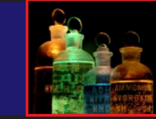
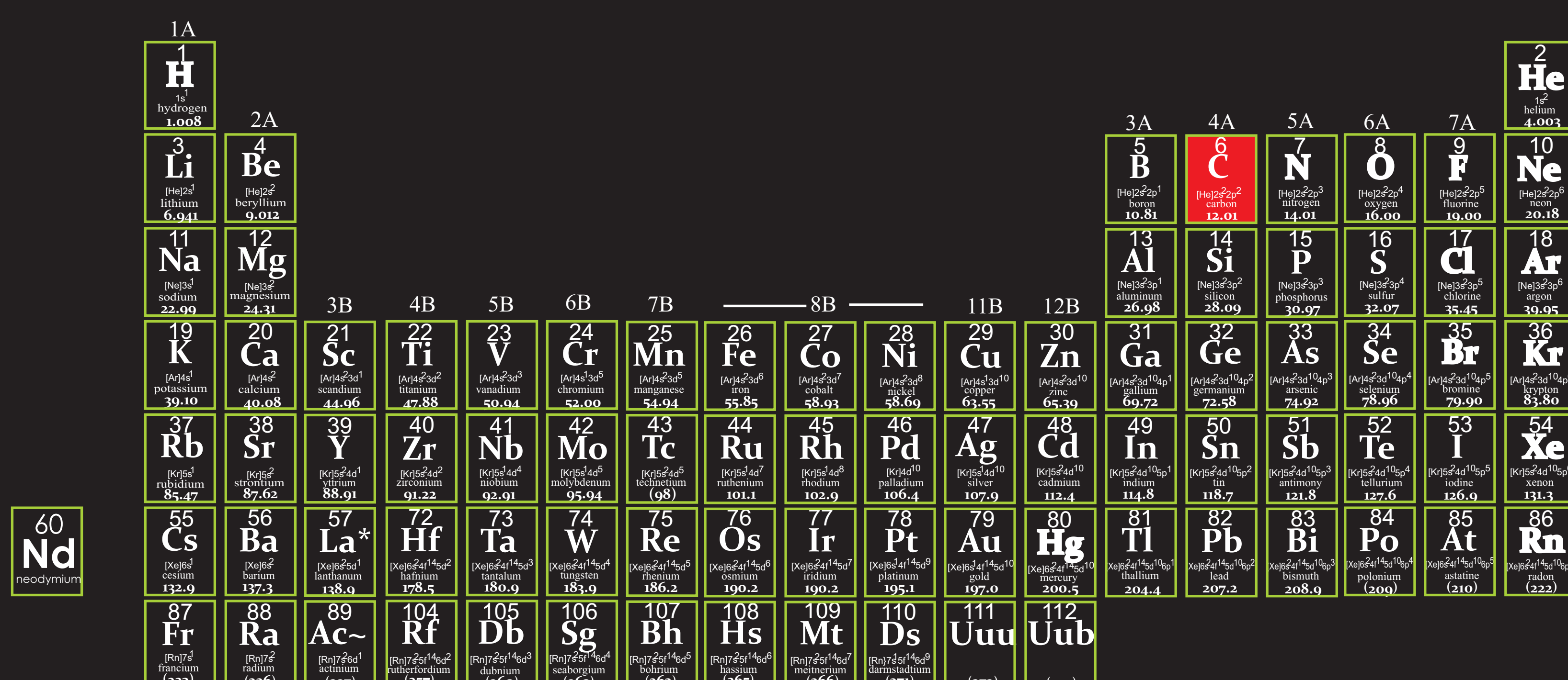
Paleocene-Eocene Thermal Maximum Meets The North Atlantic Igneous Province: Coincidence Or Global Environmental Conspiracy?

(and some other thoughts on carbon isotopes)

Andy Ridgwell

Carbon isotopes as a tracer of ... what?





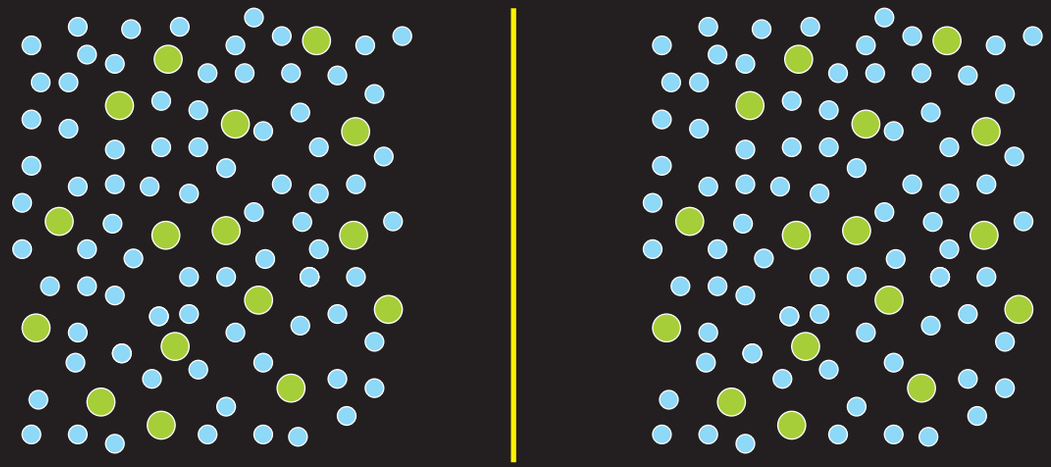
Carbon isotopes as a tracer of ... what?

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



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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')

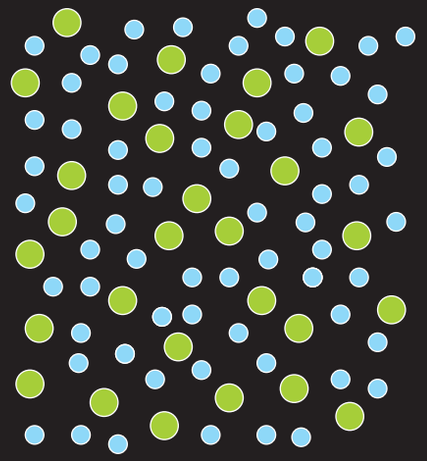
$R_{Sample} > R_{Stand.}$

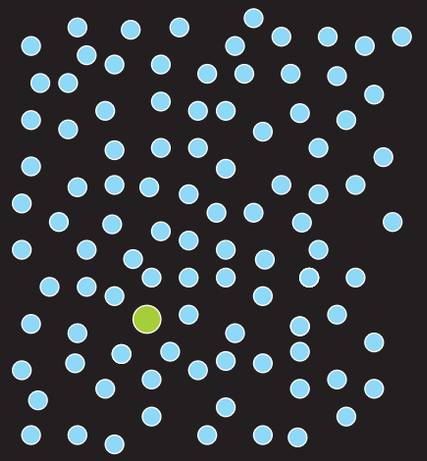
$\delta(sample) = (R_{Sample}/R_{Stand.} - 1) \times 1000$

=> δ(sample) is NEGATIVE

('isotopically depleted')

- 'lighter' isotope
- 'heavier' isotope





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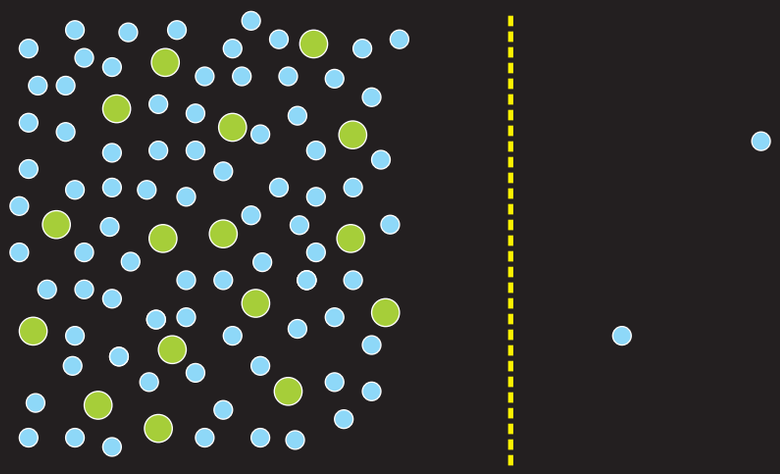
Carbon isotopes as a tracer of … what?

● 'lighter' isotope

● 'heavier' isotope



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11 **Na** $[Ne]3s^1$ sodium 22.99	12 **Mg** $[Ne]3s^2$ magnesium 24.31	3B	4B	5B	6B	7B		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	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** $[Rn]7s^15f^{14}6d^9$ darmstadtium (271)	111 **Uuu** (272)	112 **Uub** (277)						

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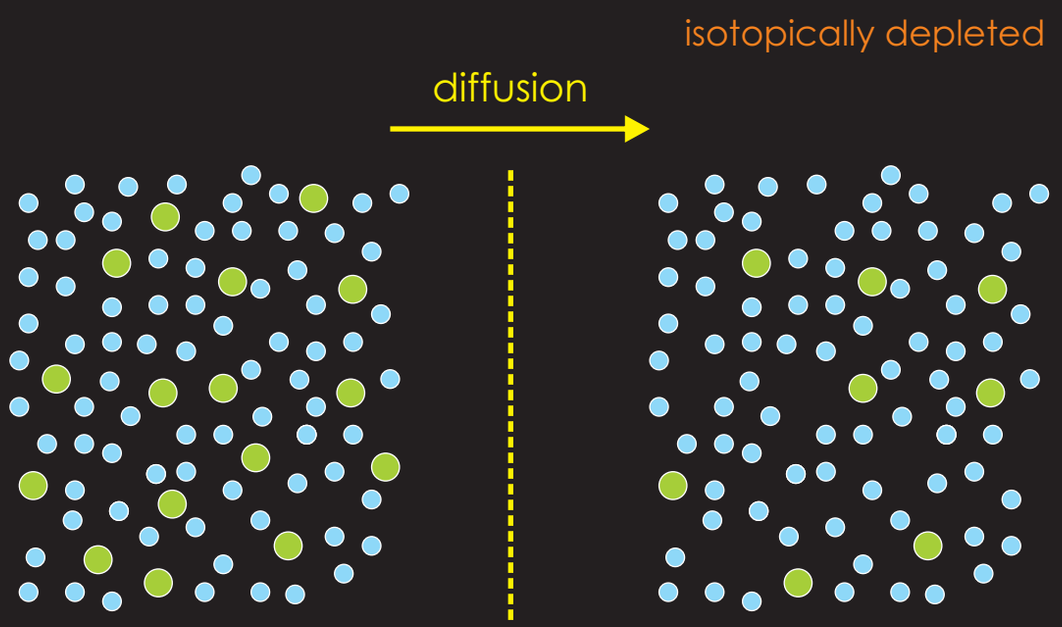

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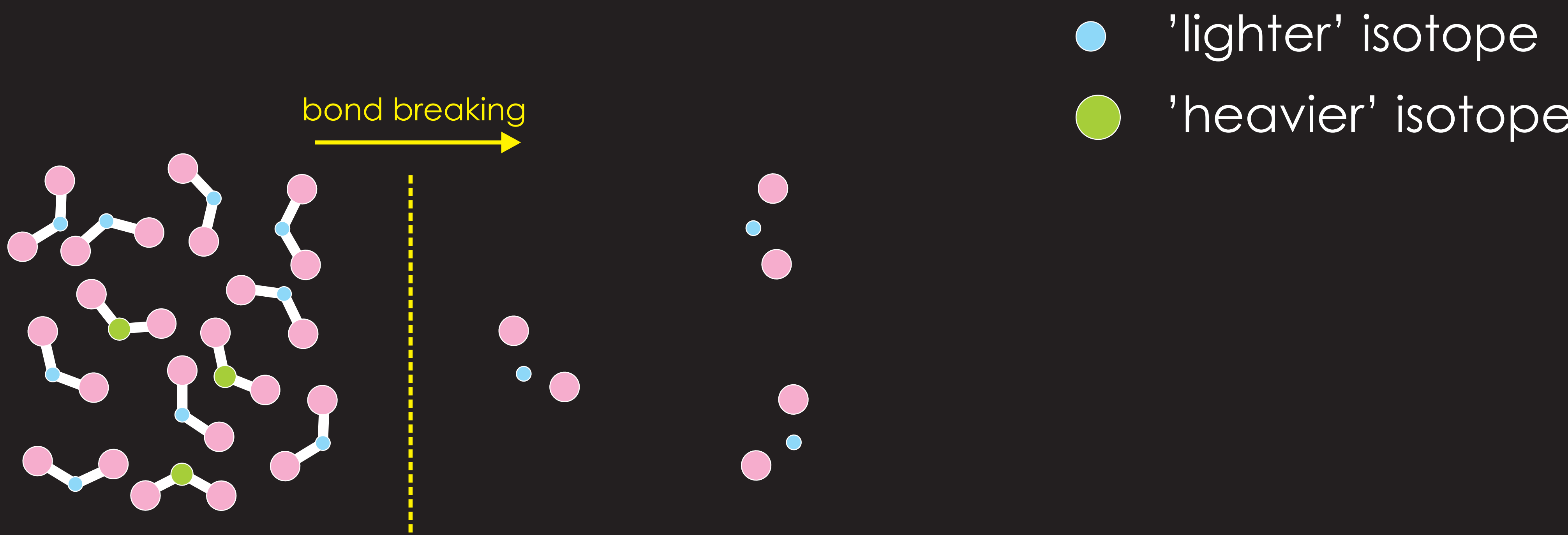

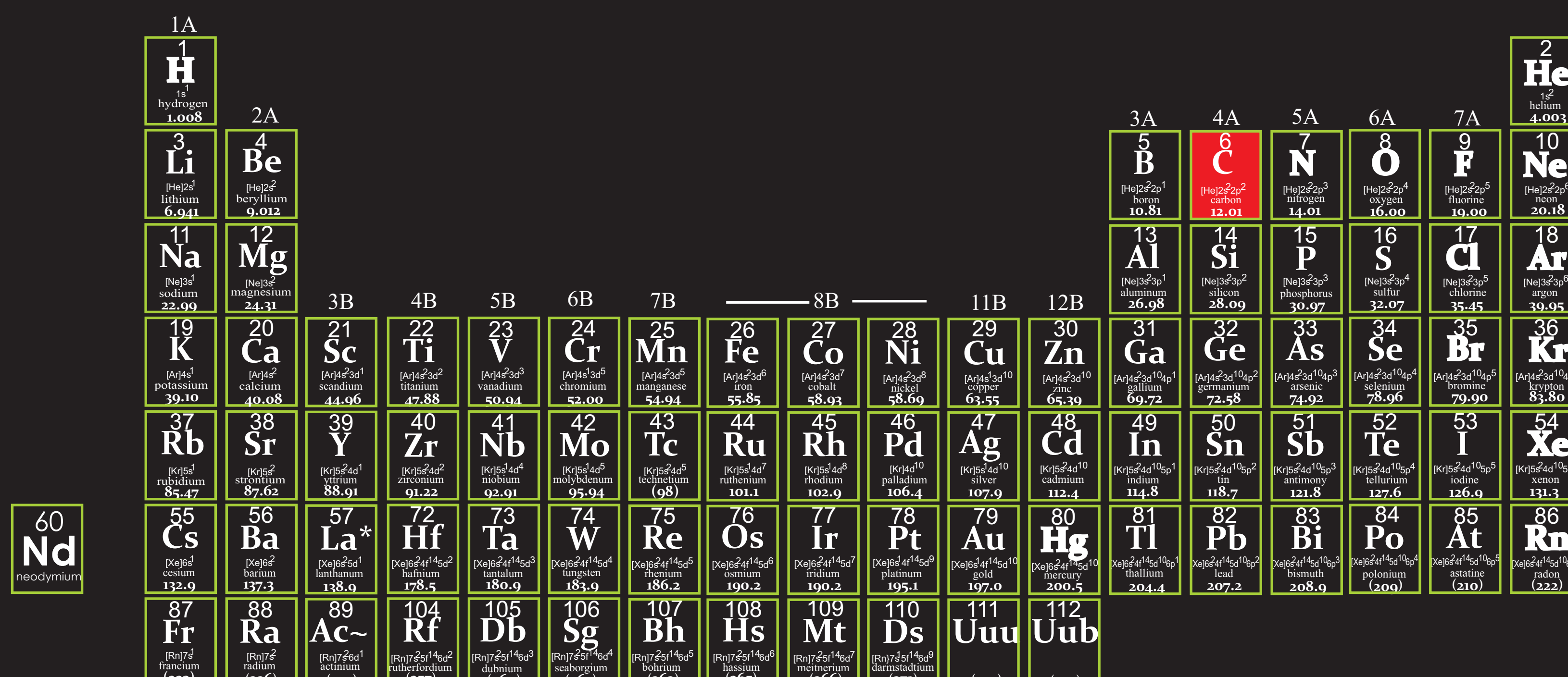

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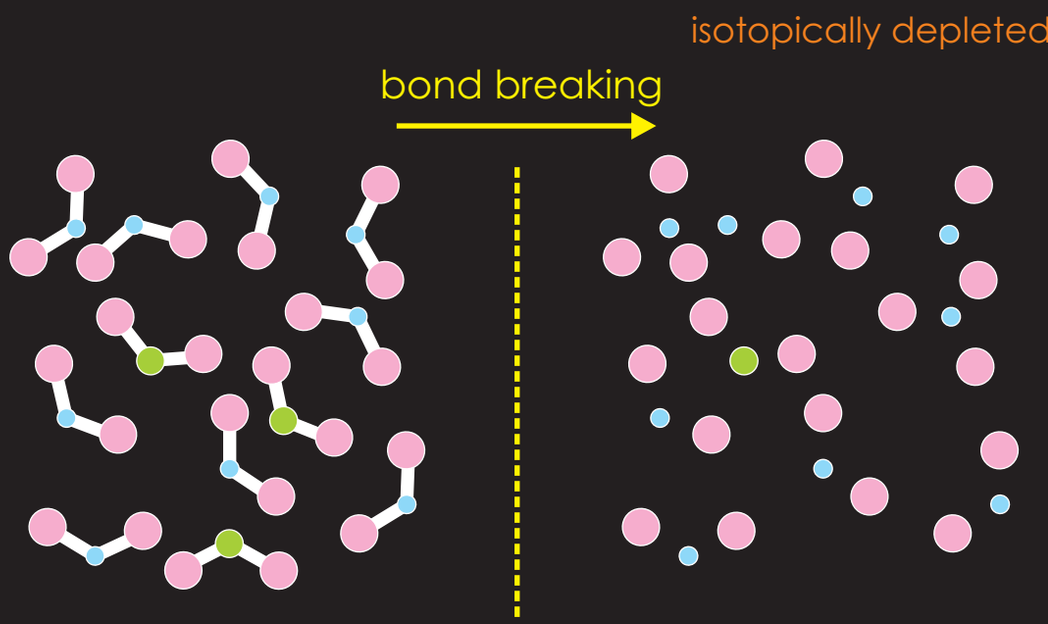

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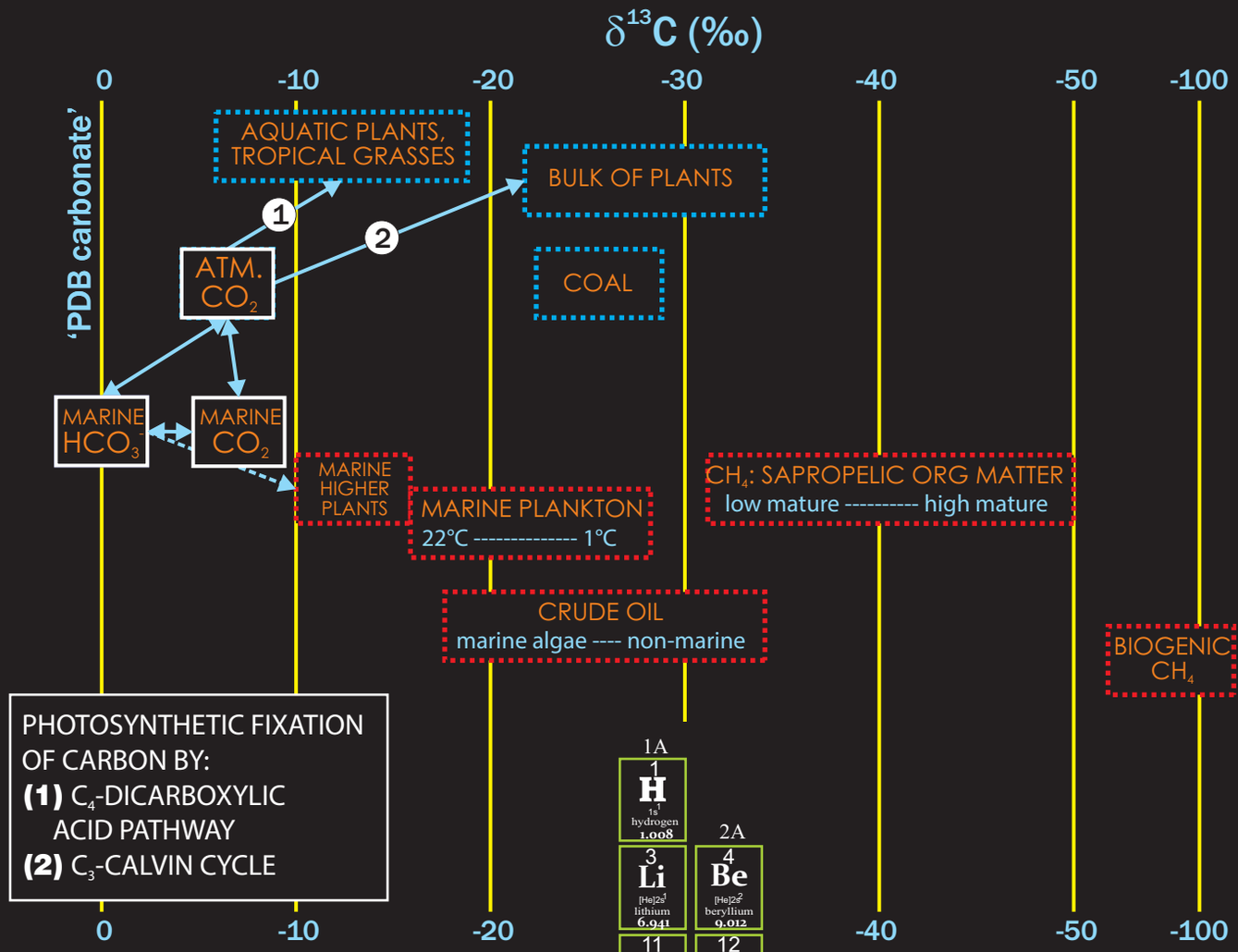

Maslin and Thomas [2003]

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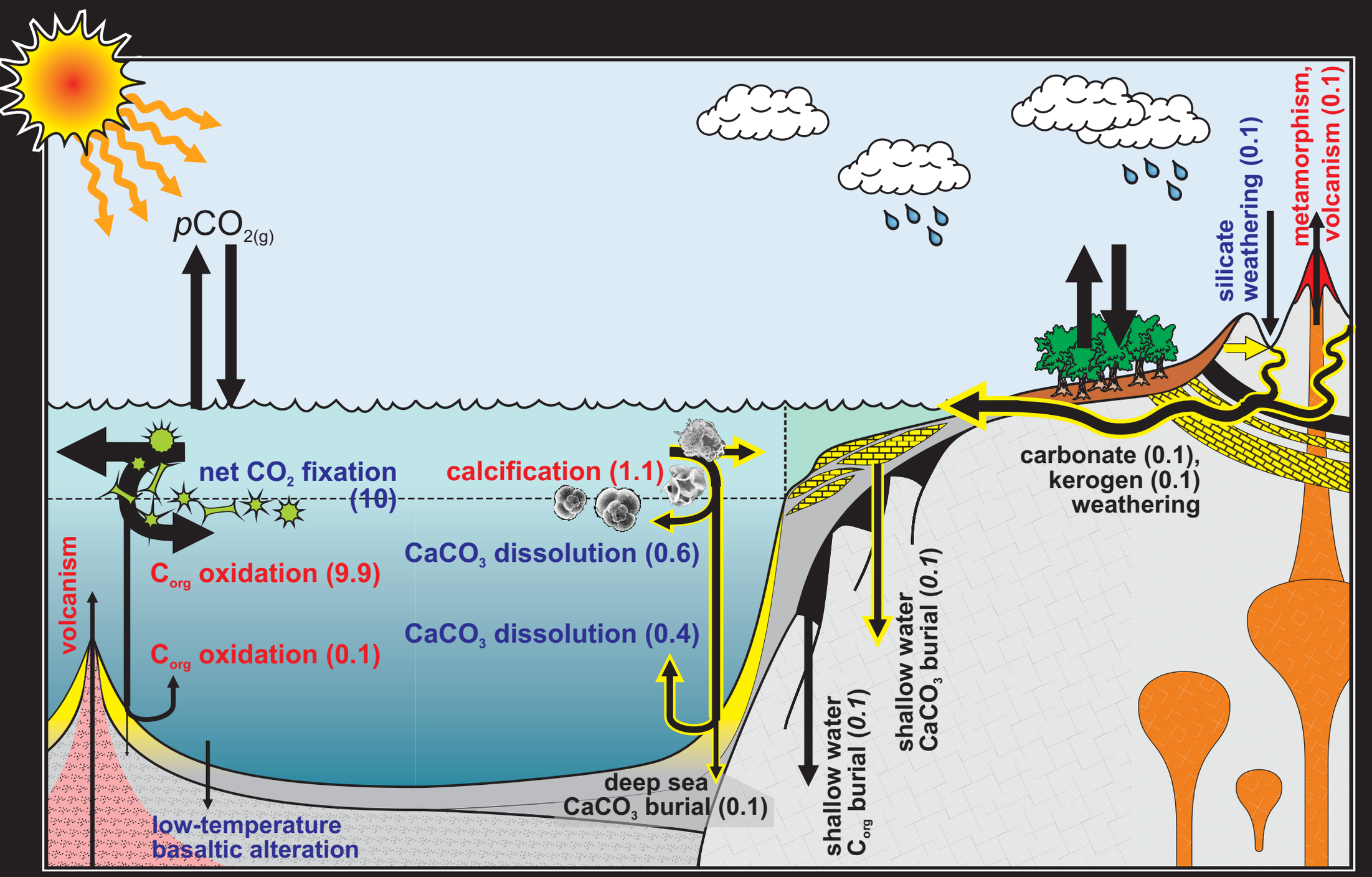
The (c)GENIE Earth system model (version muffin)



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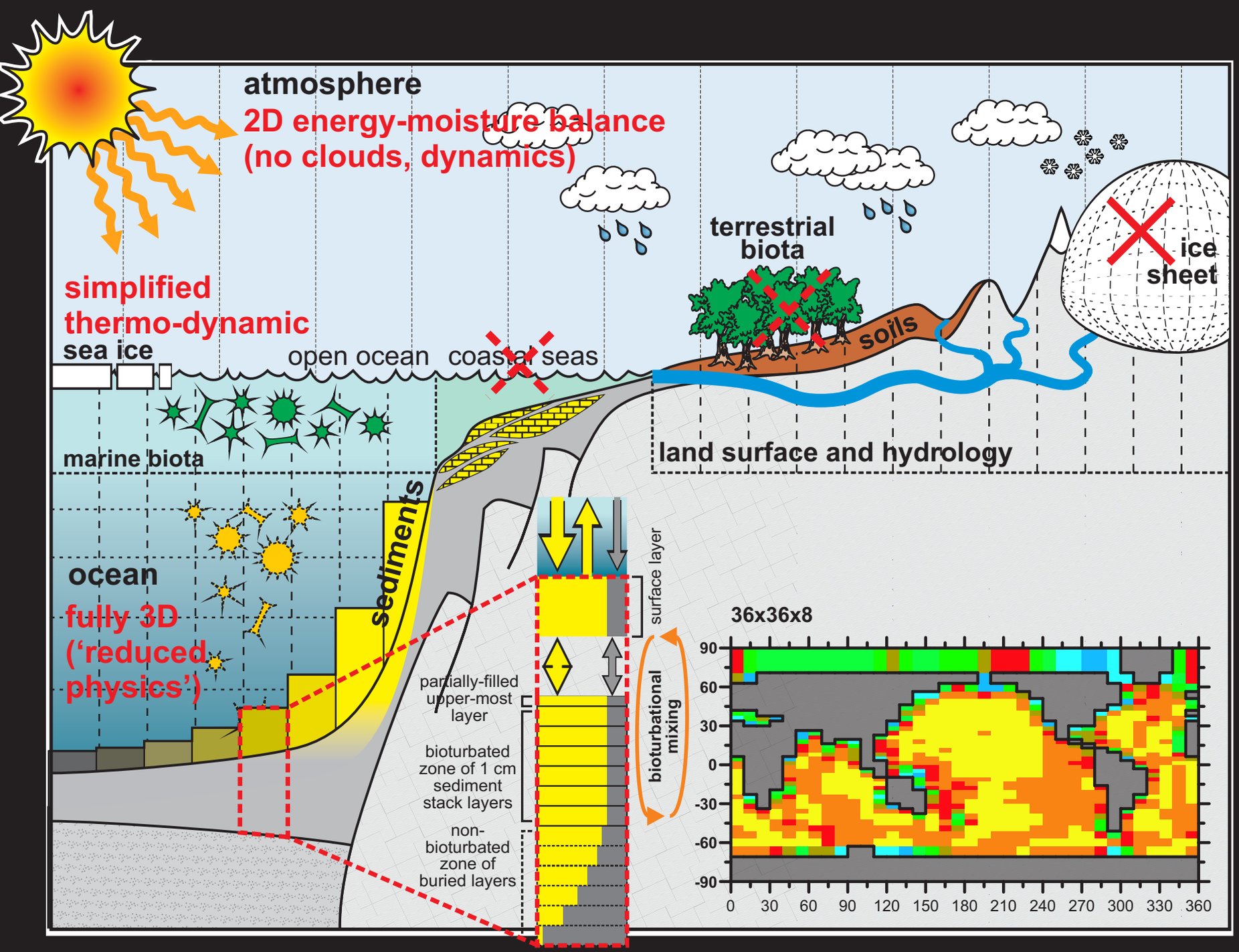
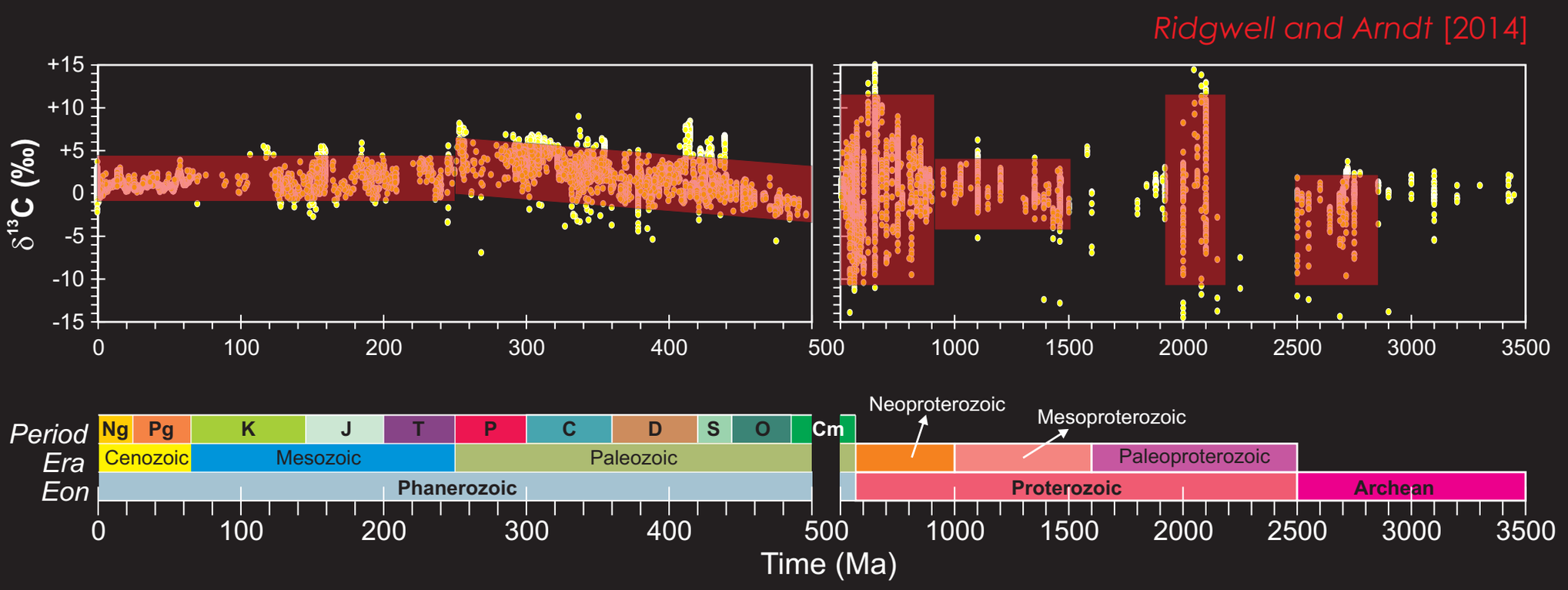


Carbonate $\delta^{13}C$ variability through time



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)?

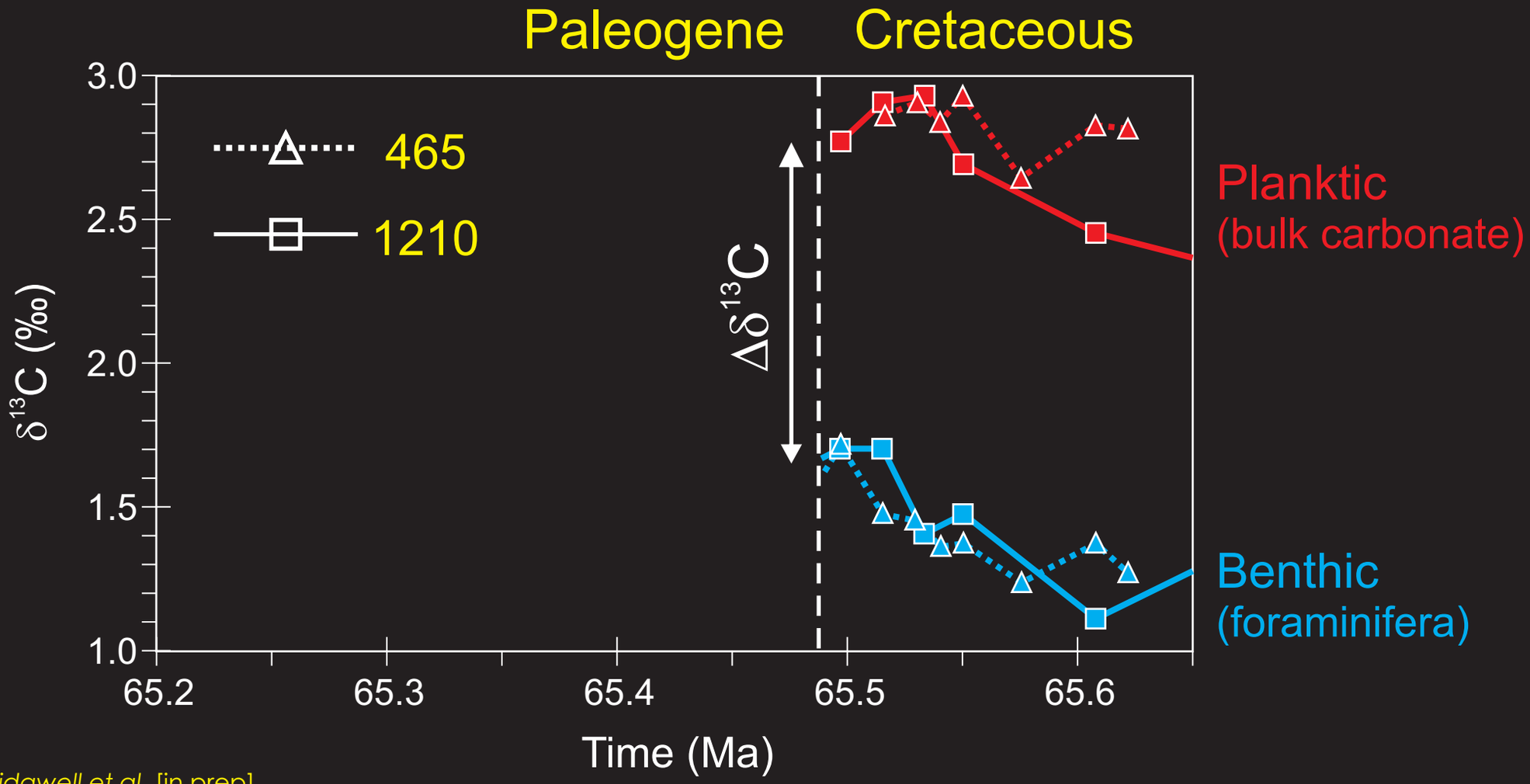
Carbonate diagenesis and loss of primary $\delta^{13}C$ signal, either marine sedimentary or subaerial.

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

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

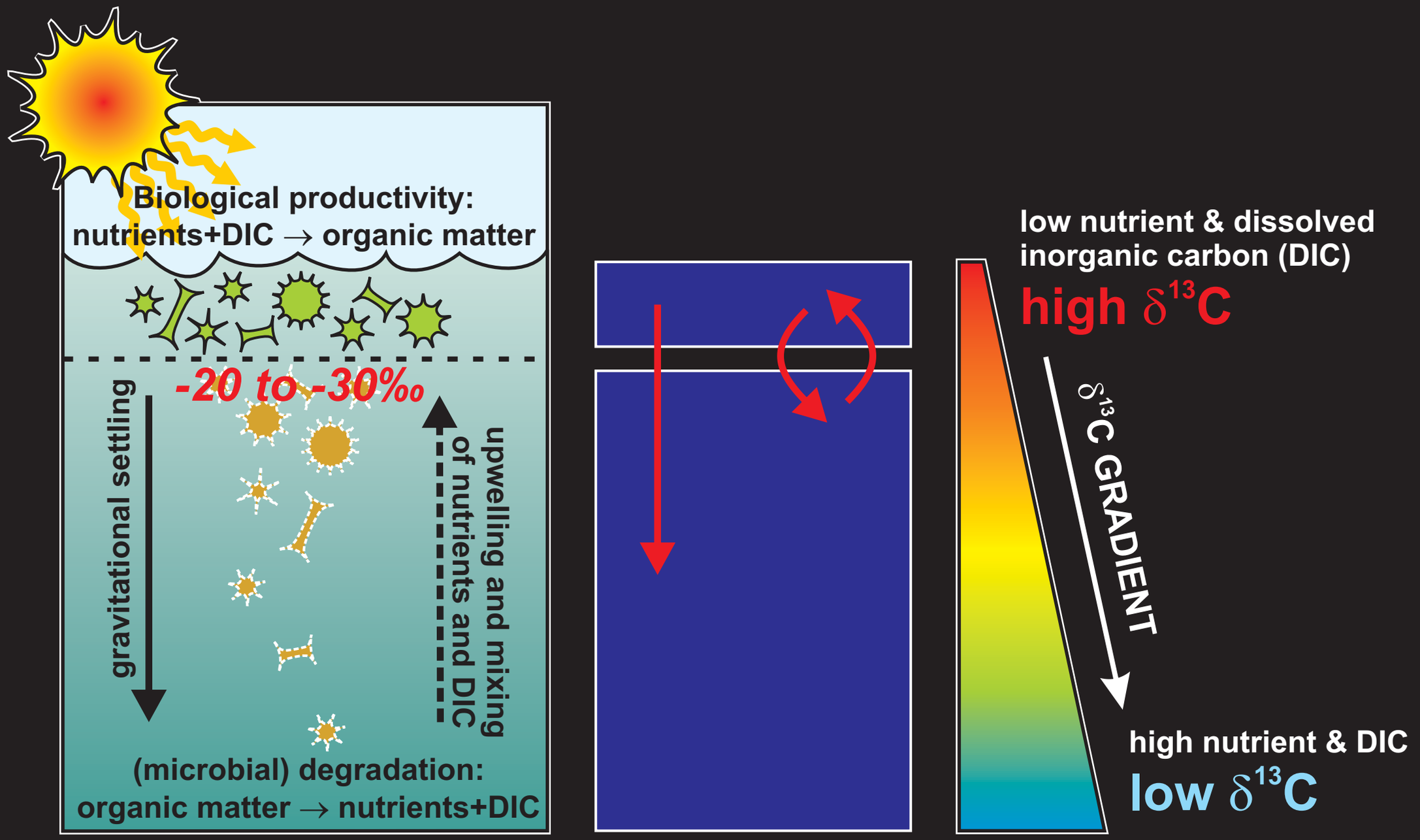
Re-partitioning of carbon ***within*** surficial reservoirs?

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

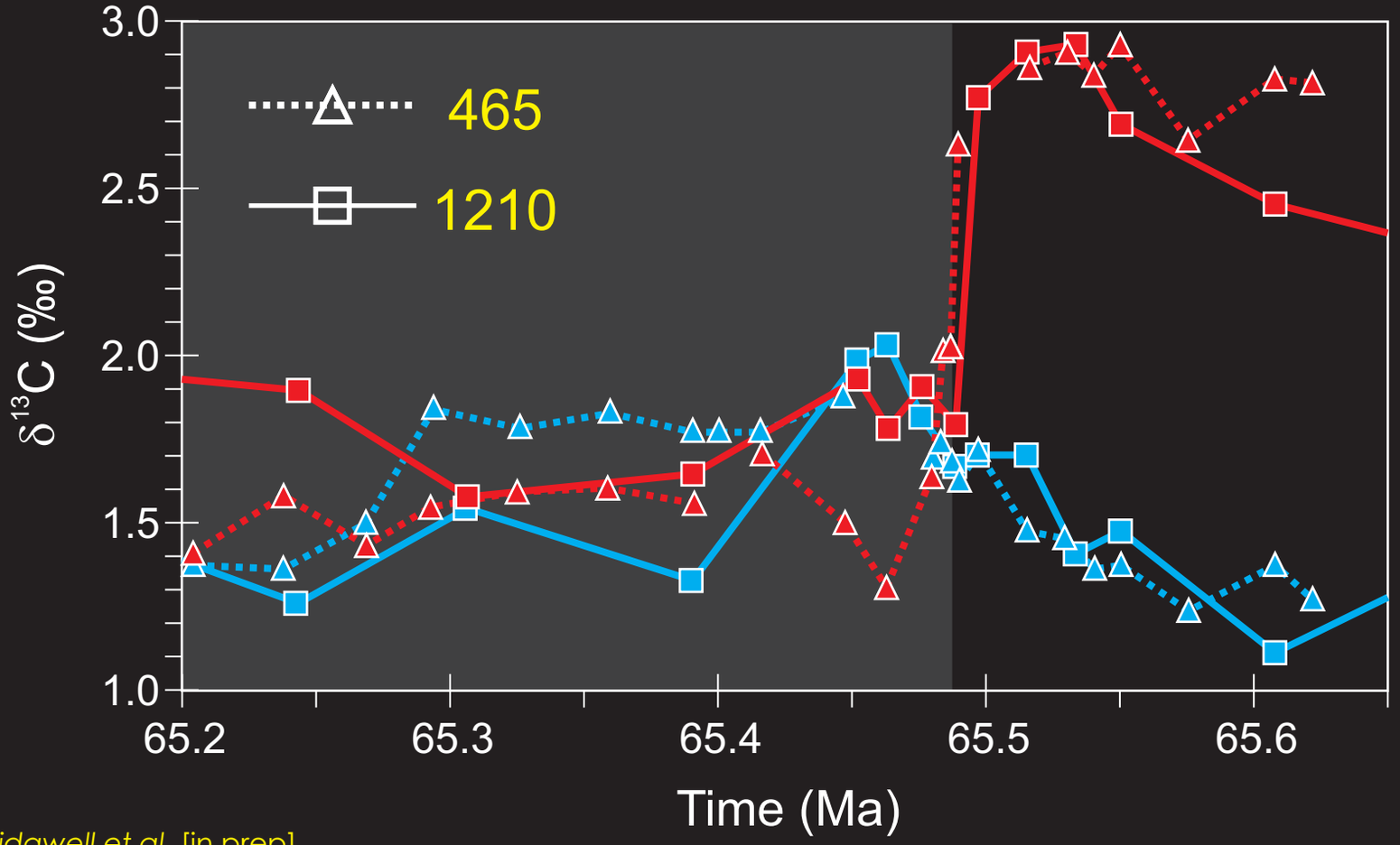


Ridgwell et al. [in prep]

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



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

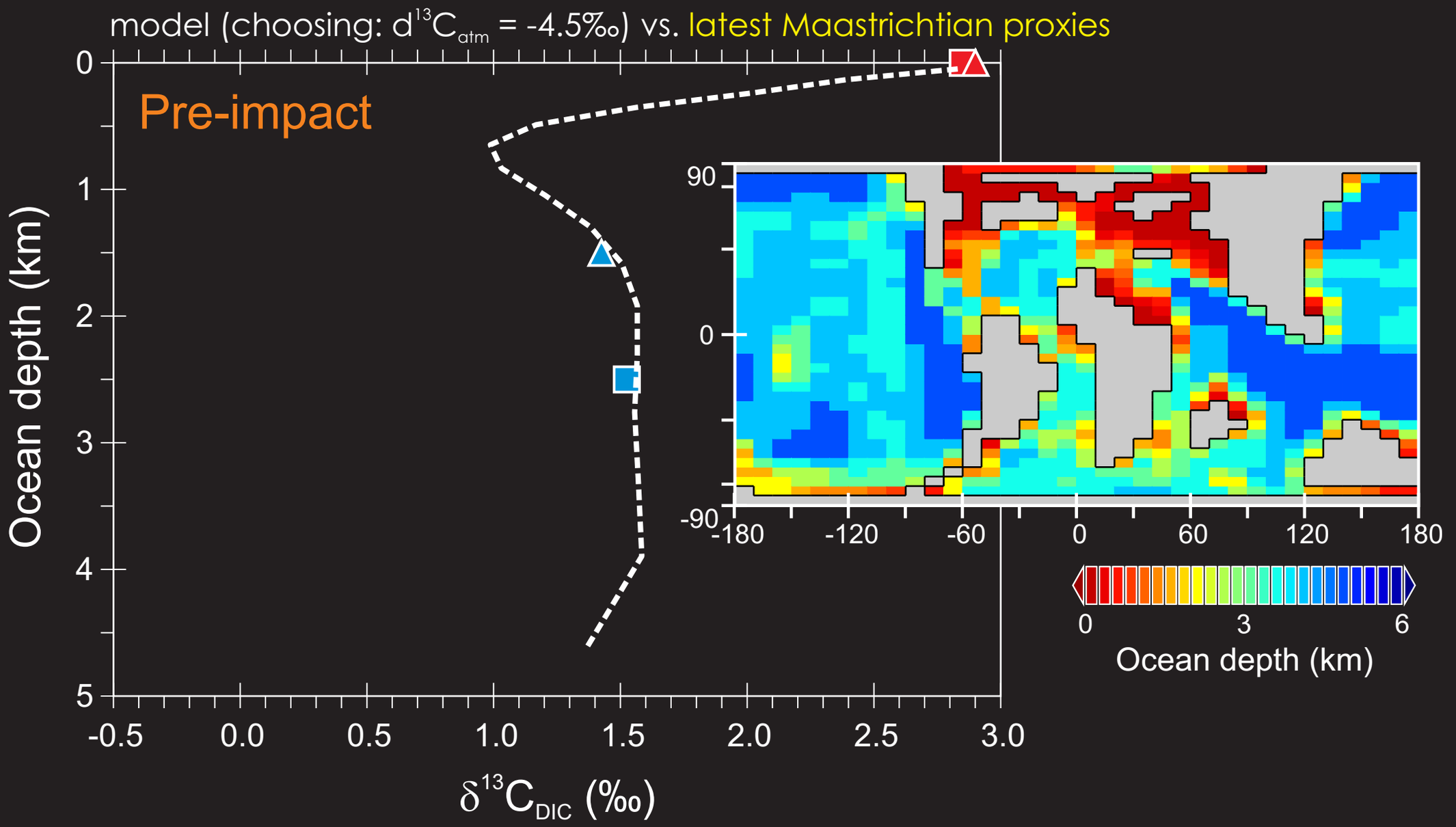


Planktic
(bulk carbonate)

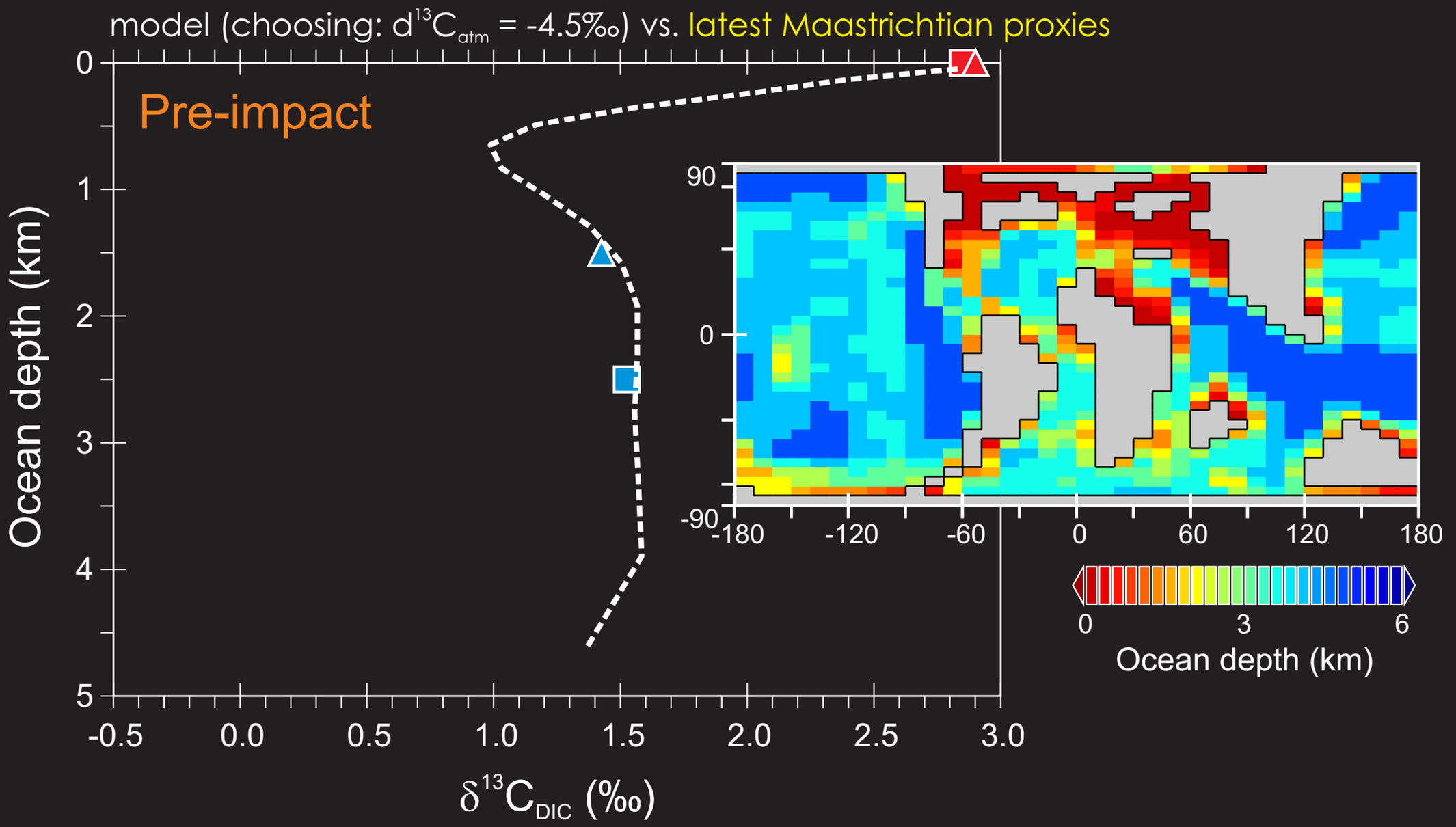
Benthic
(foraminifera)

Ridgwell et al. [in prep]

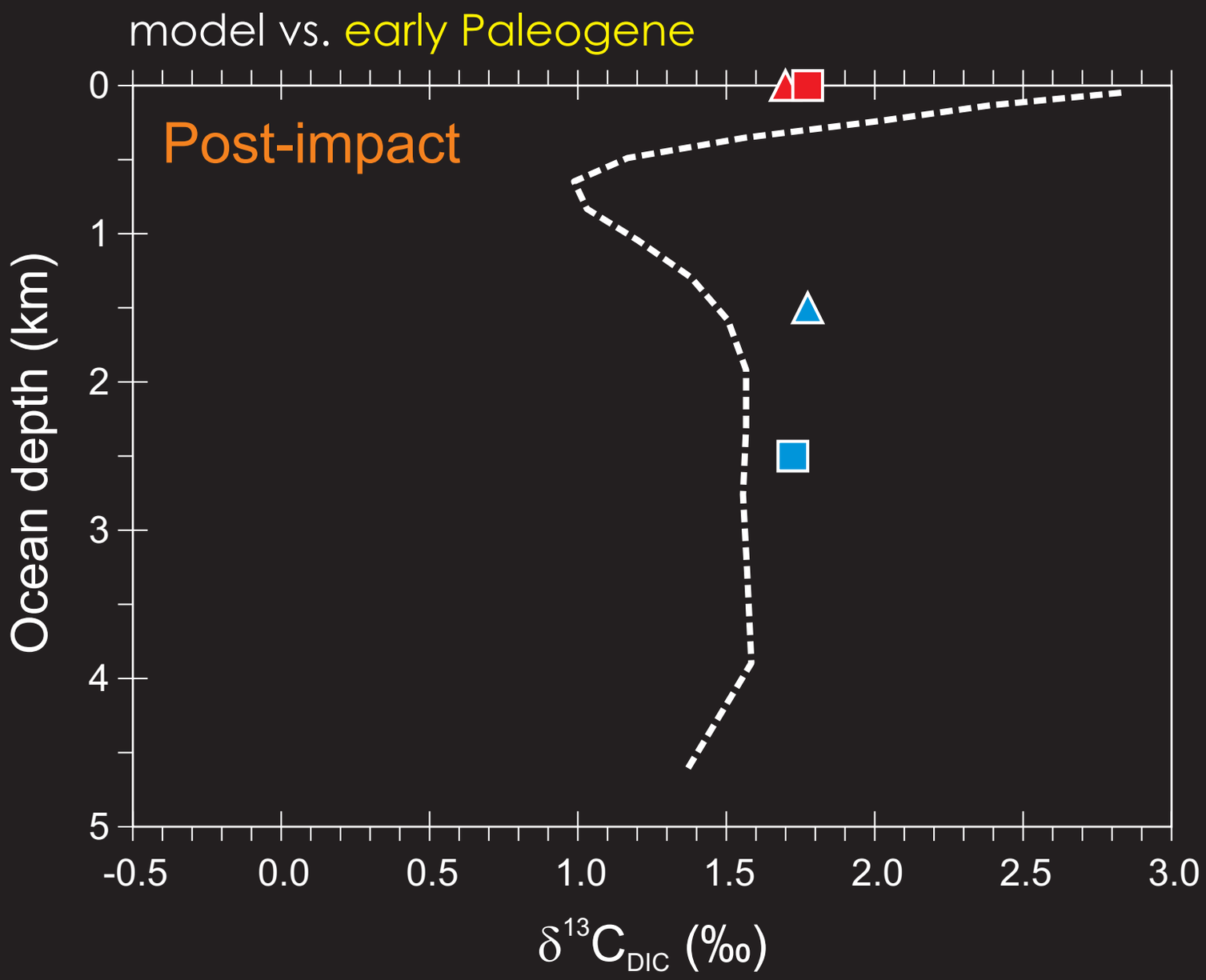
Carbonate $\delta^{13}C$ variability through time



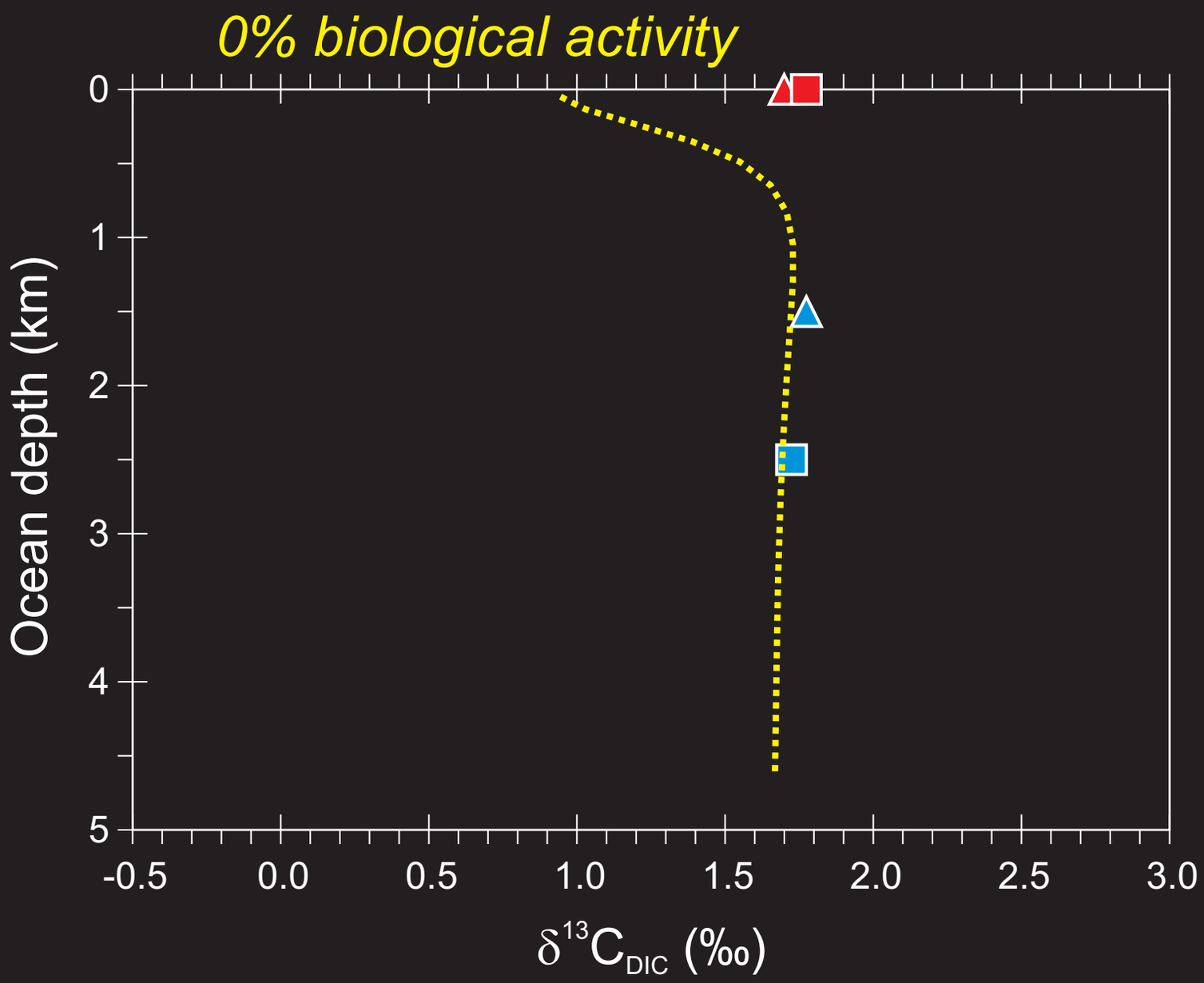
Carbonate $\delta^{13}C$ variability through time



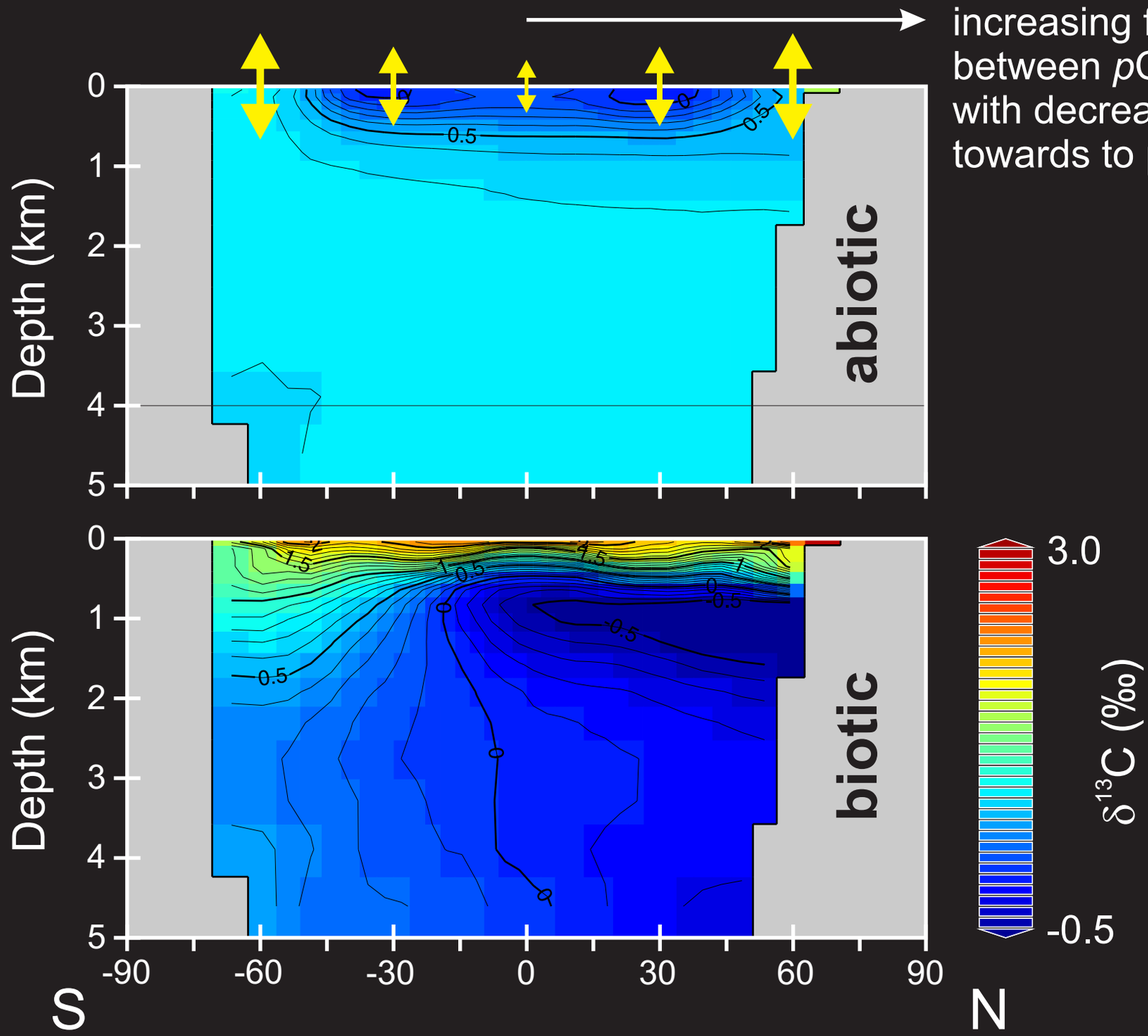
Carbonate $\delta^{13}C$ variability through time



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



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)?

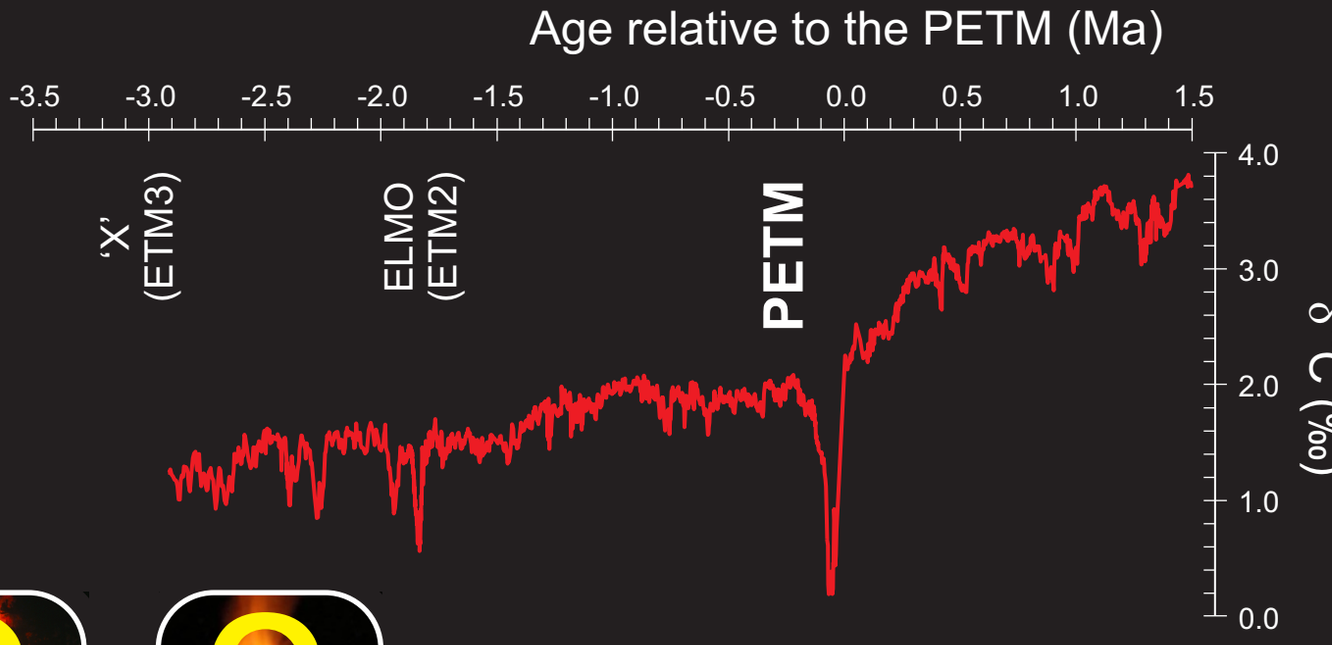
Carbonate $\delta^{13}C$ variability through time

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

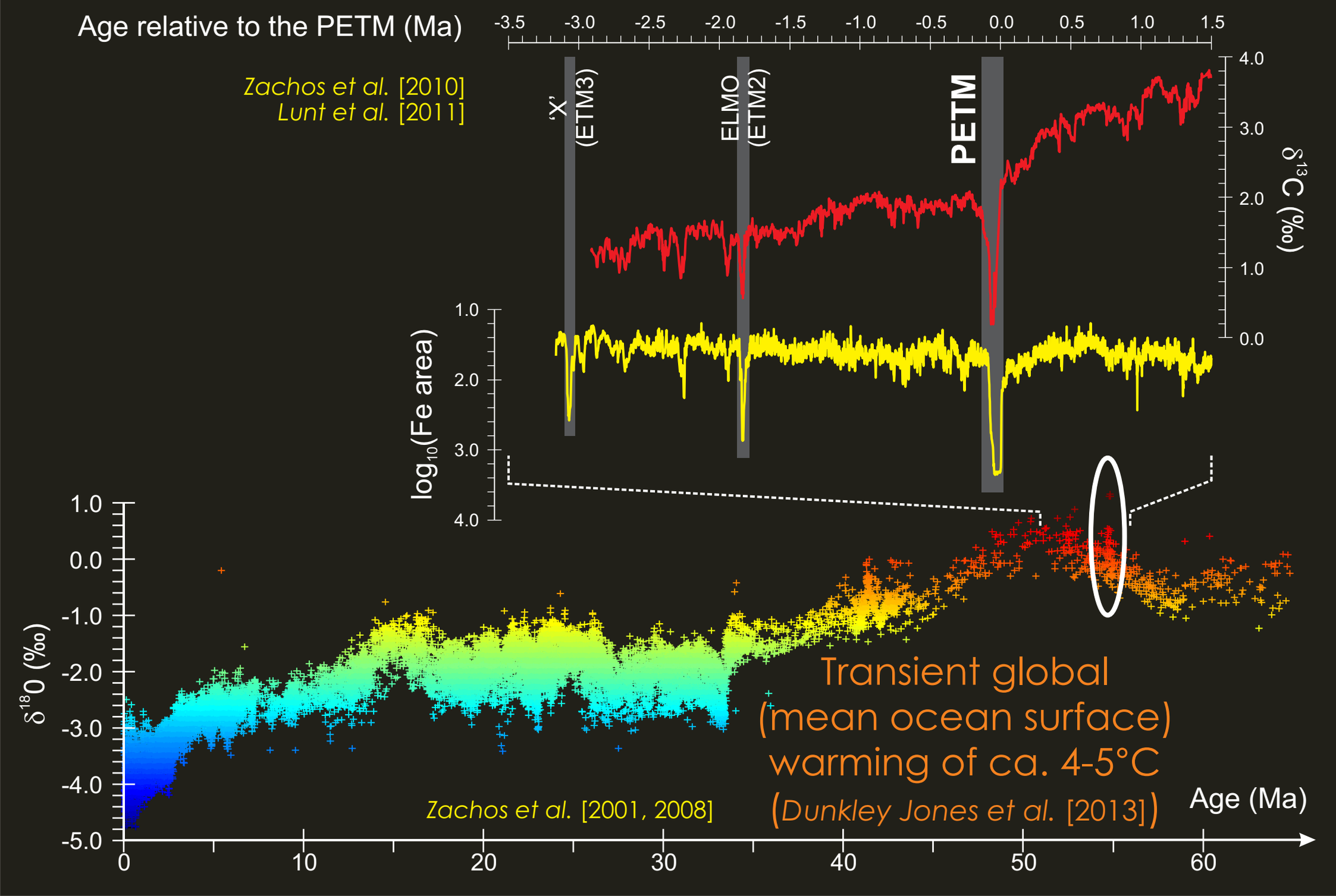
Re-partitioning of carbon ***within*** surficial reservoirs?

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

Injection (or removal) of isotopically light carbon?



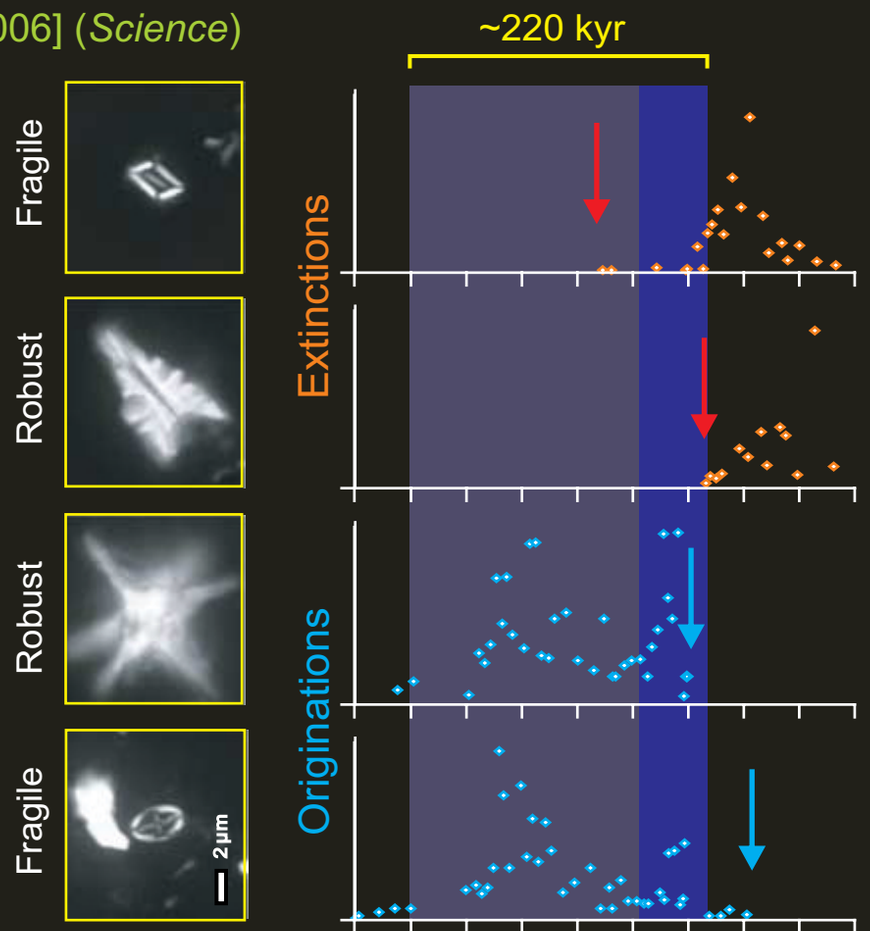
Paleo-analogues – the PETM?



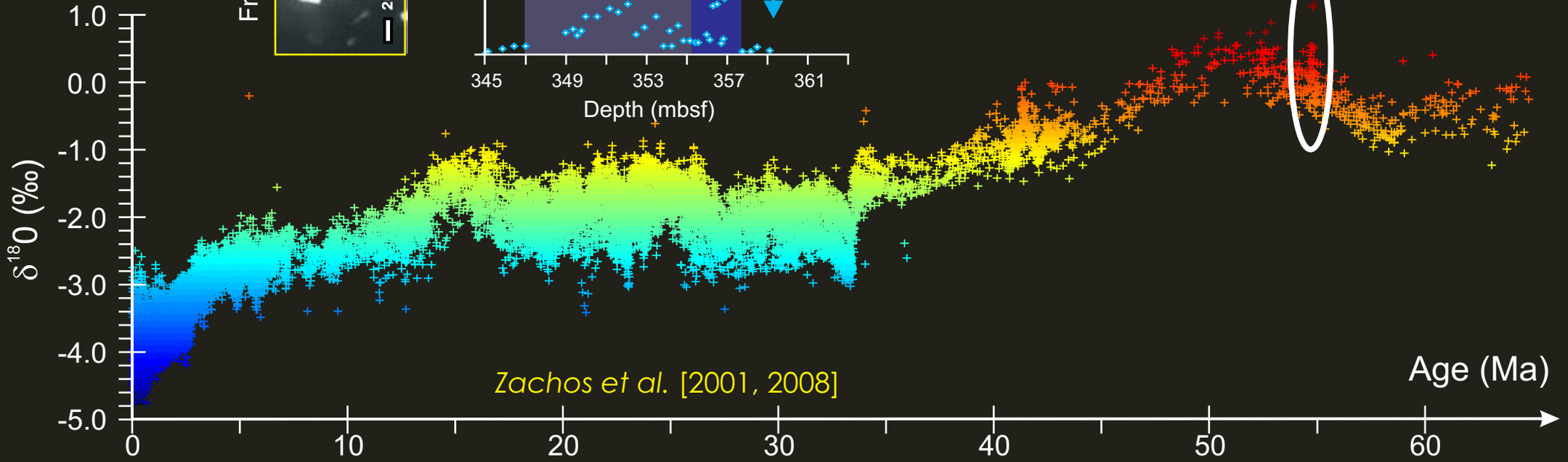
Paleo-analogues – the PETM?

Paleo-analogues – the PETM?

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



observed nanoplankton assemblage response to environmental change across the PETM

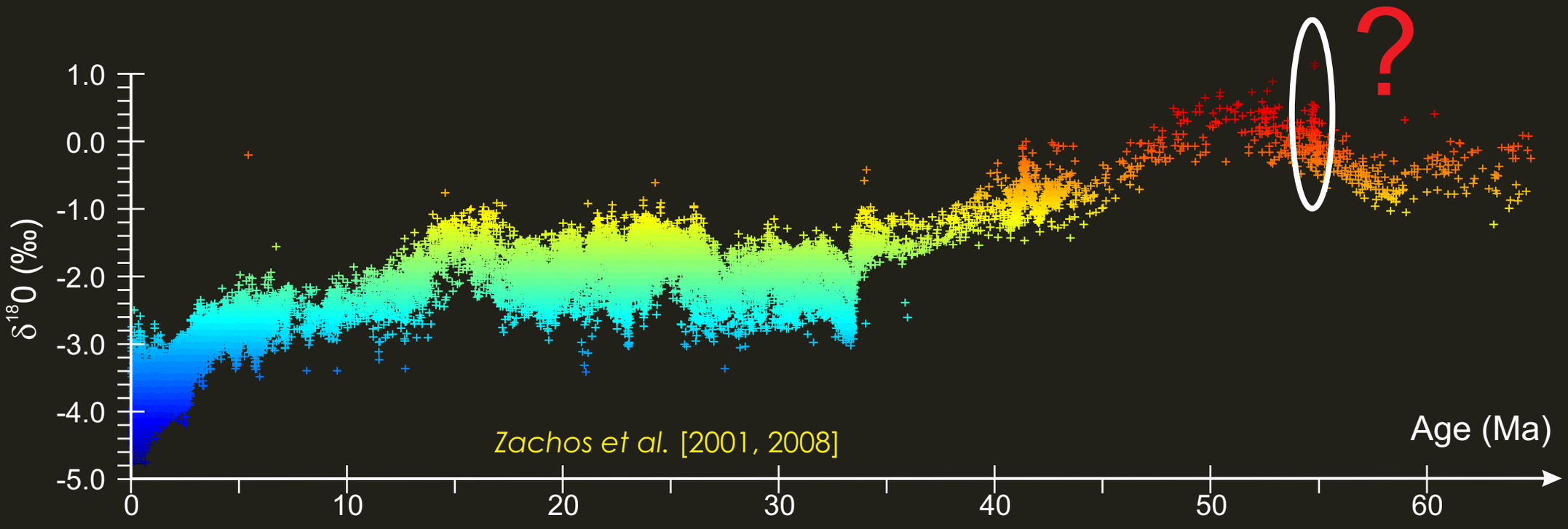


Zachos et al. [2001, 2008]

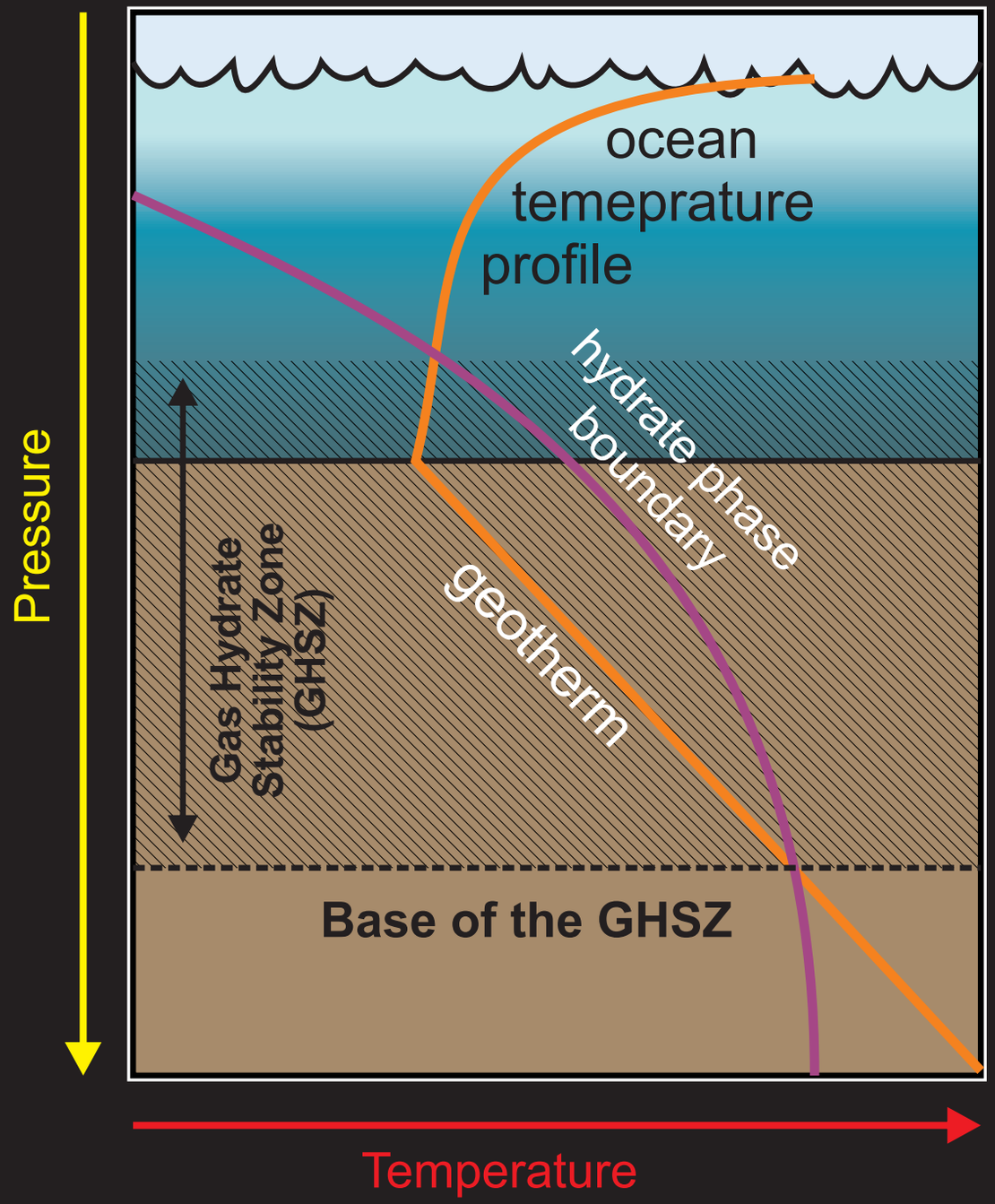
Paleo-analogues – the PETM?

'triggers'

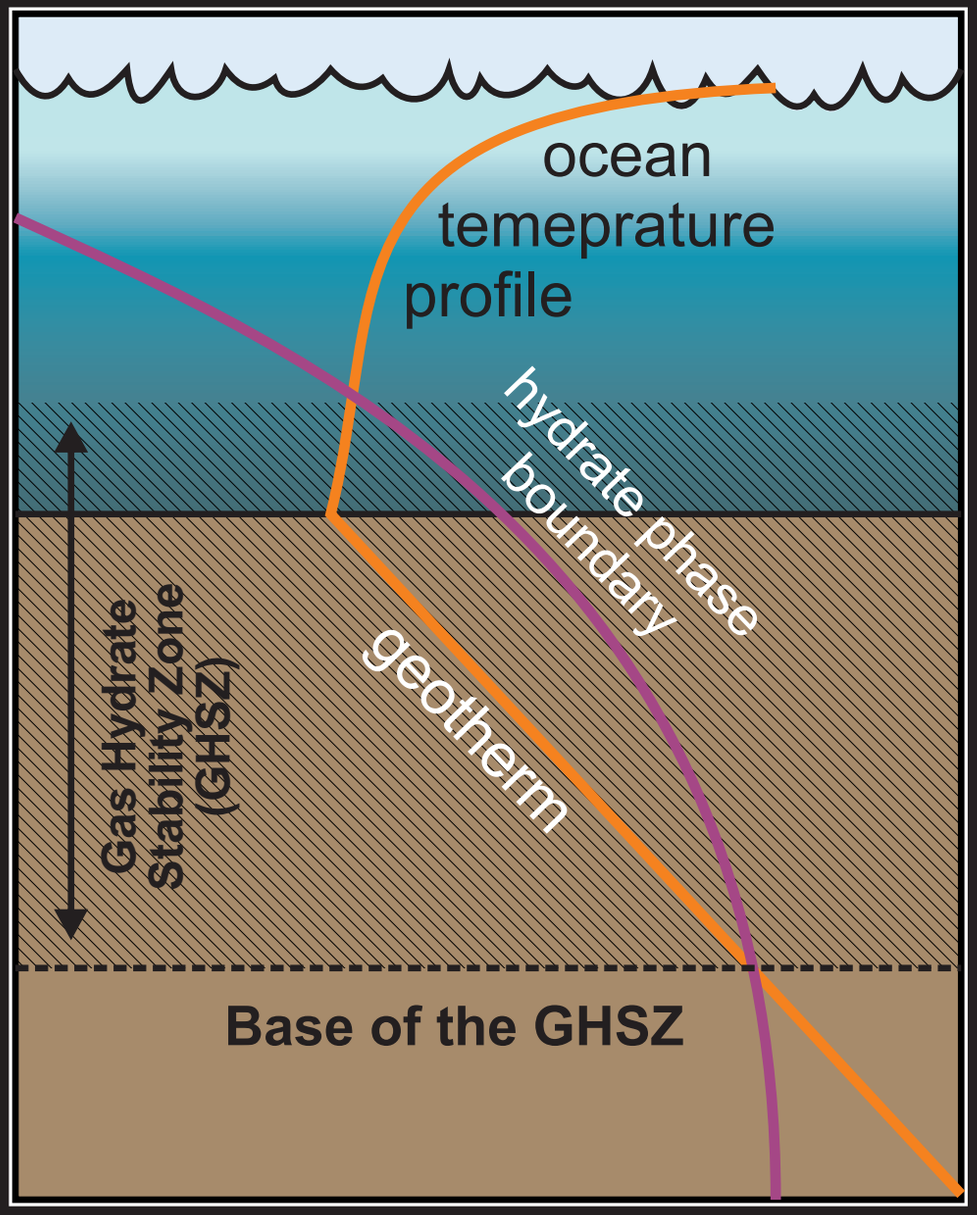
carbon cycle feedbacks



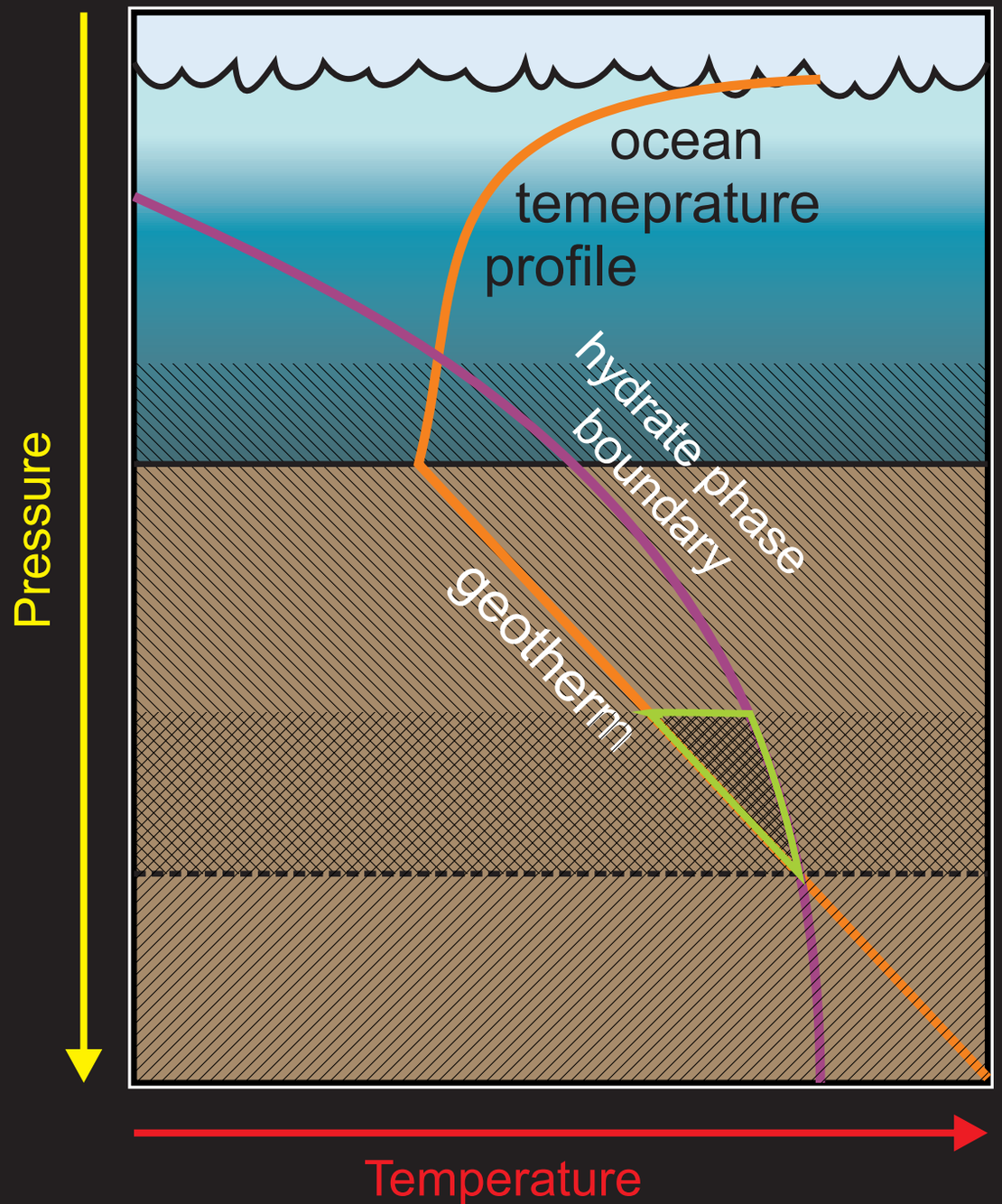
Climate fedback with methane hydrates

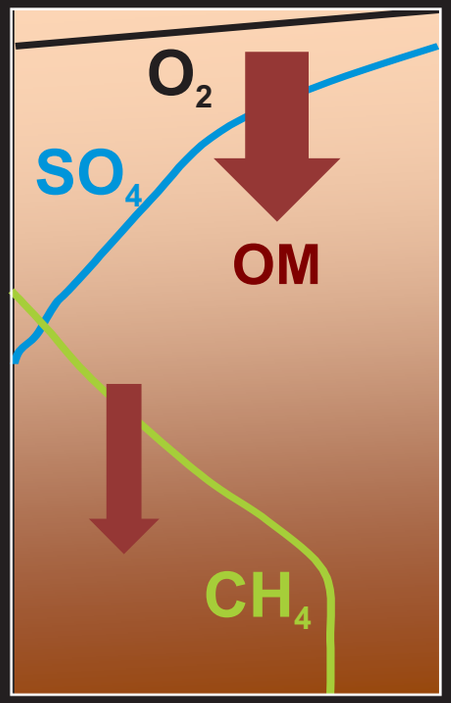


Climate fedback with methane hydrates

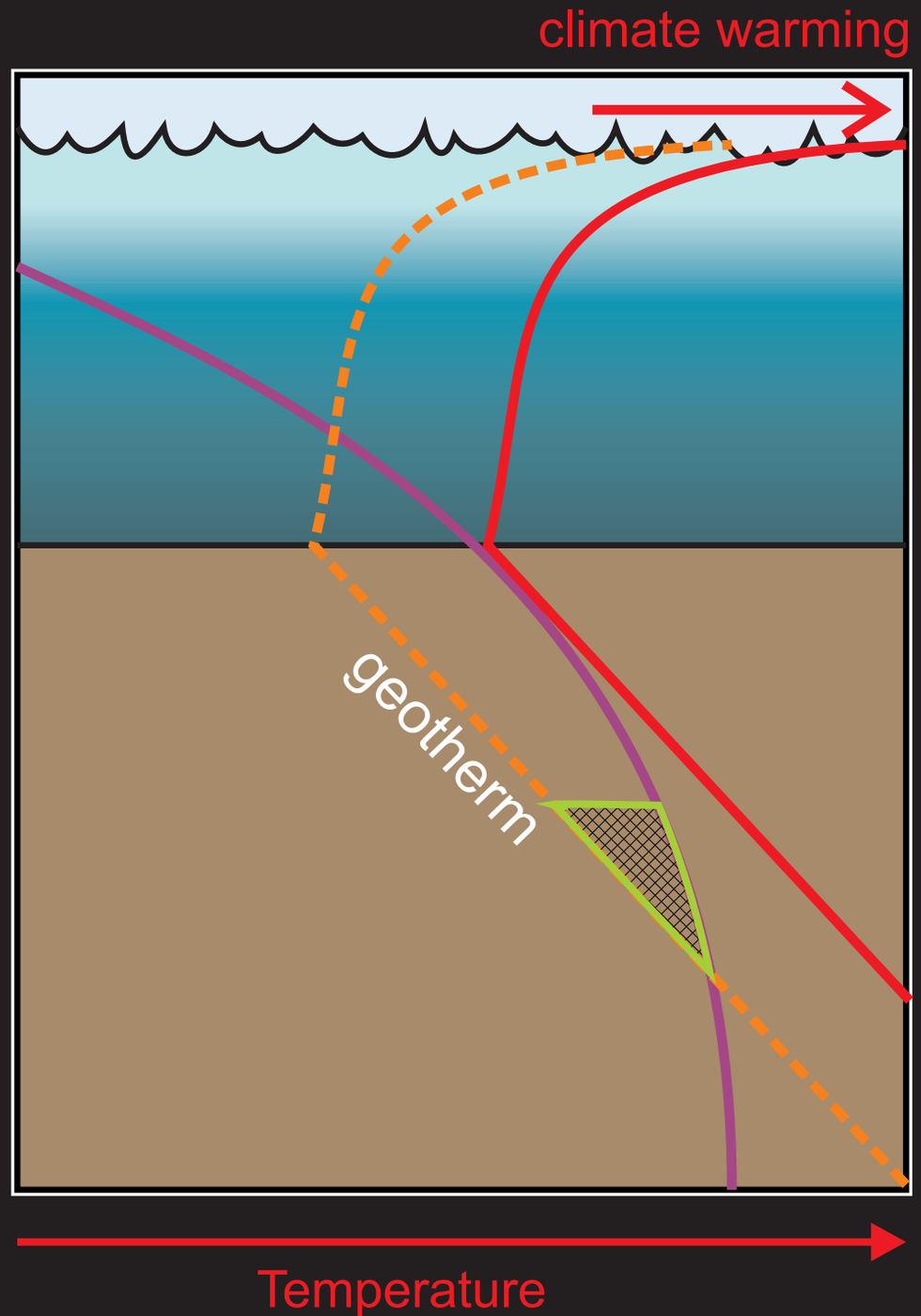


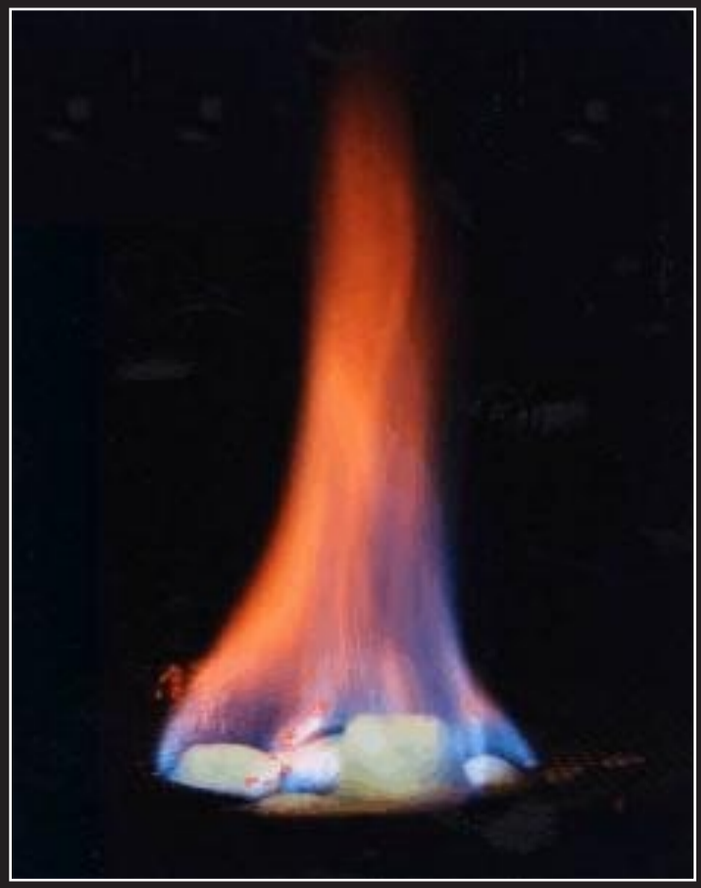
Climate fedback with methane hydrates



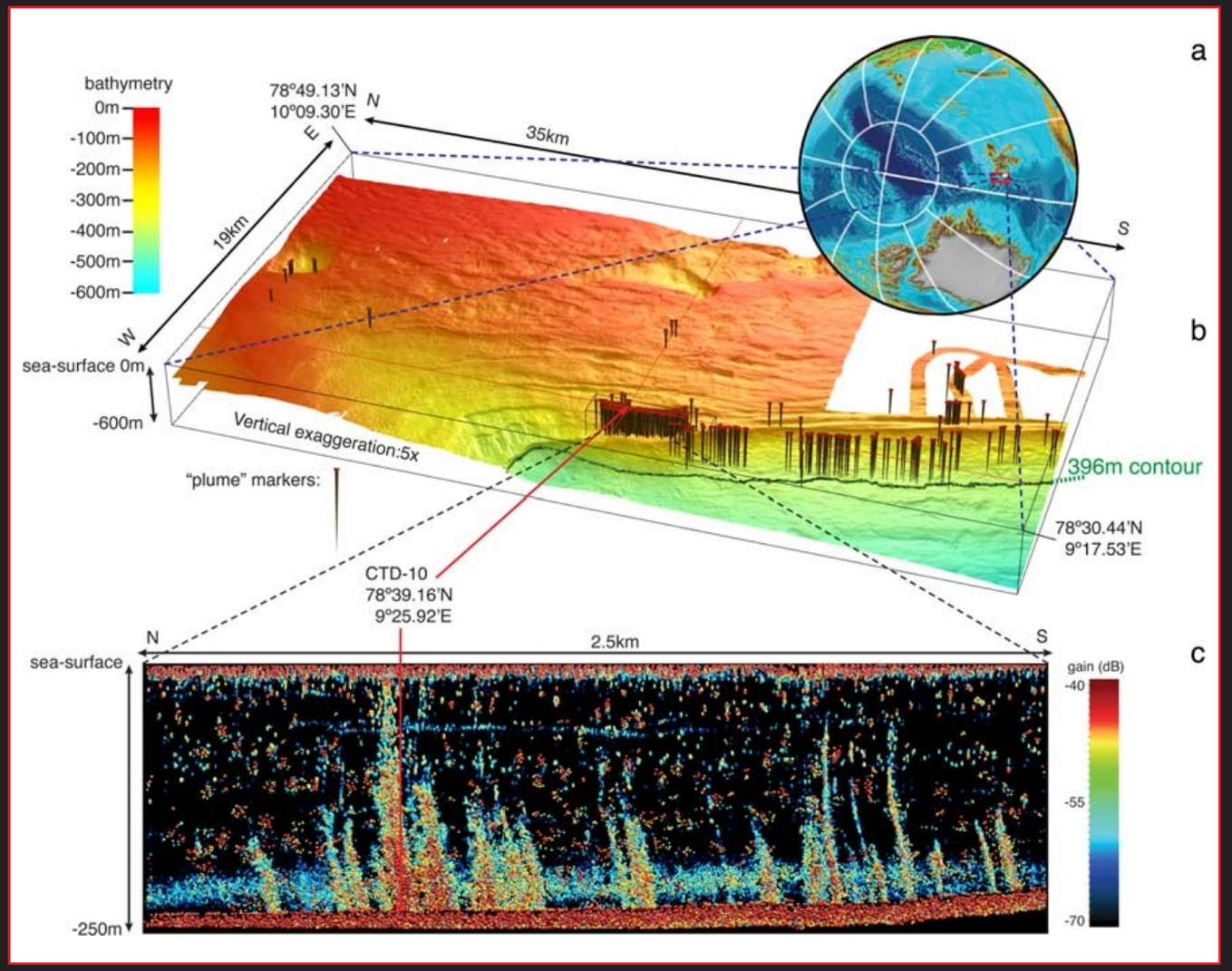


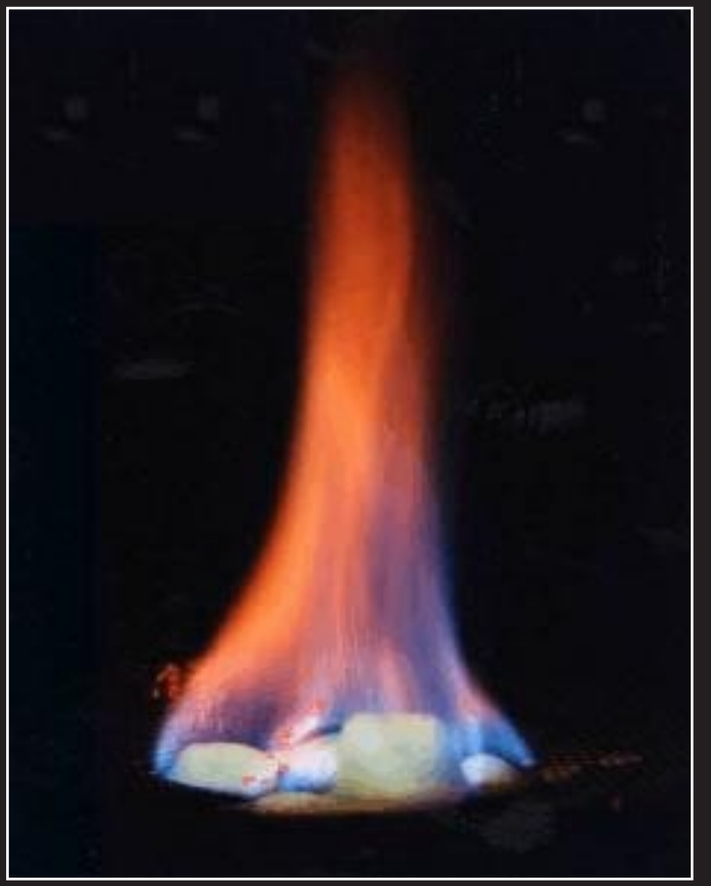
Climate fedback with methane hydrates





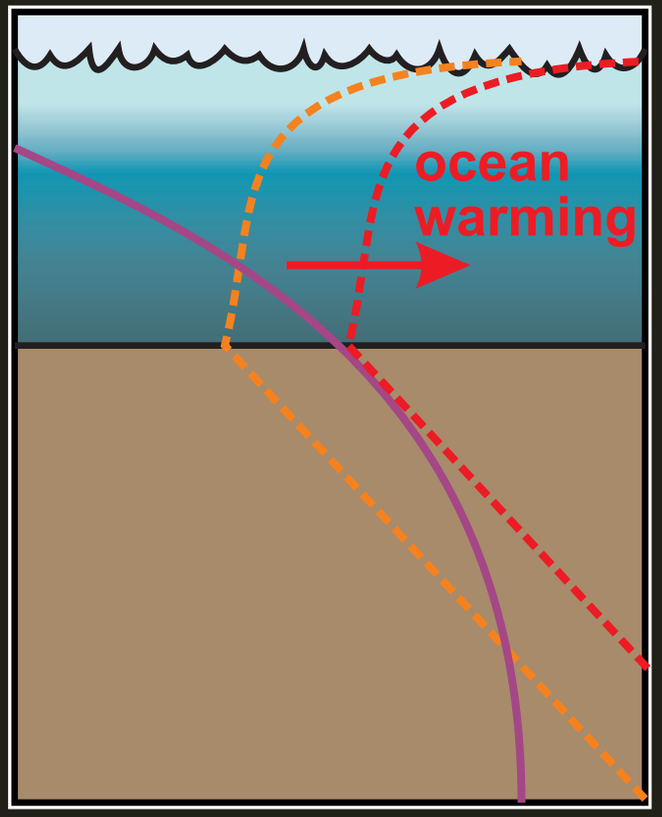
Climate fedback with methane hydrates

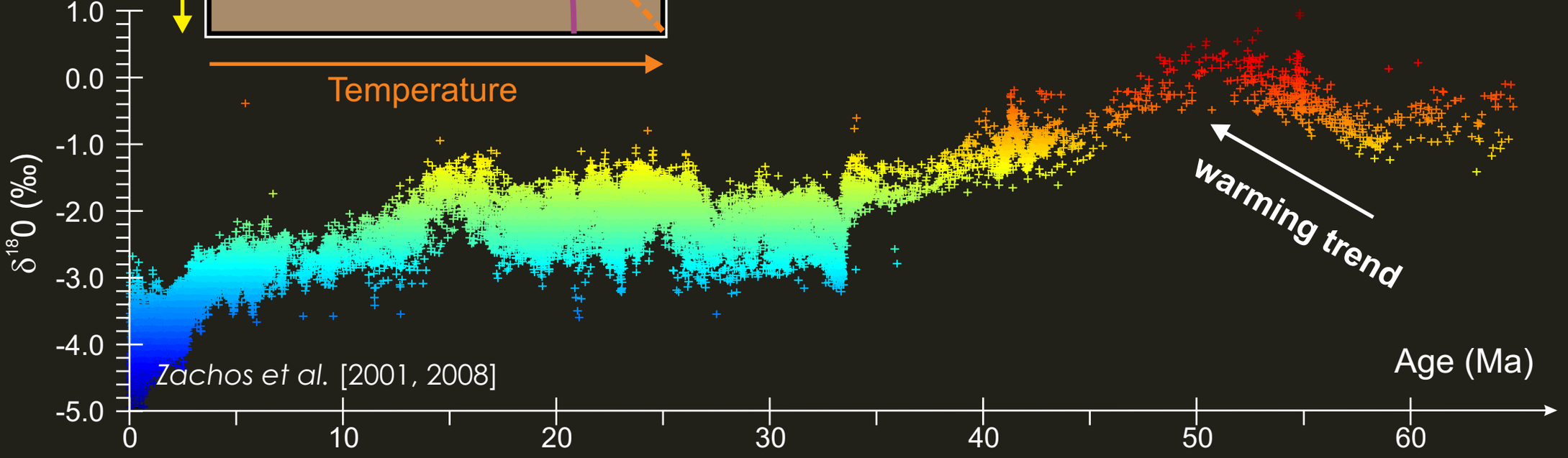




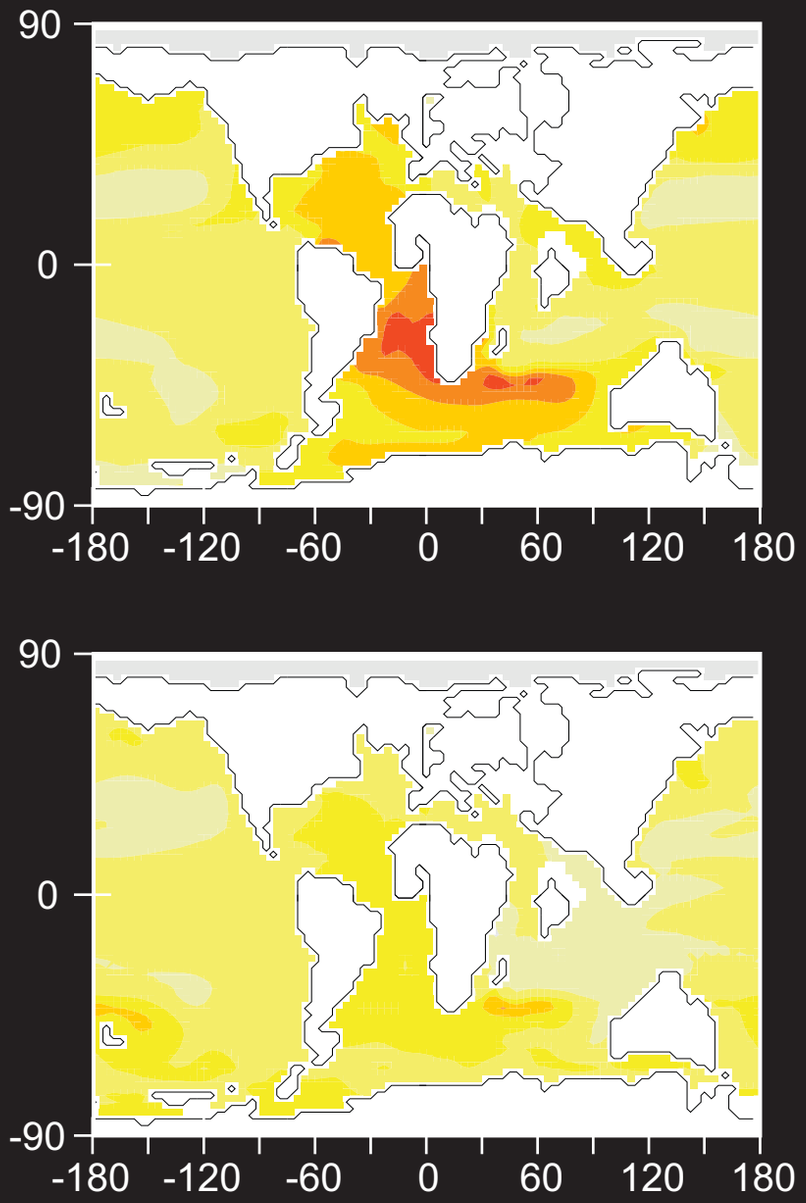
Westbrook et al. [2009]

Climate fedback with methane hydrates





Climate fedback with methane hydrates



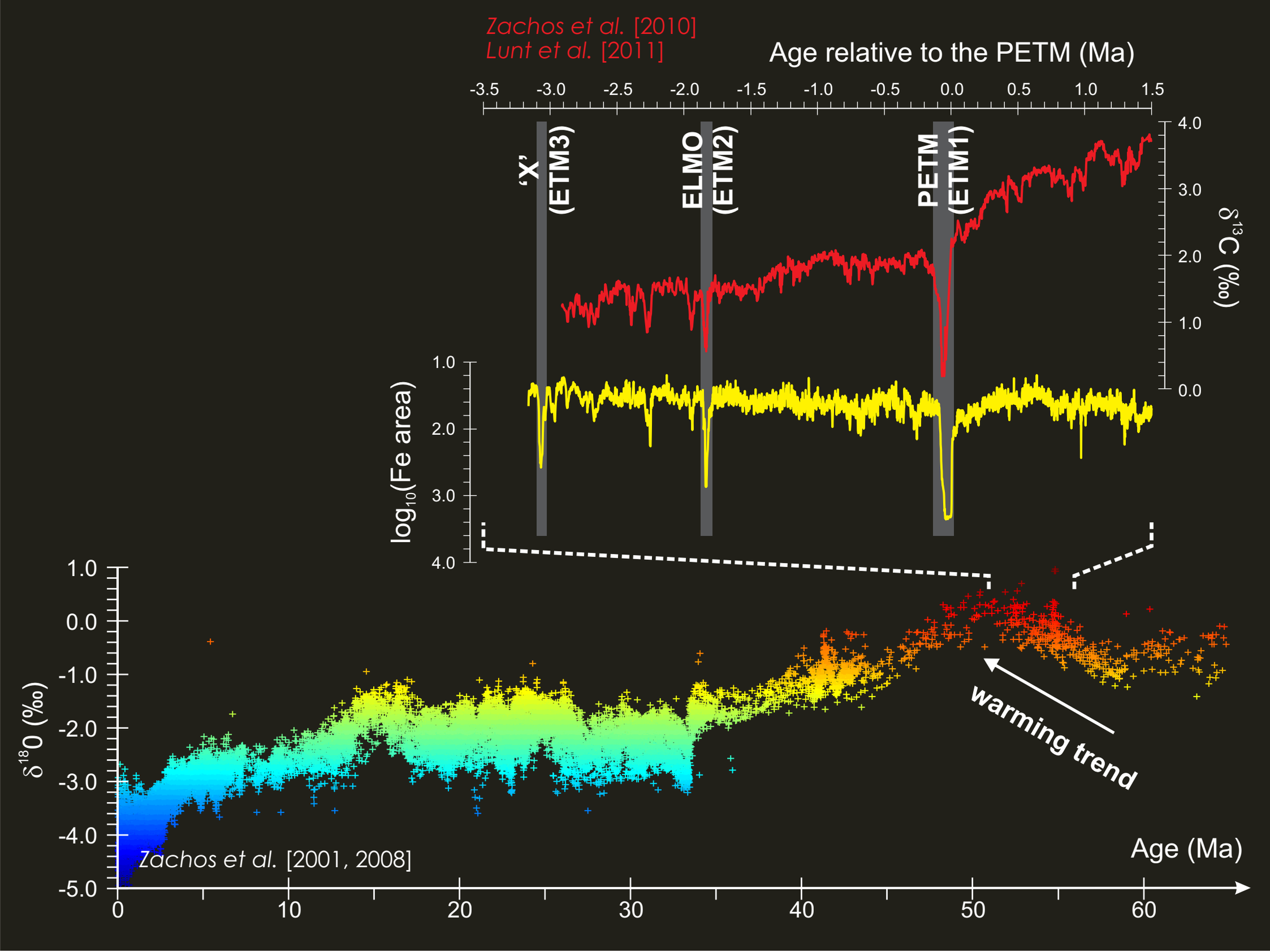
$\times 1CO_2 \rightarrow \times 4CO_2$

(normalized to a CO_2 doubling)

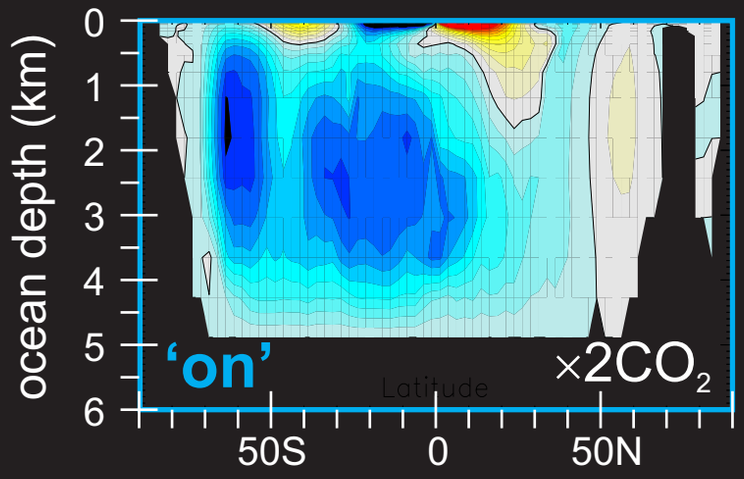
intermediate water depth warming

$\times 1CO_2 \rightarrow \times 2CO_2$

Lunt et al. [2010]


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

increasing CO_2 and radiative forcing

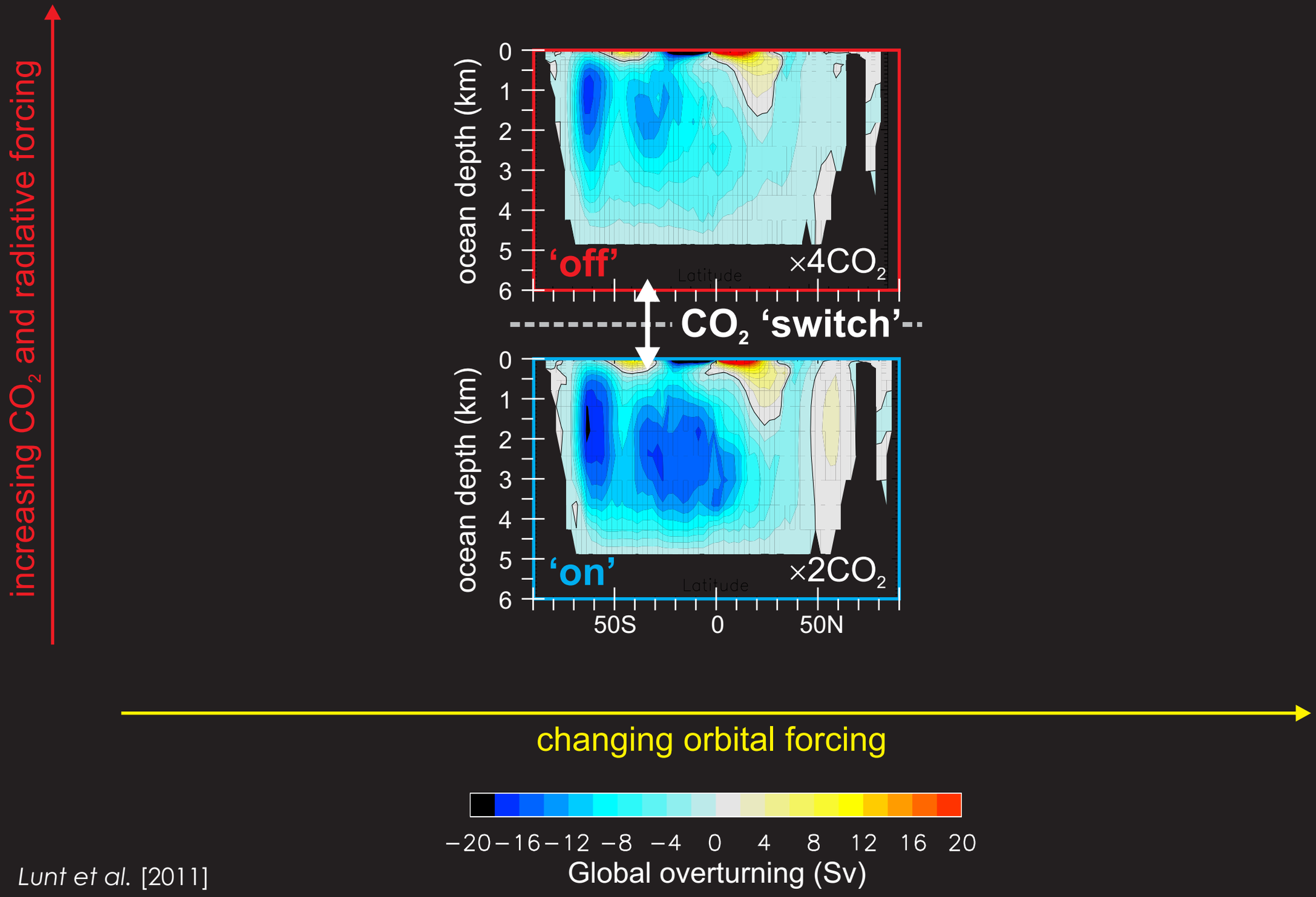


changing orbital forcing

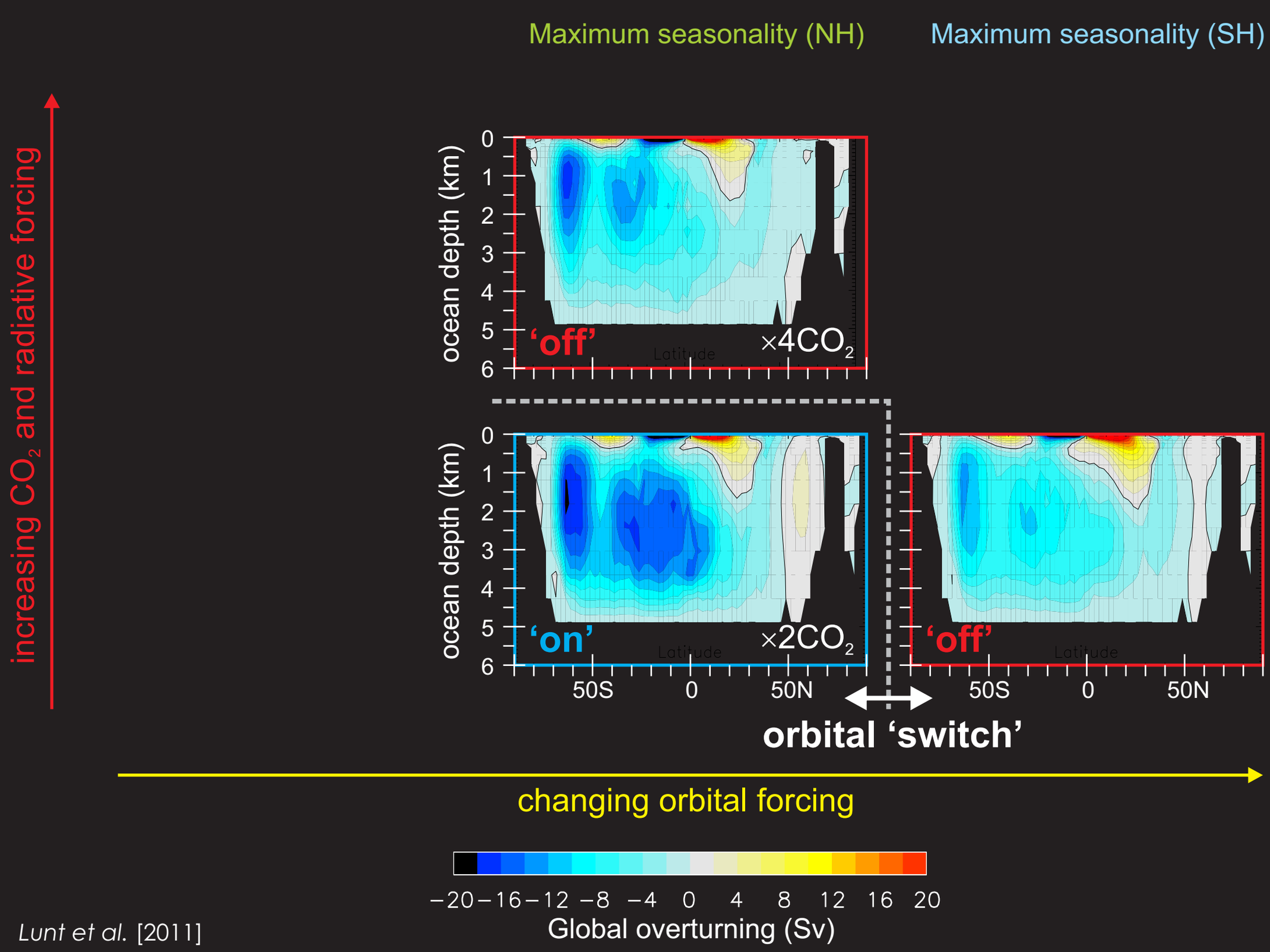
−20 −16 −12 −8 −4 0 4 8 12 16 20

Global overturning (Sv)

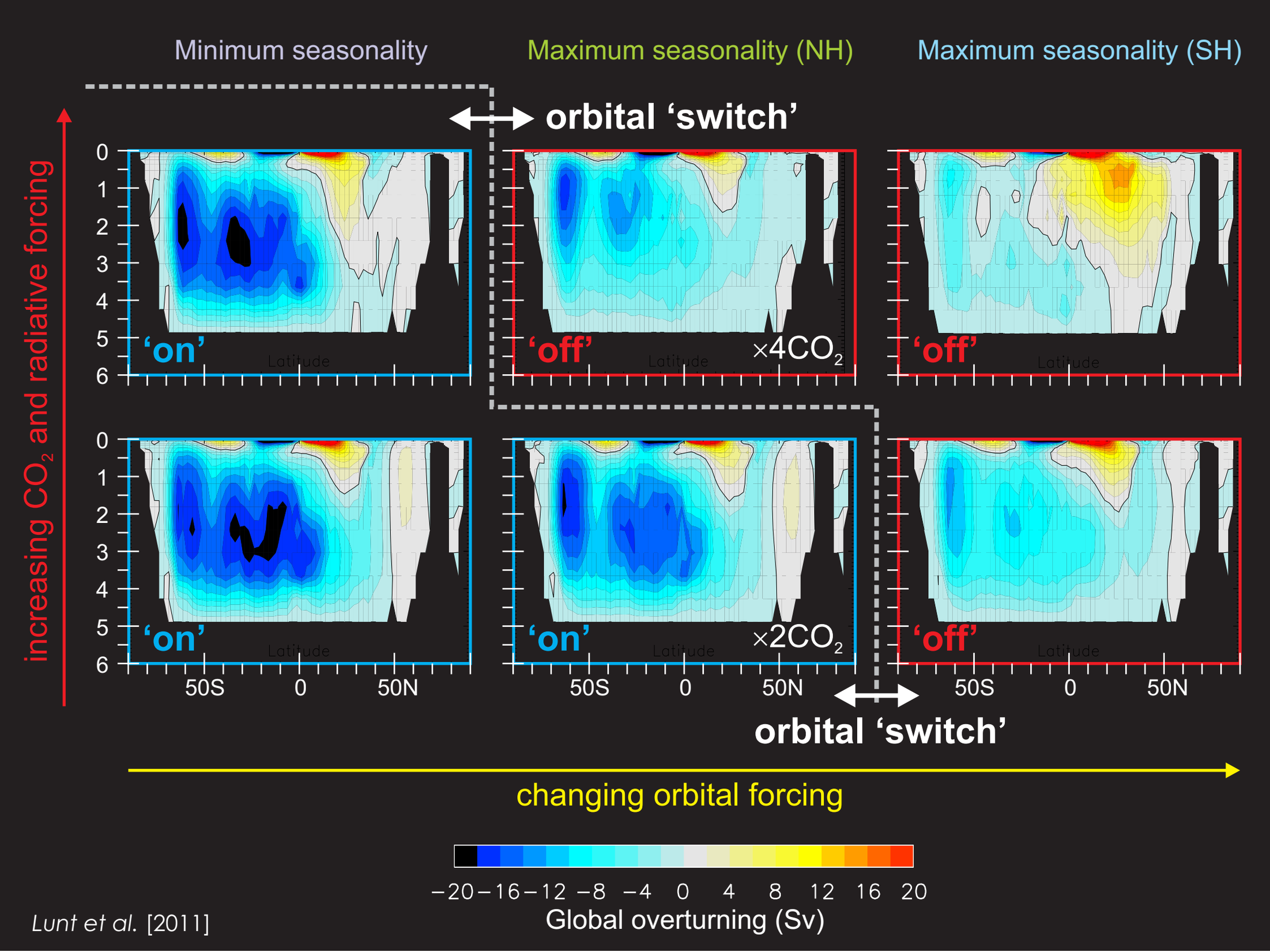
Lunt et al. [2011]



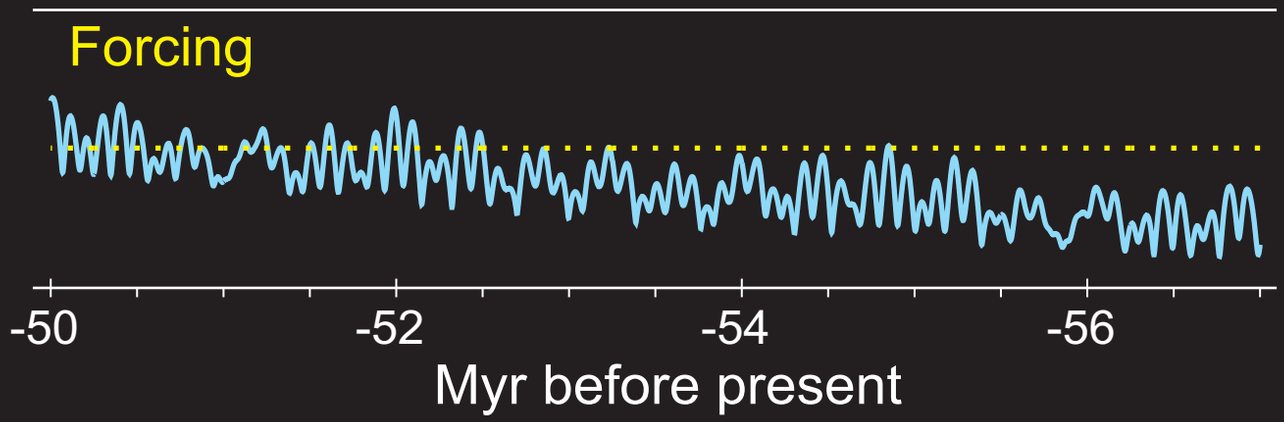
Lunt et al. [2011]



Lunt et al. [2011]



Lunt et al. [2011]



Orbital pacing of methane hydrate destabilisation during the Palaeogene?

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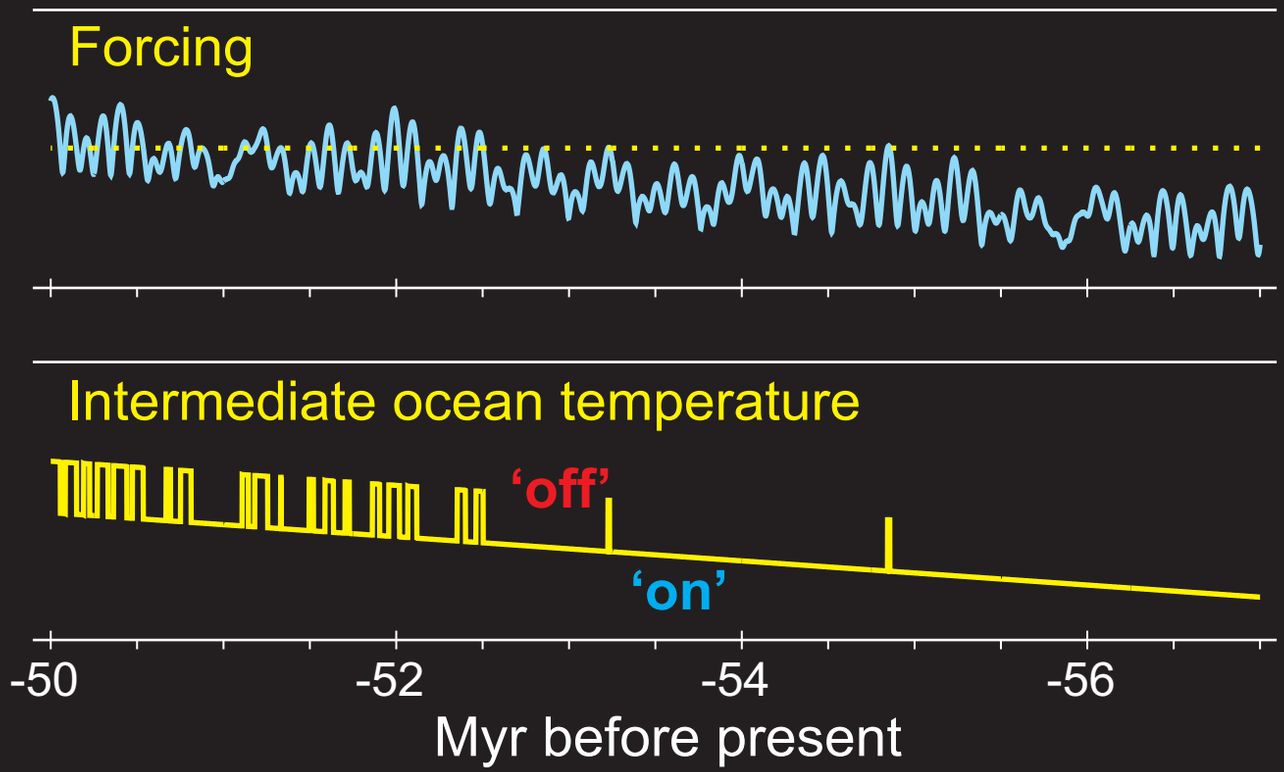
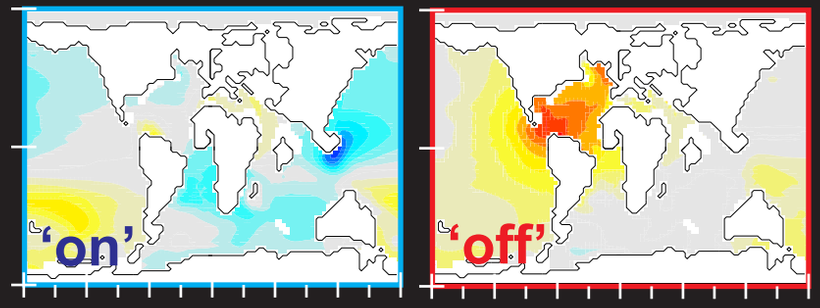
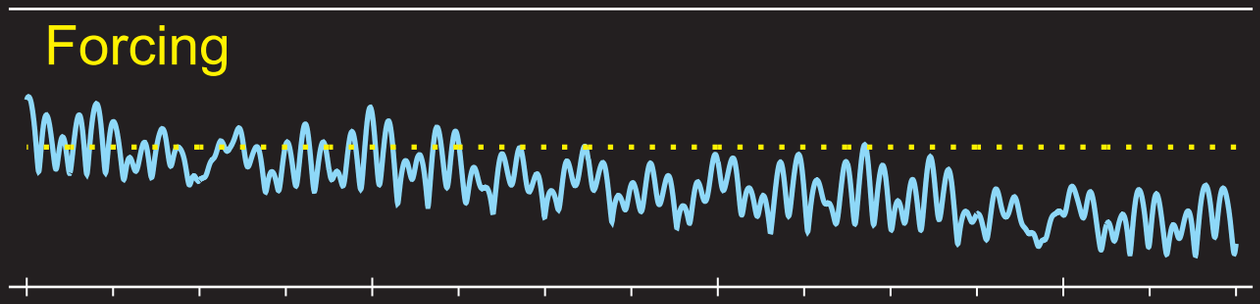
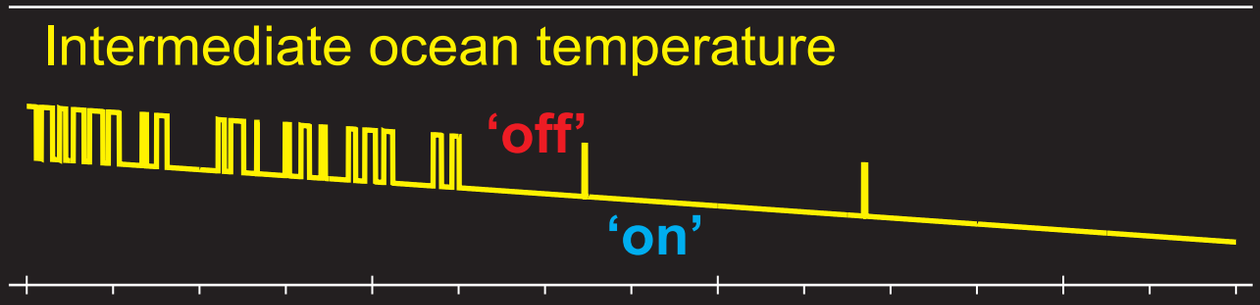
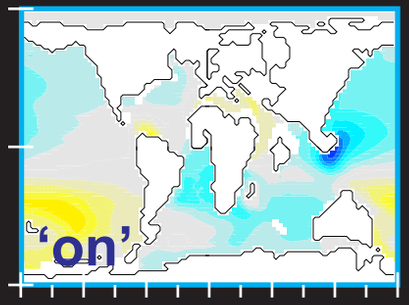


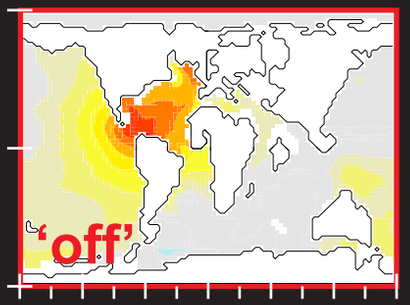


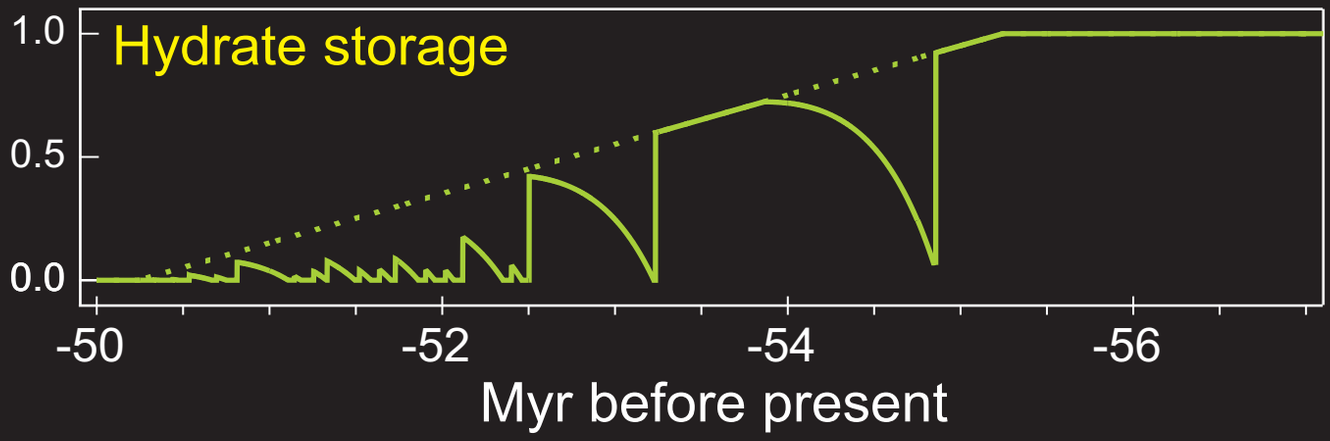
Orbital pacing of methane hydrate destabilisation during the Palaeogene?



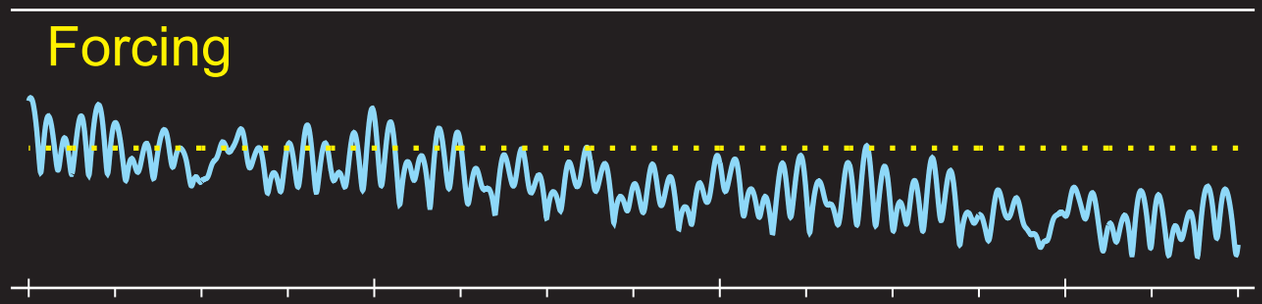


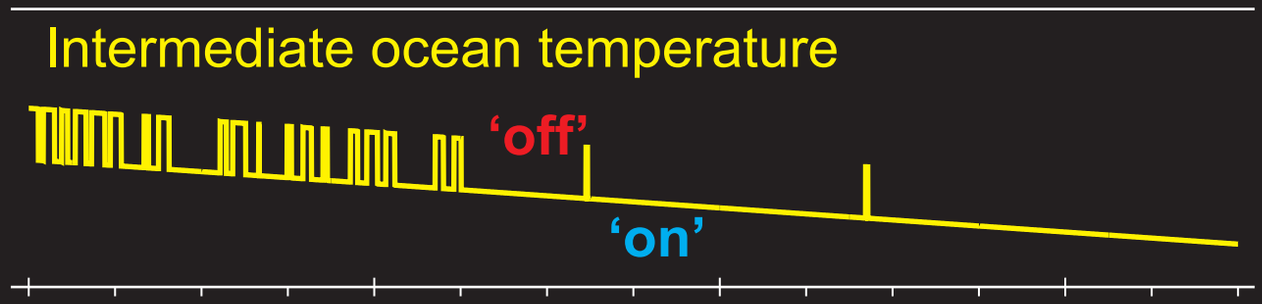


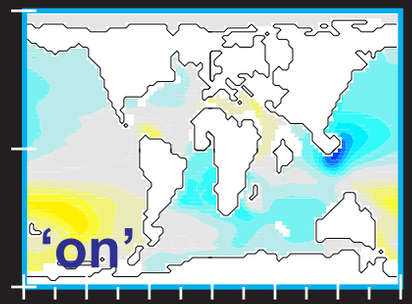


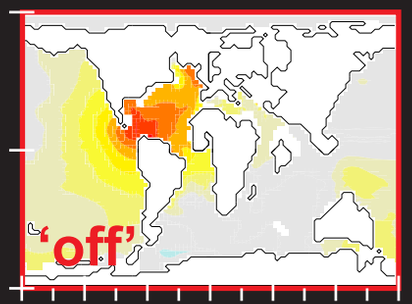


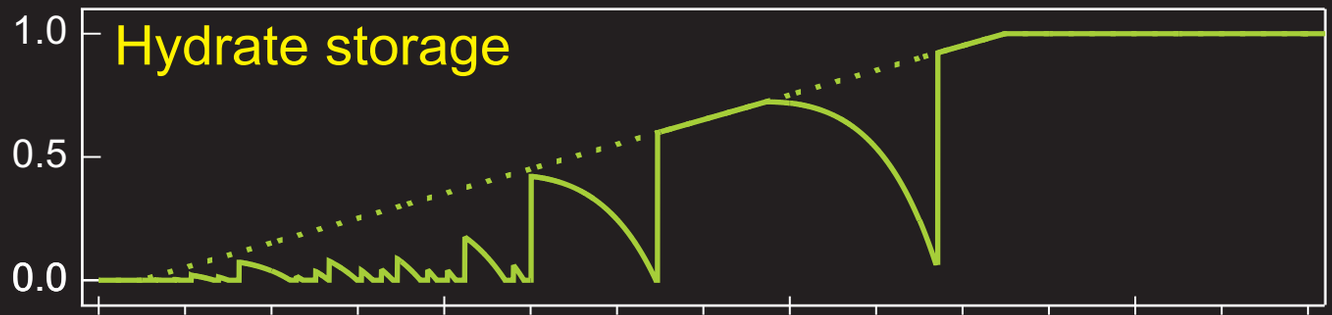
Orbital pacing of methane hydrate destabilisation during the Palaeogene?

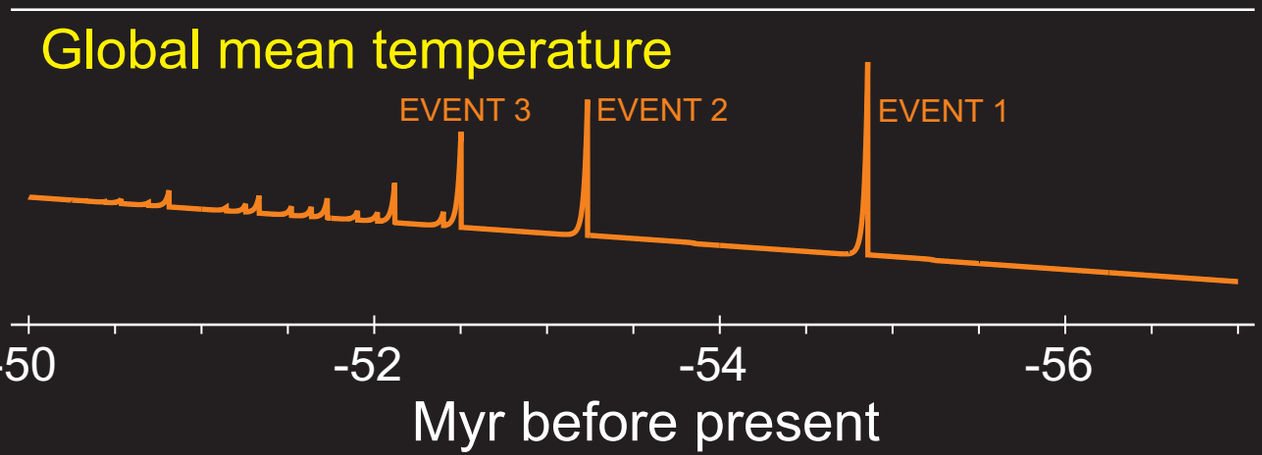












Climate fedback with methane hydrates

biological productivity

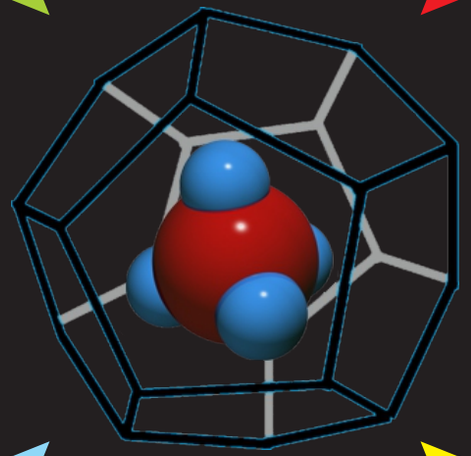
climate and ocean circulation

greenhouse gas forcing

ocean $[O_2]$

sedimentary organic matter burial flux

bottom-water temperature

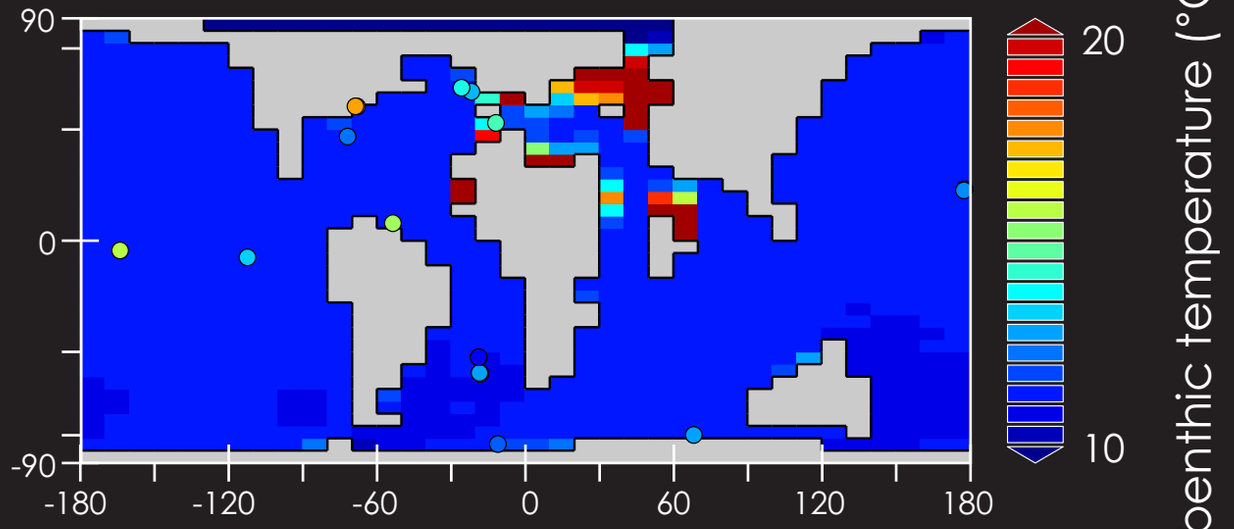


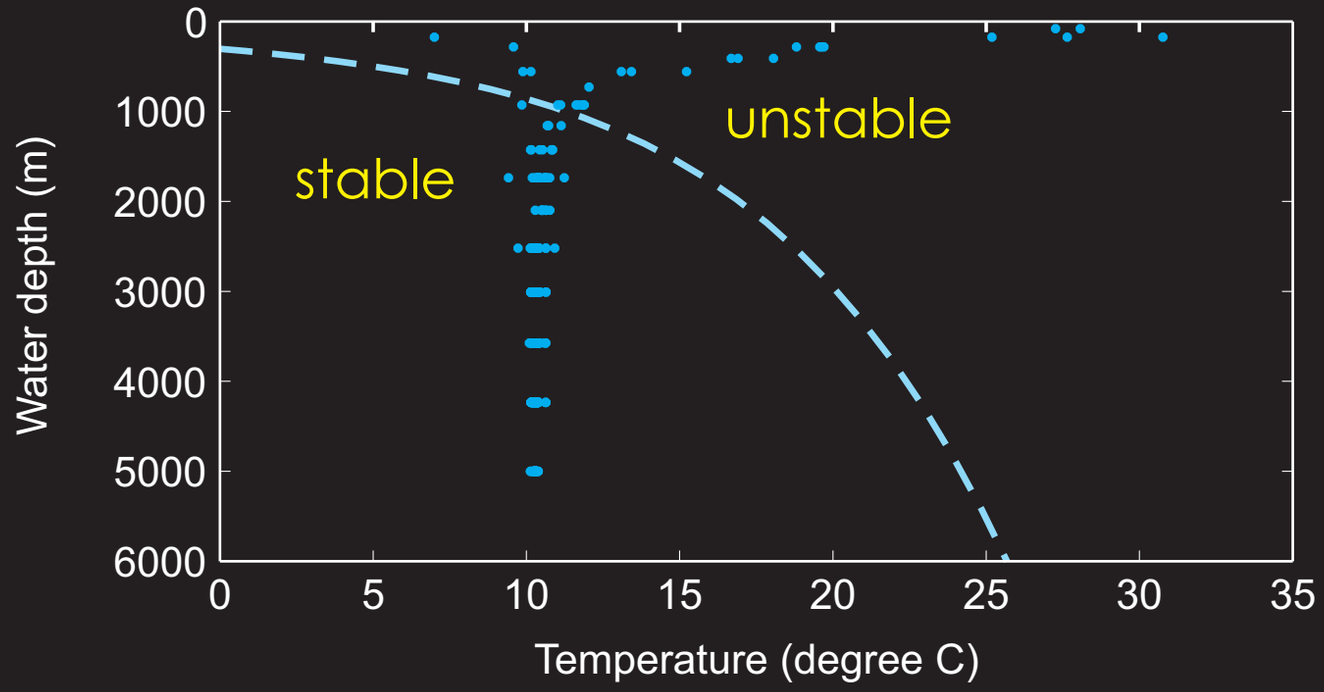
paleo topography

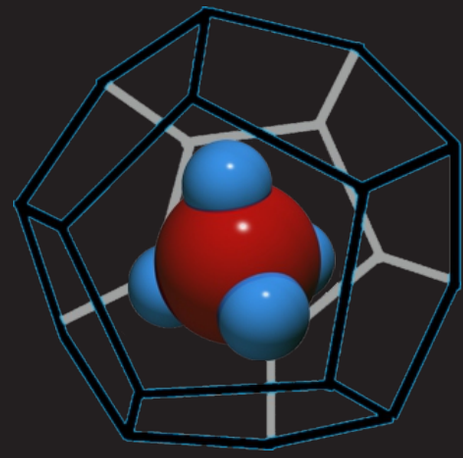
pressure

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

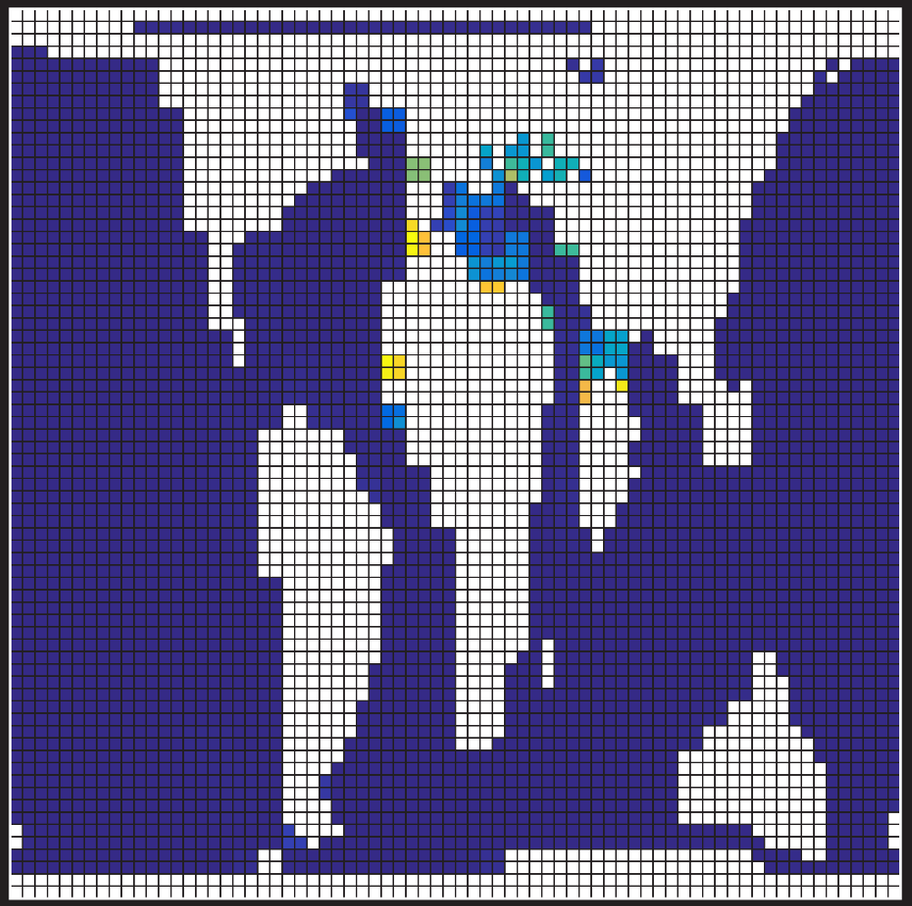
Climate fedback with methane hydrates



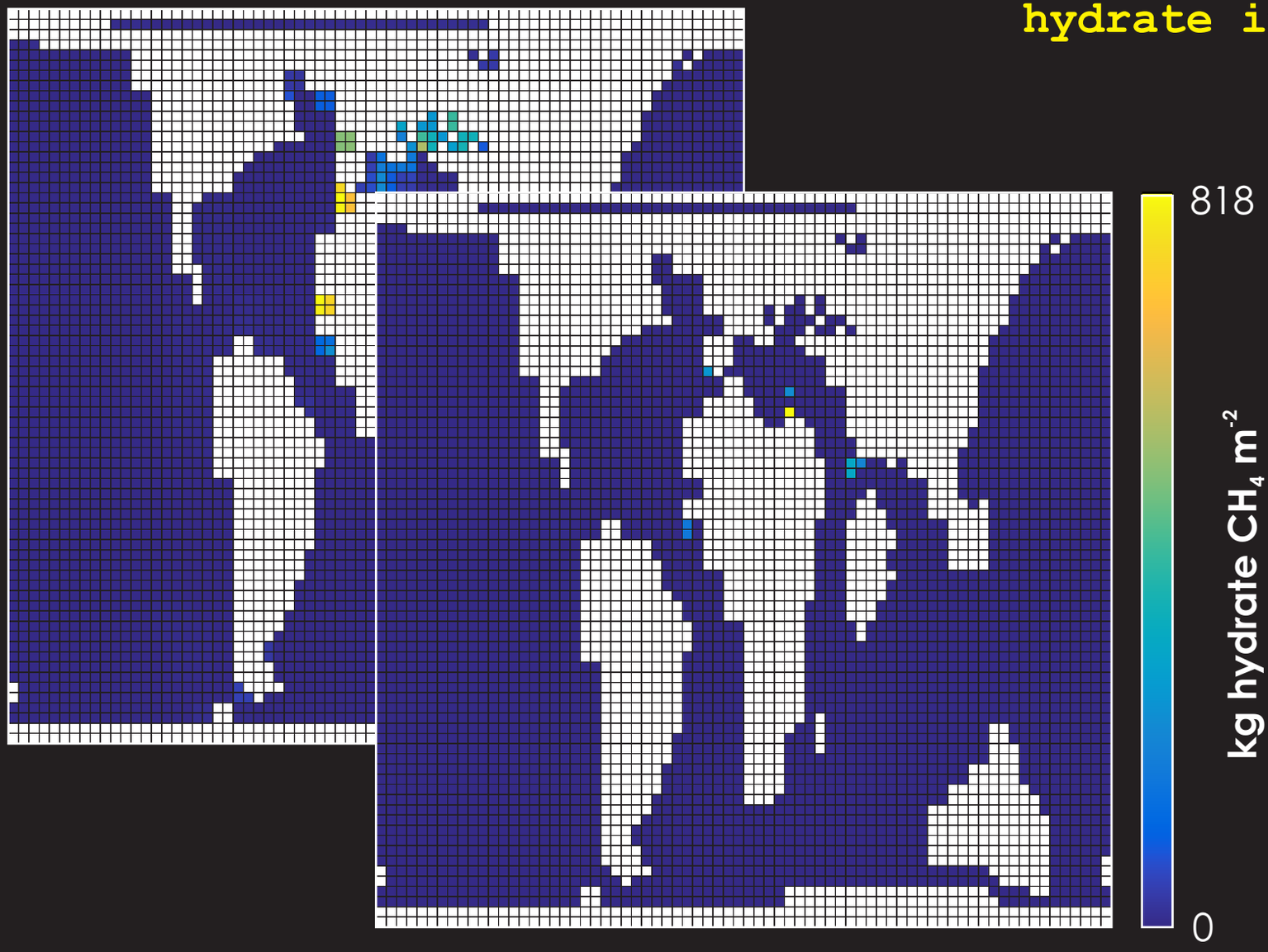




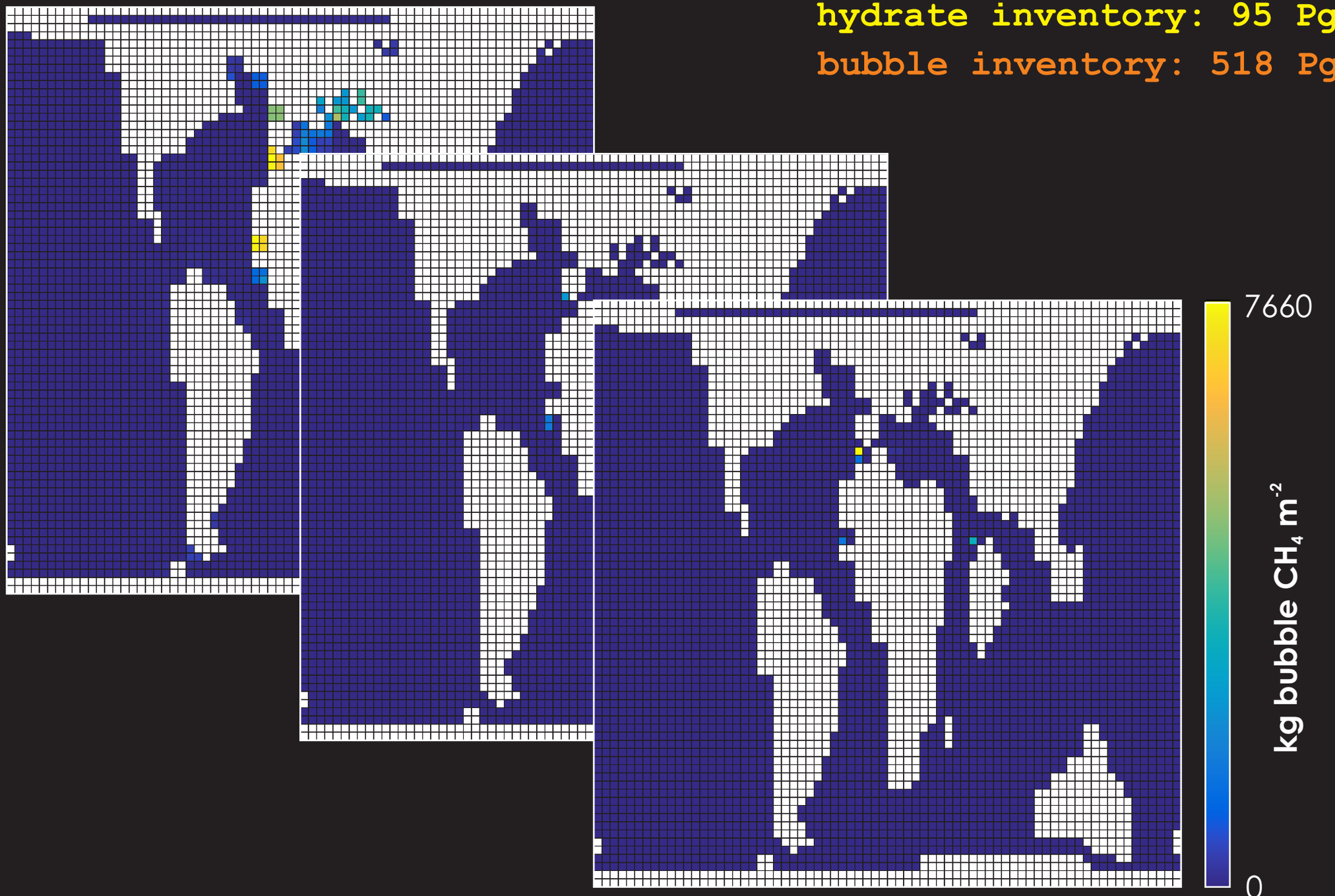
Climate fedback with methane hydrates



Climate fedback with methane hydrates



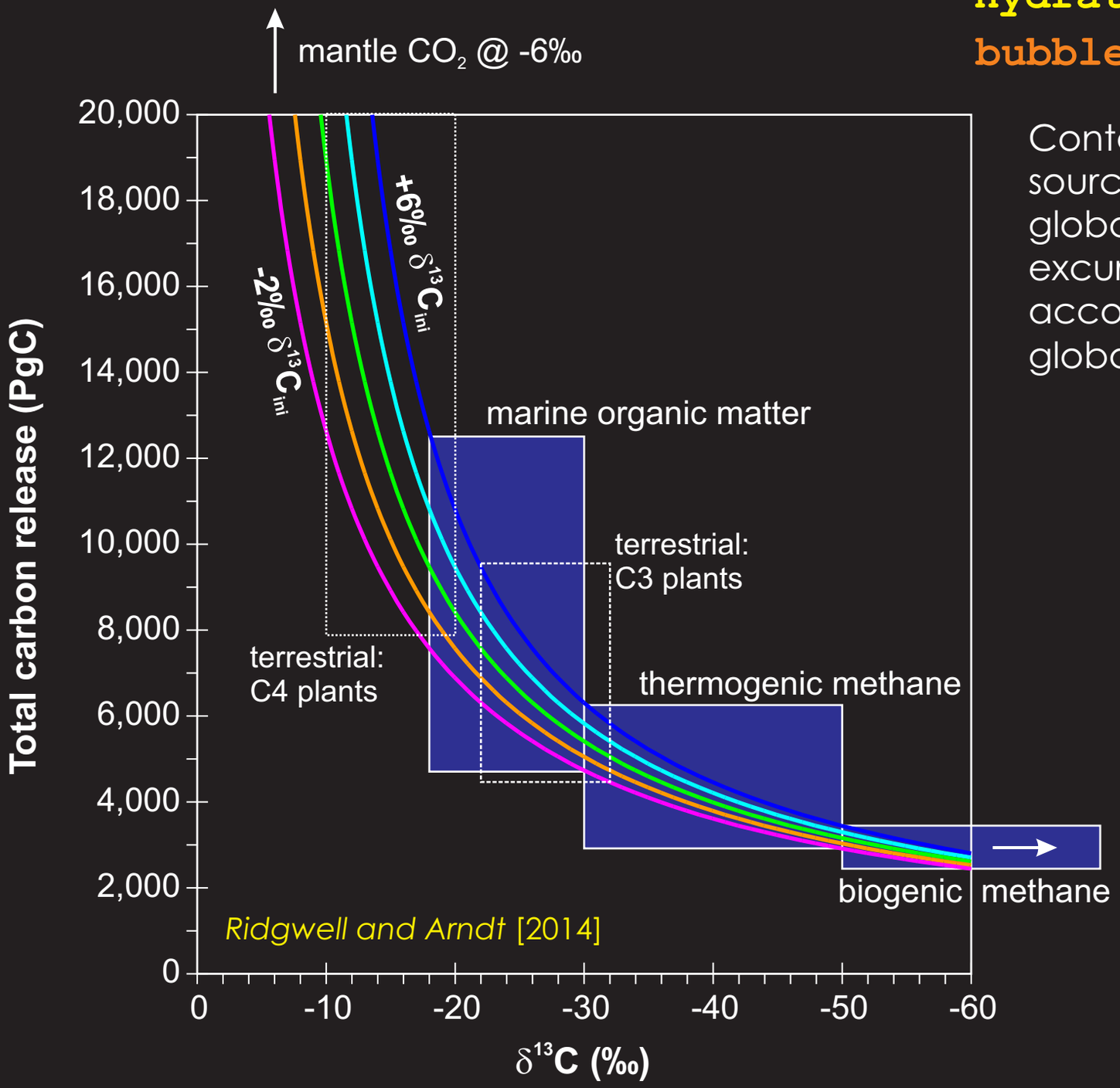
Climate fedback with methane hydrates



Climate fedback with methane hydrates

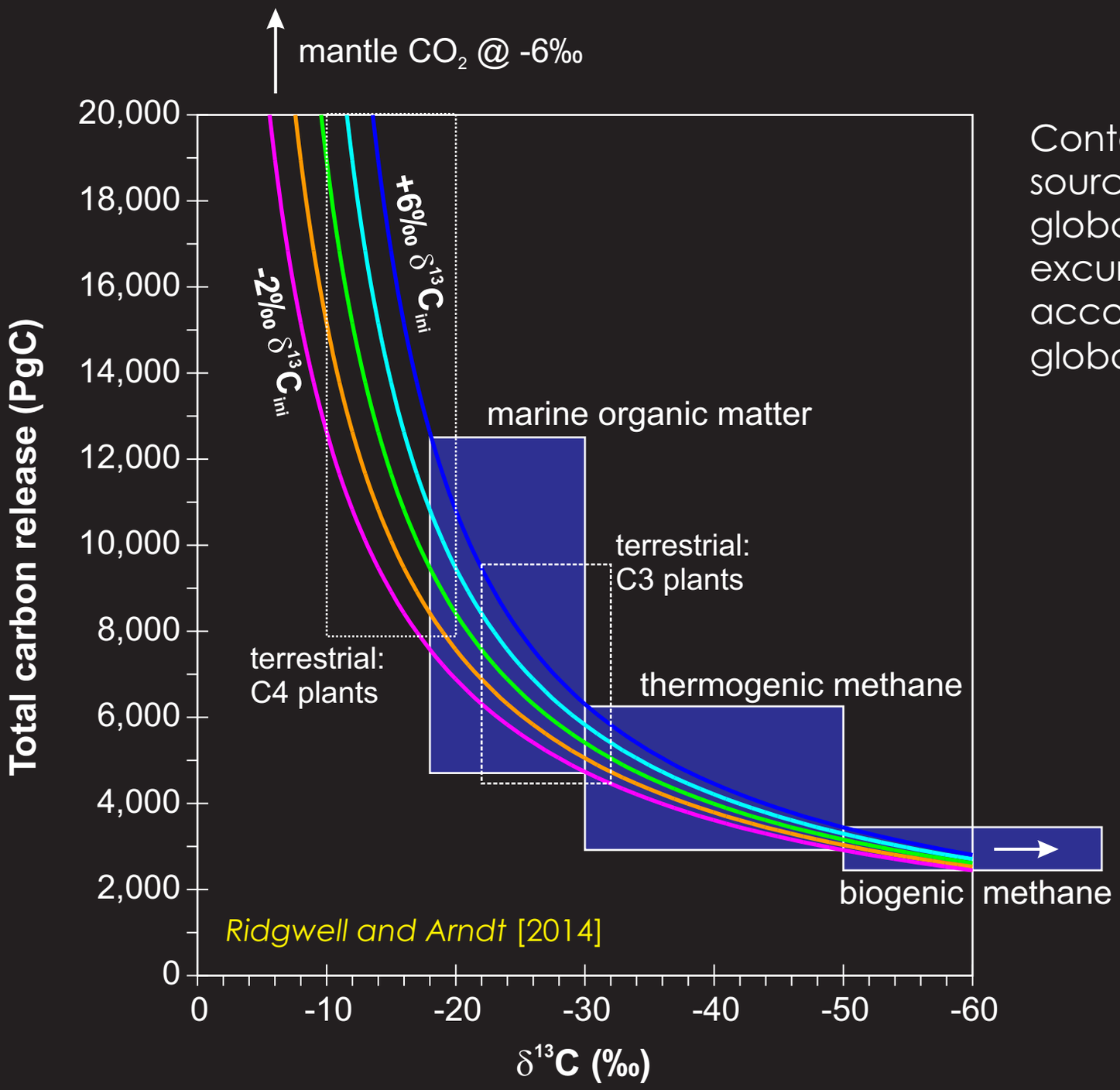
hydrate inventory: 95 PgC

bubble inventory: 518 PgC



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



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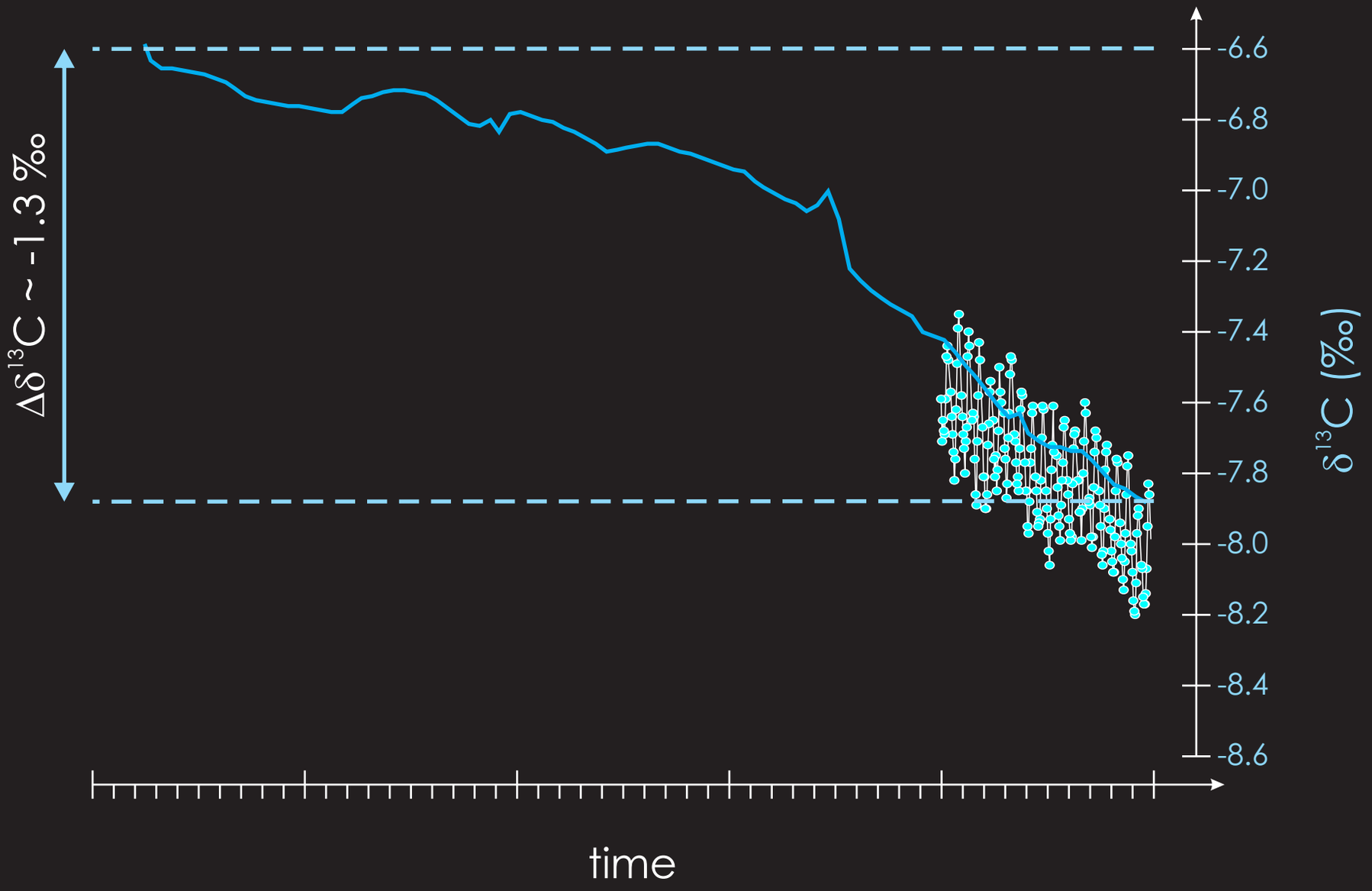
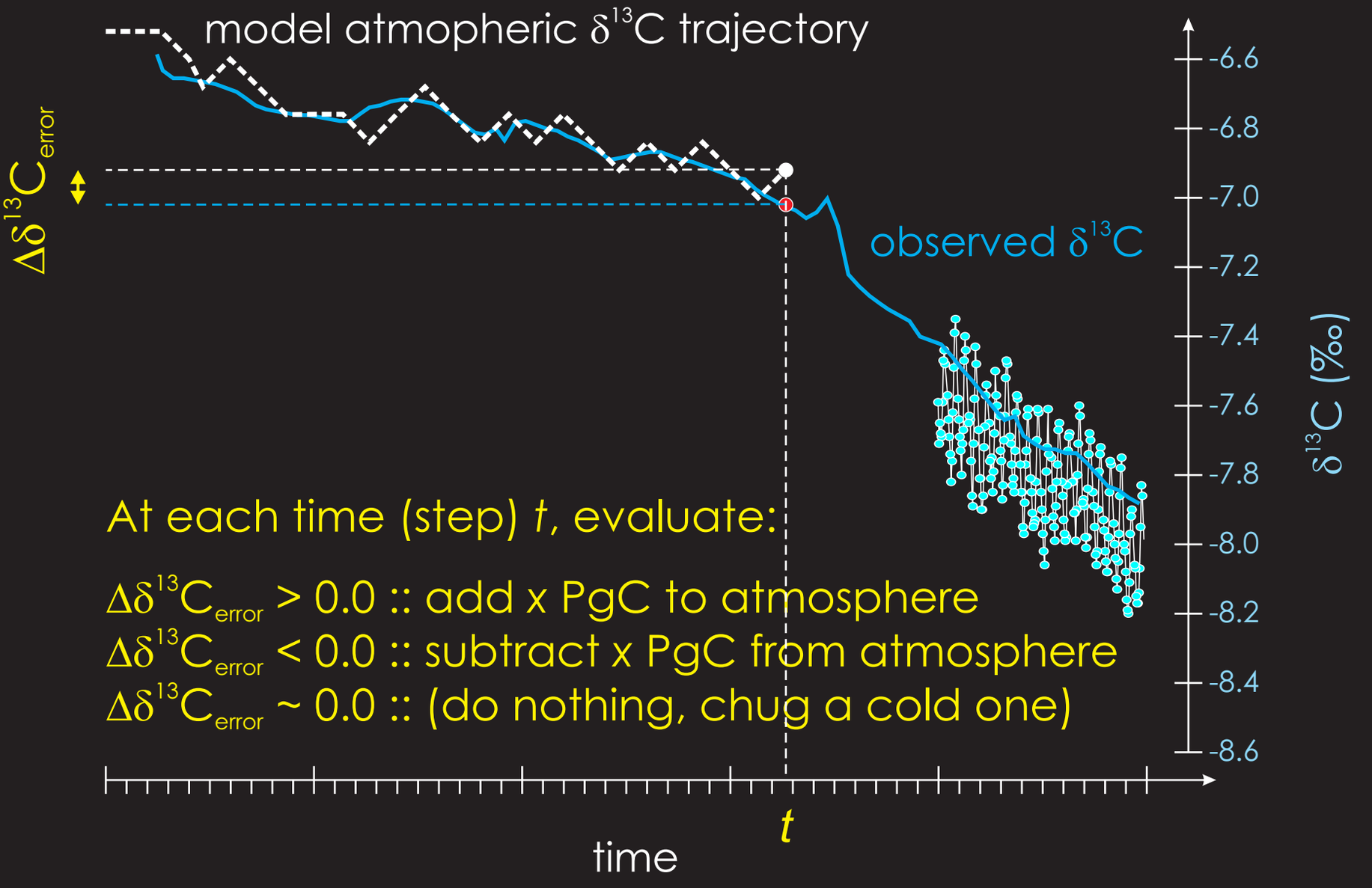
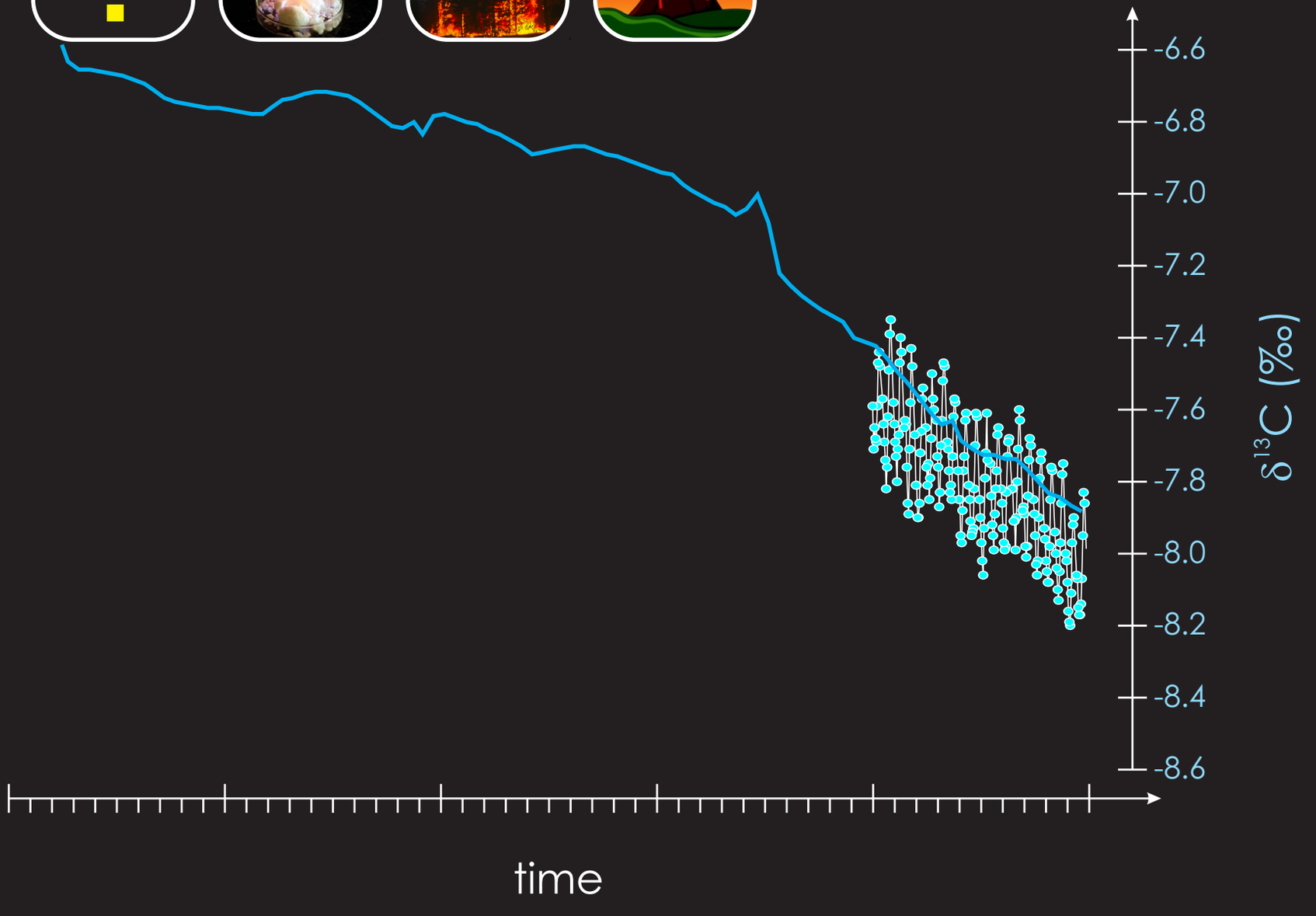
Methods



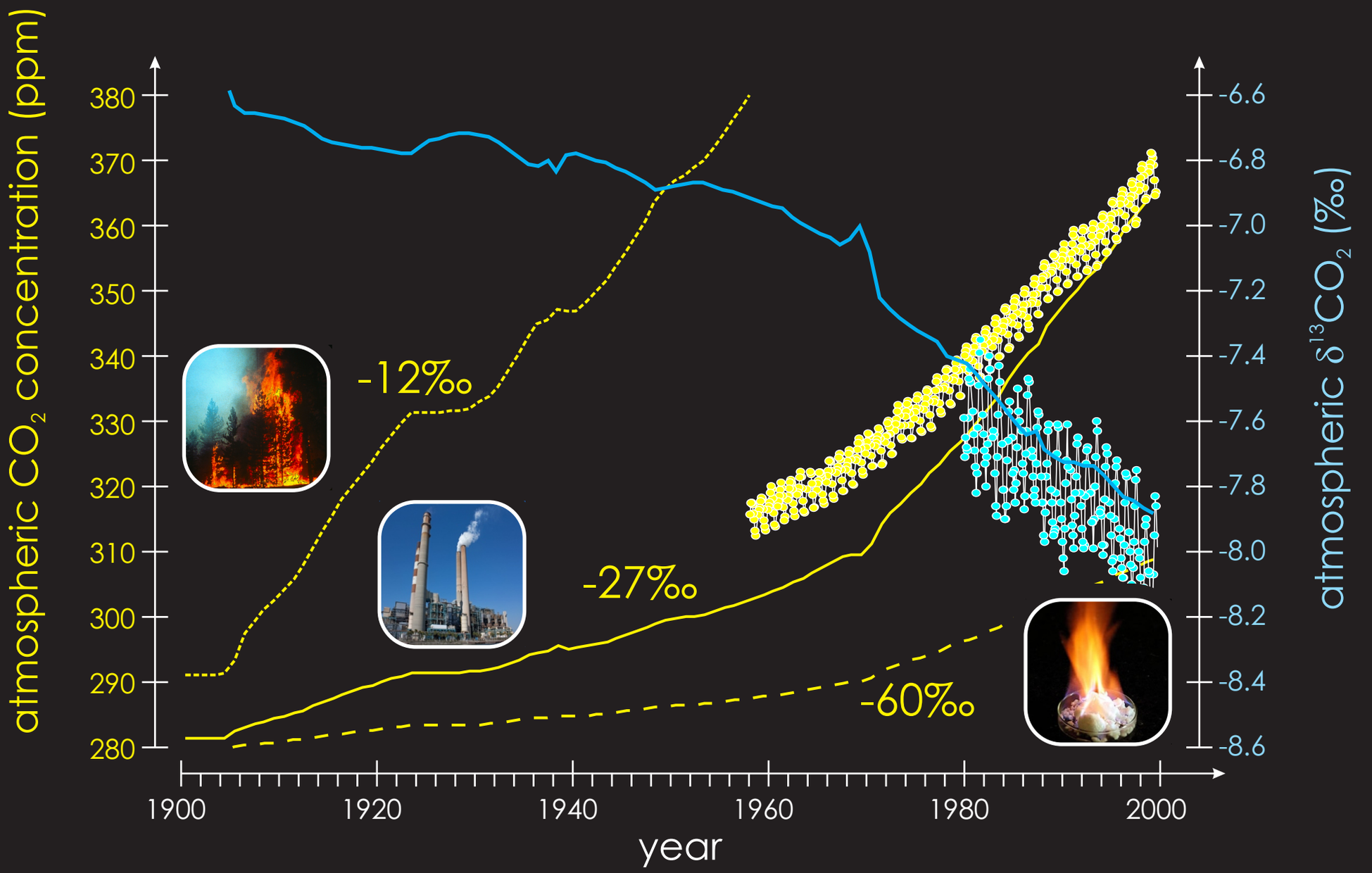
Methods


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

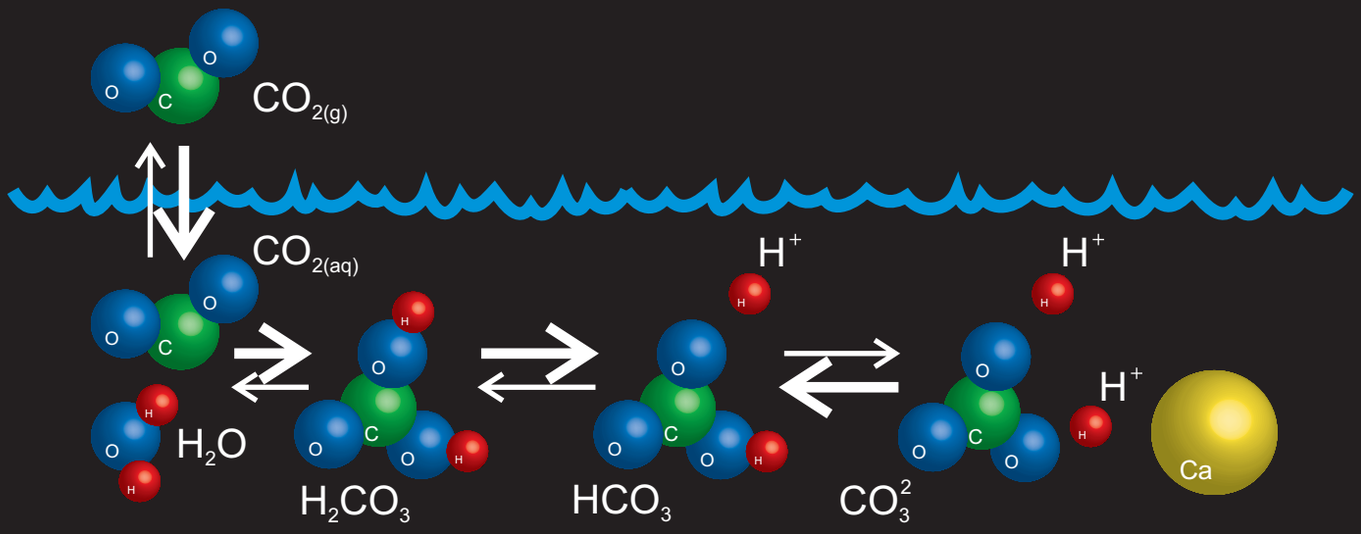
Methods



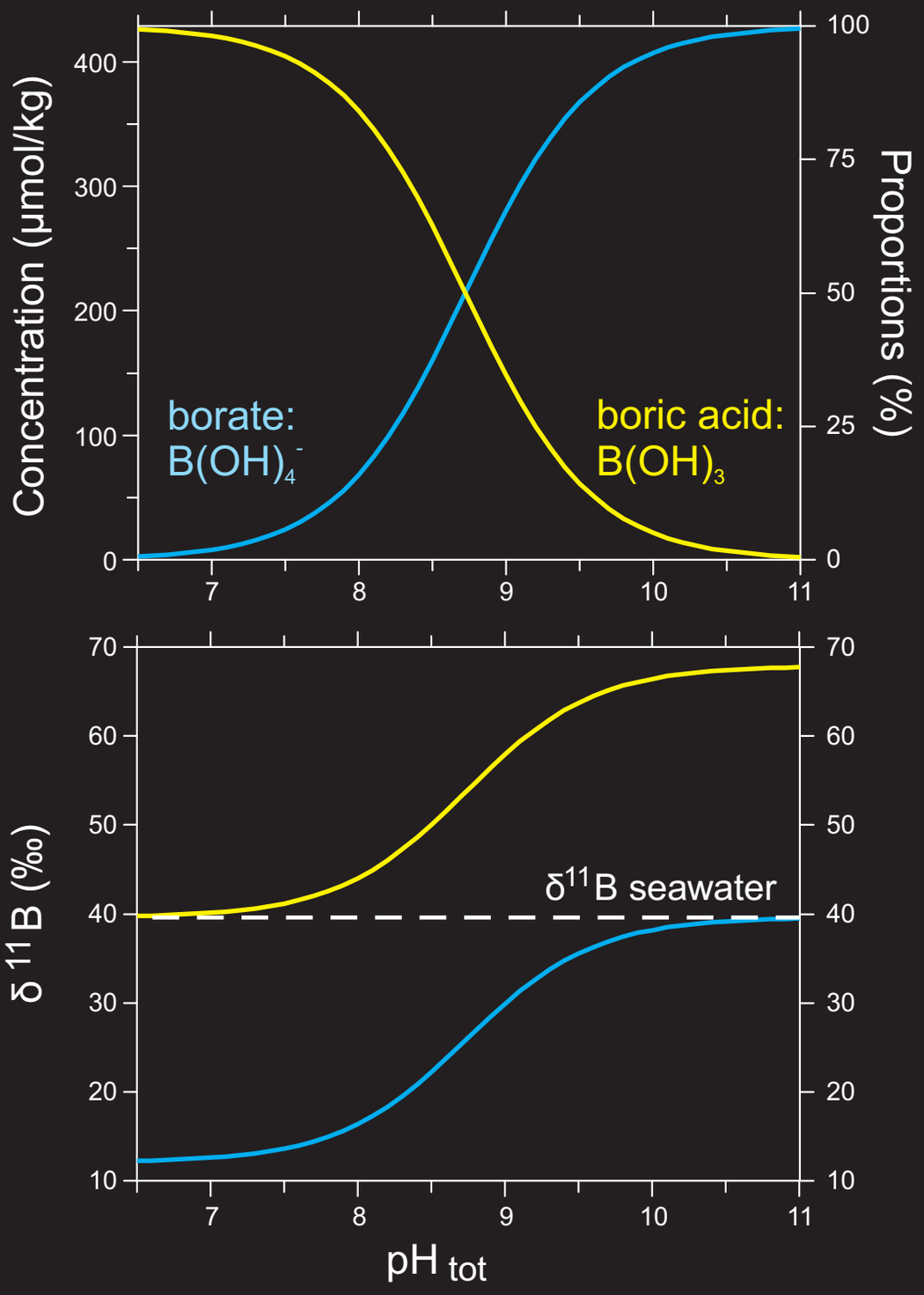
Methods


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

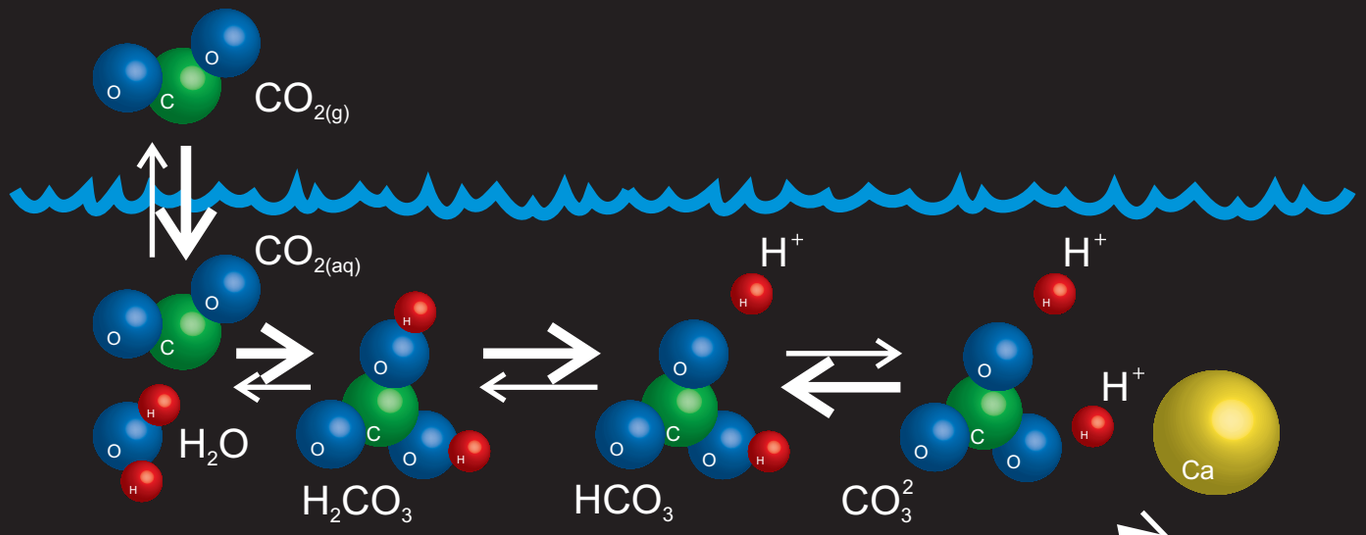
Boron, isotopes, and paleo pH

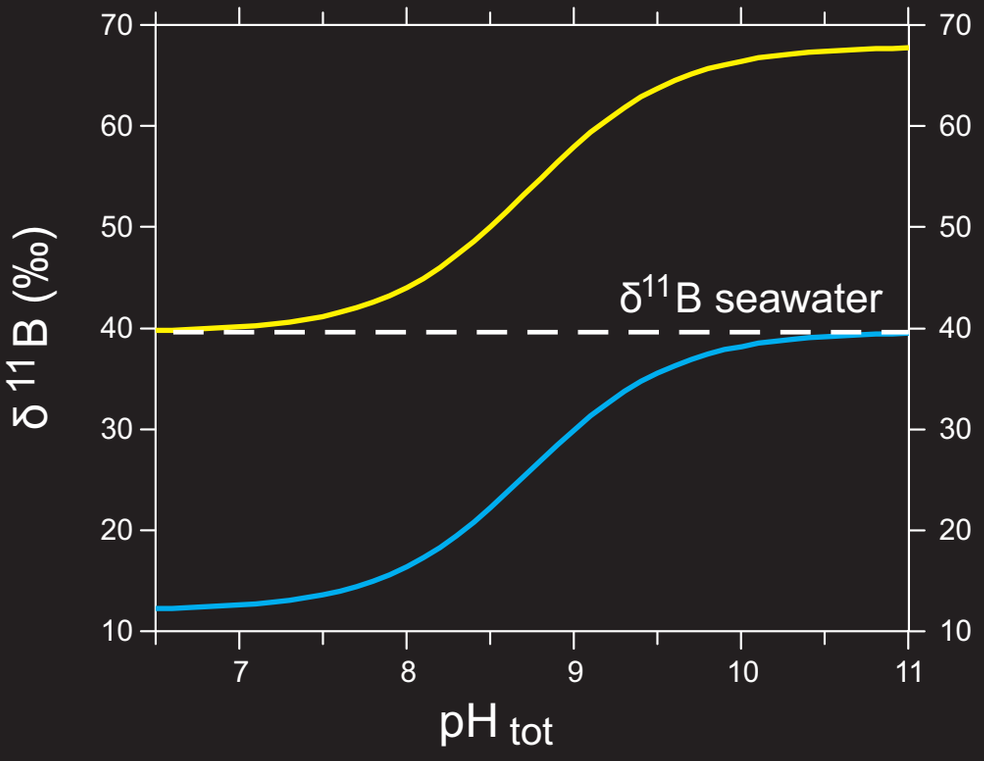


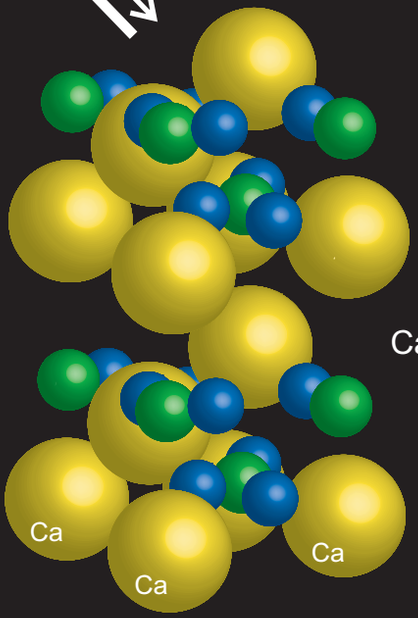
Boron, isotopes, and paleo pH



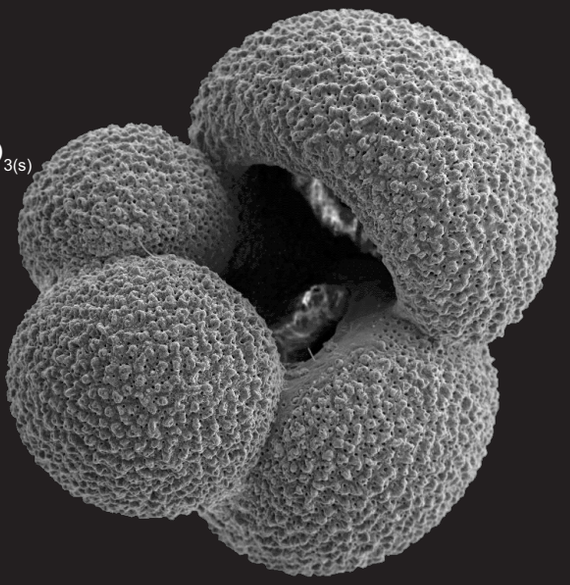
Boron, isotopes, and paleo pH



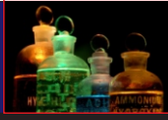


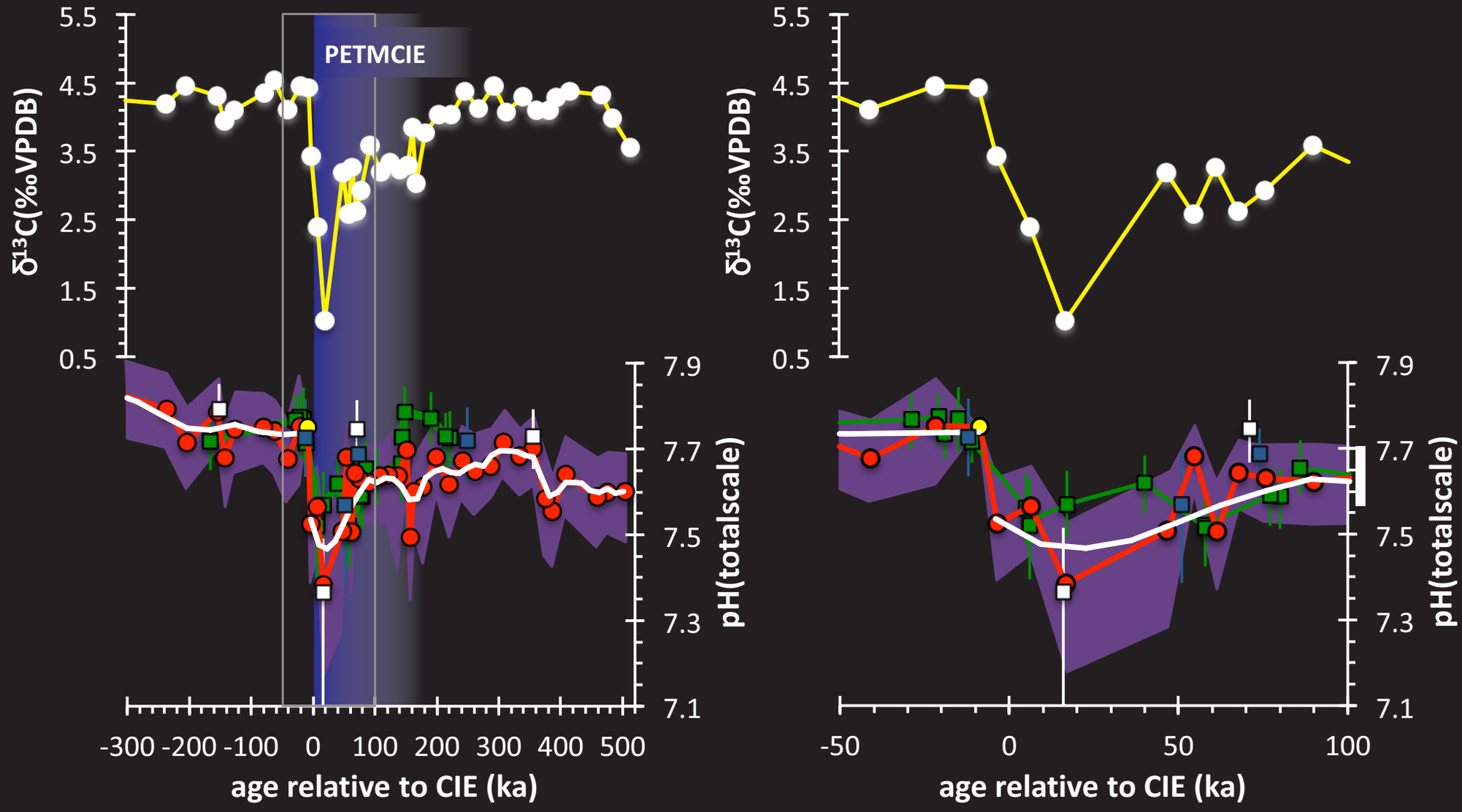


$CaCO_{3(s)}$



Boron, isotopes, and paleo pH

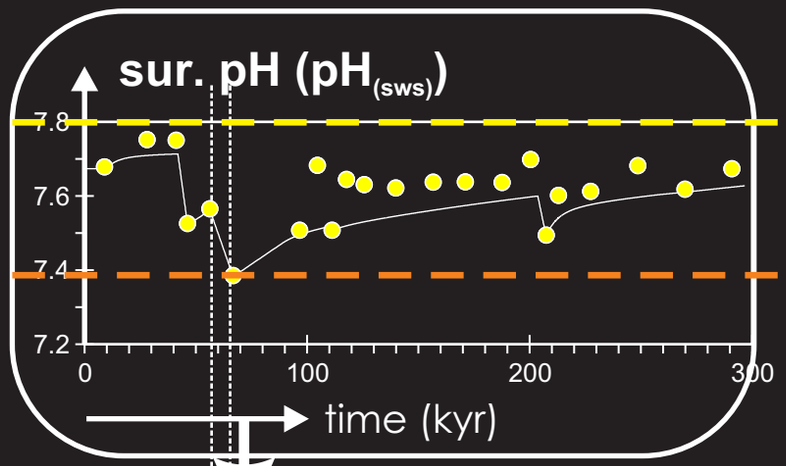




Site 401 (NE Atlantic) [unpublihed]

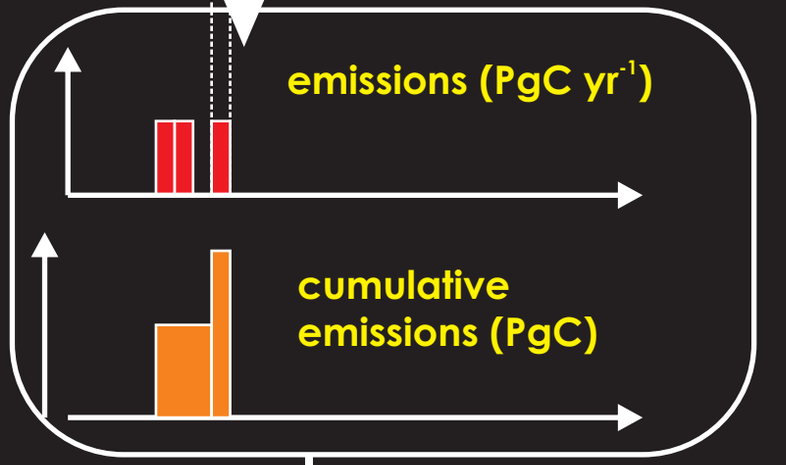
Site 865 (Eq. Pacific) Site 1263 (ES Atlantic) Site 1209 (N Pacific) [*Penman et al.*, 2014]

Assimilating surface ocean pH change (only)

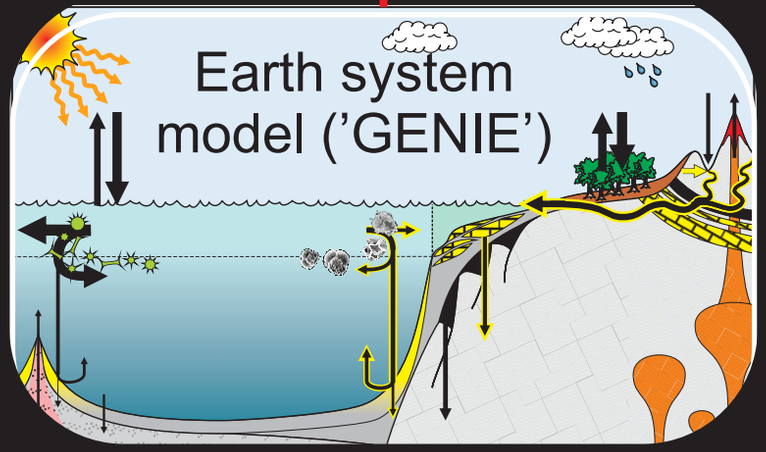


year 2100 seawater pH

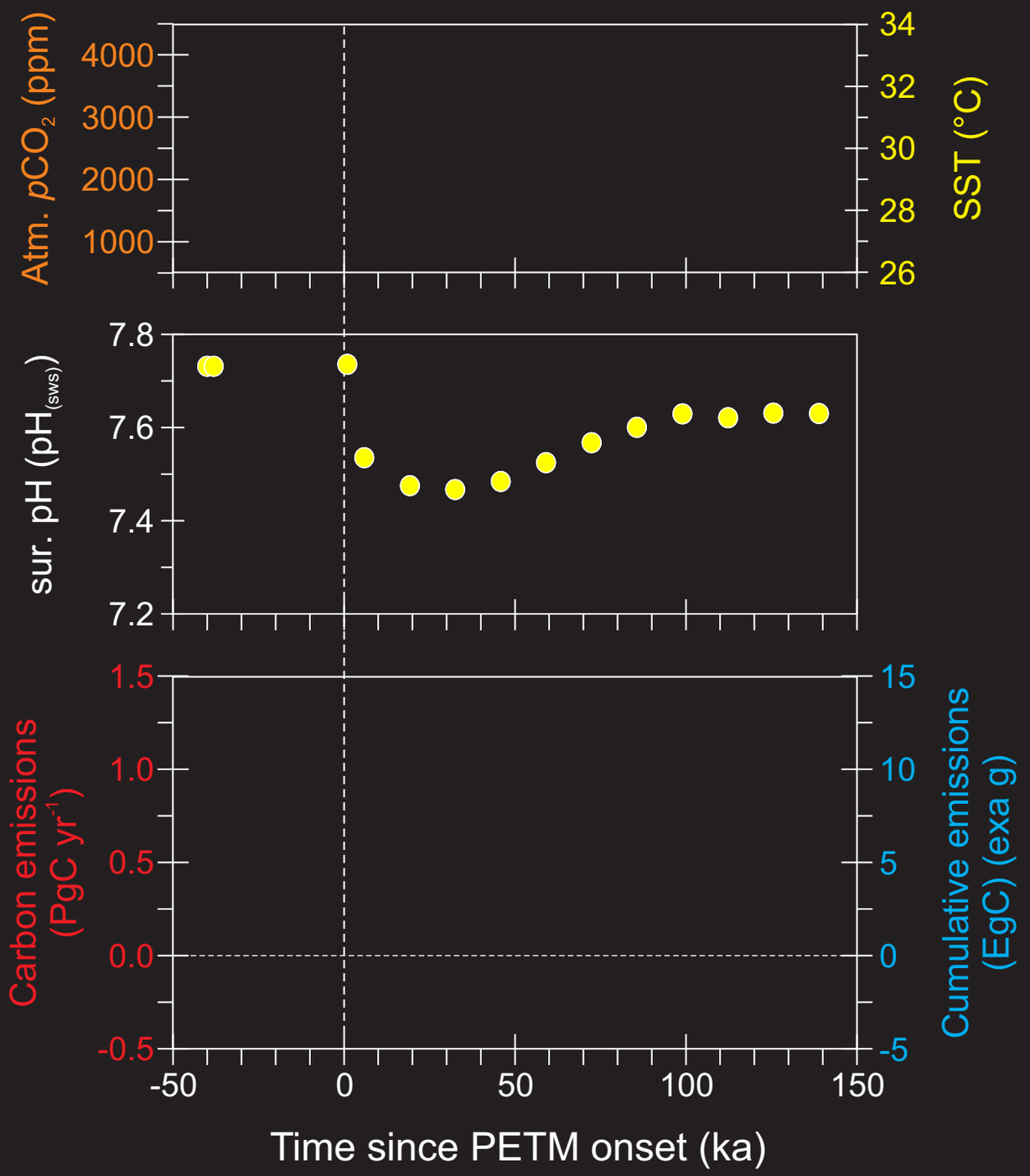
peak PETM



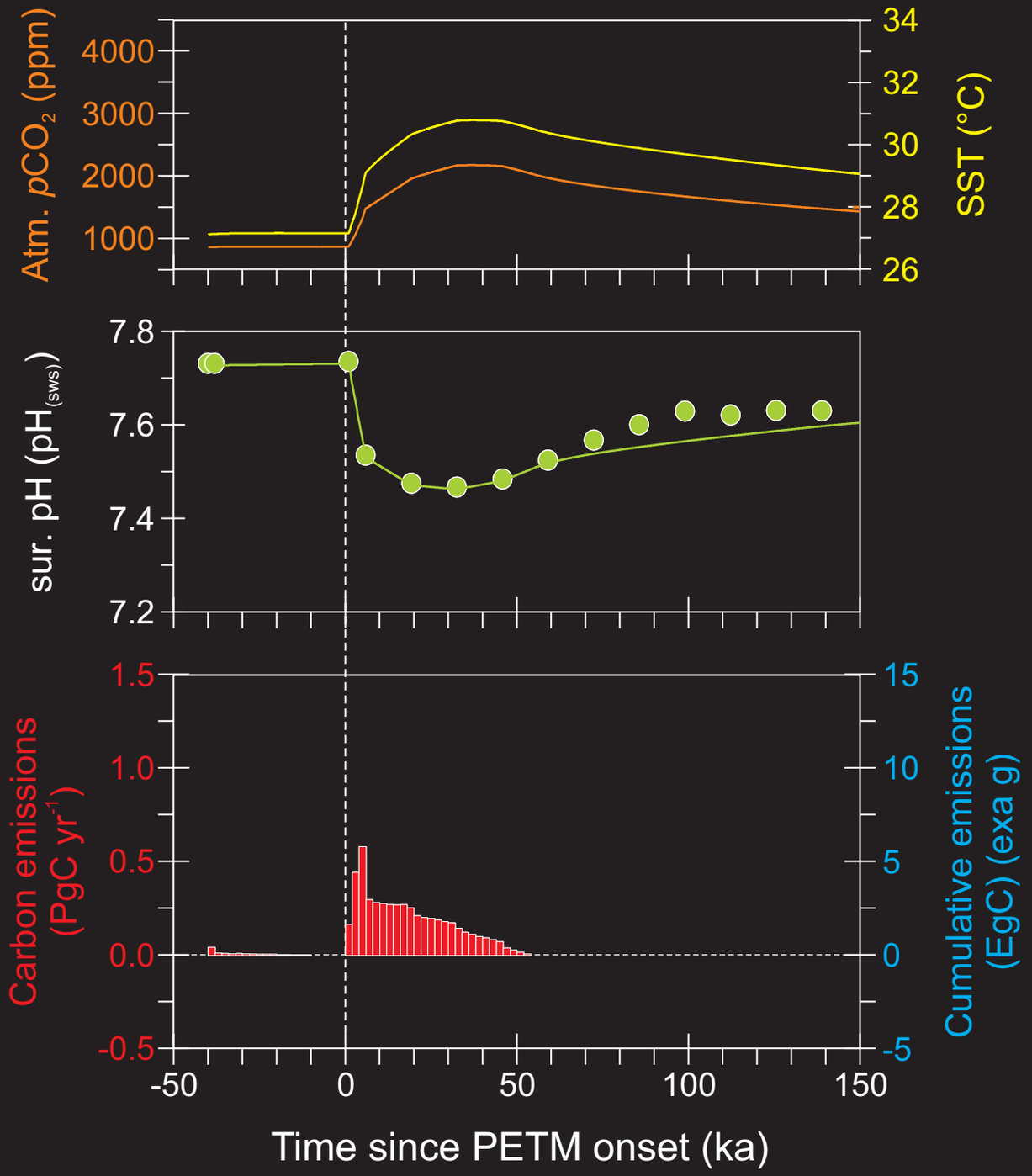
Earth system model including explicit silicate weathering feedback



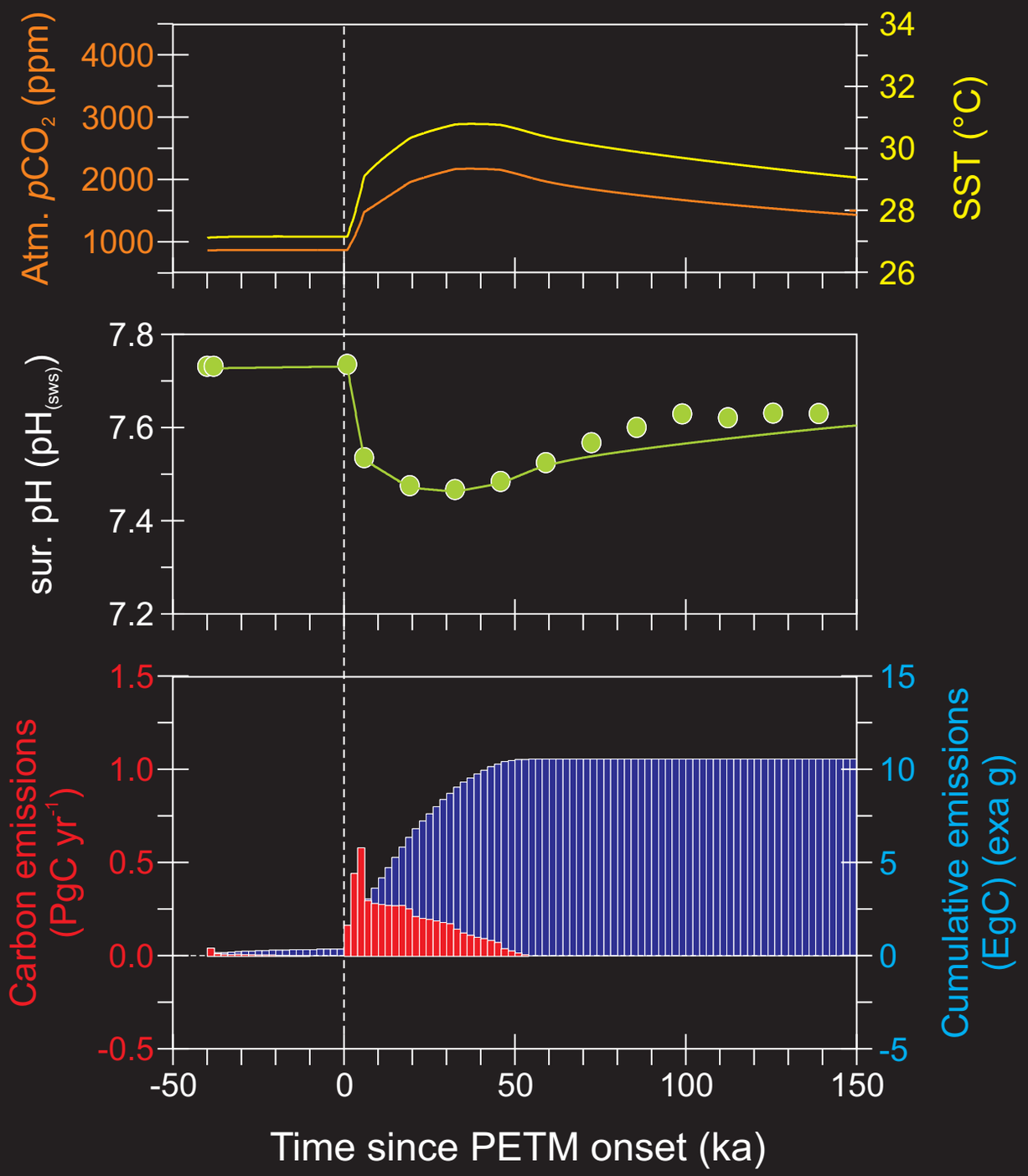
Assimilating surface ocean pH change (only)



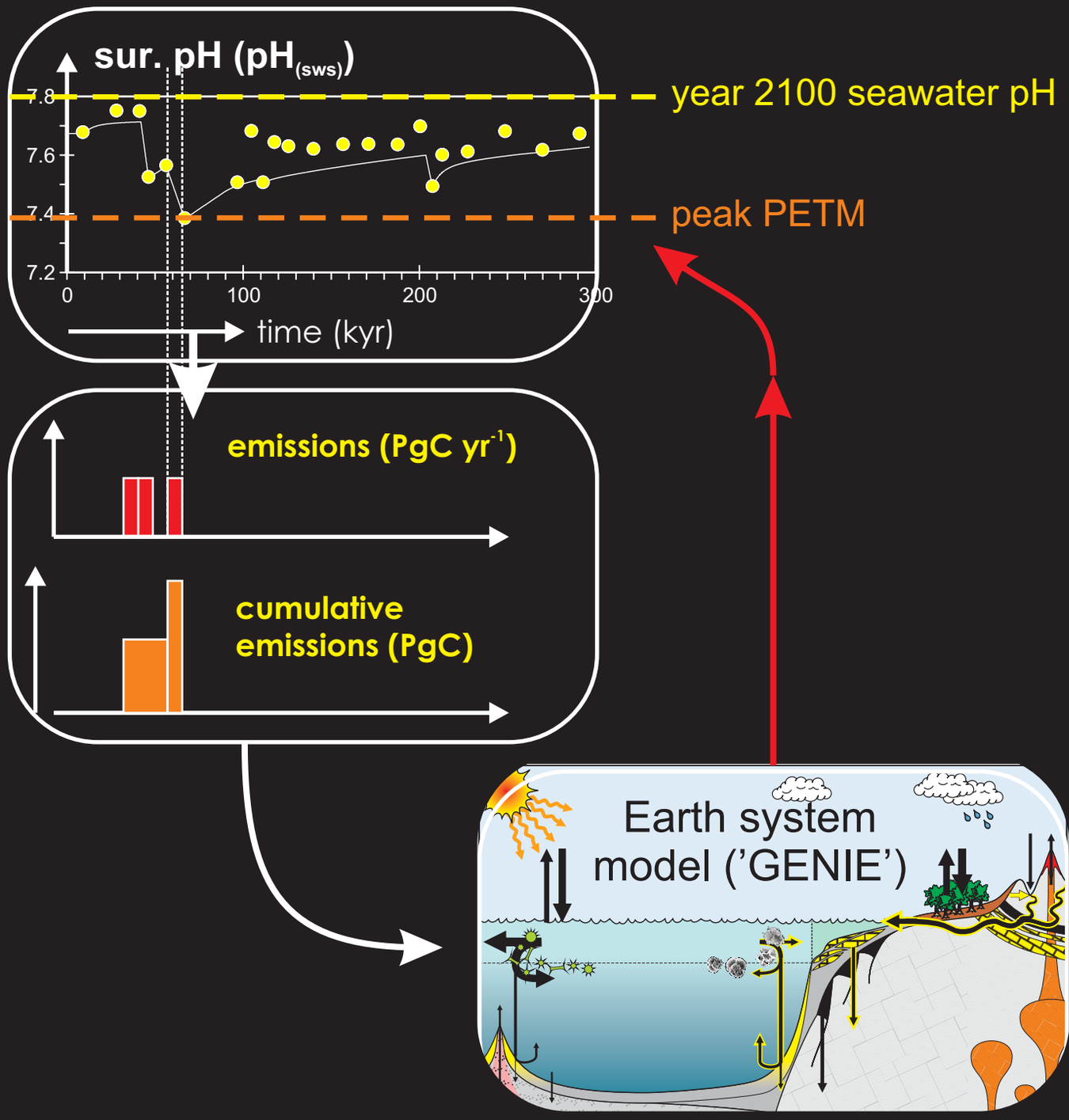
Assimilating surface ocean pH change (only)



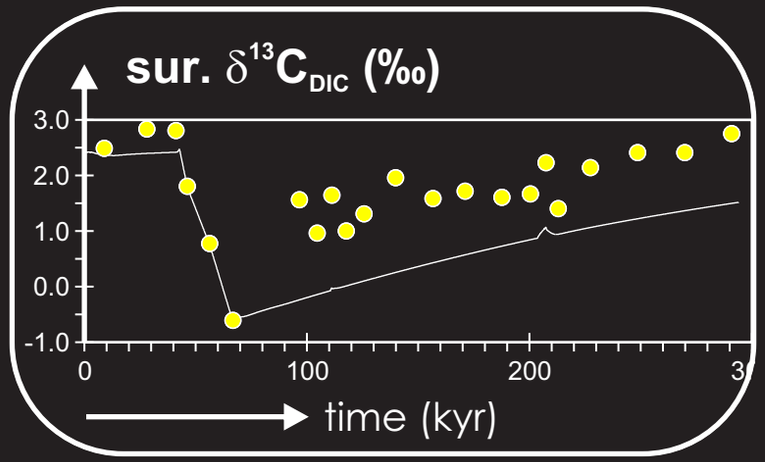
Assimilating surface ocean pH change (only)



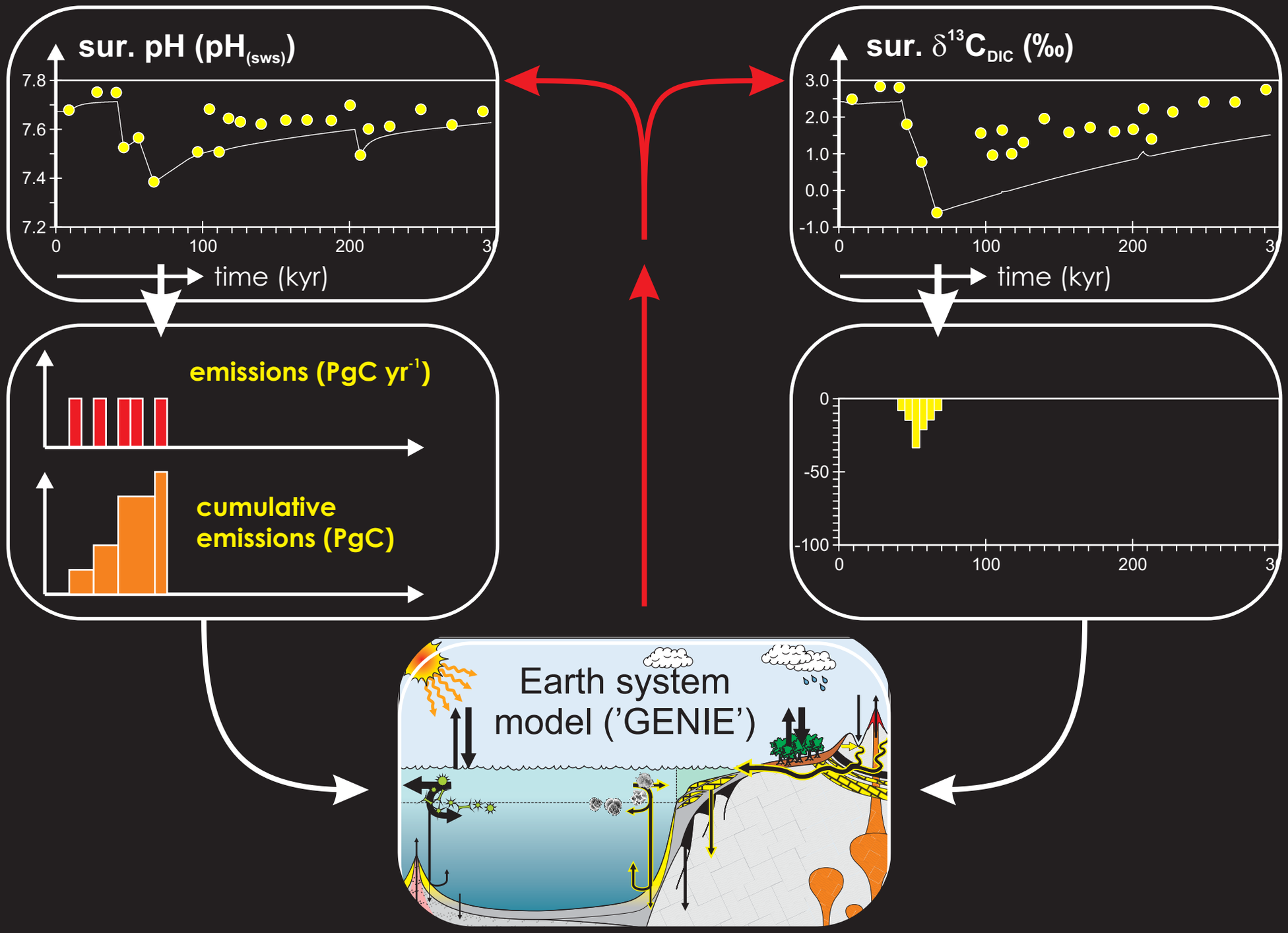
Assimilating surface ocean pH change (only)



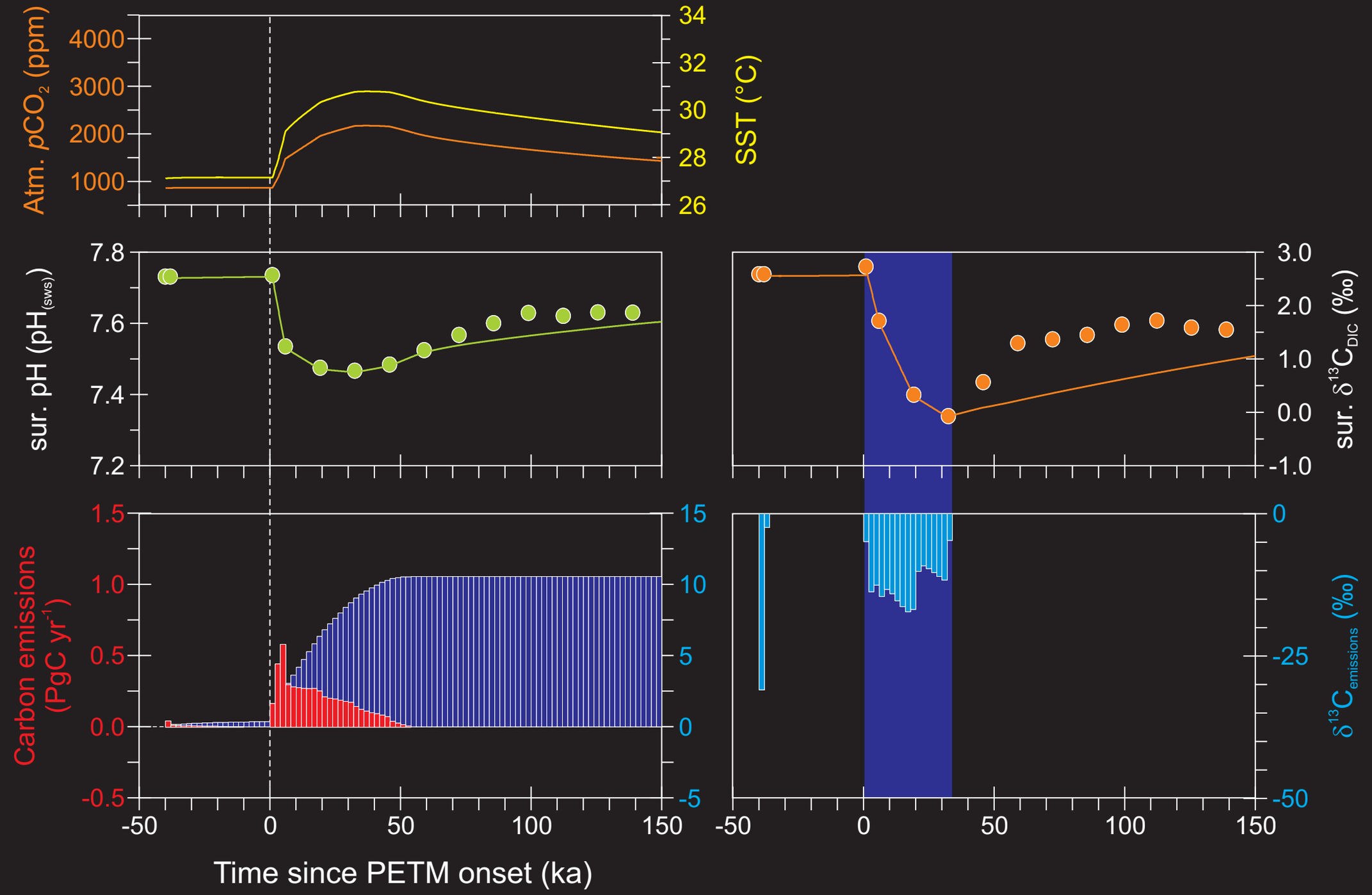
Assimilating surface ocean pH and $\delta^{13}C$



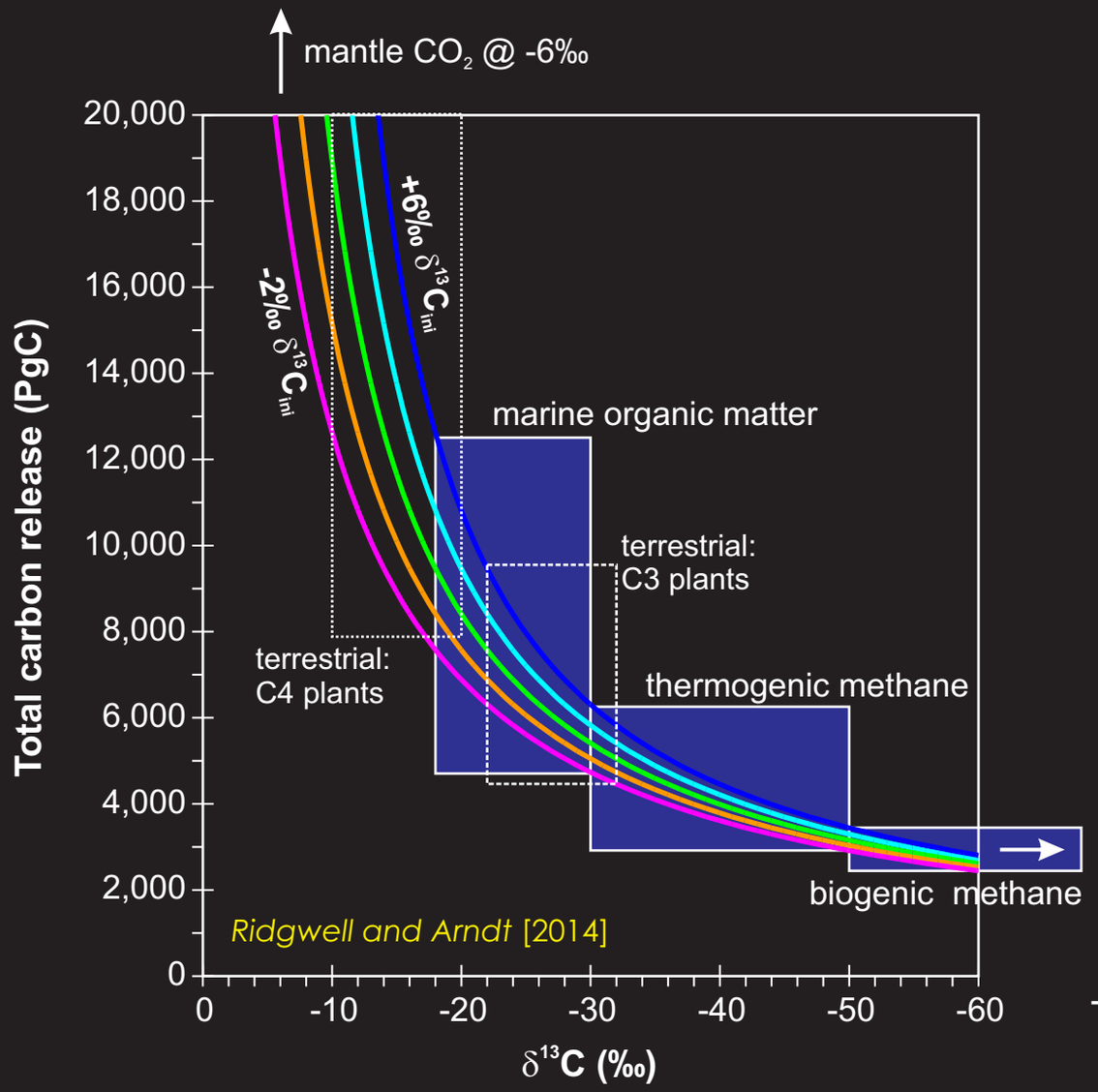
Assimilating surface ocean pH and $\delta^{13}C$

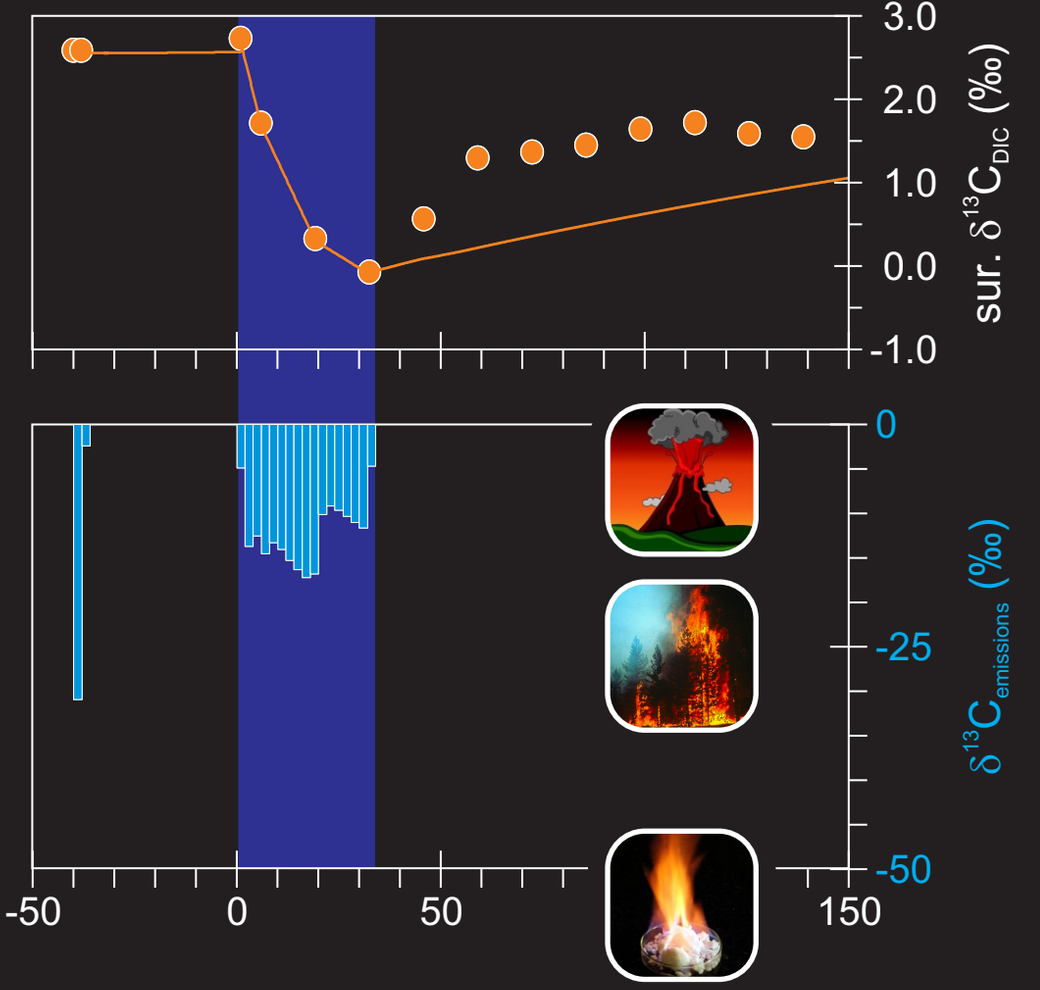


Assimilating surface ocean pH and $\delta^{13}C$



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

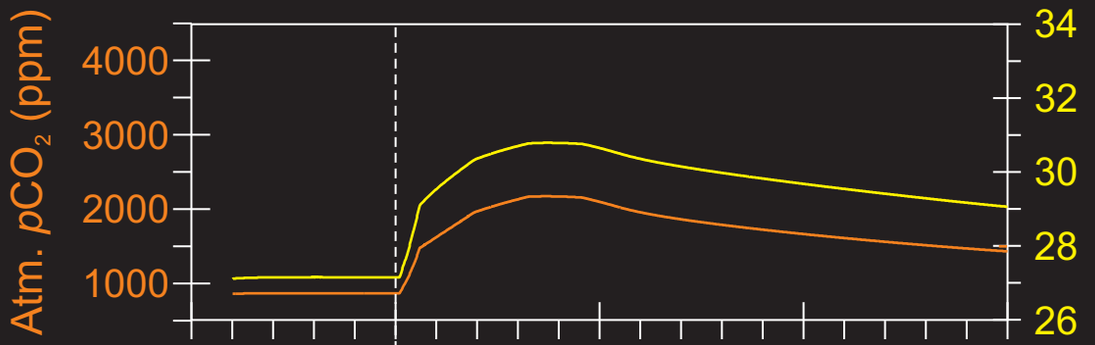


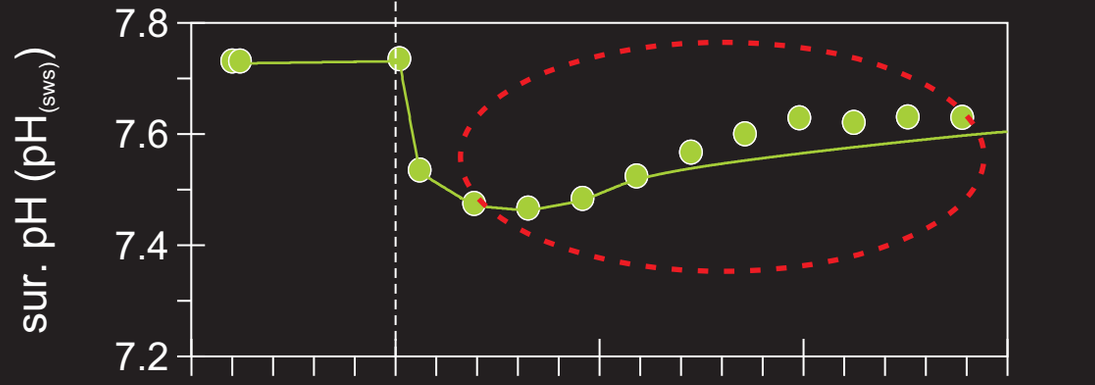


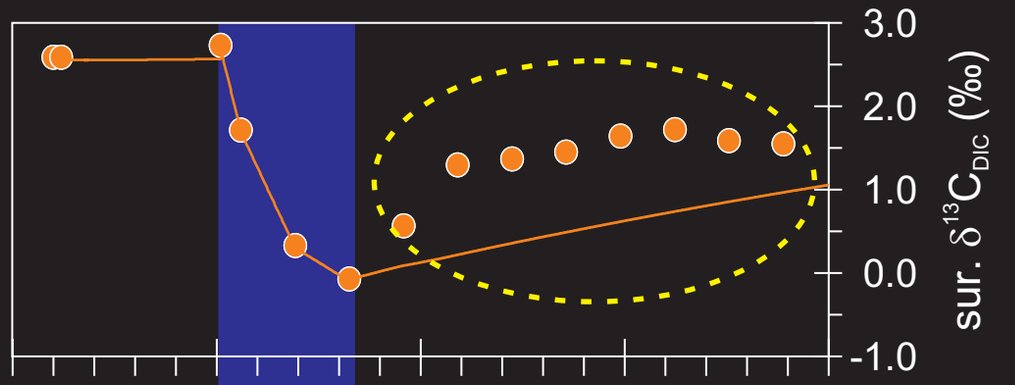
Assimilating surface ocean pH and $\delta^{13}C$

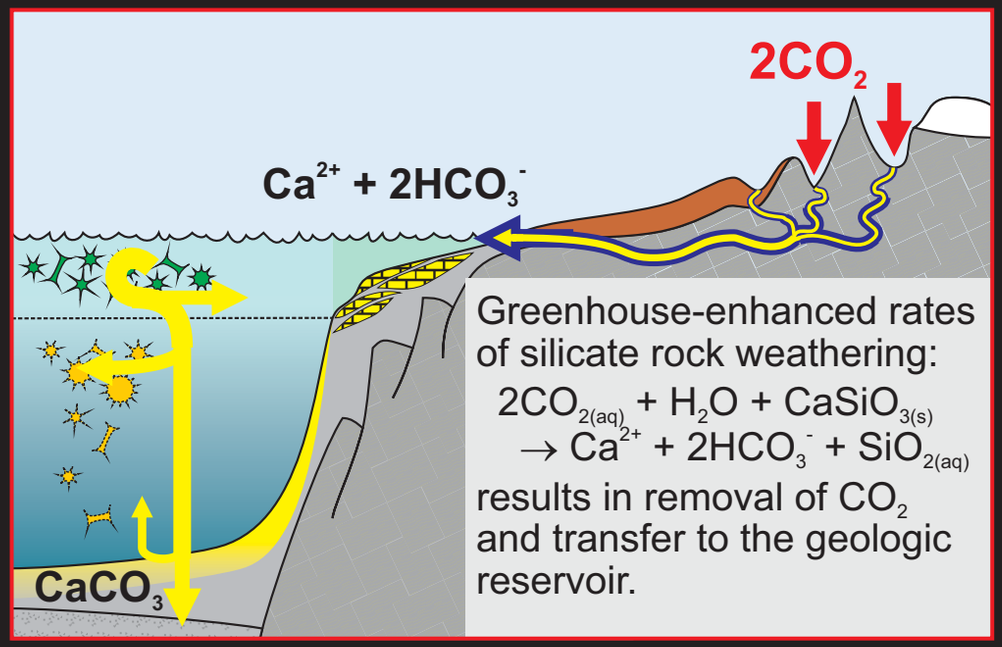
Credit: Michael Storey

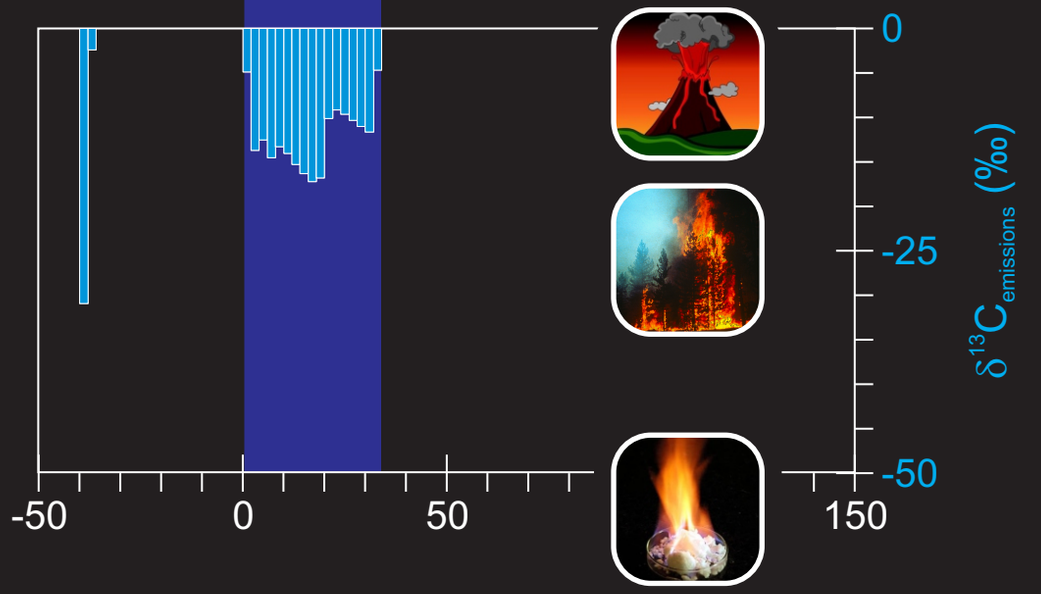
Assimilating surface ocean pH and $\delta^{13}C$



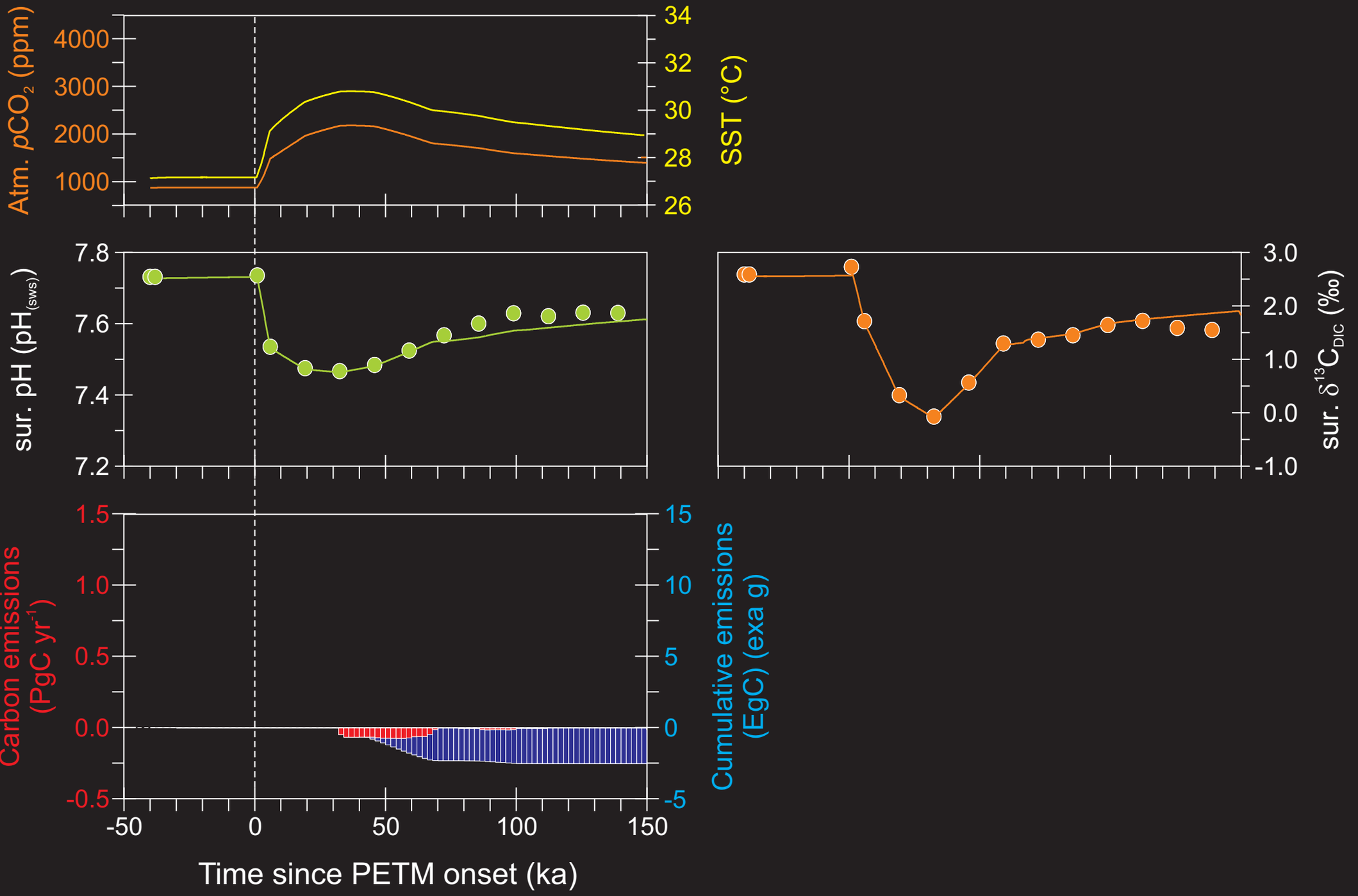




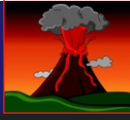




Assimilating surface ocean pH and $\delta^{13}C$



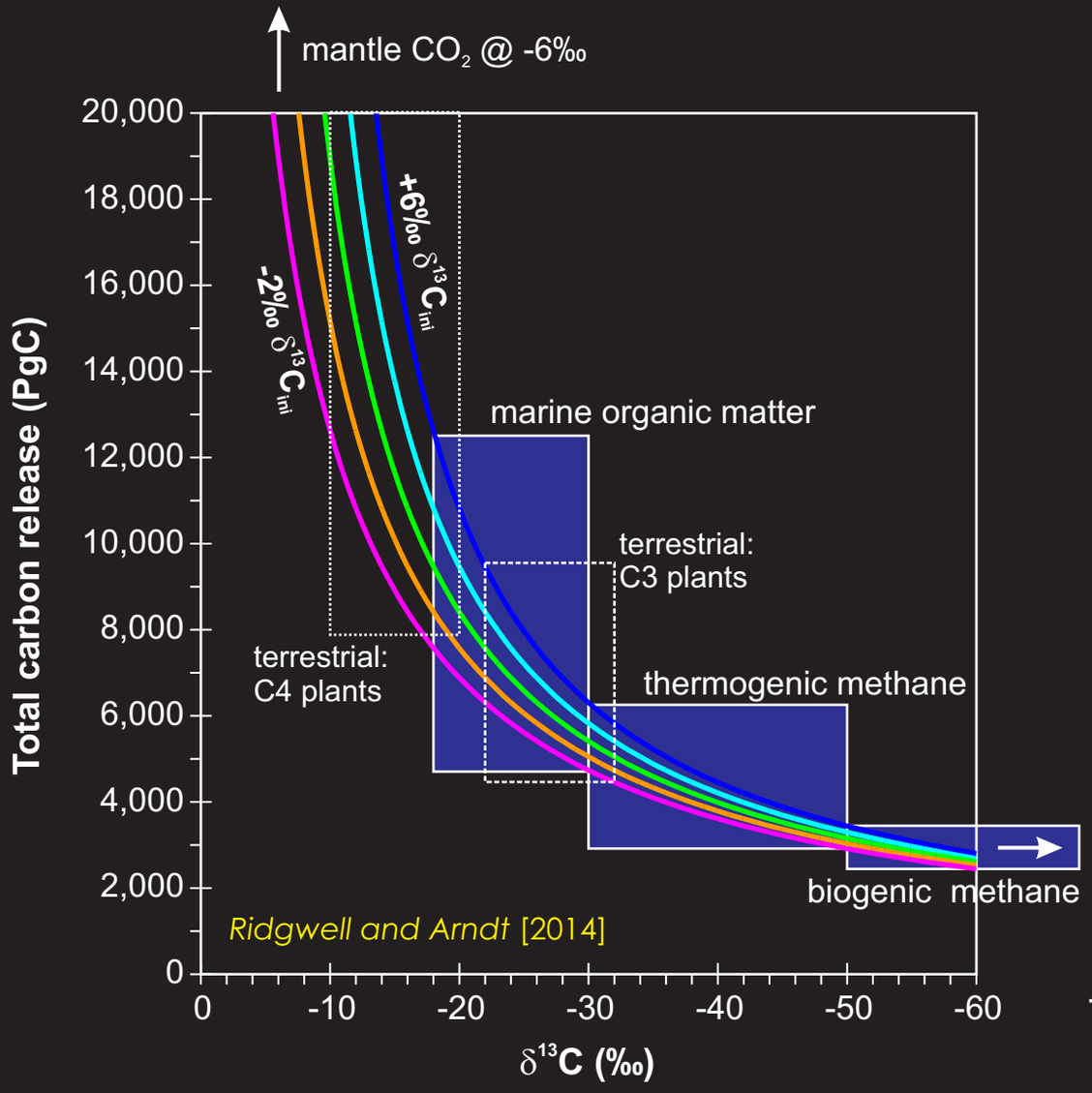
Assimilating surface ocean pH and $\delta^{13}C$

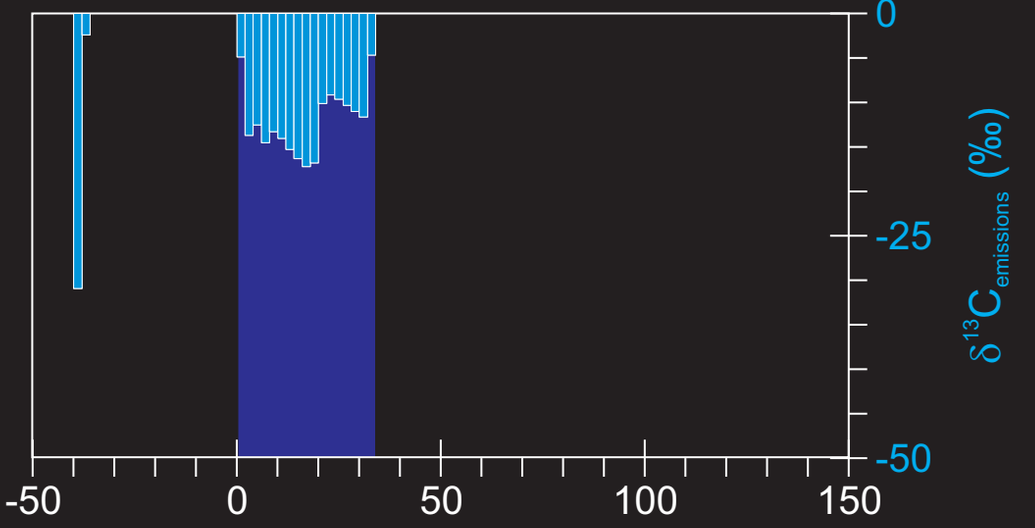


+

OR

+





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?

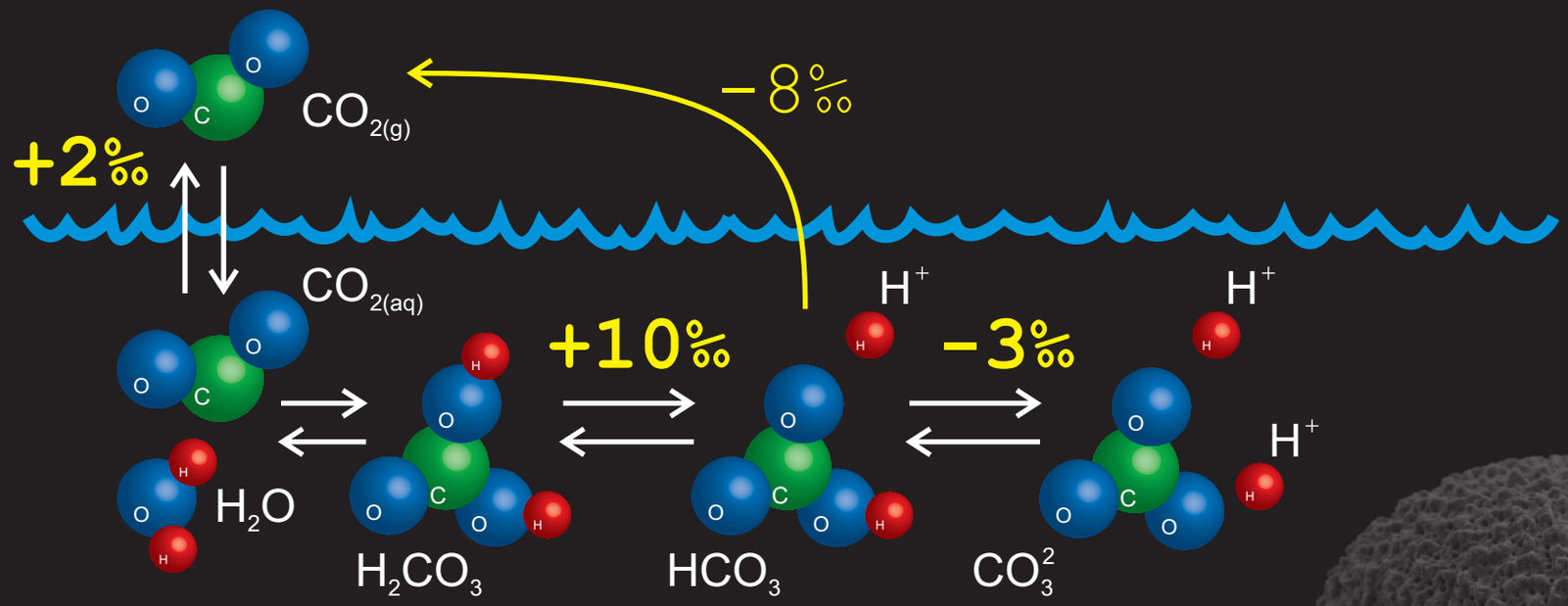
Re-partitioning of carbon ***between*** surficial reservoirs (cf. LGM)?

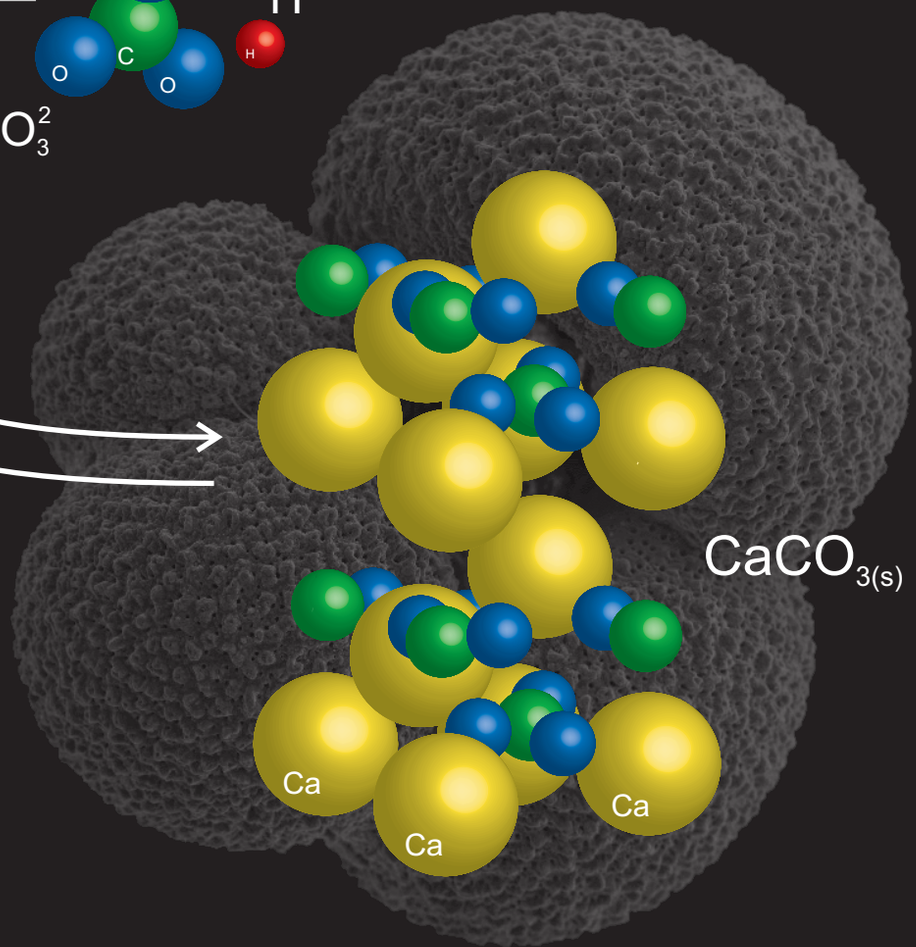
Injection (or removal) of isotopically light carbon?

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]

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

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

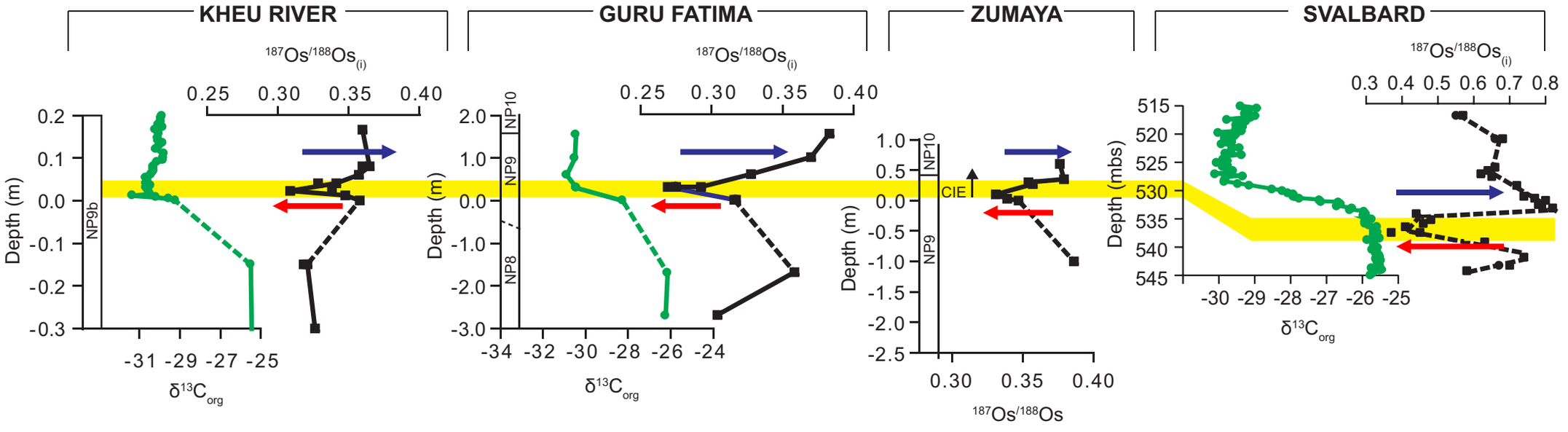
seawater:
$^{187/188}$Os~0.35

burial with
organic matter

un-radiogenic Os

un-radiogenic Os

Osmium isotope records



time

radiogenic Os

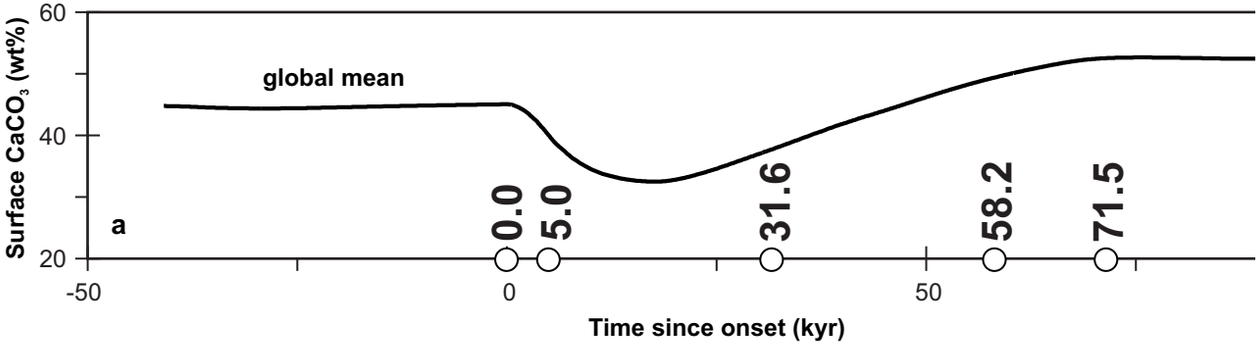
un-radiogenic Os

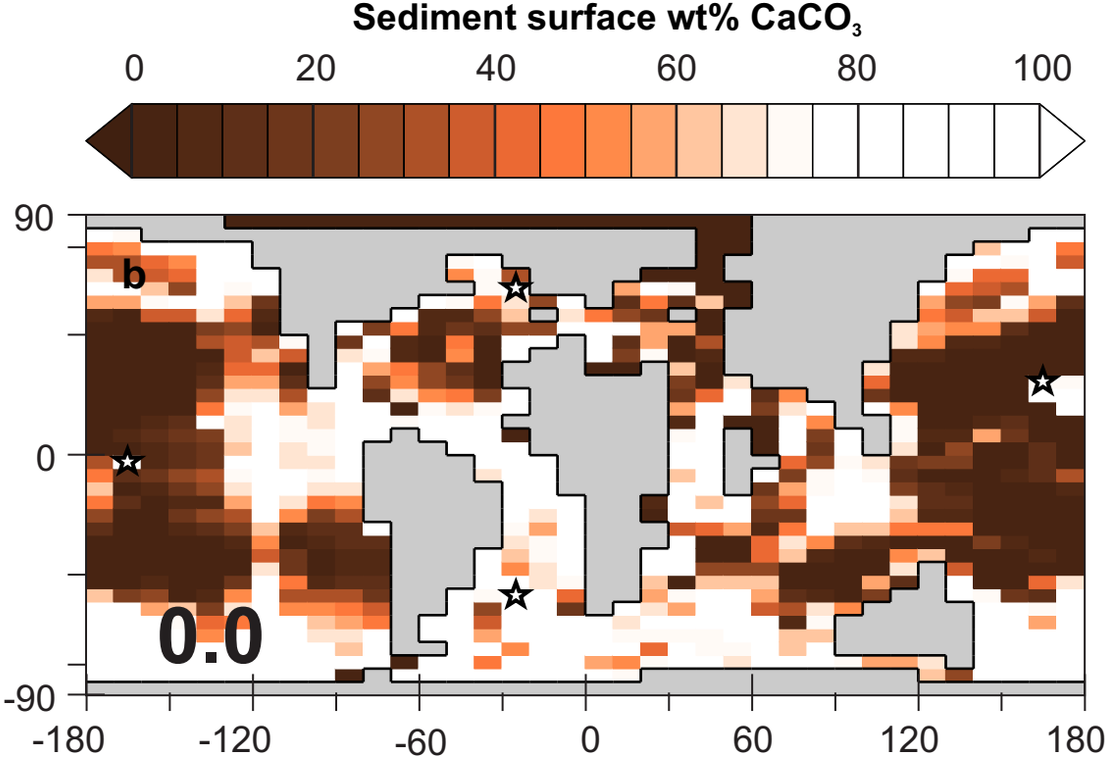
PETM recovery characterized by long-lasting shift to radiogenic Os. Consistent with enhanced granitic weathering (silicate weathering feedback).
(Also, expulsion of fluids form organic rich sediments.)

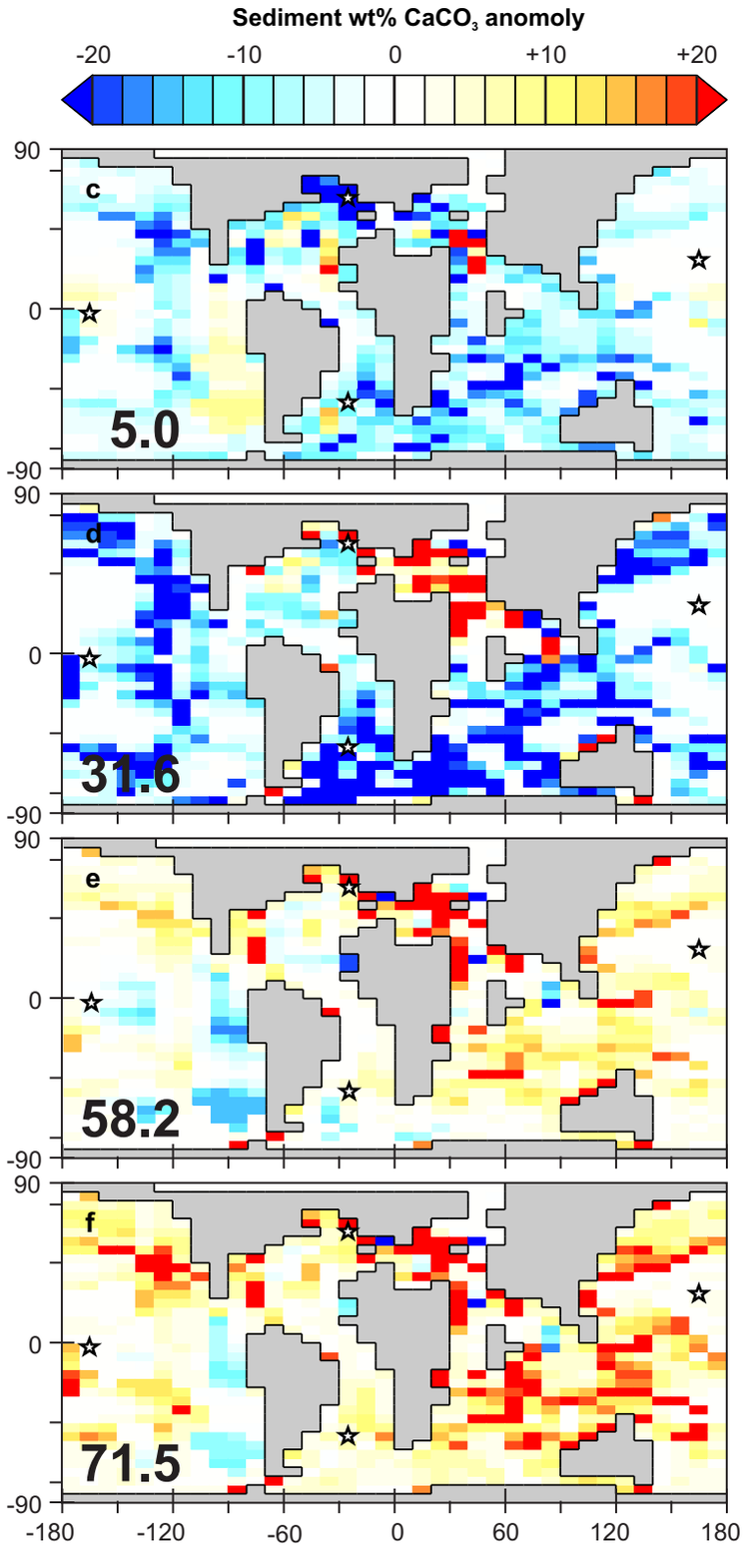
Strong transient decline in $^{187/188}Os$.
Enhanced unradiogenic input from volcanism.
(Also, extraterrestrial ...)

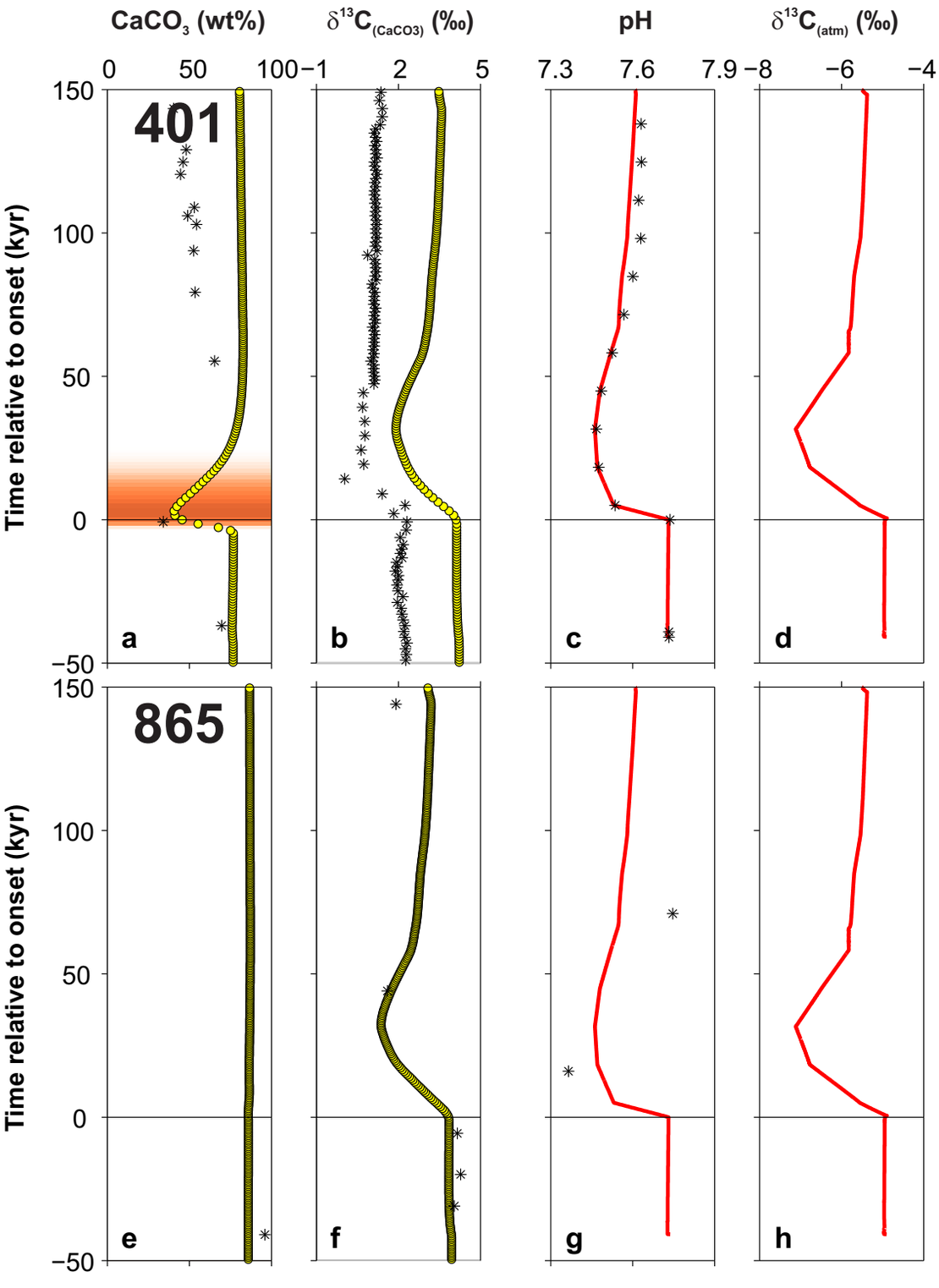
Dickson et al. [2015] (*Palaeogeography, Palaeoclimatology, Palaeoecology* **438**)
(also see: *Wieczorek et al.* [2013] (*GCA* **119**))

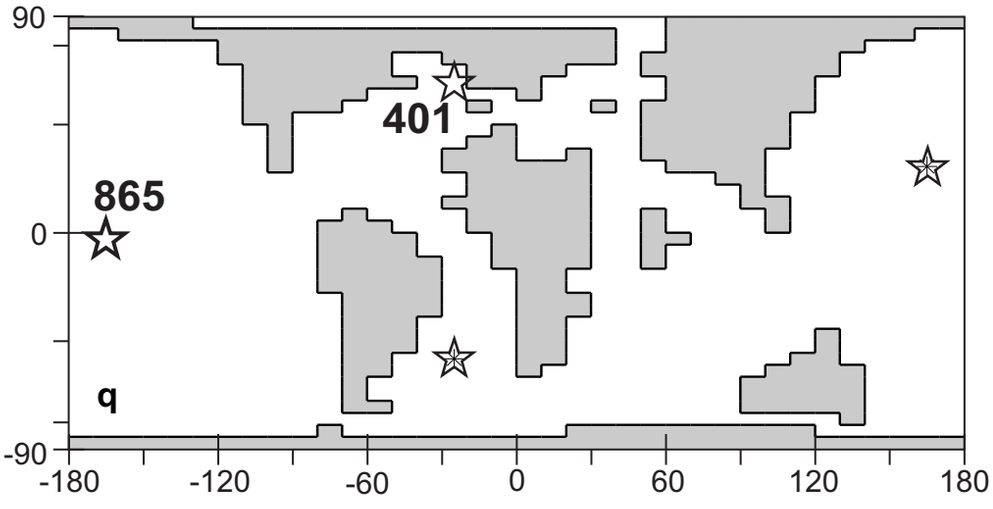
Deep-sea (modelled) carbonate response

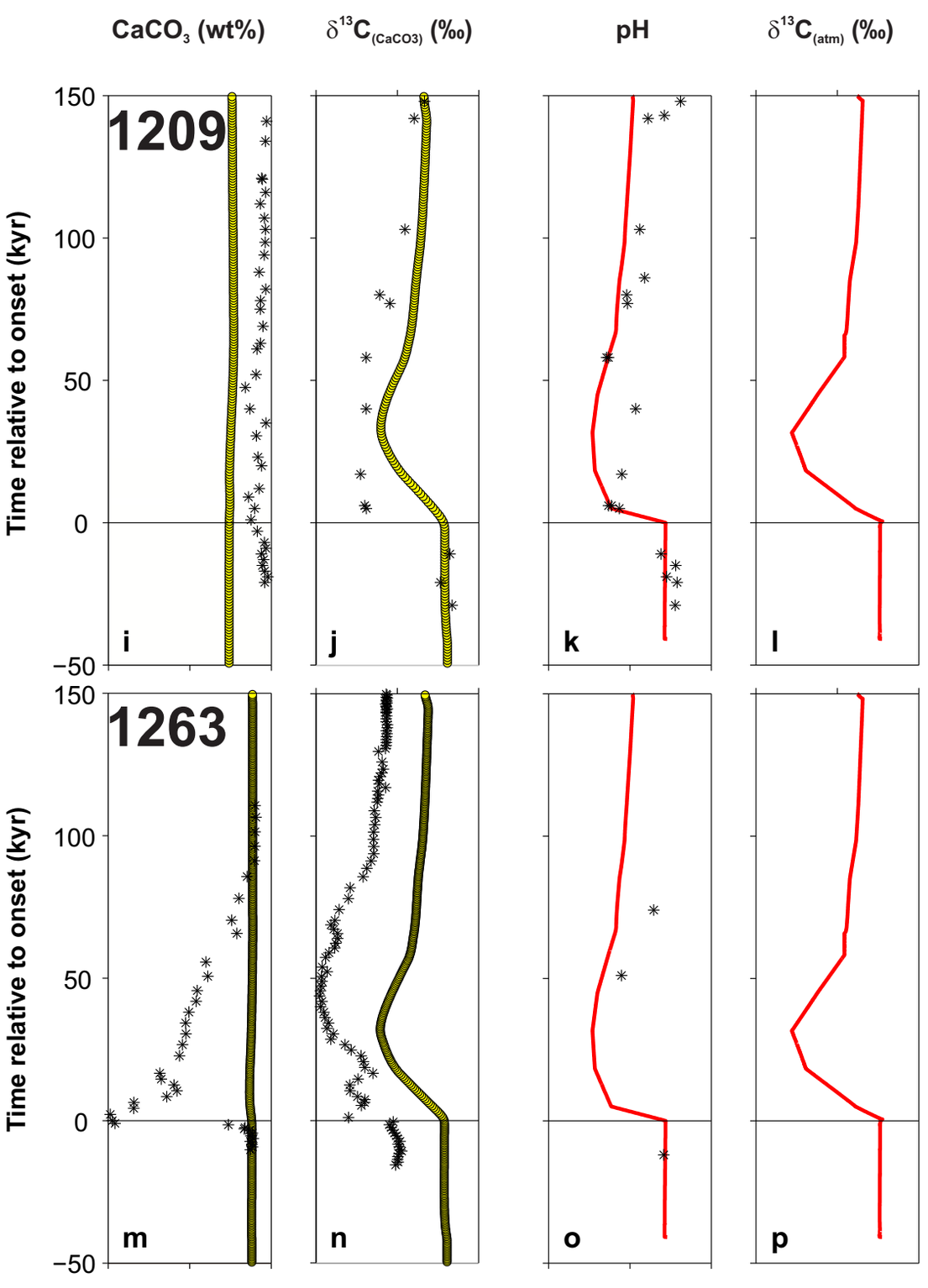


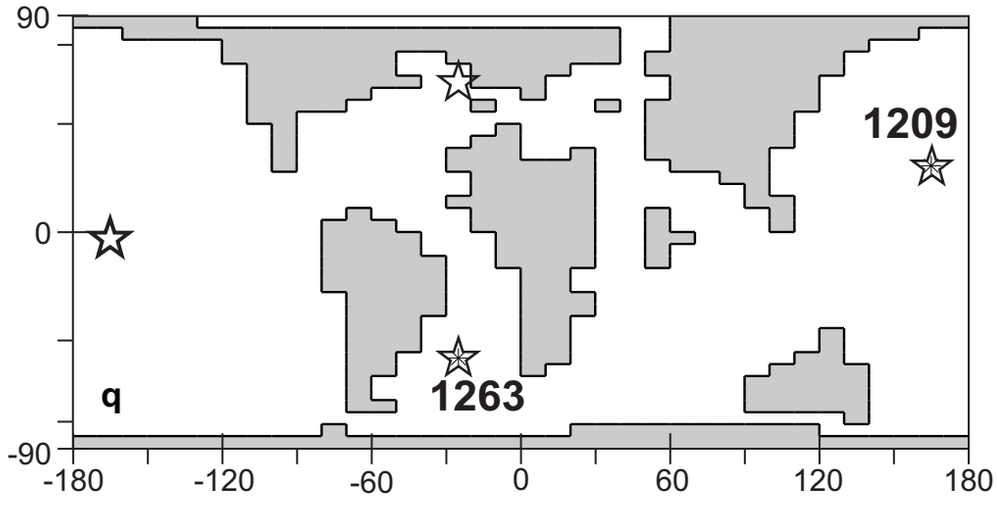





CaCO3 (wt%)
δ13C(CaCO3) (‰)
pH
δ13C(atm) (‰)
0
50
100
−1
2
5
7.3
7.6
7.9
−8
−6
−4
150
100
50
0
−50
Time relative to onset (kyr)
401
865
a
b
c
d
e
f
g
h

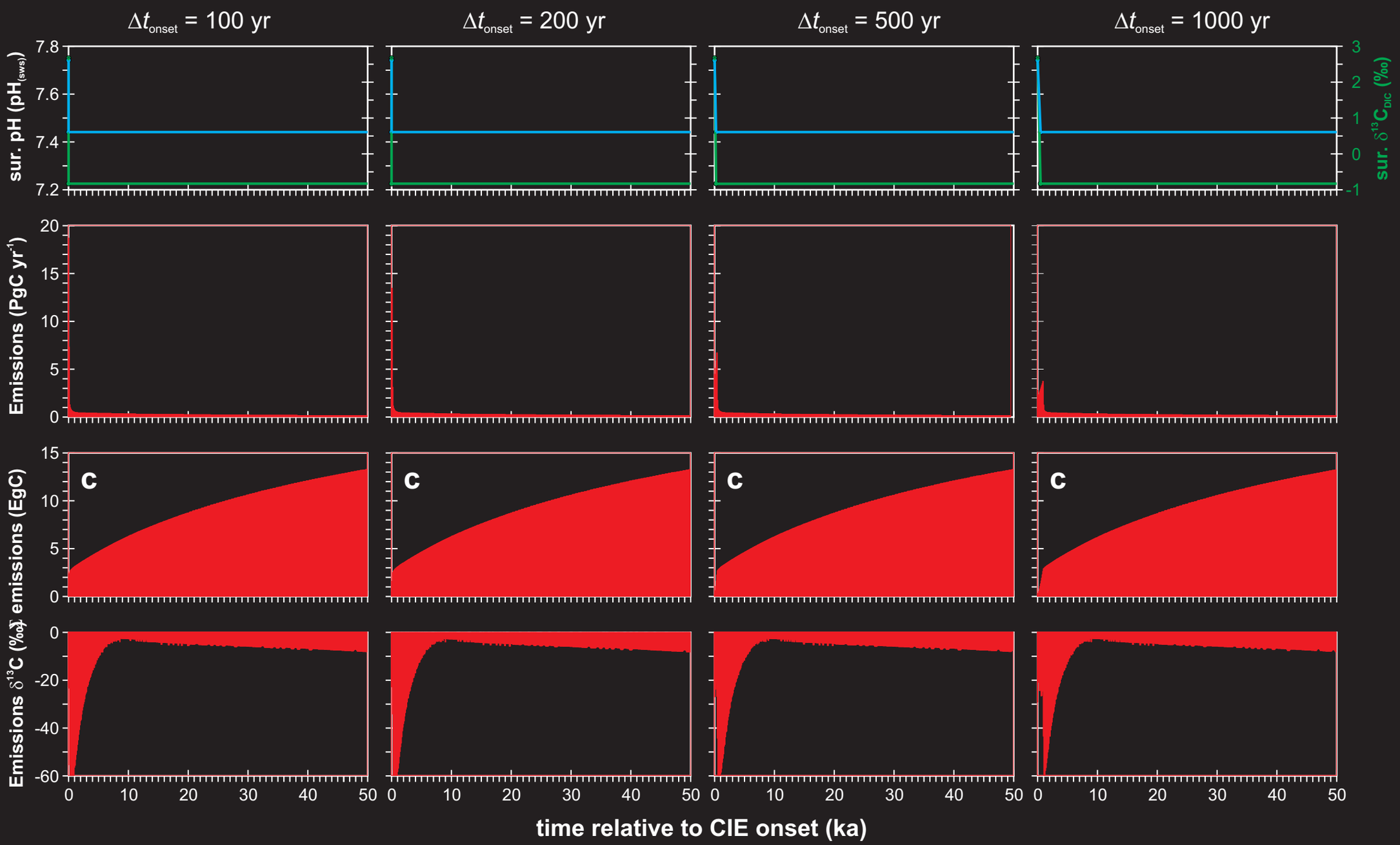

90
0
-90
-180
-120
-60
0
60
120
180
401
865
q


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