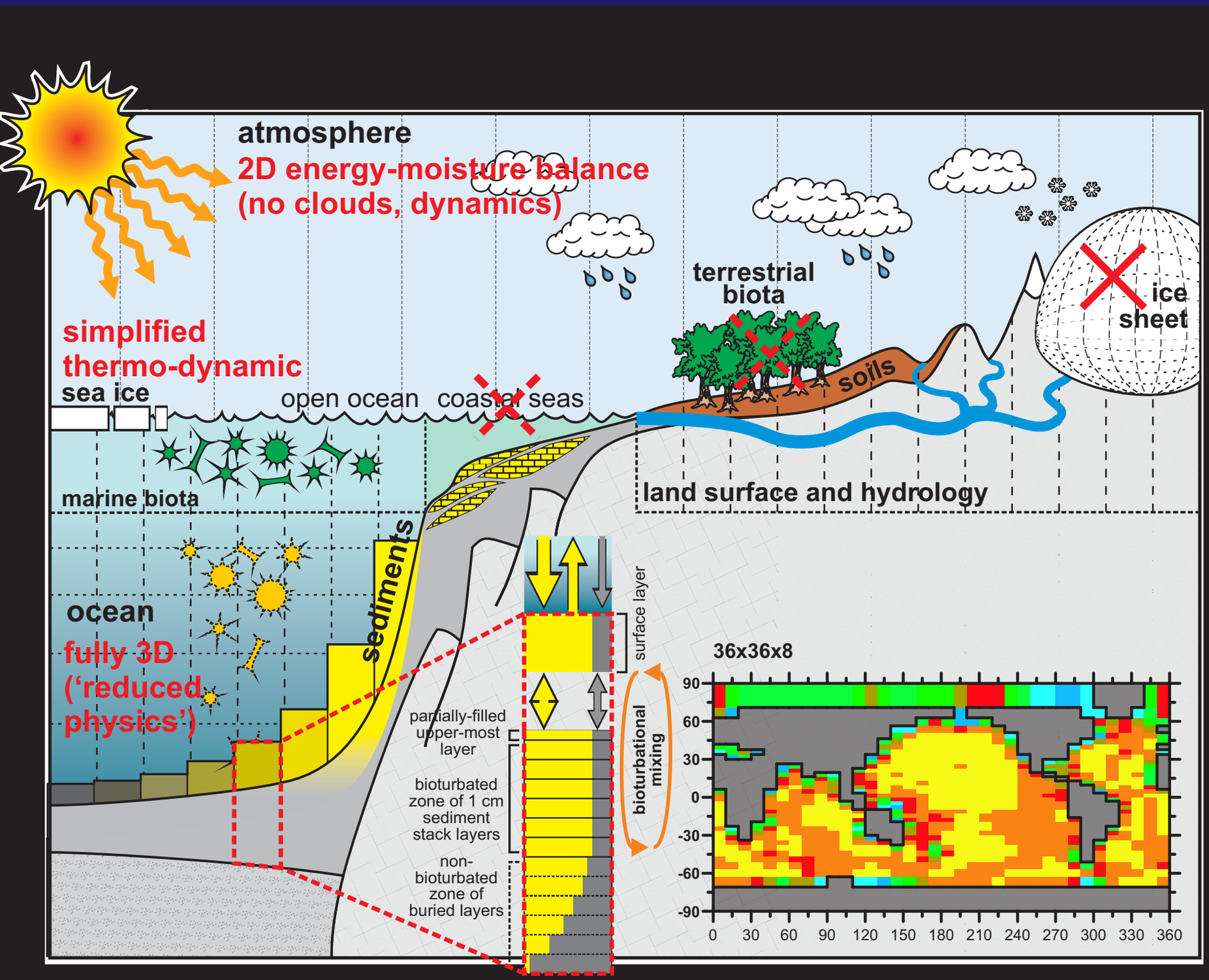
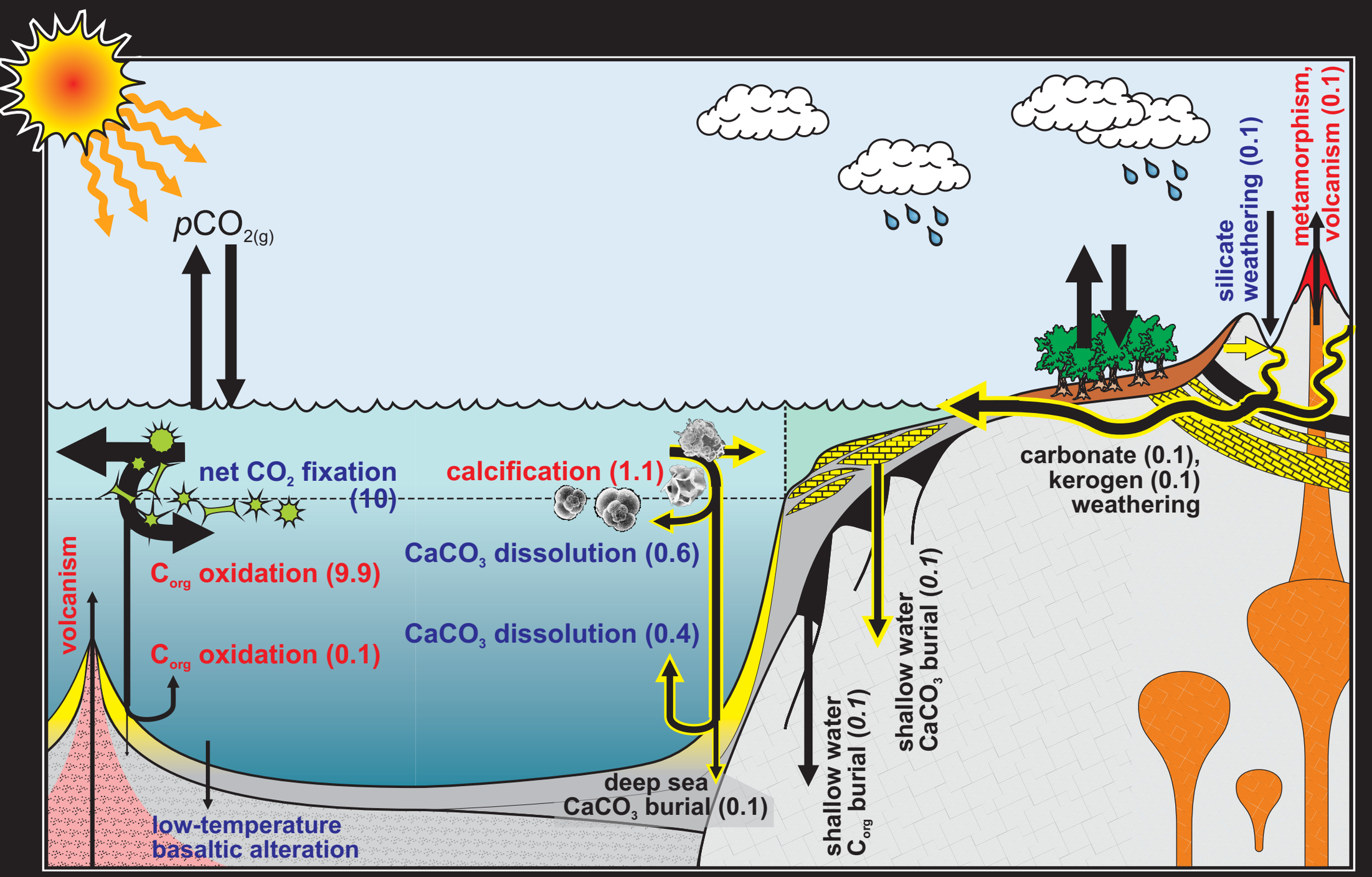
The (c)GENIE Earth system model (version muffin)



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



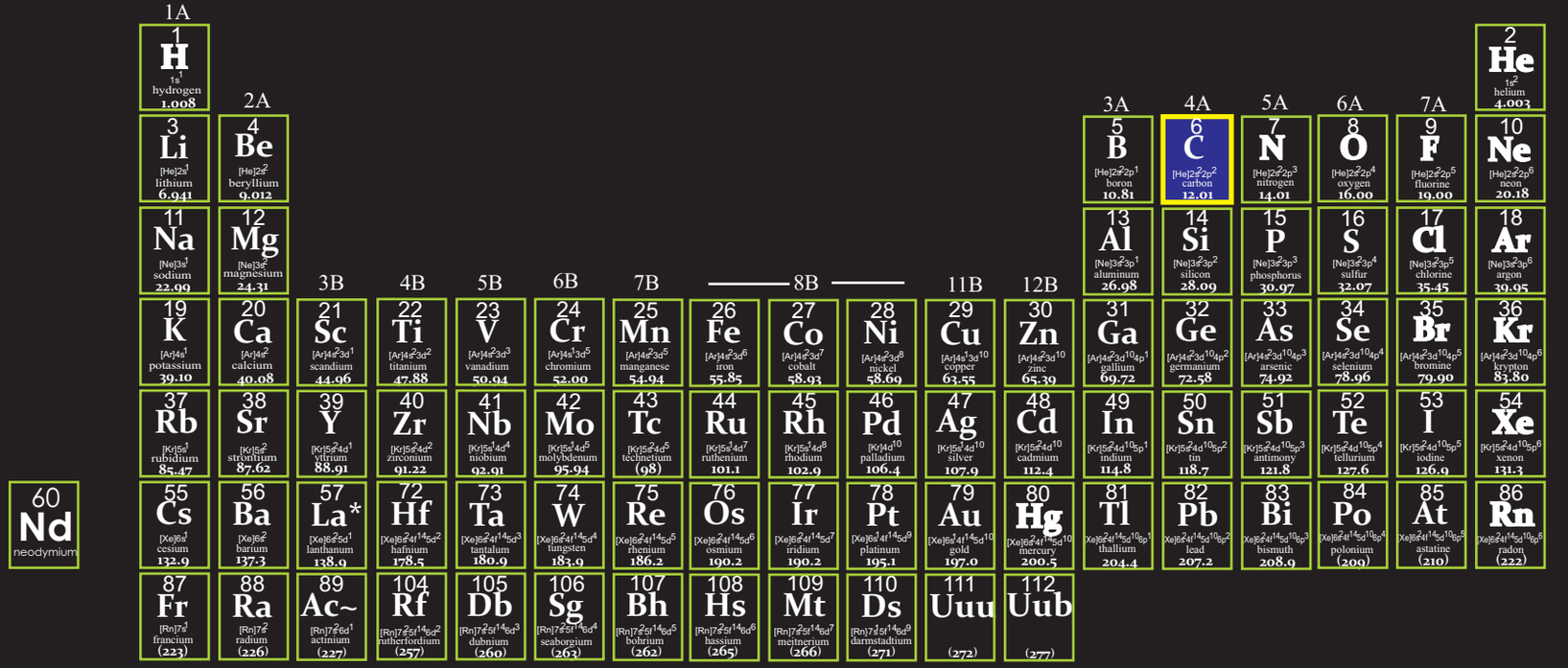
1A	2A	3B	4B	5B	6B	7B	8B	8B	8B	11B	12B	3A	4A	5A	6A	7A	
1 **H** $1s^1$ hydrogen 1.008																	2 **He** $1s^2$ helium 4.003
3 **Li** $[He]2s^1$ lithium 6.941	4 **Be** $[He]2s^2$ beryllium 9.012											5 **B** $[He]2s^22p^1$ boron 10.81	6 **C** $[He]2s^22p^2$ carbon 12.01	7 **N** $[He]2s^22p^3$ nitrogen 14.01	8 **O** $[He]2s^22p^4$ oxygen 16.00	9 **F** $[He]2s^22p^5$ fluorine 19.00	10 **Ne** $[He]2s^22p^6$ neon 20.18
11 **Na** $[Ne]3s^1$ sodium 22.99	12 **Mg** $[Ne]3s^2$ magnesium 24.31											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	18 **Ar** $[Ne]3s^23p^6$ argon 39.95
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	36 **Kr** $[Ar]4s^23d^{10}4p^6$ krypton 83.80
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	54 **Xe** $[Kr]5s^24d^{10}5p^6$ xenon 131.3
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)	86 **Rn** $Xe]6s^24f^{14}5d^{10}6p^6$ radon (222)
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** $[Rn]7s^15f^{14}6d^9$ darmstadium (271)	111 **Uuu** (272)	112 **Uub** (277)						

60 **Nd** neodymium

Insights into the evolution of life and the Planet through carbon isotopes and numerical modelling techniques

(and a flimsy excuse to talk about the PETM)

Andy Ridgwell



Carbon isotopes as a tracer of ... what?

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

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

=> δ(sample) is POSITIVE

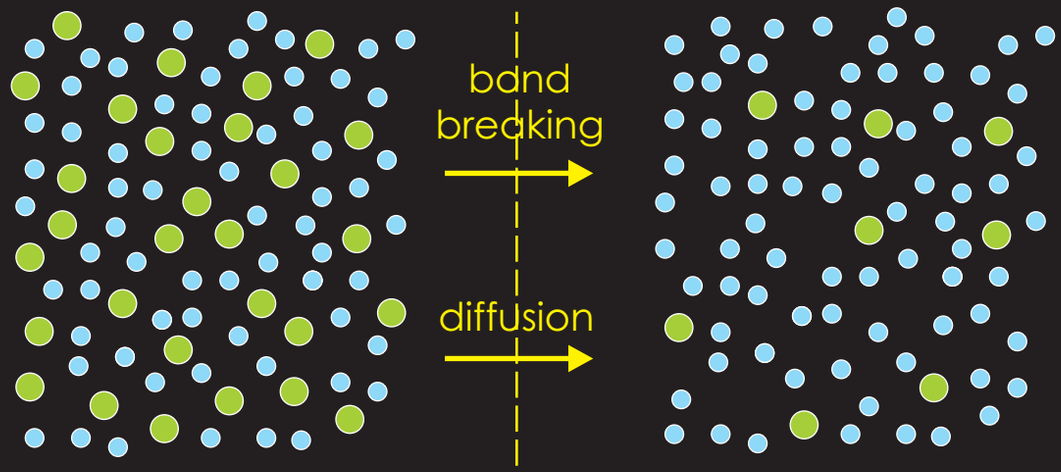
('isotopically enriched')

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

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

=> δ(sample) is NEGATIVE

('isotopically depleted')



'lighter' isotope

'heavier' isotope

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

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

1A	2A	3B	4B	5B	6B	7B	8B	8B	8B	1B	2B	3A	4A	5A	6A	7A	0
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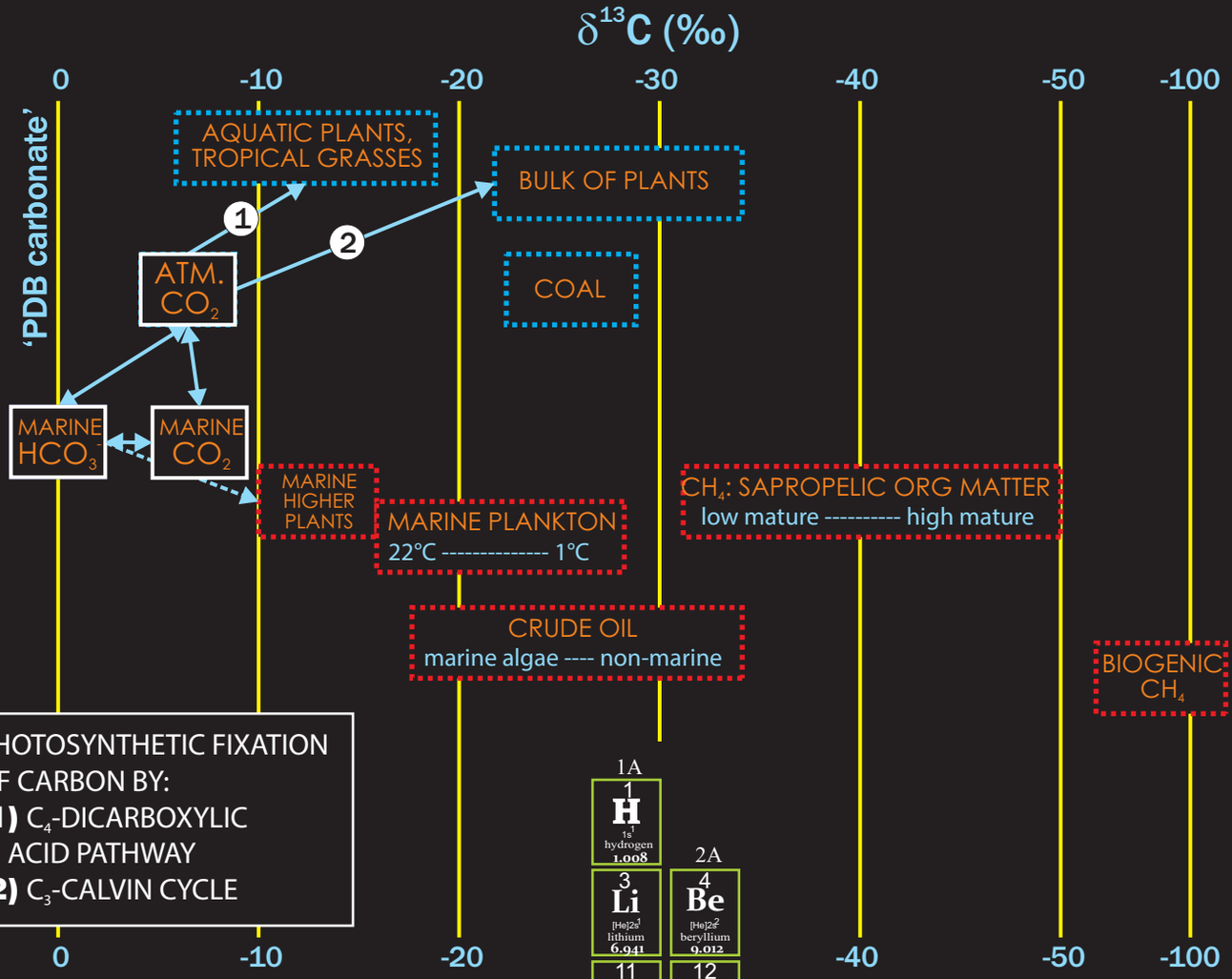
37 Rb rubidium 85.47	38 Sr strontium 87.62	39 Y yttrium 88.91	40 Zr zirconium 91.22	41 Nb niobium 92.91	42 Mo molybdenum 95.94	43 Tc technetium (98)	44 Ru ruthenium 101.1	45 Rh rhodium 102.9	46 Pd palladium 106.4	47 Ag silver 107.9	48 Cd cadmium 112.4	49 In indium 114.8	50 Sn tin 118.7	51 Sb antimony 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 darmstadtium (271)	111 Uuu (272)	112 Uub (277)						

60 Nd neodymium

Carbon isotopes as a tracer of … what?



Maslin and Thomas [2003]

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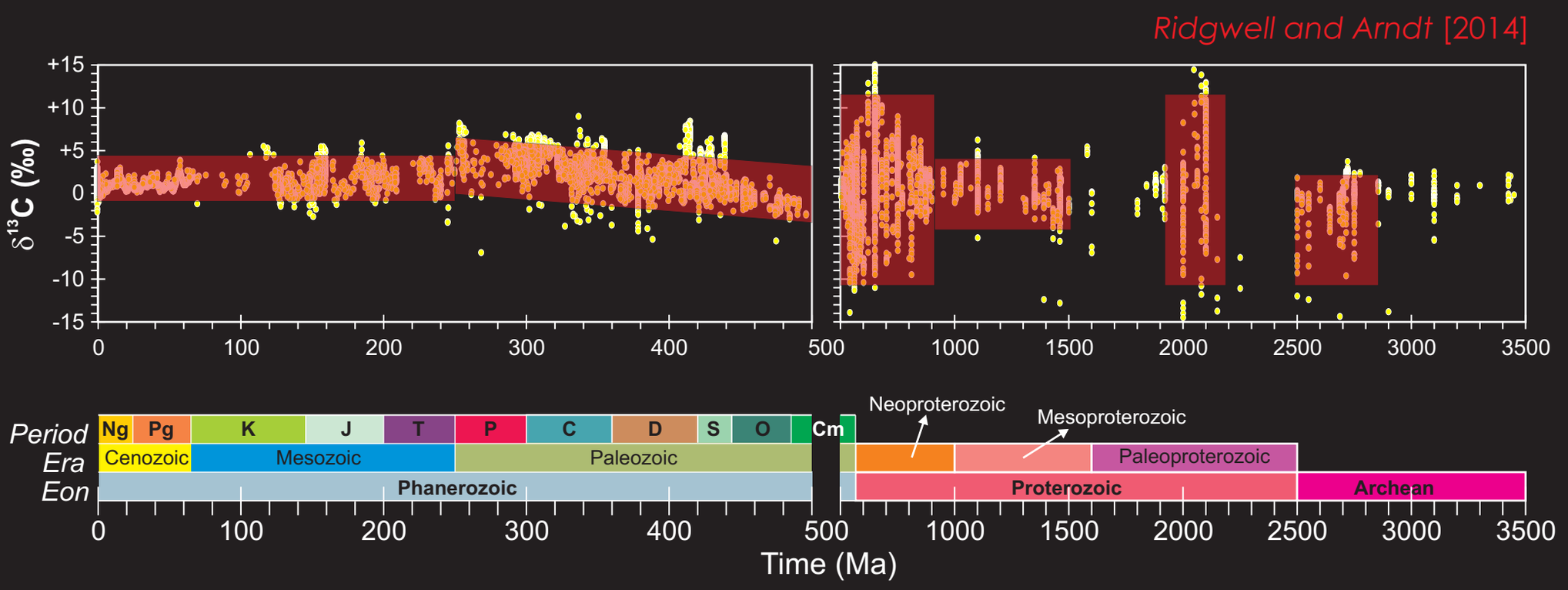
60 Nd neodymium

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?

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

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

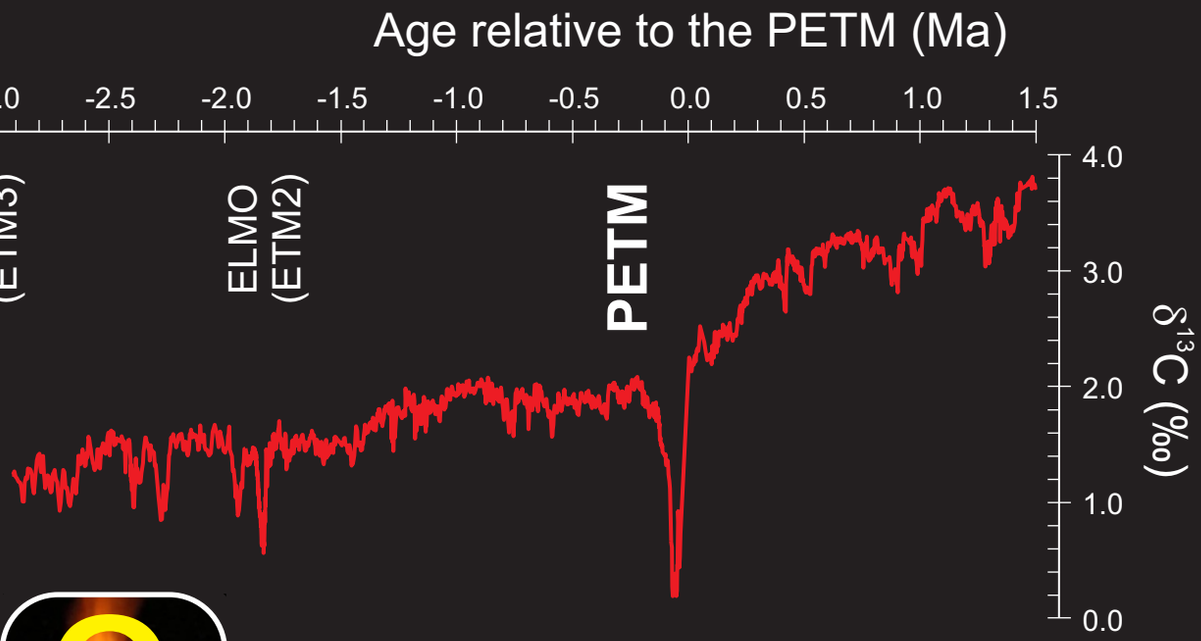
Carbonate $\delta^{13}C$ variability through time

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

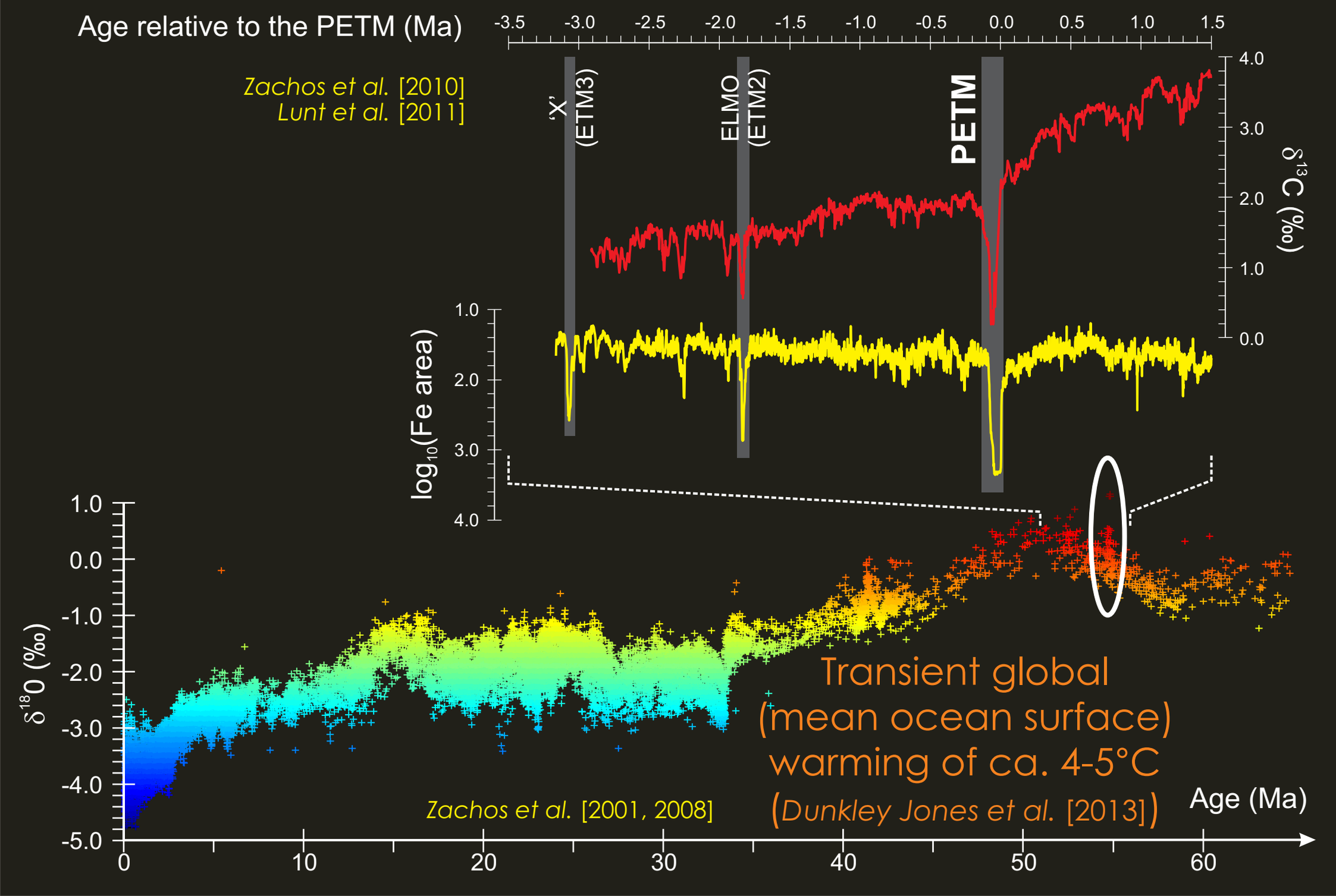
Re-partitioning of carbon ***within*** surficial reservoirs?

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

Injection (or removal) of isotopically light carbon?



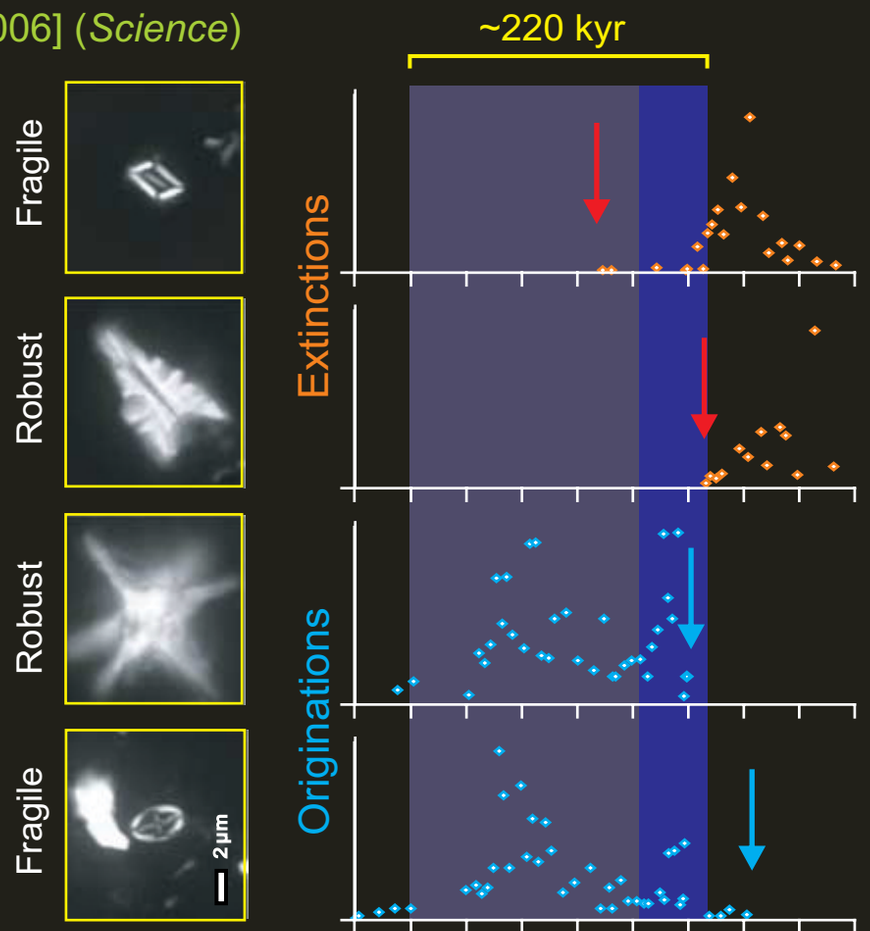
Paleo-analogues – the PETM?



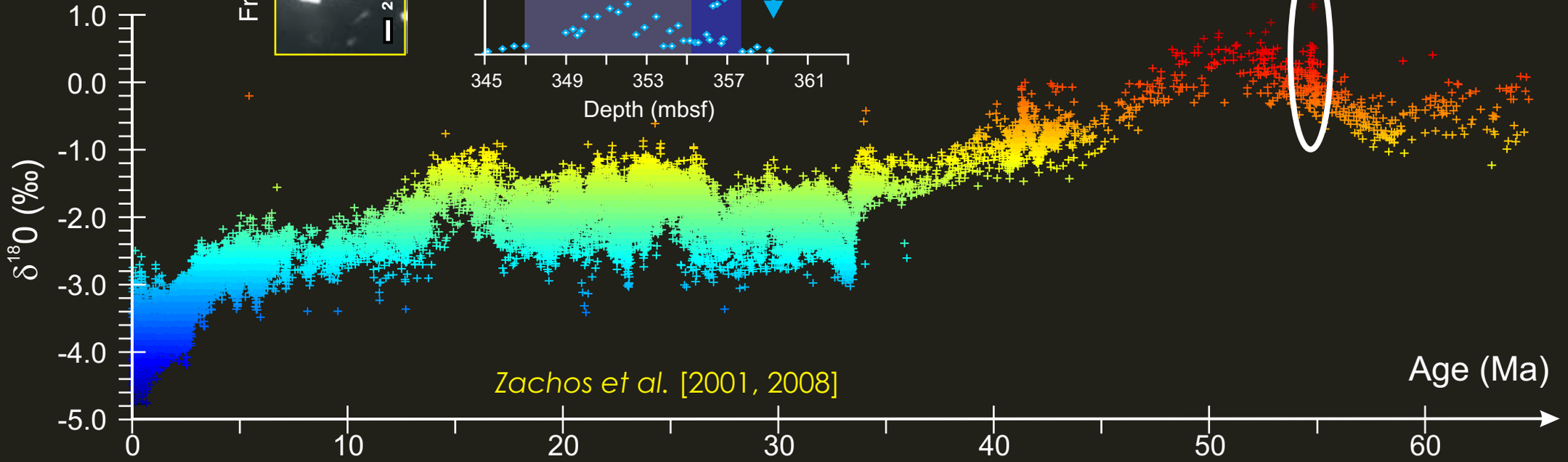
Paleo-analogues – the PETM?

Paleo-analogues – the PETM?

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



observed nanoplankton assemblage response to environmental change across the PETM

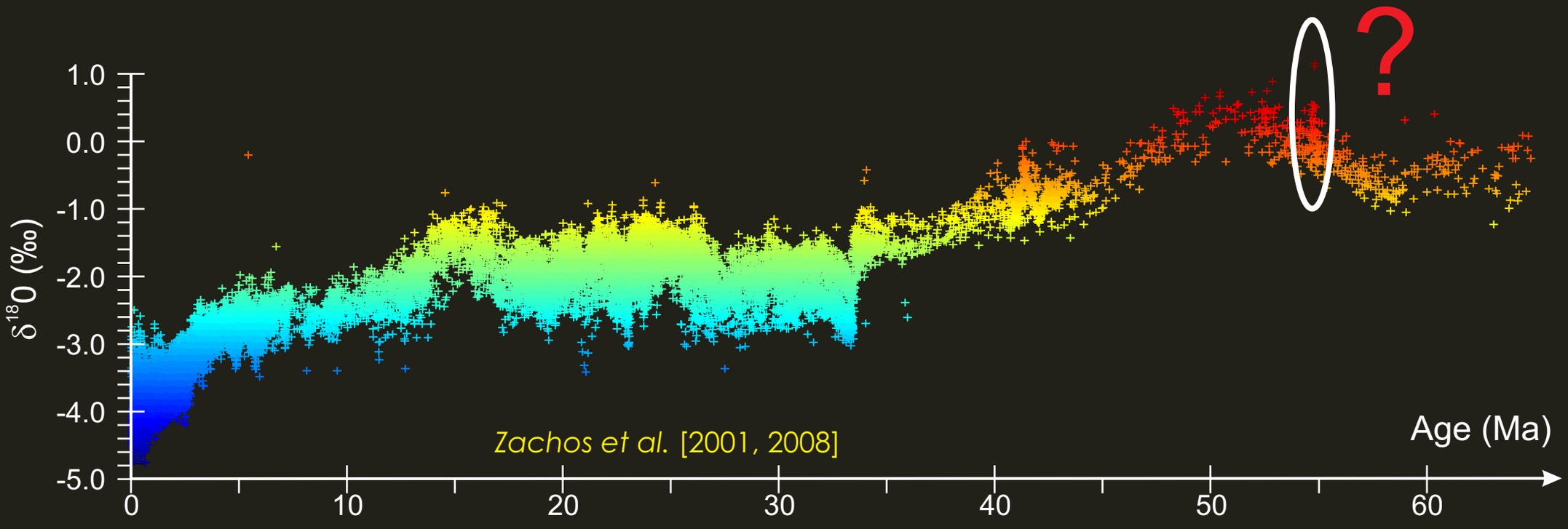


Zachos et al. [2001, 2008]

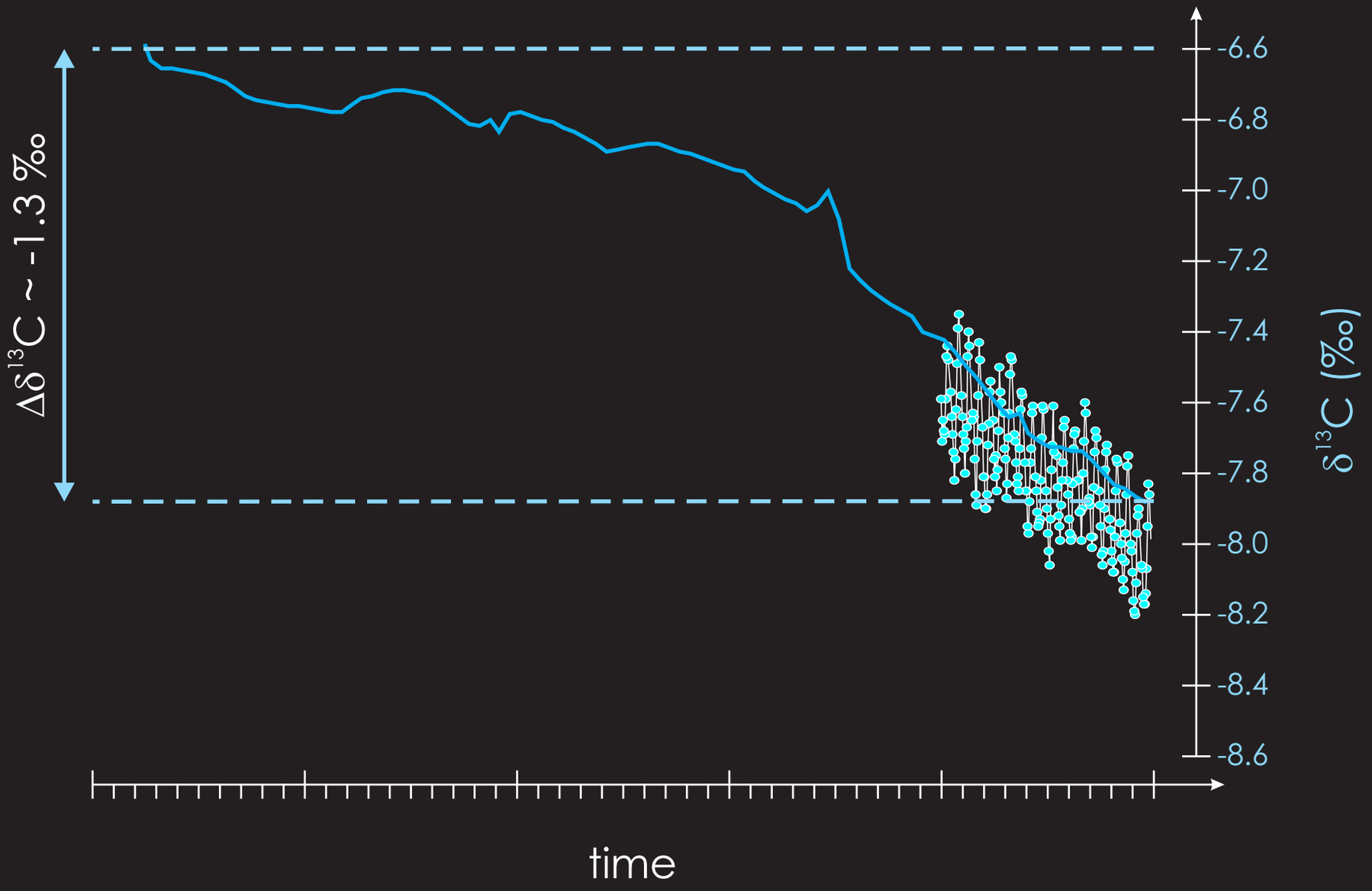
Paleo-analogues – the PETM?

'triggers'

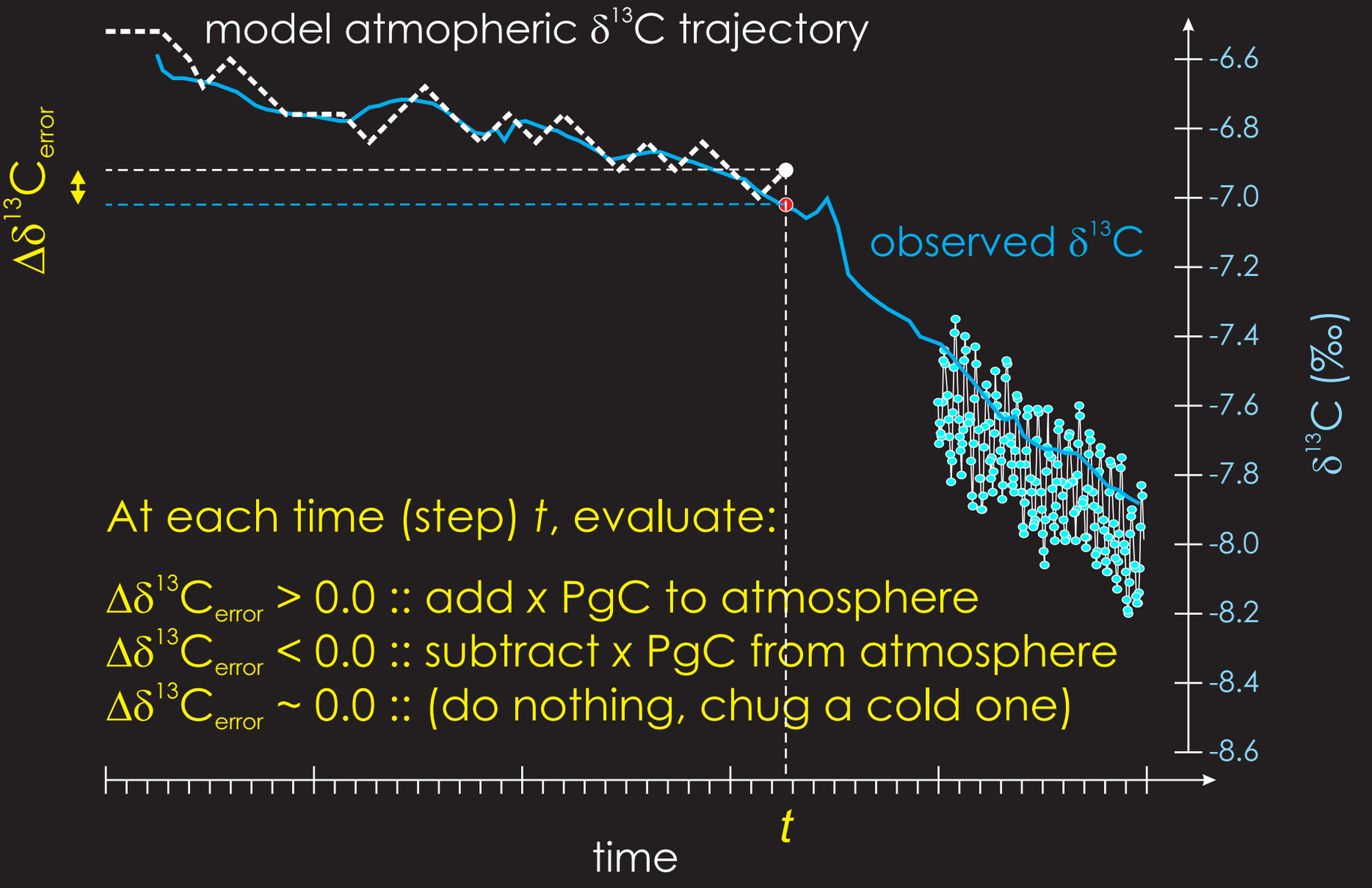
carbon cycle feedbacks



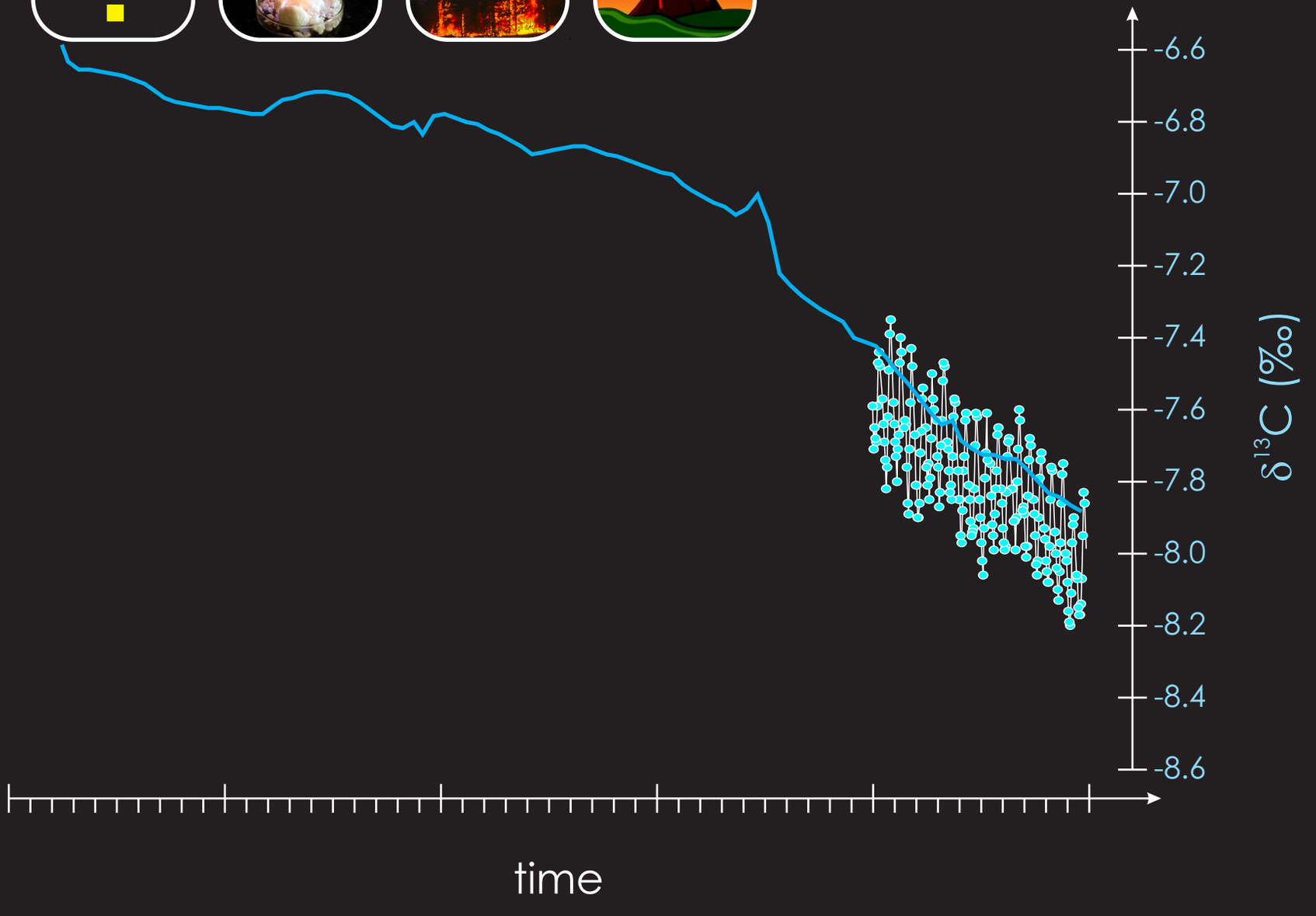
Methods



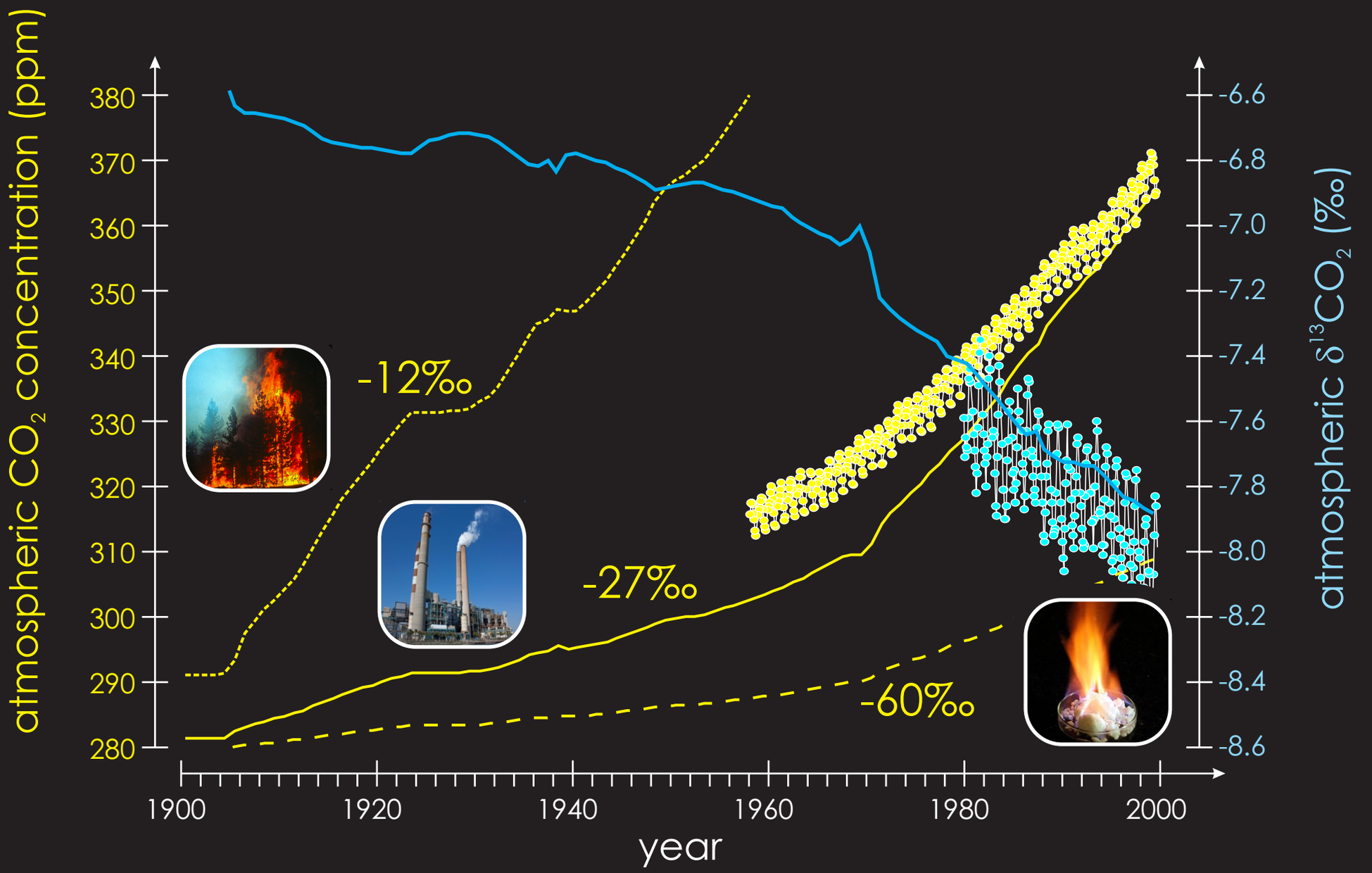
Methods


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

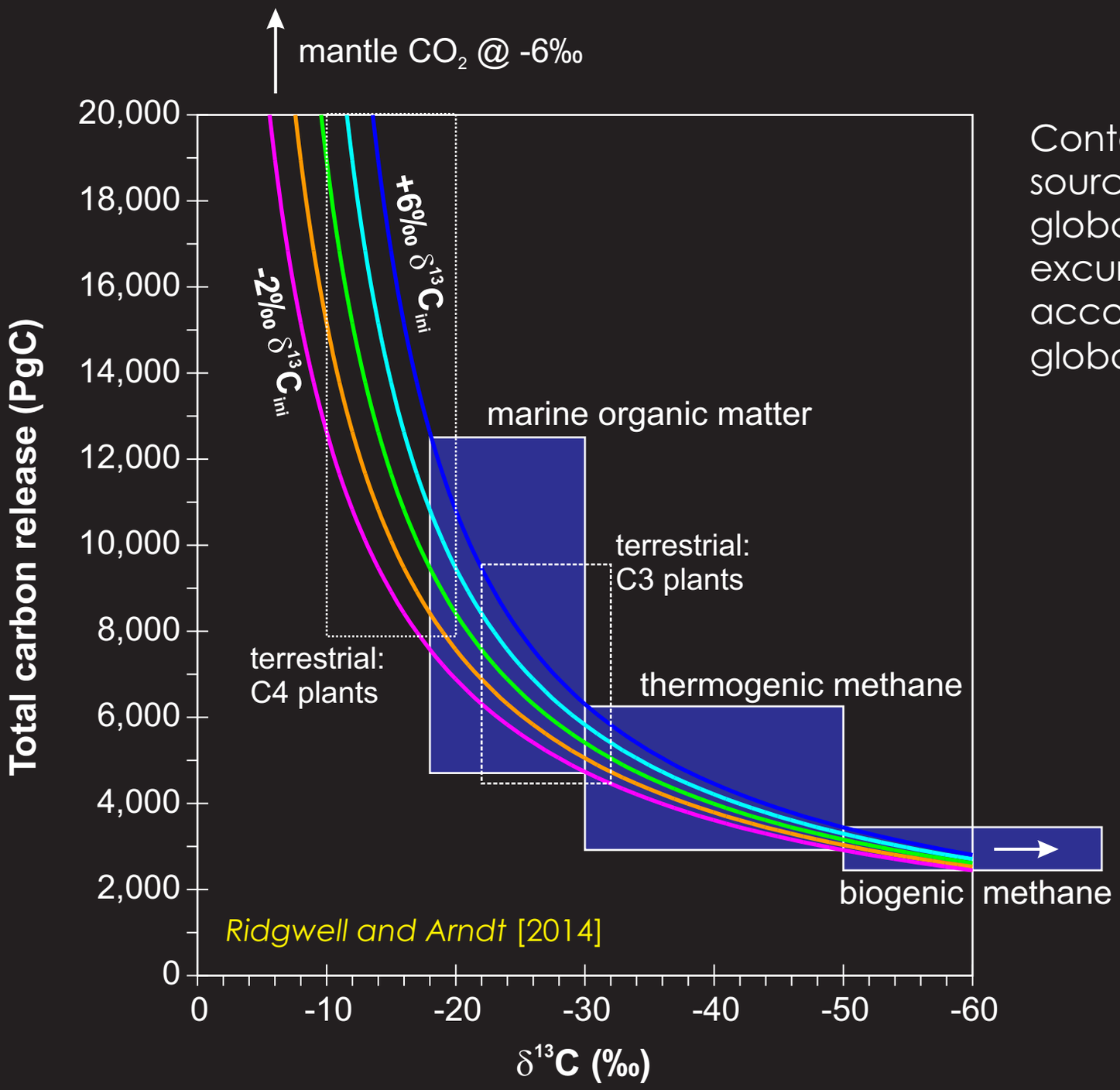
Methods



Methods

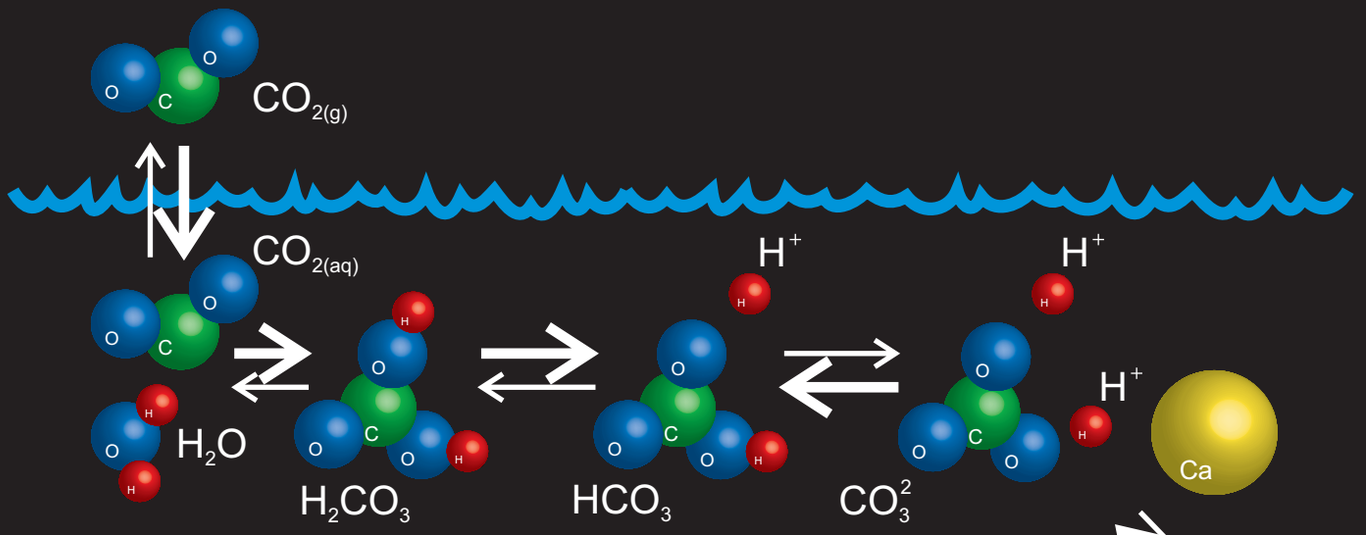

atmospheric CO_2 concentration (ppm)
380
370
360
350
340
330
320
310
300
290
280
-12‰
-27‰
-60‰
atmospheric $\delta^{13}CO_2$ (‰)
-6.6
-6.8
-7.0
-7.2
-7.4
-7.6
-7.8
-8.0
-8.2
-8.4
-8.6
1900
1920
1940
1960
1980
2000
year

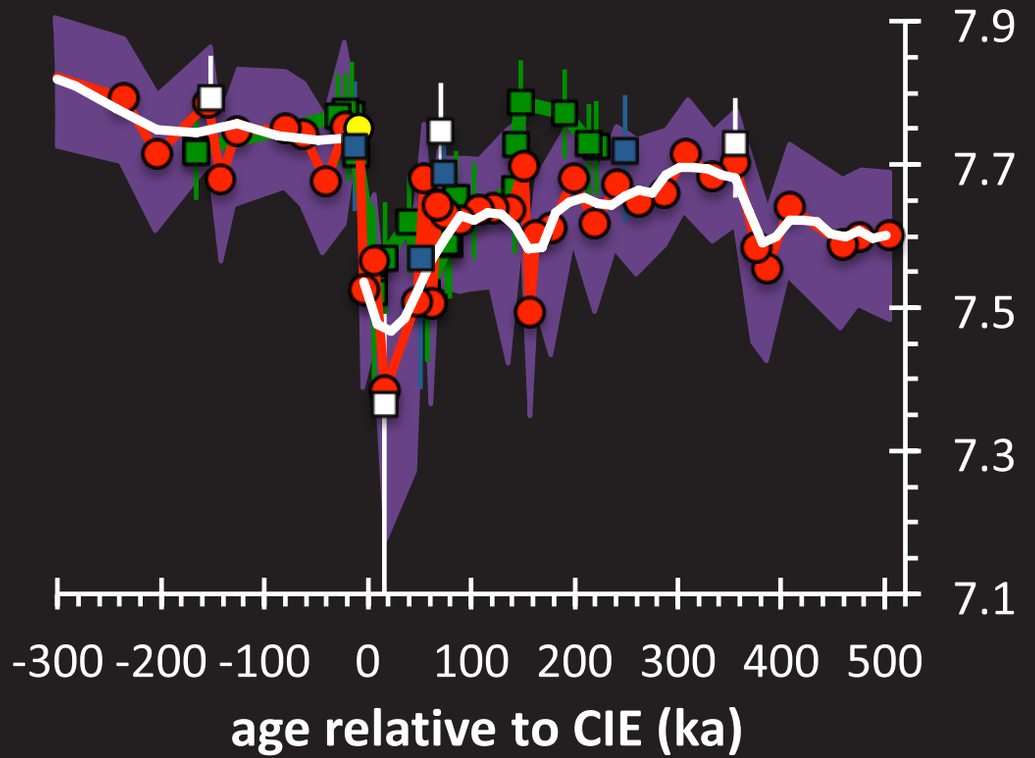
Methods

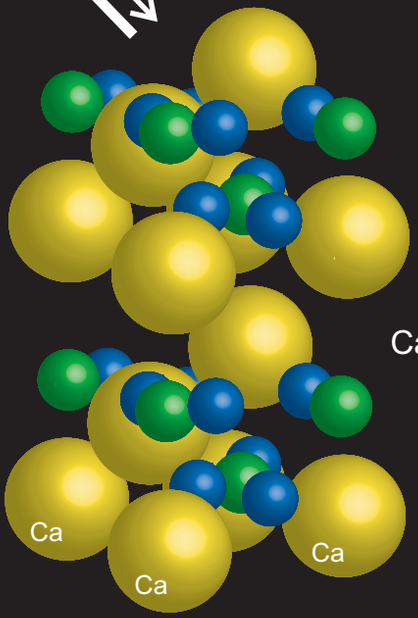


Contours of carbon release vs. source isotopic signature for a global -4‰ carbon isotopic excursion. Contours differ according to the initial mean global $\delta^{13}C$.

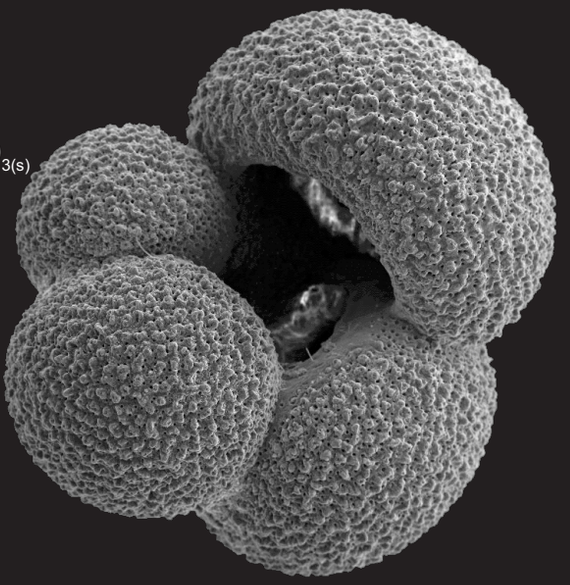
Methods



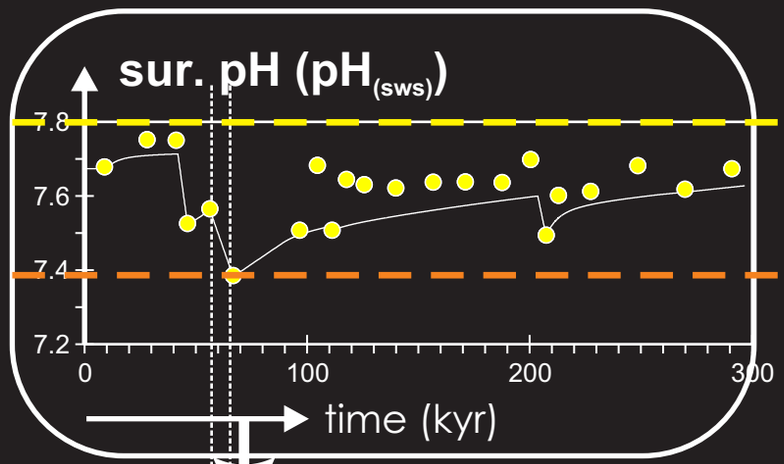




$CaCO_{3(s)}$

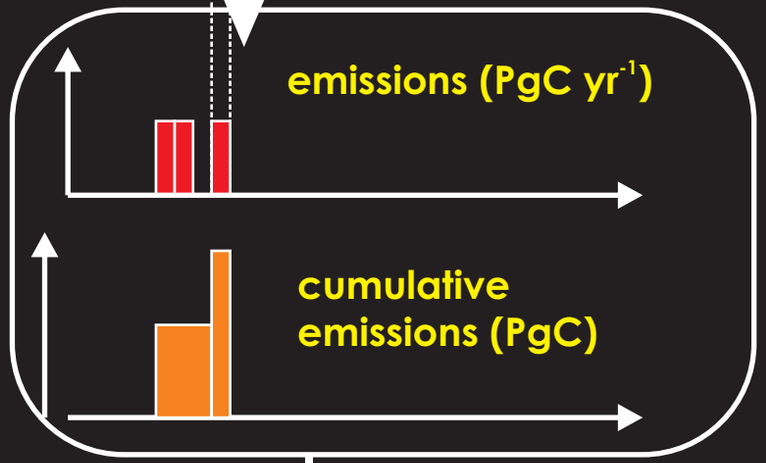


Assimilating surface ocean pH change (only)

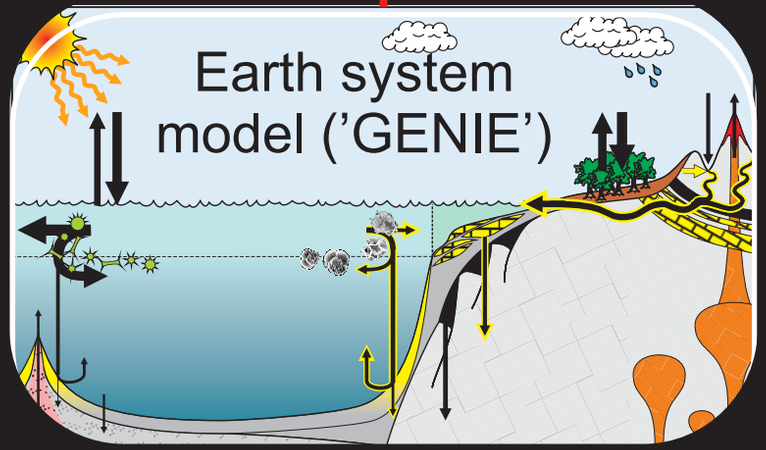


year 2100 seawater pH

peak PETM

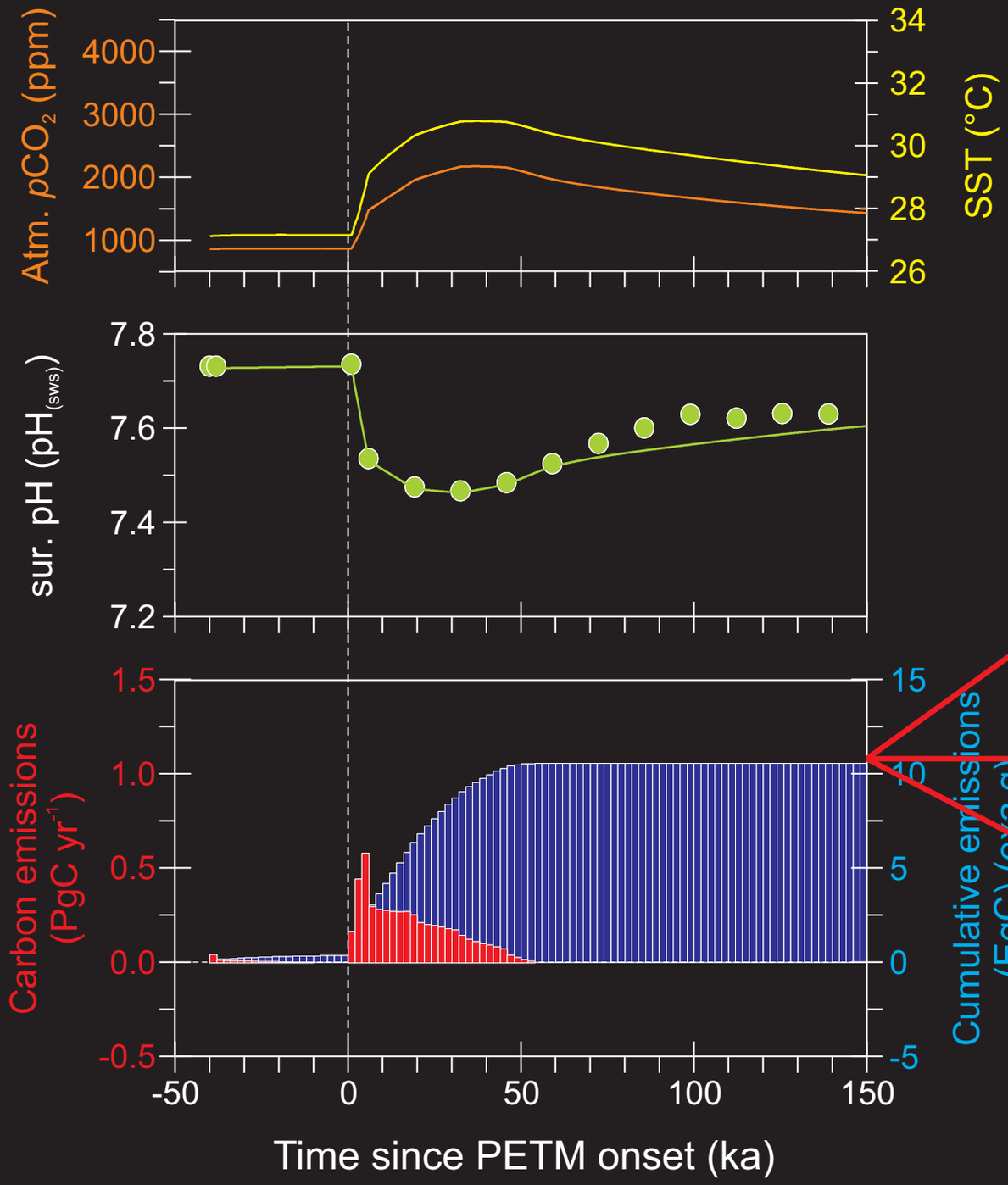


Earth system model including silicate weathering feedback



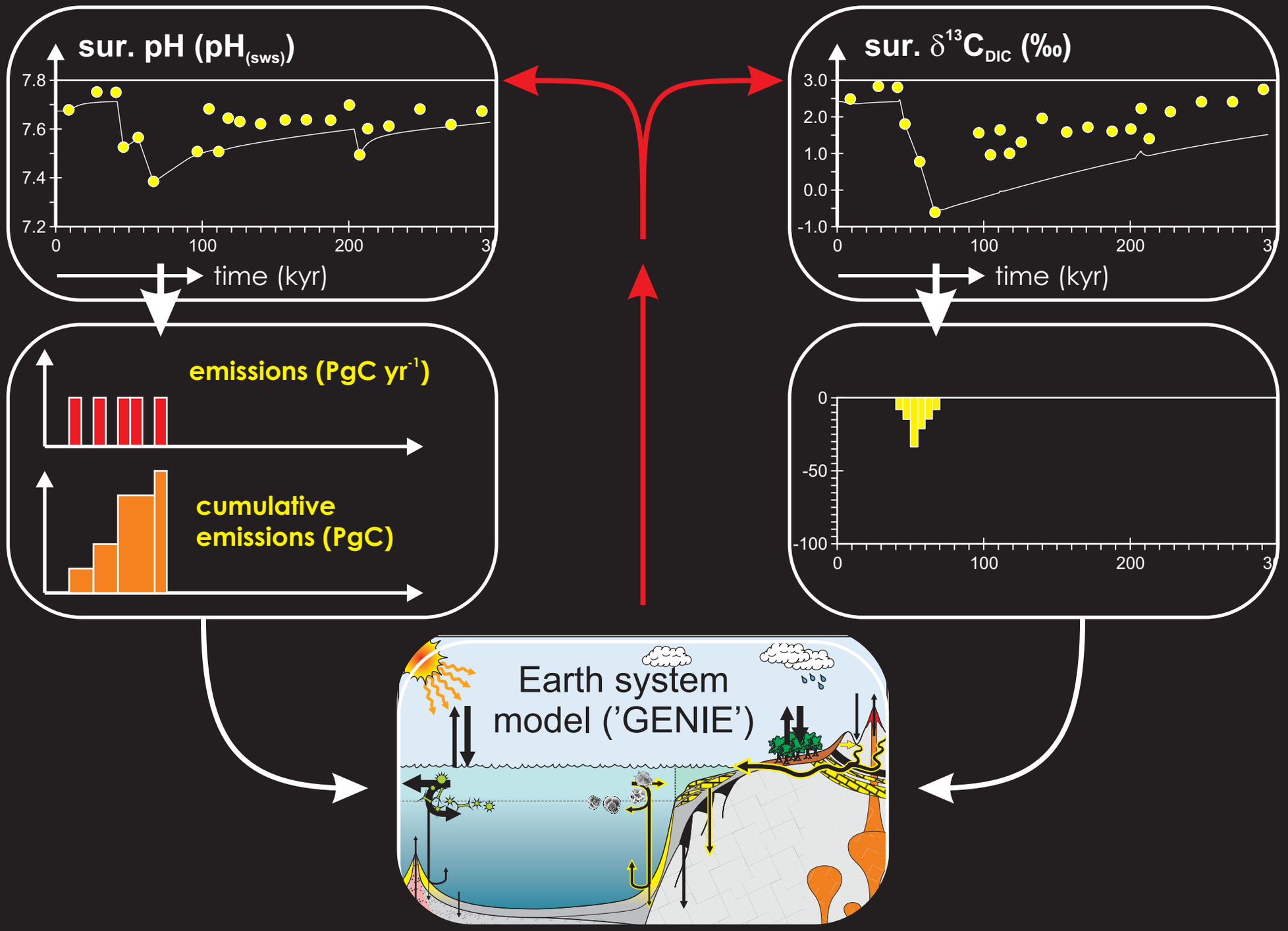
Gutjahr et al. [2017]

Assimilating surface ocean pH change (only)

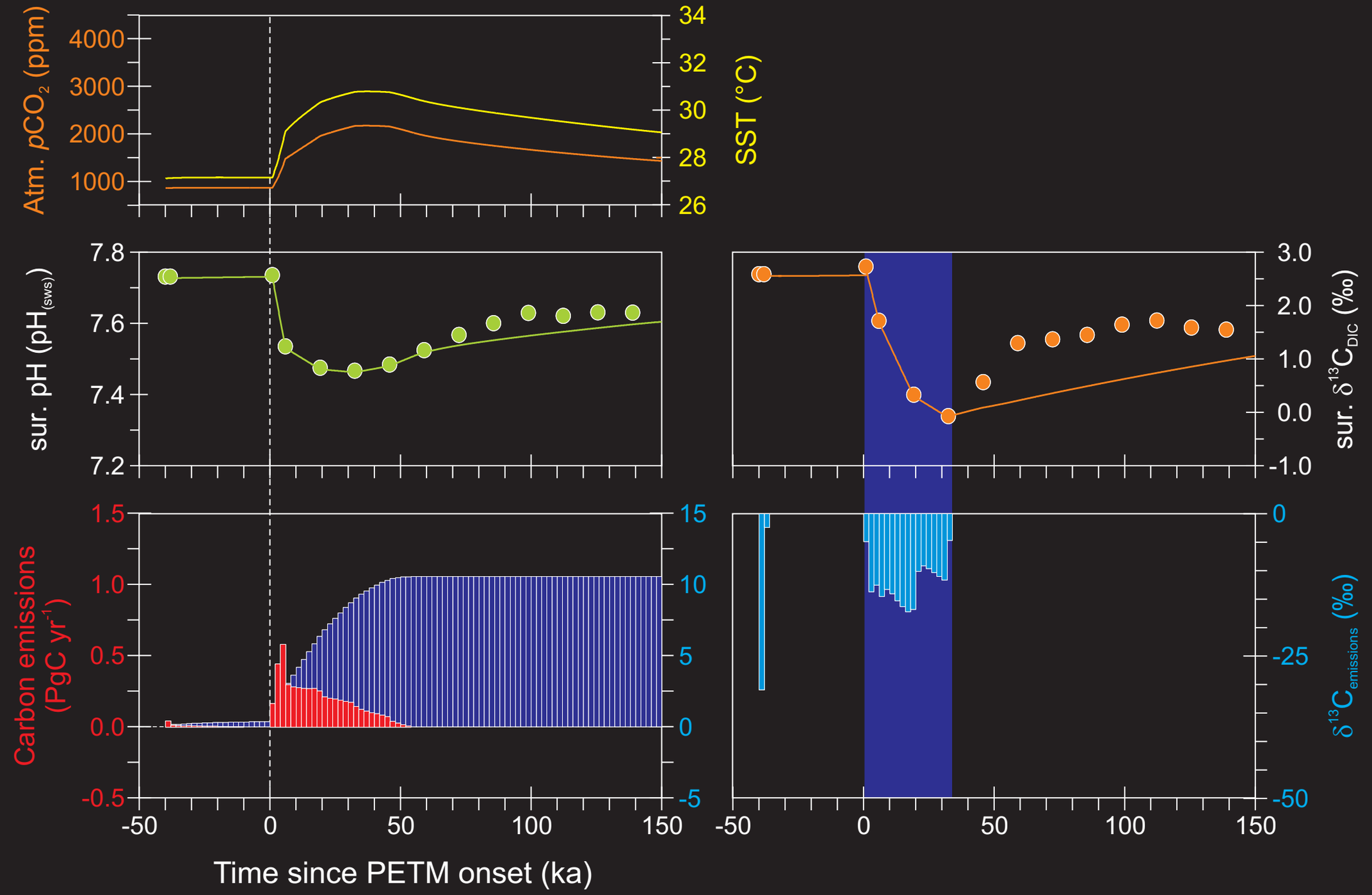


Gutjahr et al. [2017]

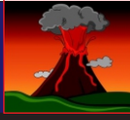
Assimilating surface ocean pH and $\delta^{13}C$



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



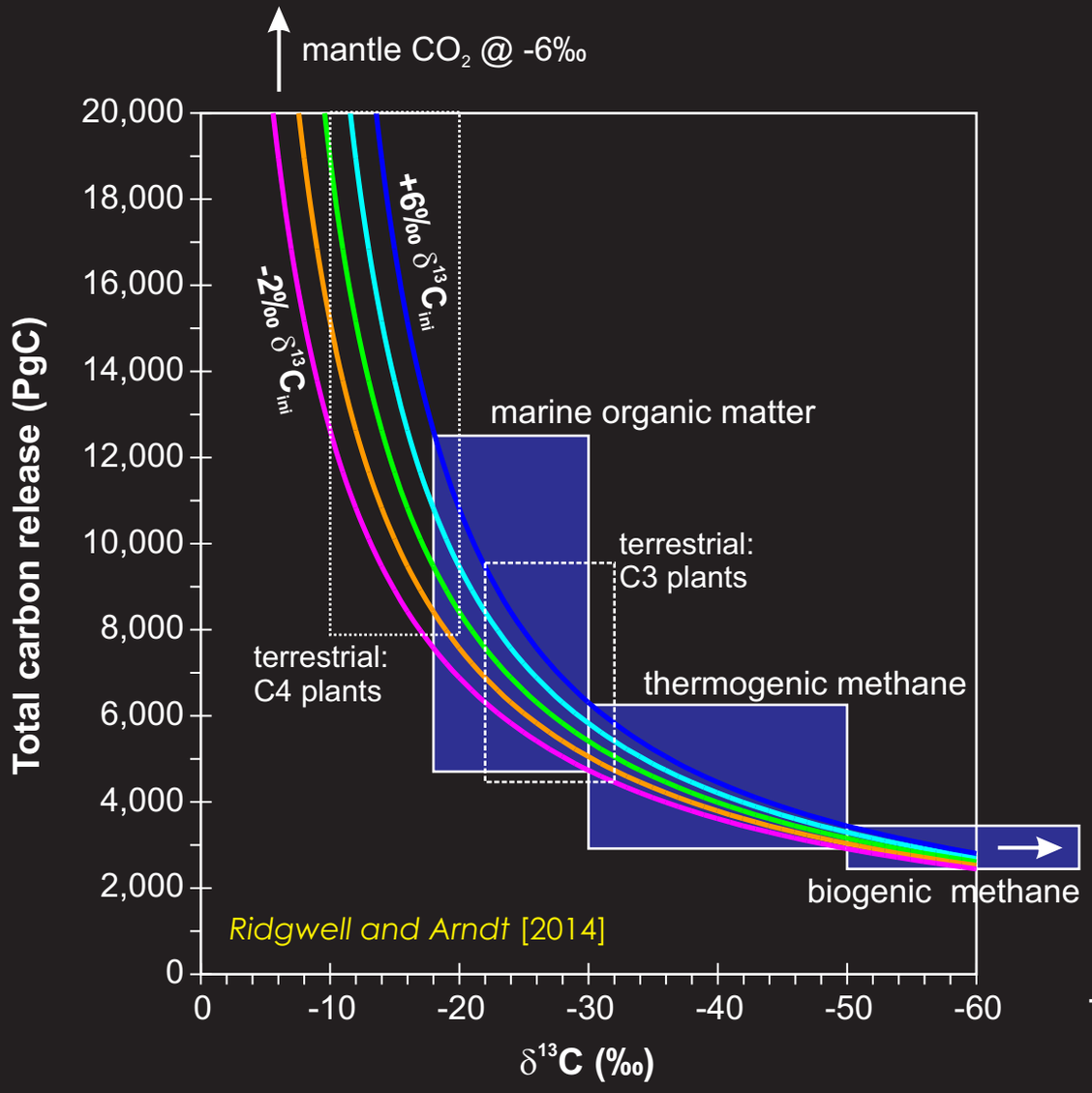
Assimilating surface ocean pH and $\delta^{13}C$

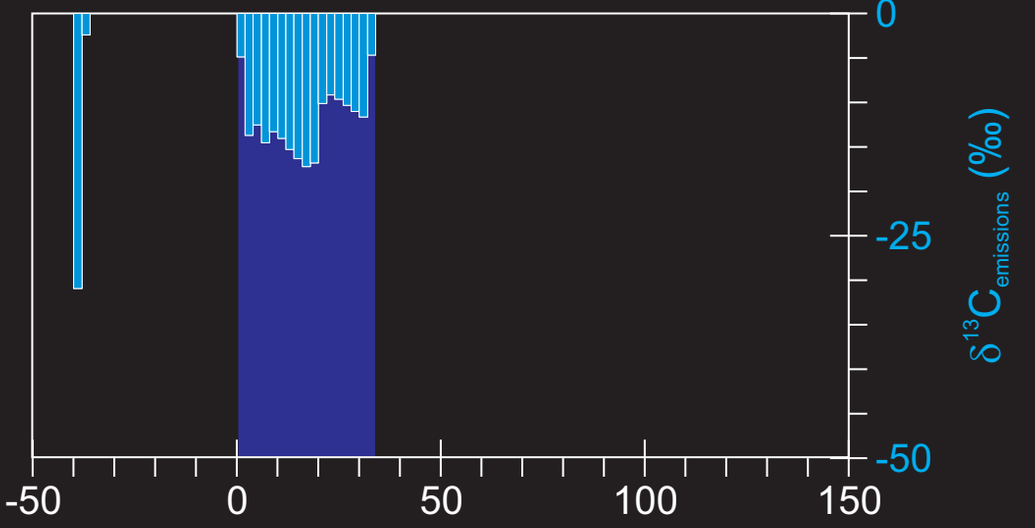


+

OR

+





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

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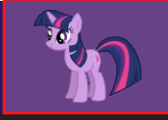
Carbonate diagenesis and loss of primary $\delta^{13}C$ signal, either marine sedimentary or subaerial.



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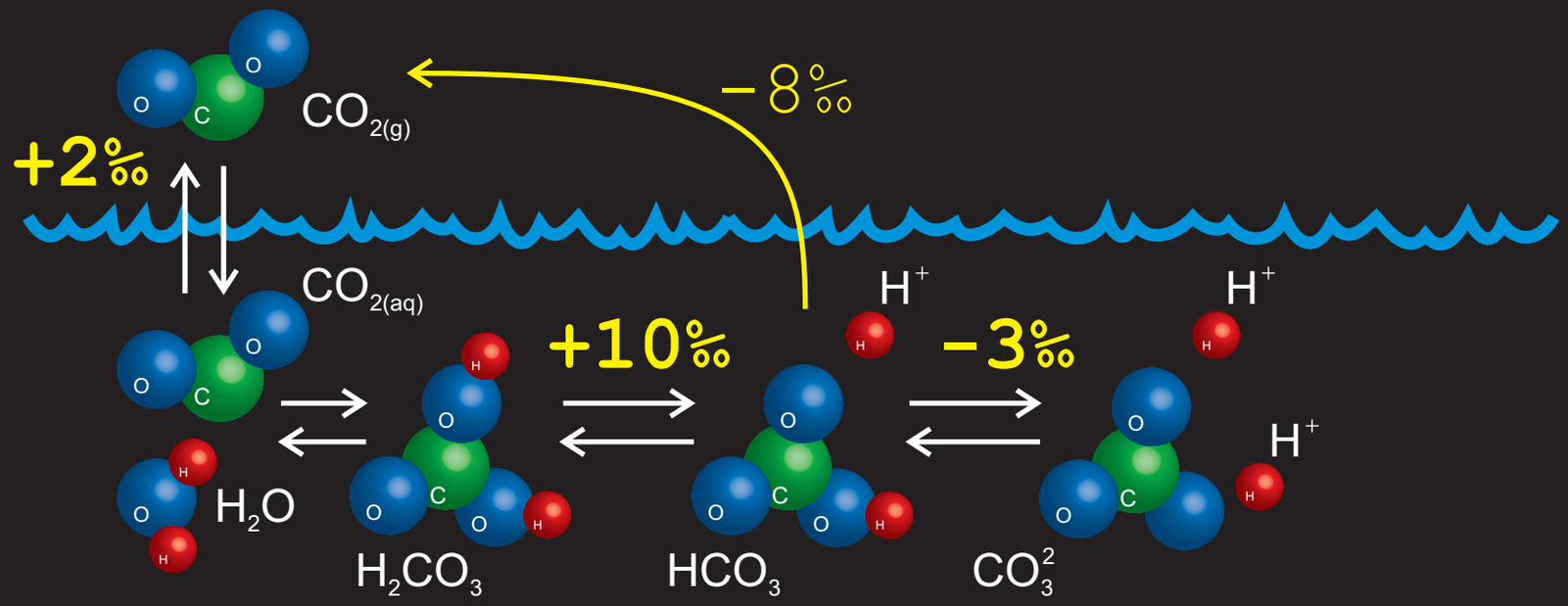
Carbonate diagenesis and loss of primary $\delta^{13}C$ signal, either marine sedimentary or subaerial.

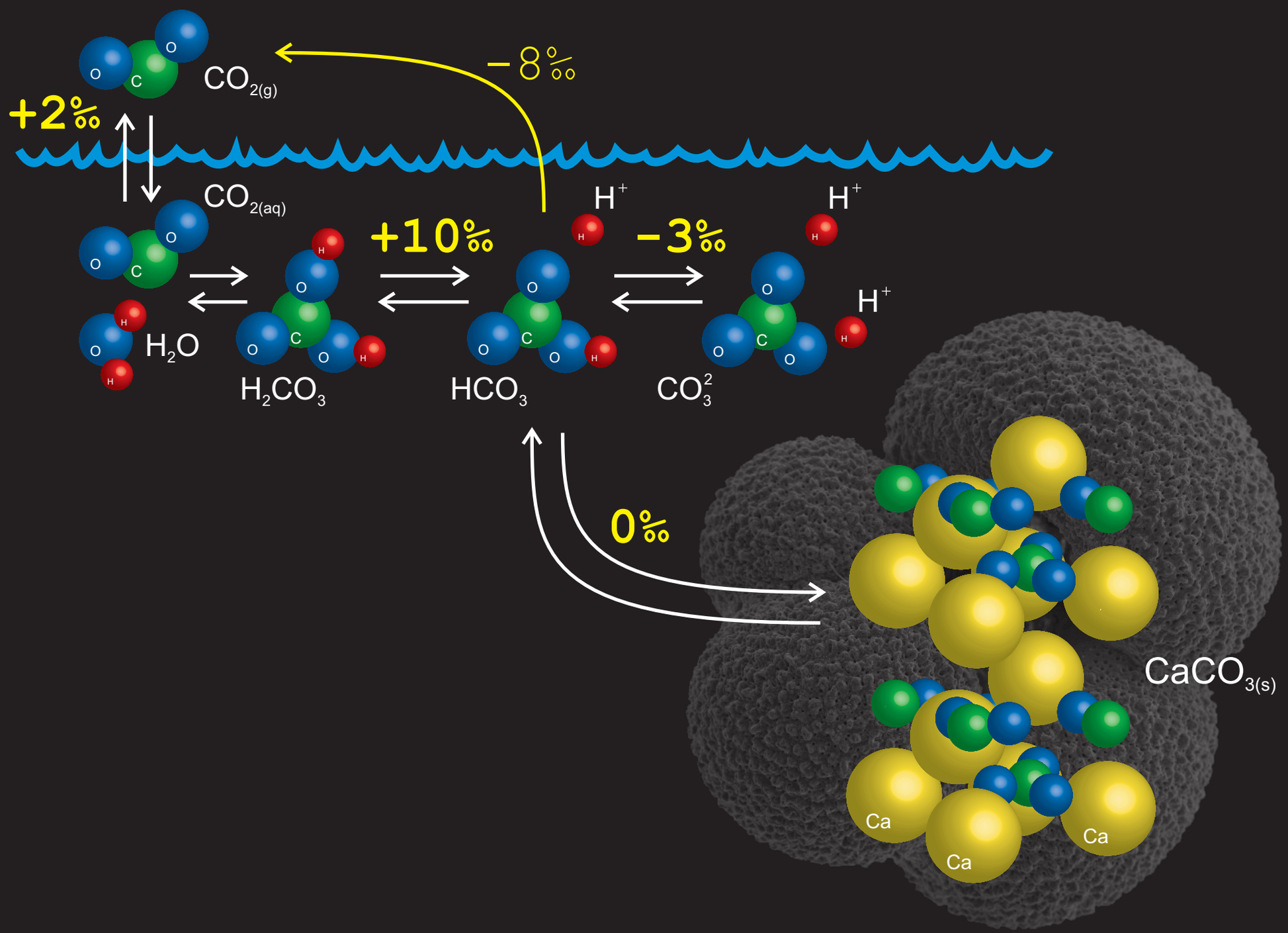
pH-driven re-partitioning of the where the isotopic composition of the mean surficial reservoir is held (and what carbonate samples)

A new paleo Pokémon appears – The pH control on carbonate $\delta^{13}C$



Adapted from: *Barker and Ridgwell* [2012]

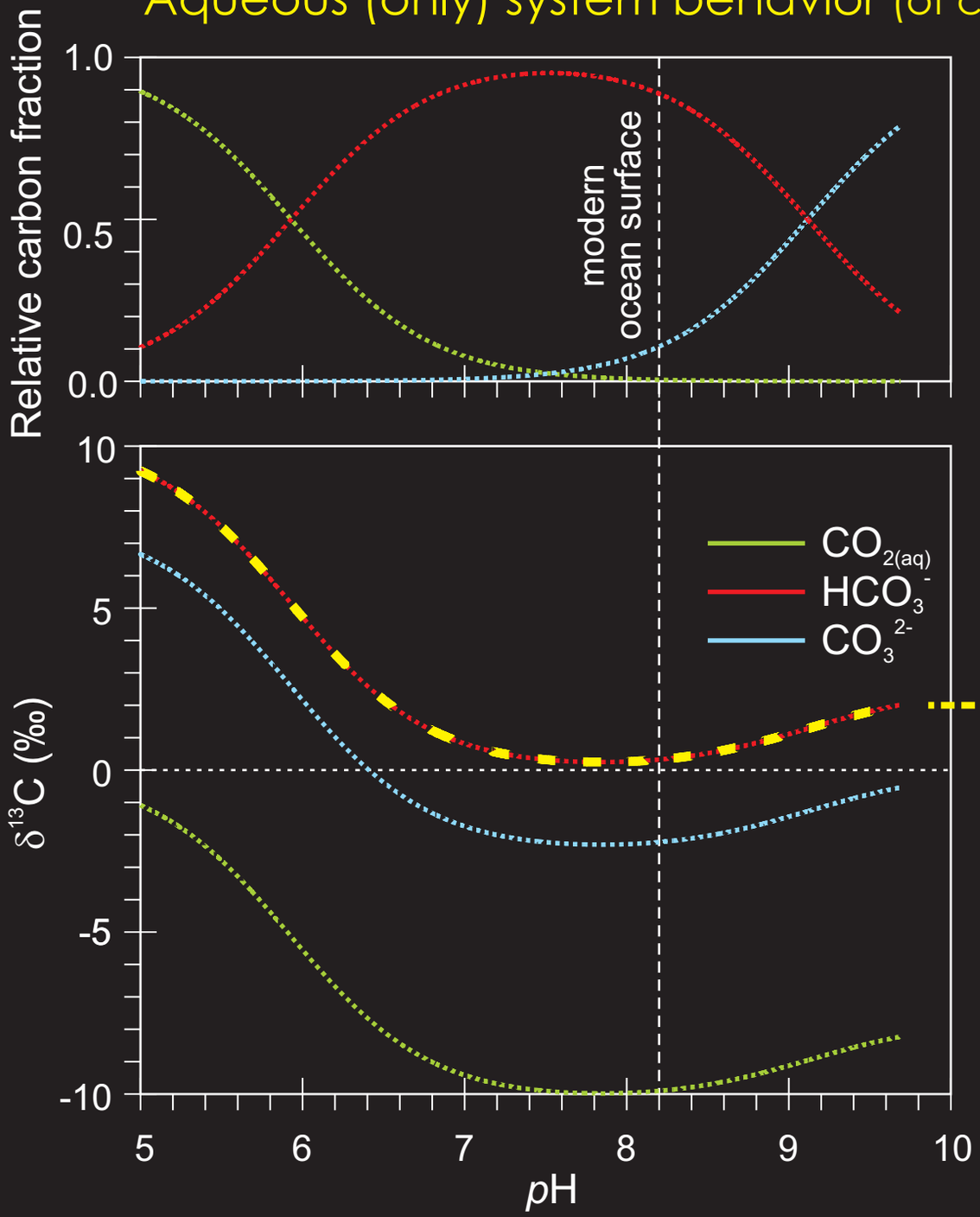
A new paleo Pokémon appears – The pH control on carbonate $\delta^{13}C$

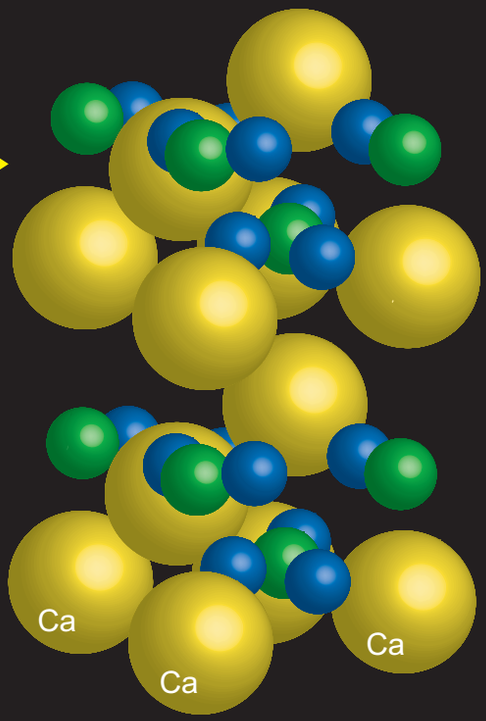


Adapted from: *Barker and Ridgwell* [2012]

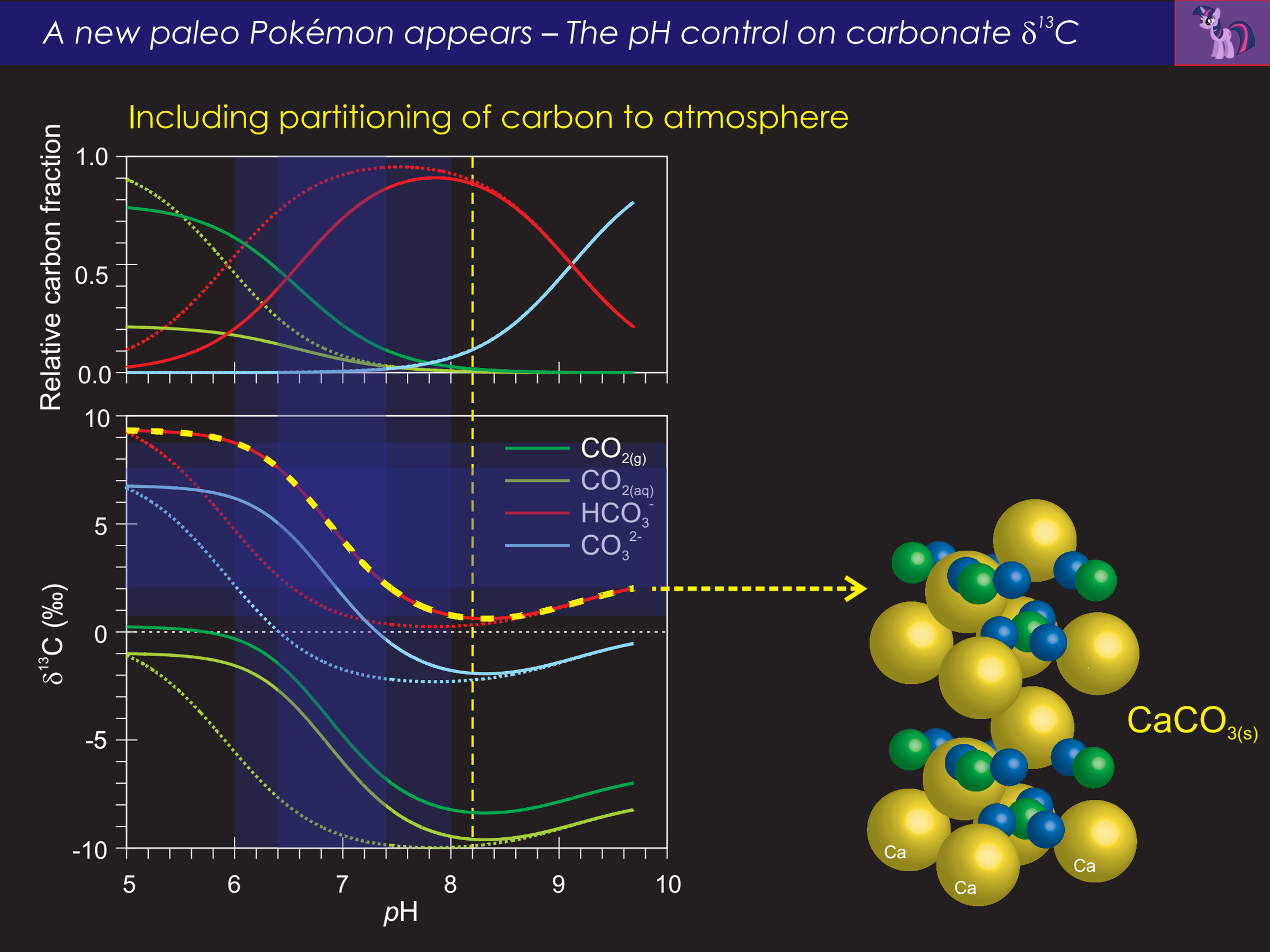
A new paleo Pokémon appears – The pH control on carbonate $\delta^{13}C$

Aqueous (only) system behavior (of carbon partitioning between reservoirs)

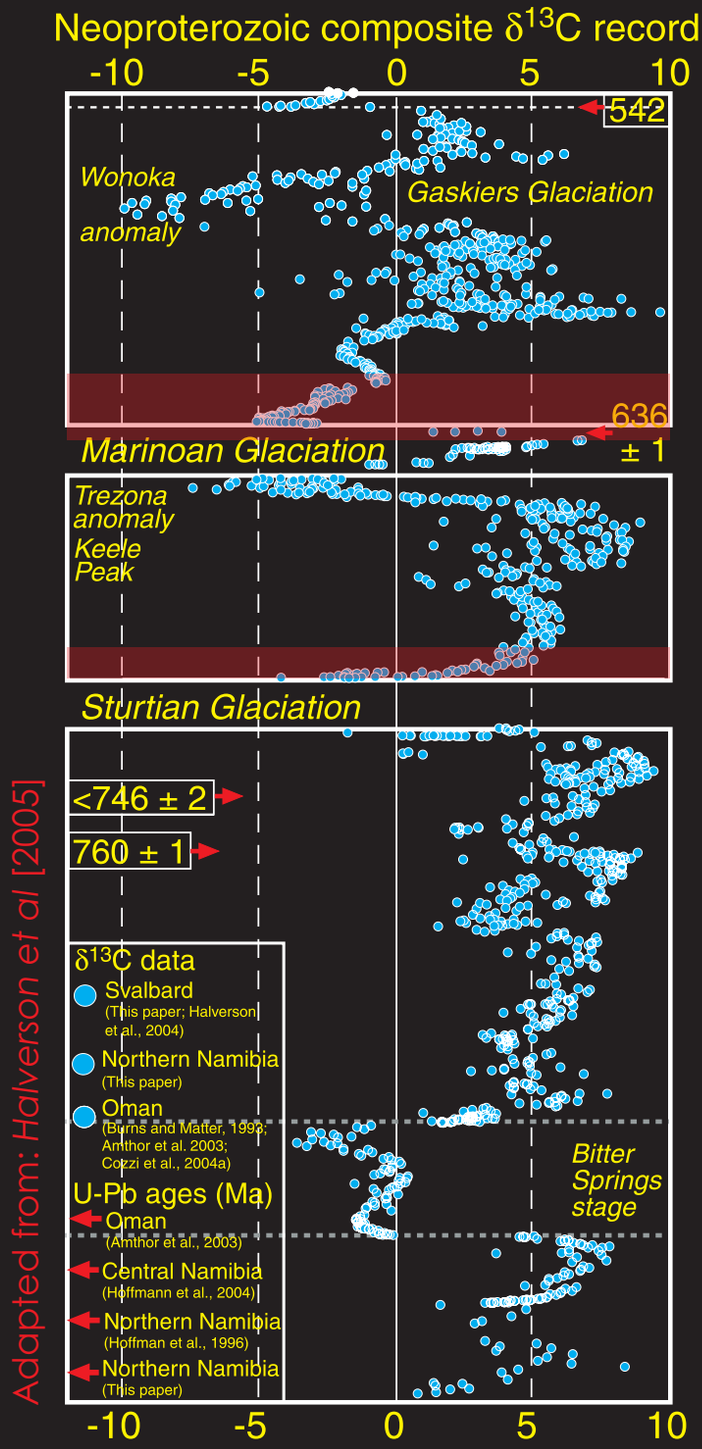




A new paleo Pokémon appears – The pH control on carbonate $\delta^{13}C$

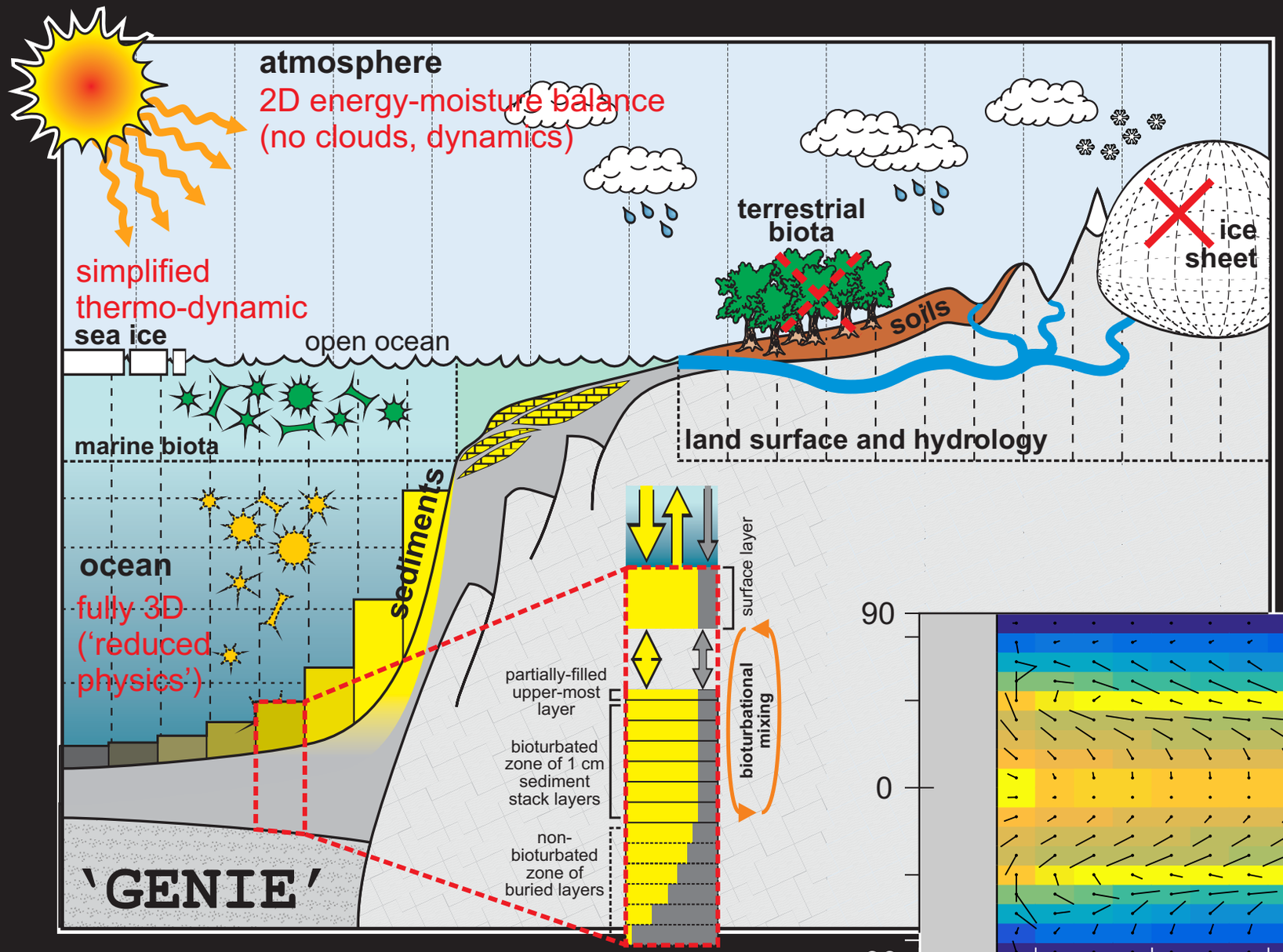


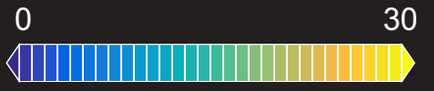
Numerical modelling – Results

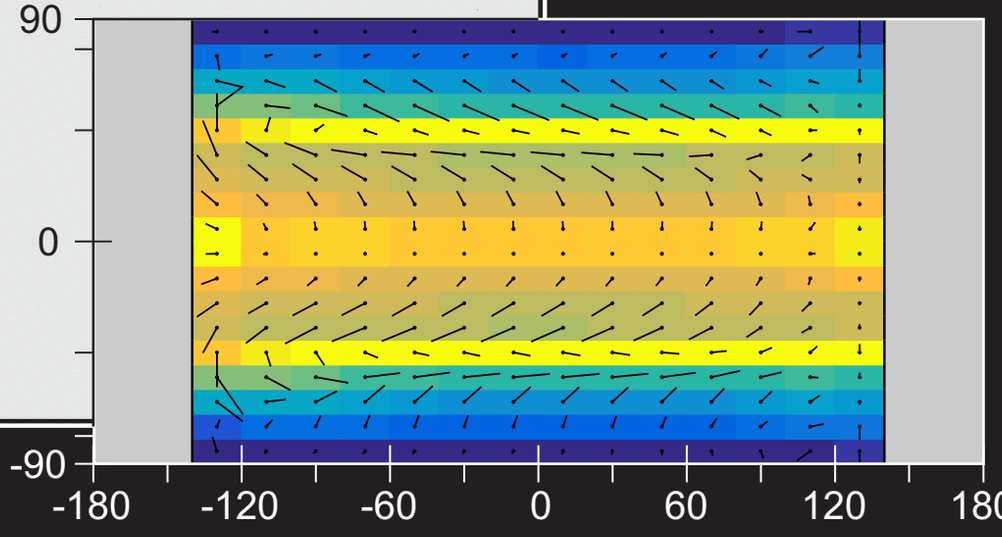


Adapted from: *Halverson et al* [2005]

Earth system model – physical configuration

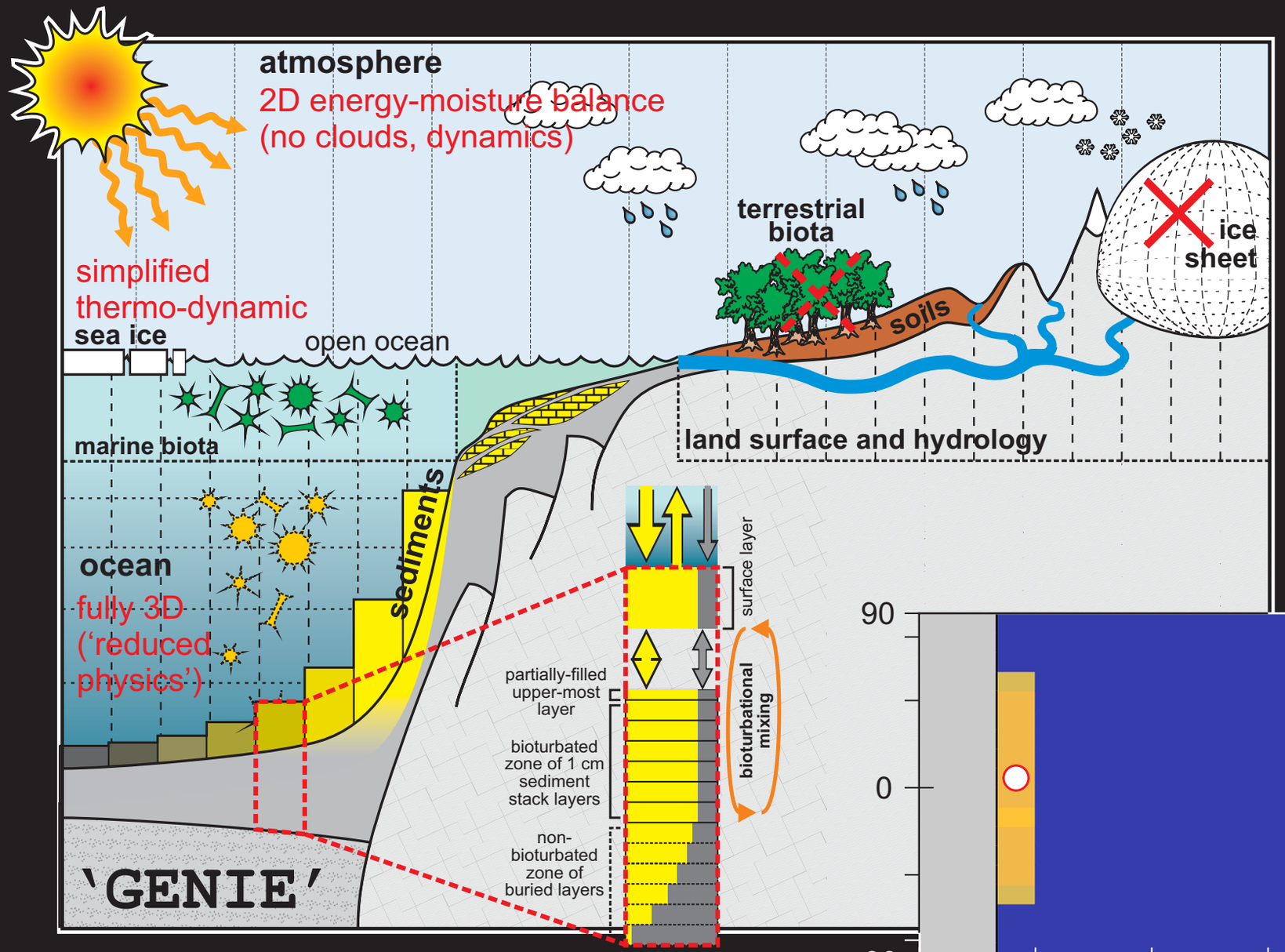


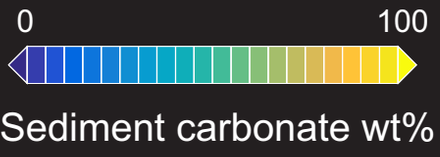


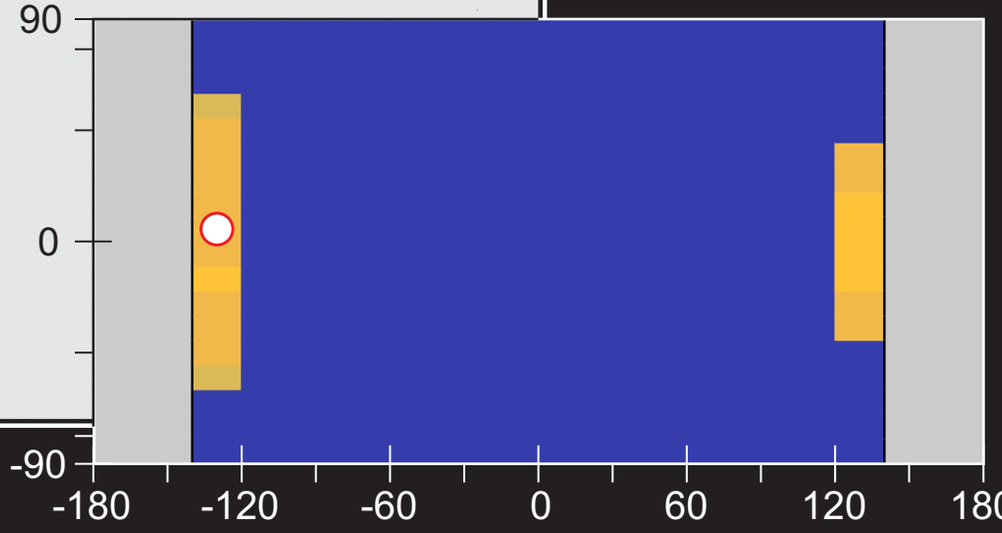


www.seao2.org/mycgenie.html

Earth system model – carbon cycle (sedimentary) configuration

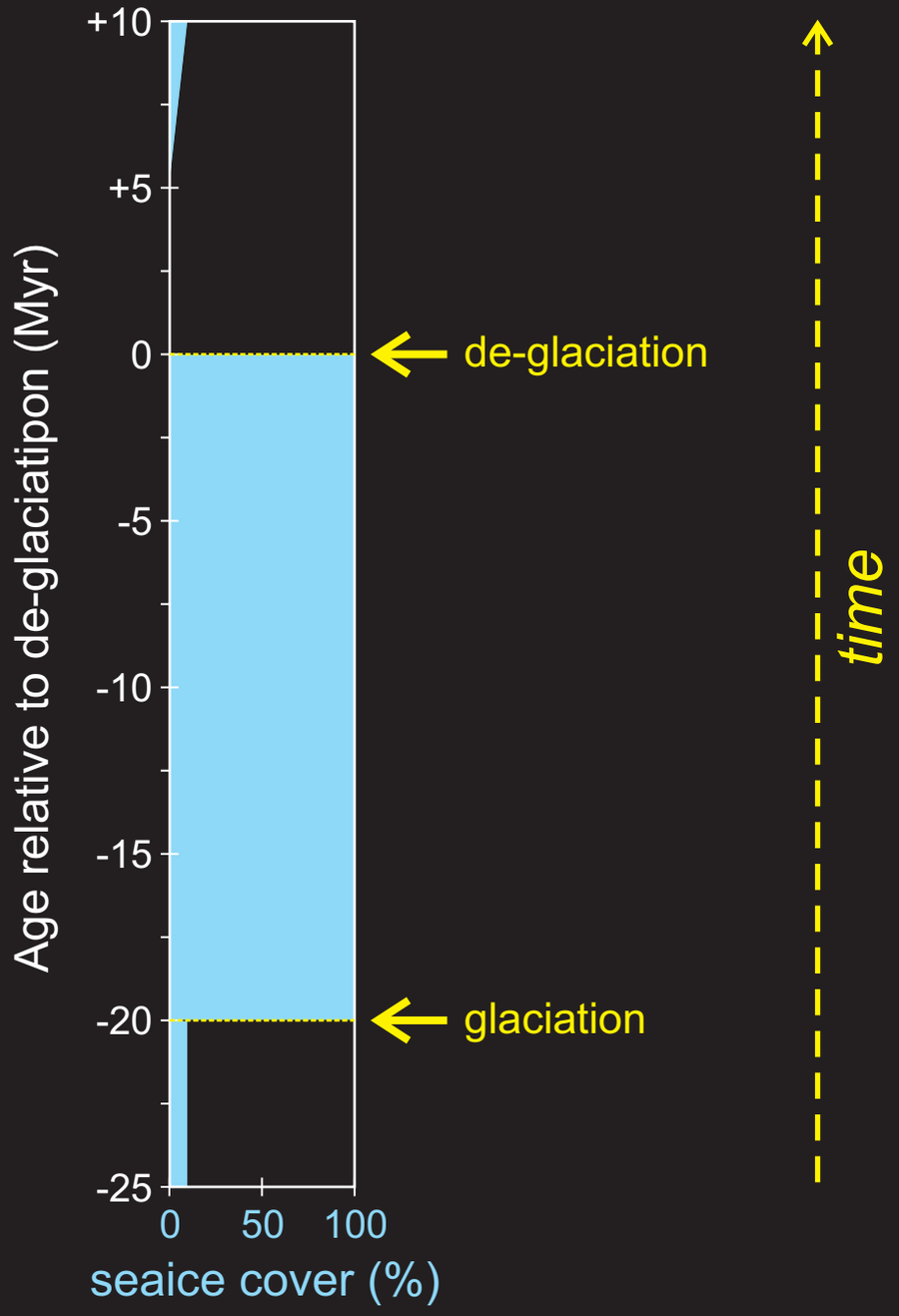




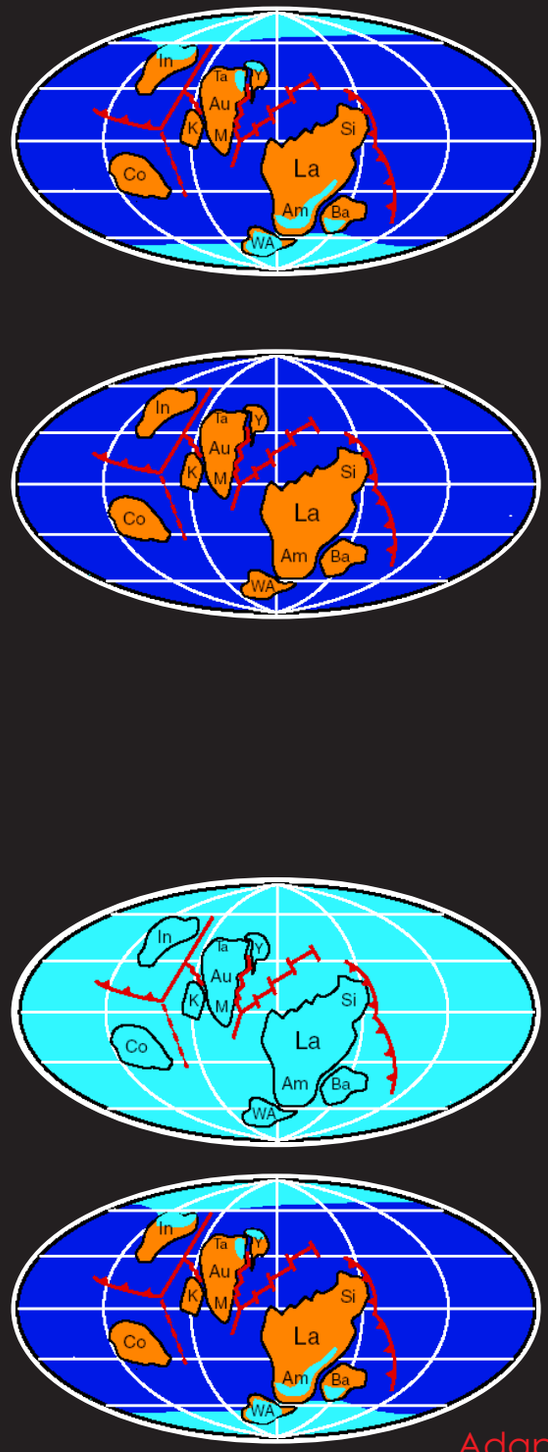


www.seao2.org/mycgenie.html

Numerical modelling – Approach

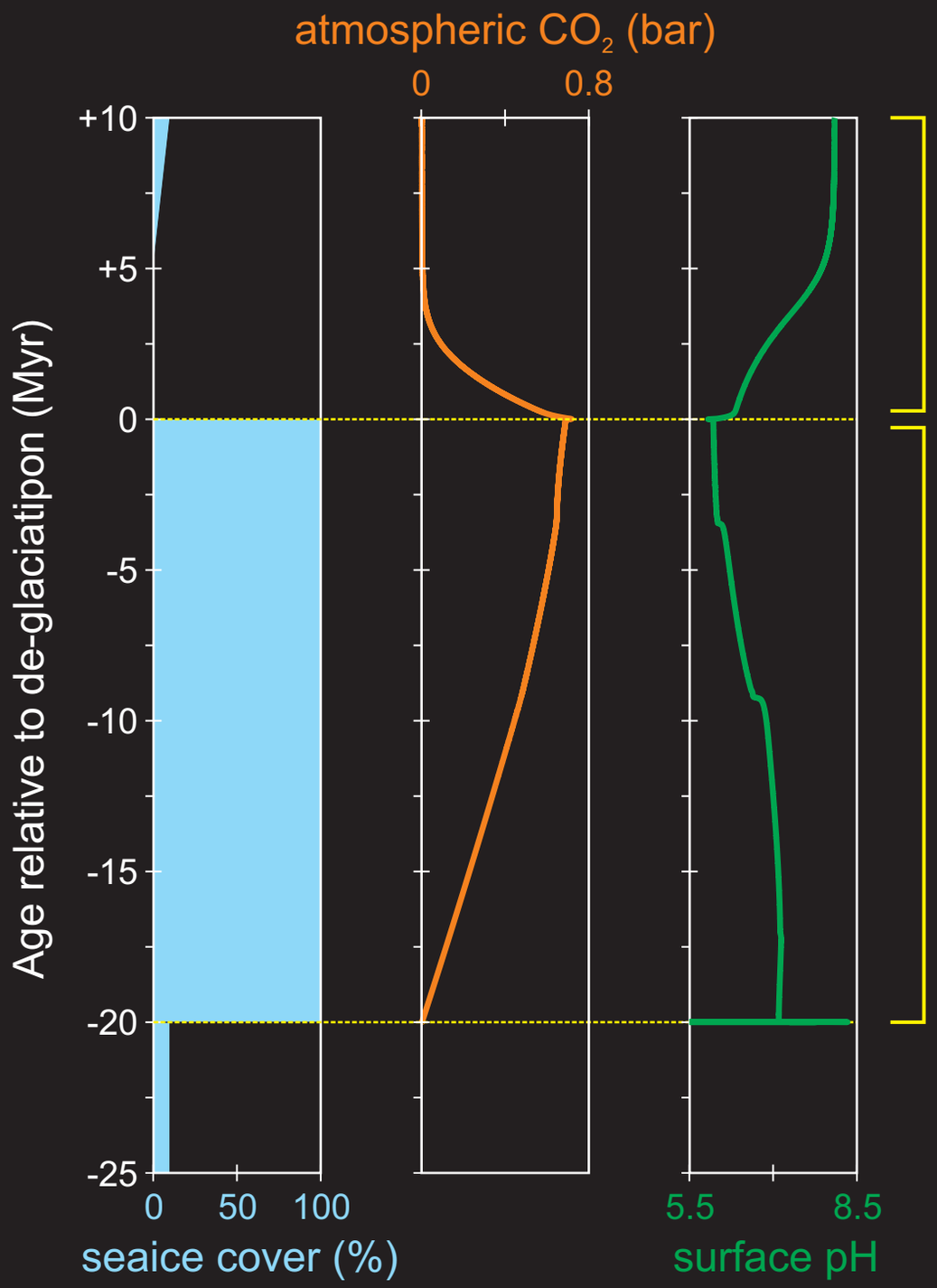


time



Adapted from: *Hoffman and Schrag* [2002]

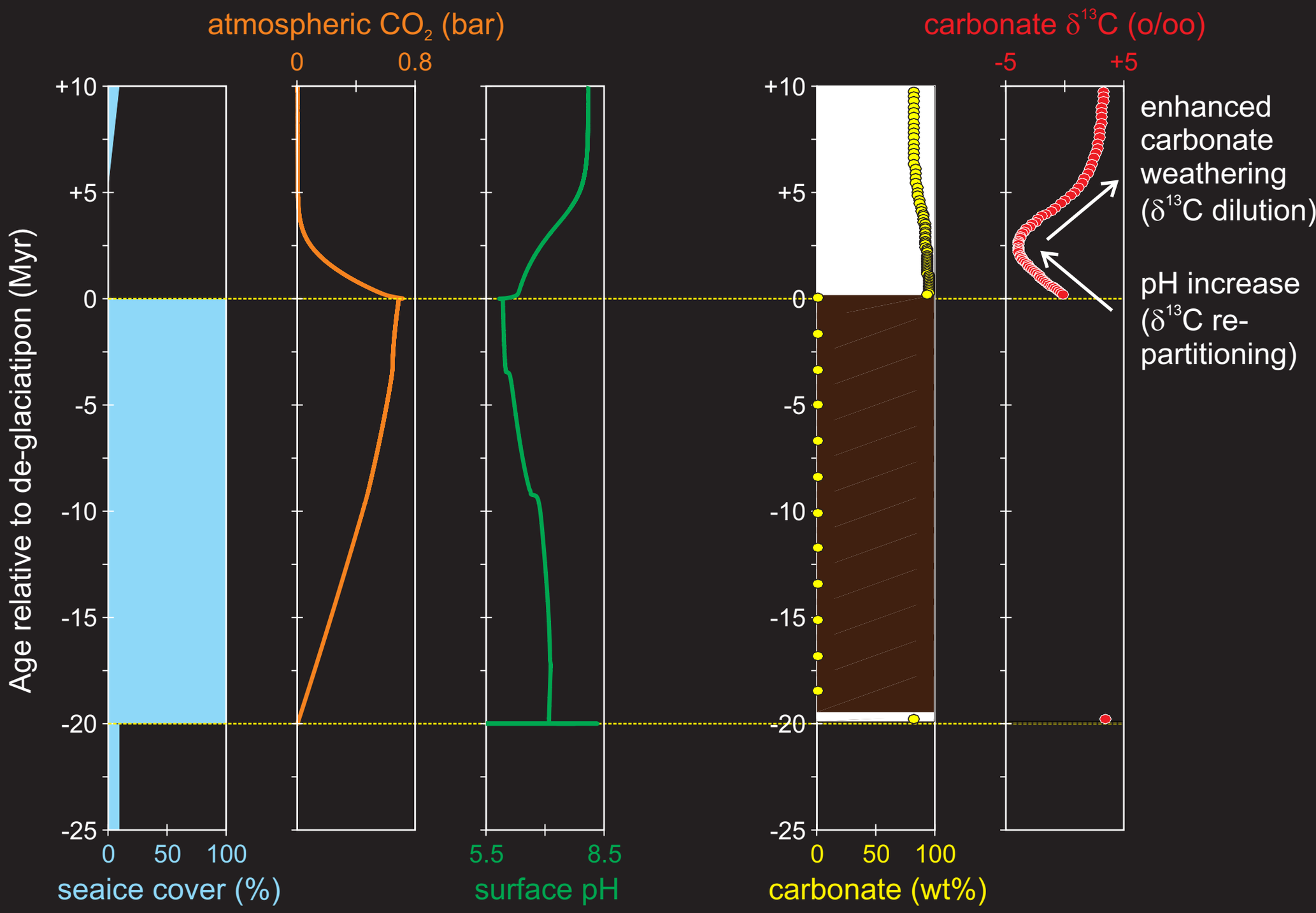
Numerical modelling – Results



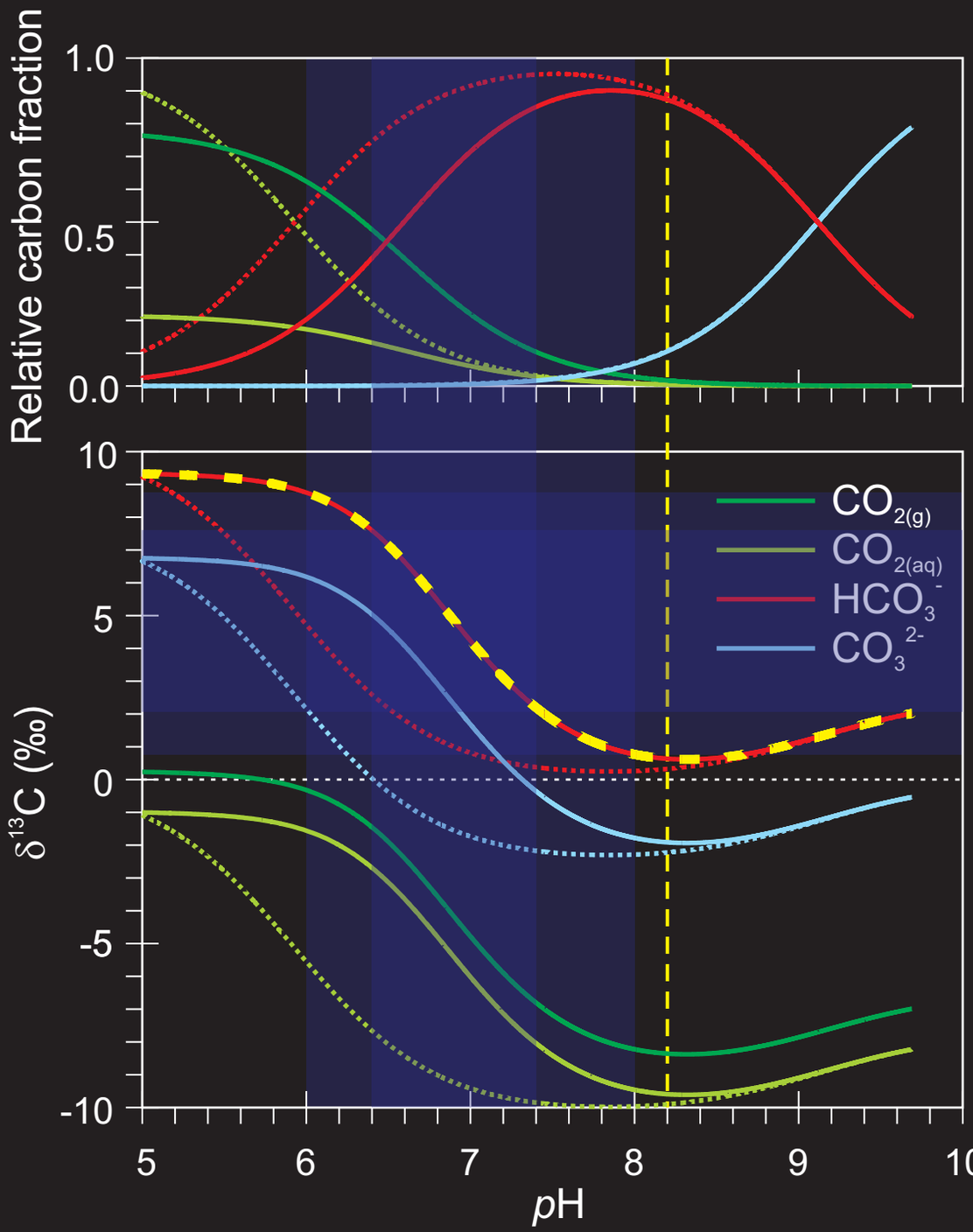
Enhanced weathering
$\Rightarrow$ CO_2 draw-down
and pH increase

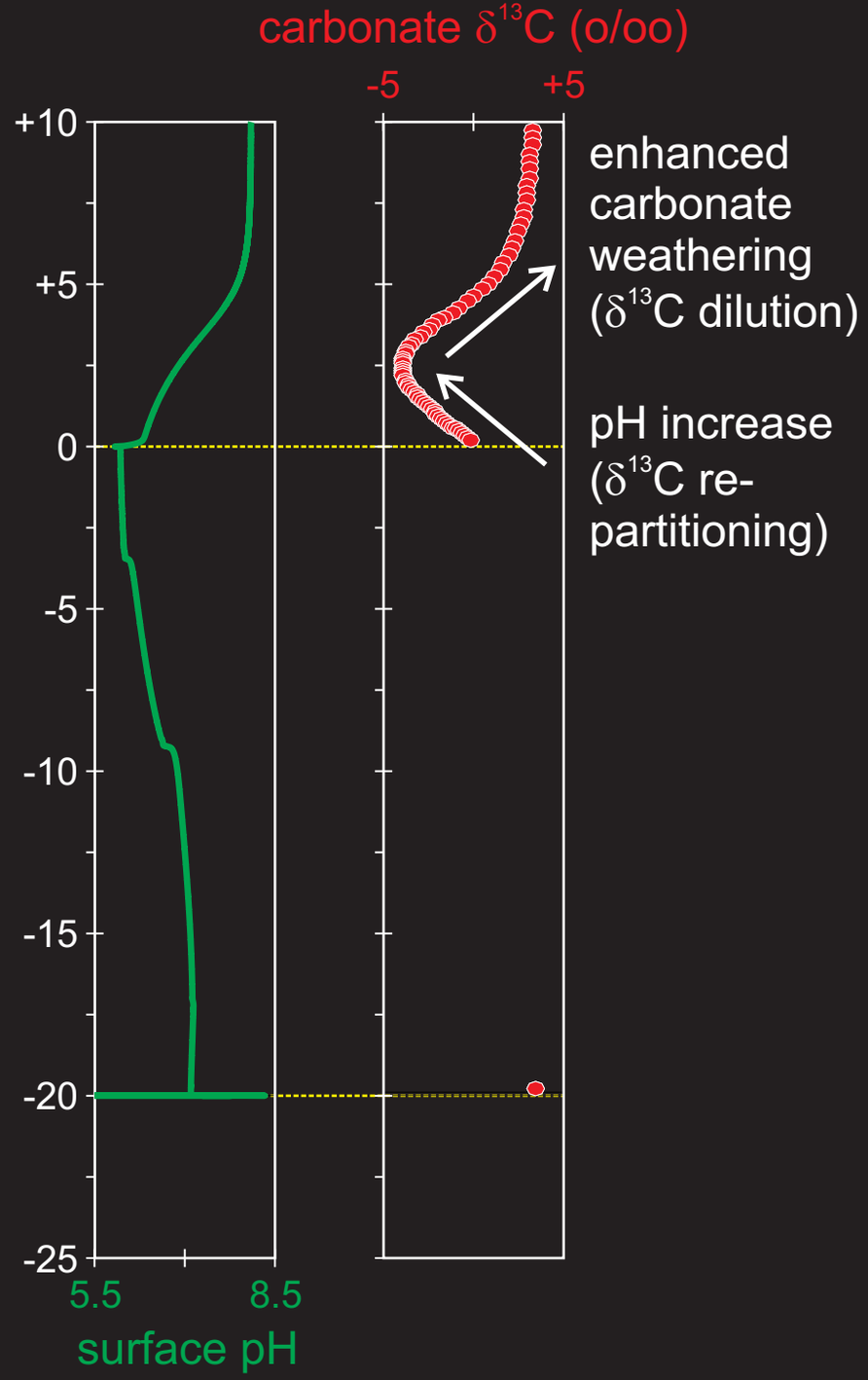
Continued CO_2 out-gasssing
but ... minimal weathering
$\Rightarrow$ CO_2 buildup @ -6 o/oo
and ocean pH decline

Numerical modelling – Results

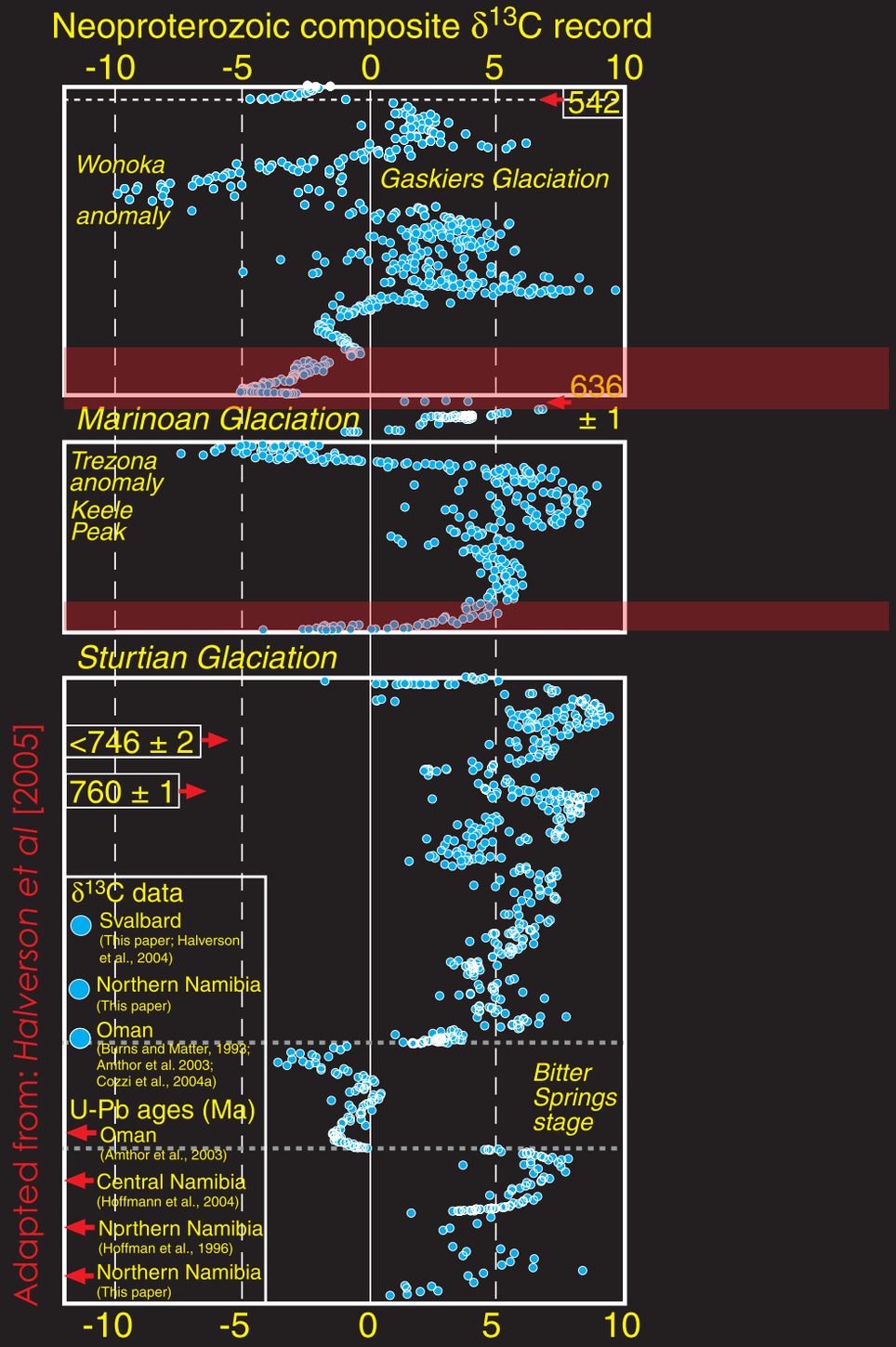


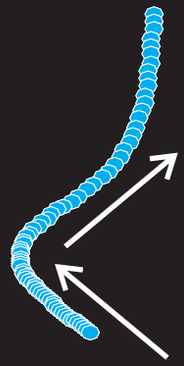
Numerical modelling – Results





Numerical modelling – Results



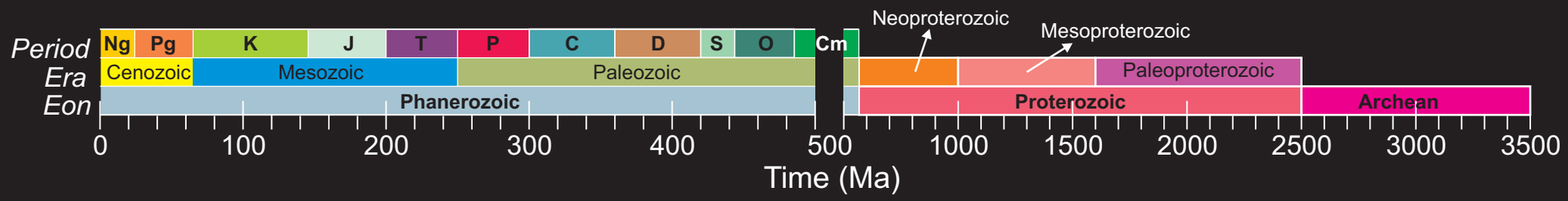


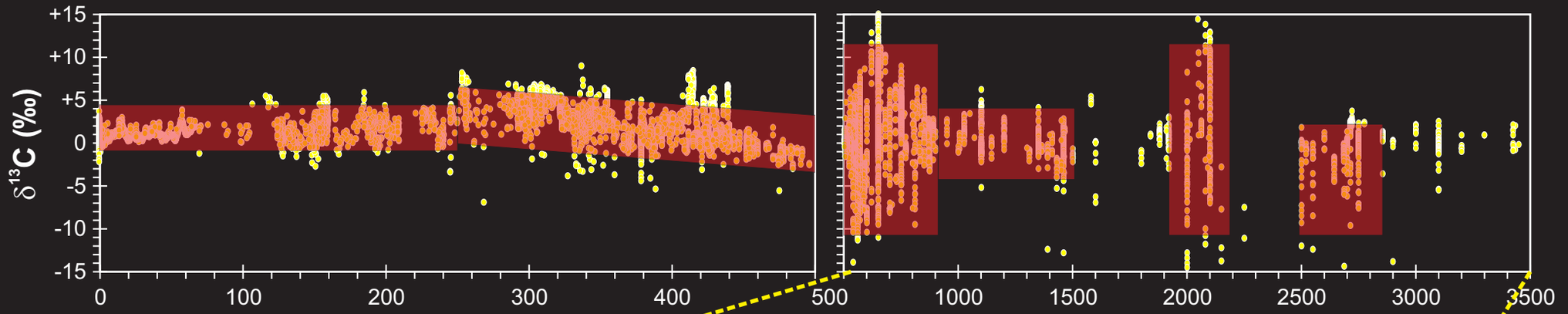
enhanced carbonate weathering ($\delta^{13}C$ dilution)

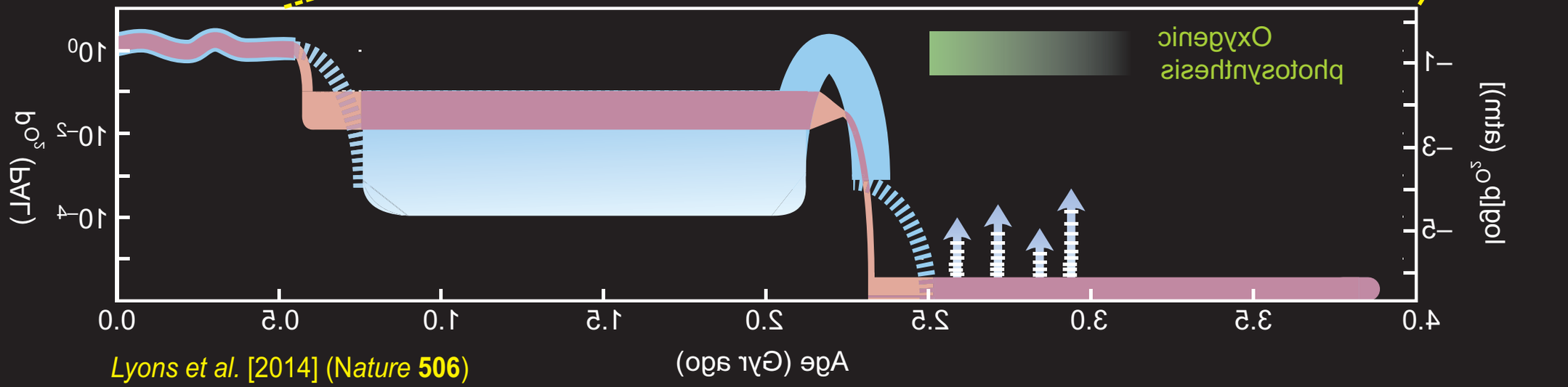
pH increase ($\delta^{13}C$ re-partitioning)

(model simulation on a very differenty x/y scale)

Deep-time inferences (aka 'speculation')







Lyons et al. [2014] (*Nature* **506**)

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