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Silicate weathering vs. organic carbon burial: Who wins?

Andy Ridgwell

University of California – Riverside
University of Bristol

+ Dominik Hülse (UC Riverside)
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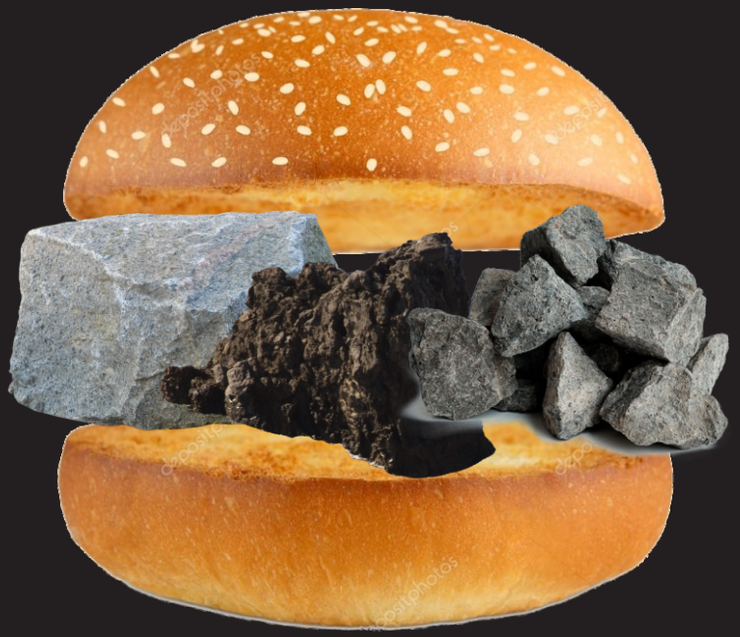
+ embarrassed co-authors

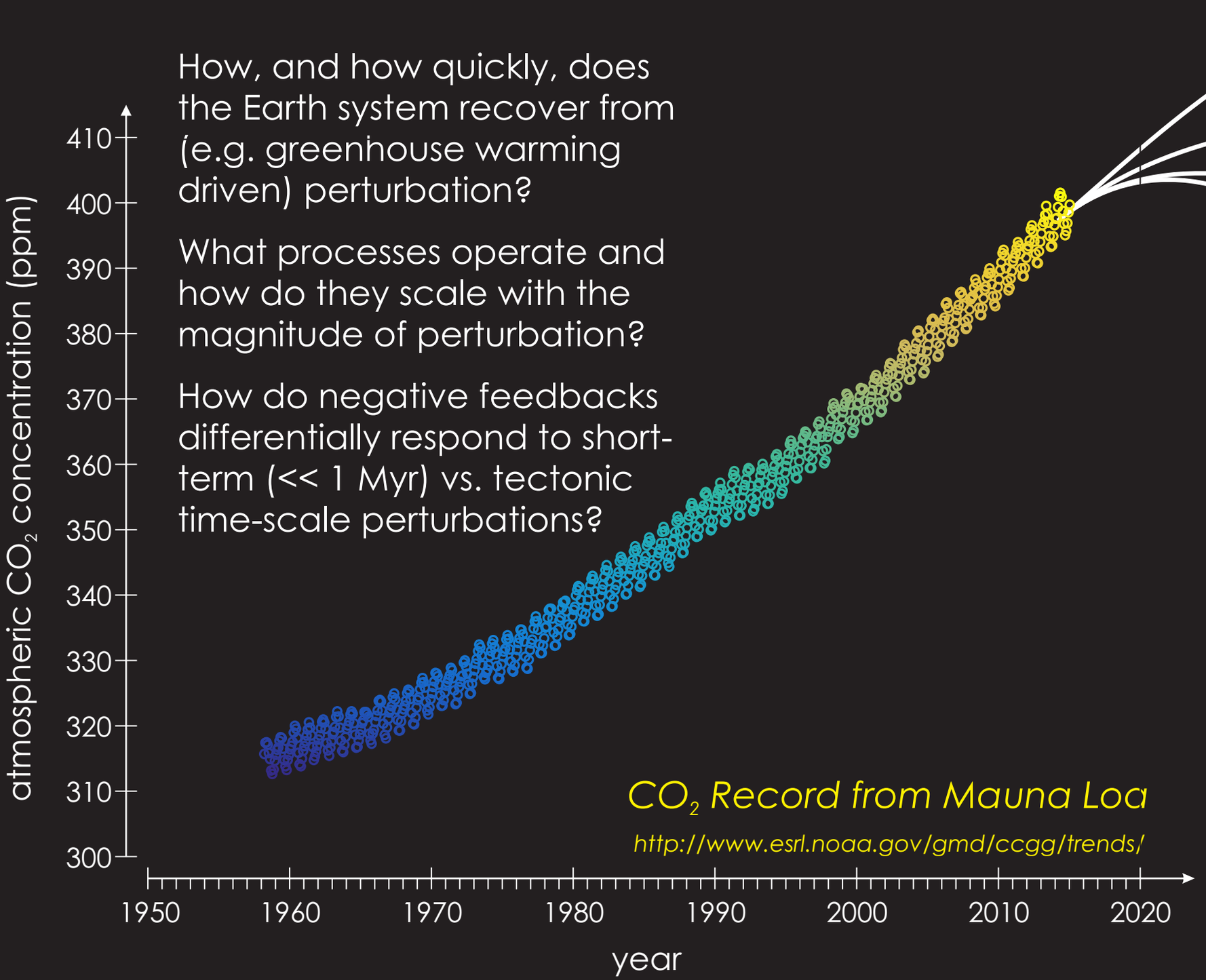


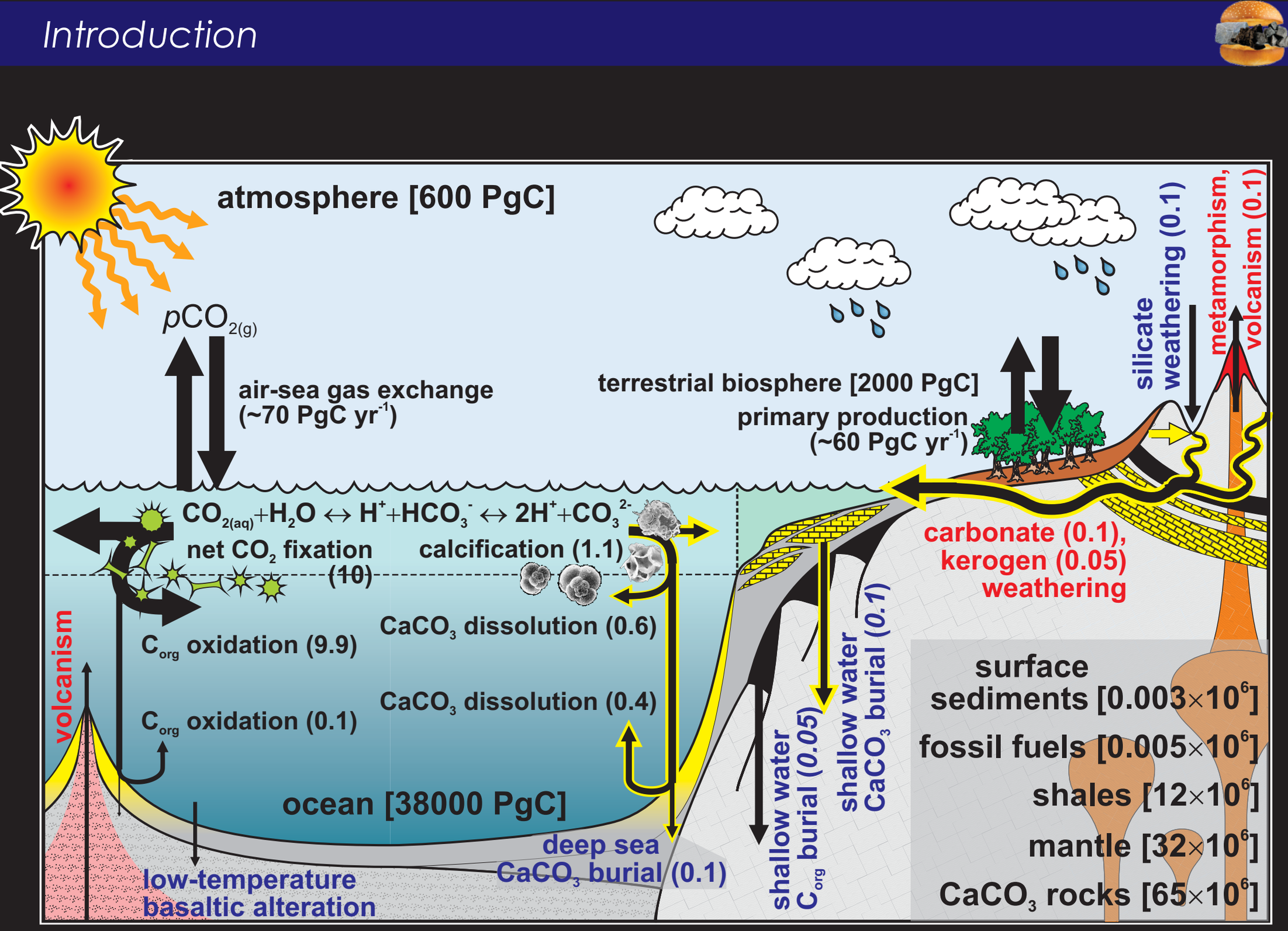
Introduction

How, and how quickly, does the Earth system recover from (e.g. greenhouse warming driven) perturbation?

What processes operate and how do they scale with the magnitude of perturbation?

How do negative feedbacks differentially respond to short-term (<< 1 Myr) vs. tectonic time-scale perturbations?




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)
$CO_{2(aq)}+H_2O \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-}$
net CO_2 fixation (10)
calcification (1.1)
carbonate (0.1), kerogen (0.05) weathering
$CaCO_3$ 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)
surface sediments [0.003×10^6]
fossil fuels [0.005×10^6]
shales [12×10^6]
mantle [32×10^6]
$CaCO_3$ rocks [65×10^6]

Introduction

Terrestrial weathering can be (approximately equally) divided into carbonate ($CaCO_3$) and calcium-silicate ('$CaSiO_3$') weathering:

(1) $2CO_{2(aq)} + H_2O + CaSiO_3 \rightarrow Ca^{2+} + 2HCO_3^- + SiO_2$

(2) $CO_{2(aq)} + H_2O + CaCO_3 \rightarrow Ca^{2+} + 2HCO_3^-$

Ultimately, the (alkalinity: Ca^{2+}) weathering products must be removed through carbonate precipitation and burial in marine sediments:

(3) $Ca^{2+} + 2HCO_3^- \rightarrow CO_{2(aq)} + H_2O + CaCO_3$

It can be seen that in (2) + (3), that the CO_2 removed (from the atmosphere) during weathering, is returned upon carbonate precipitation (and burial). In (1) + (3) (silicate weathering) CO_2 is permanently removed to the geological reservoir. This CO_2 must be balanced by mantle (/volcanic) out-gassing on the very long term.

Introduction

Furthermore, the rate of rock mineral dissolution should scale with climate. Hence the **silicate weathering feedback** is formed:

higher pCO_2

→

higher temperatures (& rainfall)

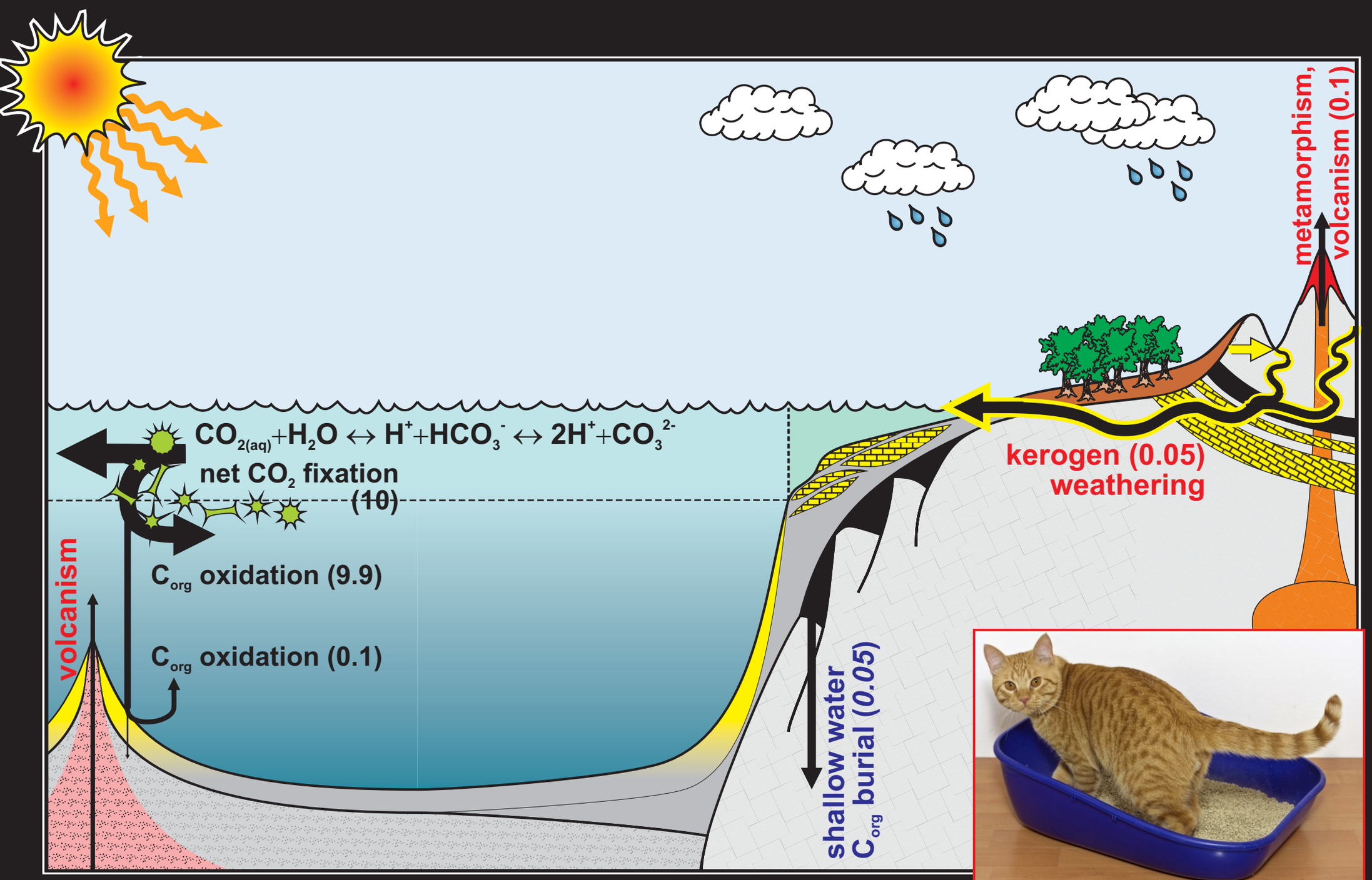
→

higher weathering rates

→

lower pCO_2

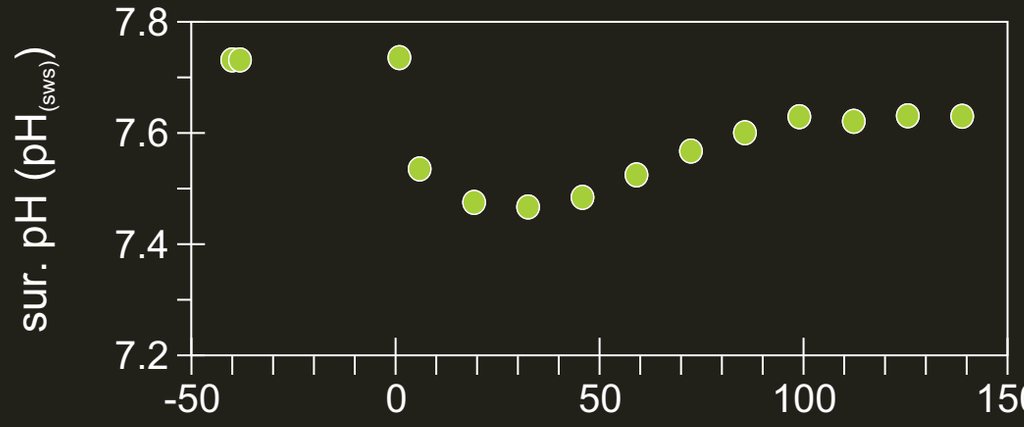
But are these important / the only factors (mostly)? Is the sensitivity of weathering to climate invarient with time (no)?

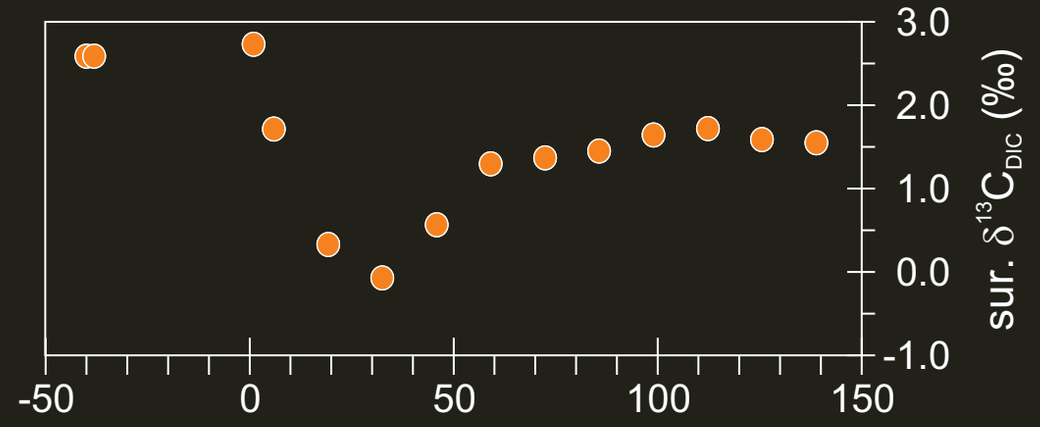

metamorphism, volcanism (0.1)
kerogen (0.05) weathering
$CO_{2(aq)}+H_2O \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-}$
net CO_2 fixation (10)
C_{org} oxidation (9.9)
C_{org} oxidation (0.1)
volcanism
shallow water C_{org} burial (0.05)

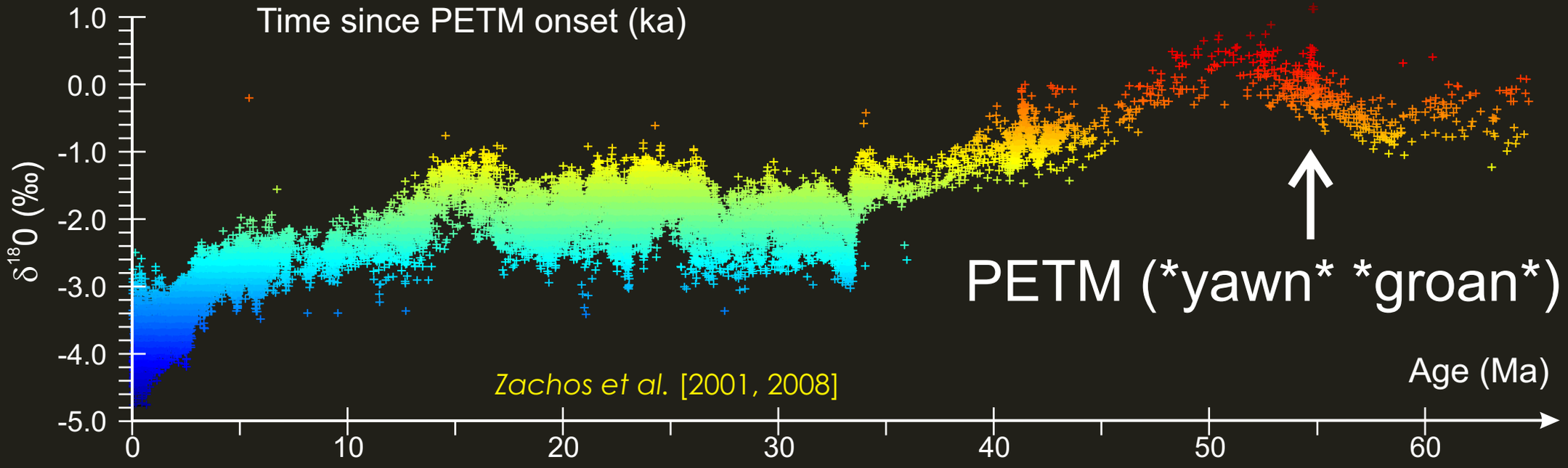
Introduction

'triggers' carbon cycle feedbacks

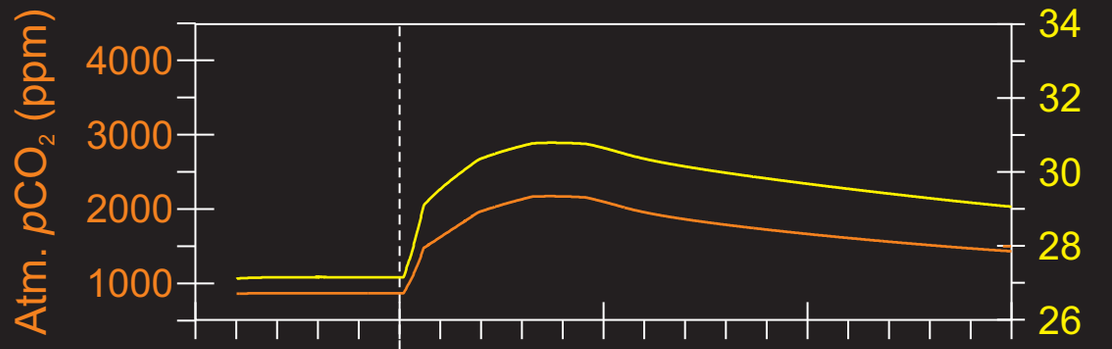
Gutjahr et al. [2007]
(*Nature* **548**, doi:10.1038/nature23646)

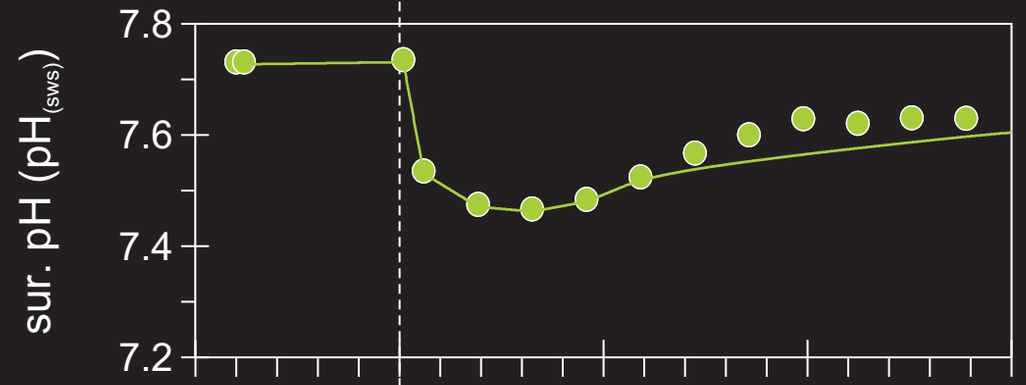


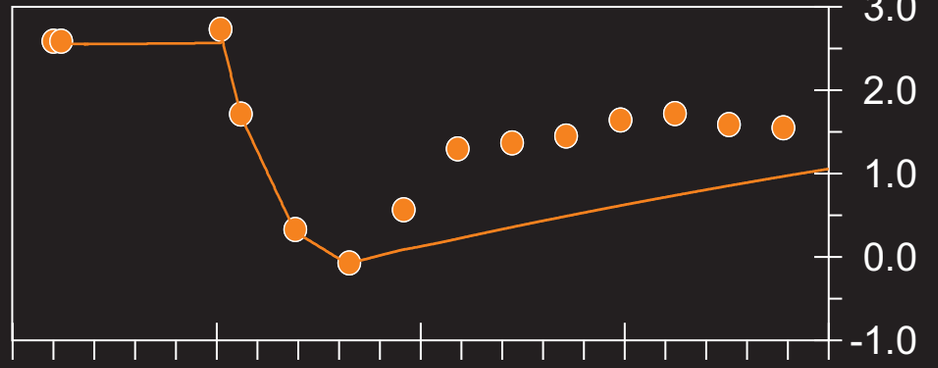


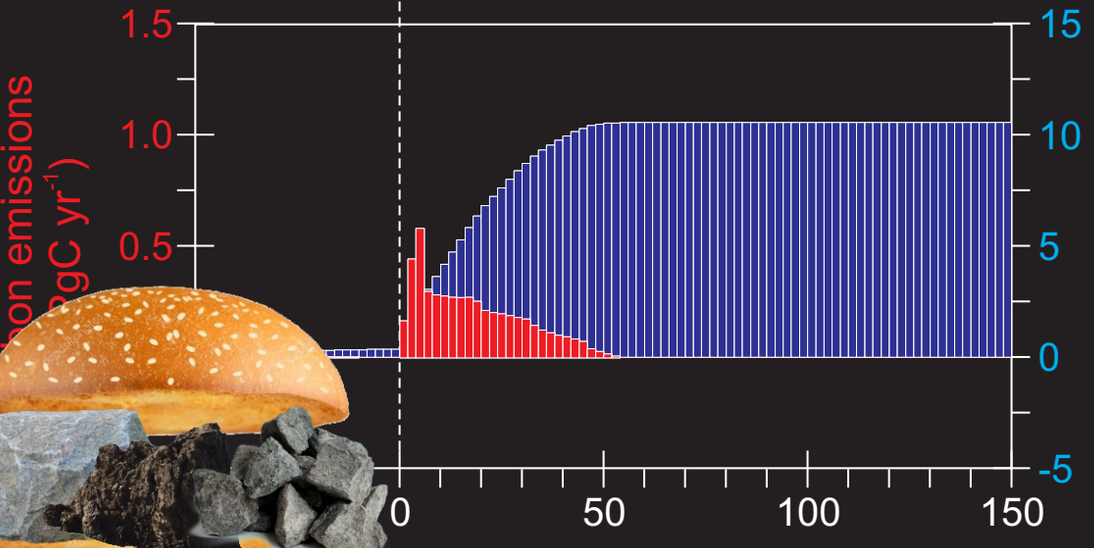


Introduction

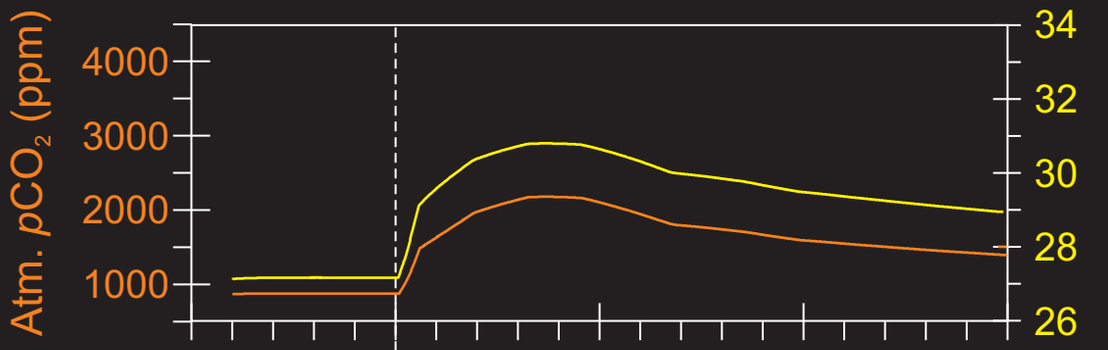


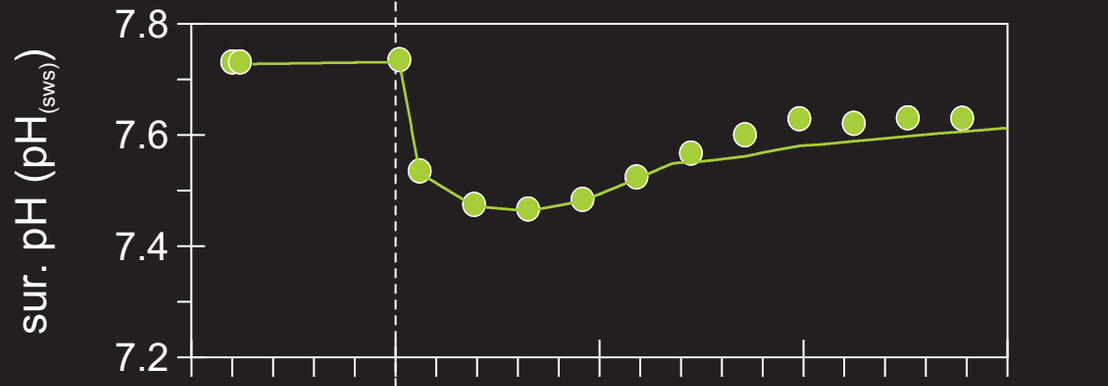


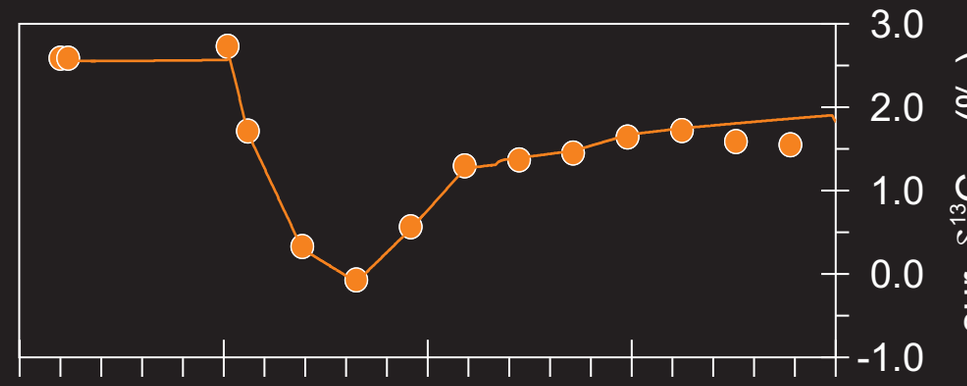


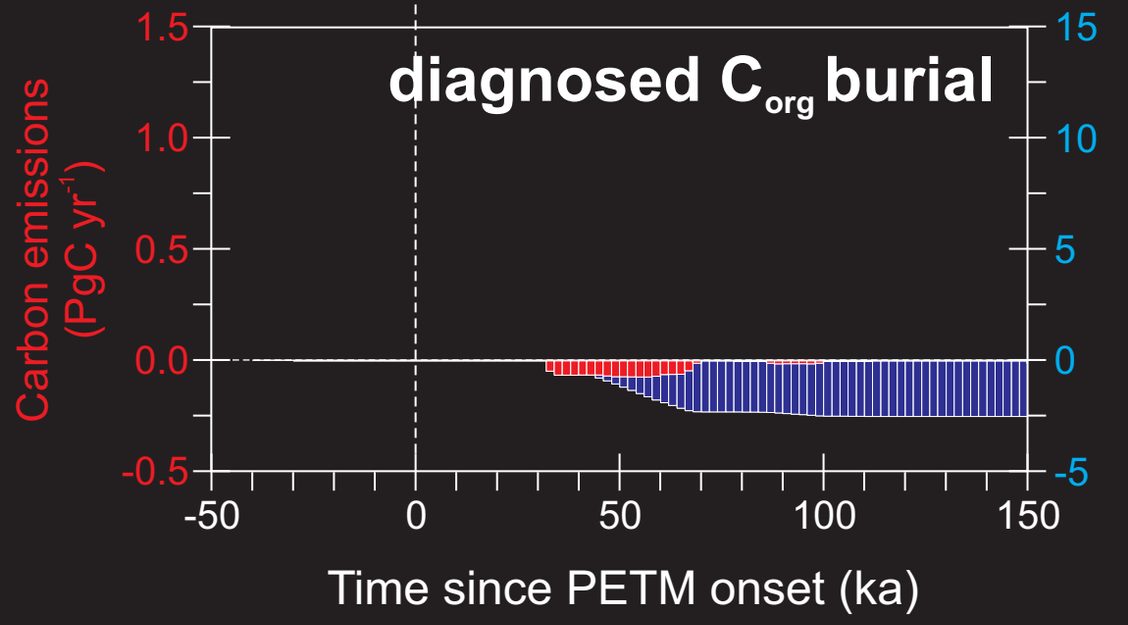


Introduction







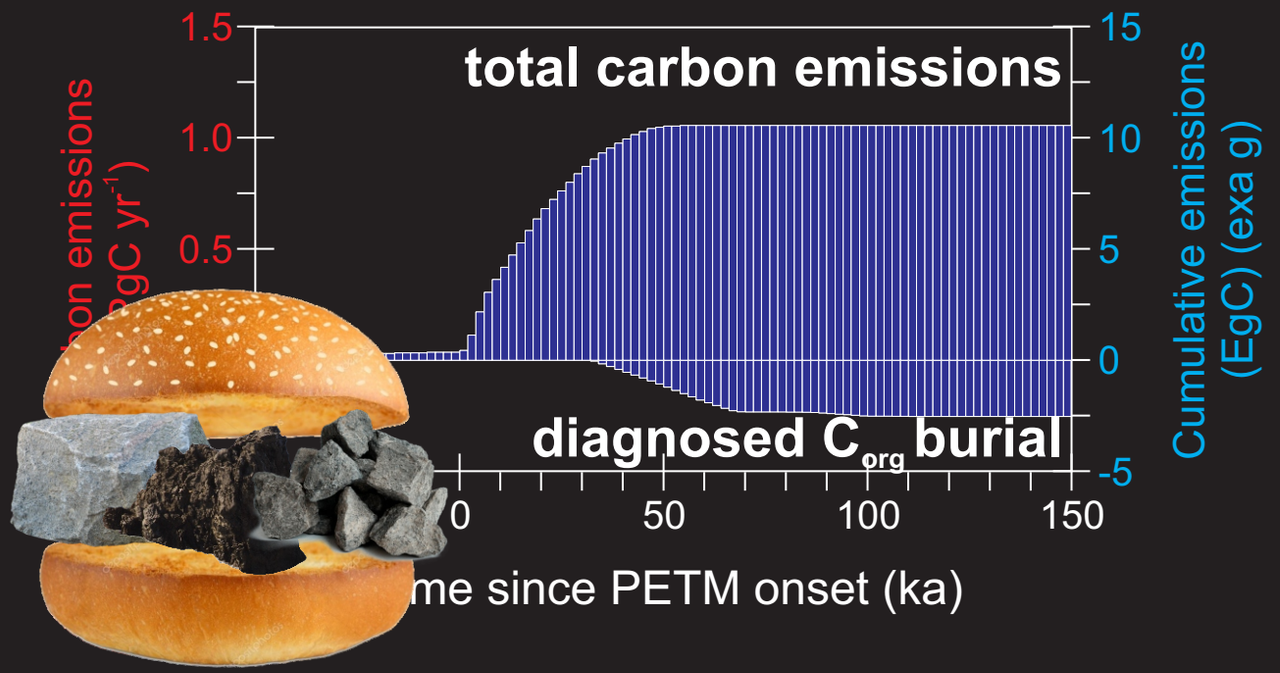


One can write (*Kump and Arthur* [1999], *Chem. Geol.*):

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

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

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



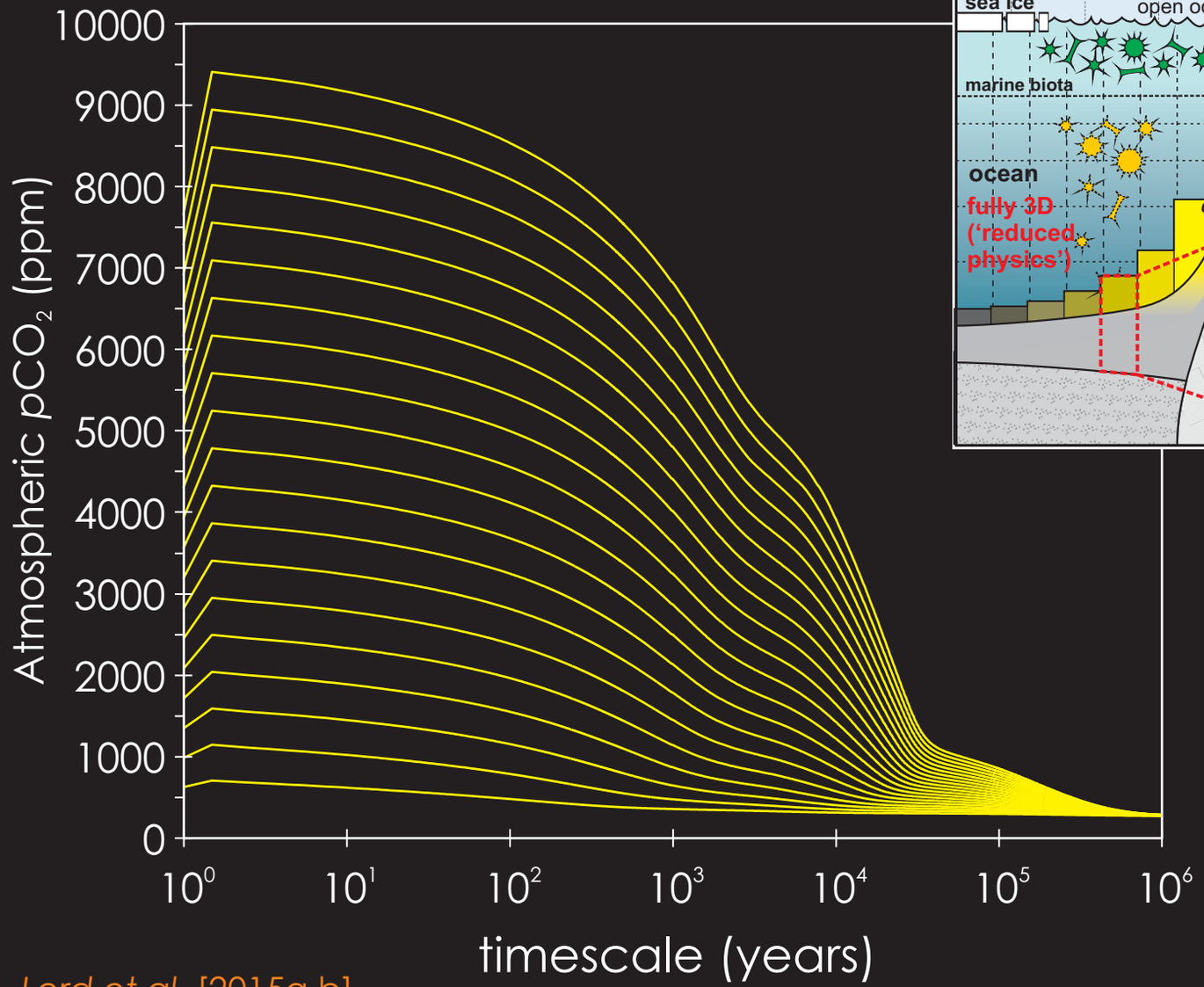
Introduction

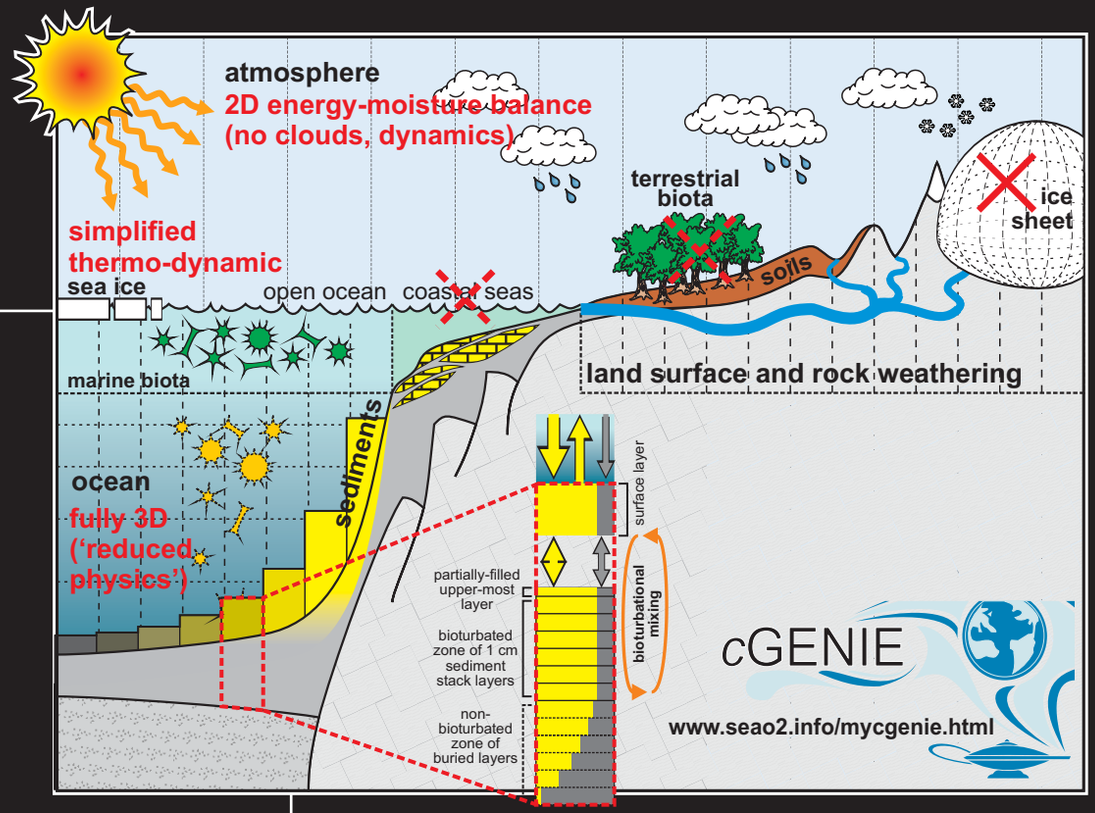
- Small perturbation
- Abundant weatherable mineral soils (post snowball?)
- Well oxygenated ocean, oligotrophic ocean state
- (Narrow continental shelves?)

- Large carbon/climate perturbation (deplete easily weatherable mineral soils, severe ocean deoxygenation)
- Reduced initial state of ocean oxygenation, productive ocean
- Extensive (latitudinally?) shelves? (/tectonic configration)

Impulse response function analysis of the 'long tail' of $CO_{2(excess)}$

(1) Series of 1 Myr Earth system model experiments. CO_2 emissions from 1,000 to 20,000 PgC (GtC). Release interval: 1 yr.





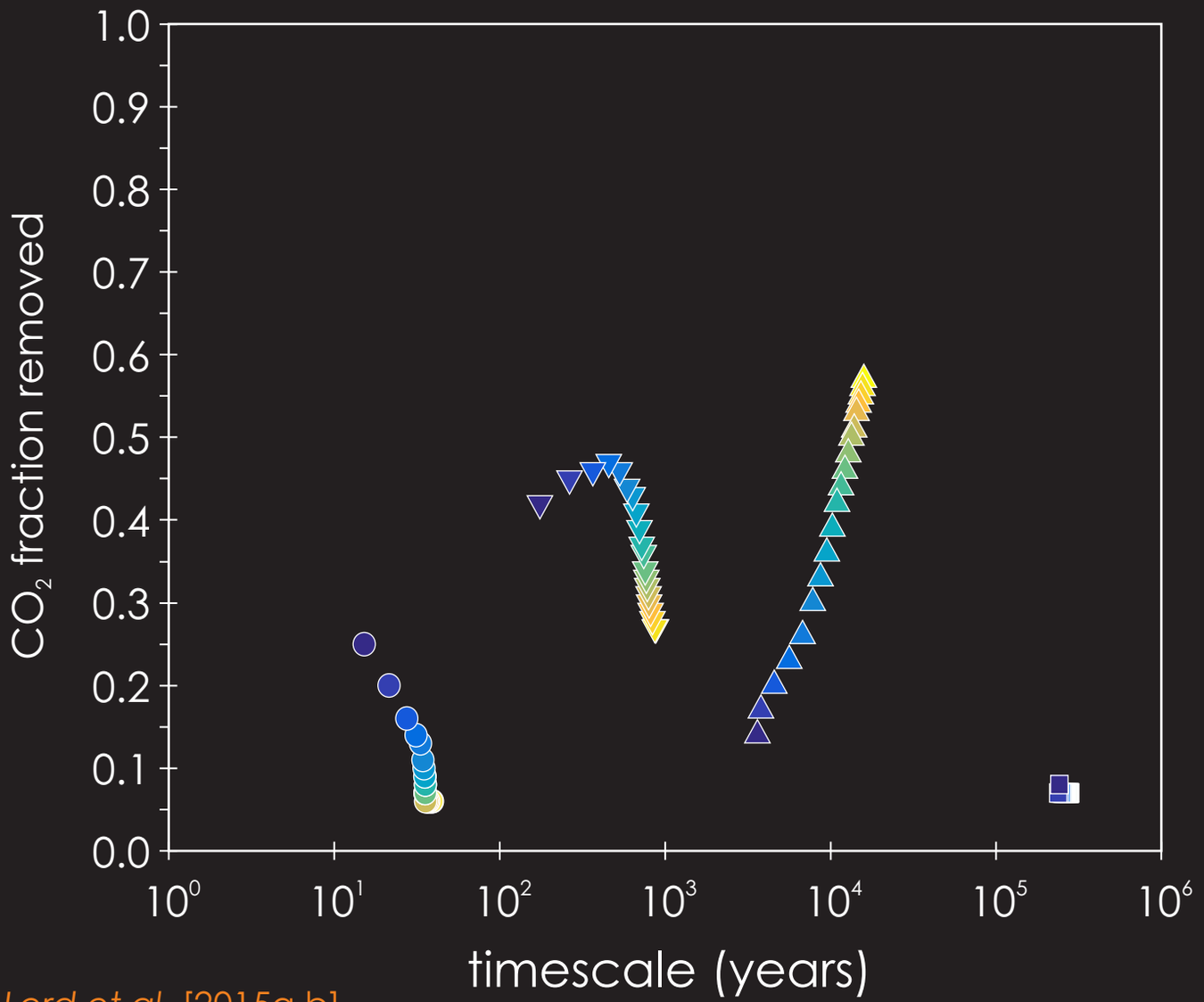
(2) Fit each CO_2 decay curve with a series (4 optimal) of exponentials. Extract the fraction of CO_2 and time-scale associated with each.

(The resulting empirical model can be used in place of a mechanistic model for projecting the long-term fate of carbon release.)

Lord et al. [2015a,b]

Impulse response function analysis of the 'long tail' of $CO_{2(excess)}$

Response of fraction of CO_2 removed vs. the characteristic time-scale, as a function of total emissions, ranging from 1,000 PgC (dark blue) to 20,000 PgC (yellow).



Lord et al. [2015a,b]

Recipies for the silicate weathering burger

As a function of ...

* Mean (annual) global (land) surface air temperature (e.g. [*Brady*, 1991])
* Temperature + rainfall
* Temperature +/- rainfall + atmospheric CO_2
* Temperature +/- rainfall +/- atmospheric CO_2 + terrestrial vegetation net primary production
* Atmospheric CO_2 only (e.g. *Walker et al.* [1981])
* Can also account for uplift and rates of physical erosion, land surface slope (requires explicit 2D scheme)
* Can employ an explicit soil weathering model (driven by GCM output) (e.g. *Taylor et al.* [2015])

...

(And see Colbourn et al. [2015] – The timescales and sensitivities of terrestrial weathering feedbacks on atmospheric CO2, GBC 29, 583–596, doi:10.1002/2014GB005054.) (also *Colbourn et al.* [2013])

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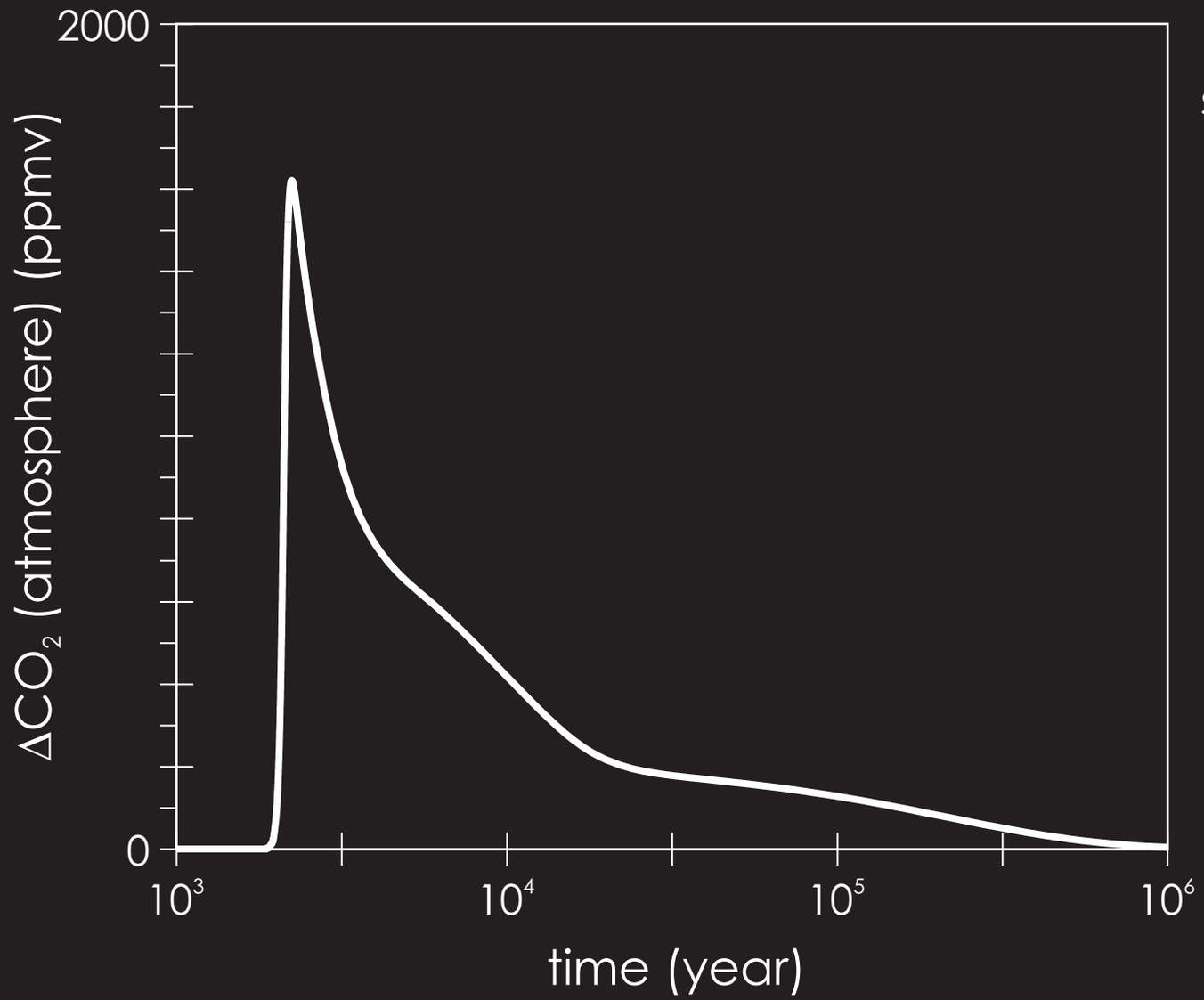
BAU future emissions scenario on top of historical emissions, to a total cumulative carbon release of 5000 PgC.



∗ Mean (annual) global (land) surface air temperature (e.g. [*Brady*, 1991])

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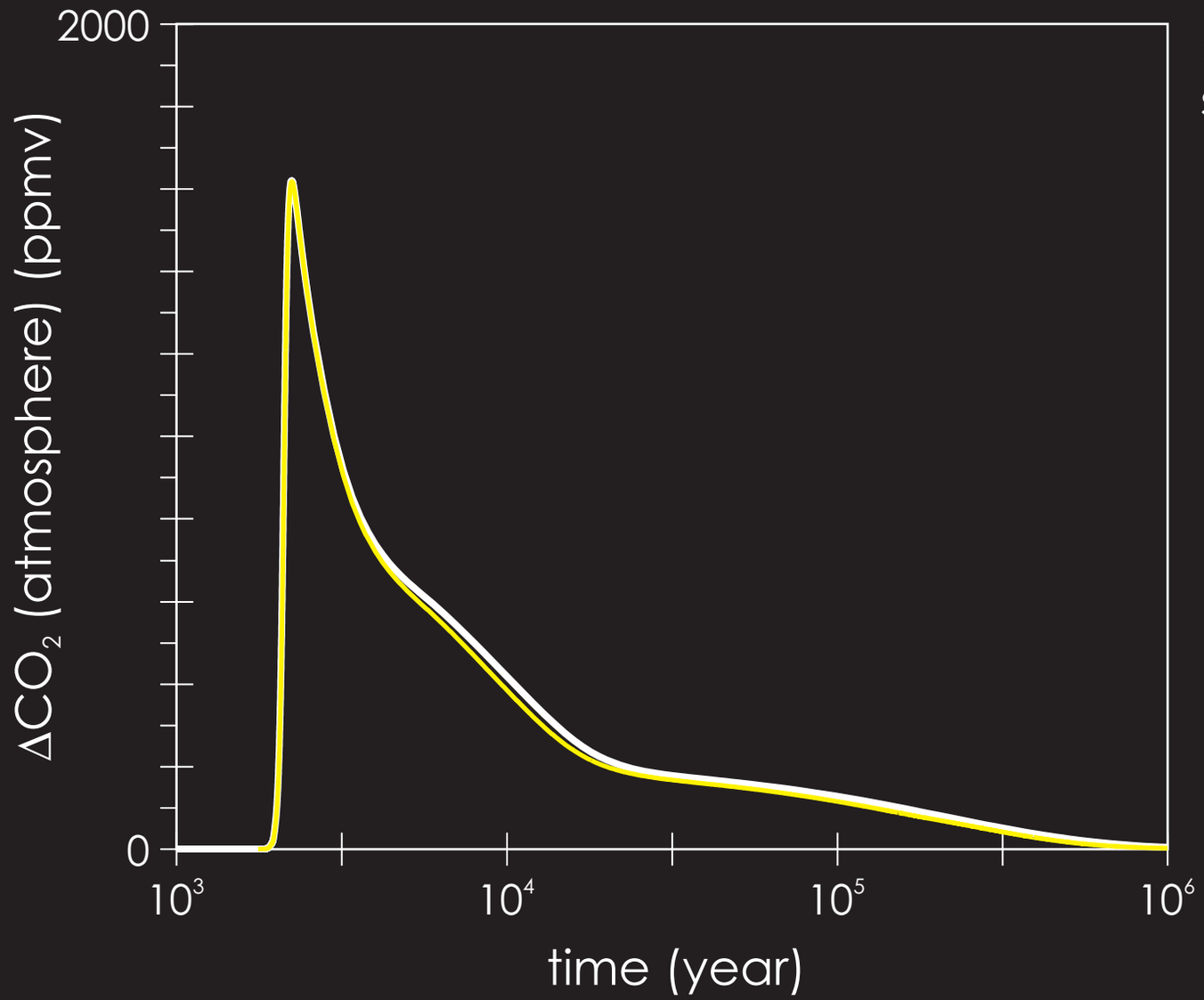

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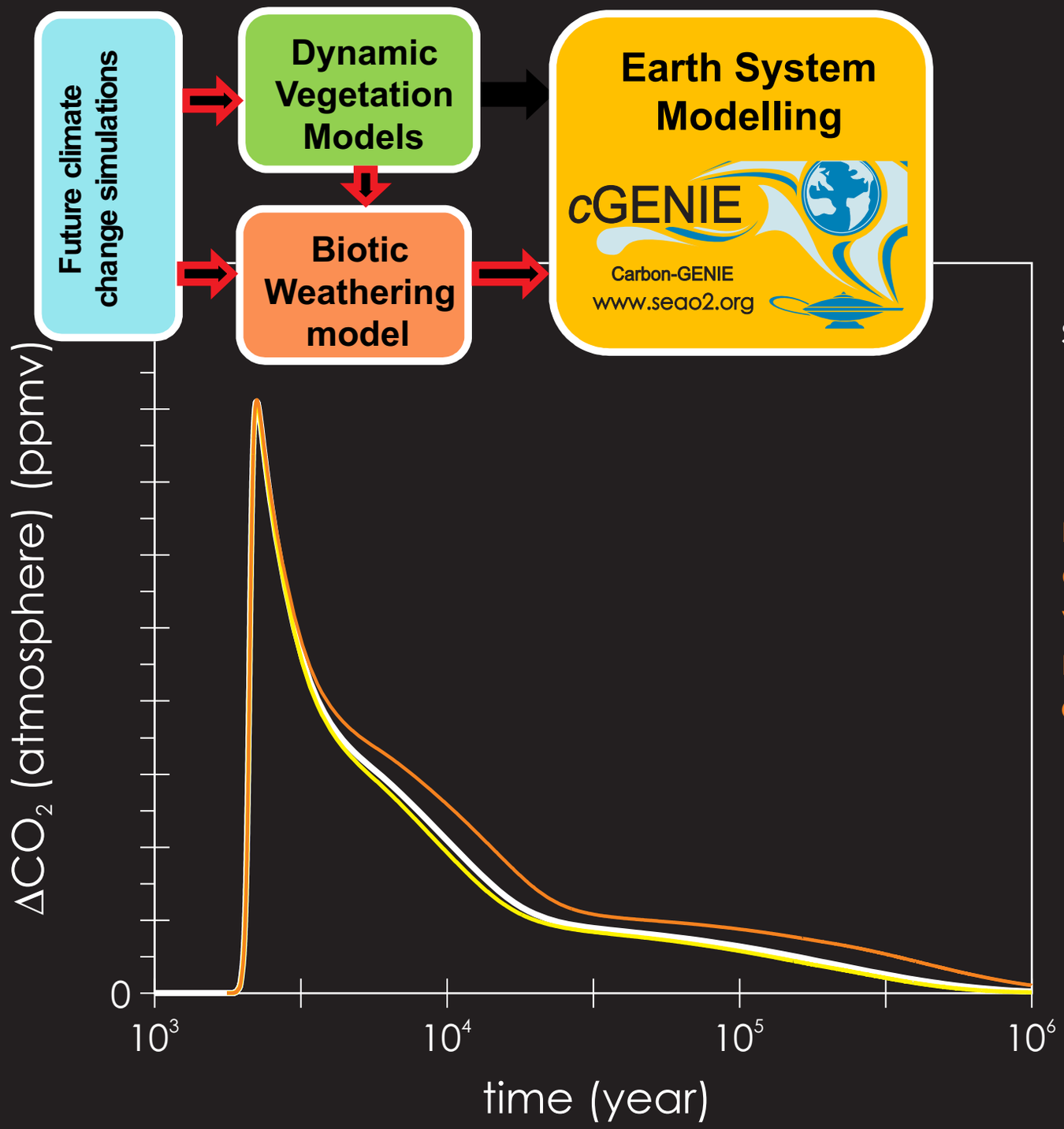

∗ Mean (annual) global (land) surface air temperature (e.g. [*Brady*, 1991])

∗ Temperature + rainfall

∗ Regression of the output of a mechanistic weathering model driven by GCM and terrestrial vegetation output ... against mean global temperature [*Taylor et al.*, 2015]

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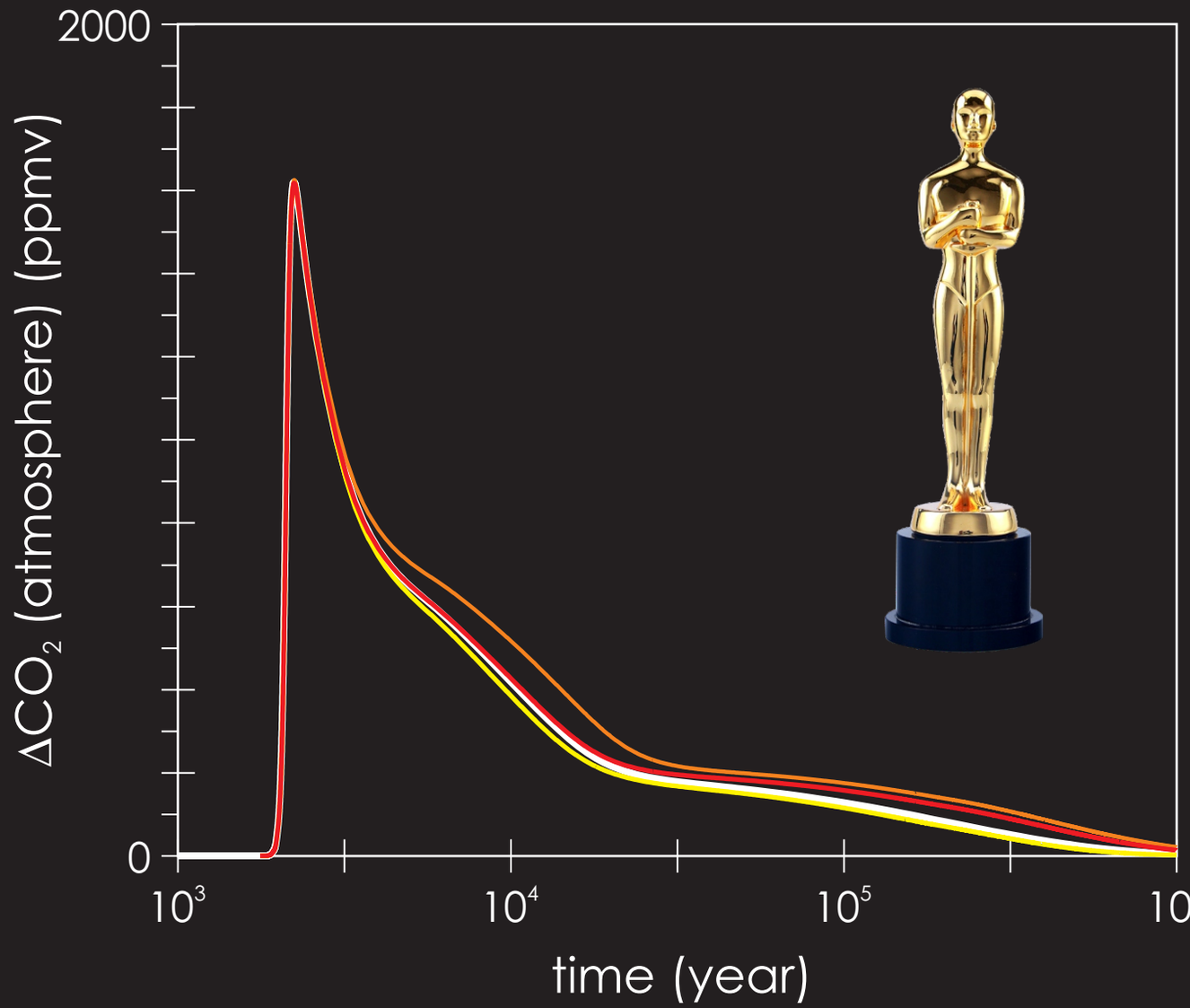

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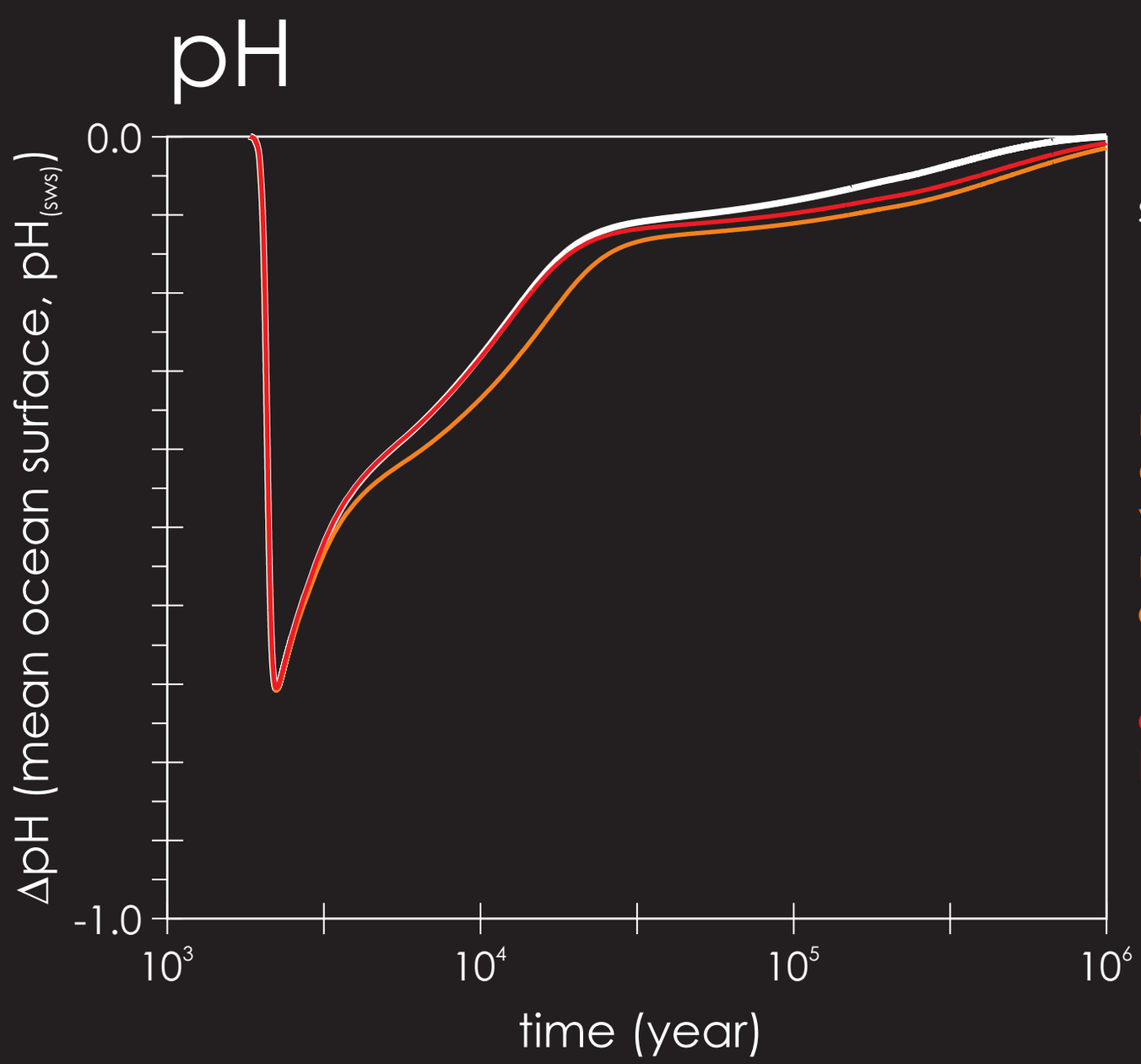

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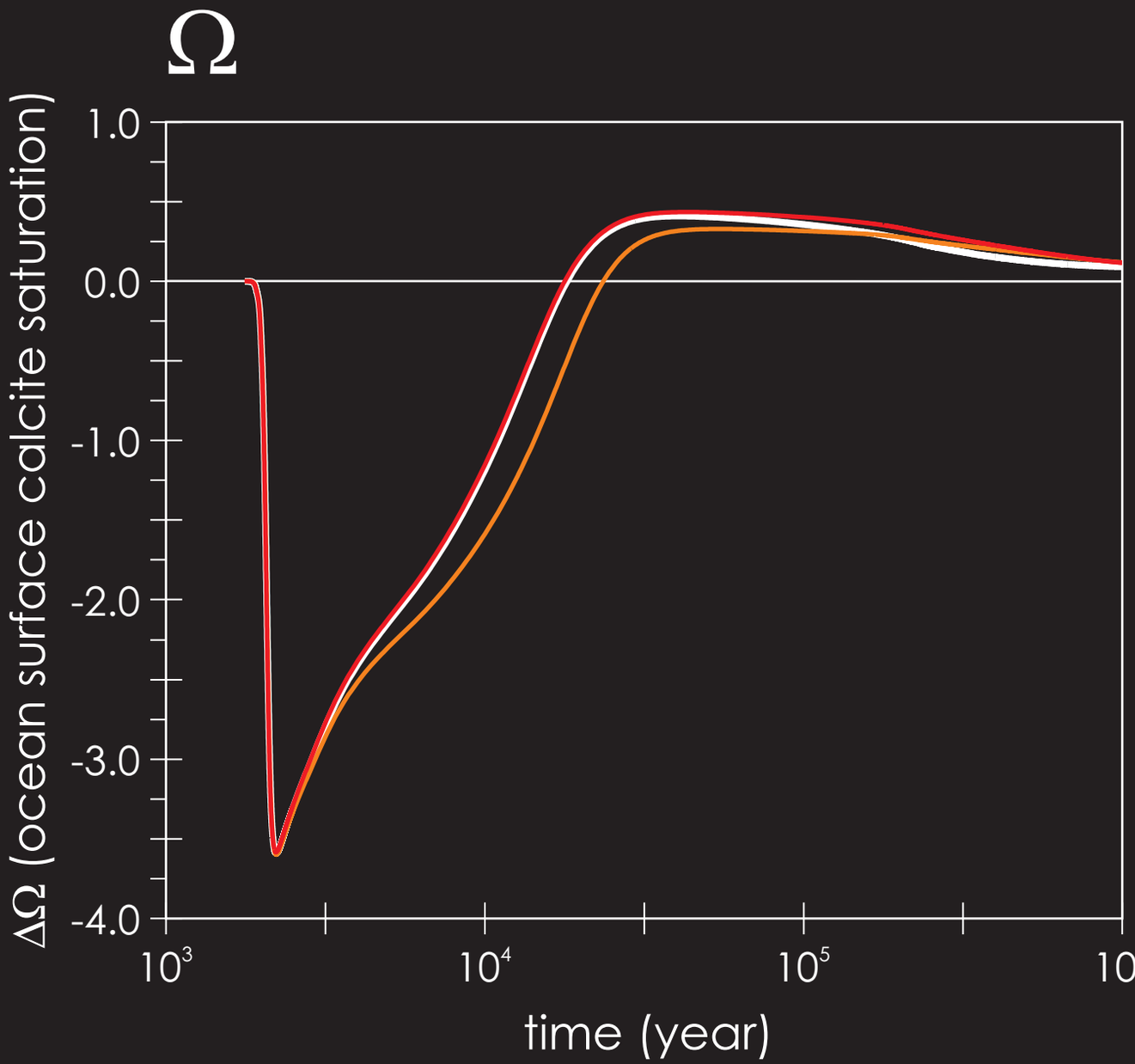

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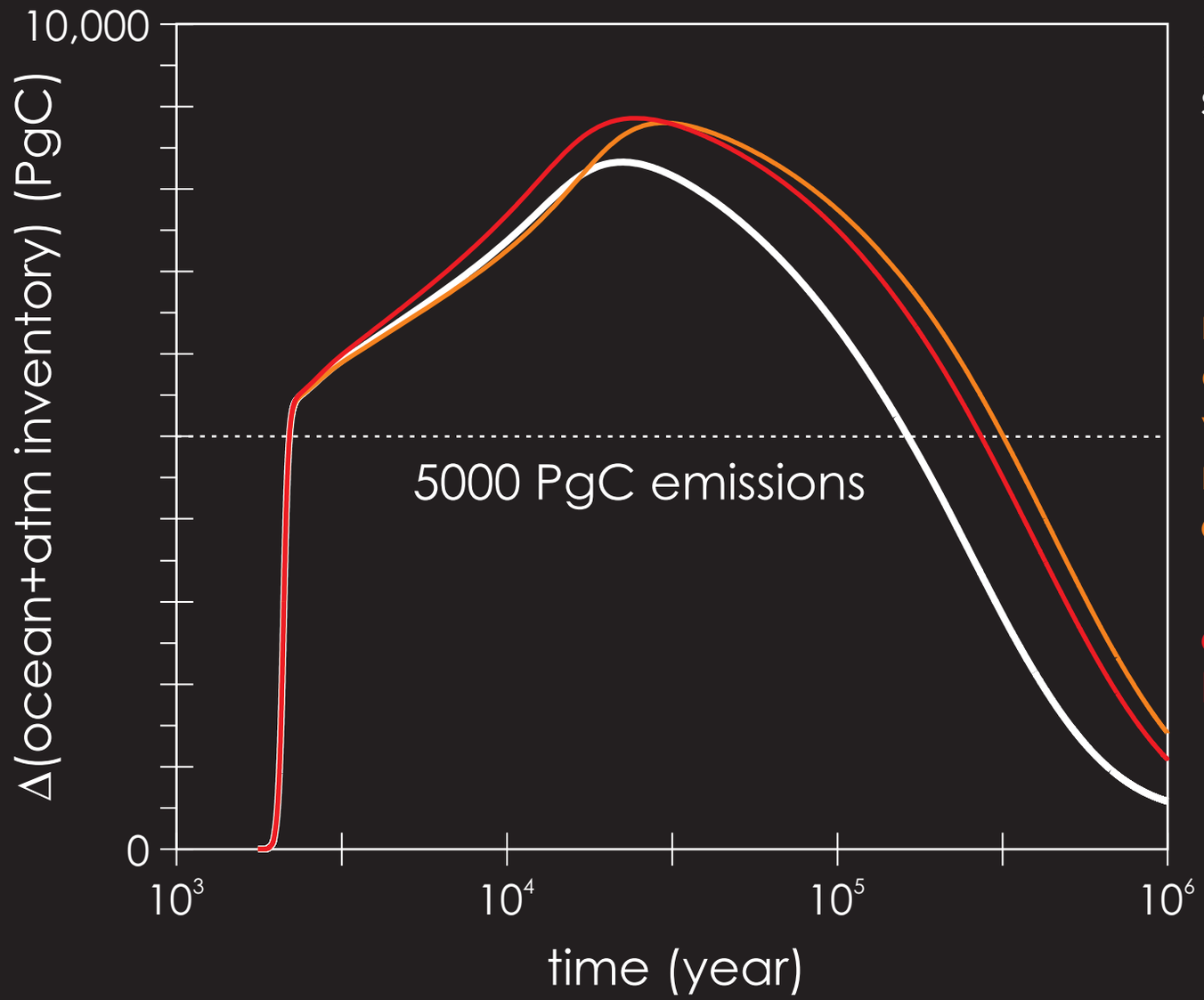
Σ (carbon inventory)



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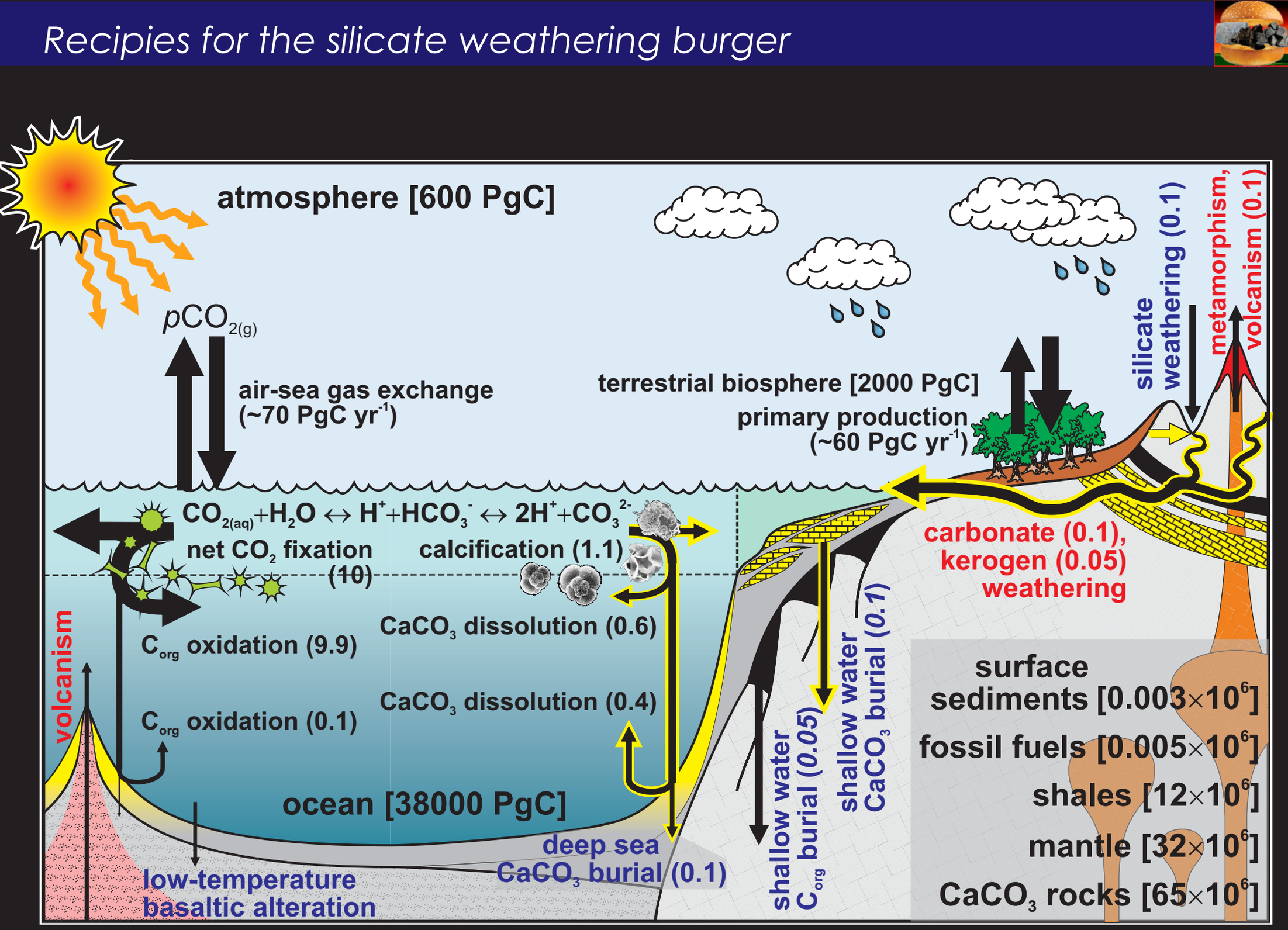

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Lyla Taylor and David Beerling [Sheffield], *et al.*

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ERC