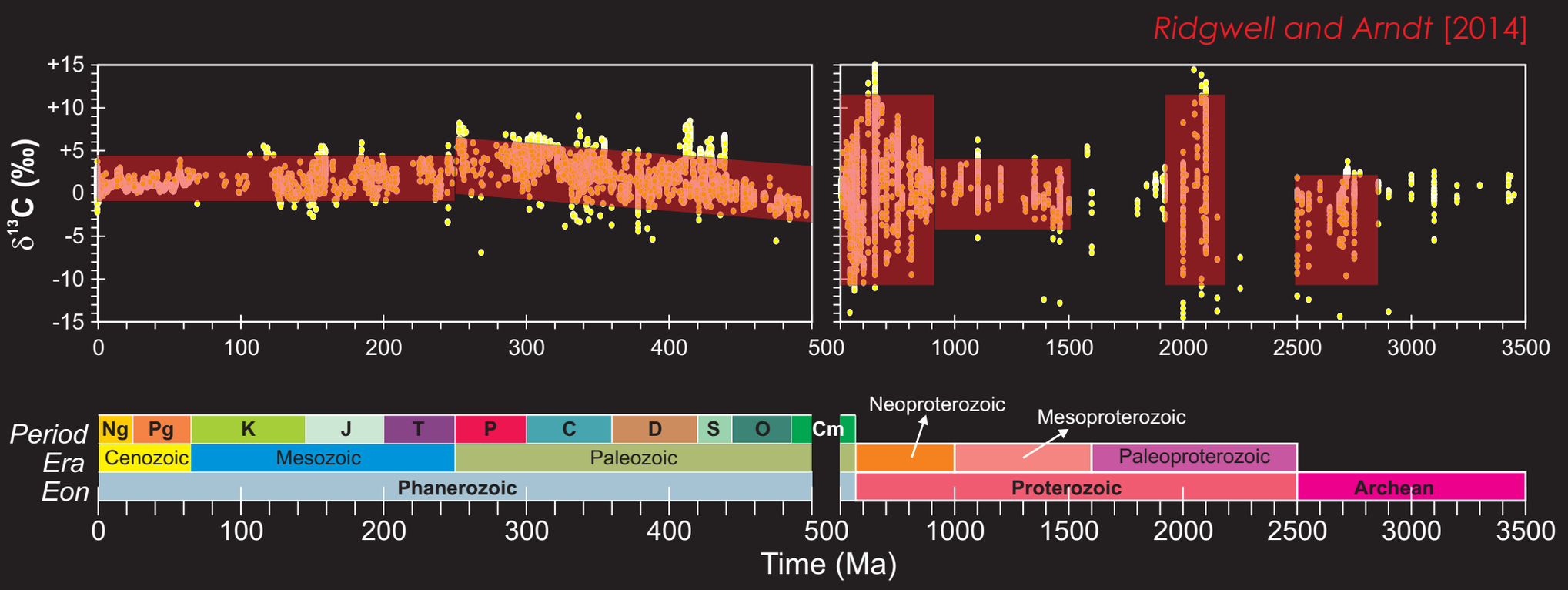
Carbon isotopes as a tracer of ... what?



The (c)GENIE Earth system model (version muffin)



Carbonate $\delta^{13}C$ variability through time



Carbonate $\delta^{13}C$ 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 $\delta^{13}C$ signal, either marine sedimentary or subaerial.

Carbonate $\delta^{13}C$ variability through time

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

Re-partitioning of carbon ***within*** surficial reservoirs?

Carbonate $\delta^{13}C$ 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)?

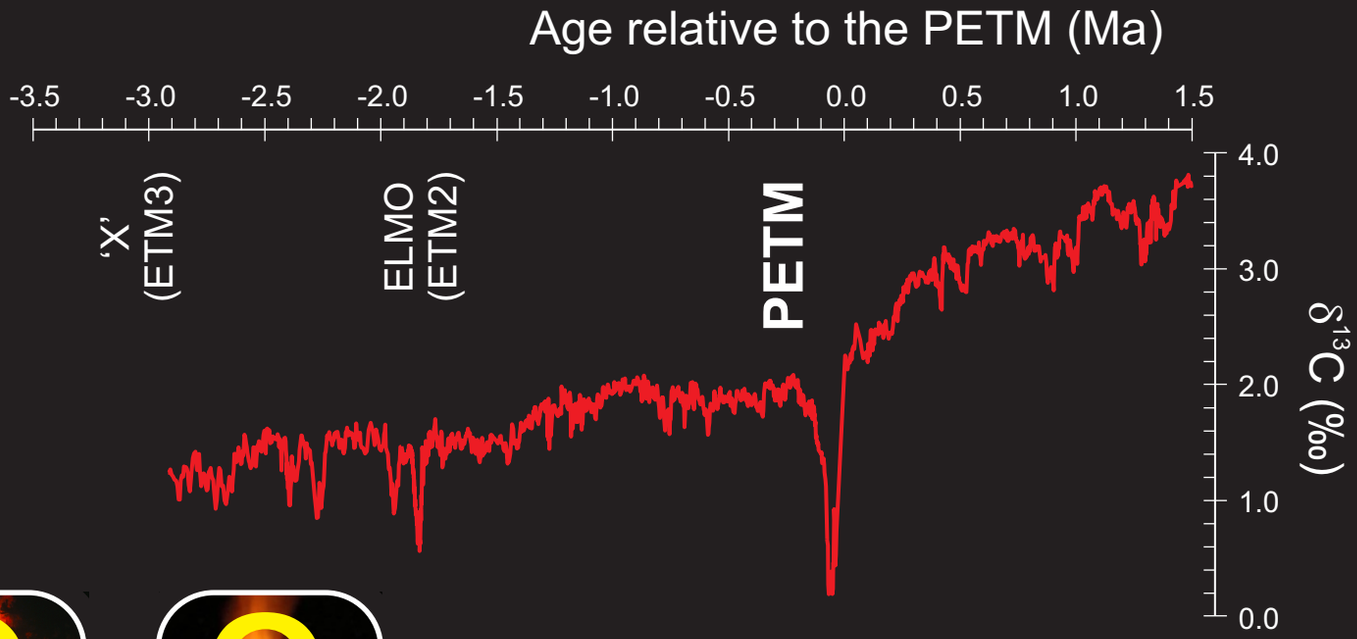
Carbonate $\delta^{13}C$ variability through time

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

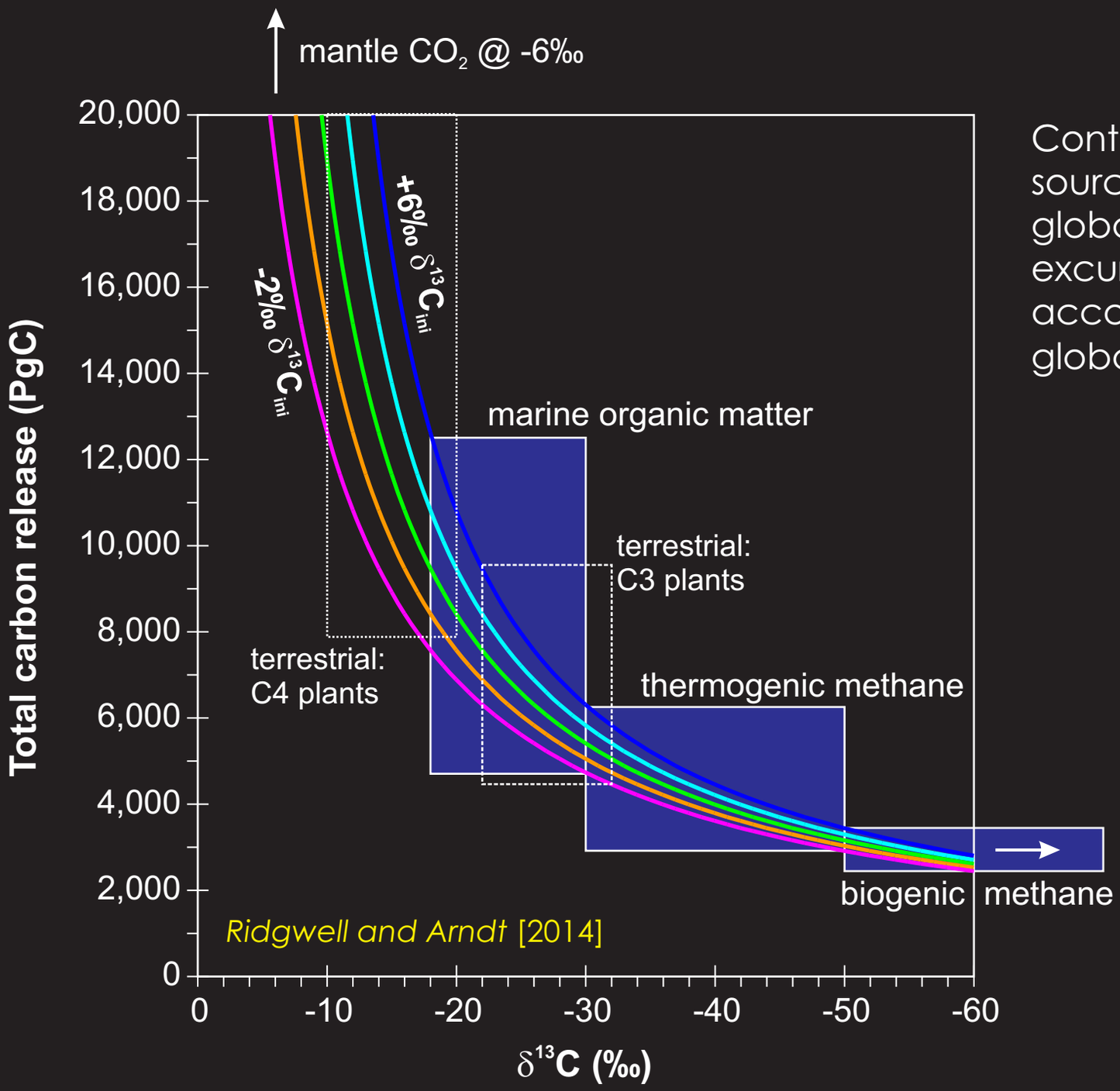
Re-partitioning of carbon ***within*** surficial reservoirs?

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

Injection (or removal) of isotopically light carbon?



Carbonate $\delta^{13}C$ variability through time



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

Carbonate $\delta^{13}C$ 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)?

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

$$F_{Corg} / (F_{Corg} + F_{CaCO3}) = \text{C burial ratio}$$

$$(\delta^{13}C_{obs} - \delta^{13}C_{input}) / (\delta^{13}C_{CaCO3} - \delta^{13}C_{Corg})$$

observed (recorded) carbonate $\delta^{13}C$ | -5.0 | 25.0

Carbonate $\delta^{13}C$ variability through time

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

Re-partitioning of carbon ***within*** surficial reservoirs?

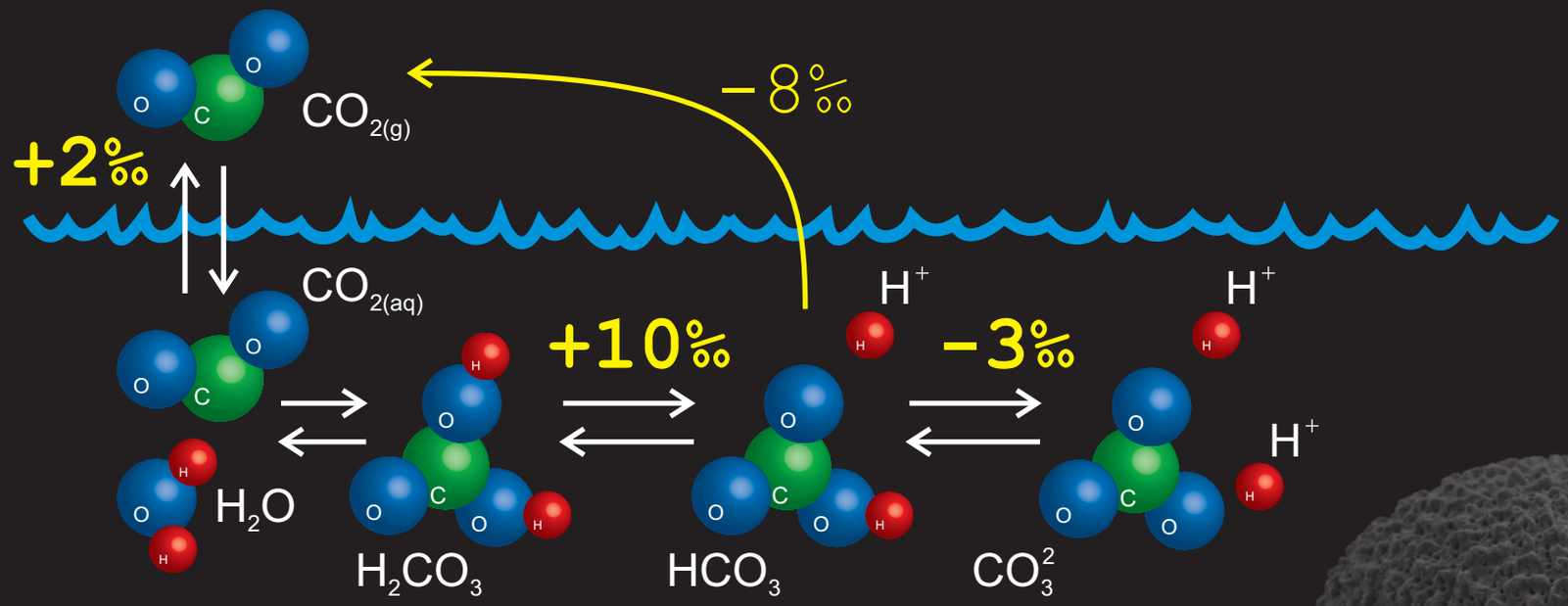
Re-partitioning of carbon ***between*** surficial reservoirs (cf. LGM)?

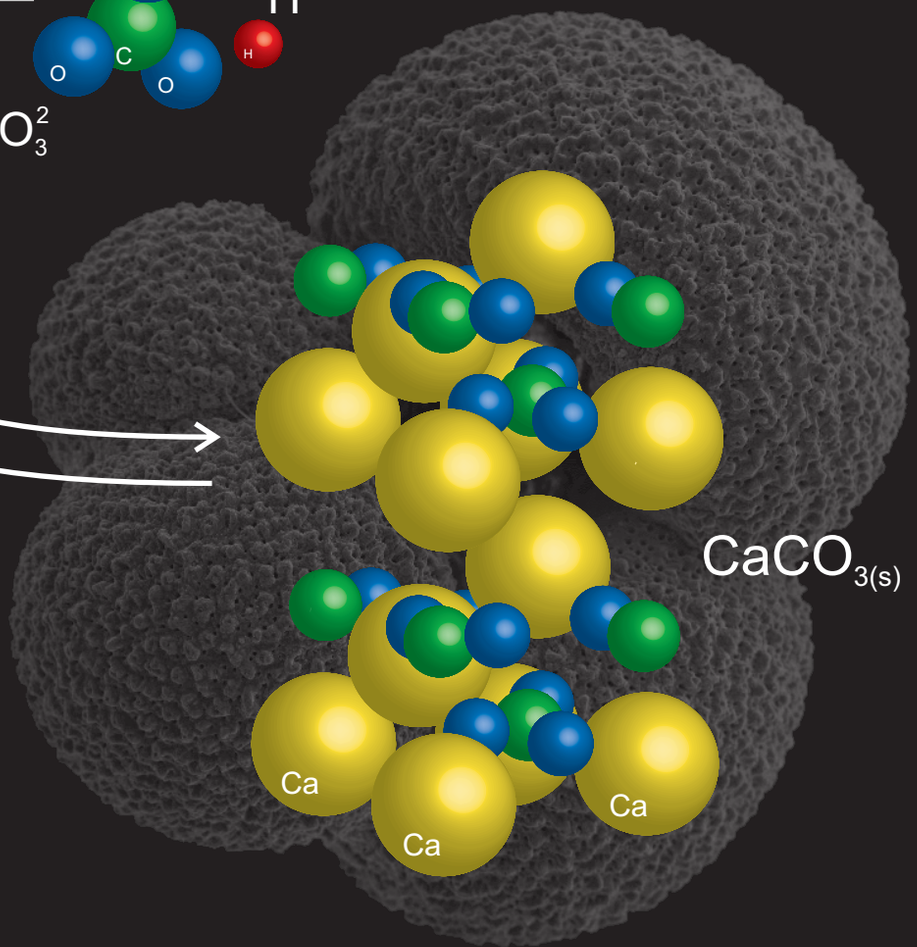
Injection (or removal) of isotopically light carbon?

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 $\delta^{13}C$ signal, either marine sedimentary or subaerial.

Carbonate $\delta^{13}C$ variability through time

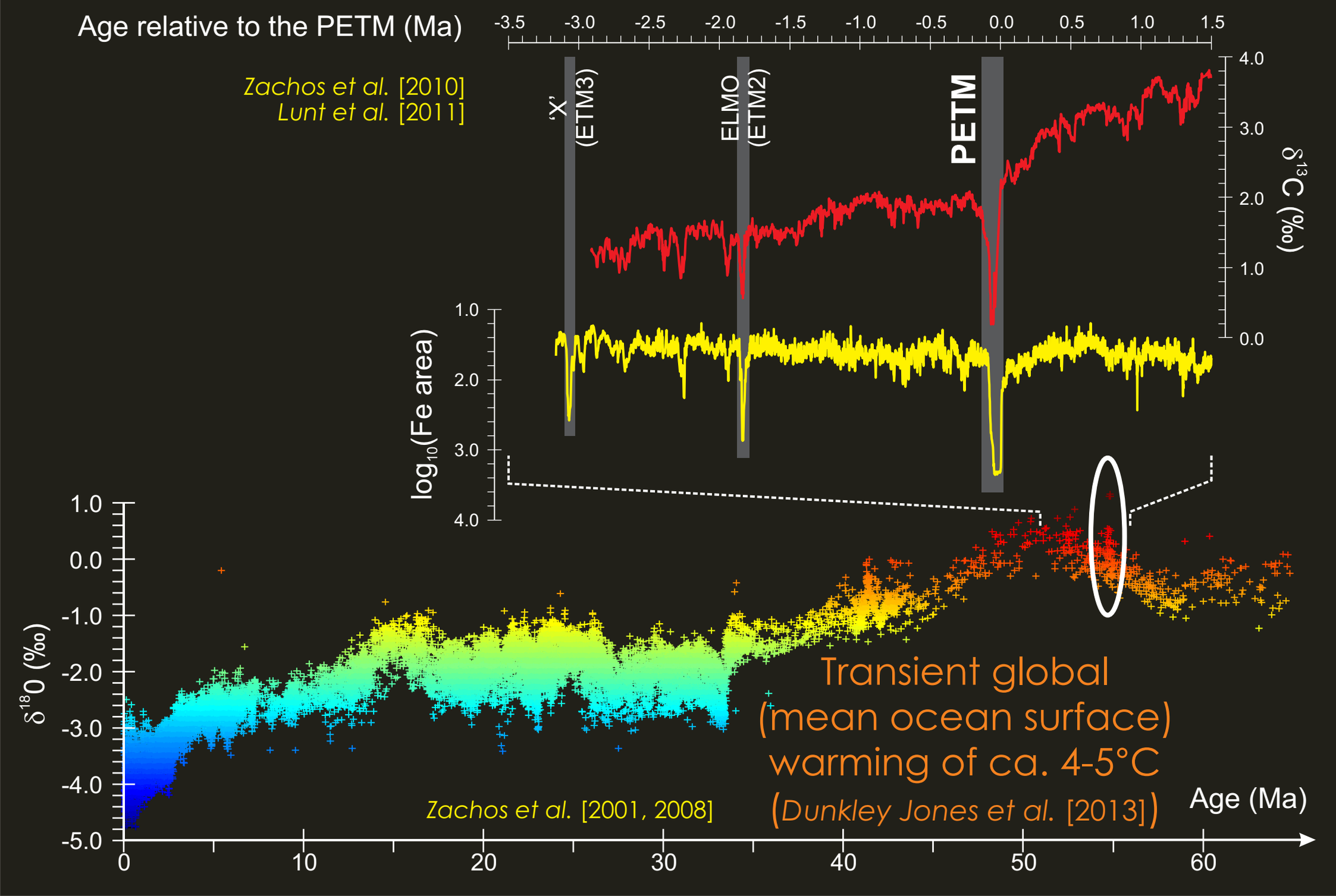




pH-driven re-partitioning of the where the isotopic composition of the mean surficial reservoir is held

Adapted from: *Barker and Ridgwell* [2012]

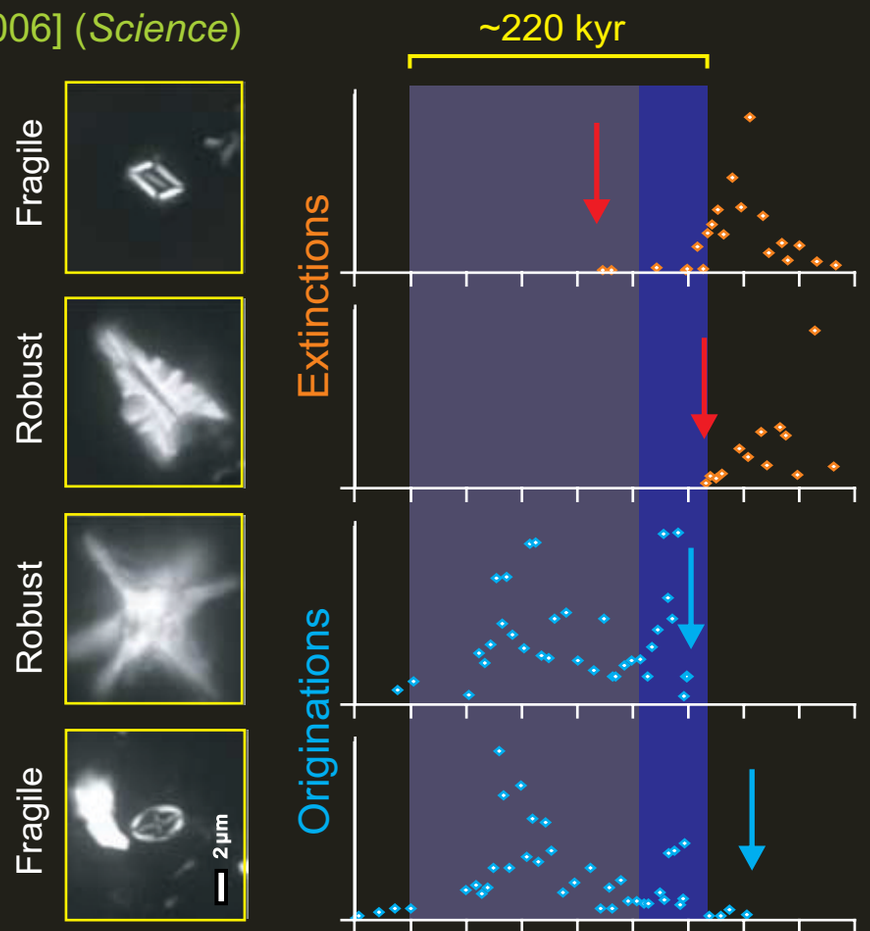
Paleo-analogues – the PETM?



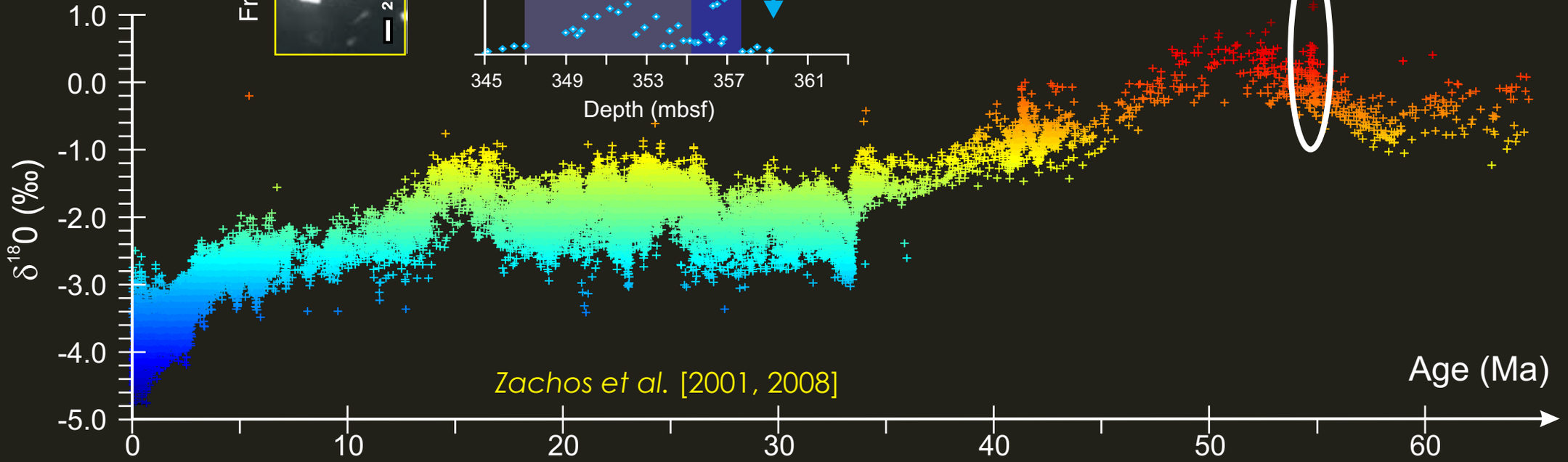
Paleo-analogues – the PETM?

Paleo-analogues – the PETM?

Gibbs et al. [2006] (*Science*)



observed nanoplankton assemblage response to environmental change across the PETM

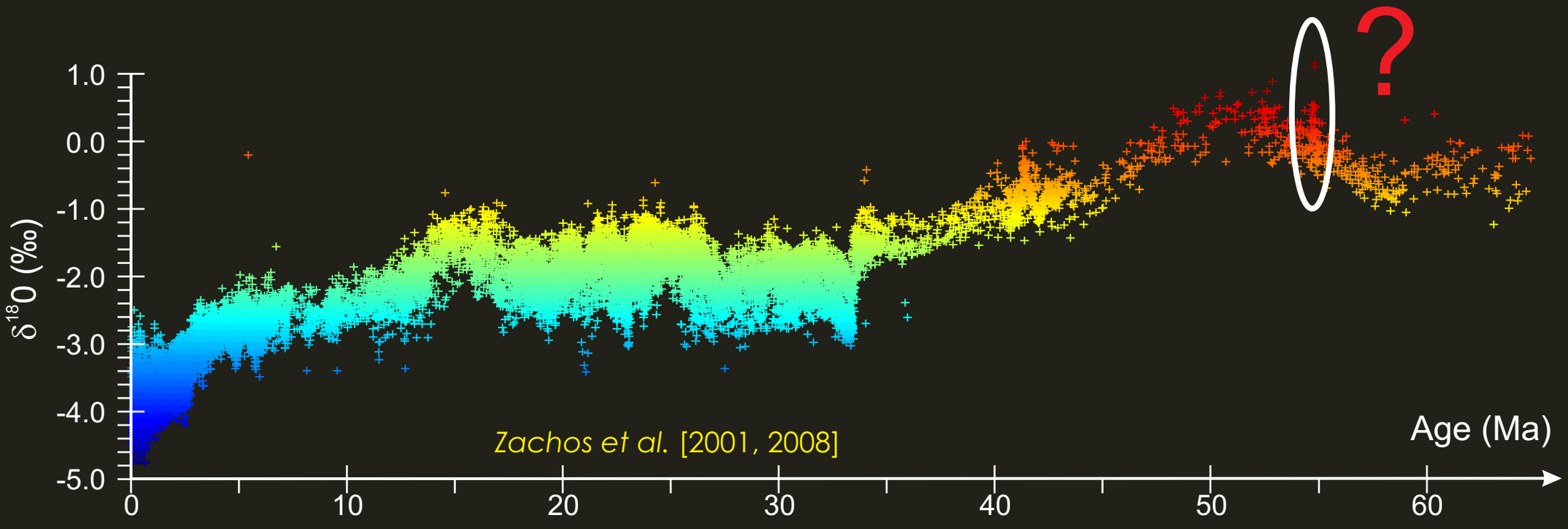


Zachos et al. [2001, 2008]

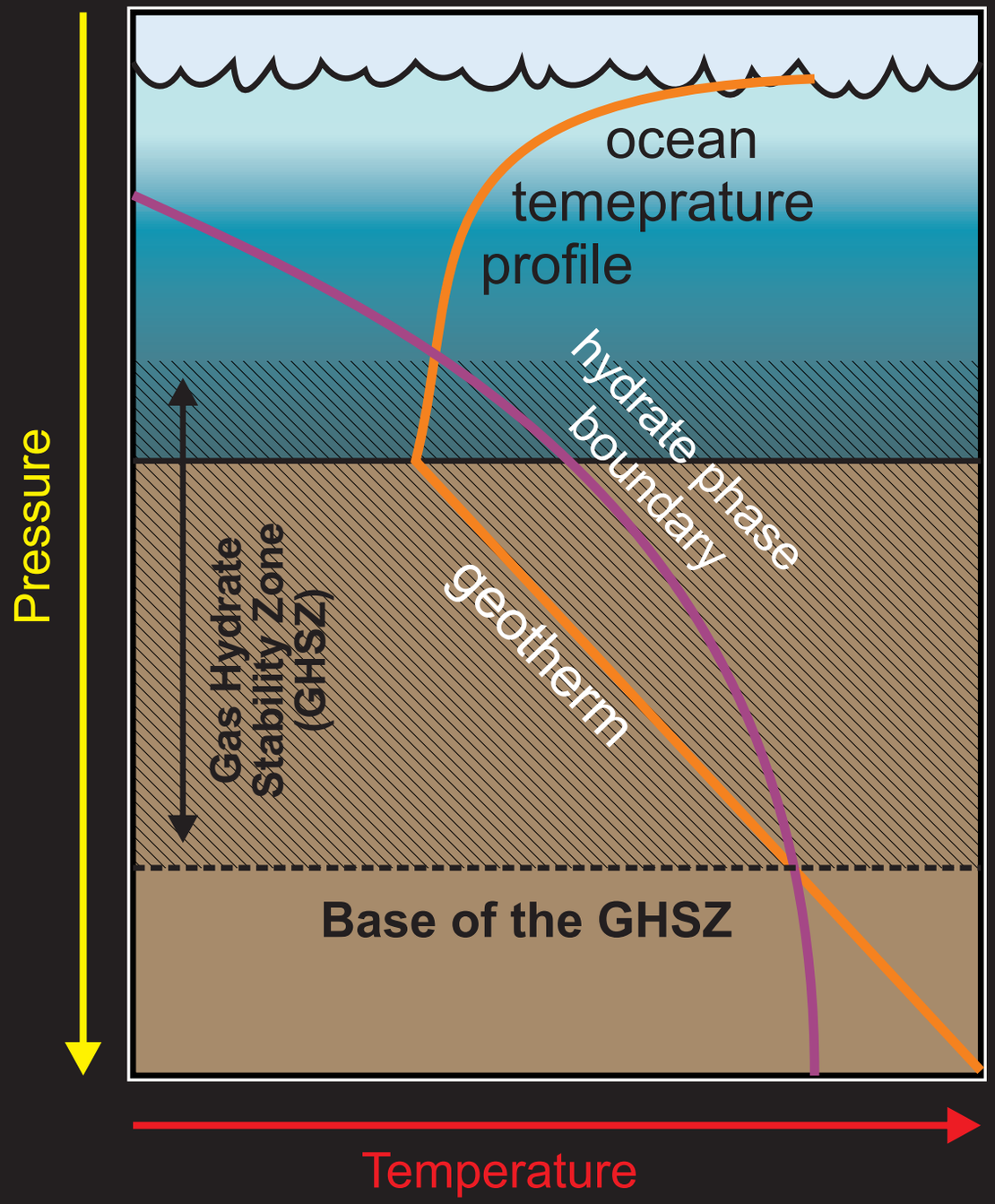
Paleo-analogues – the PETM?

'triggers'

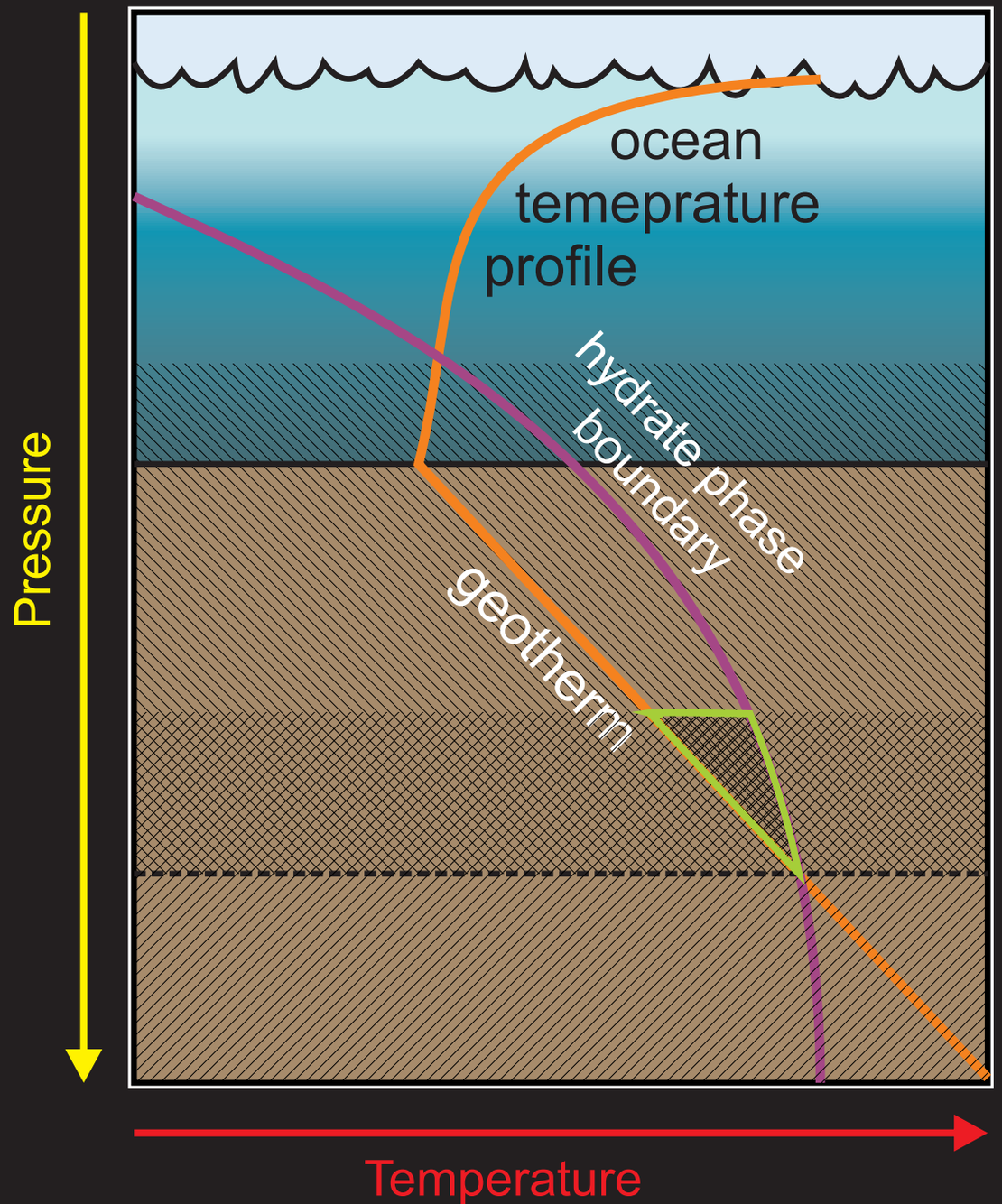
carbon cycle feedbacks

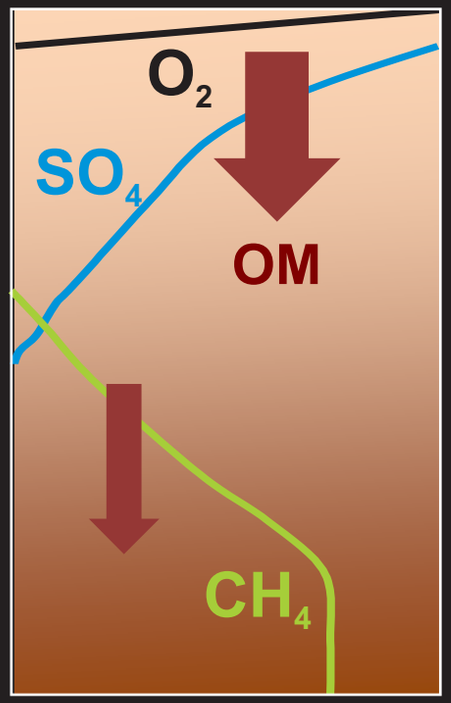


Climate fedback with methane hydrates

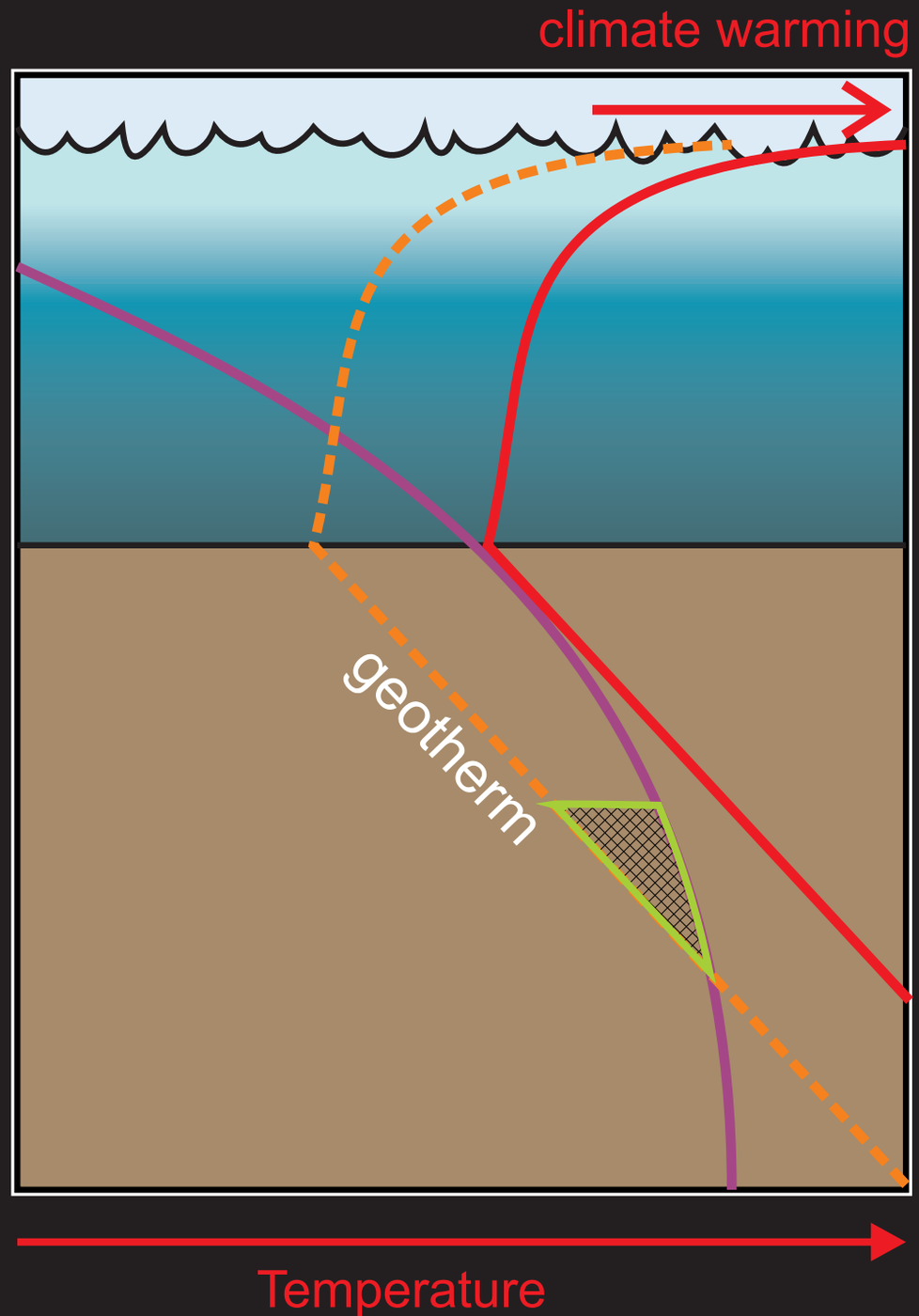


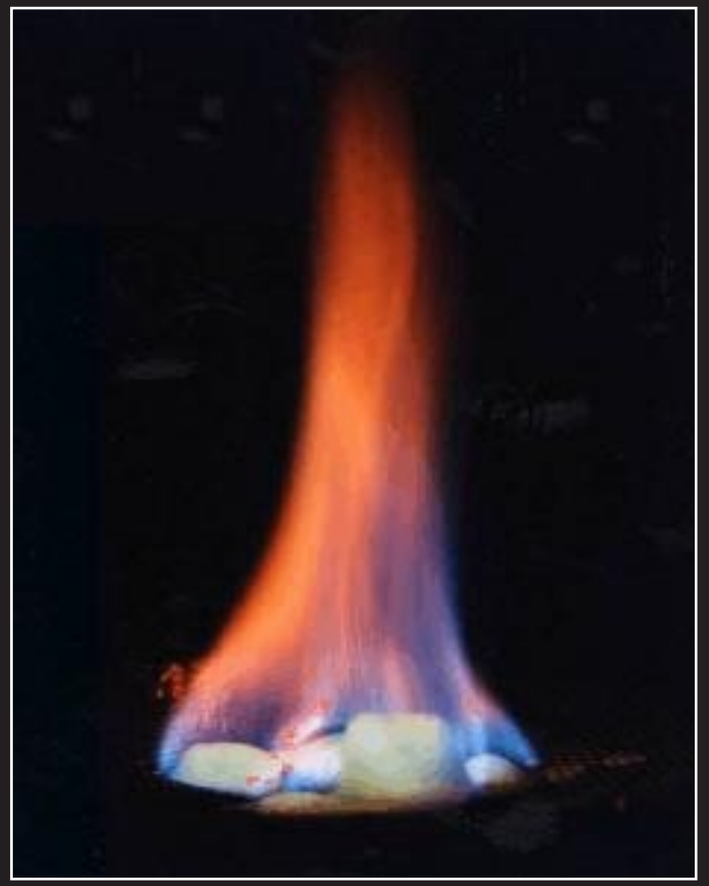
Climate fedback with methane hydrates



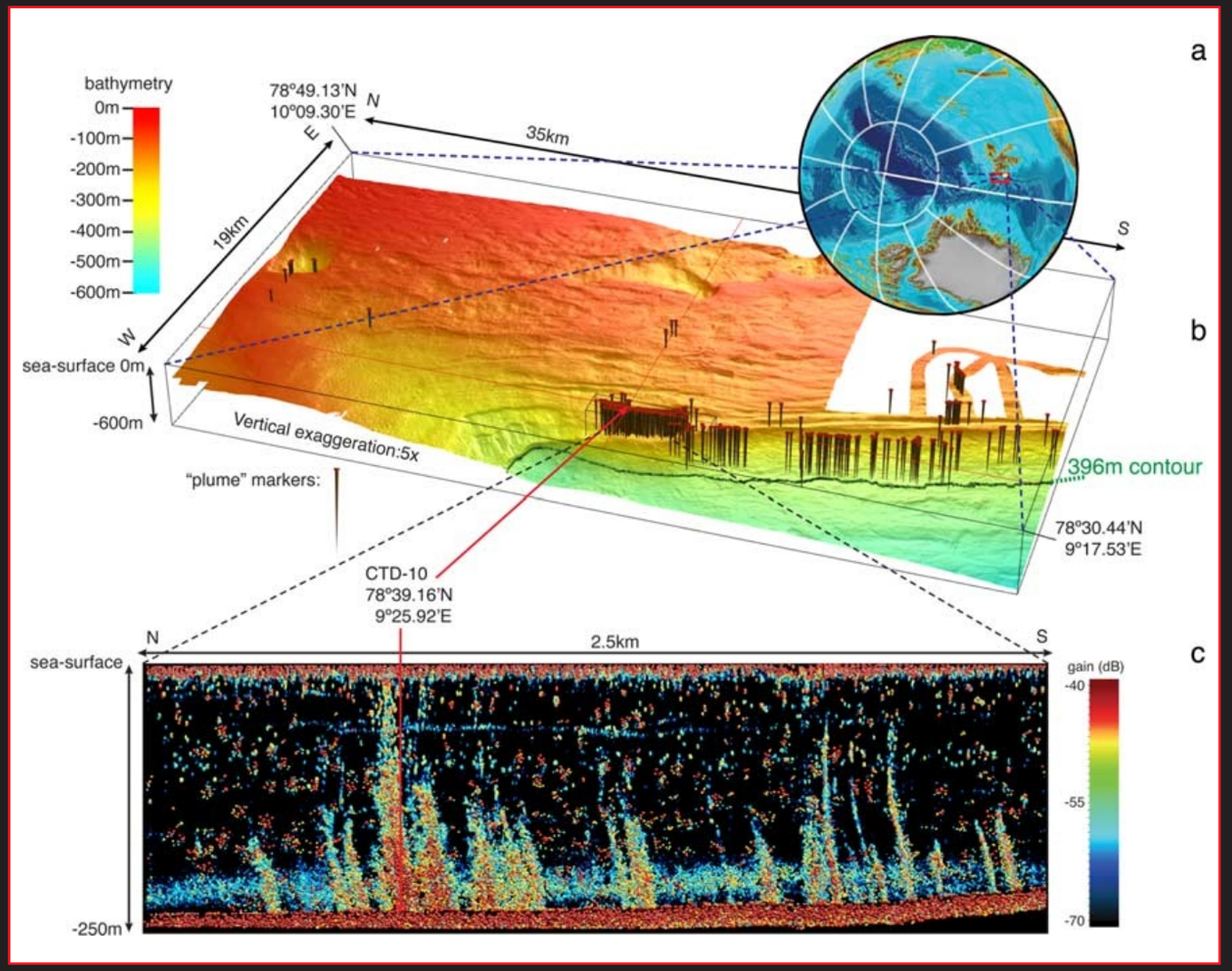


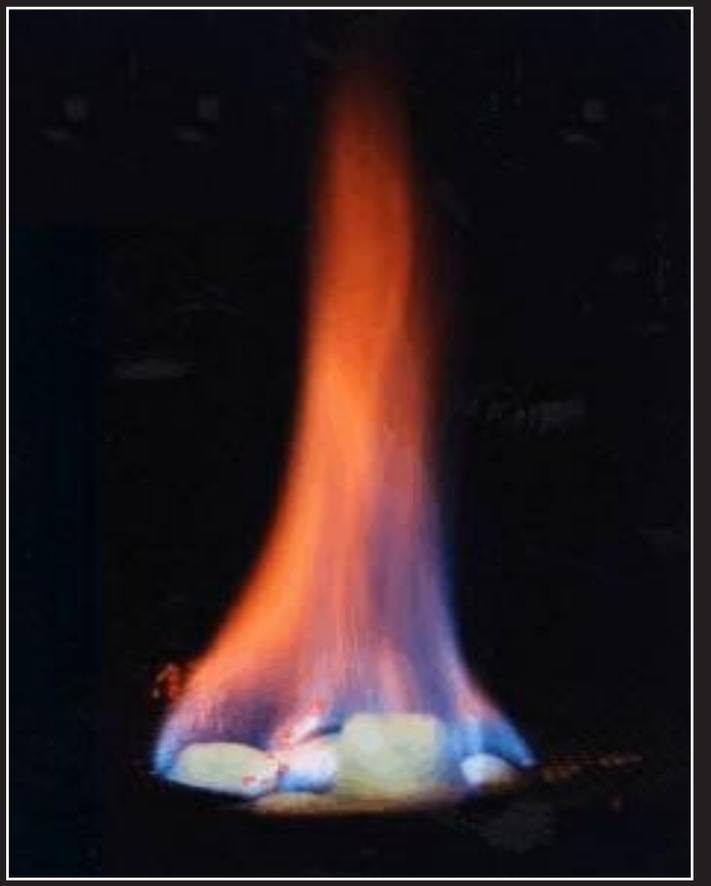
Climate fedback with methane hydrates





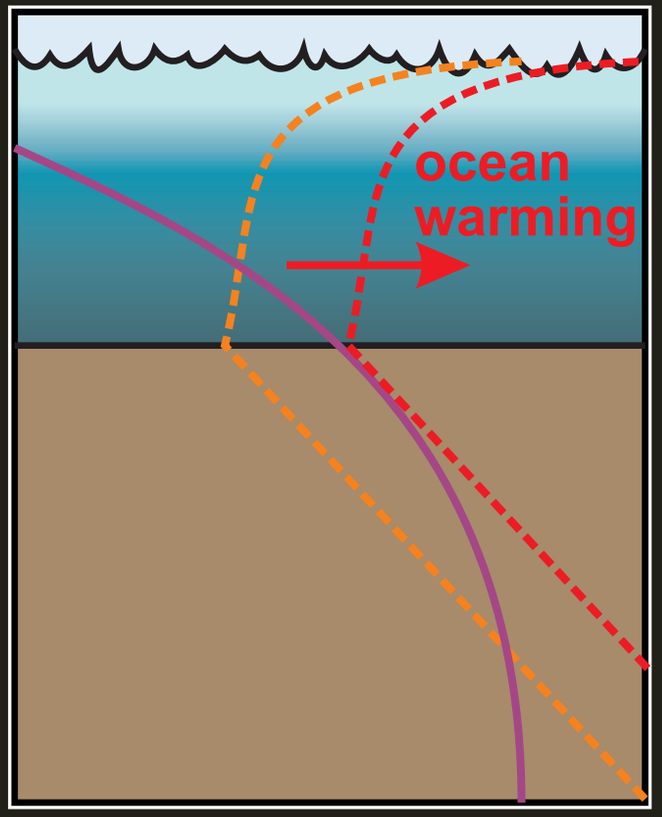
Climate fedback with methane hydrates

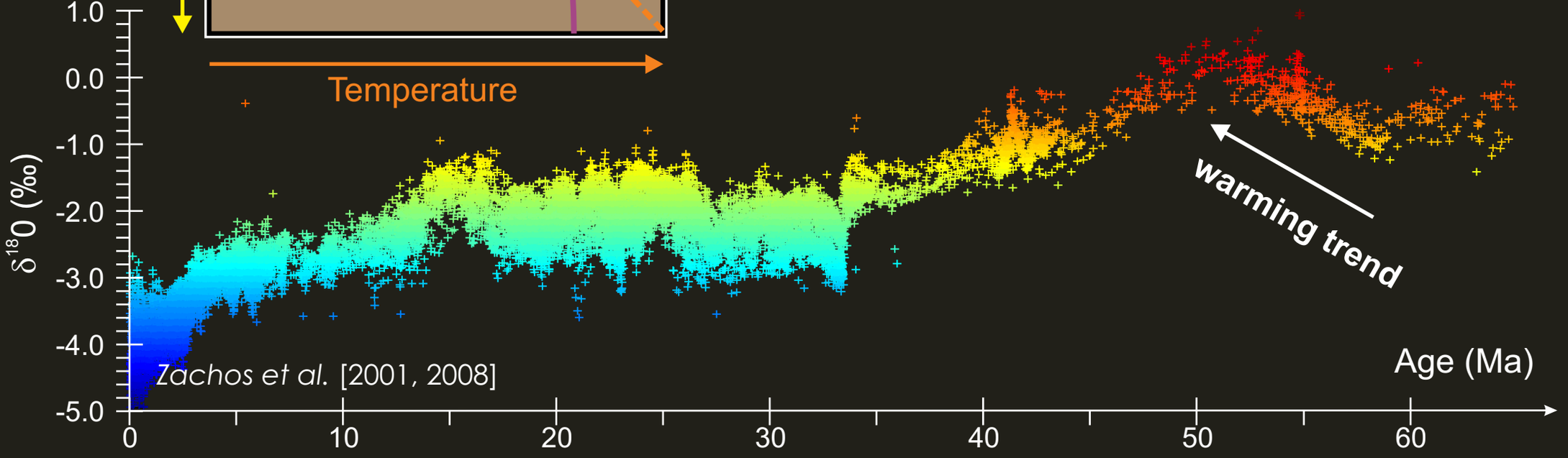




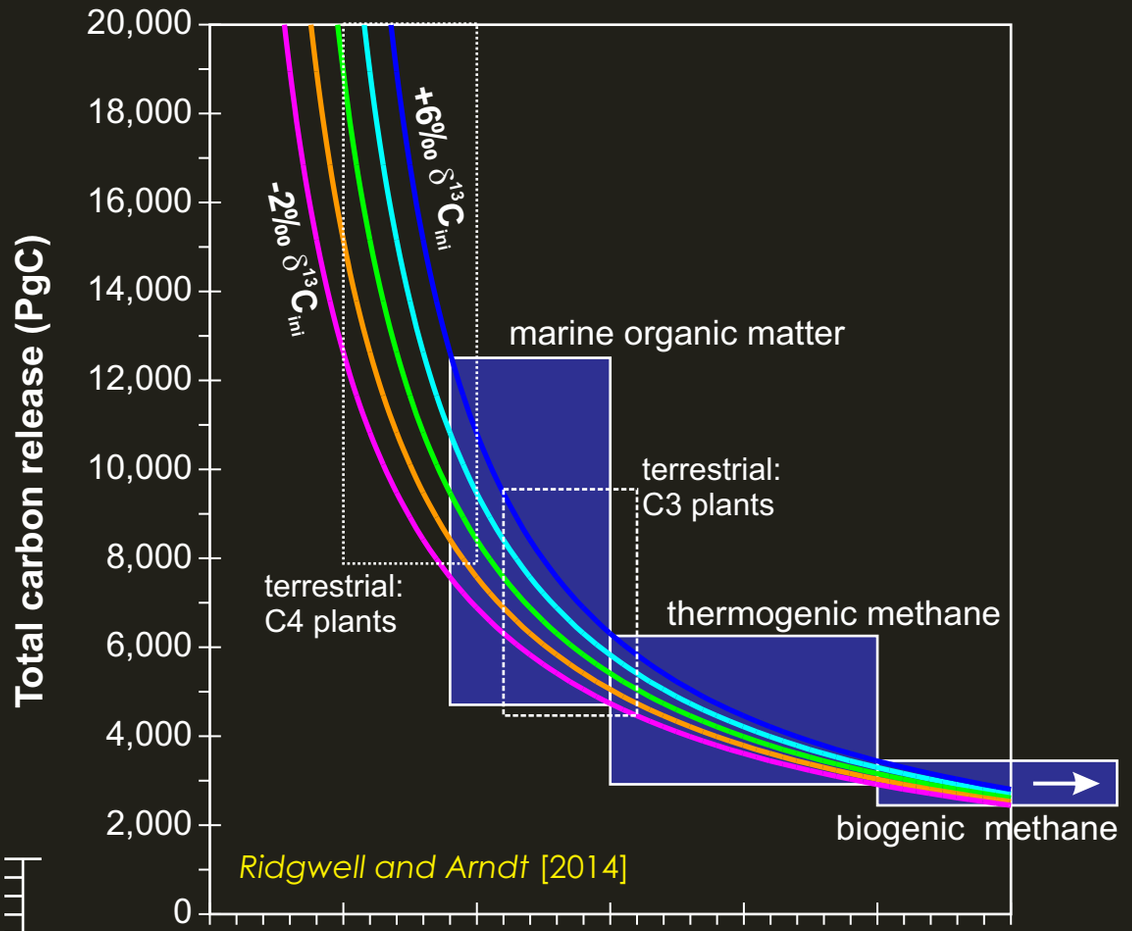
Westbrook et al. [2009]

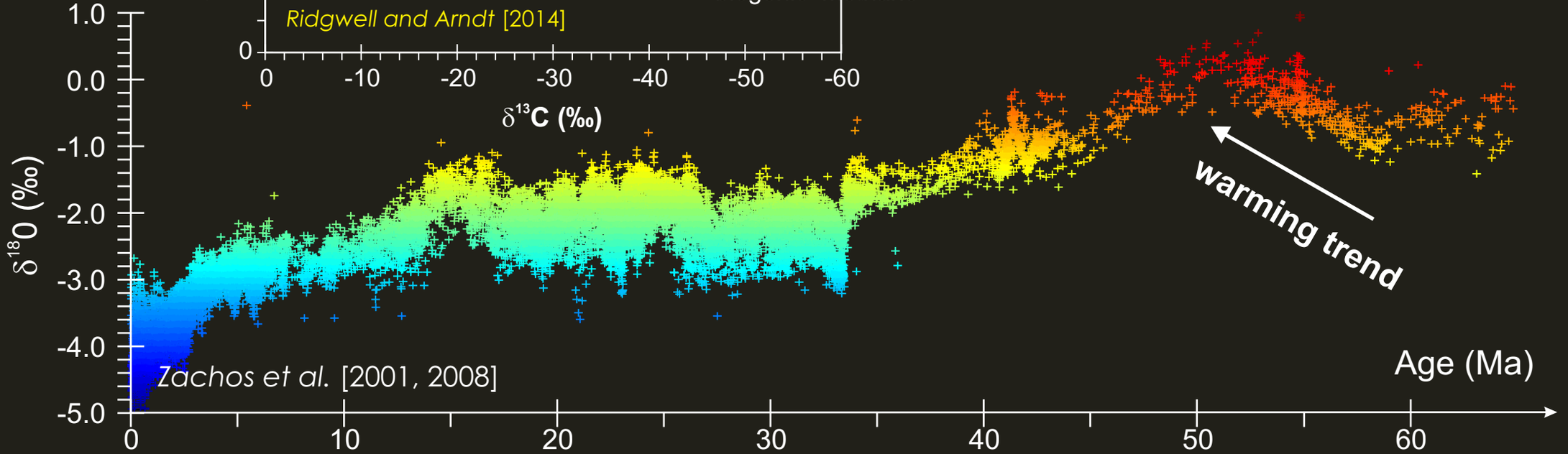
Climate fedback with methane hydrates

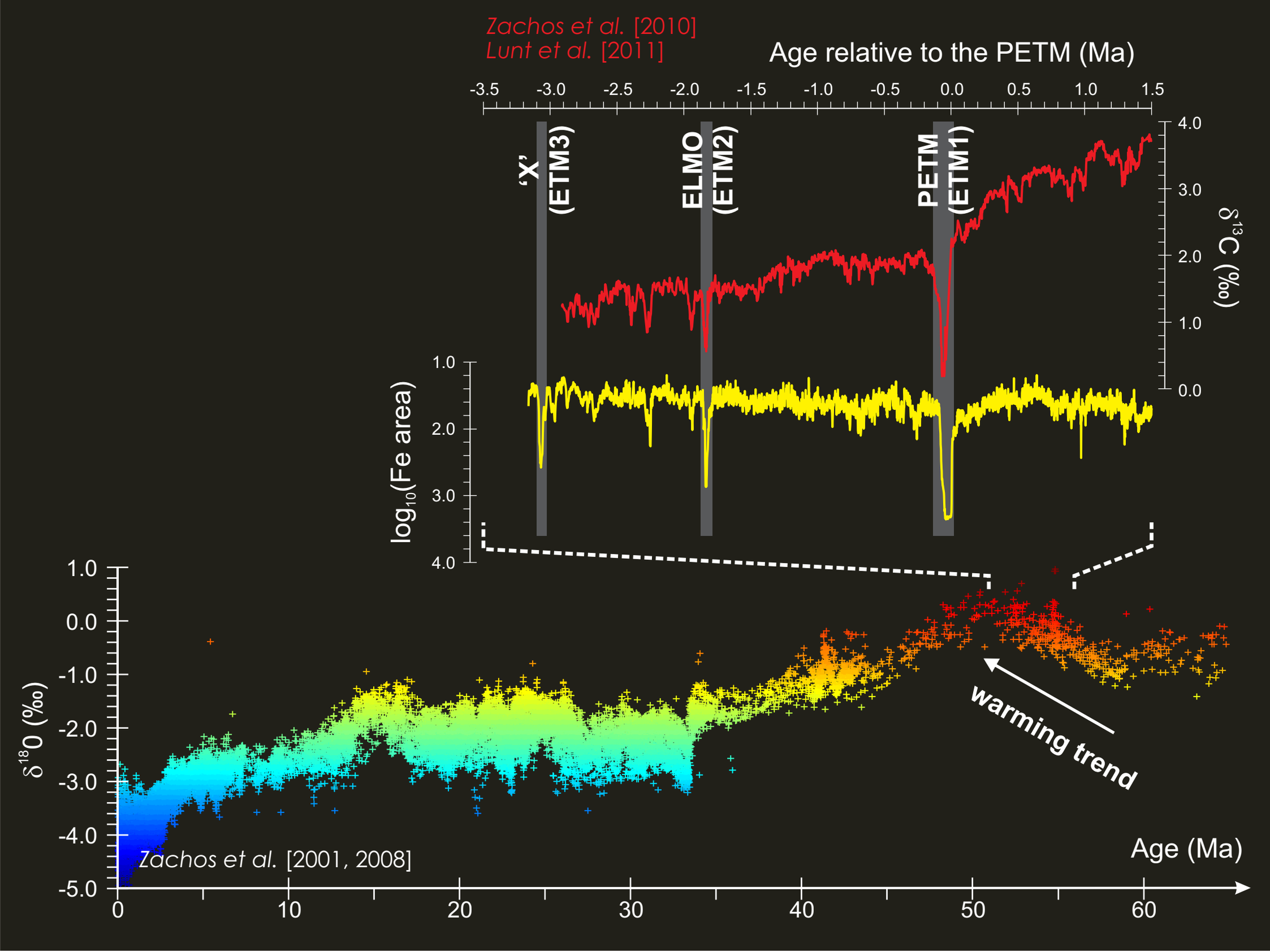




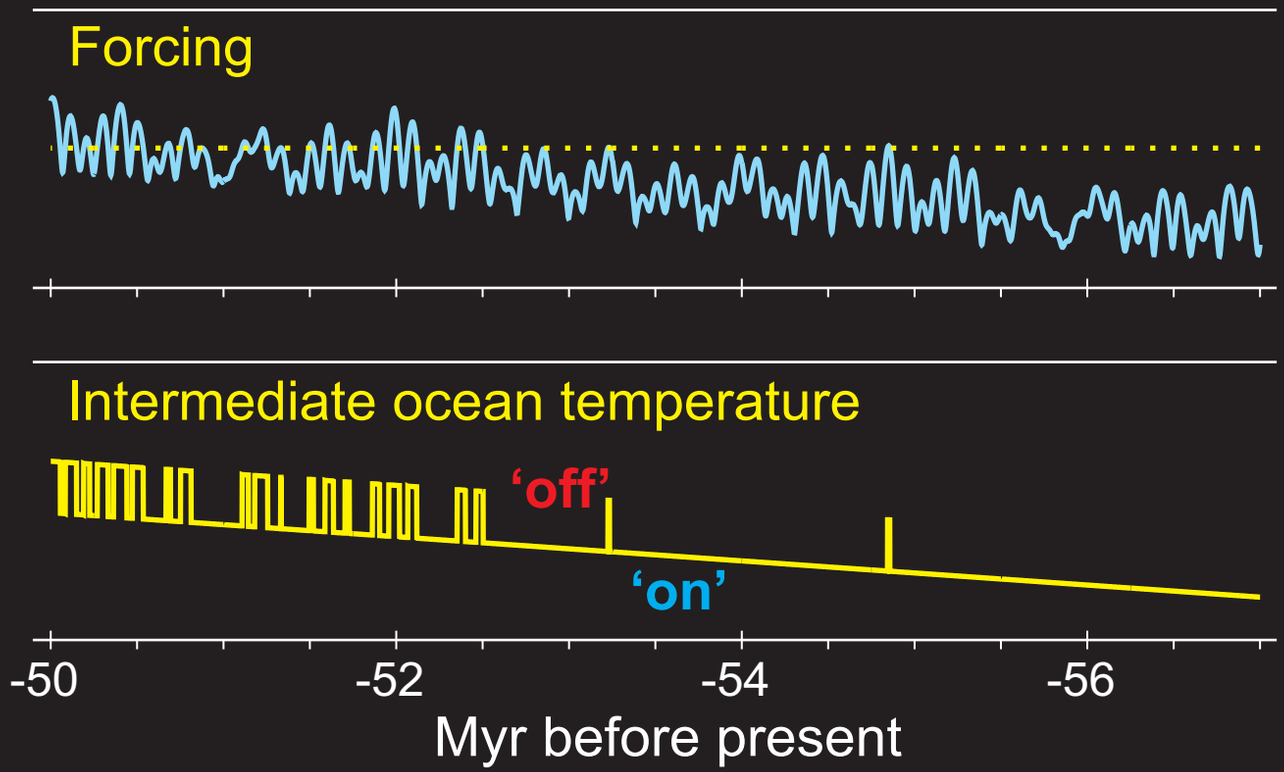
Climate fedback with methane hydrates

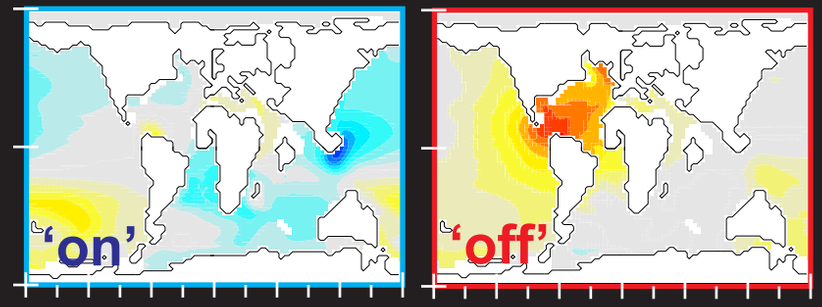





Zachos et al. [2010]
Lunt et al. [2011]
Age relative to the PETM (Ma)
-3.5
-3.0
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
'X' (ETM3)
ELMO (ETM2)
PETM (ETM1)
4.0
3.0
2.0
1.0
0.0
δ13C (‰)
log10(Fe area)
1.0
2.0
3.0
4.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
δ18O (‰)
warming trend
Zachos et al. [2001, 2008]
Age (Ma)
0
10
20
30
40
50
60

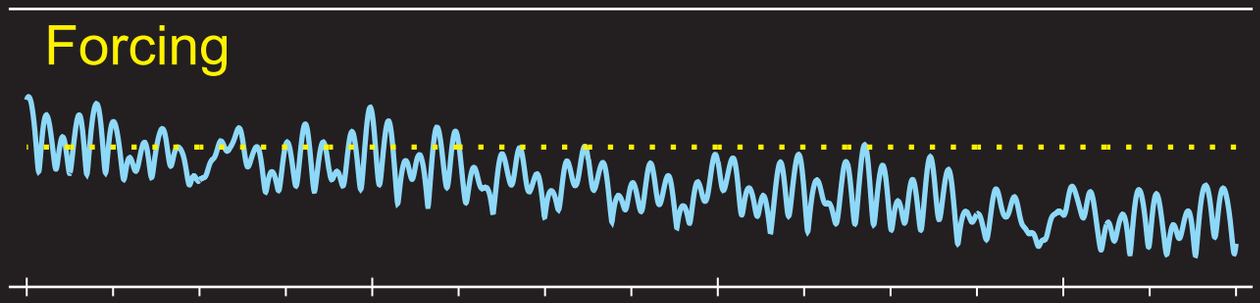
Orbital pacing of methane hydrate destabilisation during the Palaeogene?

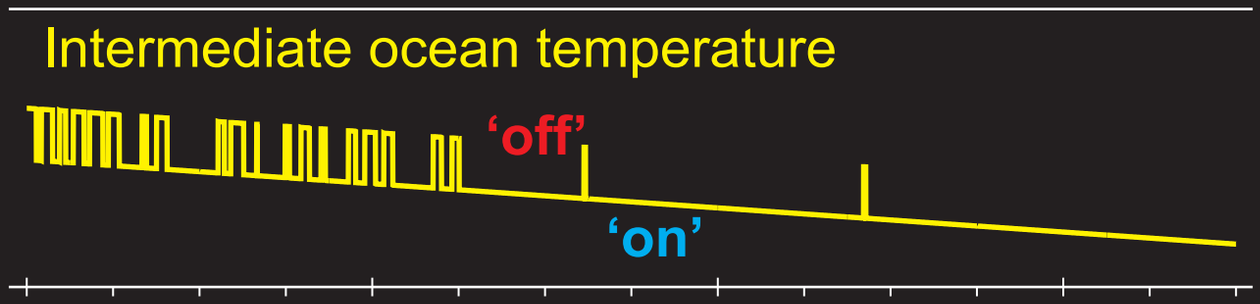


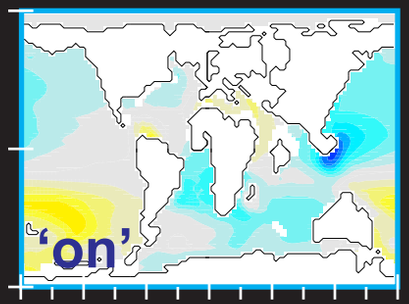


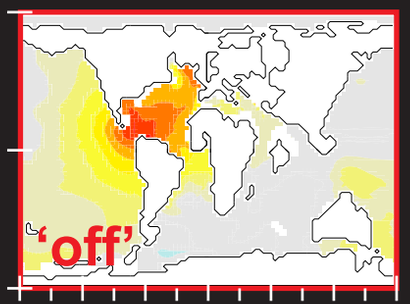
Lunt et al. [2011]

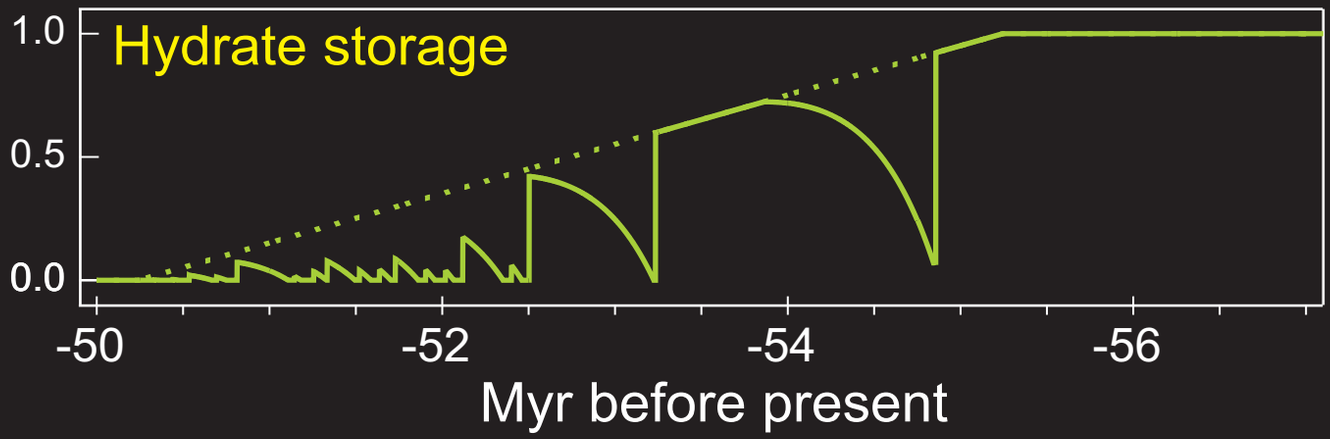
Orbital pacing of methane hydrate destabilisation during the Palaeogene?





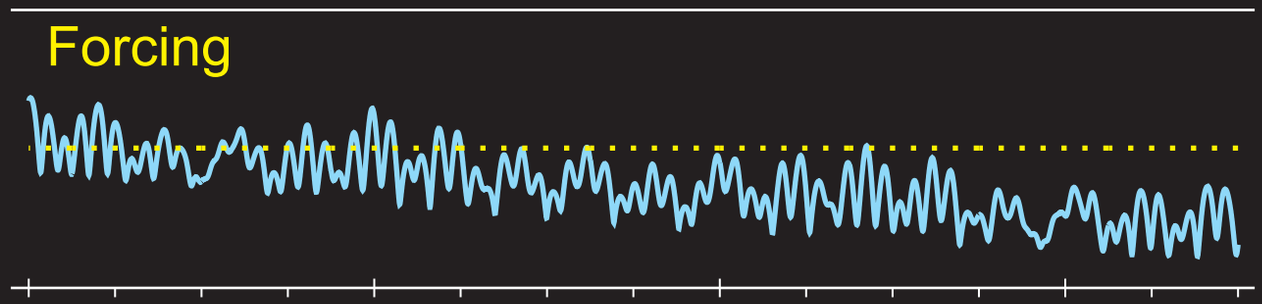


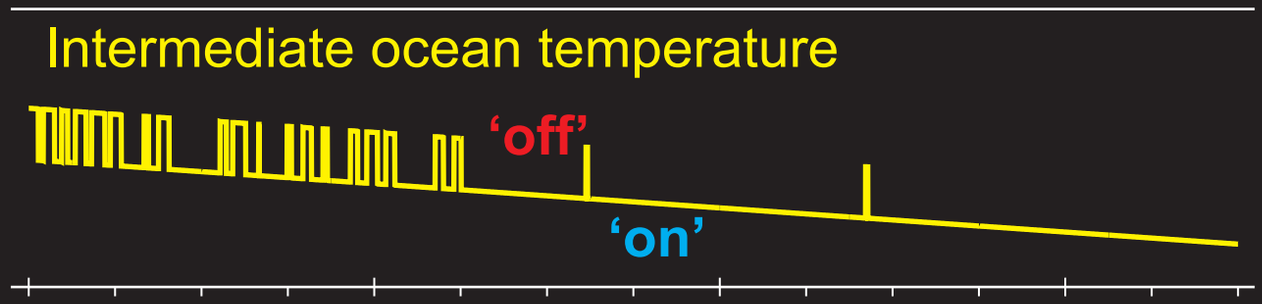


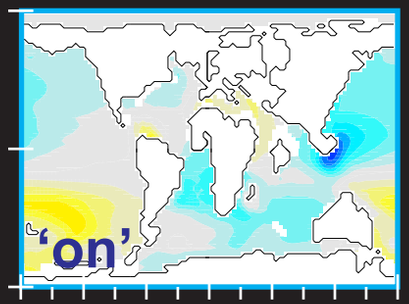


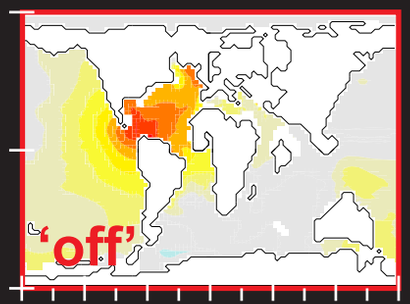
Lunt et al. [2011]

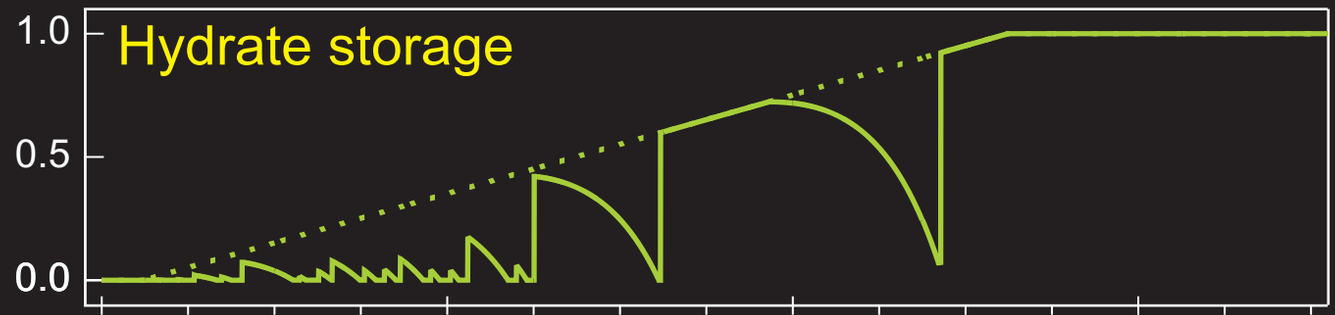
Orbital pacing of methane hydrate destabilisation during the Palaeogene?

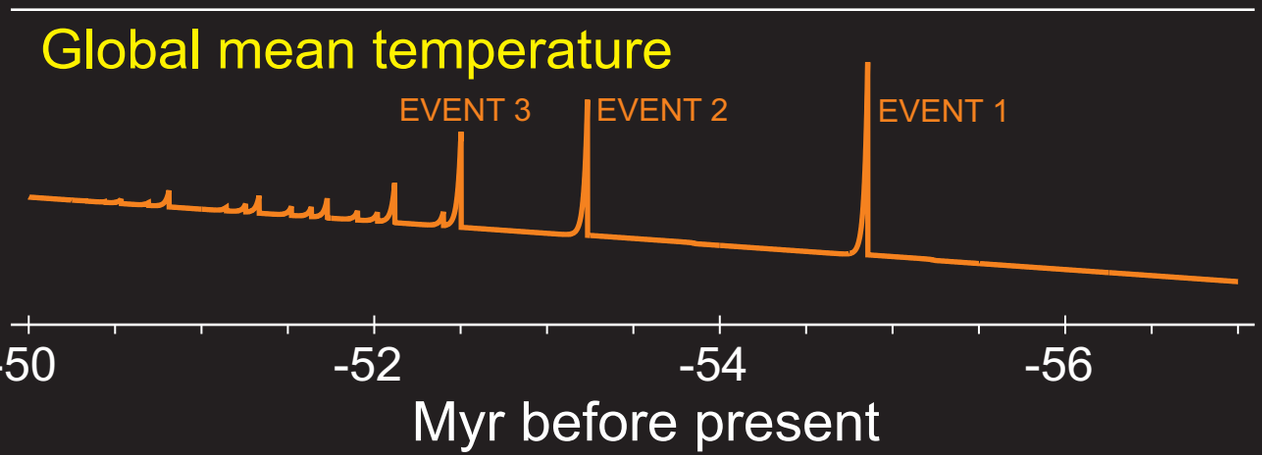












Lunt et al. [2011]

Climate fedback with methane hydrates

biological productivity

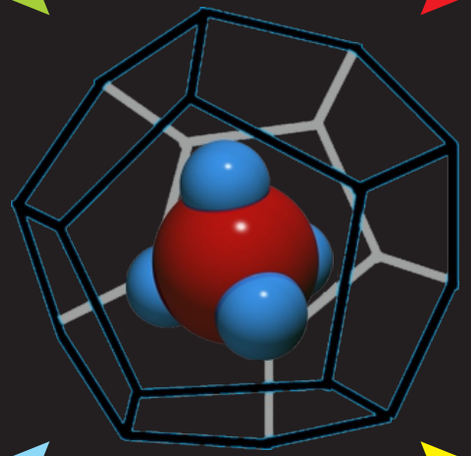
climate and ocean circulation

greenhouse gas forcing

ocean $[O_2]$

sedimentary organic matter burial flux

bottom-water temperature

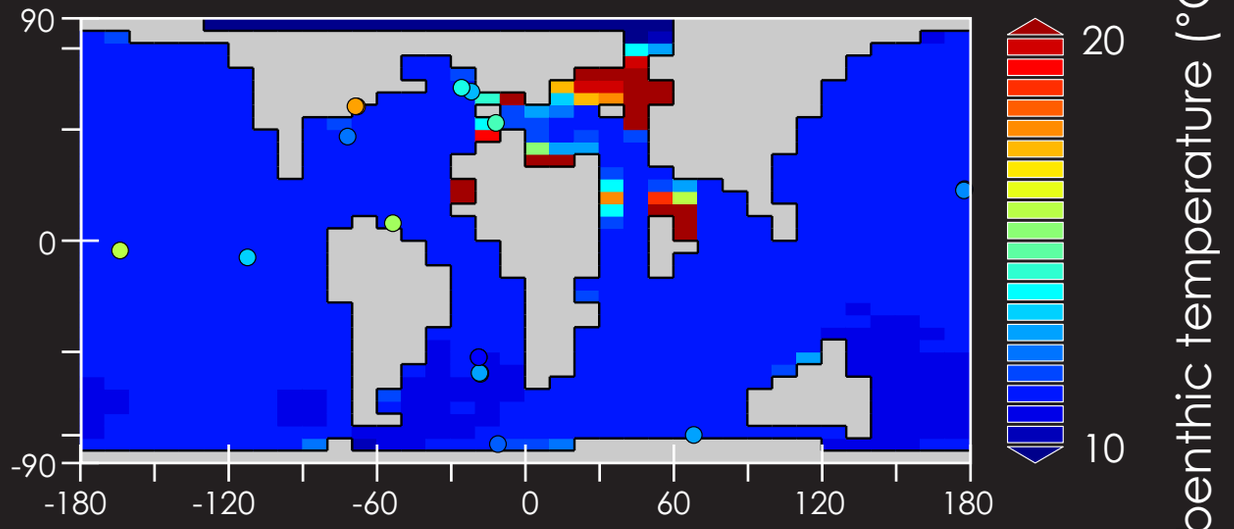


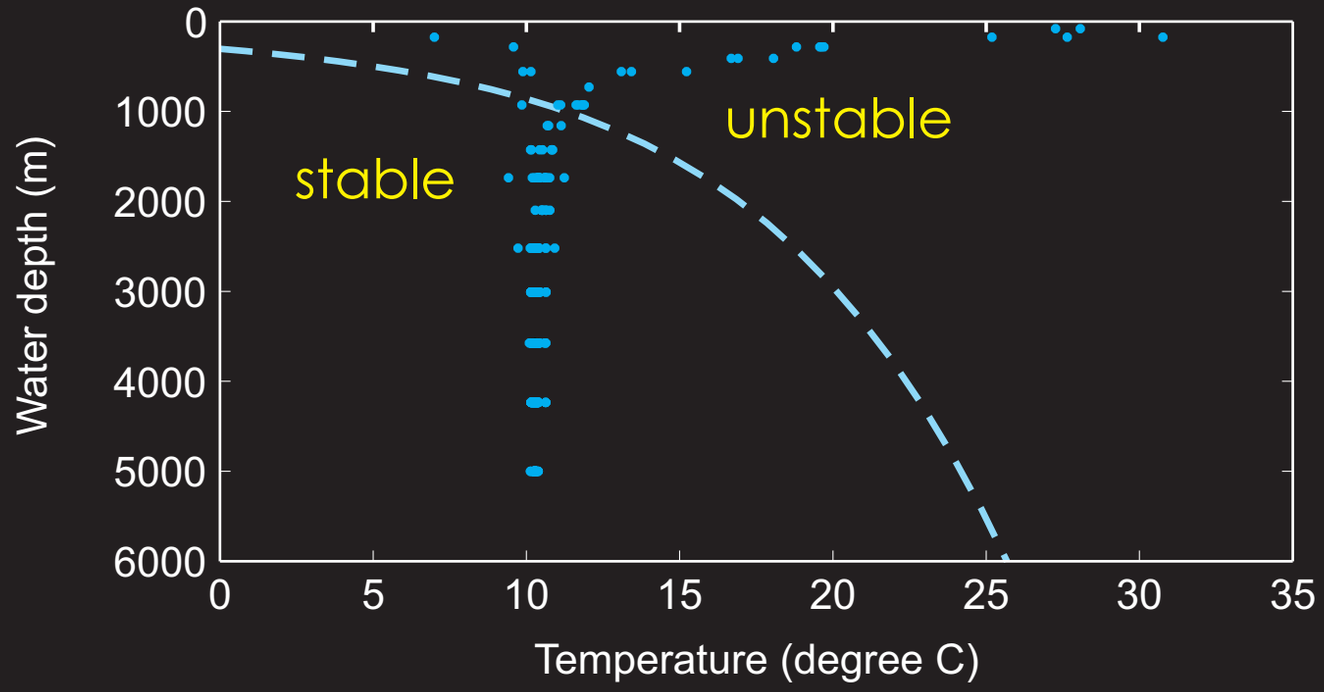
paleo topography

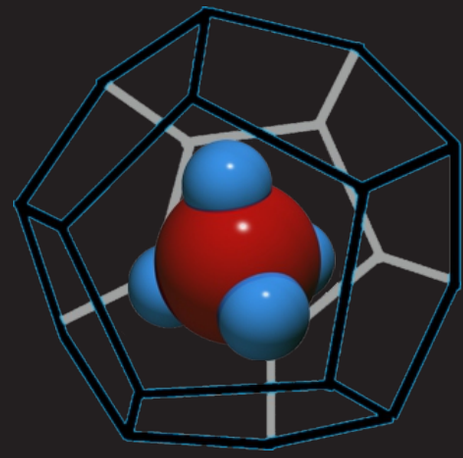
pressure

active/passive margin
bulk sedimentation rate
geothermal gradient
organic matter degradability

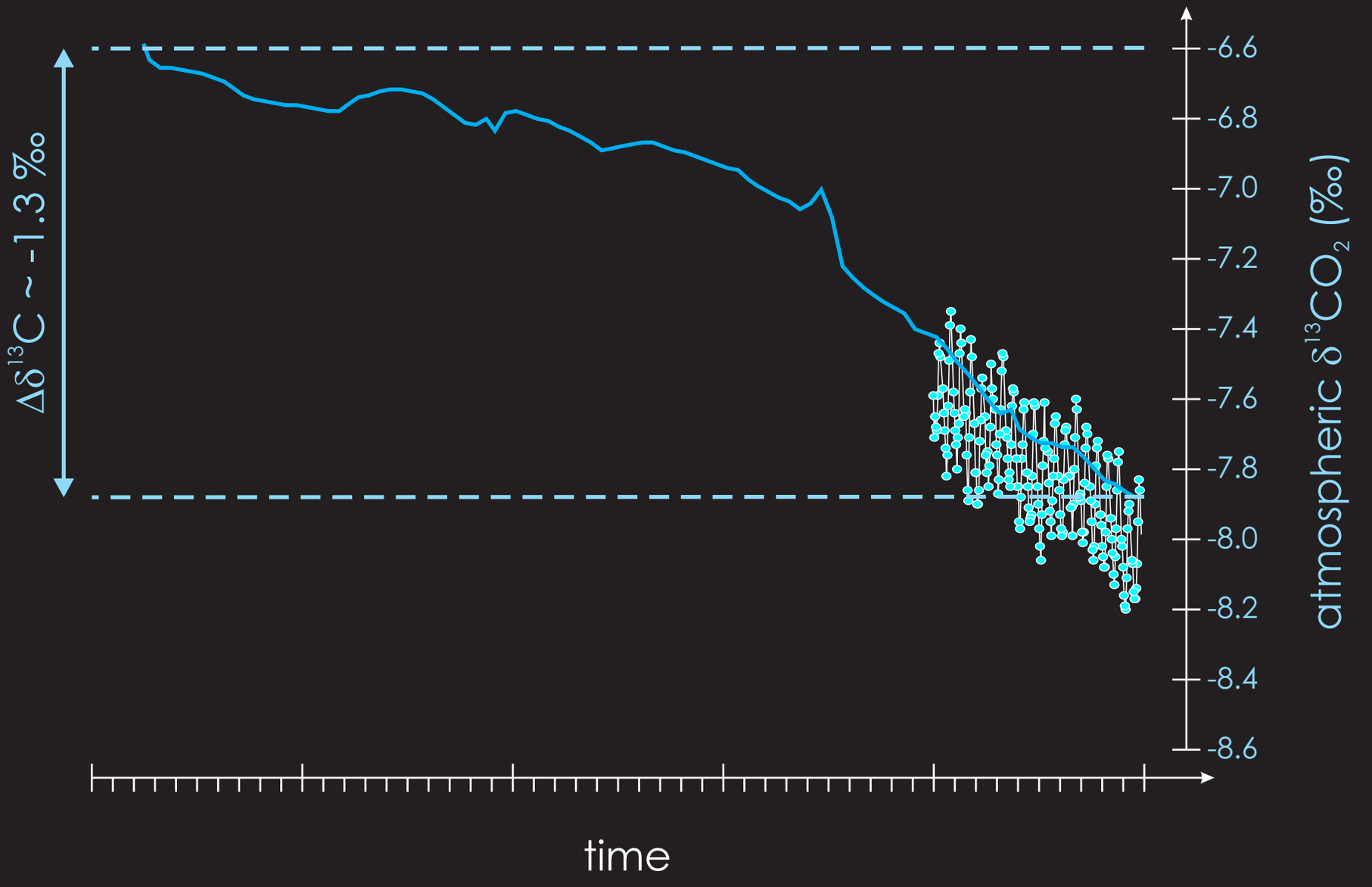
Climate fedback with methane hydrates



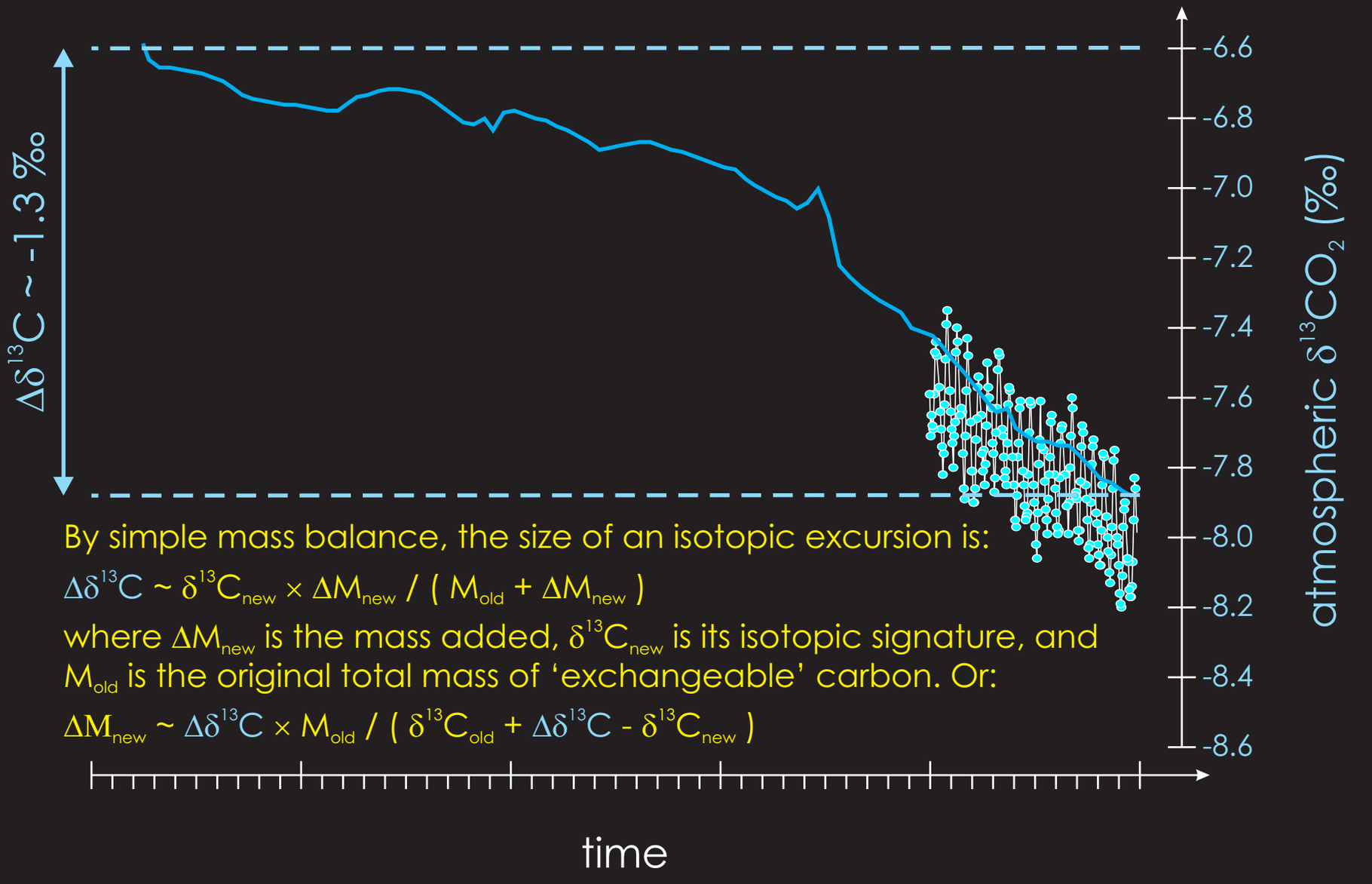




Methods


$\Delta\delta^{13}C \sim -1.3$ ‰
-6.6
-6.8
-7.0
-7.2
-7.4
-7.6
-7.8
-8.0
-8.2
-8.4
-8.6
atmospheric $\delta^{13}CO_2$ (‰)
time

Methods



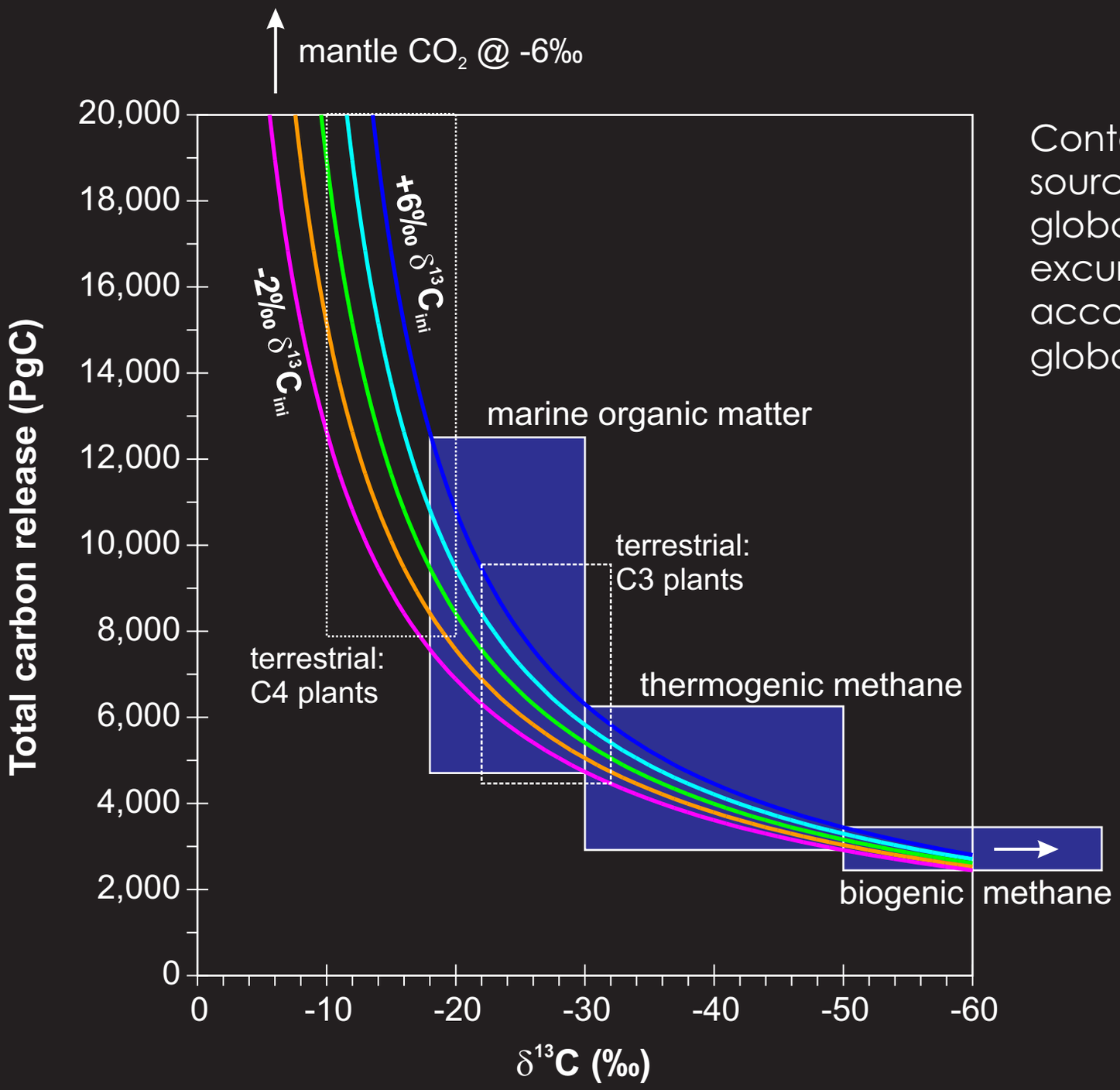
By simple mass balance, the size of an isotopic excursion is:

$\Delta\delta^{13}C \sim \delta^{13}C_{new} \times \Delta M_{new} / (M_{old} + \Delta M_{new})$

where ΔM_{new} is the mass added, $\delta^{13}C_{new}$ is its isotopic signature, and M_{old} is the original total mass of 'exchangeable' carbon. Or:

$\Delta M_{new} \sim \Delta\delta^{13}C \times M_{old} / (\delta^{13}C_{old} + \Delta\delta^{13}C - \delta^{13}C_{new})$

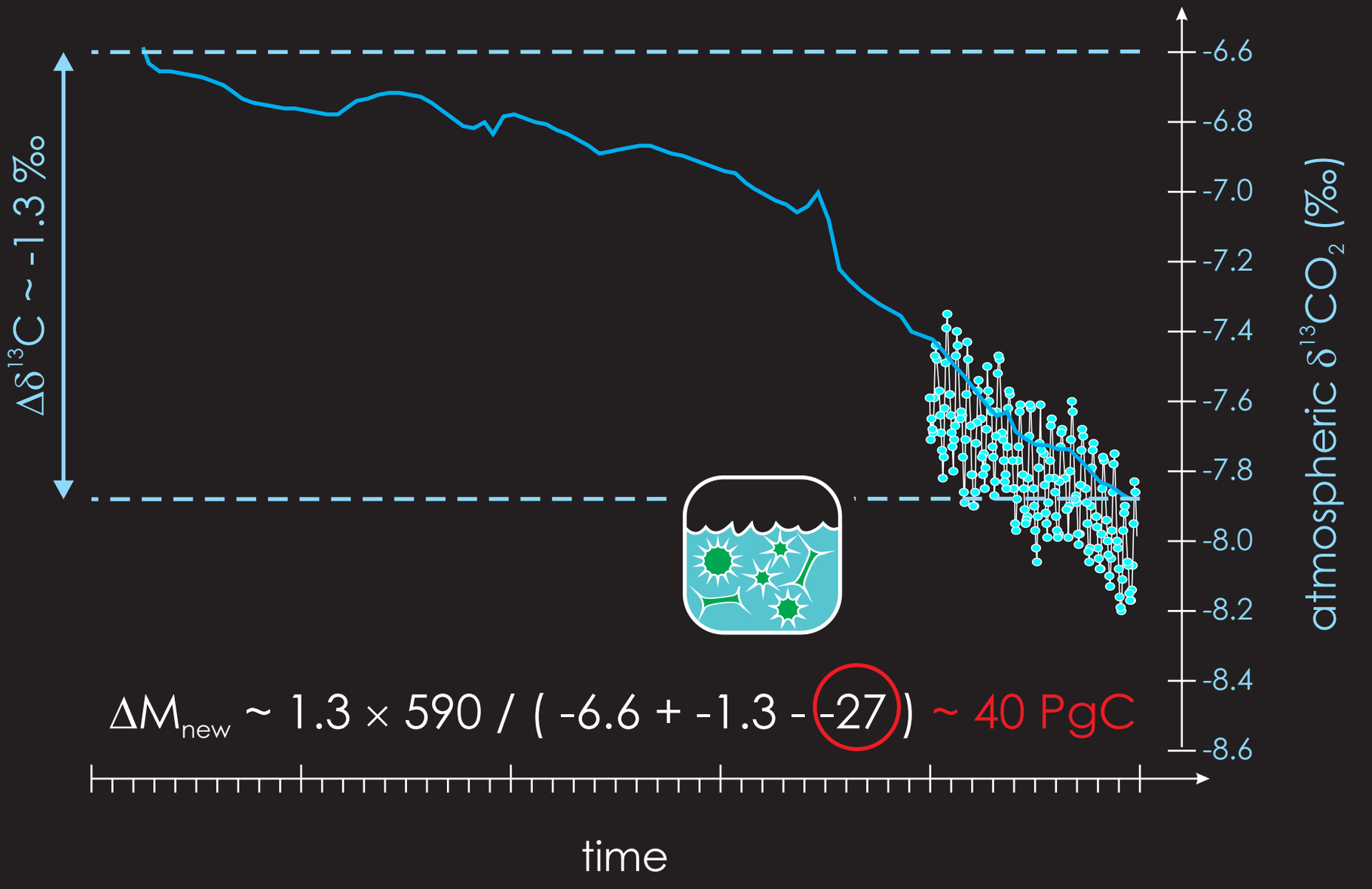
Methods



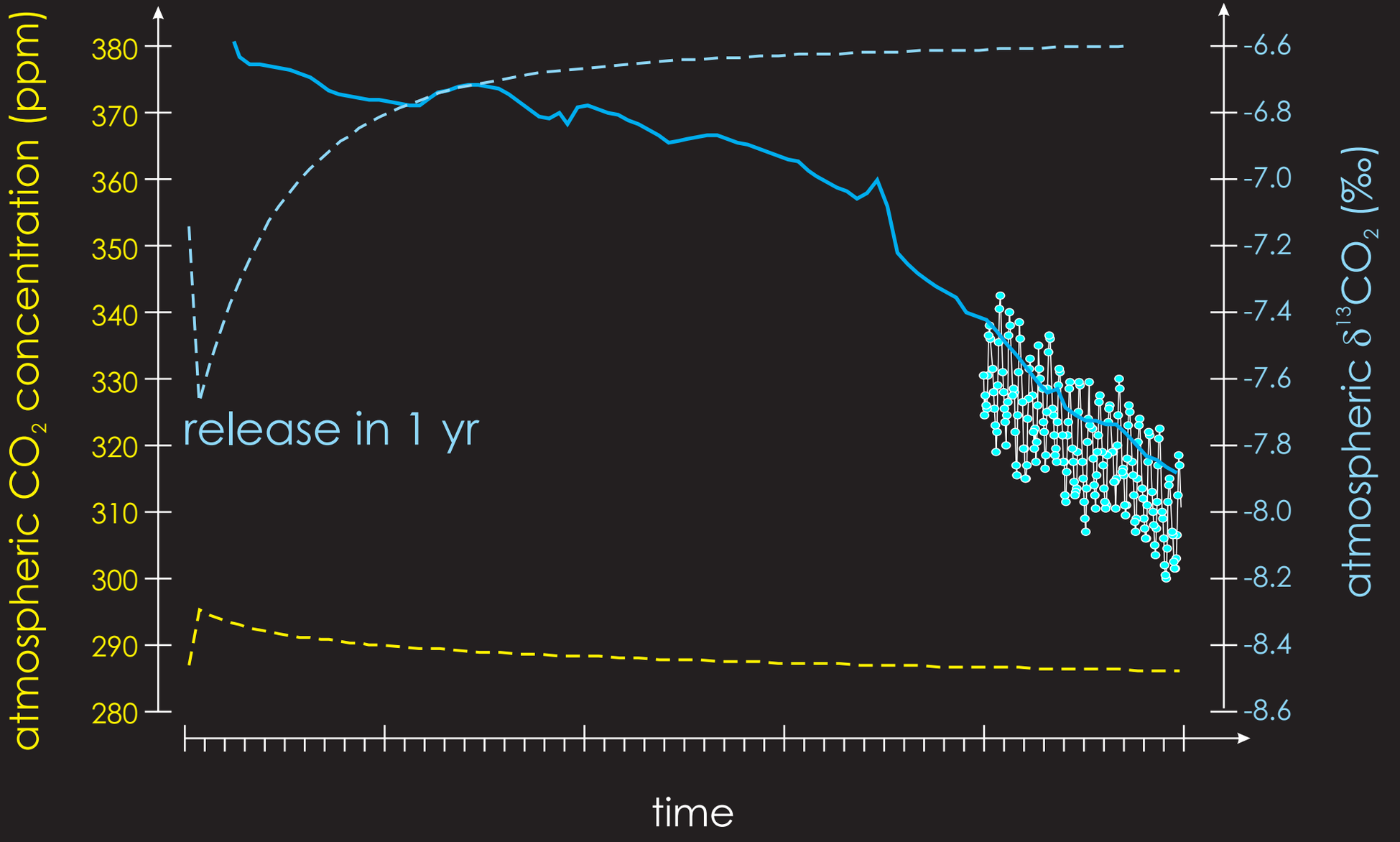
Contours of carbon release vs. source isotopic signature for a global -4‰ carbon isotopic excursion. Contours differ according to the initial mean global $\delta^{13}C$.

Ridgwell and Arndt [2014]

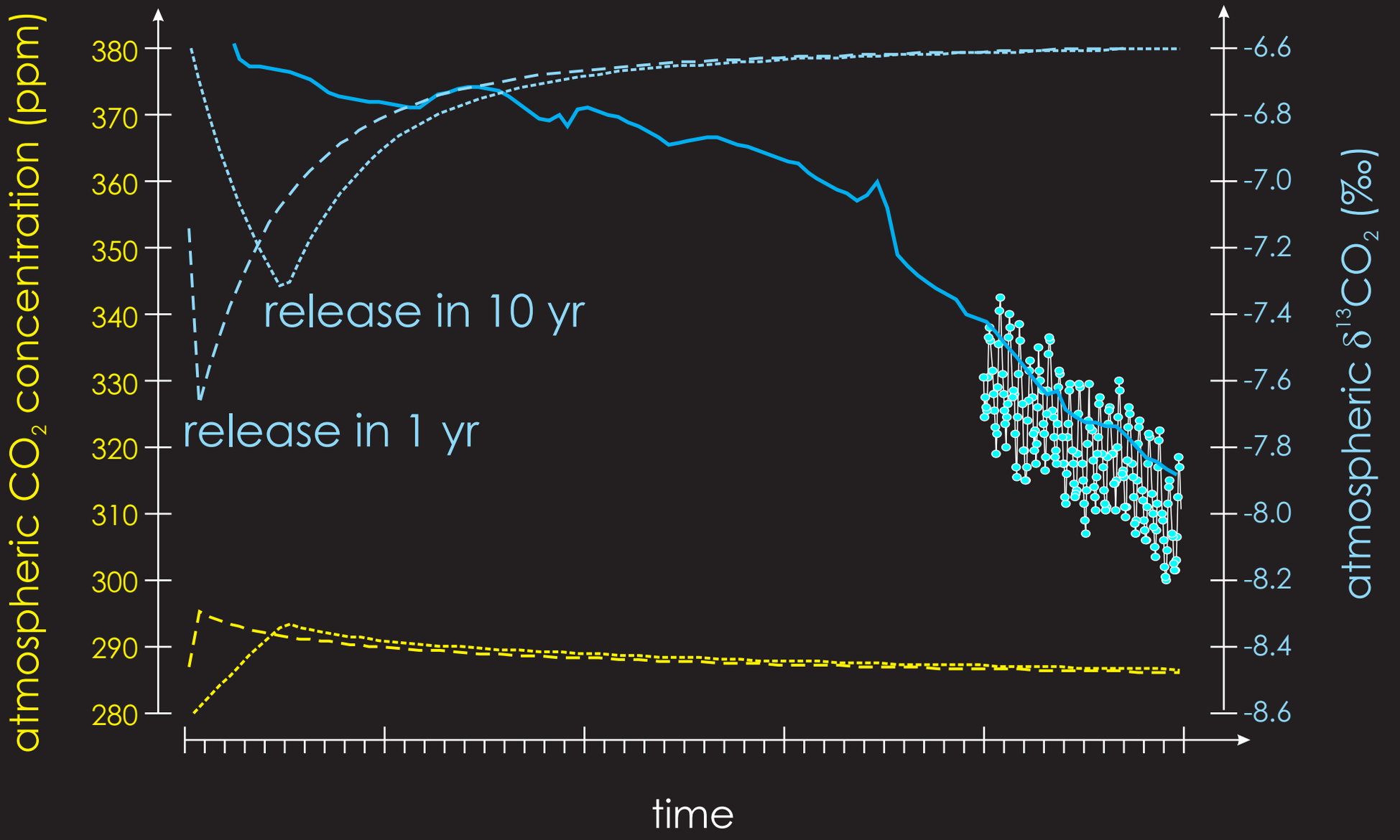
Methods


$\Delta\delta^{13}C \sim -1.3$ ‰
-6.6
-6.8
-7.0
-7.2
-7.4
-7.6
-7.8
-8.0
-8.2
-8.4
-8.6
atmospheric $\delta^{13}CO_2$ (‰)
$\Delta M_{new} \sim 1.3 \times 590 / (-6.6 + -1.3 - -27) \sim 40$ PgC
time

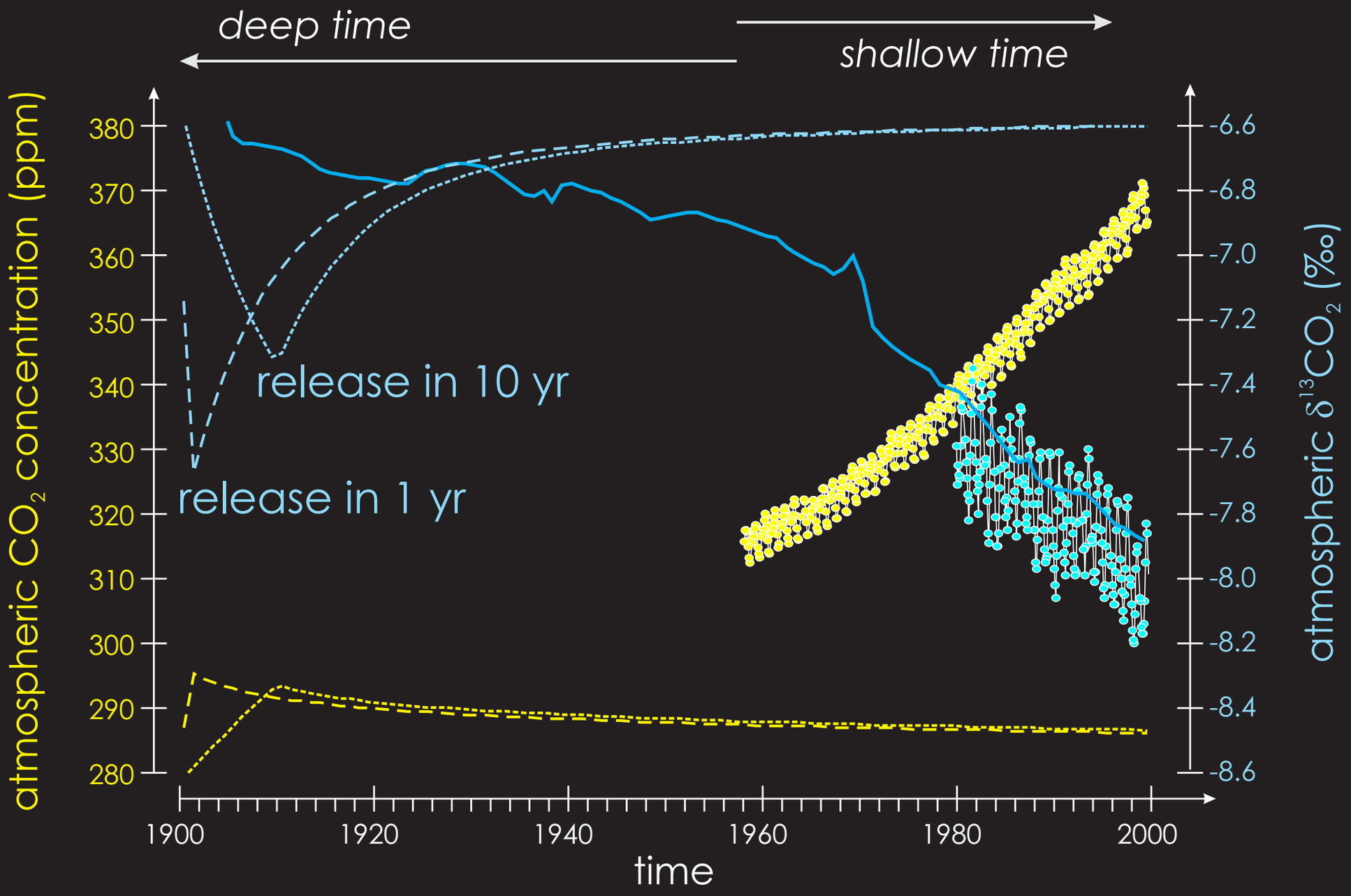
Methods

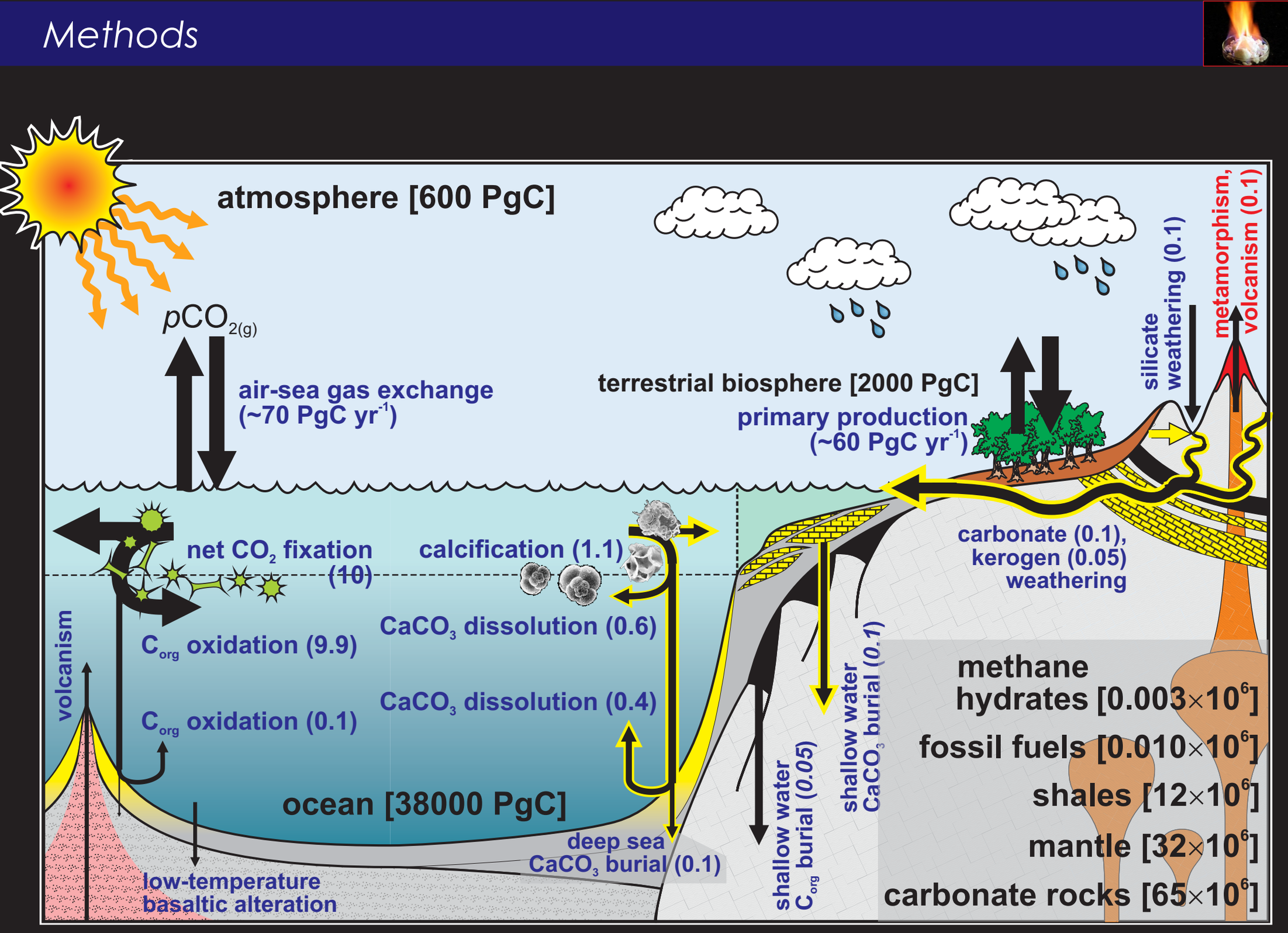

atmospheric CO_2 concentration (ppm)
380
370
360
350
340
330
320
310
300
290
280
release in 1 yr
-6.6
-6.8
-7.0
-7.2
-7.4
-7.6
-7.8
-8.0
-8.2
-8.4
-8.6
atmospheric $\delta^{13}CO_2$ (‰)
time

Methods

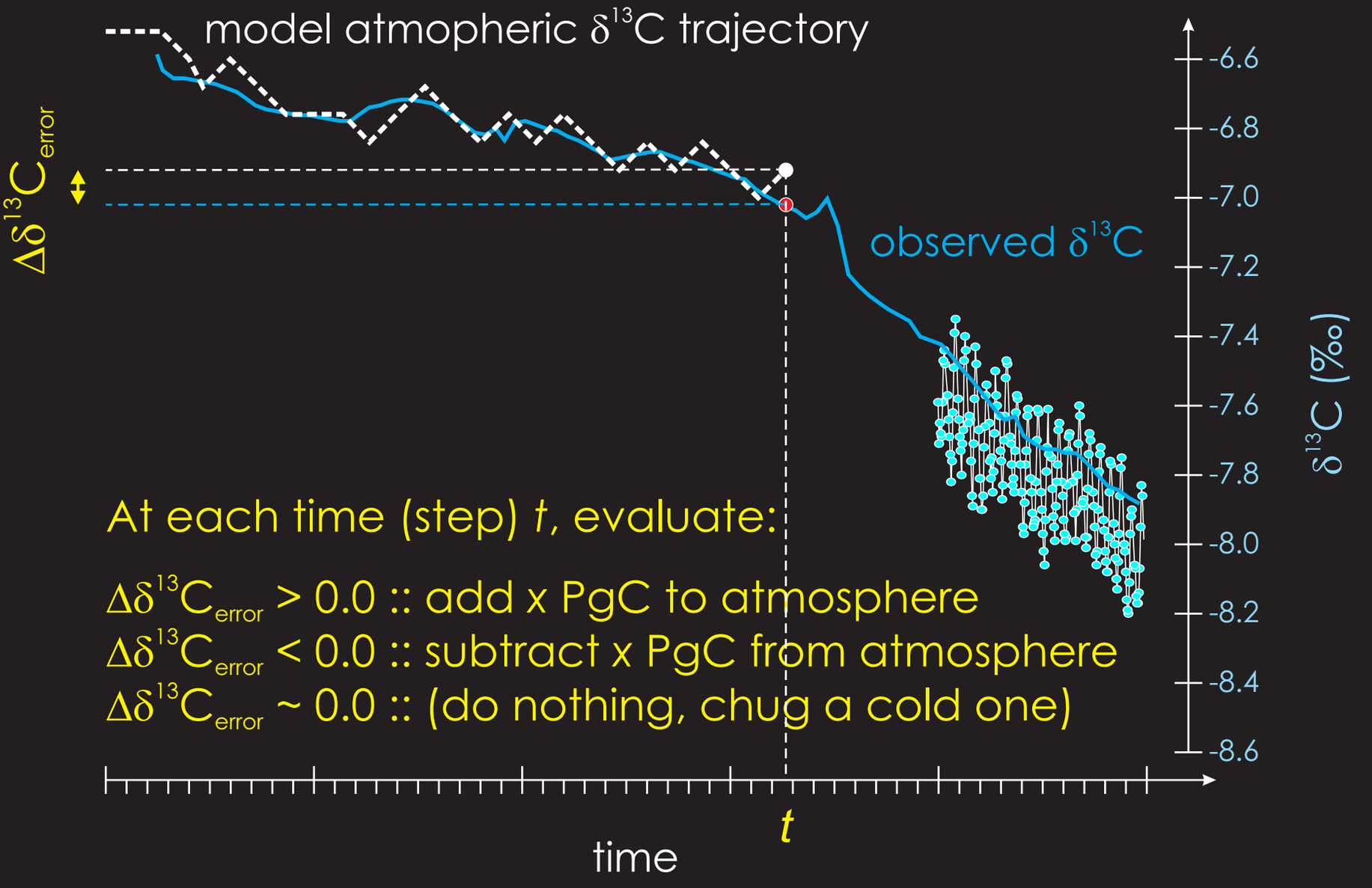

atmospheric CO_2 concentration (ppm)
380
370
360
350
340
330
320
310
300
290
280
release in 10 yr
release in 1 yr
-6.6
-6.8
-7.0
-7.2
-7.4
-7.6
-7.8
-8.0
-8.2
-8.4
-8.6
atmospheric $\delta^{13}CO_2$ (‰)
time

Methods

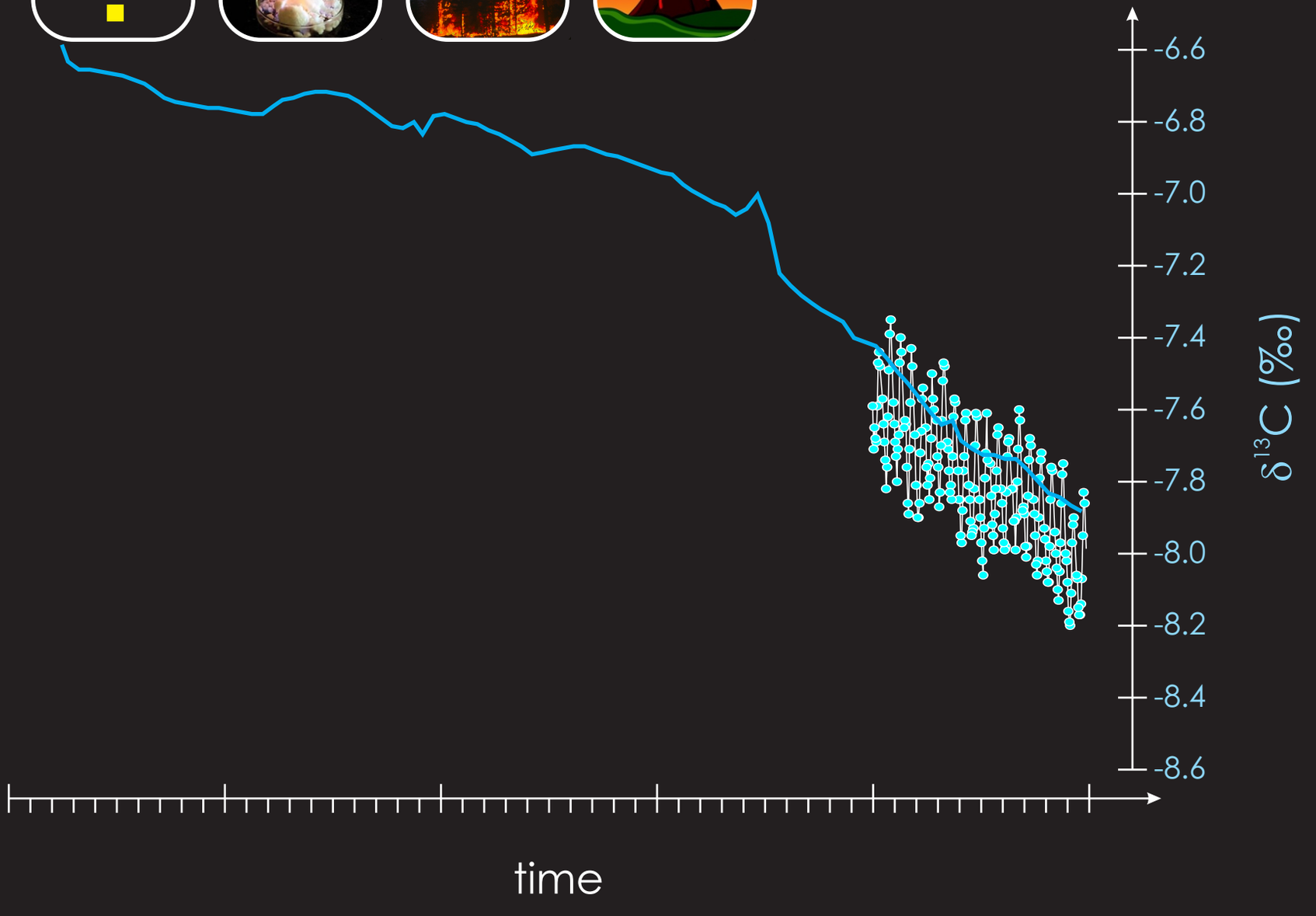

deep time
shallow time
release in 10 yr
release in 1 yr
atmospheric CO_2 concentration (ppm)
atmospheric $\delta^{13}CO_2$ (‰)
380
370
360
350
340
330
320
310
300
290
280
-6.6
-6.8
-7.0
-7.2
-7.4
-7.6
-7.8
-8.0
-8.2
-8.4
-8.6
1900
1920
1940
1960
1980
2000
time


atmosphere [600 PgC]
$pCO_{2(g)}$
air-sea gas exchange
(~70 PgC yr^{-1})
terrestrial biosphere [2000 PgC]
primary production
(~60 PgC yr^{-1})
silicate
weathering (0.1)
metamorphism,
volcanism (0.1)
carbonate (0.1),
kerogen (0.05)
weathering
net CO_2 fixation
(10)
calcification (1.1)
$CaCO_3$ dissolution (0.6)
C_{org} oxidation (9.9)
$CaCO_3$ dissolution (0.4)
C_{org} oxidation (0.1)
volcanism
ocean [38000 PgC]
deep sea
$CaCO_3$ burial (0.1)
low-temperature
basaltic alteration
shallow water
C_{org} burial (0.05)
shallow water
$CaCO_3$ burial (0.1)
methane
hydrates [0.003×10^6]
fossil fuels [0.010×10^6]
shales [12×10^6]
mantle [32×10^6]
carbonate rocks [65×10^6]

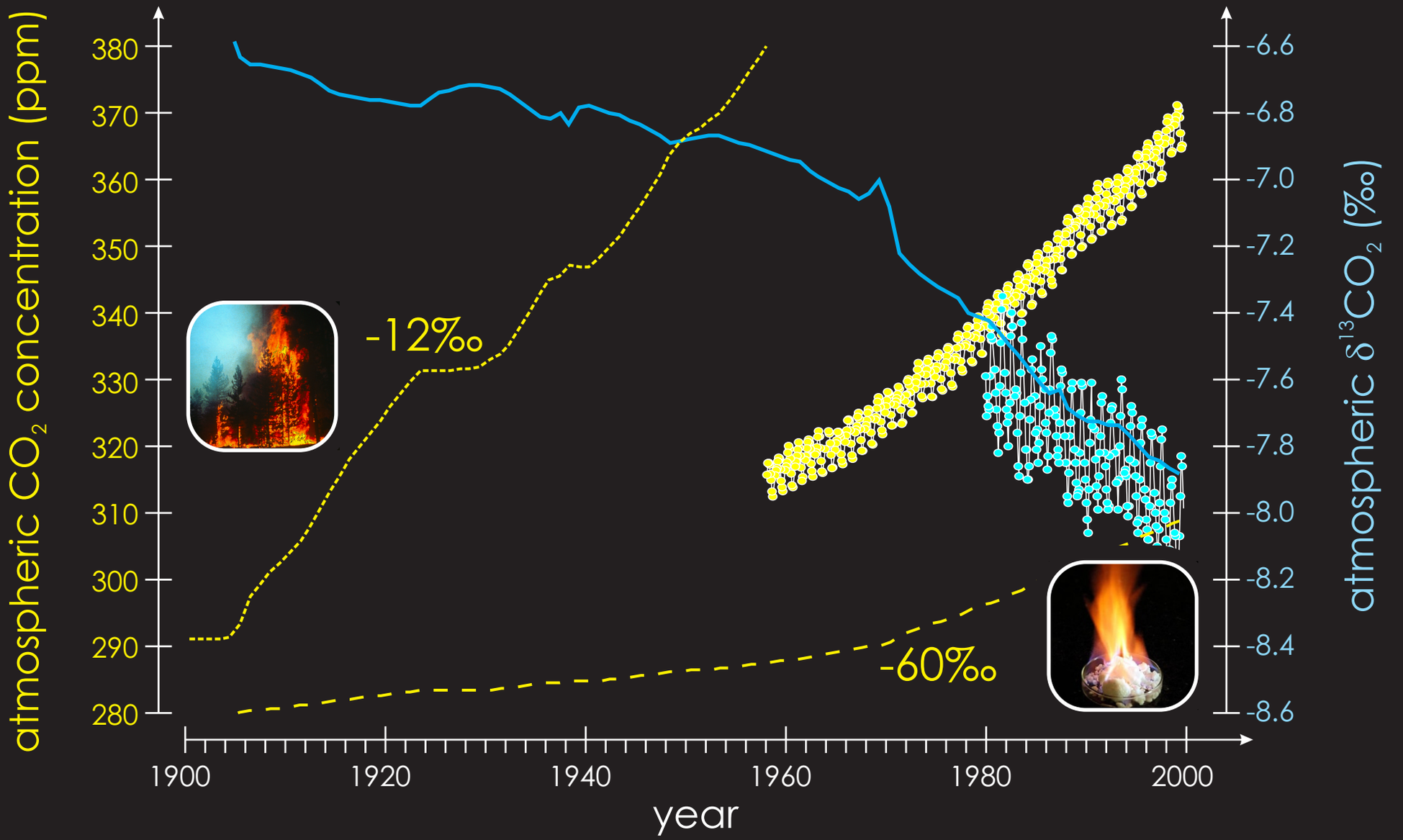
Methods


model atmopheric δ13C trajectory
observed δ13C
Δδ13Cerror
δ13C (‰)
-6.6
-6.8
-7.0
-7.2
-7.4
-7.6
-7.8
-8.0
-8.2
-8.4
-8.6
At each time (step) t, evaluate:
Δδ13Cerror > 0.0 :: add x PgC to atmosphere
Δδ13Cerror < 0.0 :: subtract x PgC from atmosphere
Δδ13Cerror ~ 0.0 :: (do nothing, chug a cold one)
t
time

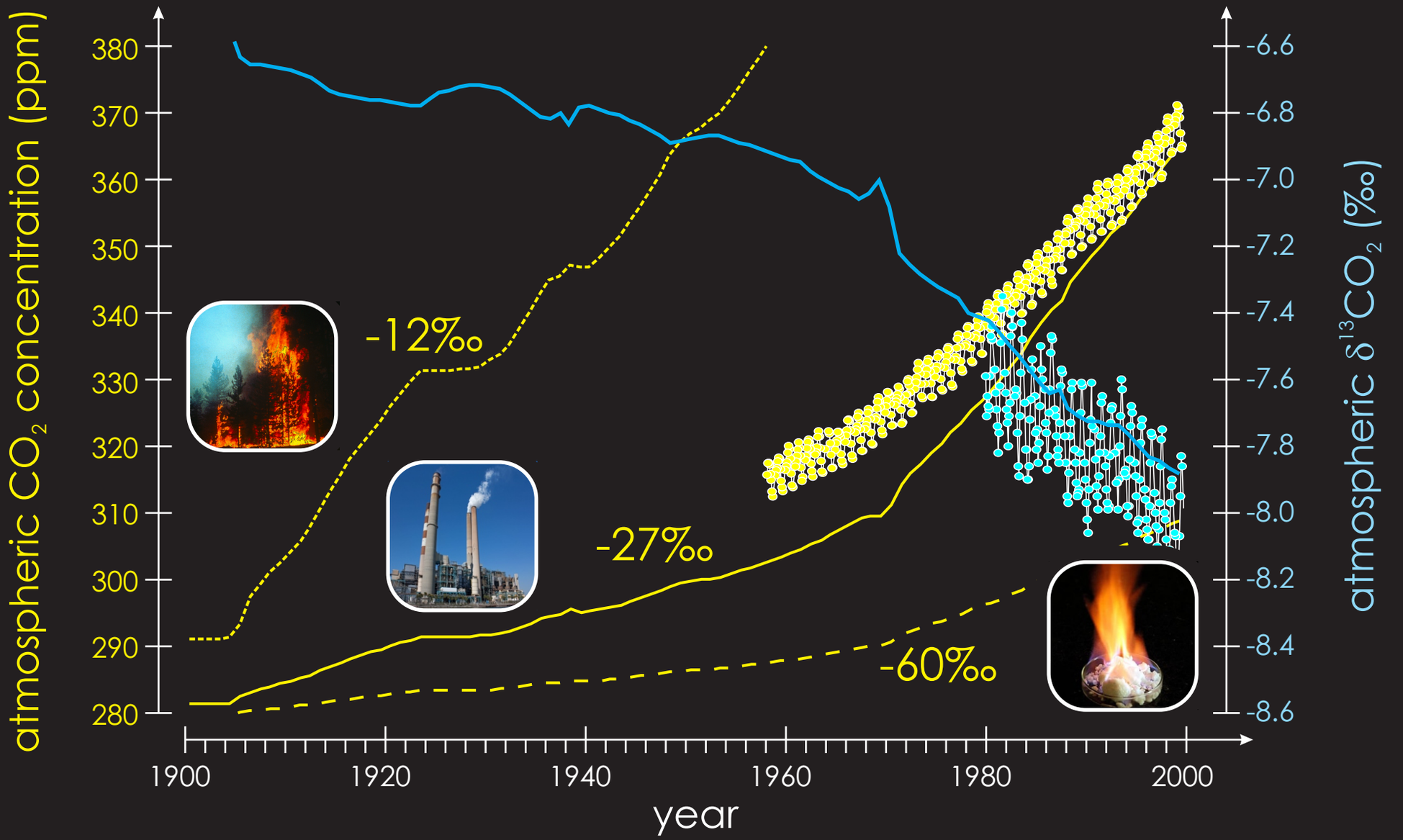
Methods



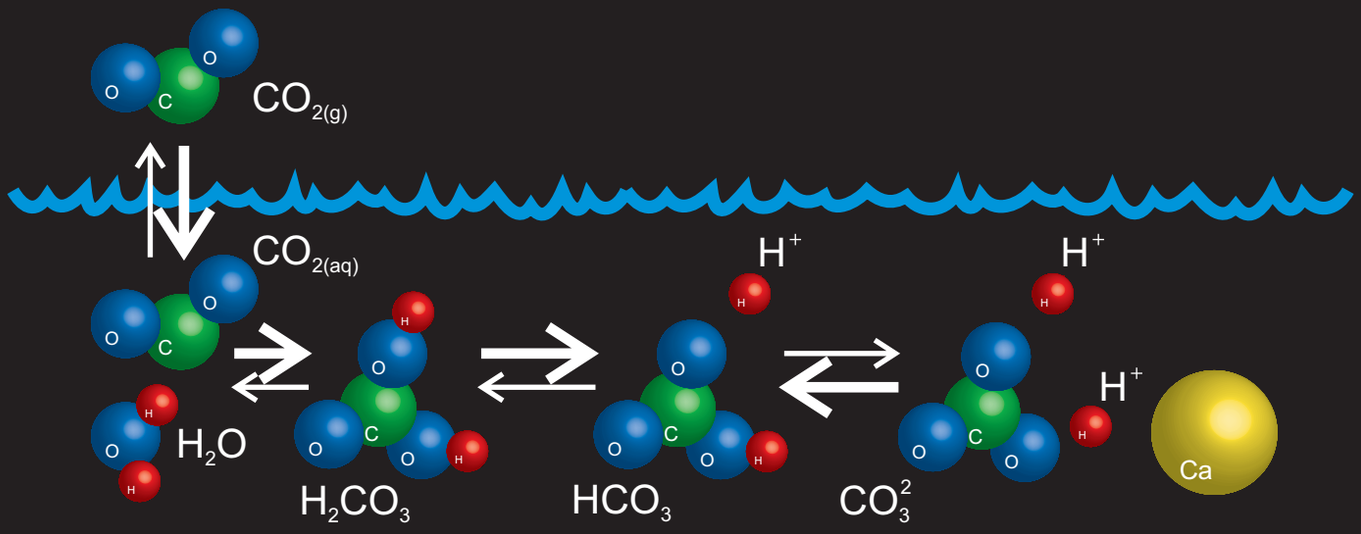
Methods


atmospheric CO_2 concentration (ppm)
380
370
360
350
340
330
320
310
300
290
280
-12‰
-60‰
atmospheric $\delta^{13}CO_2$ (‰)
-6.6
-6.8
-7.0
-7.2
-7.4
-7.6
-7.8
-8.0
-8.2
-8.4
-8.6
1900
1920
1940
1960
1980
2000
year

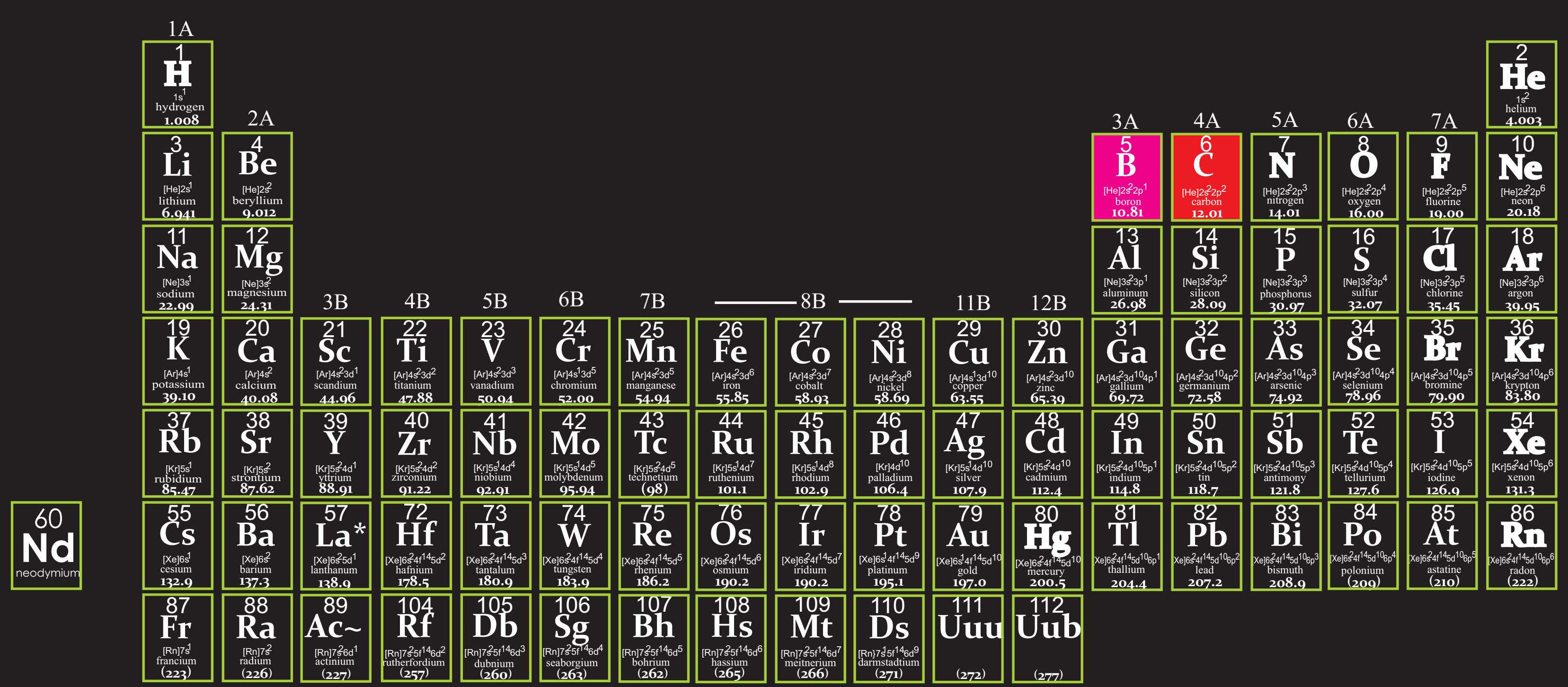
Methods


atmospheric CO_2 concentration (ppm)
380
370
360
350
340
330
320
310
300
290
280
-12‰
-27‰
-60‰
1900
1920
1940
1960
1980
2000
year
-6.6
-6.8
-7.0
-7.2
-7.4
-7.6
-7.8
-8.0
-8.2
-8.4
-8.6
atmospheric $\delta^{13}CO_2$ (‰)

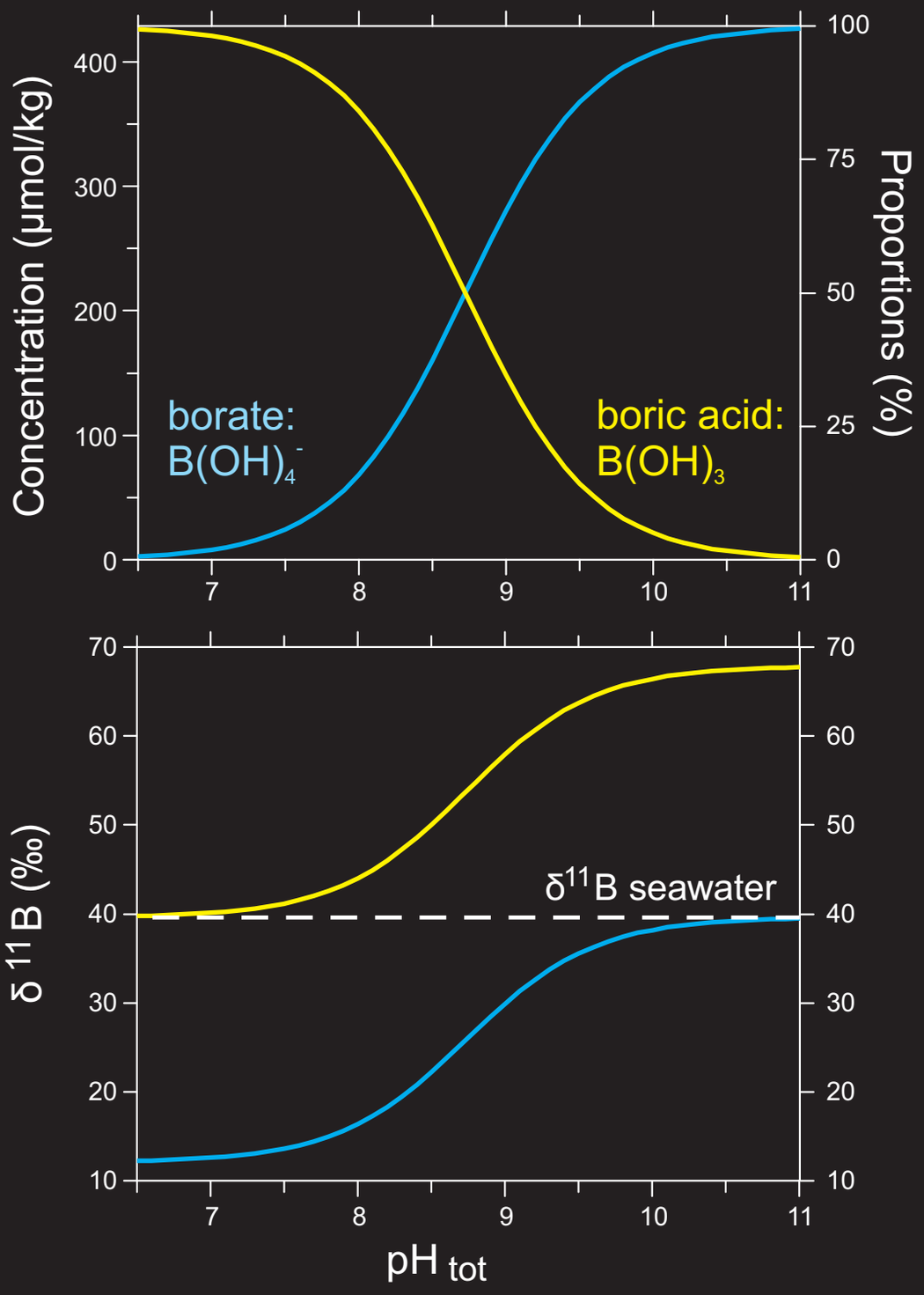
Boron, isotopes, and paleo pH



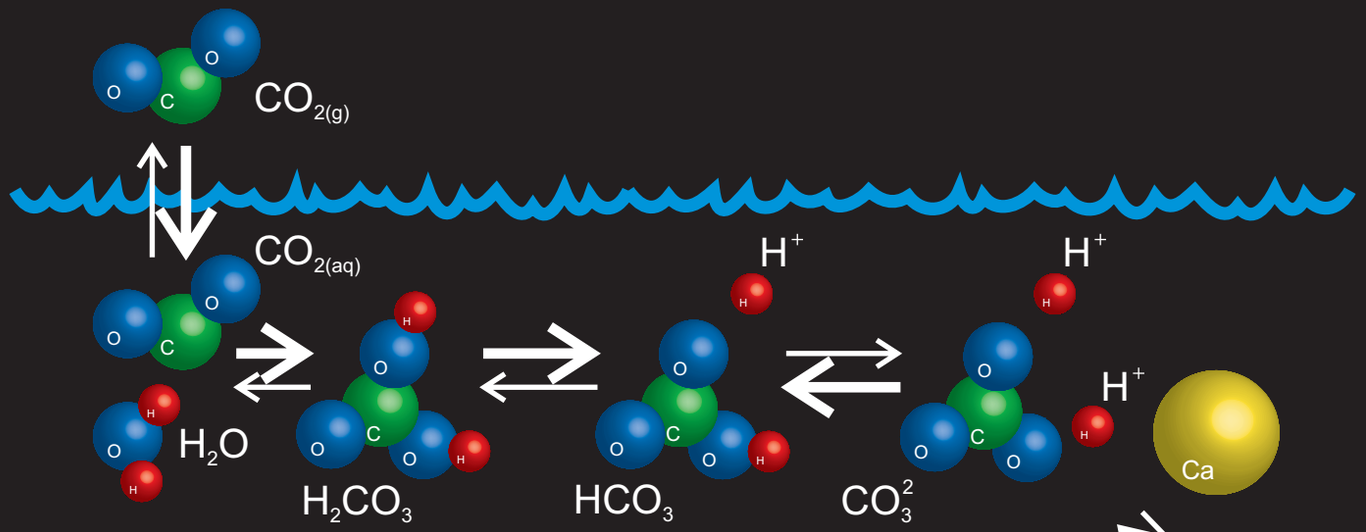
Boron, isotopes, and paleo pH

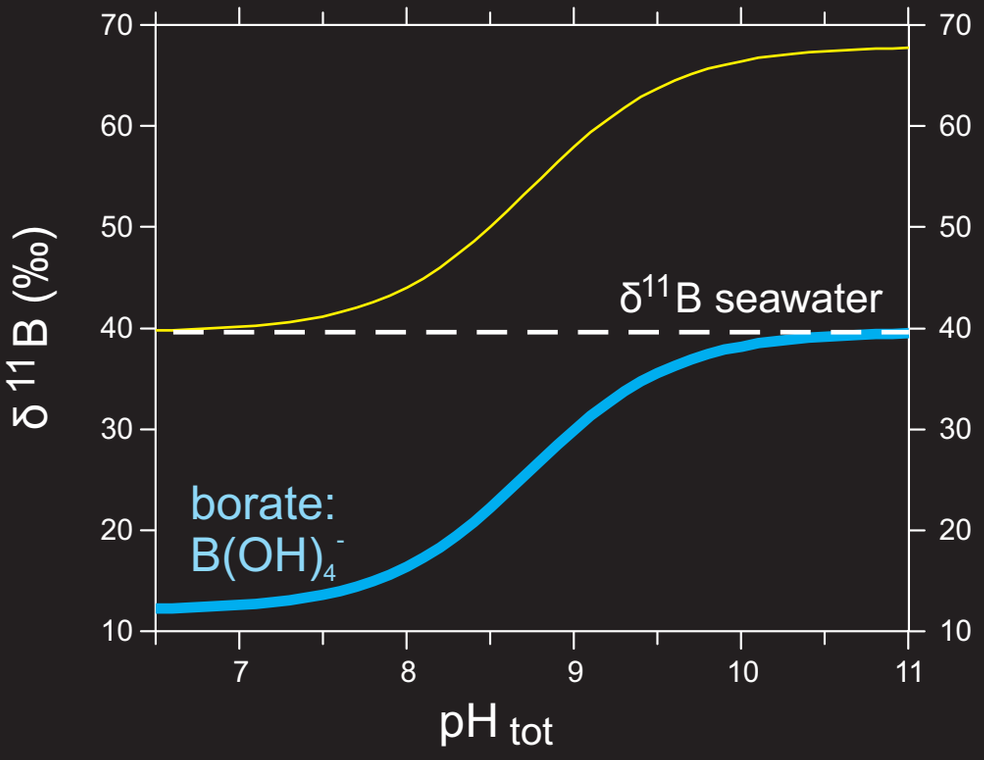


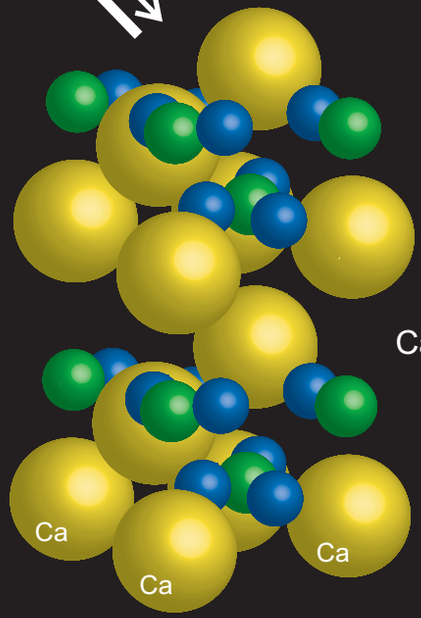
Boron, isotopes, and paleo pH



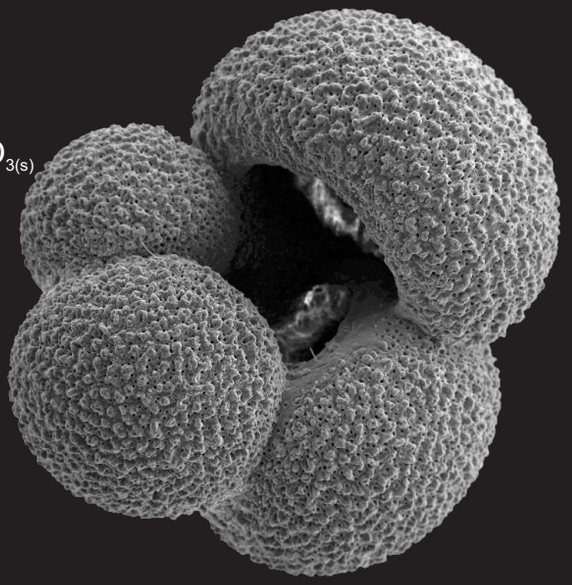
Boron, isotopes, and paleo pH



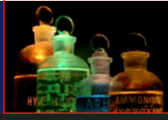


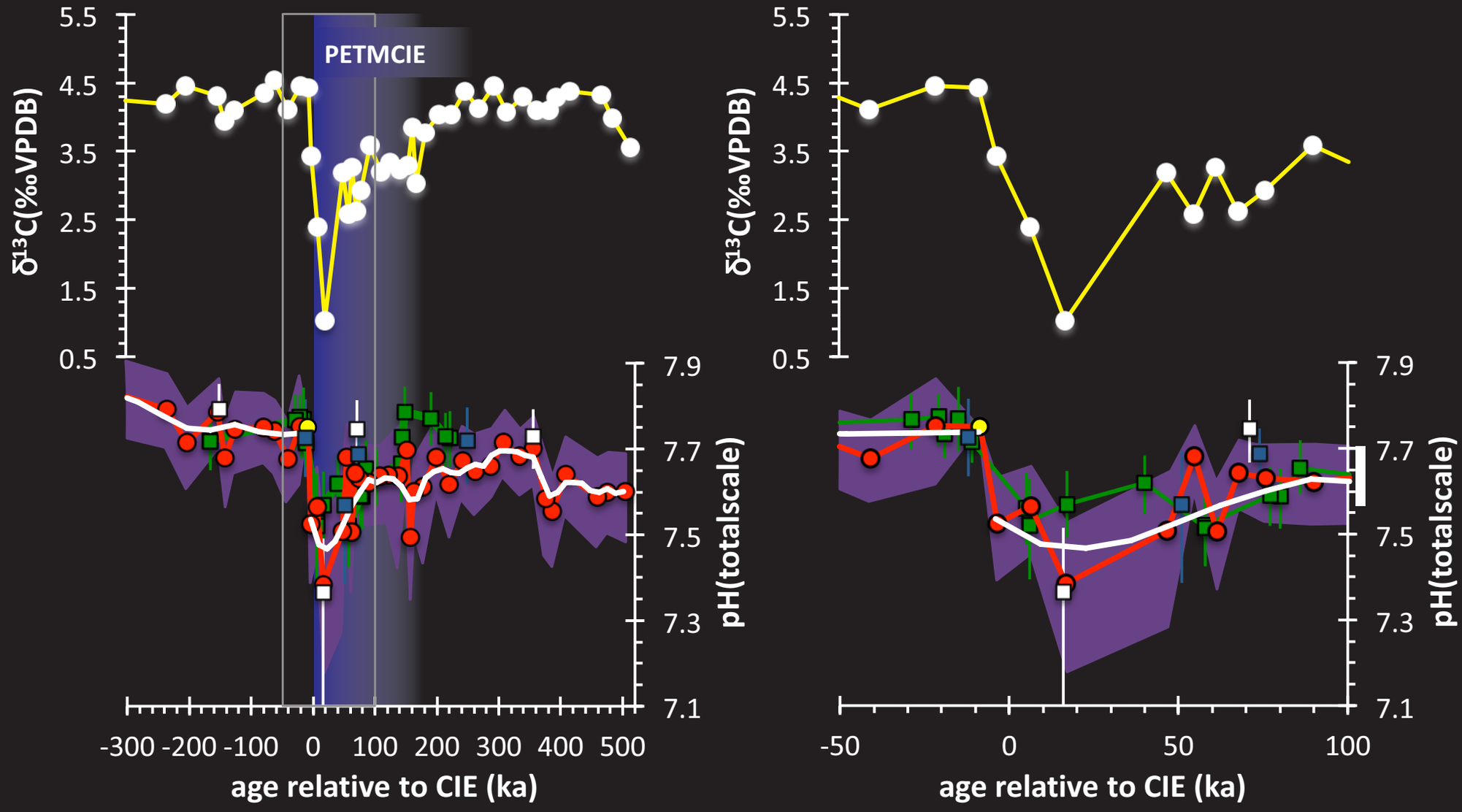


$CaCO_{3(s)}$



Boron, isotopes, and paleo pH

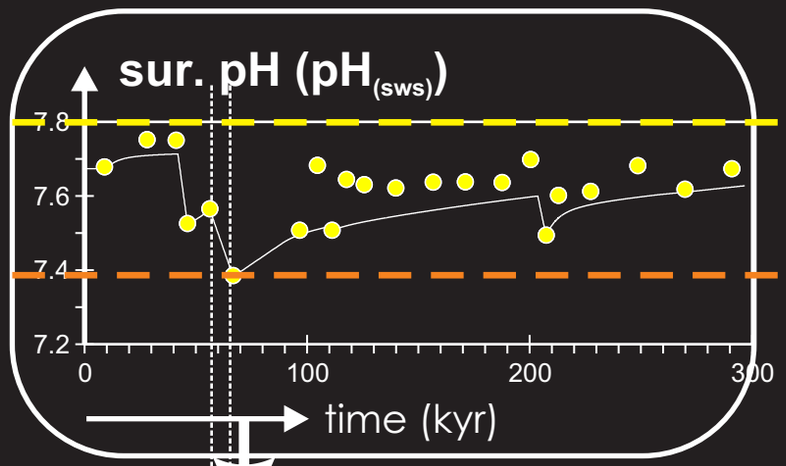




Site 401 (NE Atlantic) [unpublihed]

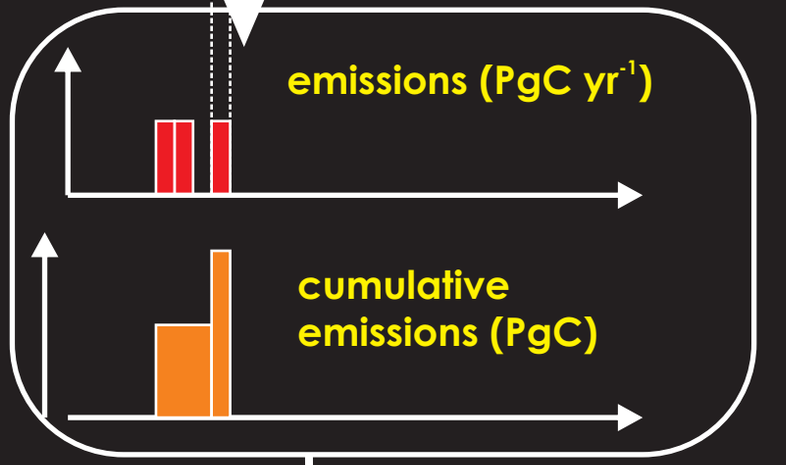
Site 865 (Eq. Pacific) Site 1263 (ES Atlantic) Site 1209 (N Pacific) [*Penman et al.*, 2014]

Assimilating surface ocean pH change (only)

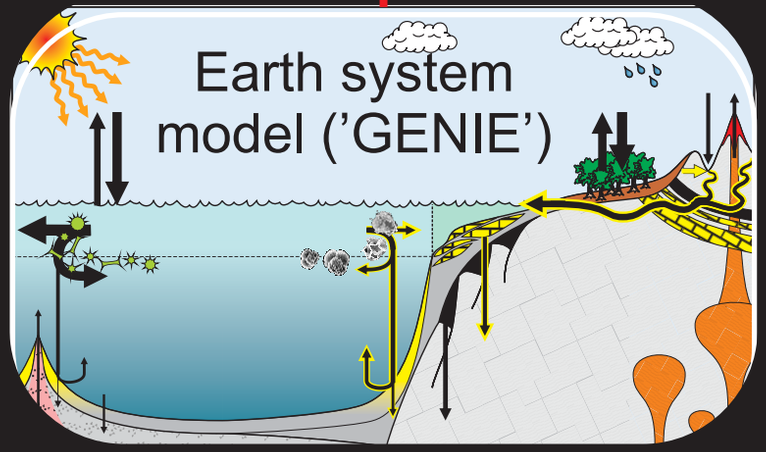


year 2100 seawater pH

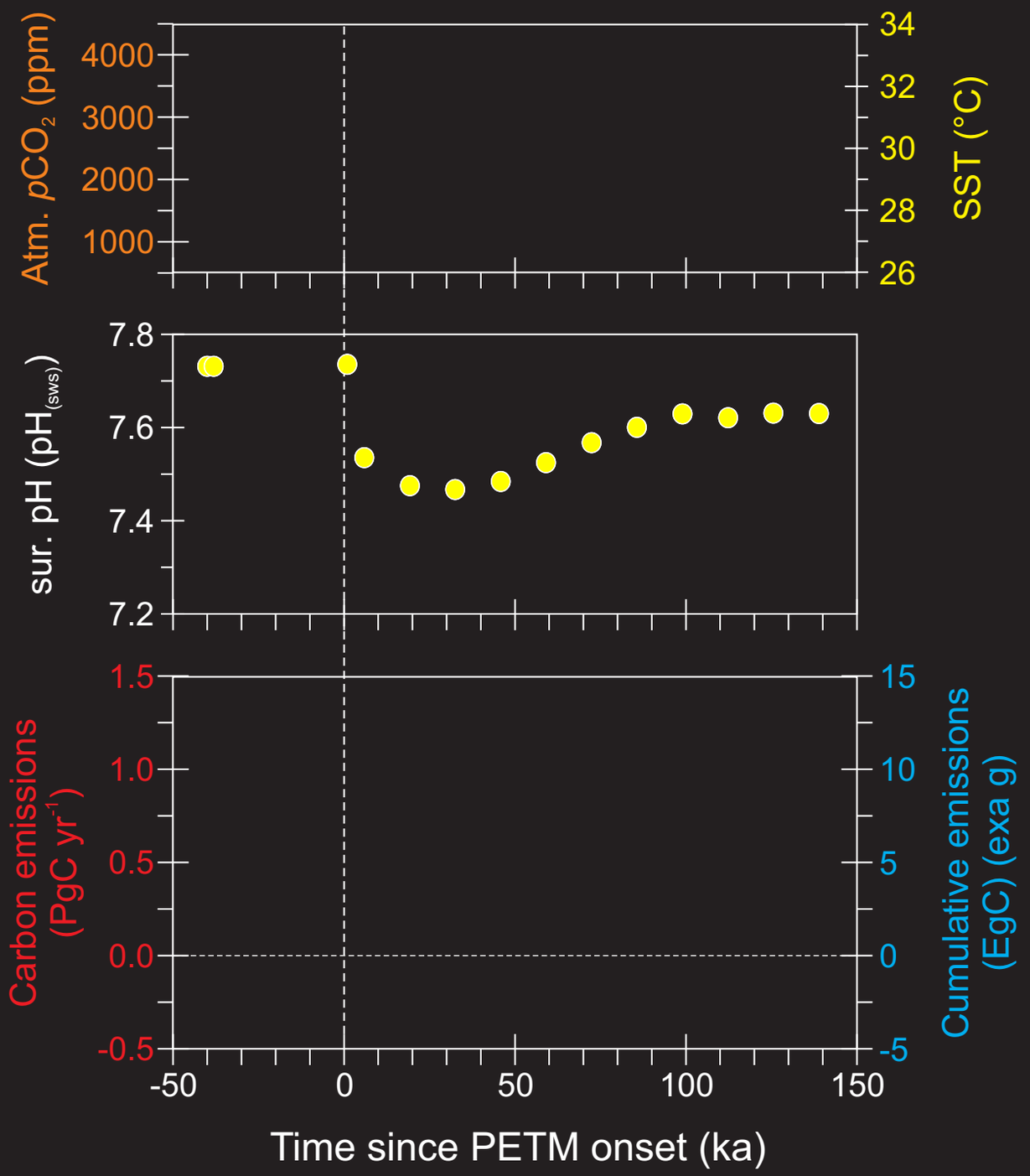
peak PETM



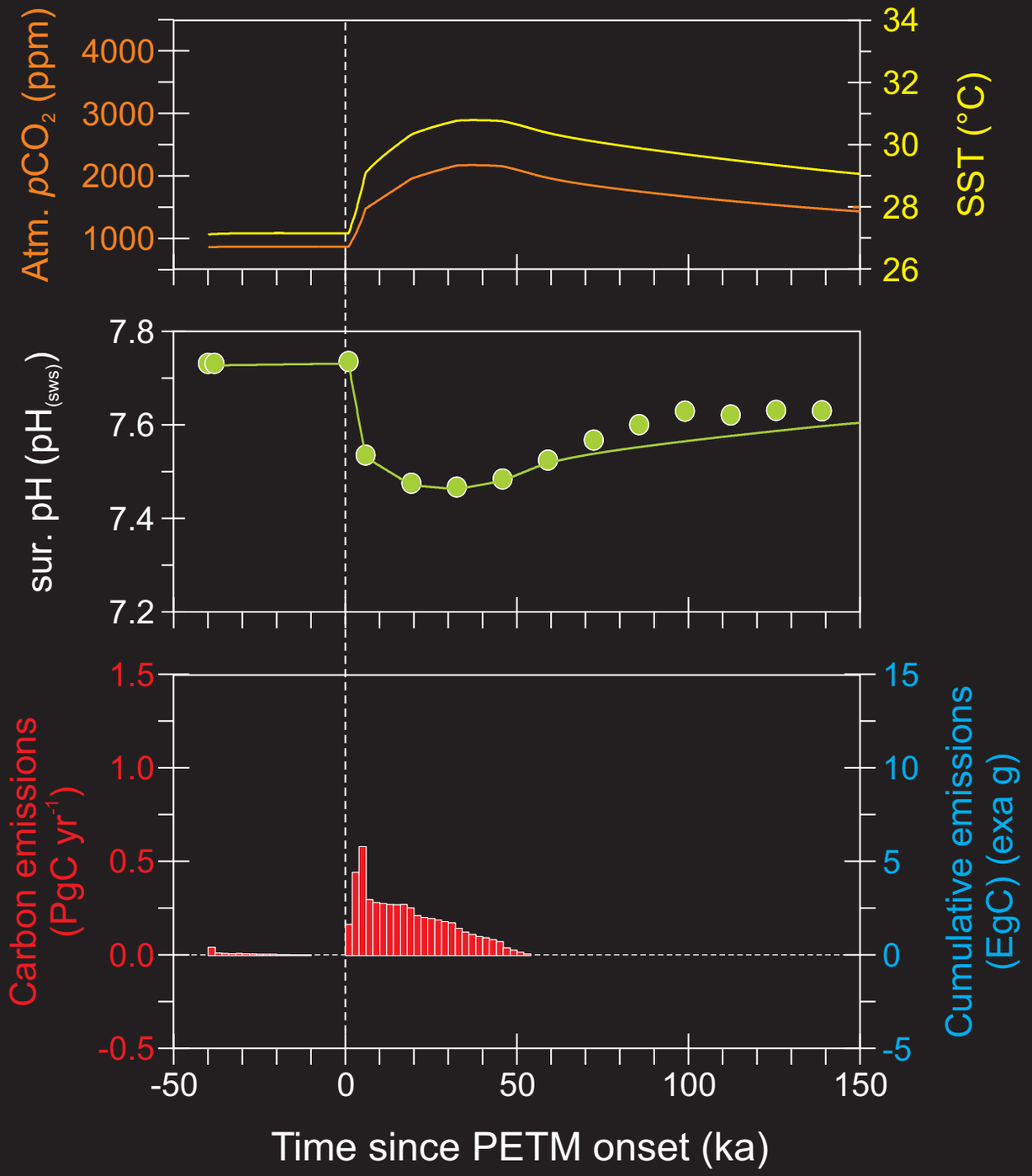
Earth system model including explicit silicate weathering feedback



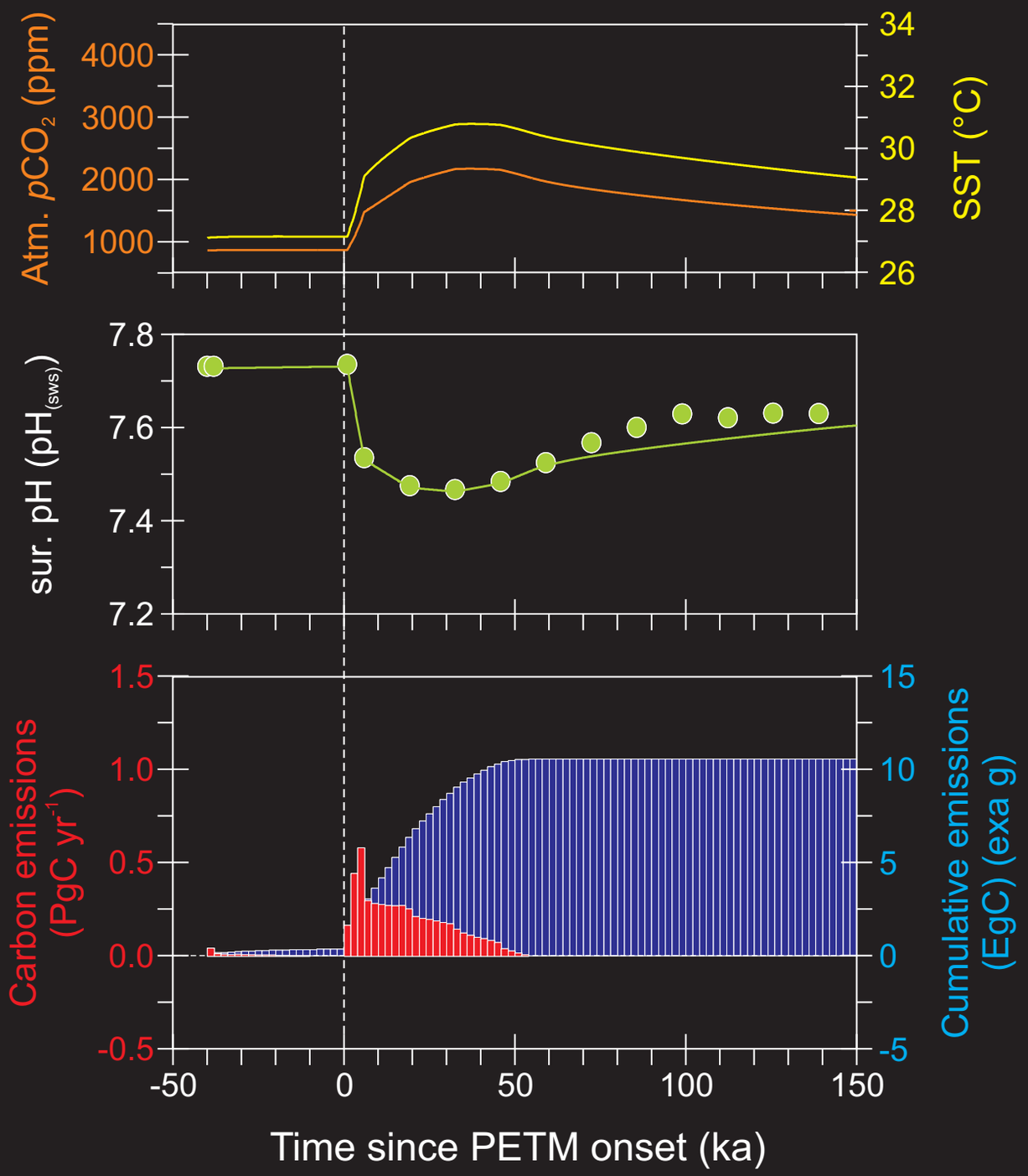
Assimilating surface ocean pH change (only)



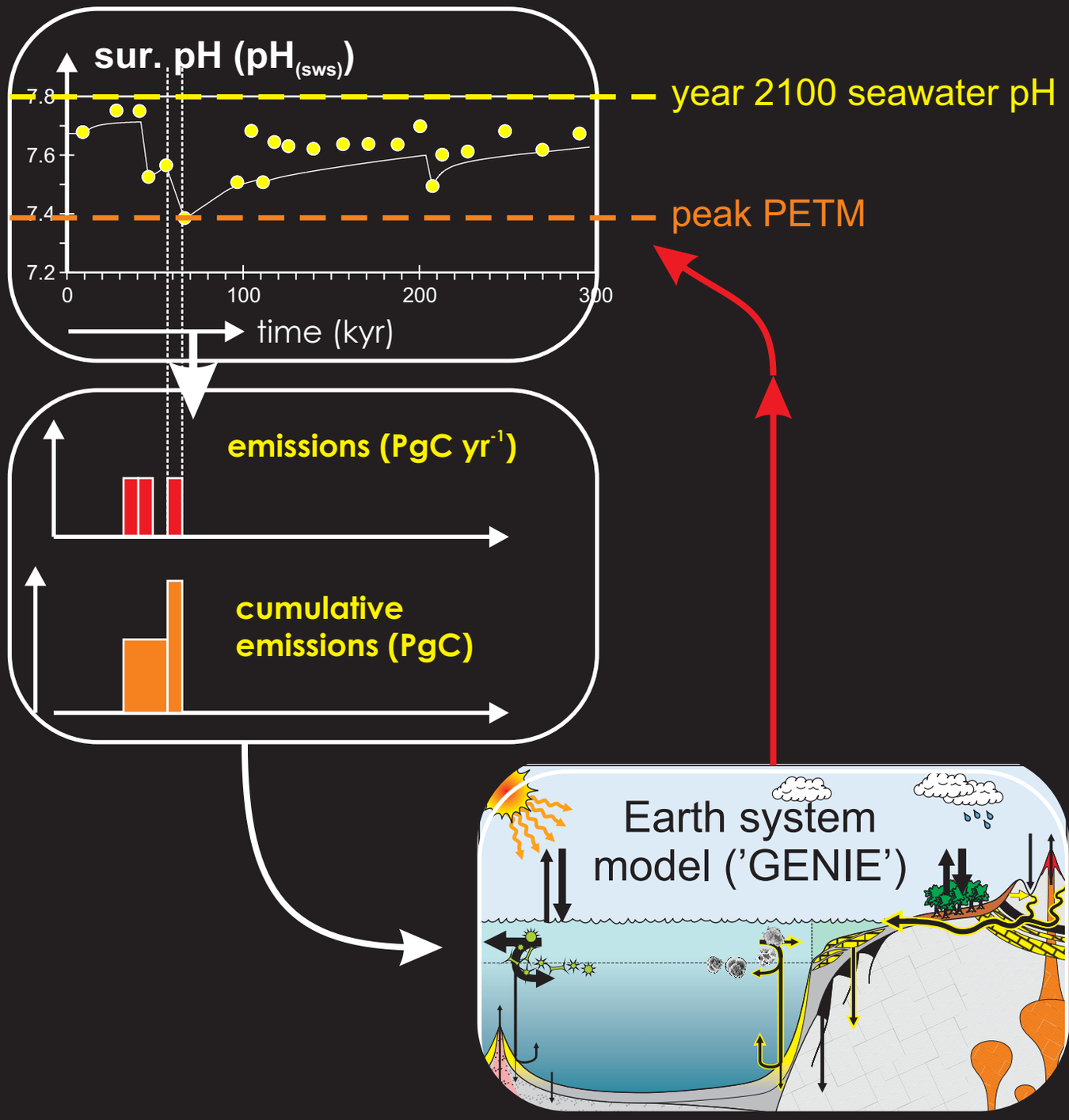
Assimilating surface ocean pH change (only)



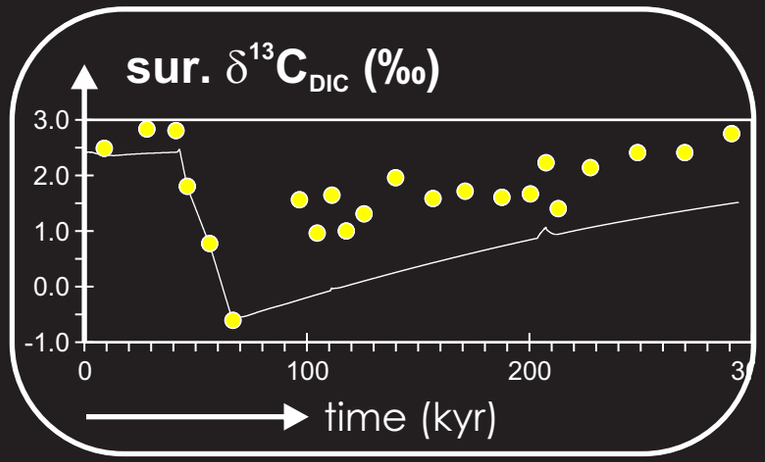
Assimilating surface ocean pH change (only)



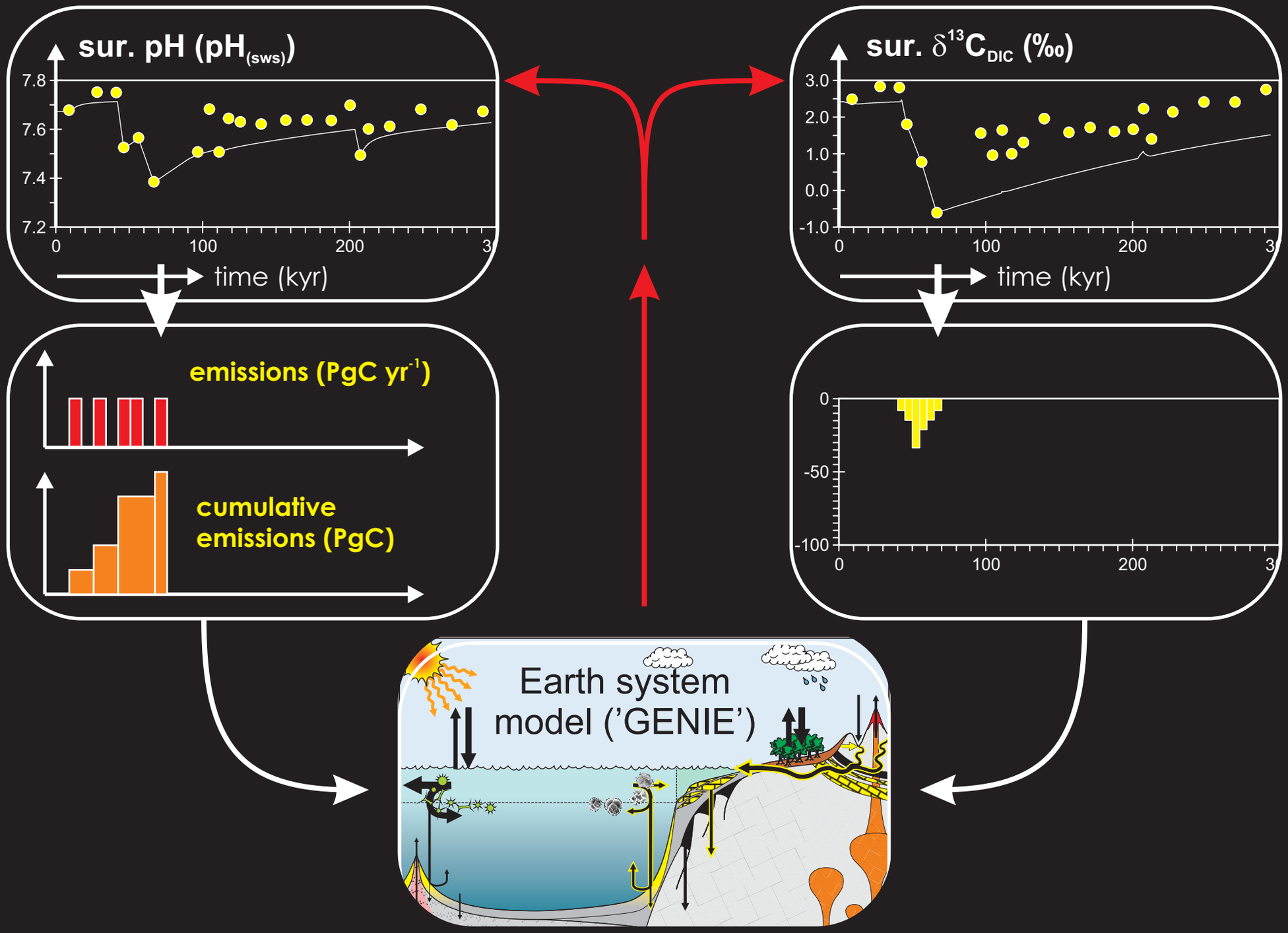
Assimilating surface ocean pH change (only)



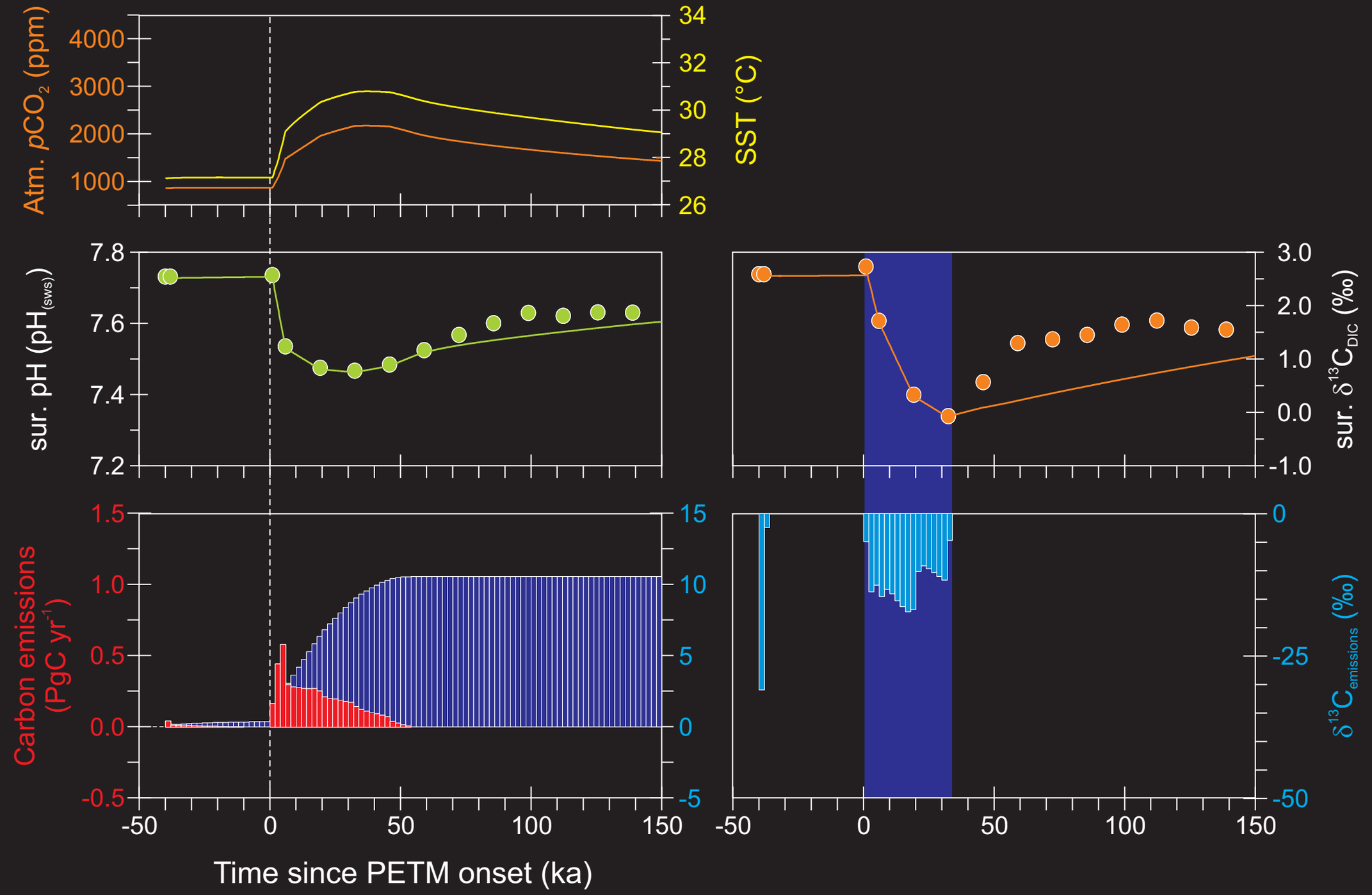
Assimilating surface ocean pH and $\delta^{13}C$



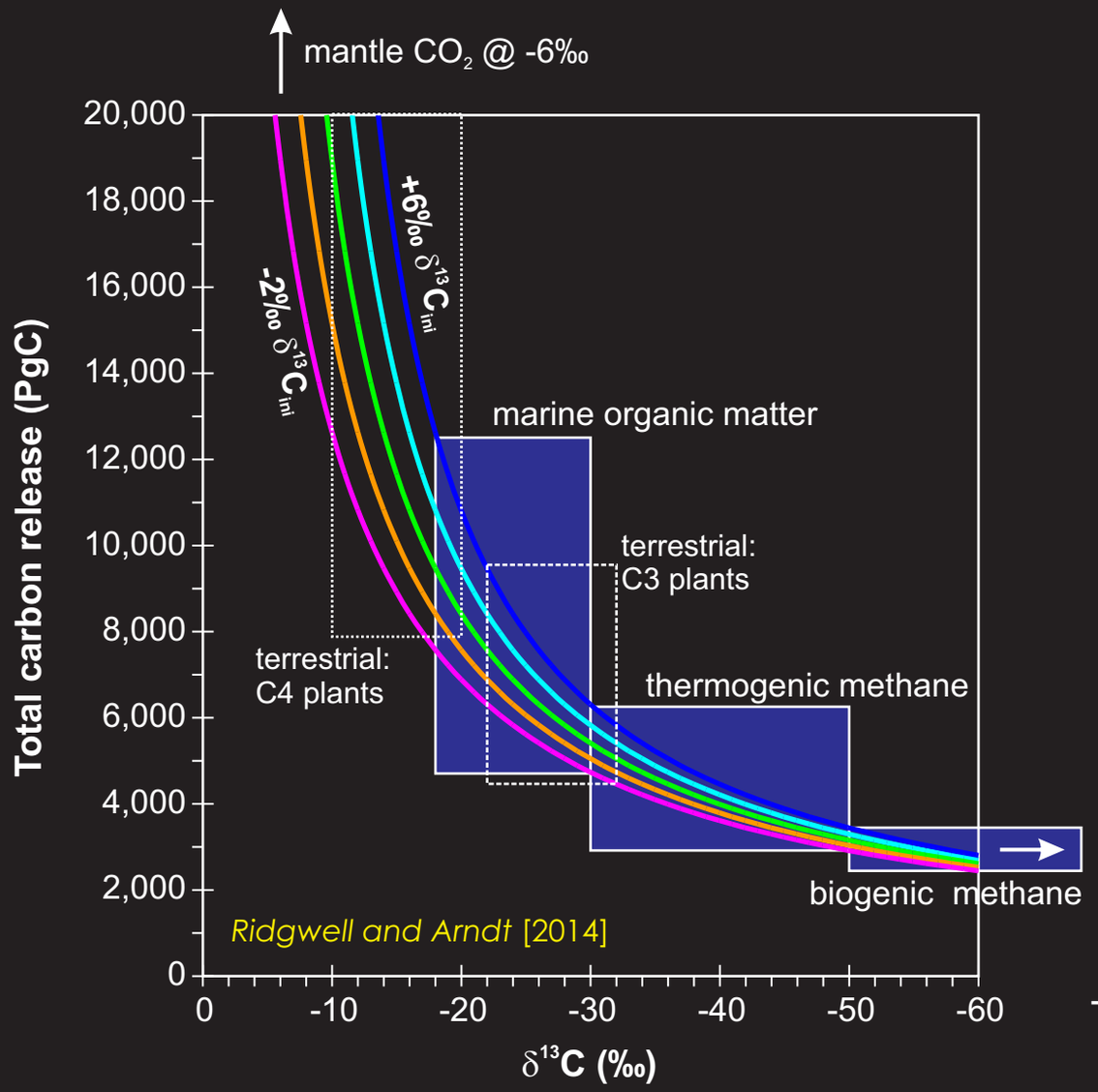
Assimilating surface ocean pH and $\delta^{13}C$

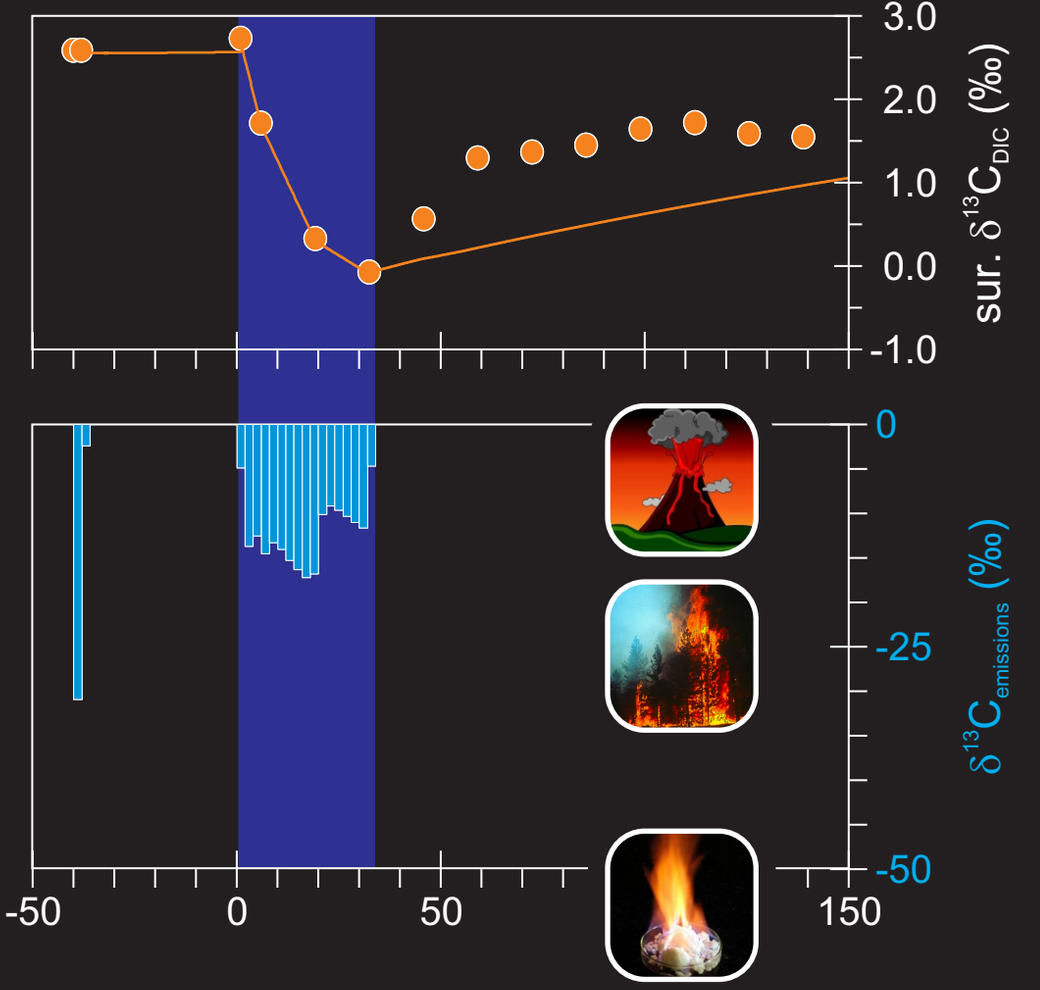


Assimilating surface ocean pH and $\delta^{13}C$



Assimilating surface ocean pH and $\delta^{13}C$

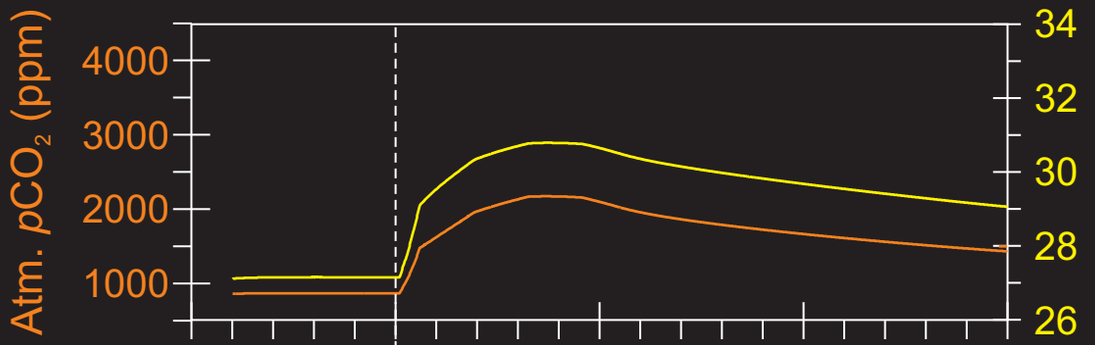


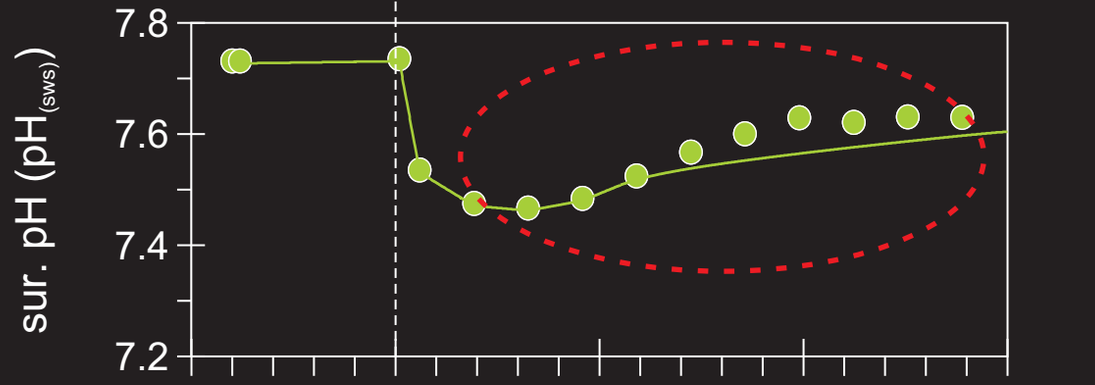


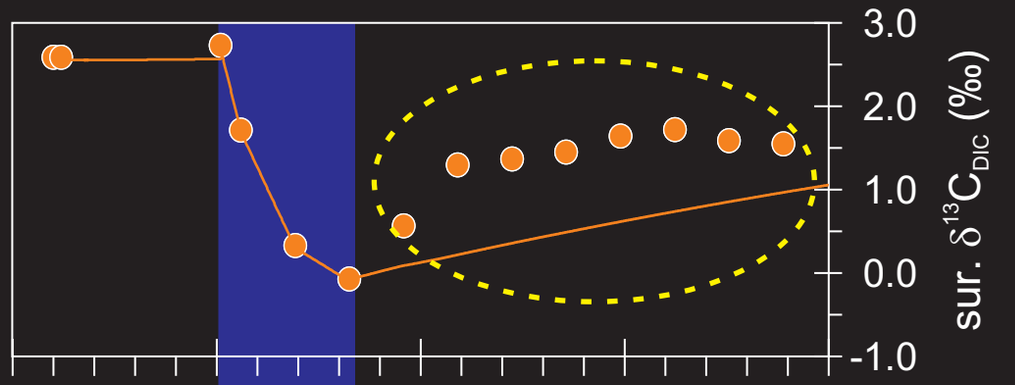
Assimilating surface ocean pH and $\delta^{13}C$

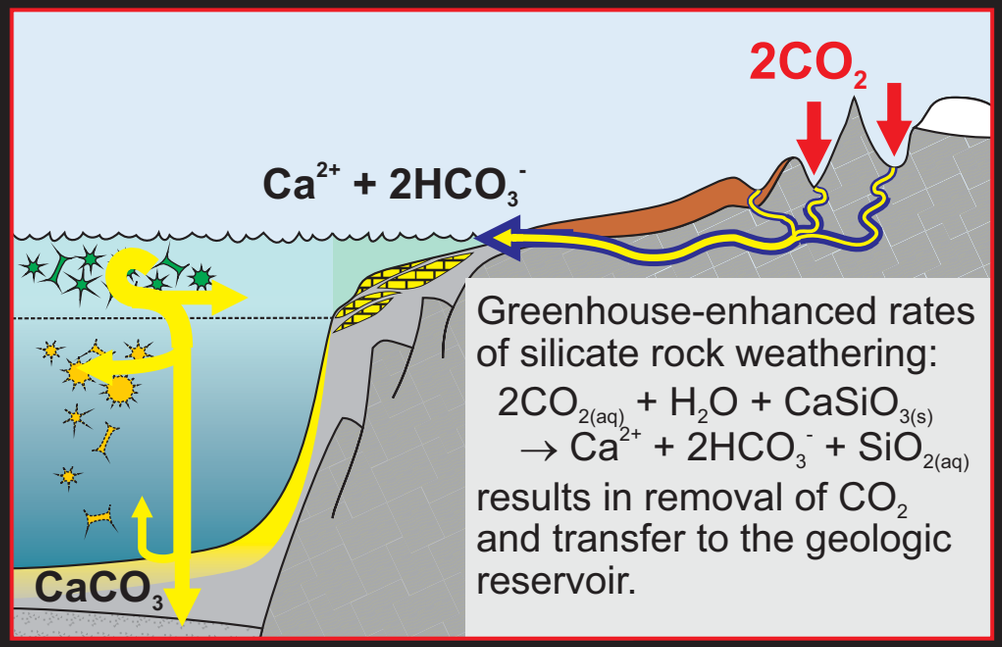
Credit: Michael Storey

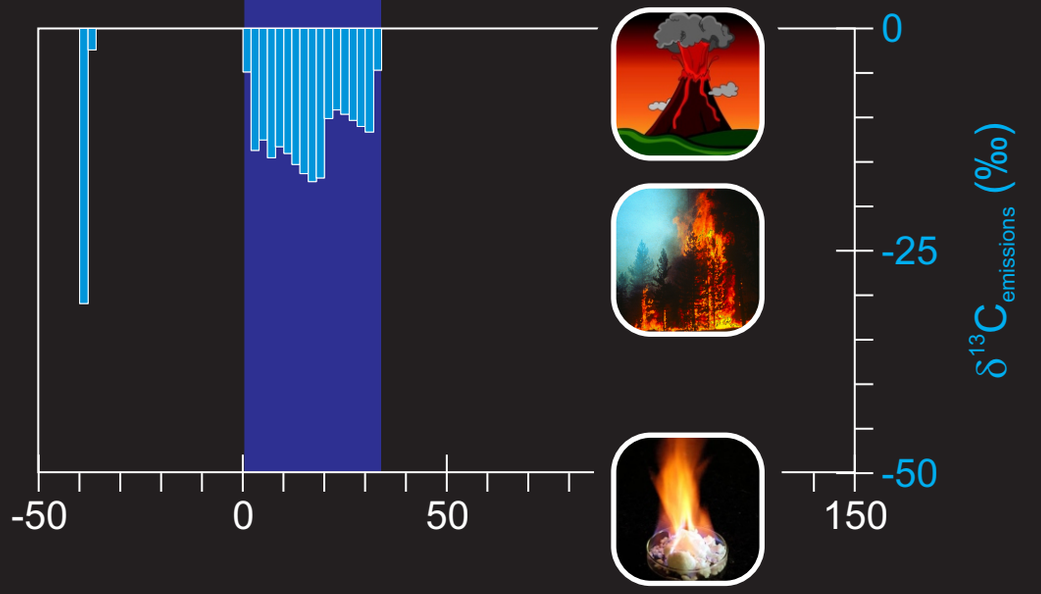
Assimilating surface ocean pH and $\delta^{13}C$



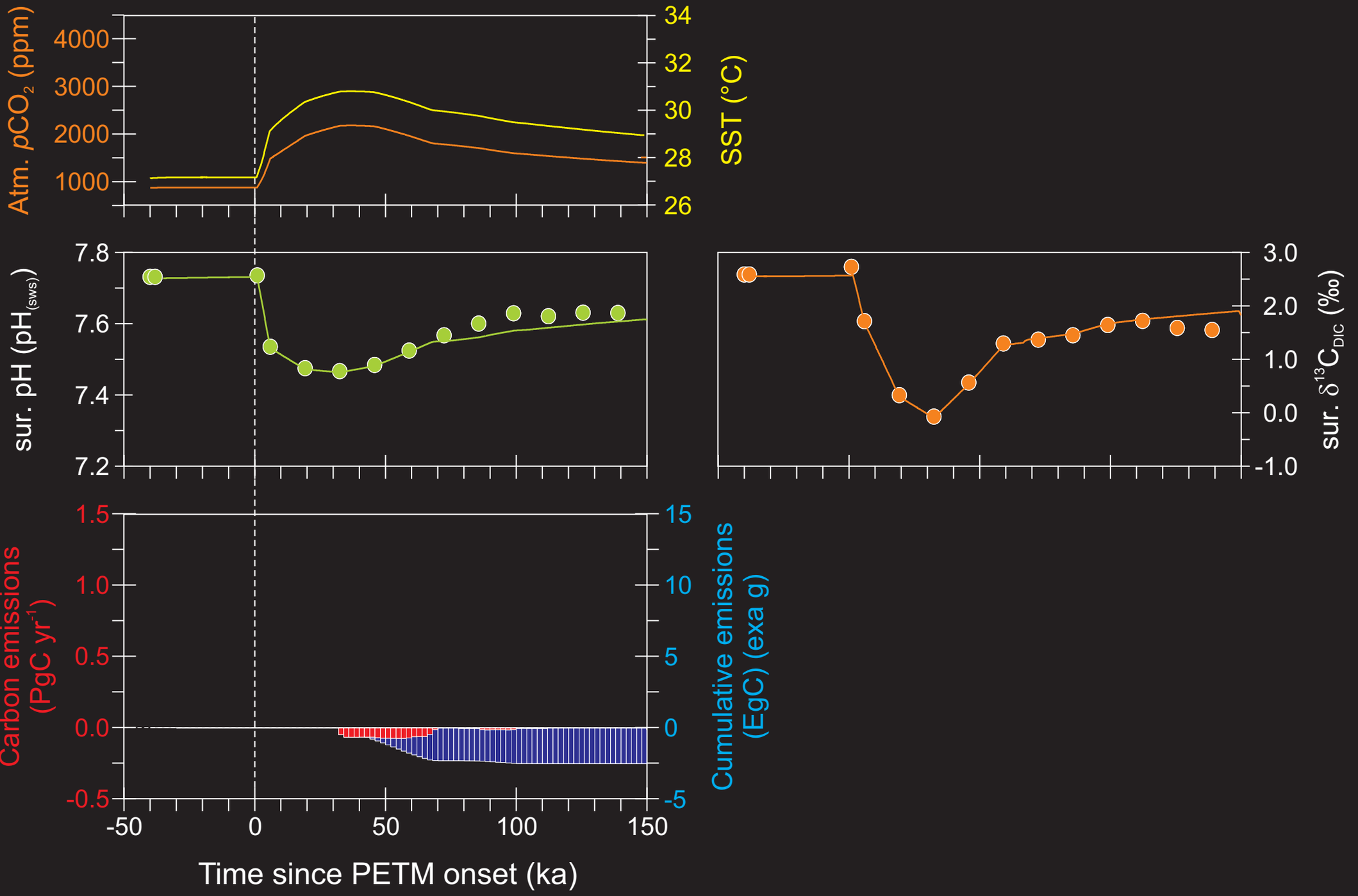




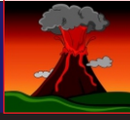




Assimilating surface ocean pH and $\delta^{13}C$



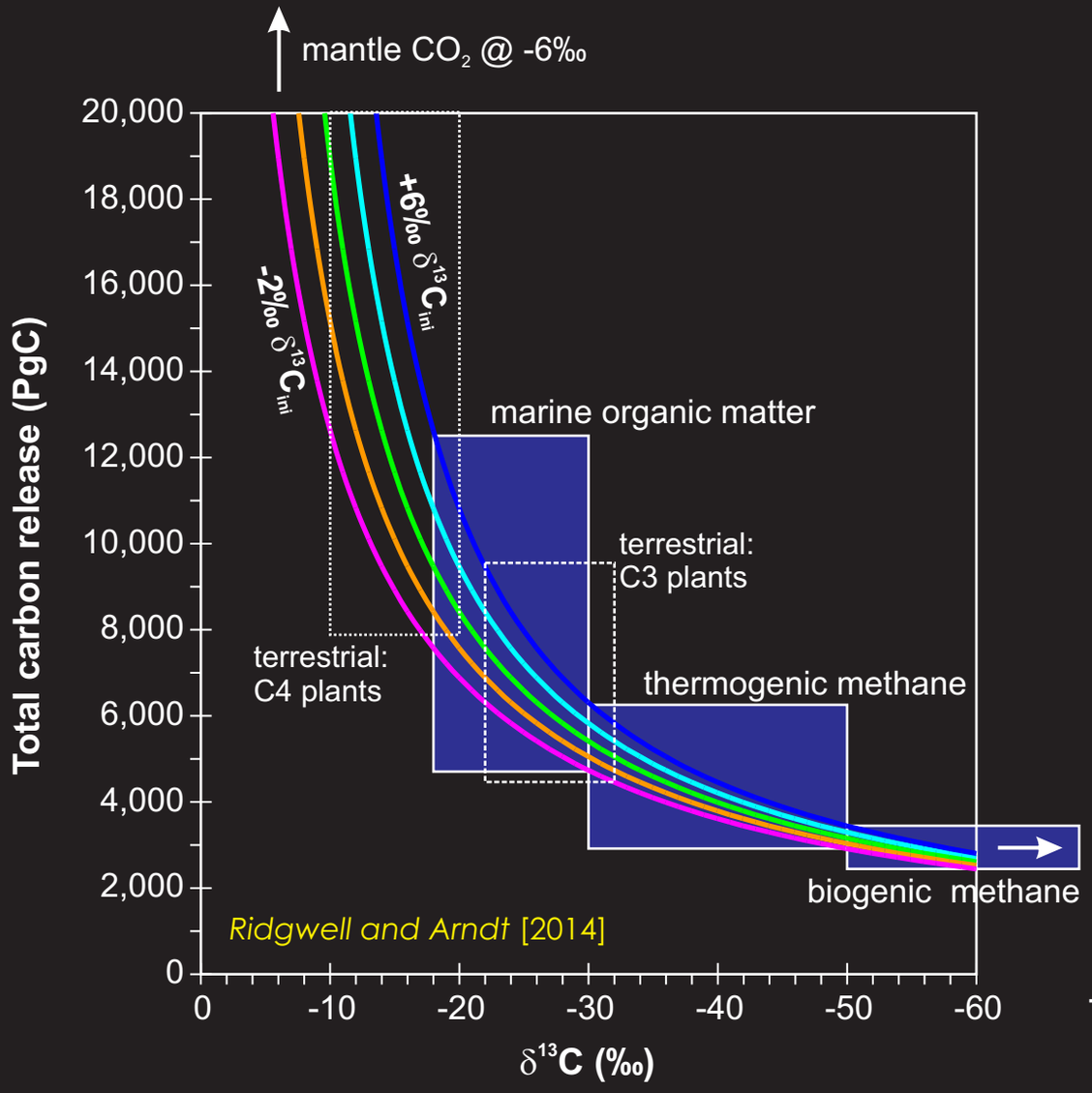
Assimilating surface ocean pH and $\delta^{13}C$

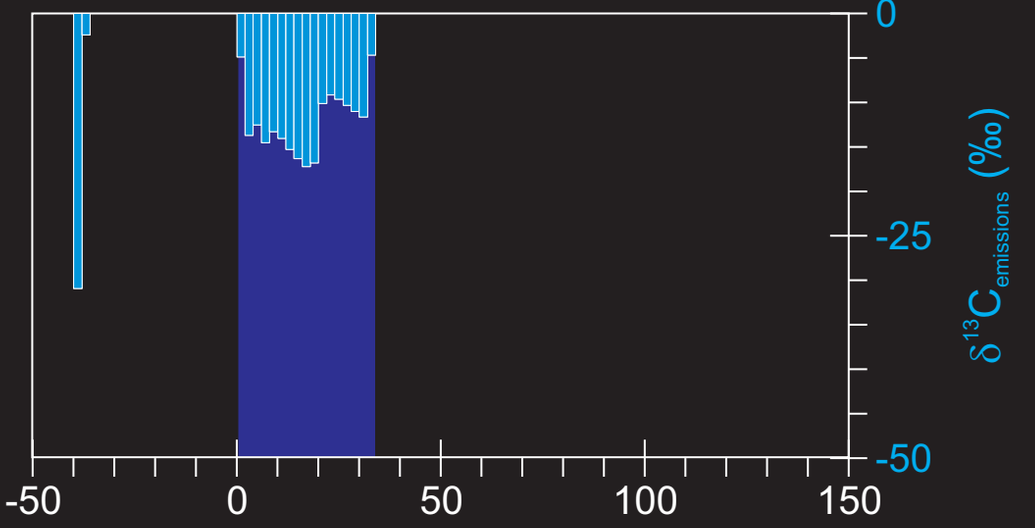


+

OR

+





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.

Thanks to:

Marcus Gutjahr [GEOMAR]
Gavin Foster [NOC]
Philip Sexton [The Open University]
Paul Pearson [Cardiff]

Sandy Kirtland Turner [UCR]

The European Research Council
Heising-Simons Foundation


vs.


Osmium isotope records

radiogenic Os

granitic weathering: $^{187/188}$Os=1.4

basaltic weathering: $^{187/188}$Os=0.12

hydrothermal:
$^{187/188}$Os=0.12

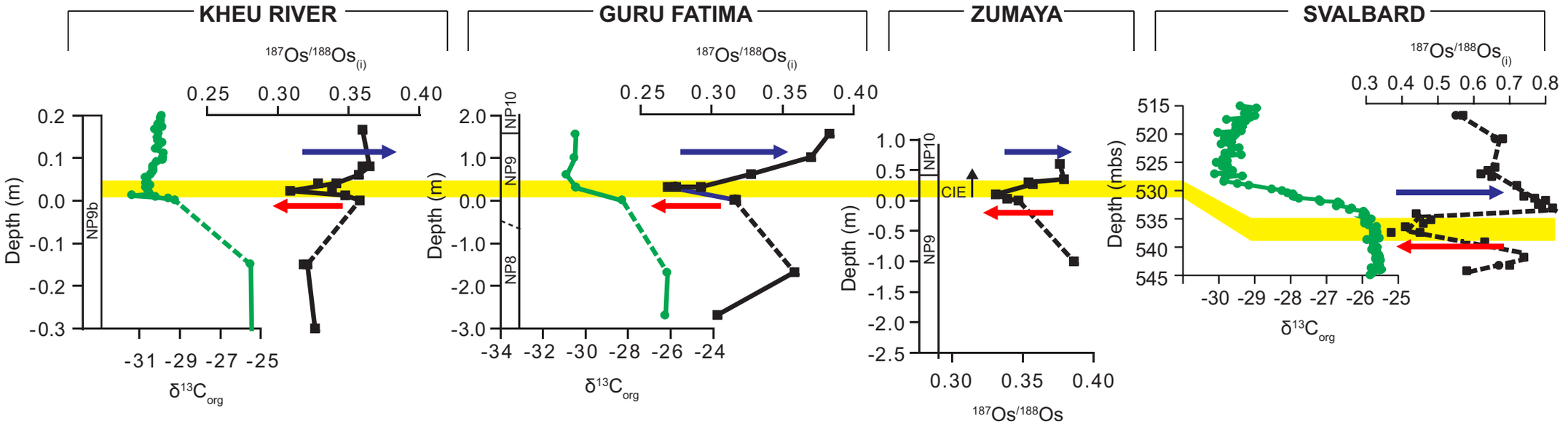
seawater:
$^{187/188}$Os~0.35

burial with
organic matter

un-radiogenic Os

un-radiogenic Os

Osmium isotope records



time

radiogenic Os

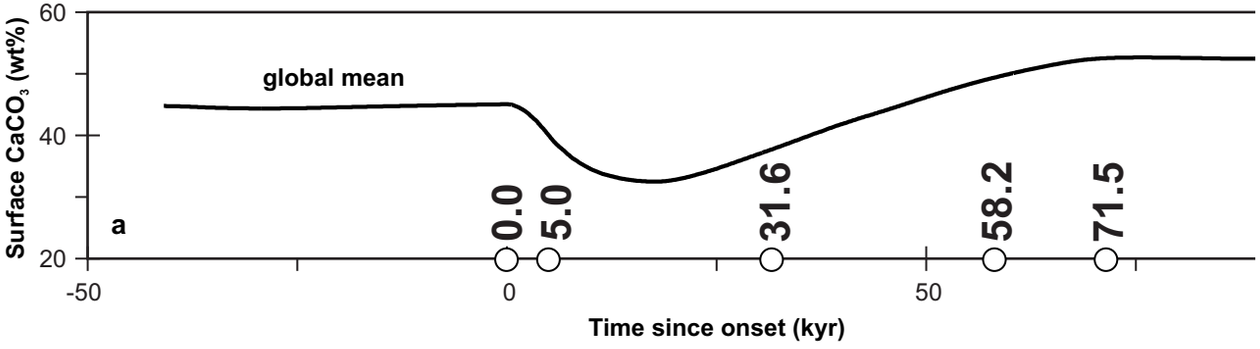
un-radiogenic Os

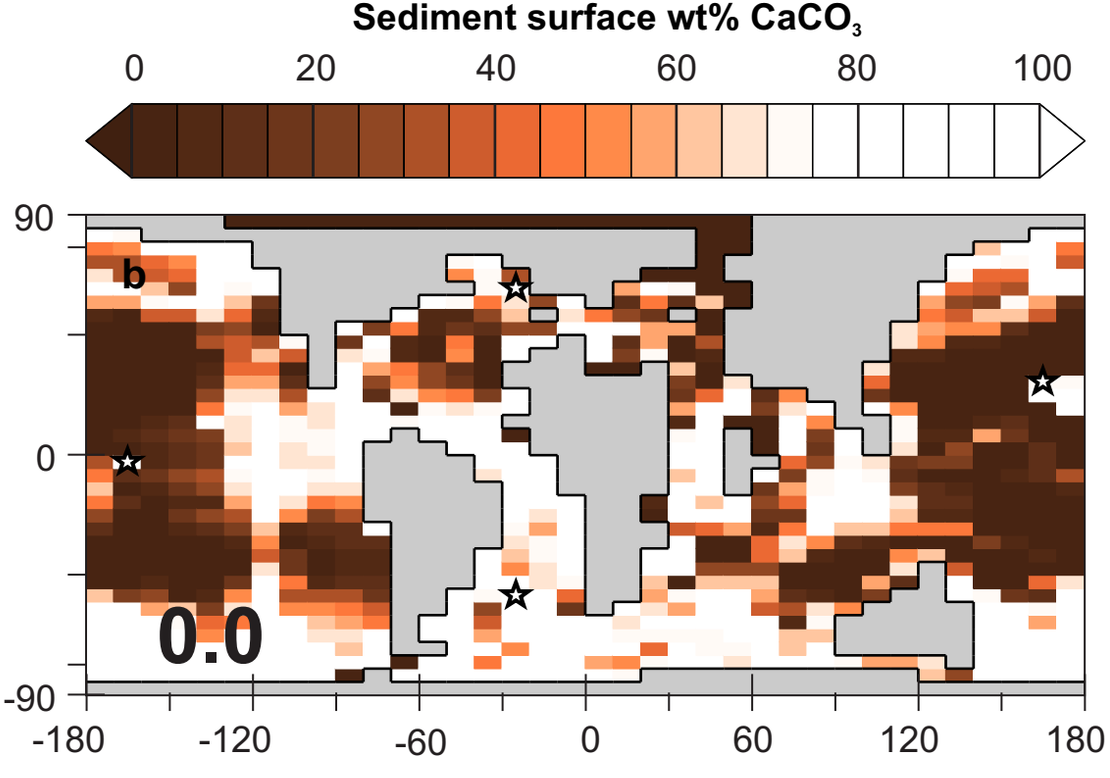
PETM recovery characterized by long-lasting shift to radiogenic Os. Consistent with enhanced granitic weathering (silicate weathering feedback).
(Also, expulsion of fluids form organic rich sediments.)

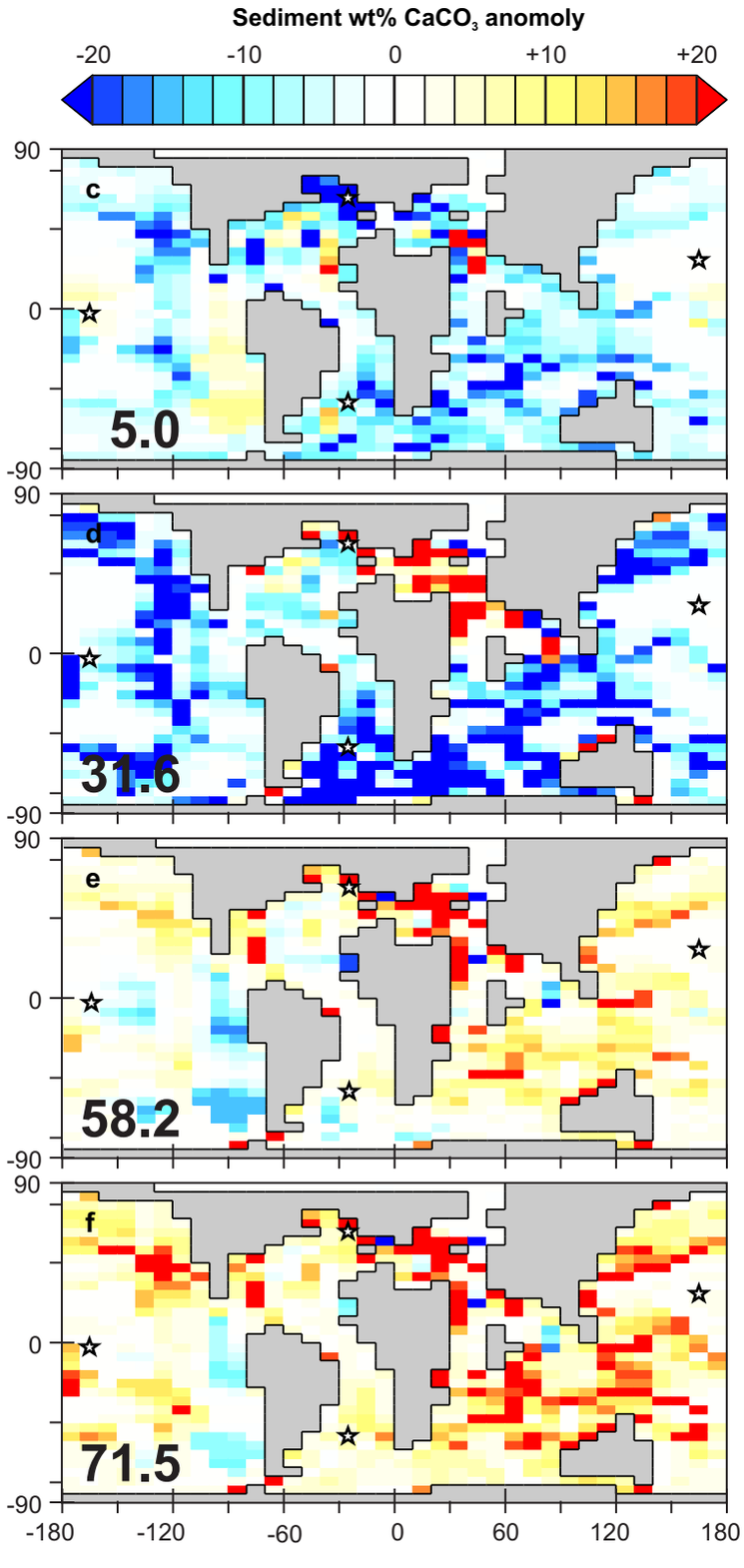
Strong transient decline in $^{187/188}Os$.
Enhanced unradiogenic input from volcanism.
(Also, extraterrestrial ...)

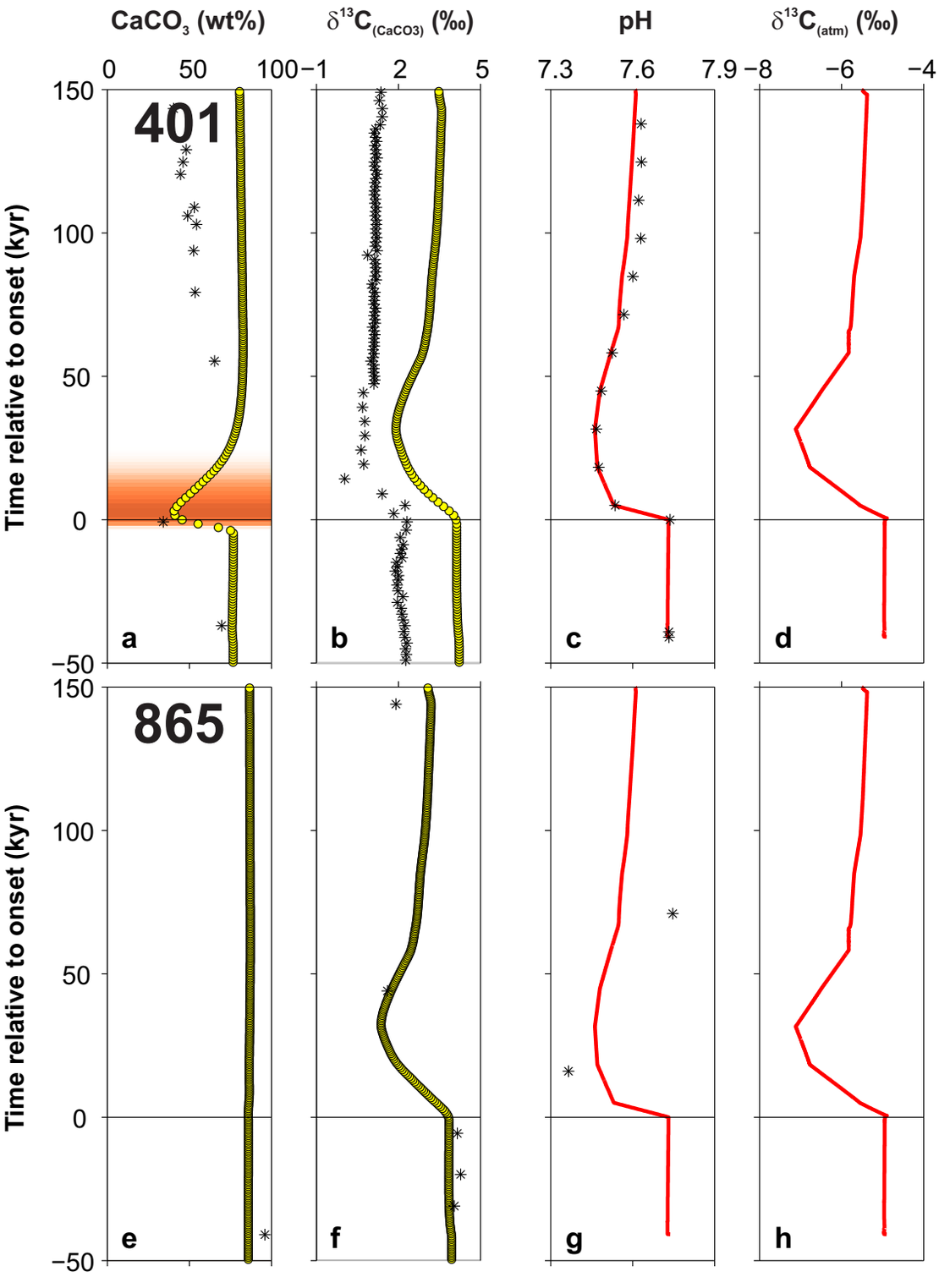
Dickson et al. [2015] (*Palaeogeography, Palaeoclimatology, Palaeoecology* **438**)
(also see: *Wieczorek et al.* [2013] (*GCA* **119**))

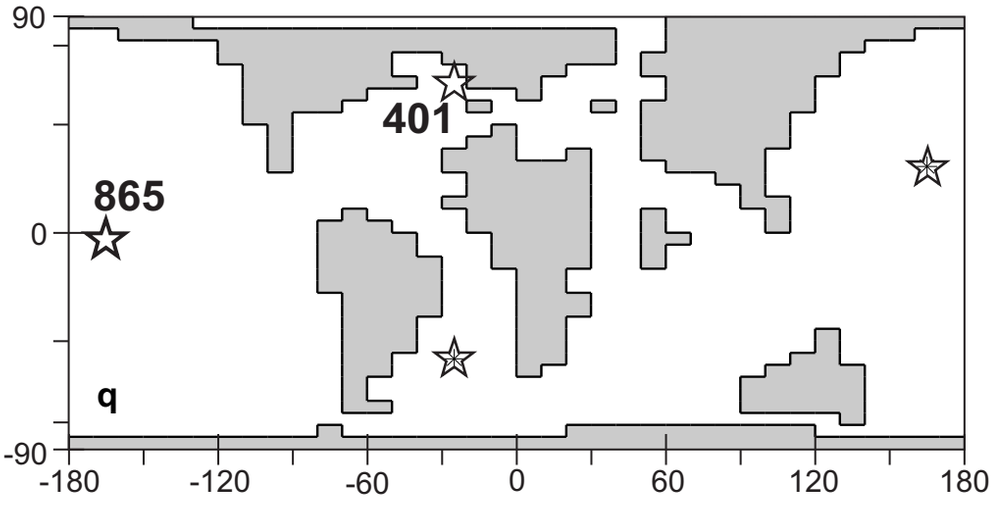
Deep-sea (modelled) carbonate response

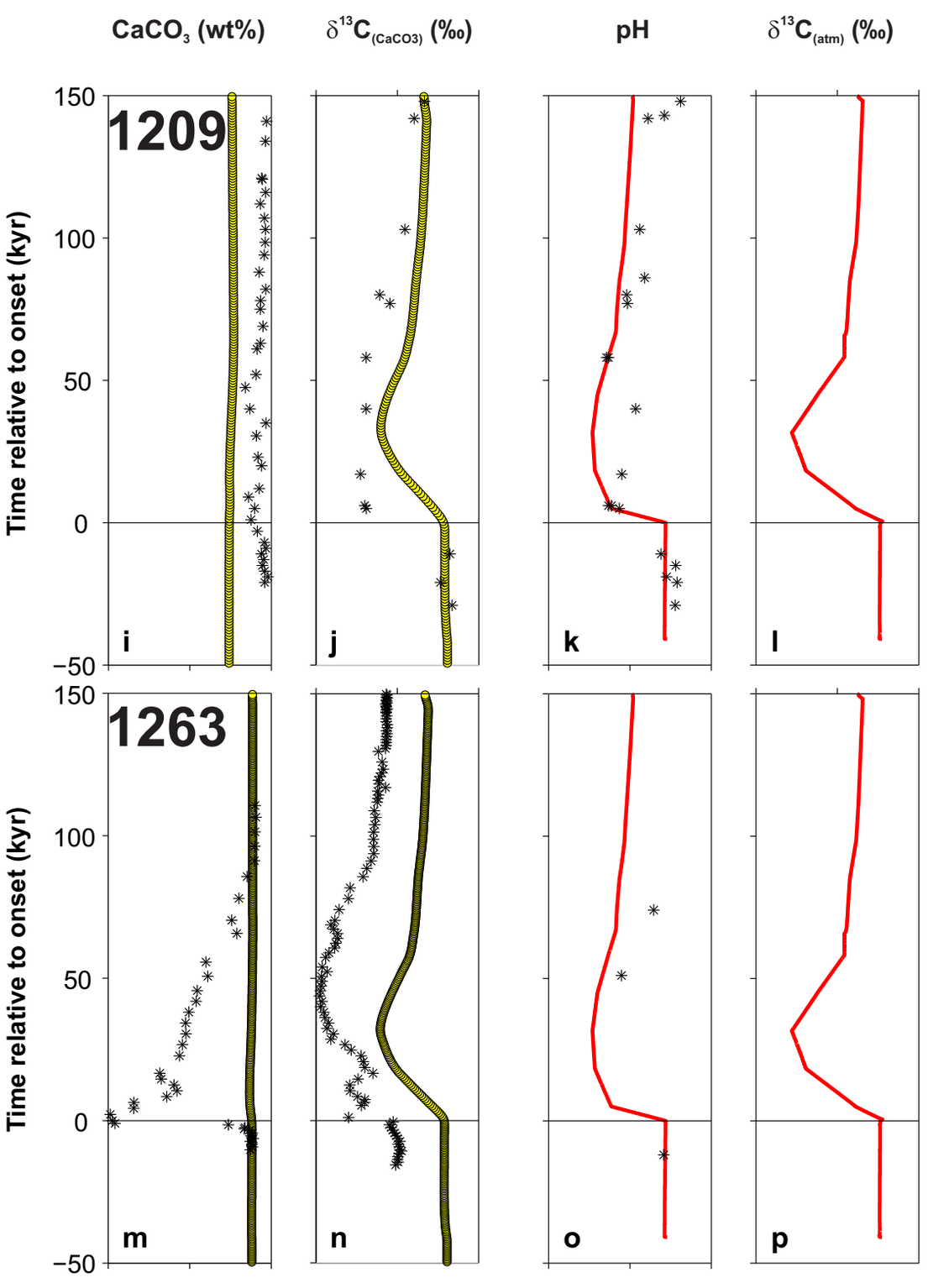


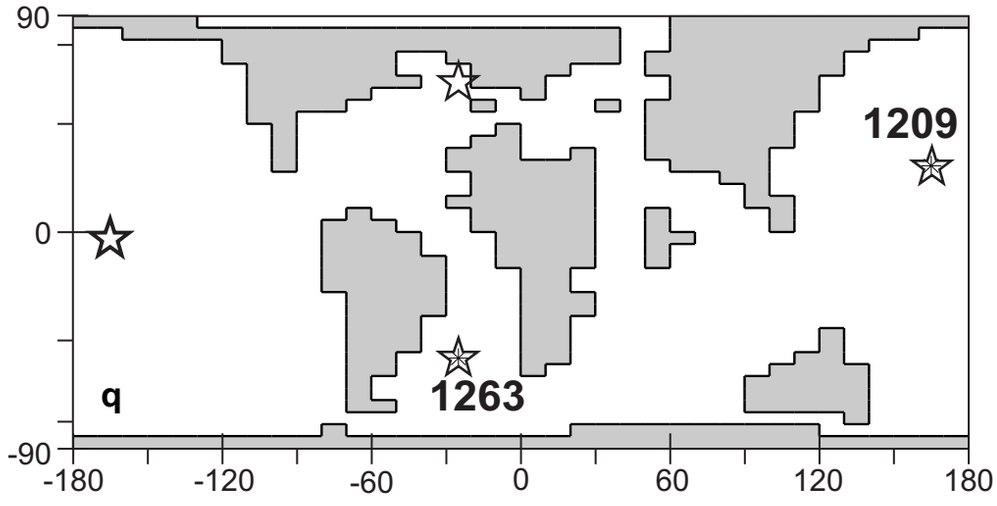





CaCO3 (wt%)
δ13C(CaCO3) (‰)
pH
δ13C(atm) (‰)
0
50
100
−1
2
5
7.3
7.6
7.9
−8
−6
−4
150
100
50
0
−50
Time relative to onset (kyr)
401
865
a
b
c
d
e
f
g
h

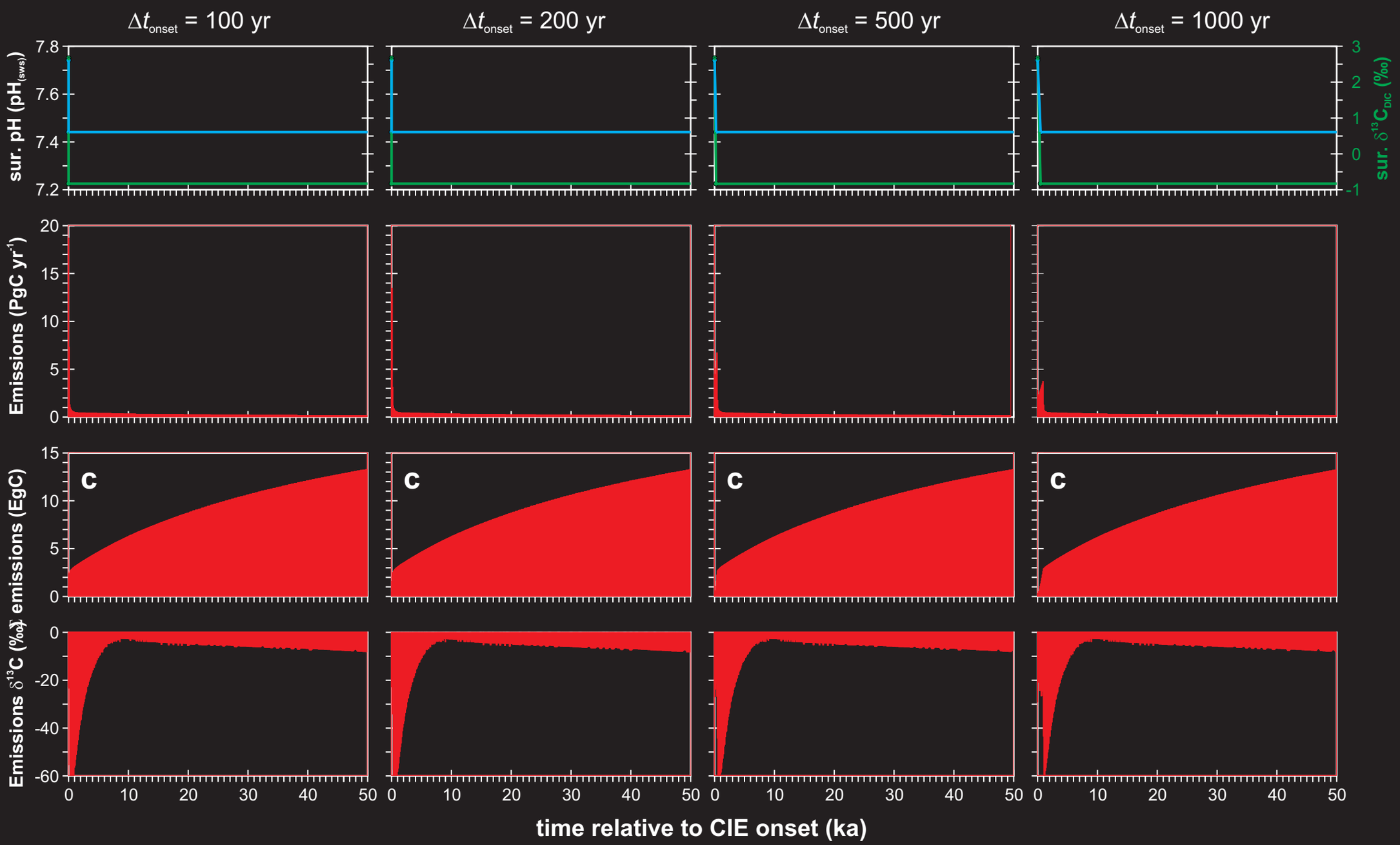

90
0
-90
-180
-120
-60
0
60
120
180
401
865
q


CaCO3 (wt%)
δ13C(CaCO3) (‰)
pH
δ13C(atm) (‰)
1209
1263
Time relative to onset (kyr)
150
100
50
0
−50
i
j
k
l
m
n
o
p


90
0
-90
-180
-120
-60
0
60
120
180
1209
1263
q

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