The Global Weathering Thermostat in the Anthropocene

(numerical fun with silicate weathering and other climate control knobs)

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University of BRISTOL

European Research Council
Established by the European Commission

UCR

Regulation of global climate

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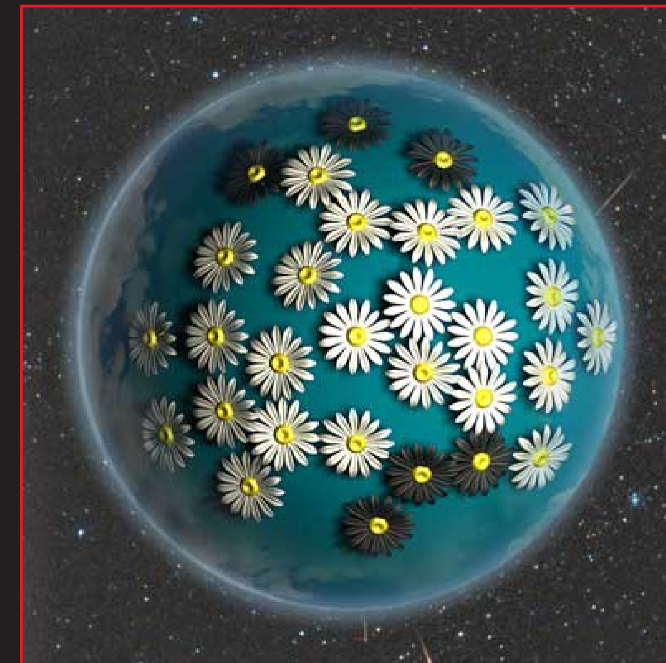
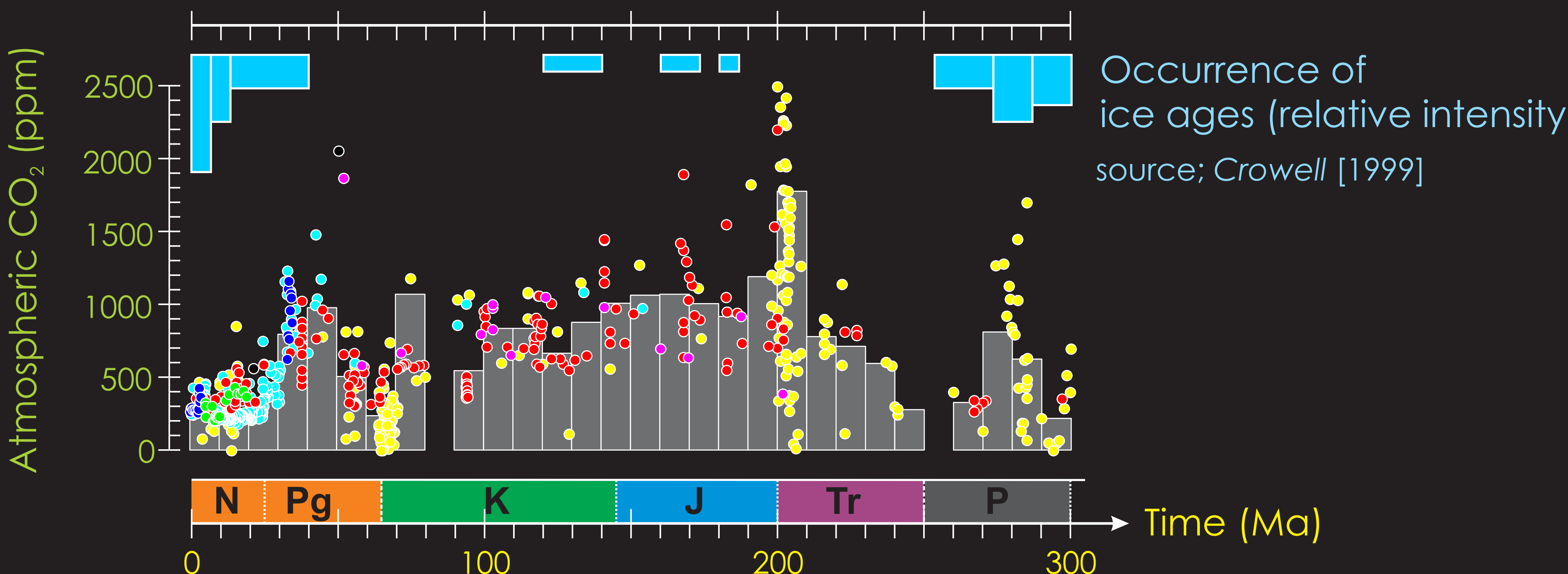
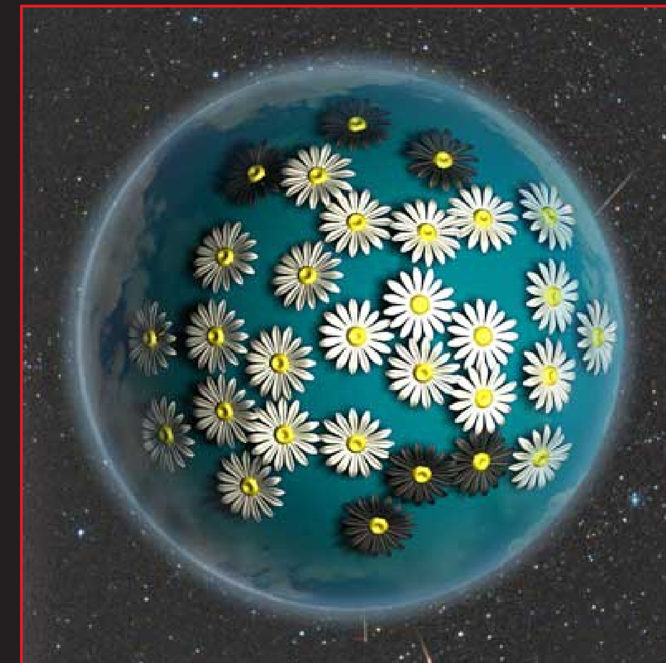


From: *Hönisch et al.* [2012]



Regulation of global ~~climate~~ carbon cycling



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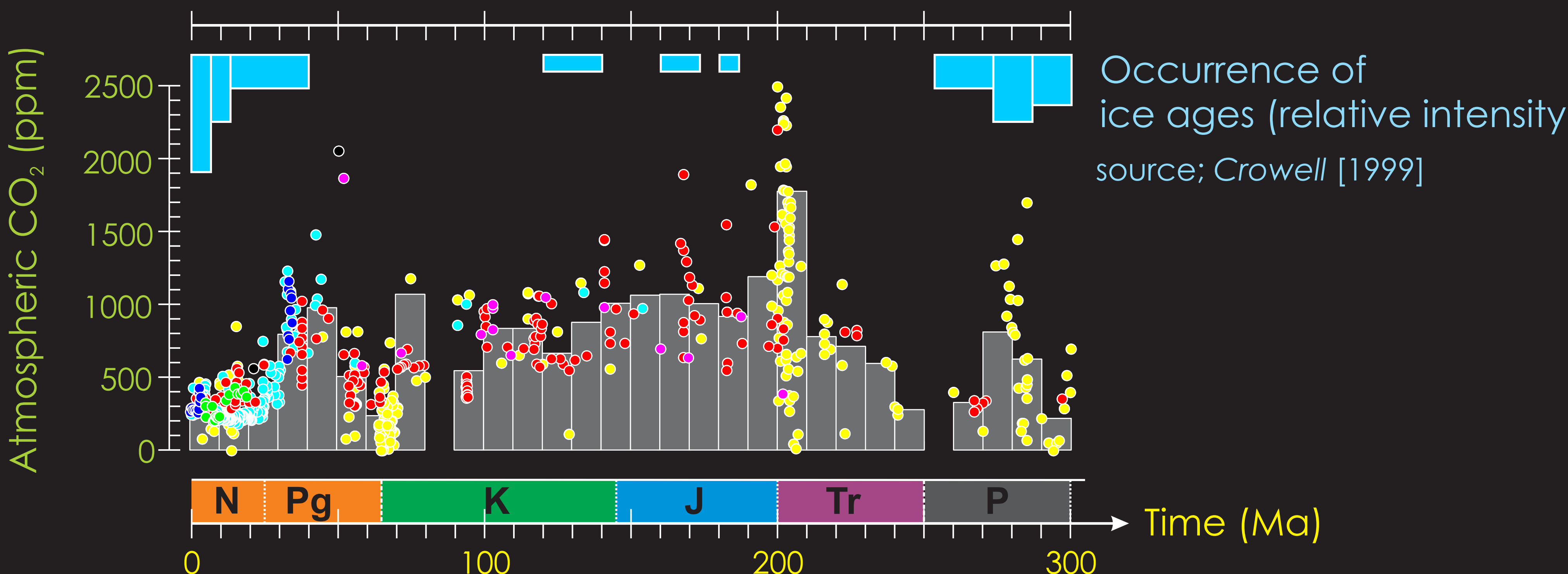

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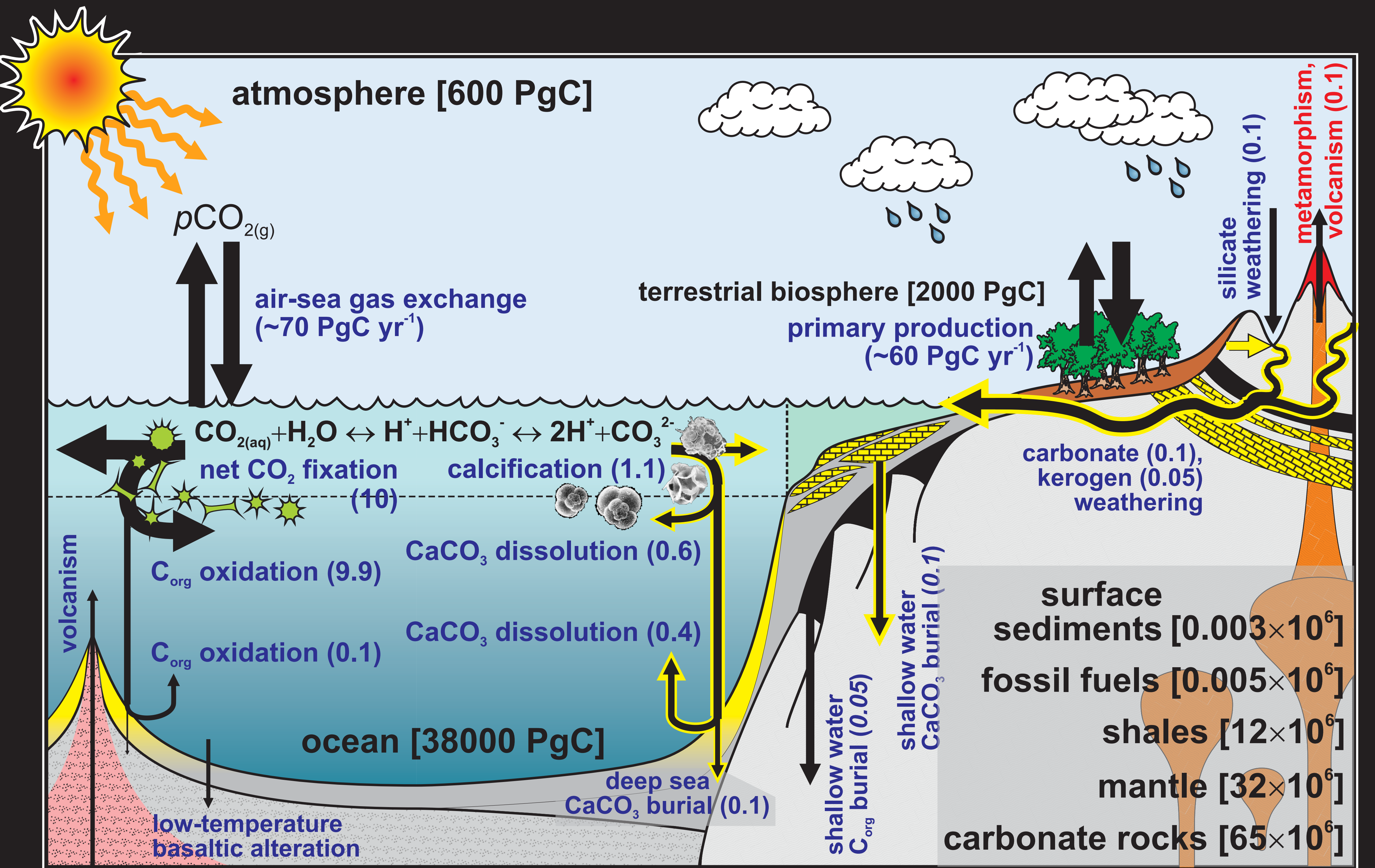

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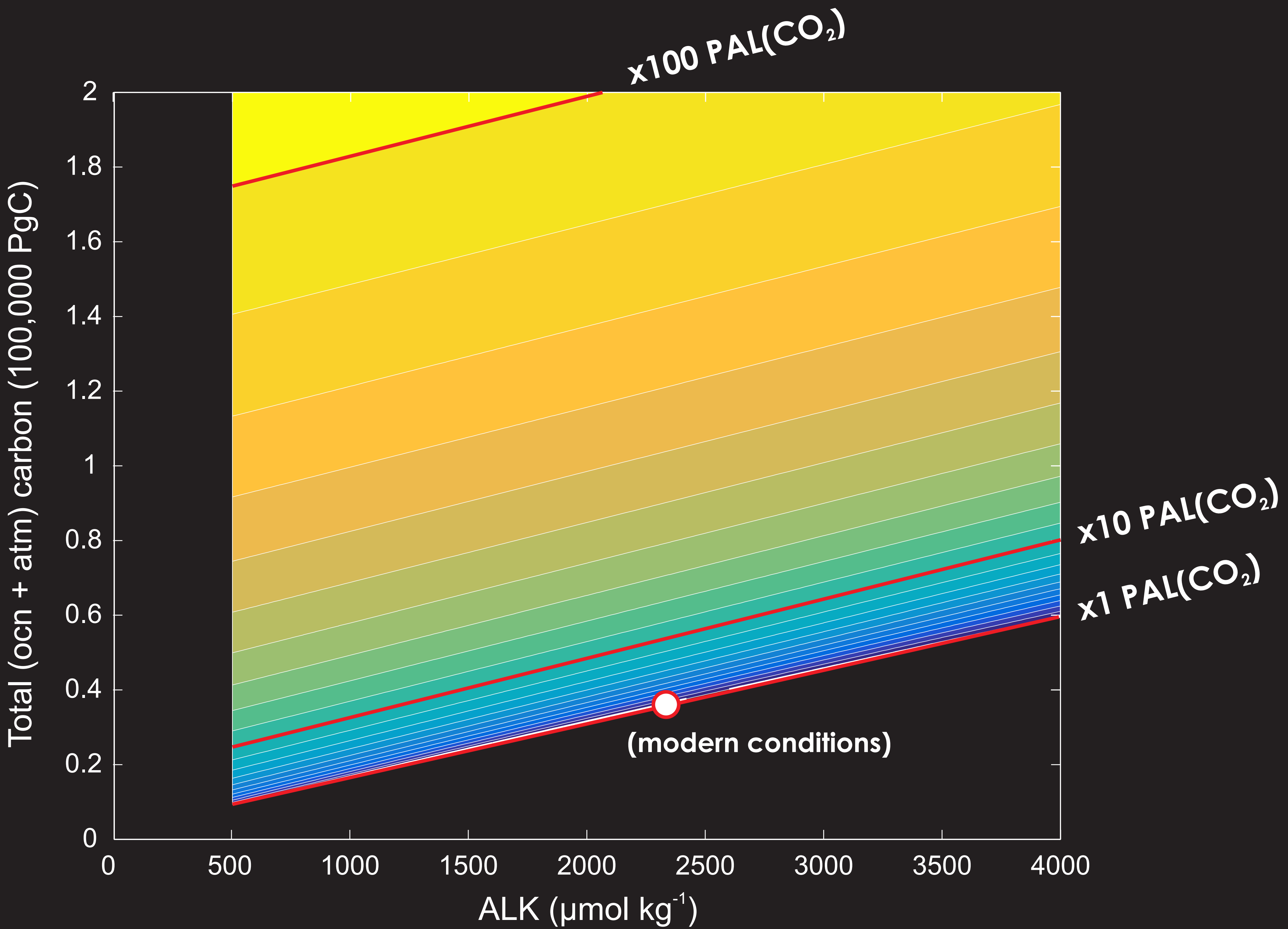

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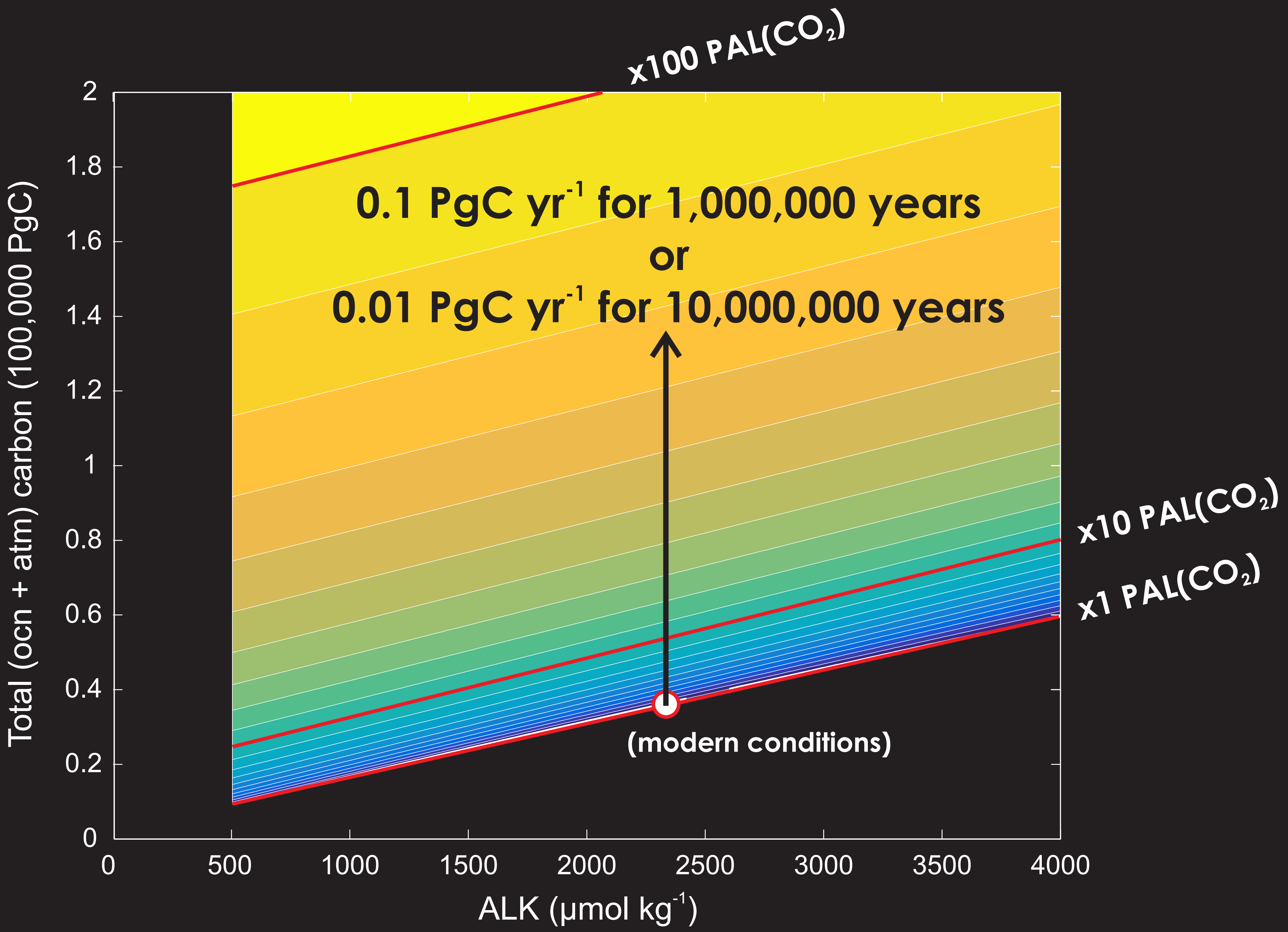


Regulation of global ~~climate~~ carbon cycling

Regulation of global ~~climate~~ carbon cycling

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

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

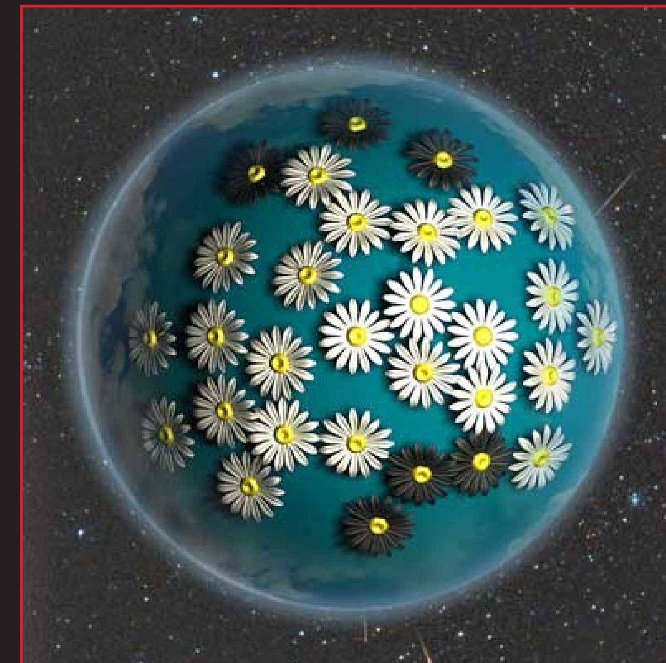
(2) $CO_{2(aq)} + H_2O + CaCO_3 \rightarrow Ca^{2+} + 2HCO_3^-$

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.

Regulation of global ~~climate~~ carbon cycling

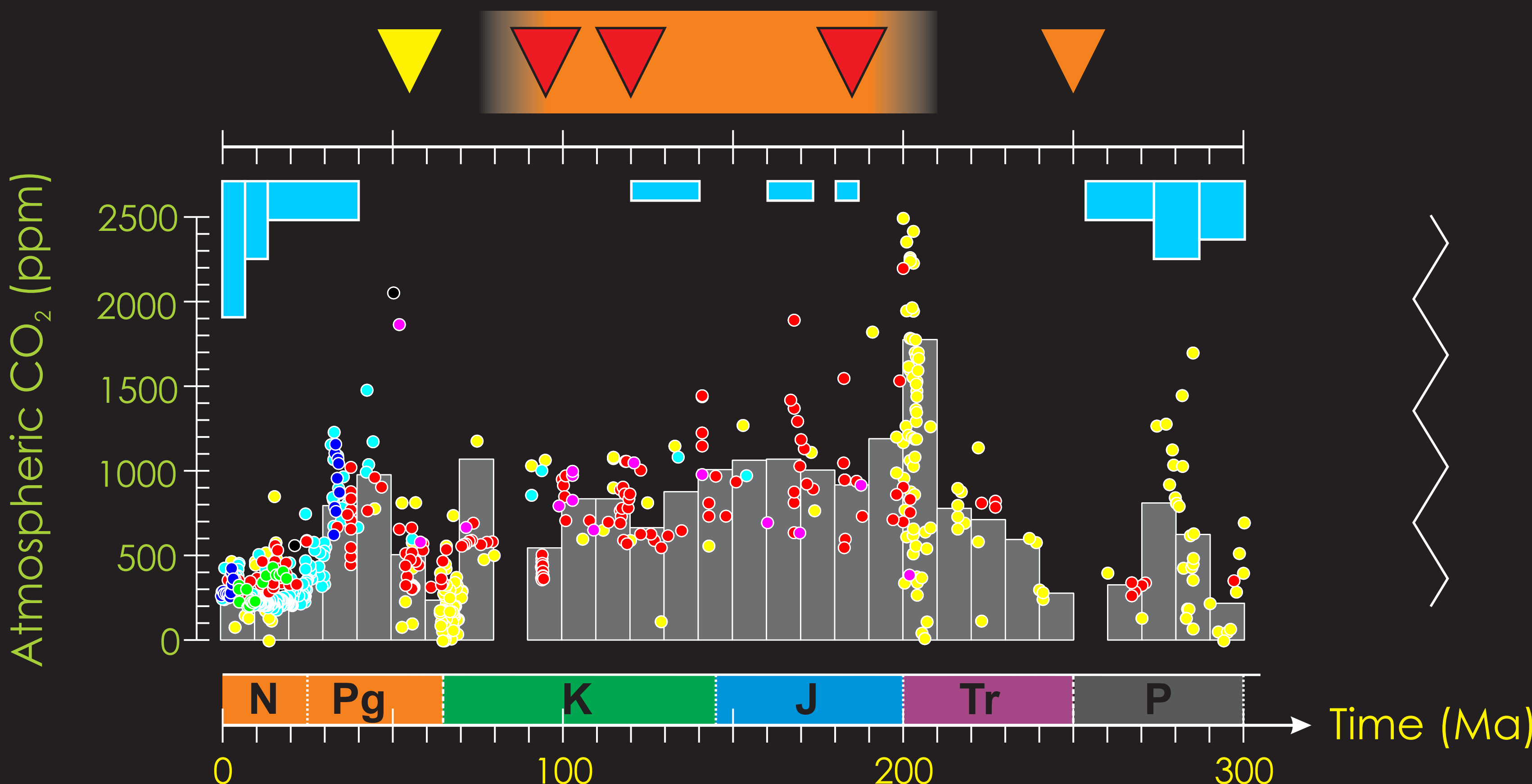


Furthermore, the rate of silicate weathering should scale with climate.

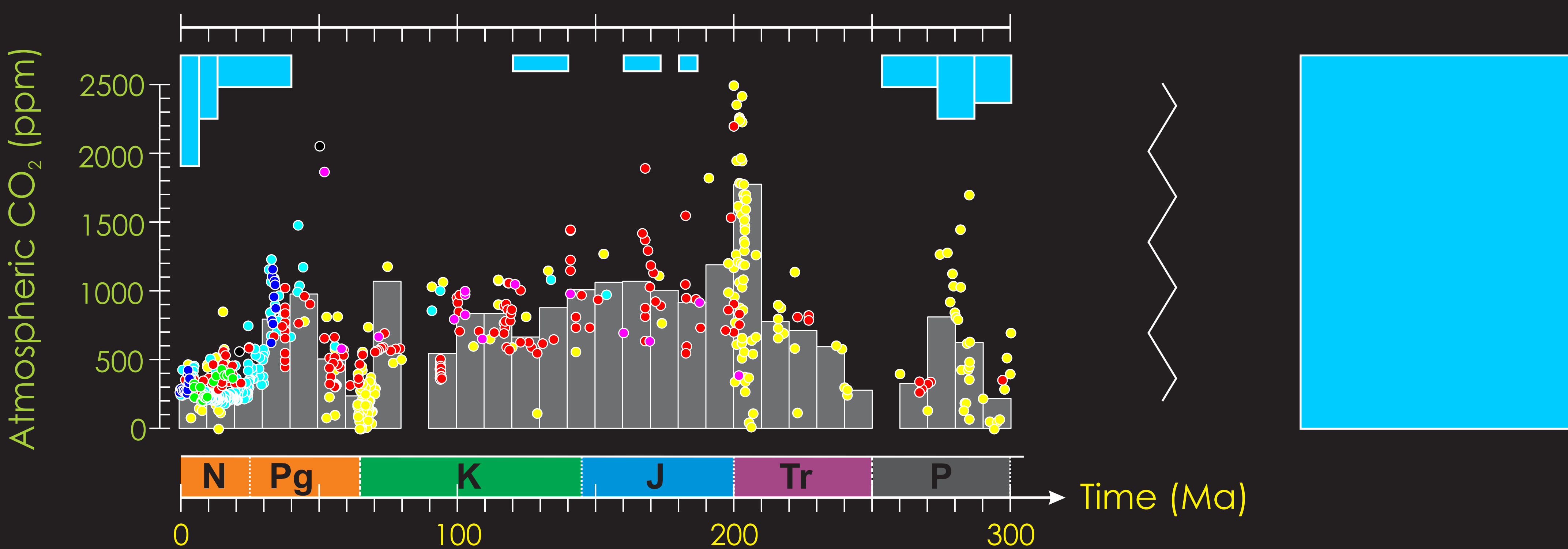
Hence the **silicate weathering feedback** is formed:

higher pCO_2 → higher temperatures (& rainfall) → higher weathering rates → lower pCO_2

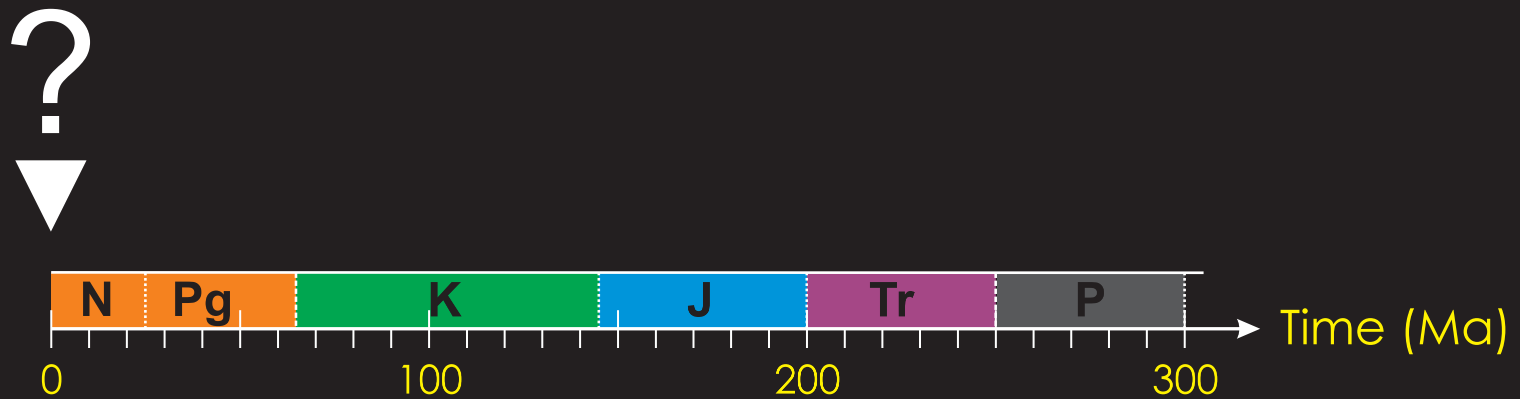
Regulation of global ~~climate~~ carbon cycling



Regulation of global ~~climate~~ carbon cycling

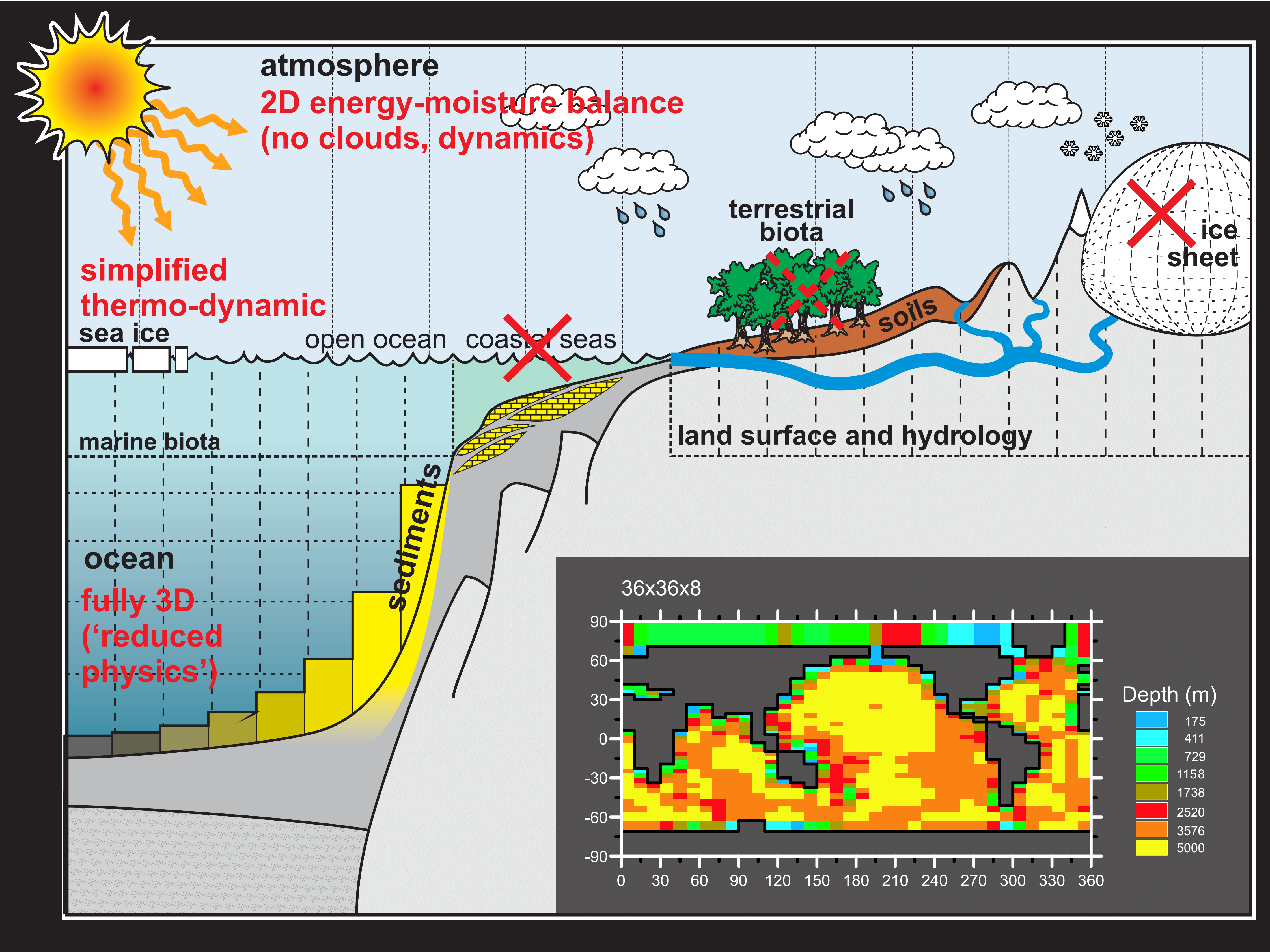


Outline



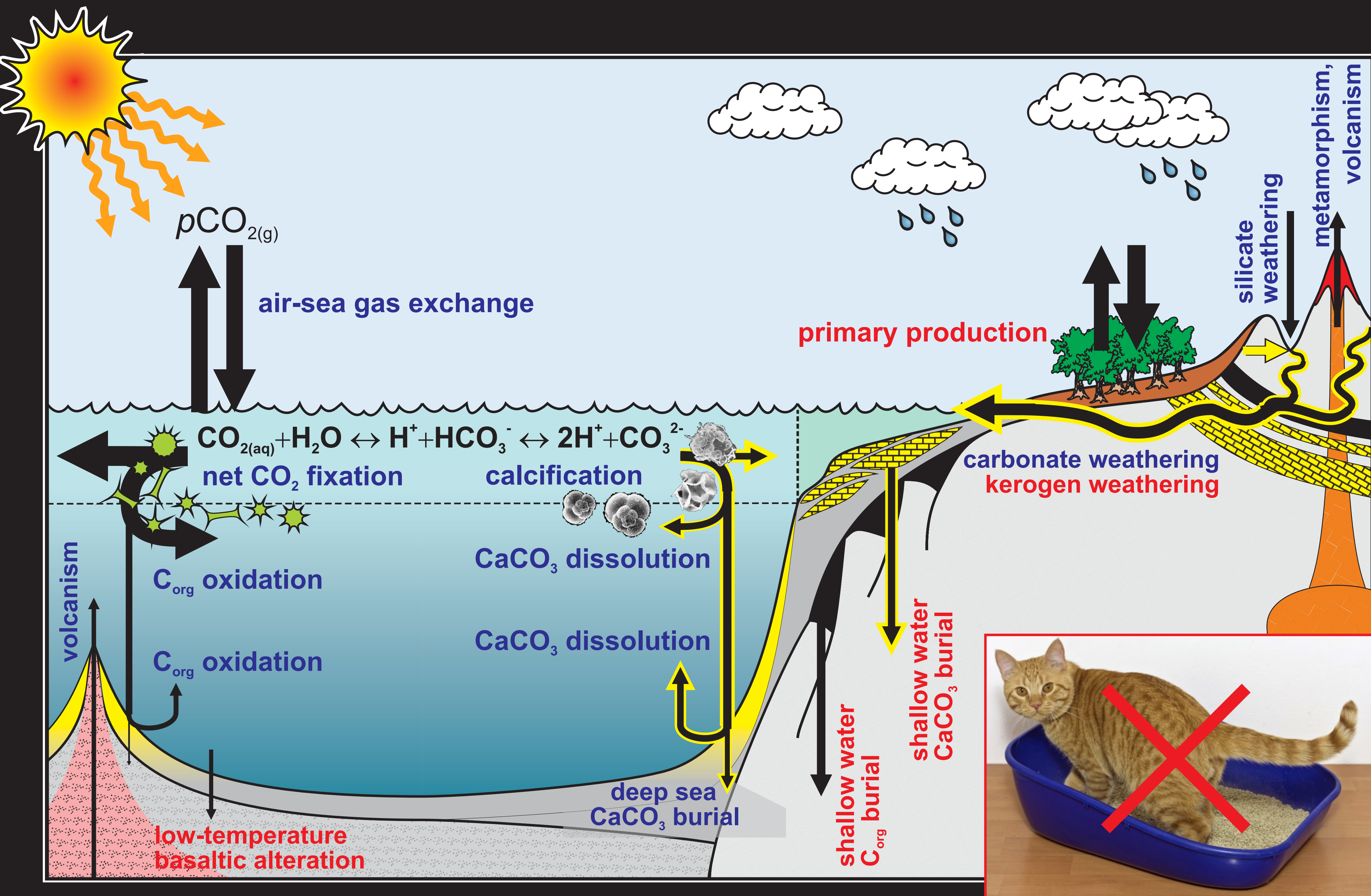
lies, damn lies, and computer models

```
! calculate carbonate alkalinity

loc_ALK_DIC = dum_ALK &
& - loc_H4BO4 - loc_OH - loc_HPO4 - 2.0*loc_PO4 - loc_H3SiO4 - loc_NH3 - loc_HS &
& + loc_H + loc_HSO4 + loc_HF + loc_H3PO4

! estimate the partitioning between the aqueous carbonate species

loc_zed = ( &
&   (4.0*loc_ALK_DIC + dum_DIC*dum_carbconst(icc_k) -
loc_ALK_DIC*dum_carbconst(icc_k))**2 + &
&   4.0*(dum_carbconst(icc_k) - 4.0)*loc_ALK_DIC**2 &
& )**0.5        loc_conc_HCO3 = (dum_DIC*dum_carbconst(icc_k) -
loc_zed)/(dum_carbconst(icc_k) - 4.0)

loc_conc_CO3 = &
& ( &
&   loc_ALK_DIC*dum_carbconst(icc_k) - dum_DIC*dum_carbconst(icc_k) - &
&   4.0*loc_ALK_DIC + loc_zed &
& ) &
& /(2.0*(dum_carbconst(icc_k) - 4.0))

loc_conc_CO2 = dum_DIC - loc_ALK_DIC + &
& ( &
&   loc_ALK_DIC*dum_carbconst(icc_k) - dum_DIC*dum_carbconst(icc_k) - &
&   4.0*loc_ALK_DIC + loc_zed &
& ) &
& /(2.0*(dum_carbconst(icc_k) - 4.0))

loc_H1 = dum_carbconst(icc_k1)*loc_conc_CO2/loc_conc_HCO3

loc_H2 = dum_carbconst(icc_k2)*loc_conc_HCO3/loc_conc_CO3
```



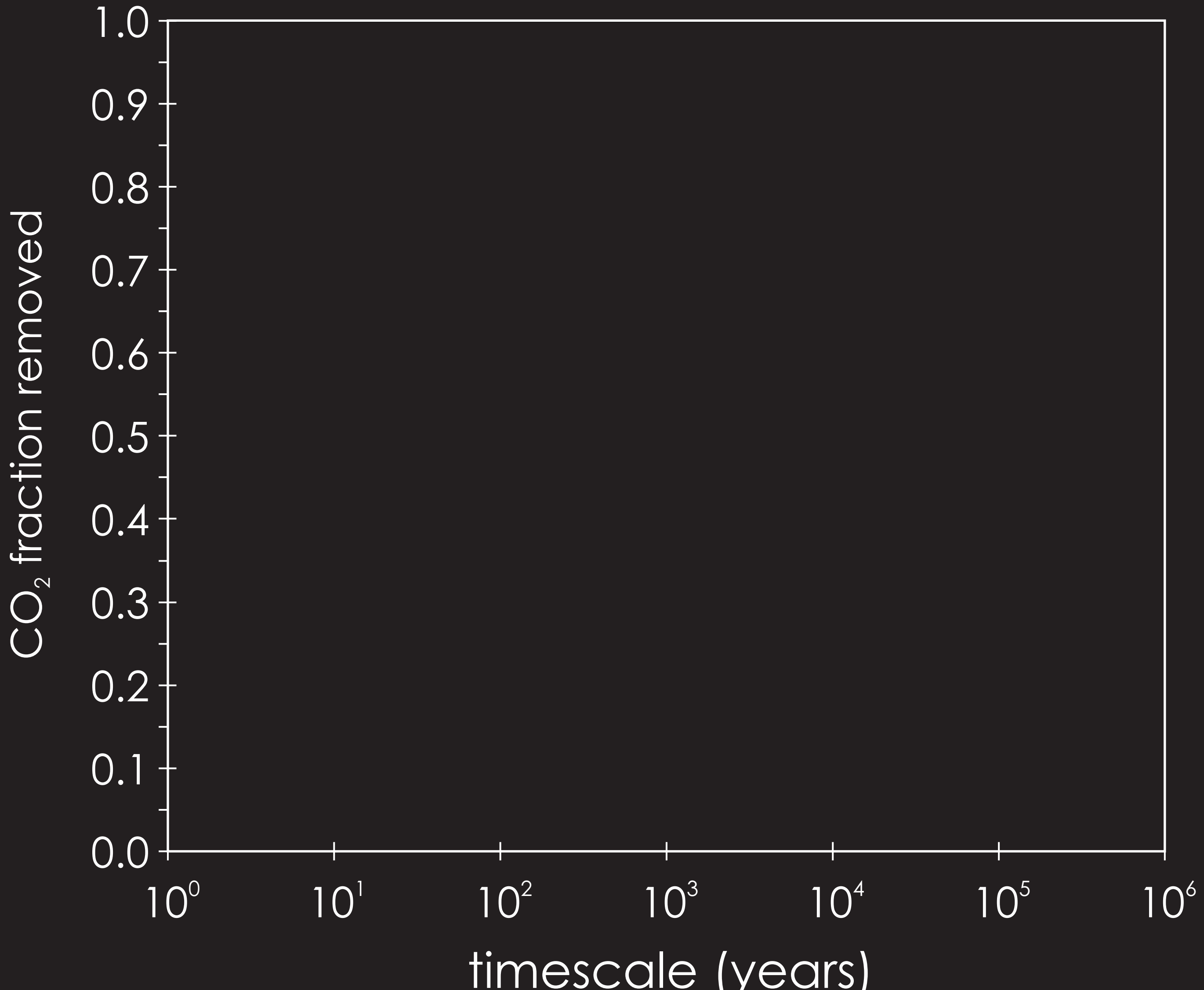
atmosphere
2D energy-moisture balance
(no clouds, dynamics)
simplified
thermo-dynamic
sea ice
open ocean
coastal seas
terrestrial
biota
soils
ice
sheet
land surface and hydrology
marine biota
sediments
ocean
fully 3D
('reduced
physics')
36x36x8
Depth (m)
175
411
729
1158
1738
2520
3576
5000

lies, damn lies, and computer models



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

Cross-plot of the fraction of total CO_2 emissions to the atmosphere removed by a particular process (carbon sink), vs. the characteristic (e-folding) time-scale of that process (log_{10} scale).



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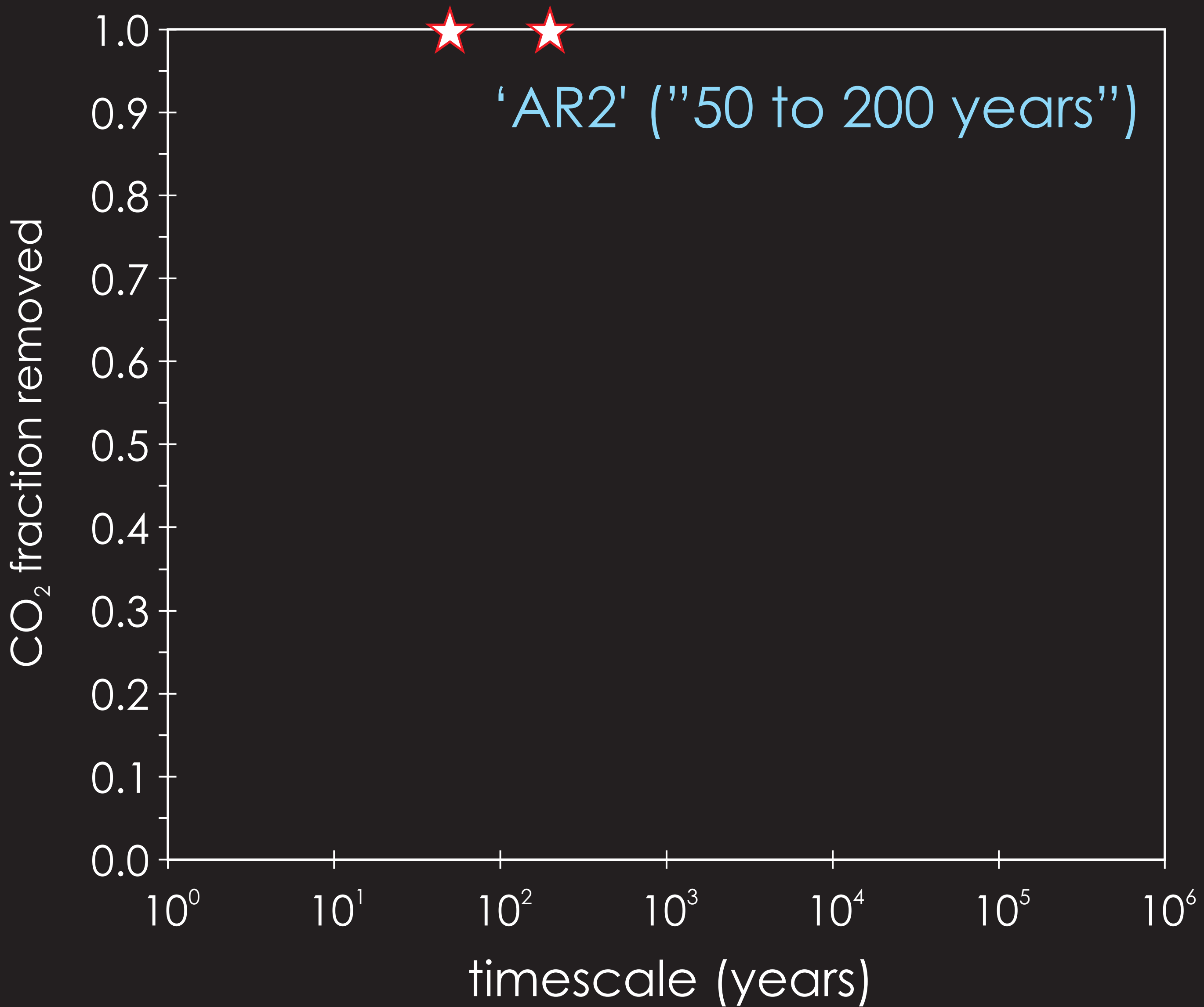

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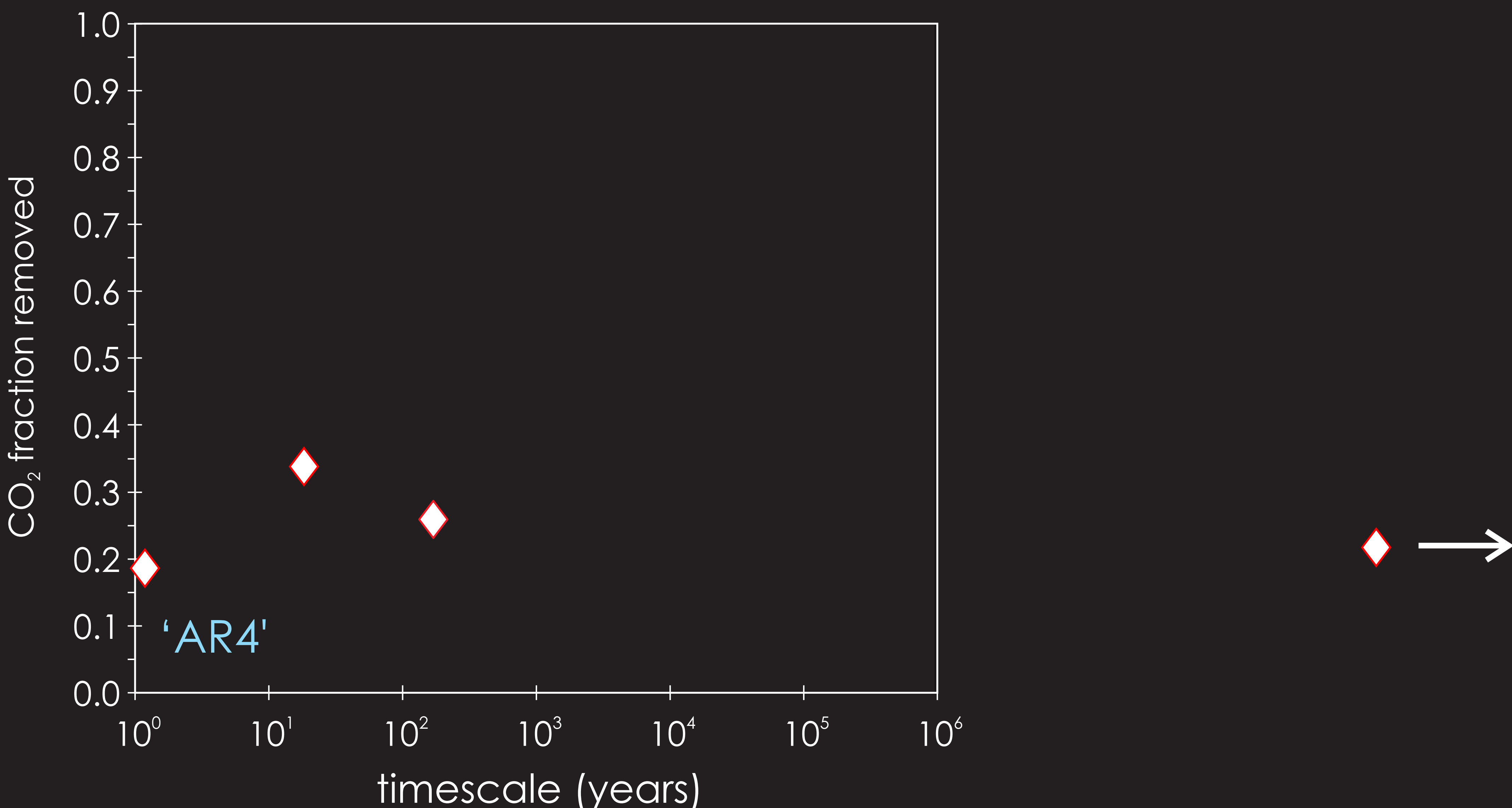
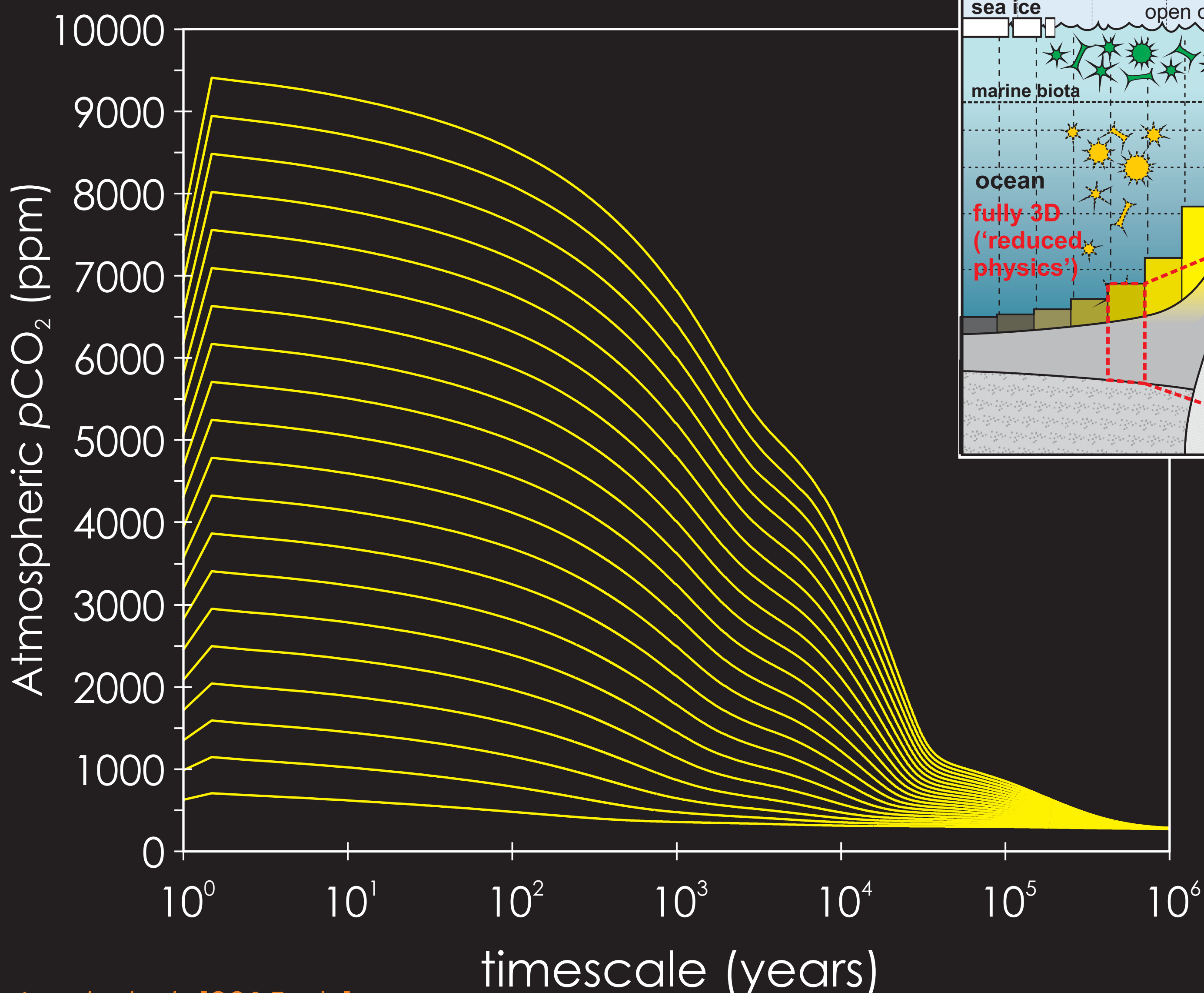
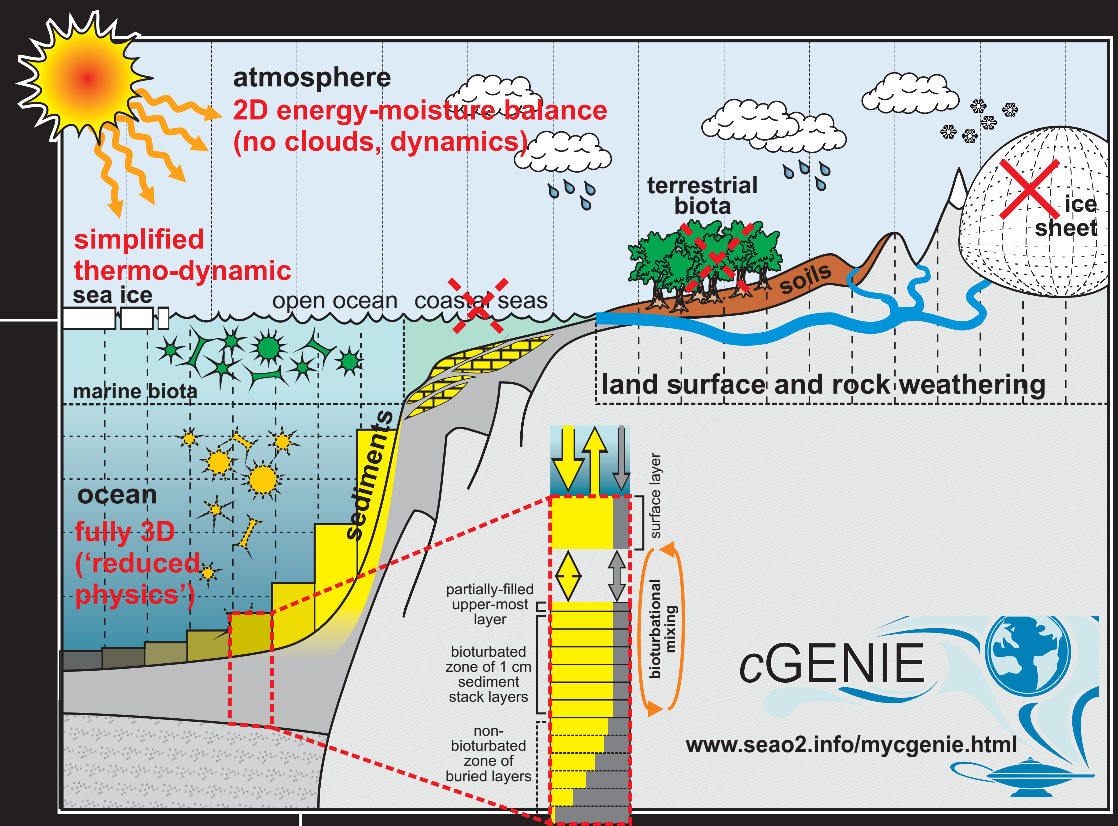


Impulse response function analysis of the 'long tail' of $CO_{2(excess)}$

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





Lord et al. [2015a,b]

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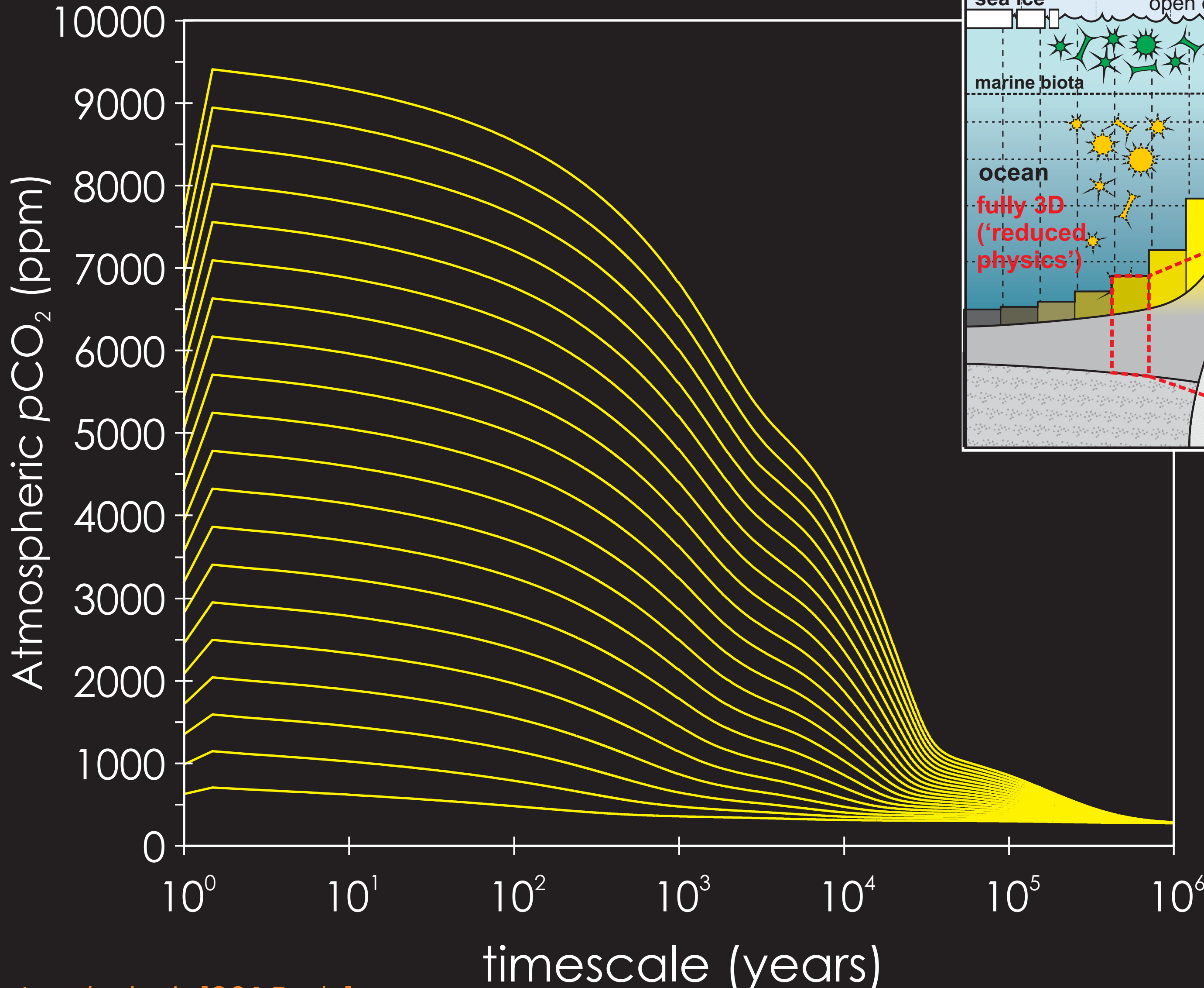
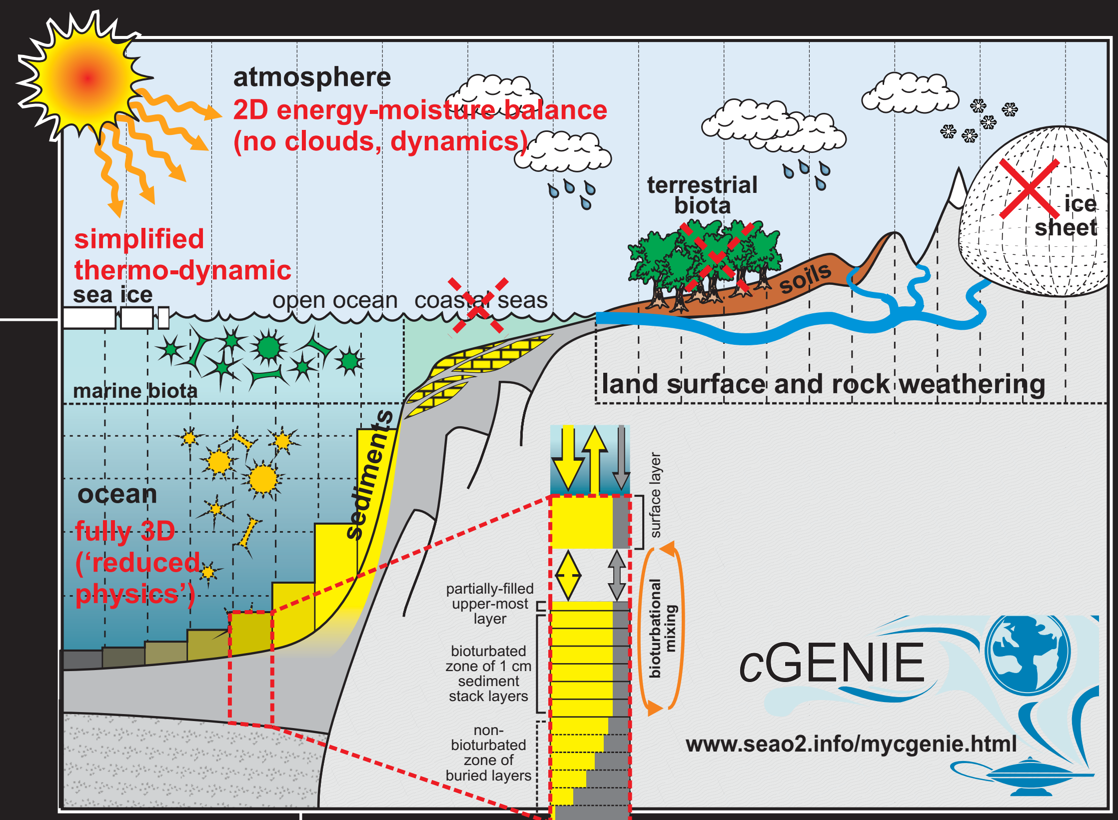




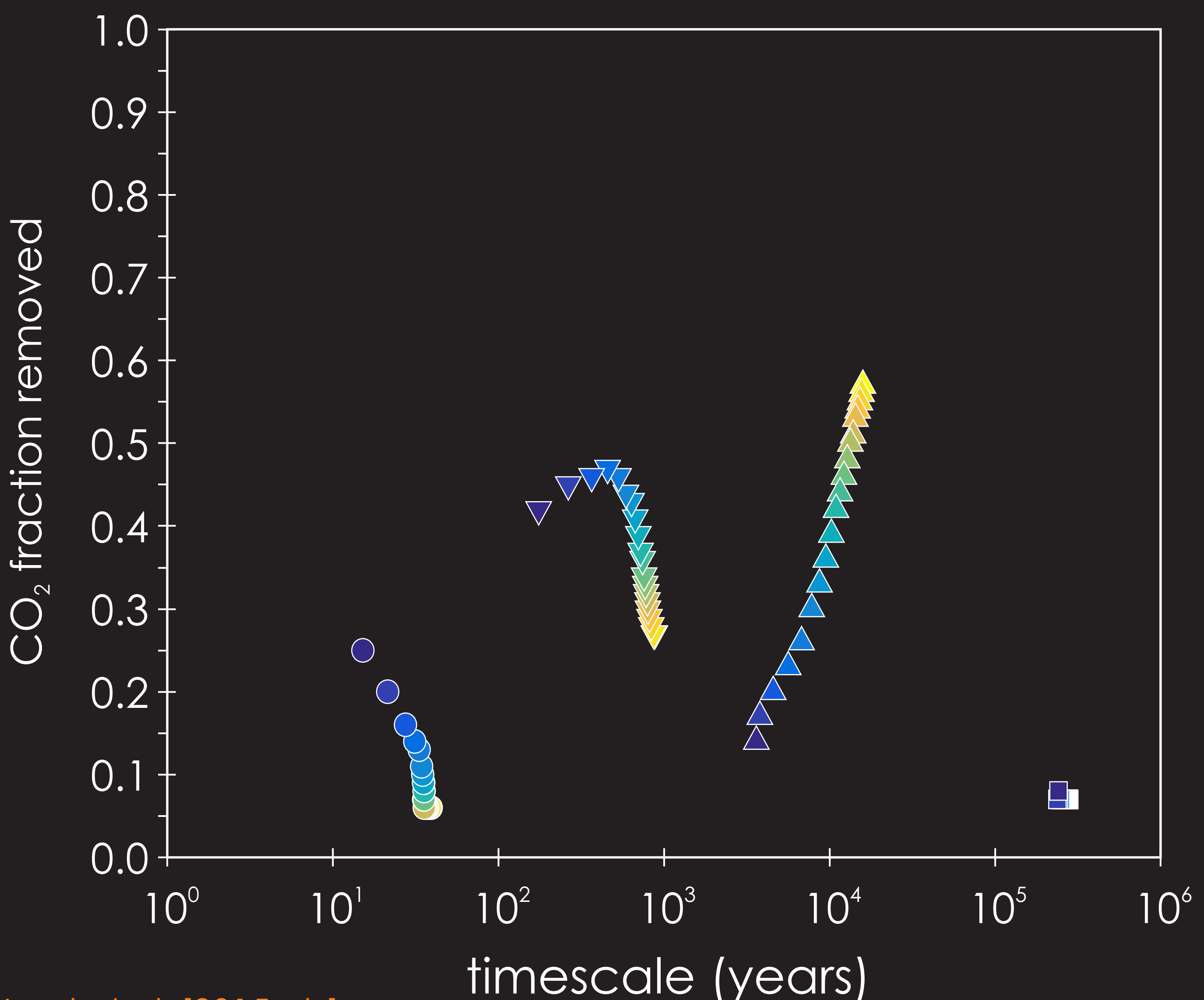
(2) Fit each CO_2 decay curve with a series (4 optimal) of exponentials. Extract the fraction of CO_2 and time-scale associated with each.

(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 $CO_{2(excess)}$

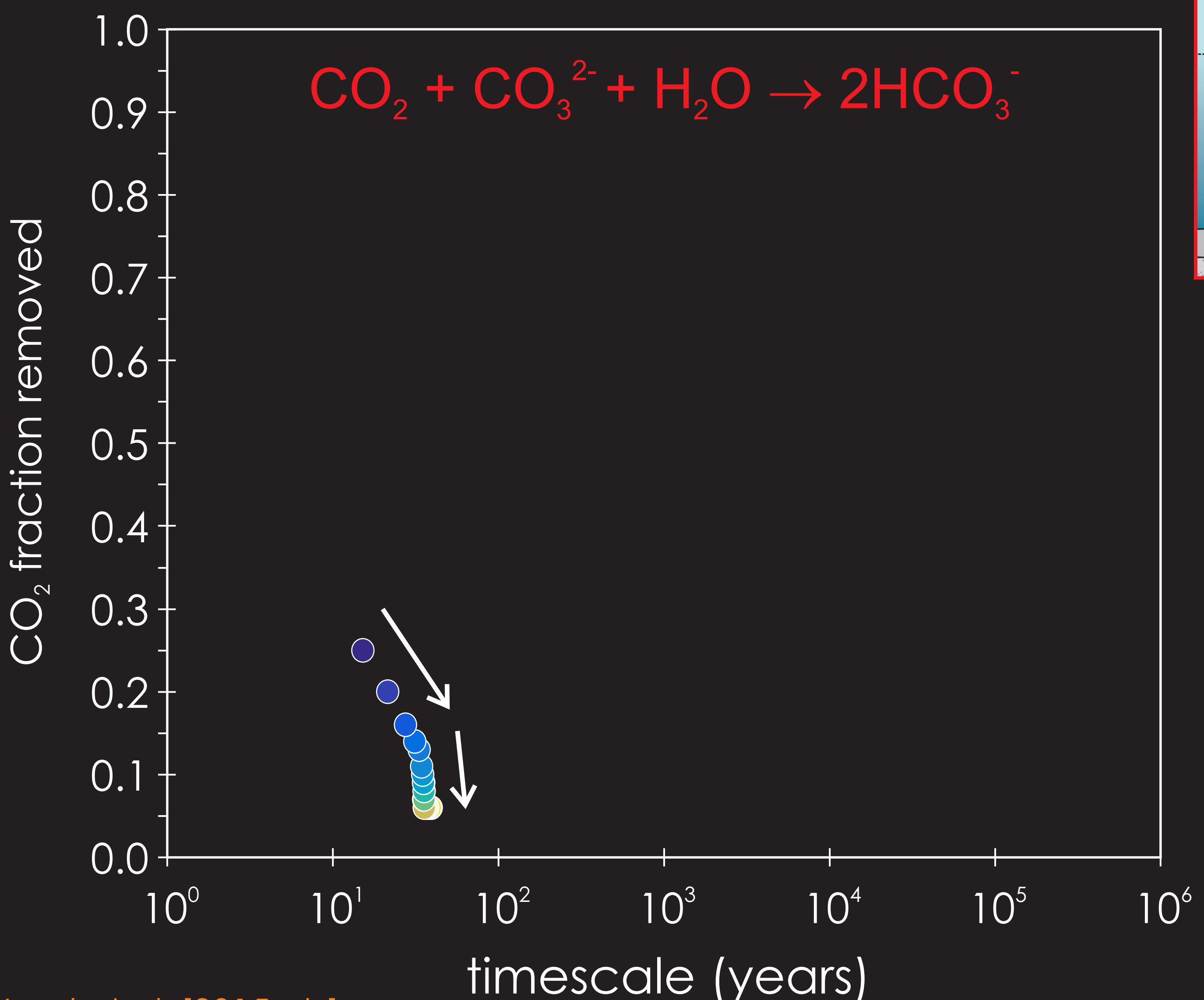
Response of fraction of CO_2 removed vs. the characteristic time-scale, as a function of total emissions, ranging from 1,000 PgC (dark blue) to 20,000 PgC (yellow).

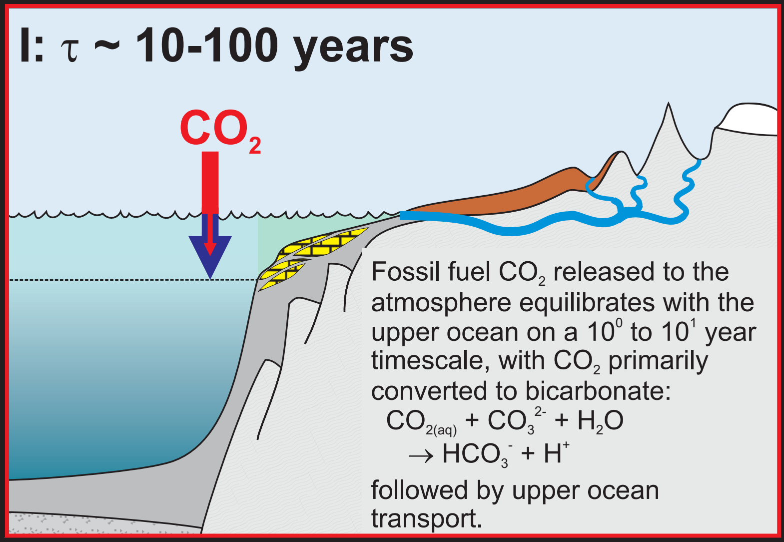


Lord et al. [2015a,b]

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

Depletion of mixed layer carbonate buffer; ocean stratification and reduced surface mixing. Warming and reduced CO_2 solubility.

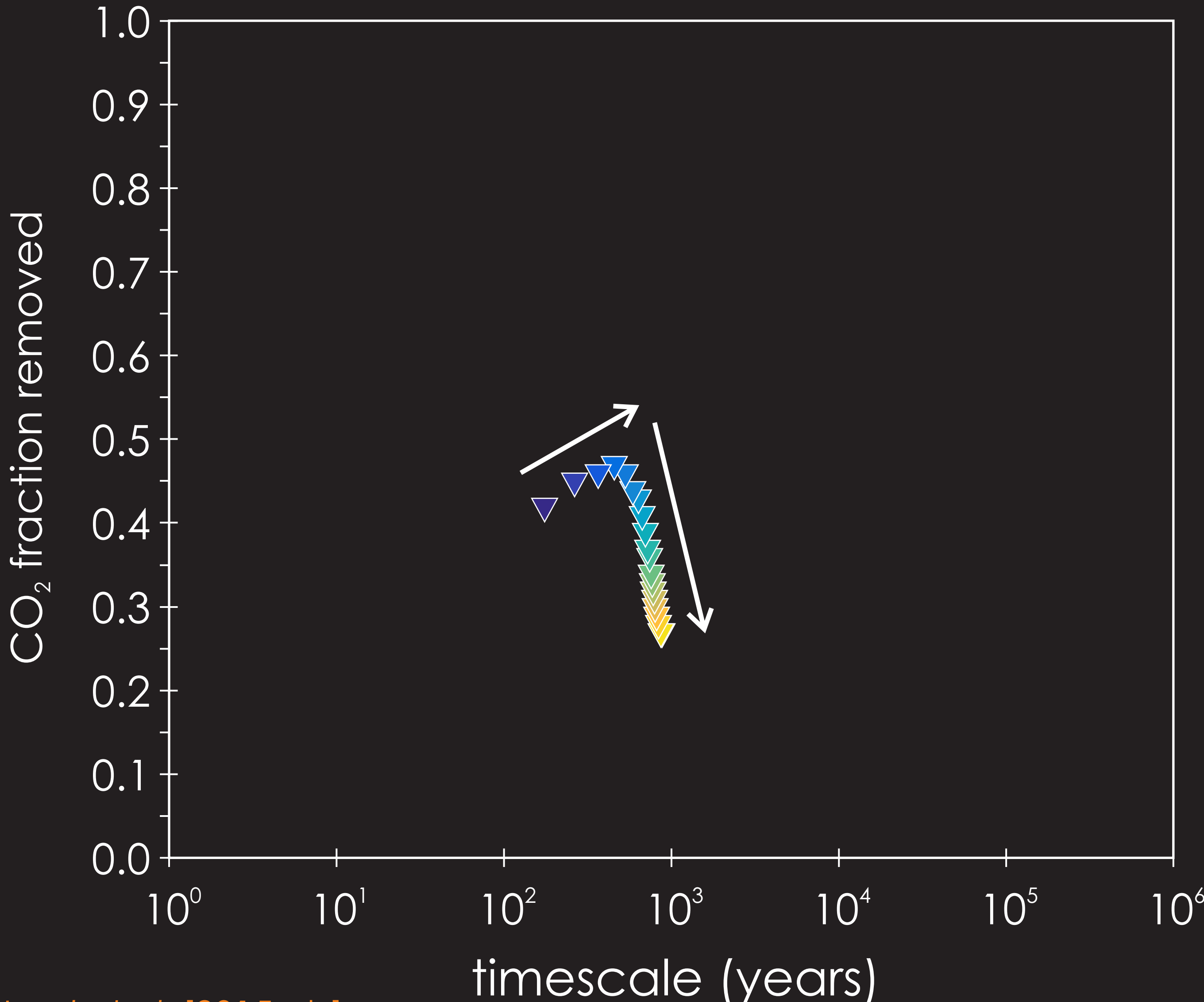


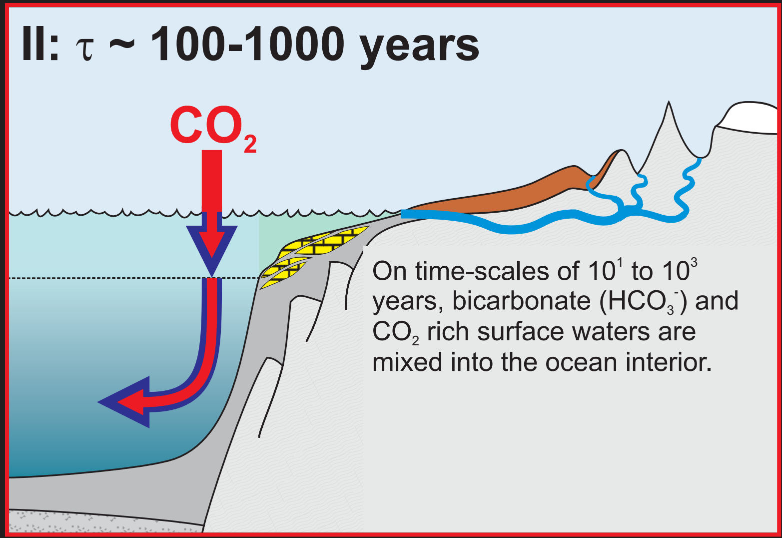


Lord et al. [2015a,b]

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

Ocean stratification and collapse of the AMOC (in this particular model).
Threshold reached @ ~4000 PgC?

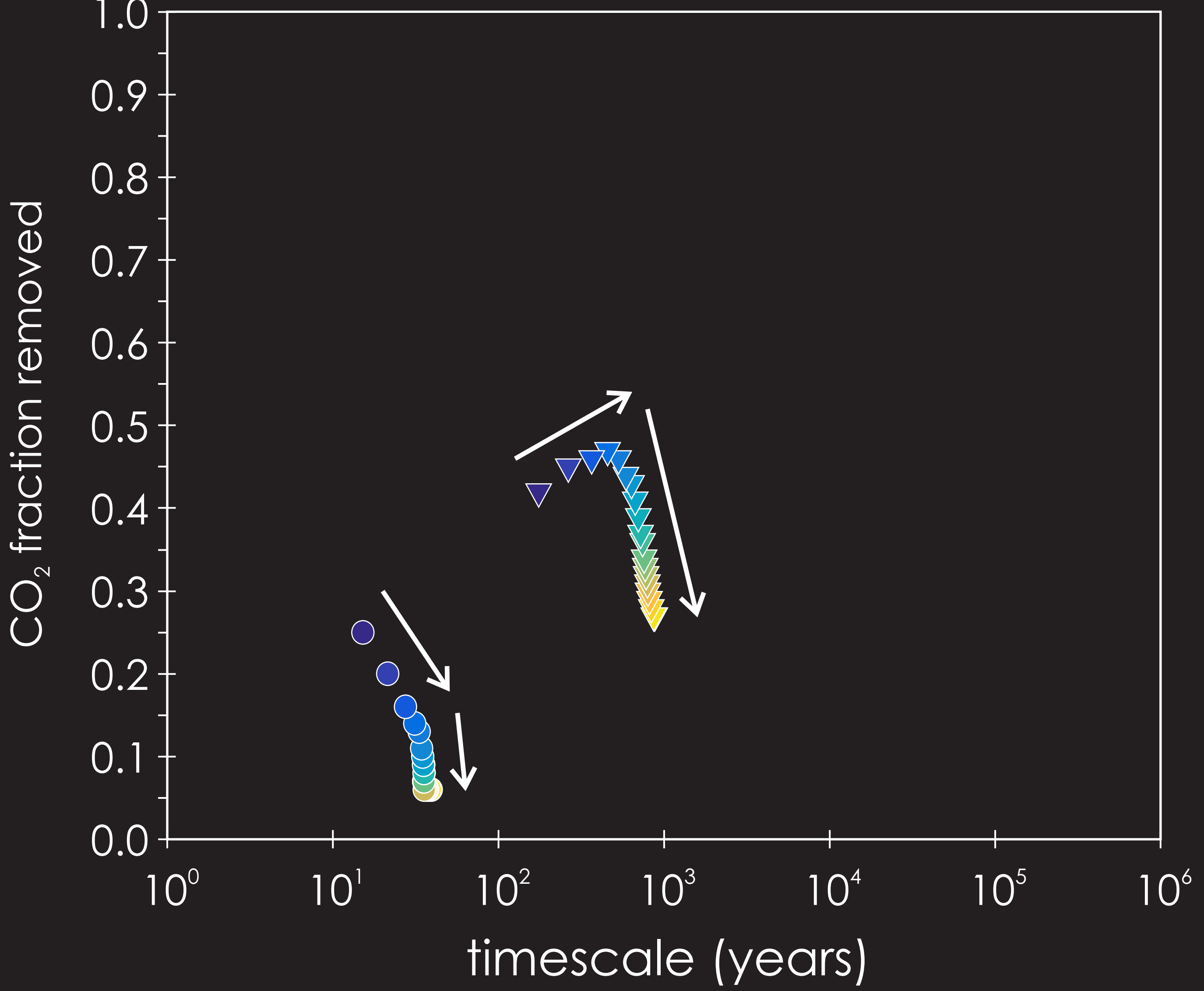




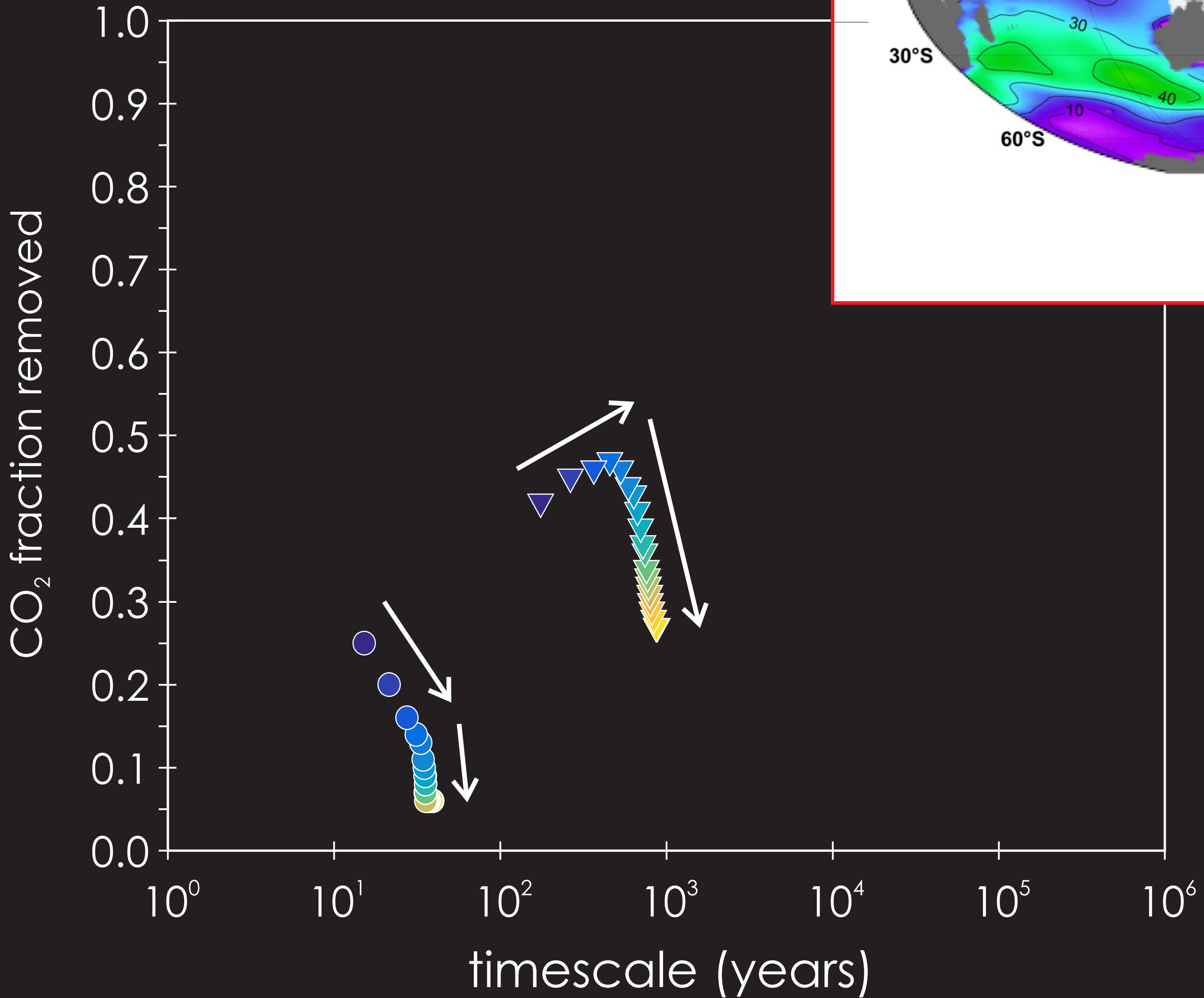
Lord et al. [2015a,b]

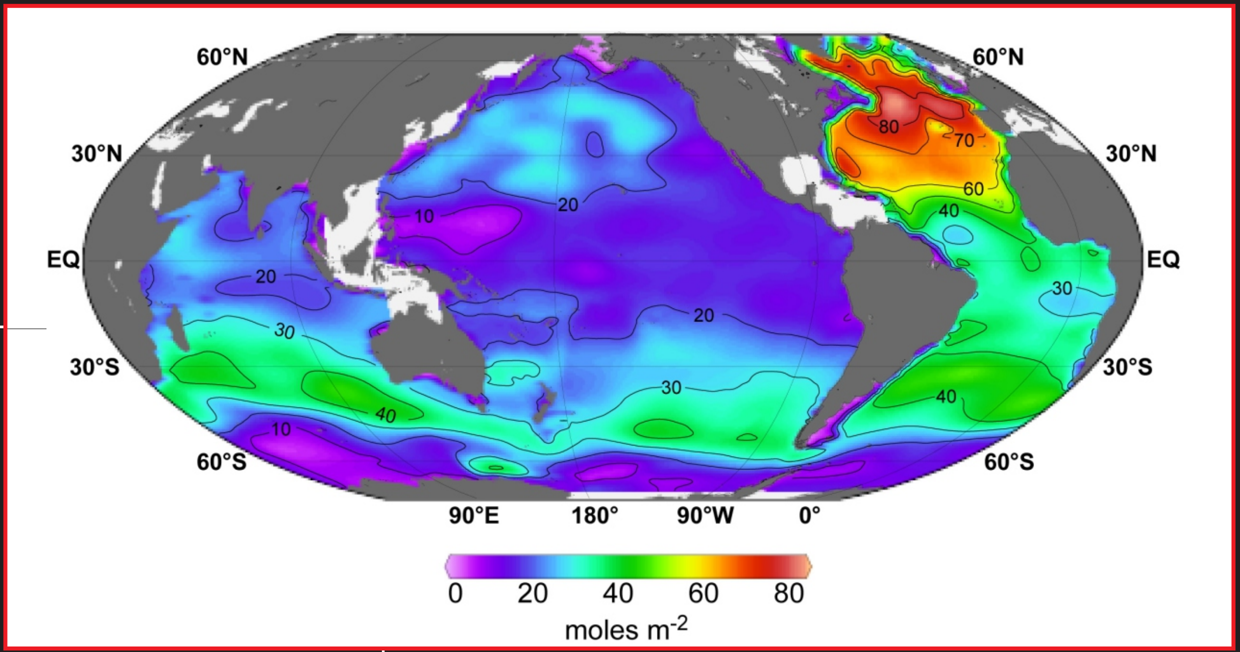
Impulse response function analysis of the 'long tail' of $CO_{2(excess)}$

evidence?



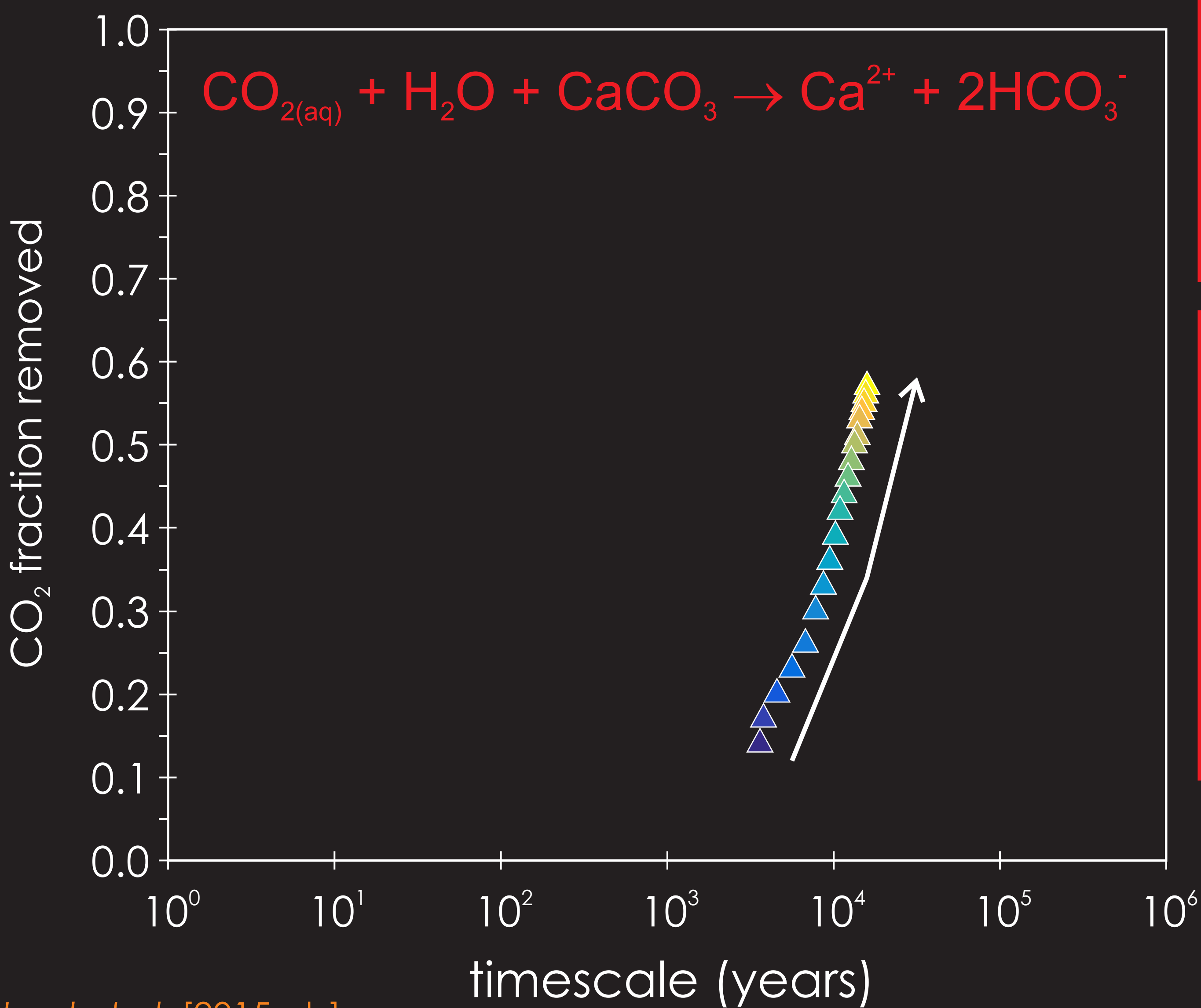
Impulse response function analysis of the 'long tail' of $CO_{2(excess)}$

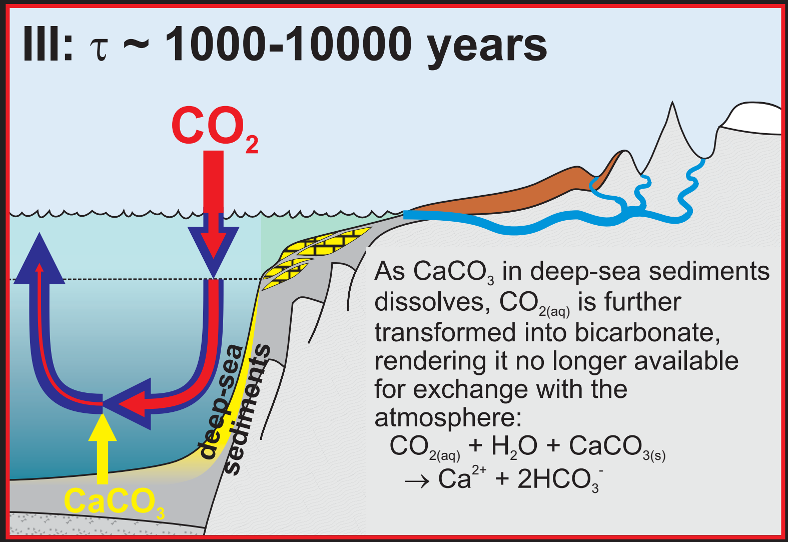


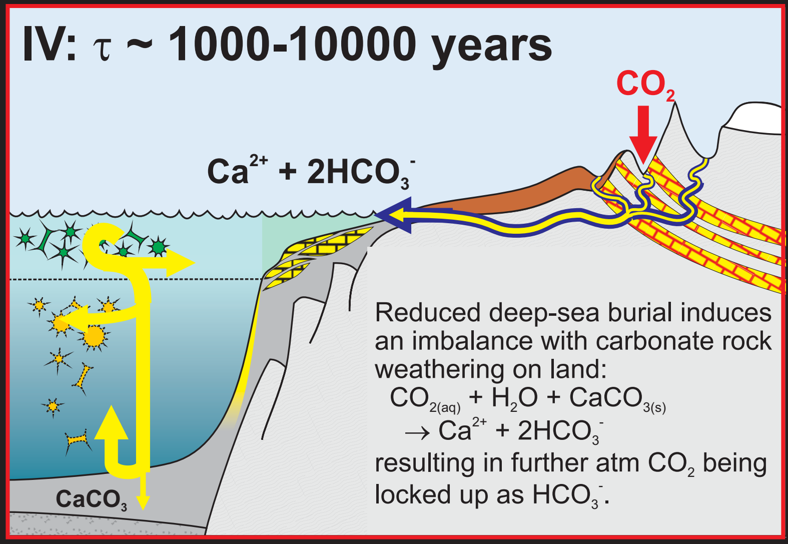


Impulse response function analysis of the 'long tail' of $CO_{2(excess)}$

Geologic CO_2 removal via carbonate rocks and marine sediments – occurring on an increasing protracted time-scale.







Lord et al. [2015a,b]

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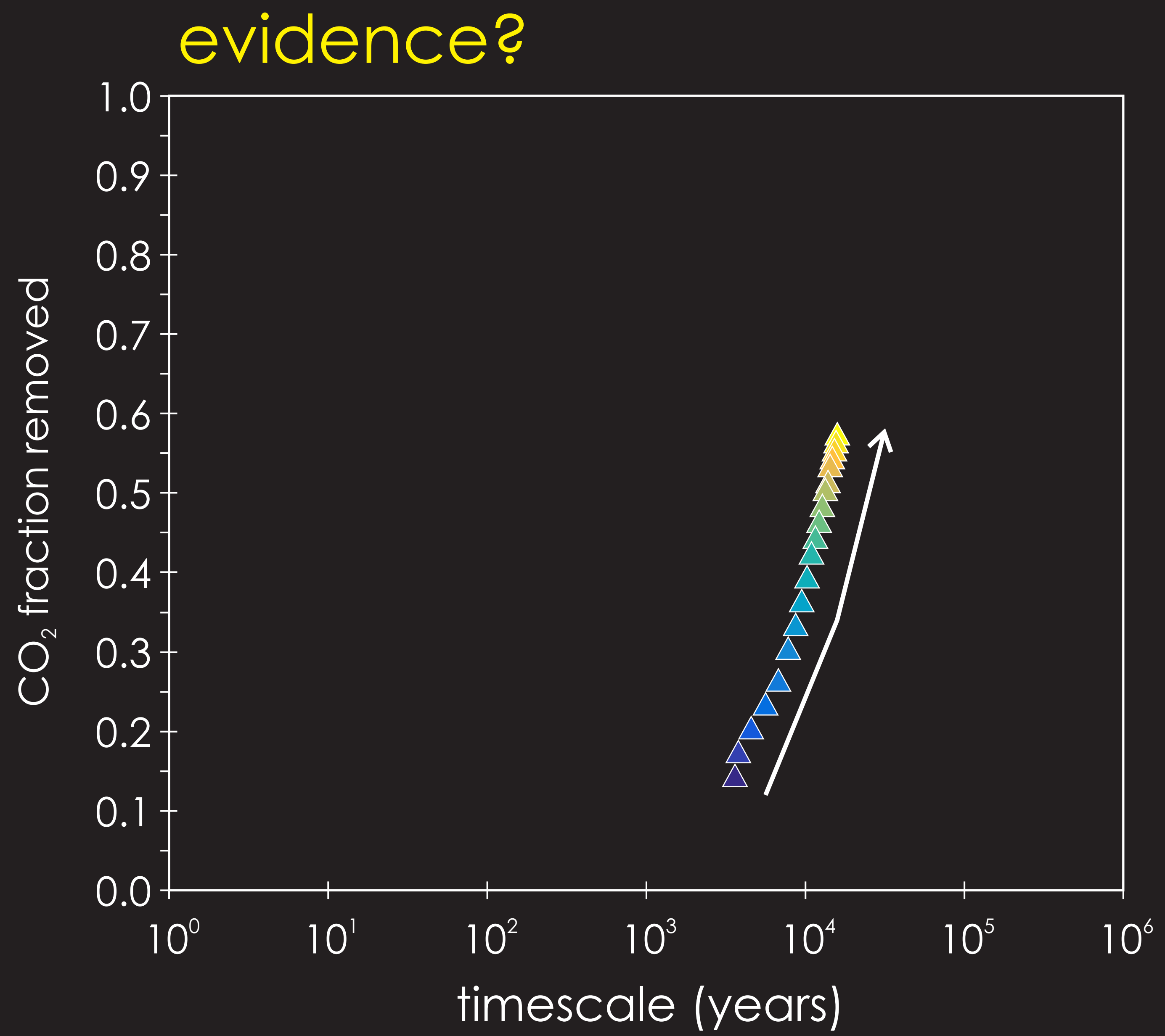

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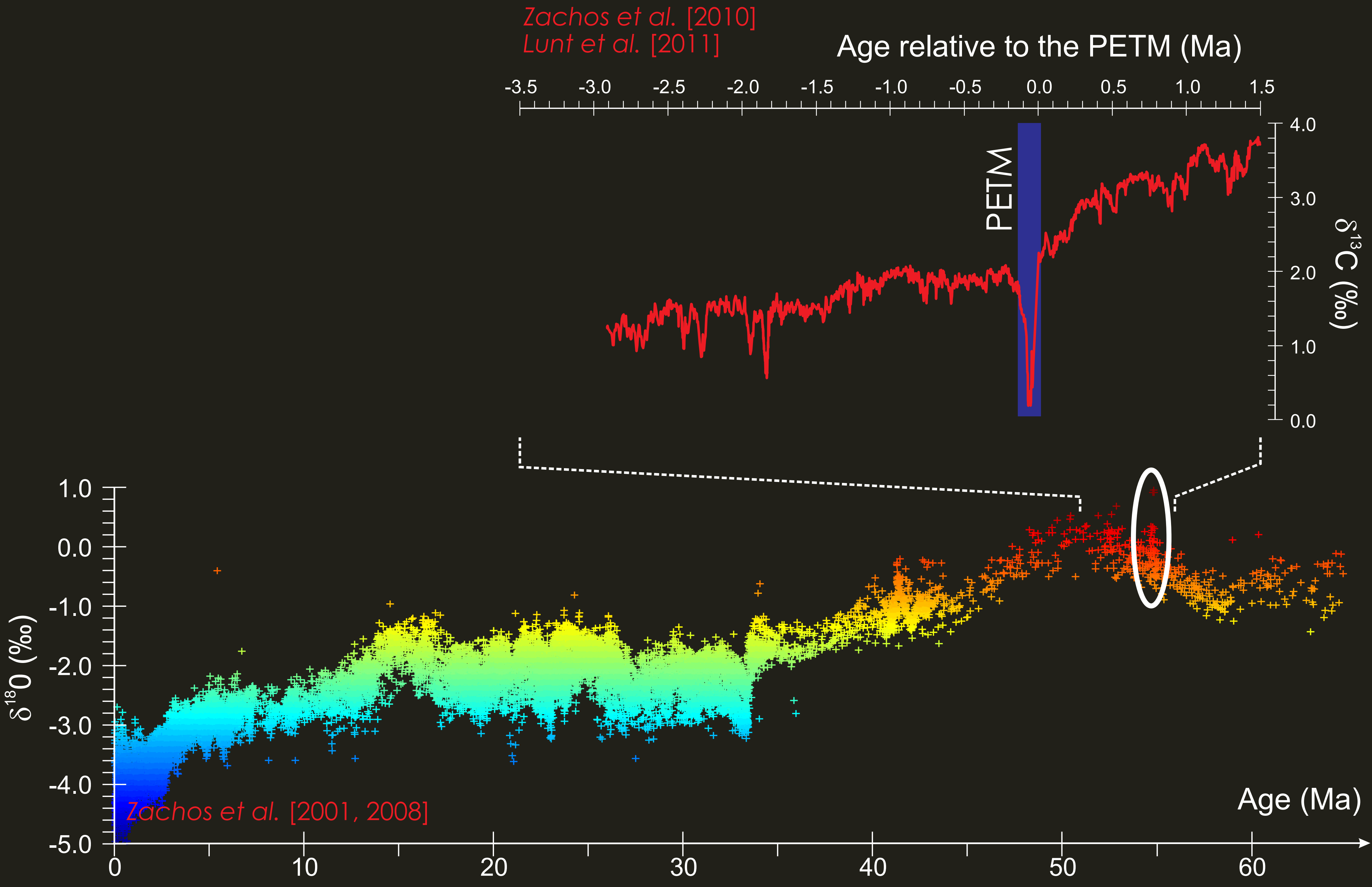

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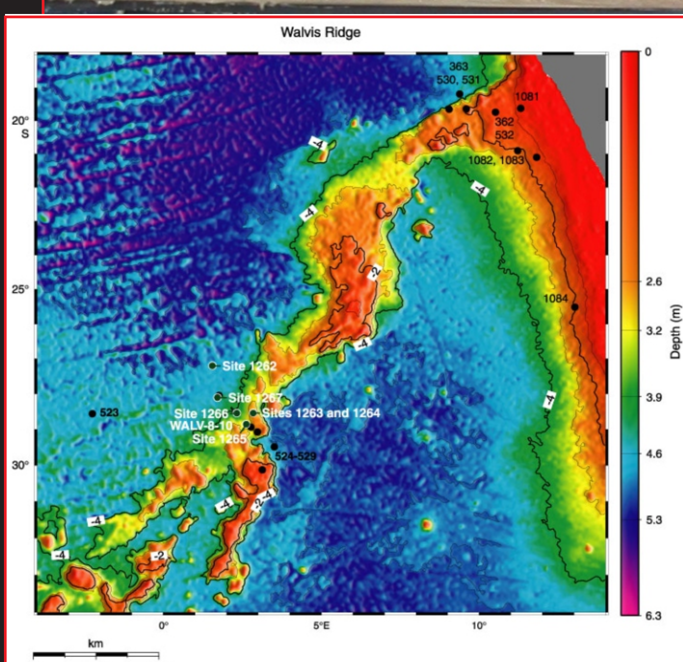
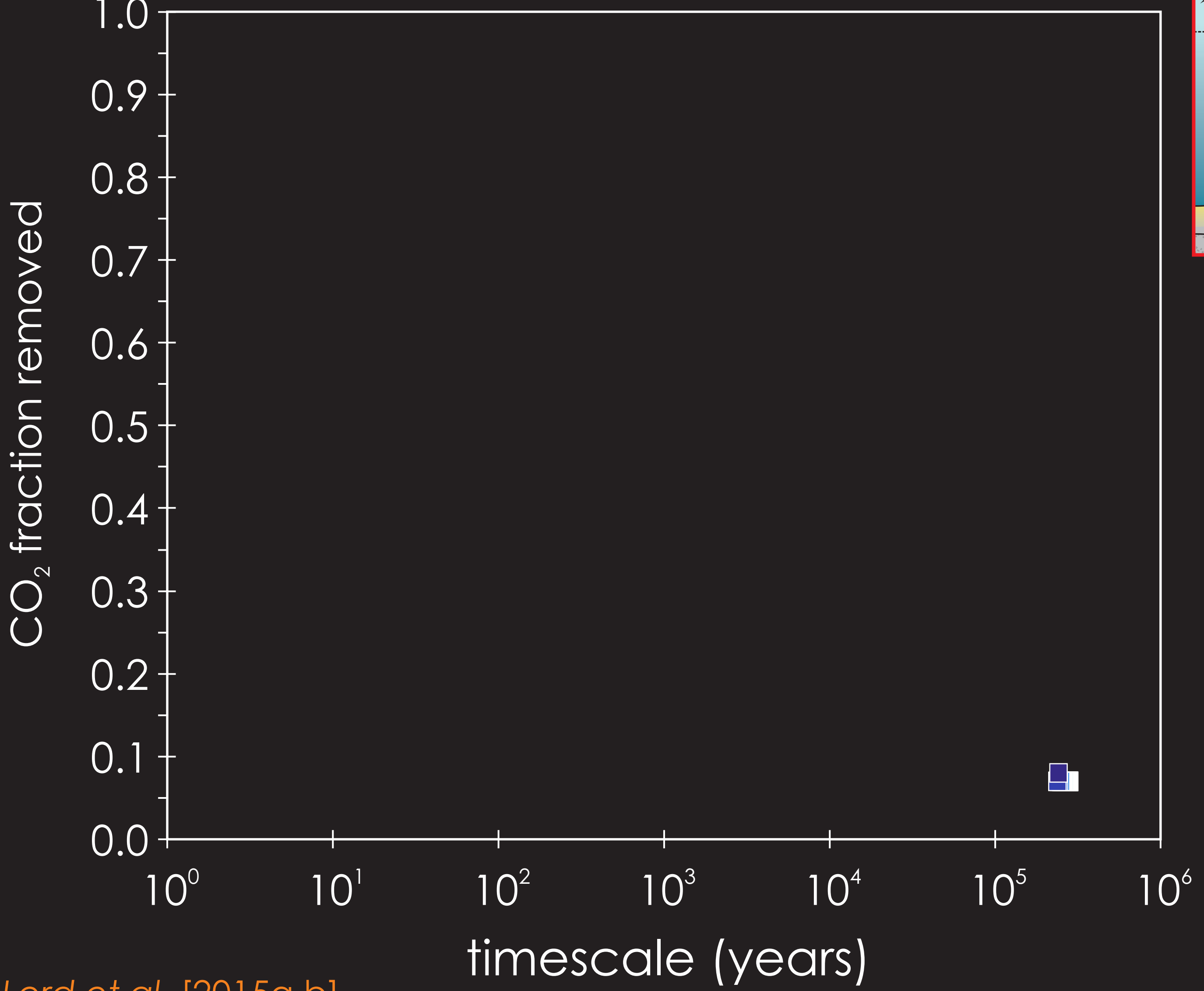
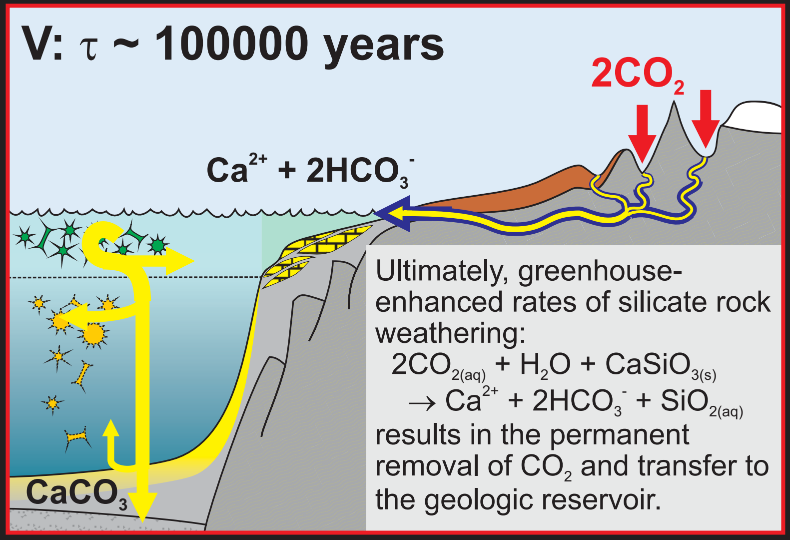


Sediments spanning the Palaeocene-Eocene boundary from ODP Leg 208 (Walvis Ridge)
Picture courtesy of Dani Schmidt (University of Bristol)

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

Silicate weathering (no time-scale response!).





Lord et al. [2015a,b]

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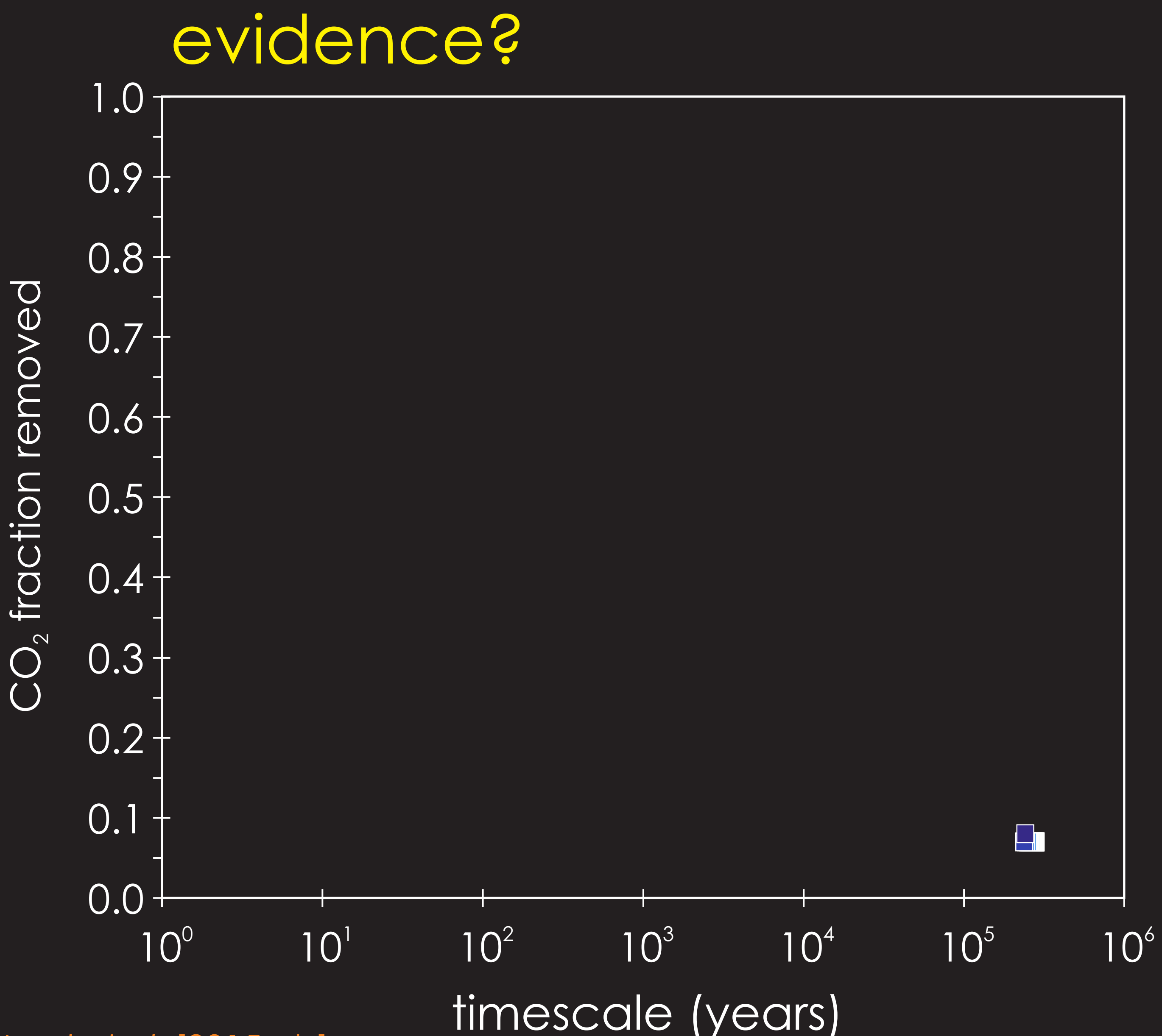

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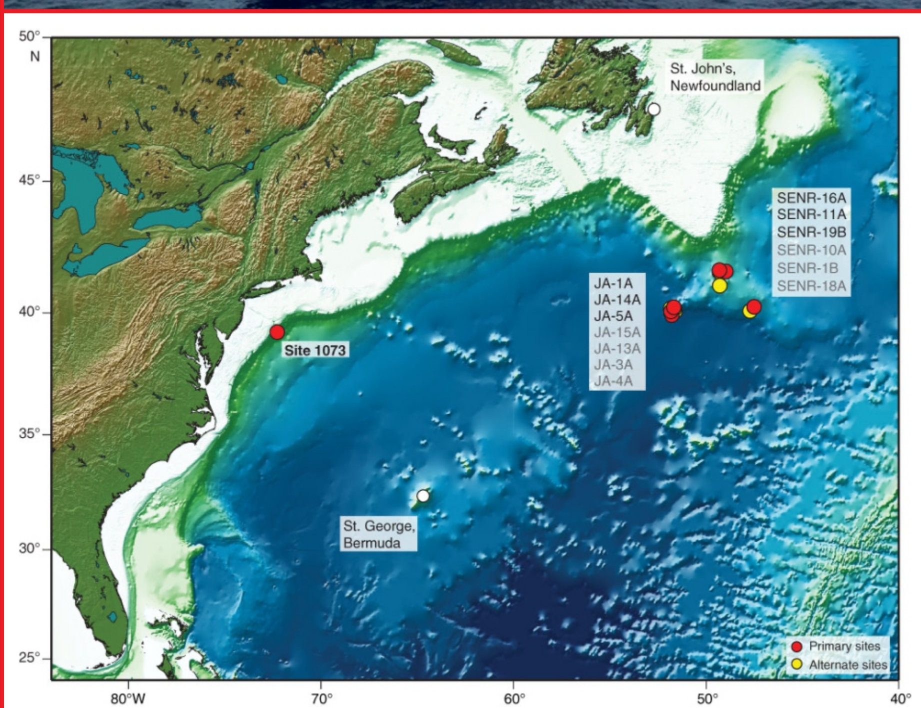
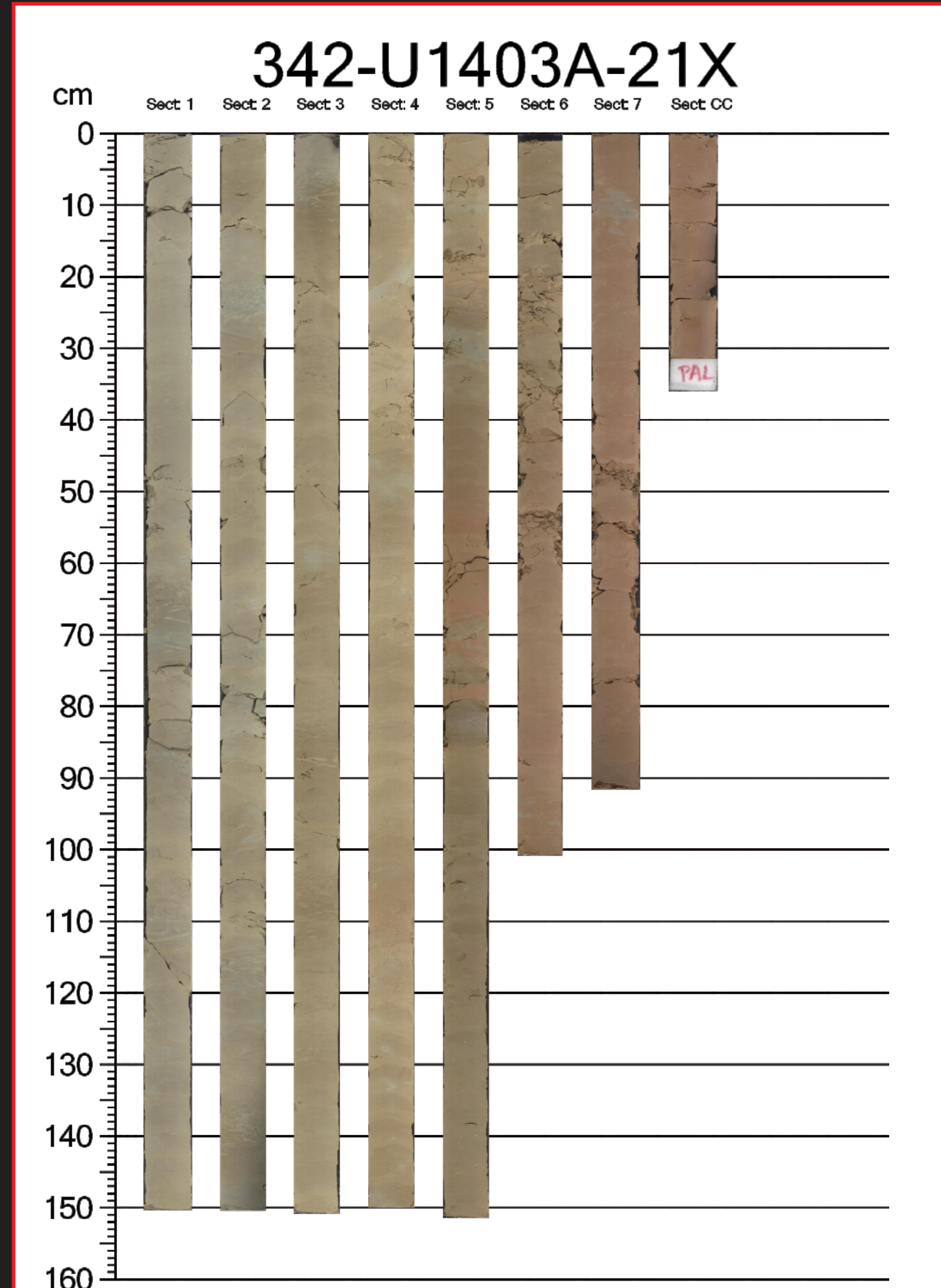
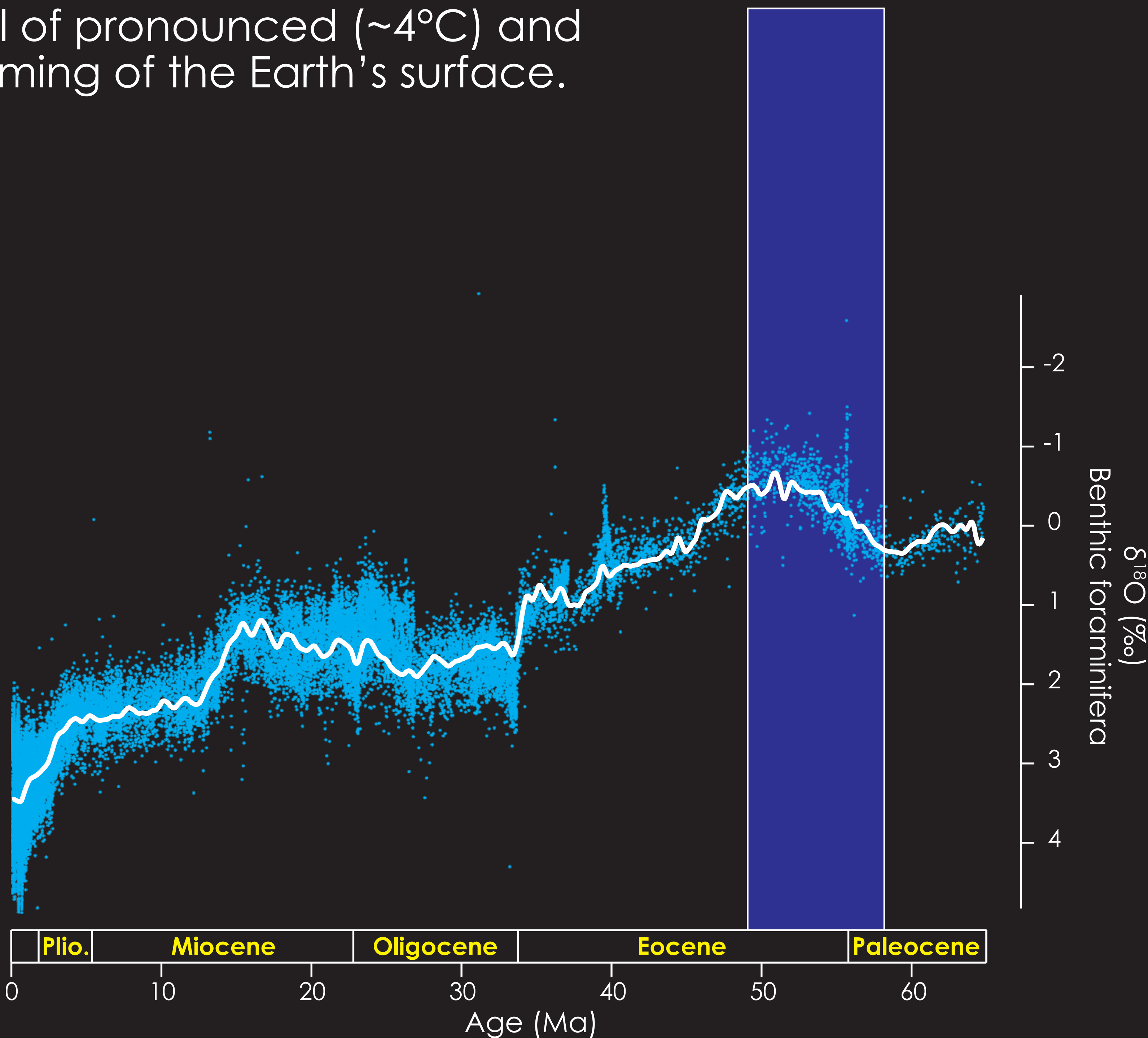




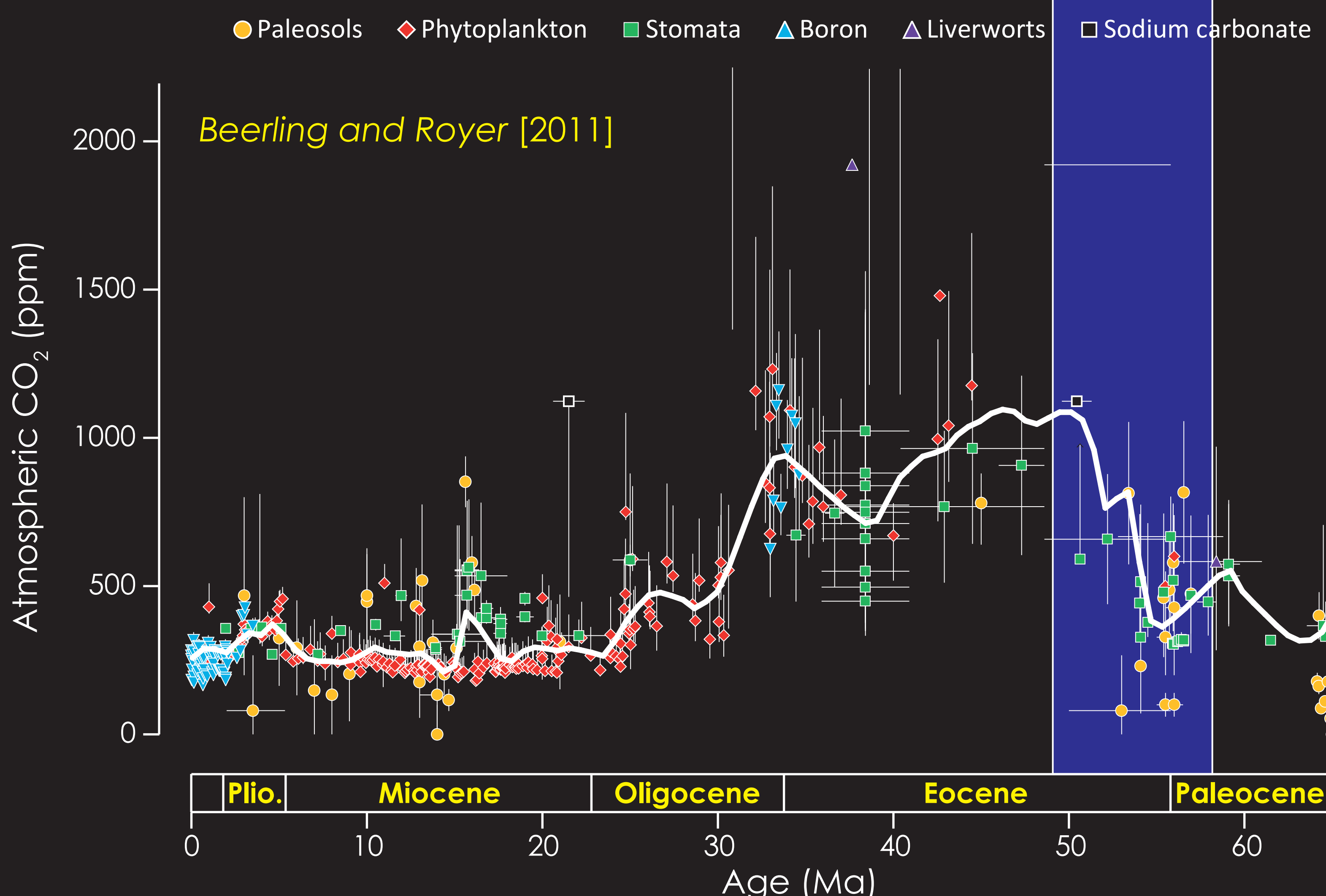
Evidence for climate-CO_2 weathering feedback?

✓ ~9 Ma interval of pronounced (~4°C) and progressive warming of the Earth's surface.



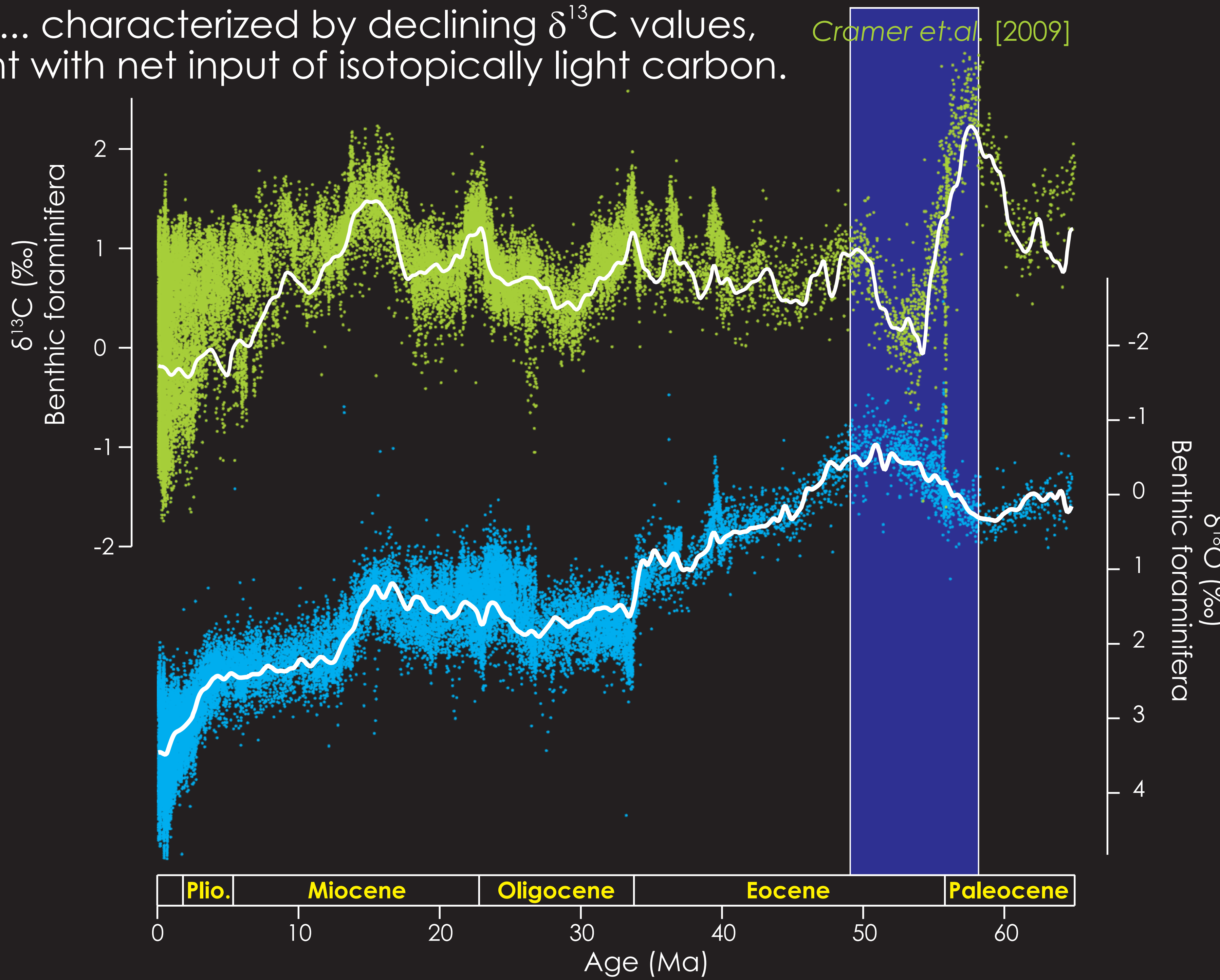
Evidence for climate-CO_2 weathering feedback?

✓ Increasing atmospheric pCO_2.



Evidence for climate-CO_2 weathering feedback?

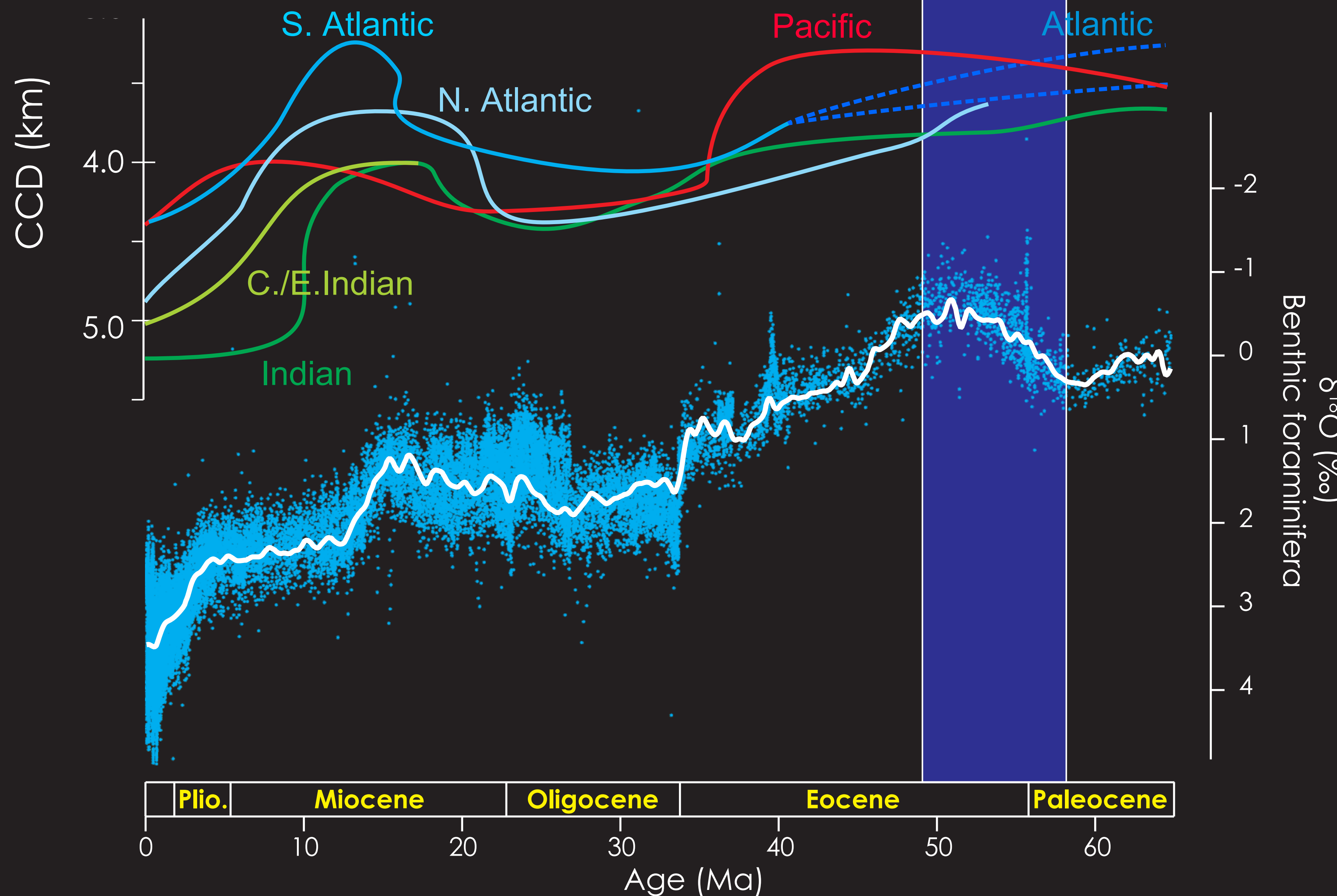
✓ Mostly ... characterized by declining $\delta^{13}C$ values, consistent with net input of isotopically light carbon.



Evidence for climate-CO_2 weathering feedback?

- Slightly deepening CCD ... but much less than box models predict (e.g. *Komar et al.* [2013]).
- Very sparse data coverage, not meaningfully updated since 1975.

Van Andel [1975]



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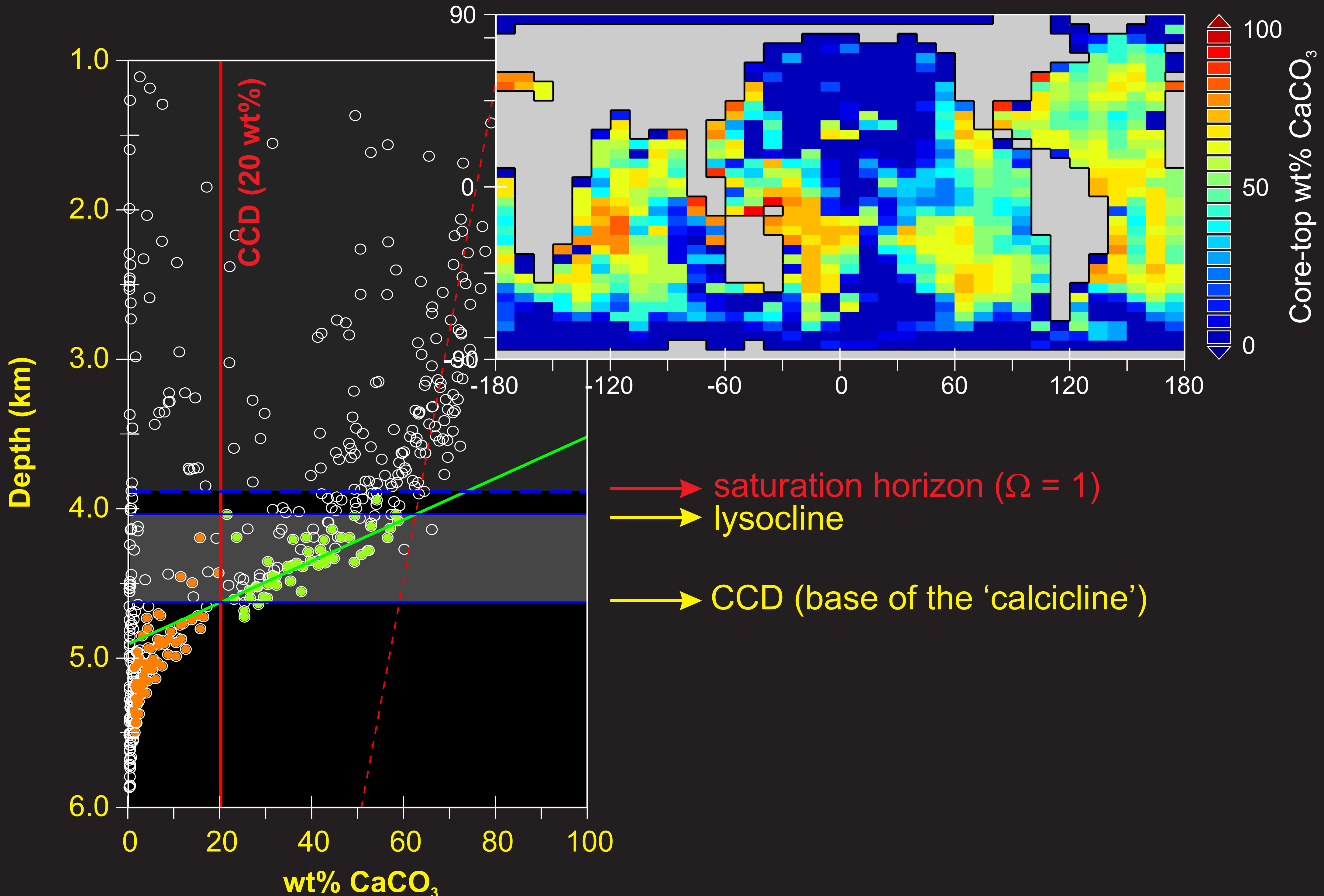

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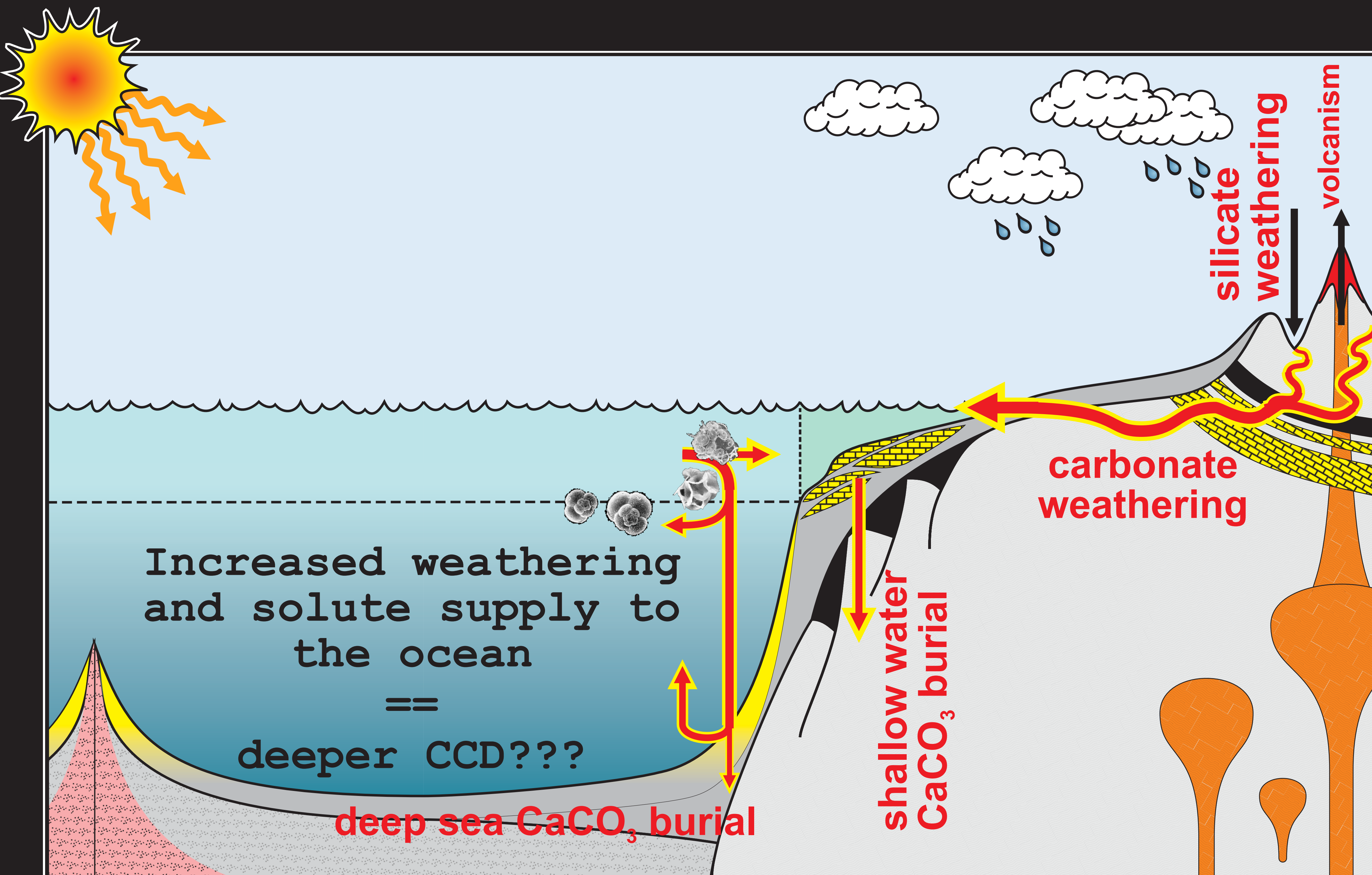
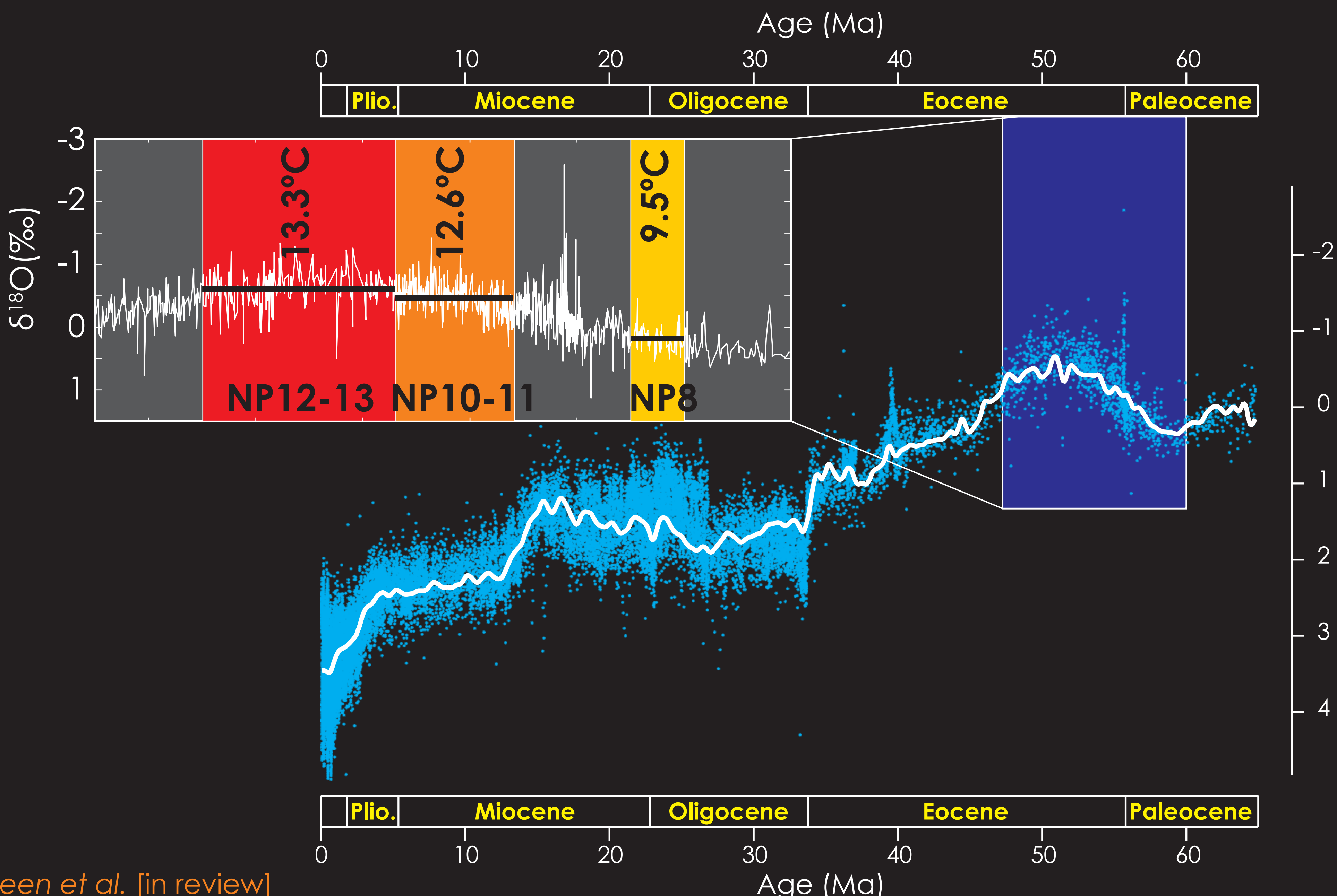


Evidence for climate-CO_2 weathering feedback?

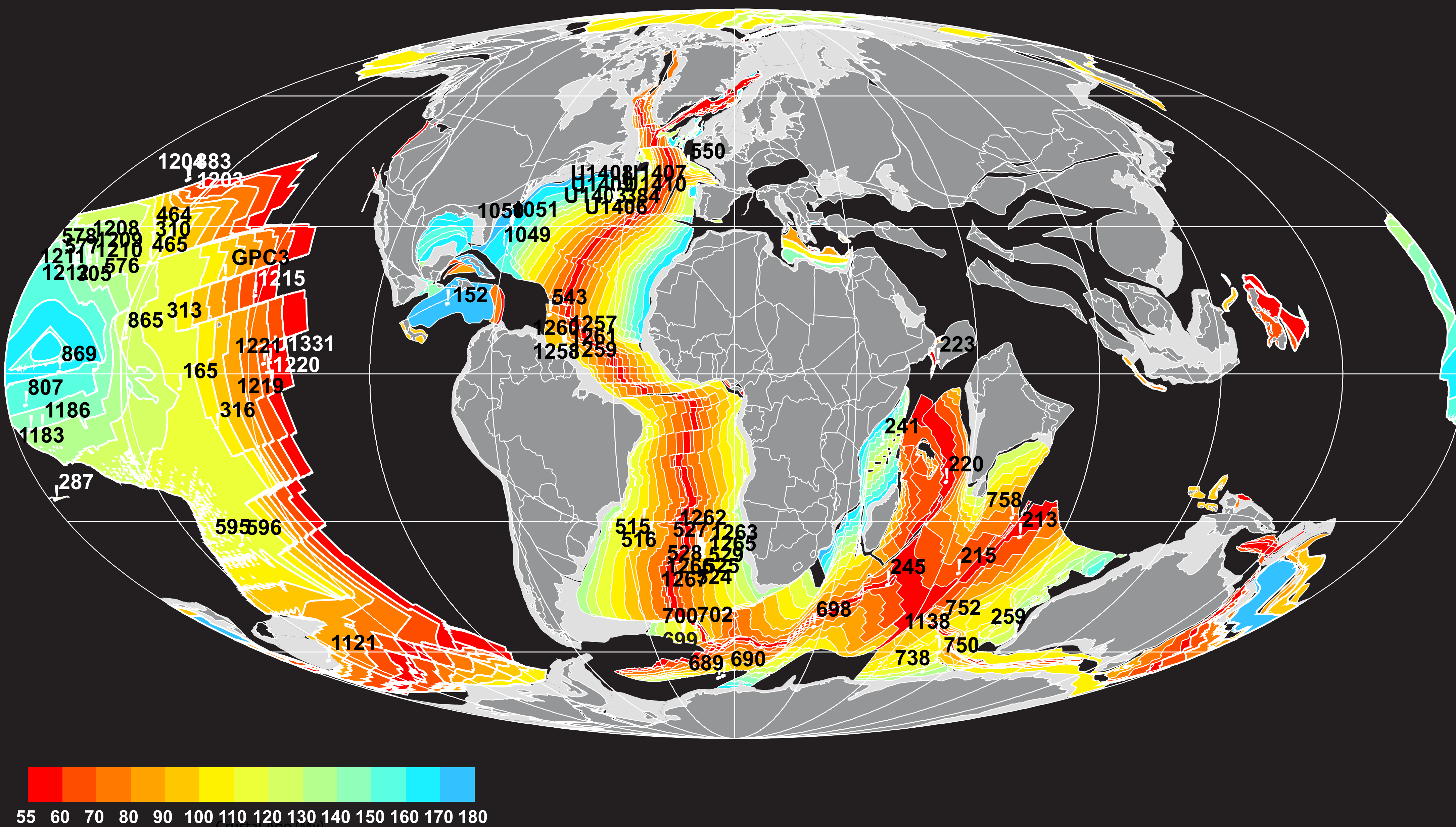
Three data slices spanning LPEE interval (and avoiding PETM).



Green *et al.* [in review]

Evidence for climate-CO_2 weathering feedback?

Site distribution (and existing crust older than 55 Ma).



Crustal age (Ma)

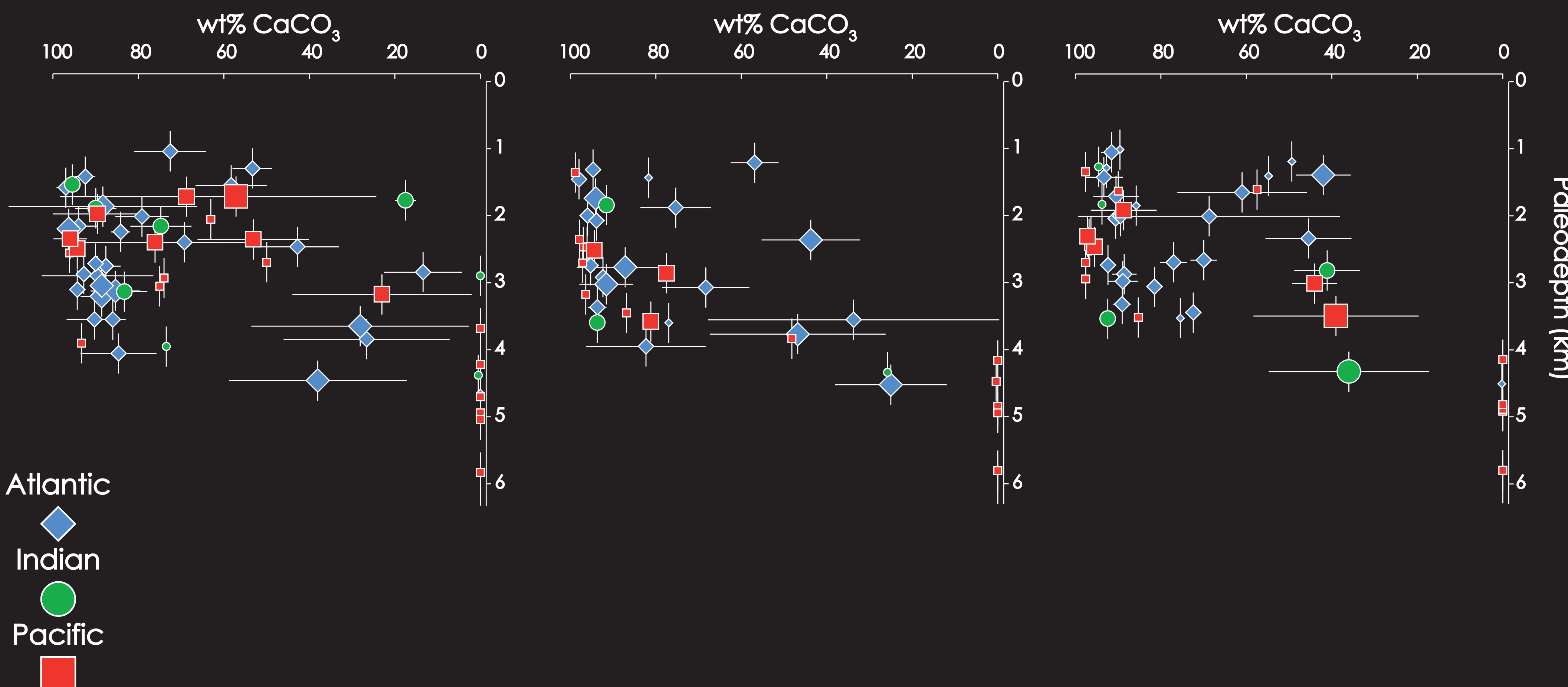
Green et al. [in review]

Evidence for climate-CO_2 weathering feedback?

'CCD' plots.

H_0: warming (=> increasing weathering?)

NP12-13 (~53-49 Ma) **NP10-11 (~55-53 Ma)** **NP8 (~58-57 Ma)**



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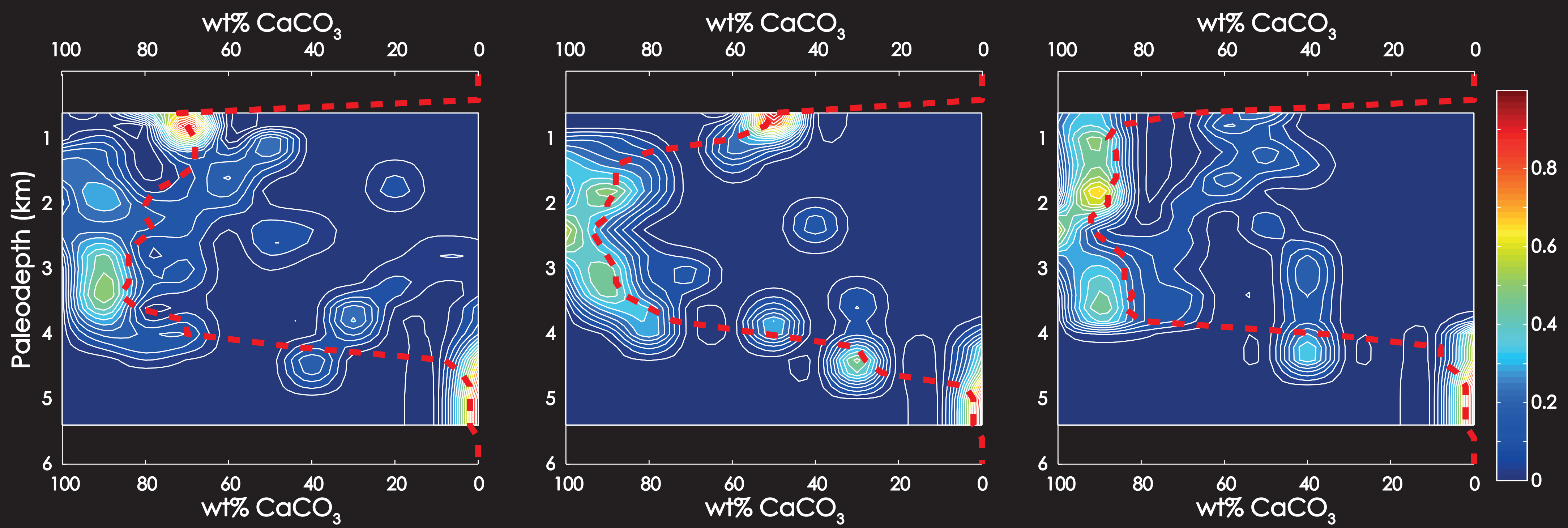
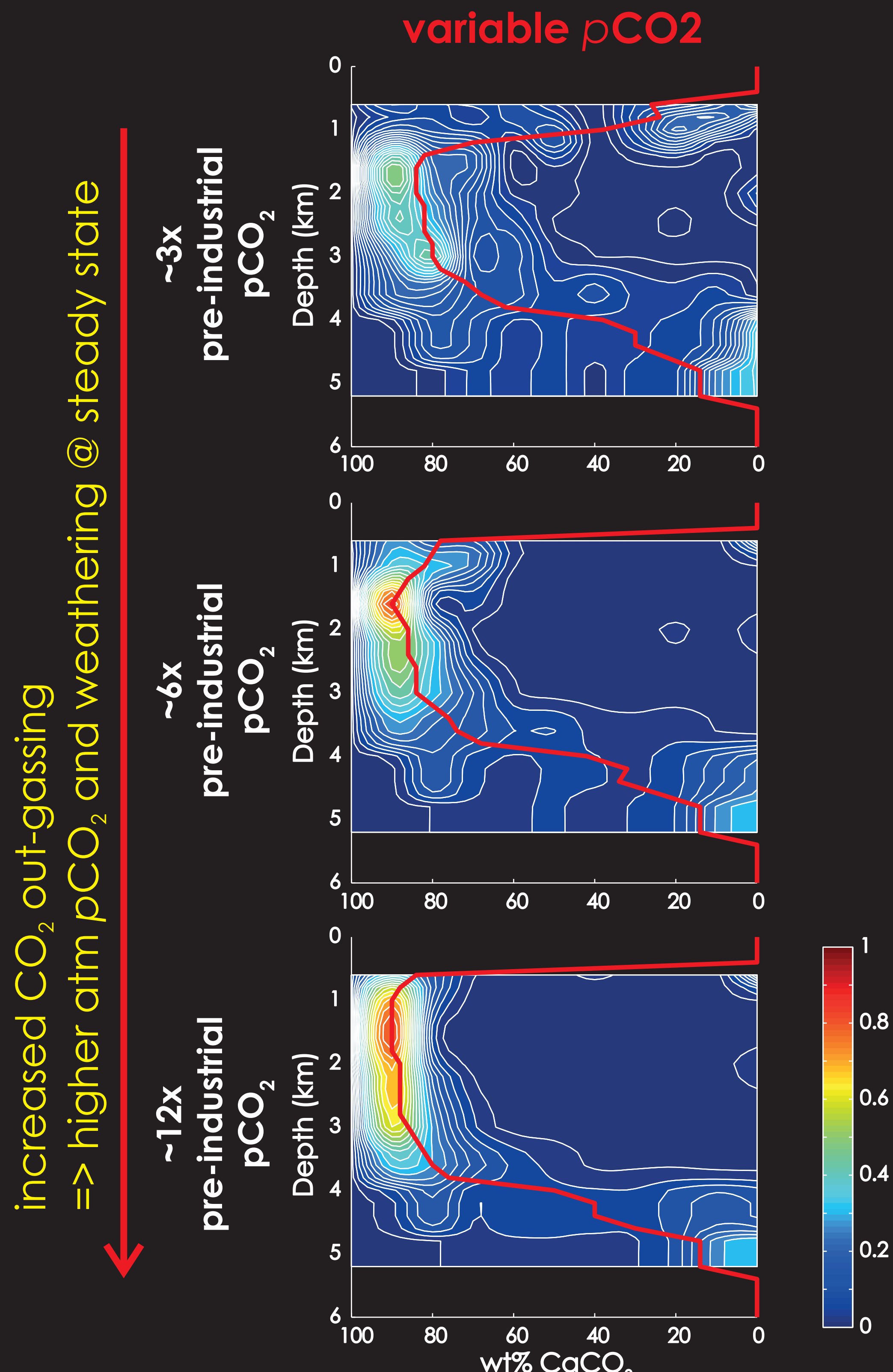


Contours are of relative data density within a sliding time-window (and wt% bin).

Red contour delineates 50% of the data.

Green et al. [in review]



cGENIE

Carbon-GENIE

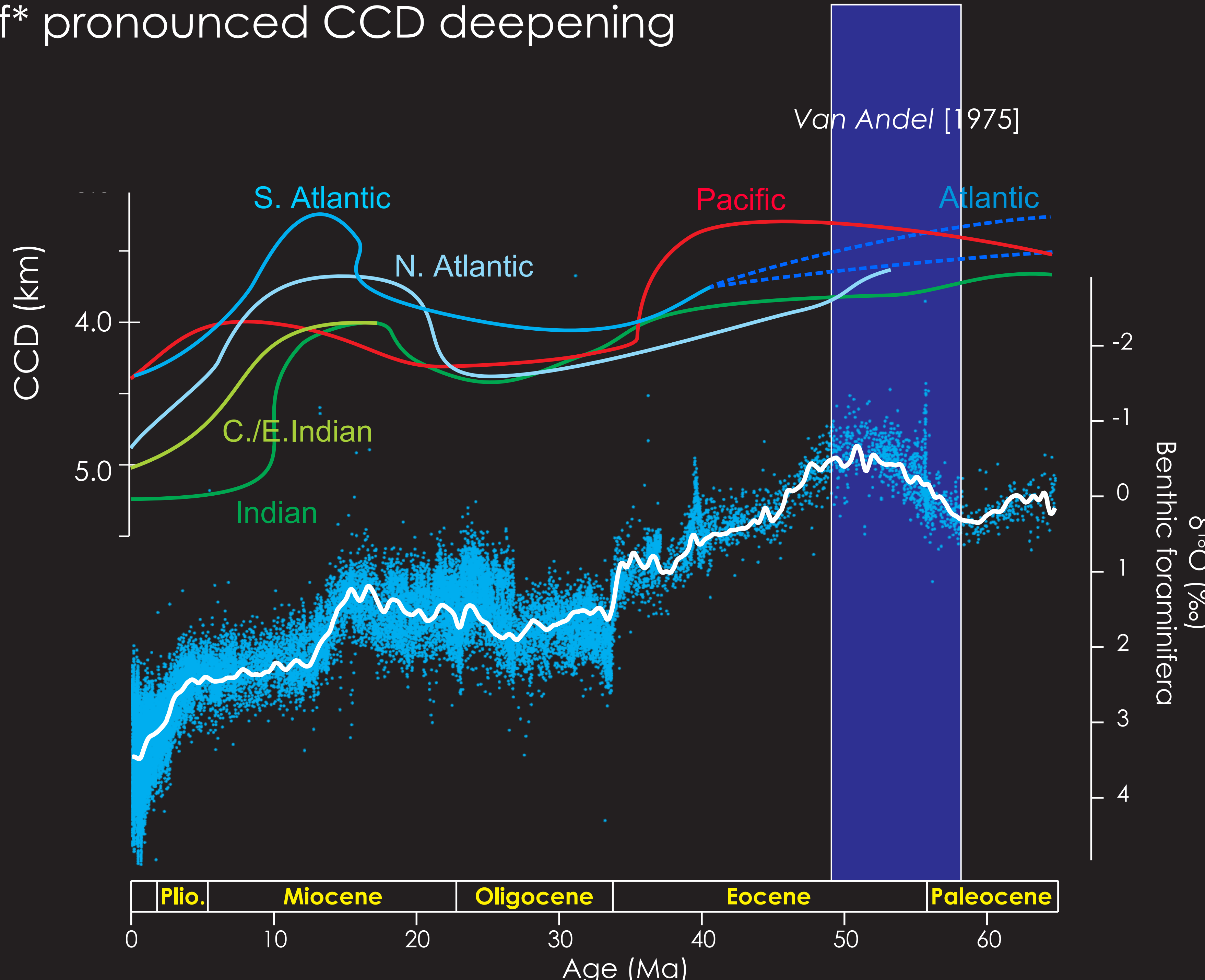
www.seao2.org

anon model

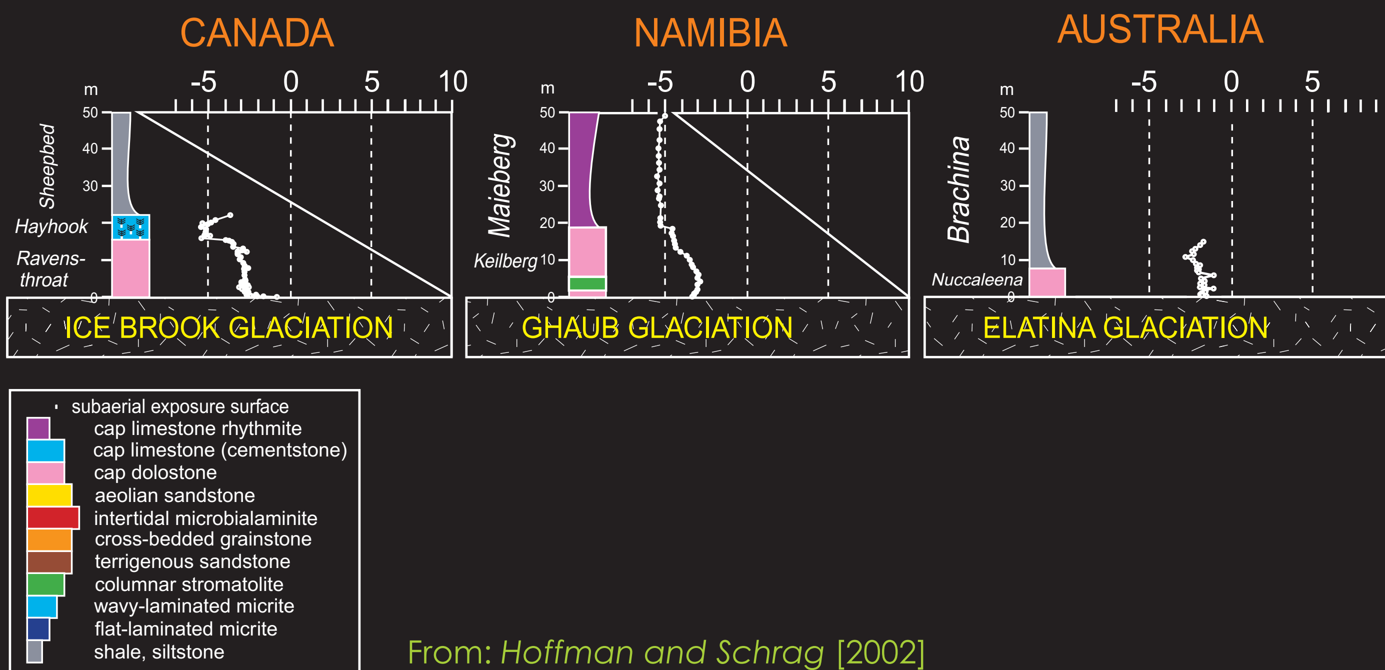
```
! calculate carbonate alkalinity

loc_ALK_DIC = dum_ALK &
& - loc_H4BO4 - loc_OH - loc_HPO4 -
2.0*loc_PO4 - loc_H3SiO4 - loc_NH3 - loc_HS
&
& + loc_H + loc_HSO4 + loc_HF + loc_H3PO4

! estimate the partitioning between the
aqueous carbonate species

loc_zed = ( &
&   (4.0*loc_ALK_DIC +
dum_DIC*dum_carbconst(icc_k) -
loc_ALK_DIC*dum_carbconst(icc_k))**2 + &
&   4.0*(dum_carbconst(icc_k) -
4.0)*loc_ALK_DIC**2 &
& )**0.5        loc_conc_HCO3 =
(dum_DIC*dum_carbconst(icc_k) -
loc_zed)/(dum_carbconst(icc_k) - 4.0)

loc_conc_CO3 = &
& ( &
&   loc_ALK_DIC*dum_carbconst(icc_k) -
dum_DIC*dum_carbconst(icc_k) - &
&   4.0*loc_ALK_DIC + loc_zed &
& ) &
& /(2.0*(dum_carbconst(icc_k) - 4.0))

loc_conc_CO2 = dum_DIC - loc_ALK_DIC + &
& ( &
&   loc_ALK_DIC*dum_carbconst(icc_k) -
dum_DIC*dum_carbconst(icc_k) - &
&   4.0*loc_ALK_DIC + loc_zed &
& ) &
& /(2.0*(dum_carbconst(icc_k) - 4.0))

loc_H1 =
dum_carbconst(icc_k1)*loc_conc_CO2/loc_conc_
HCO3

loc_H2 =
dum_carbconst(icc_k2)*loc_conc_HCO3/loc_conc
_CO3
```

Evidence for climate-CO_2 weathering feedback?

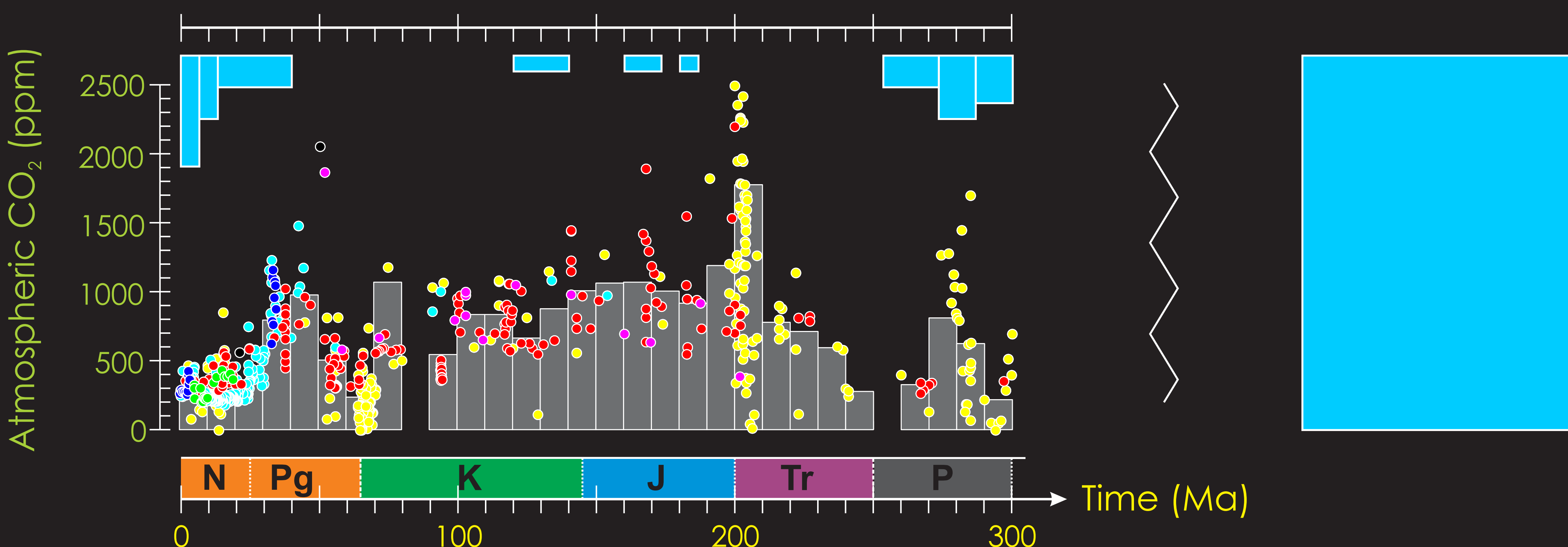
✓ *lack of* pronounced CCD deepening



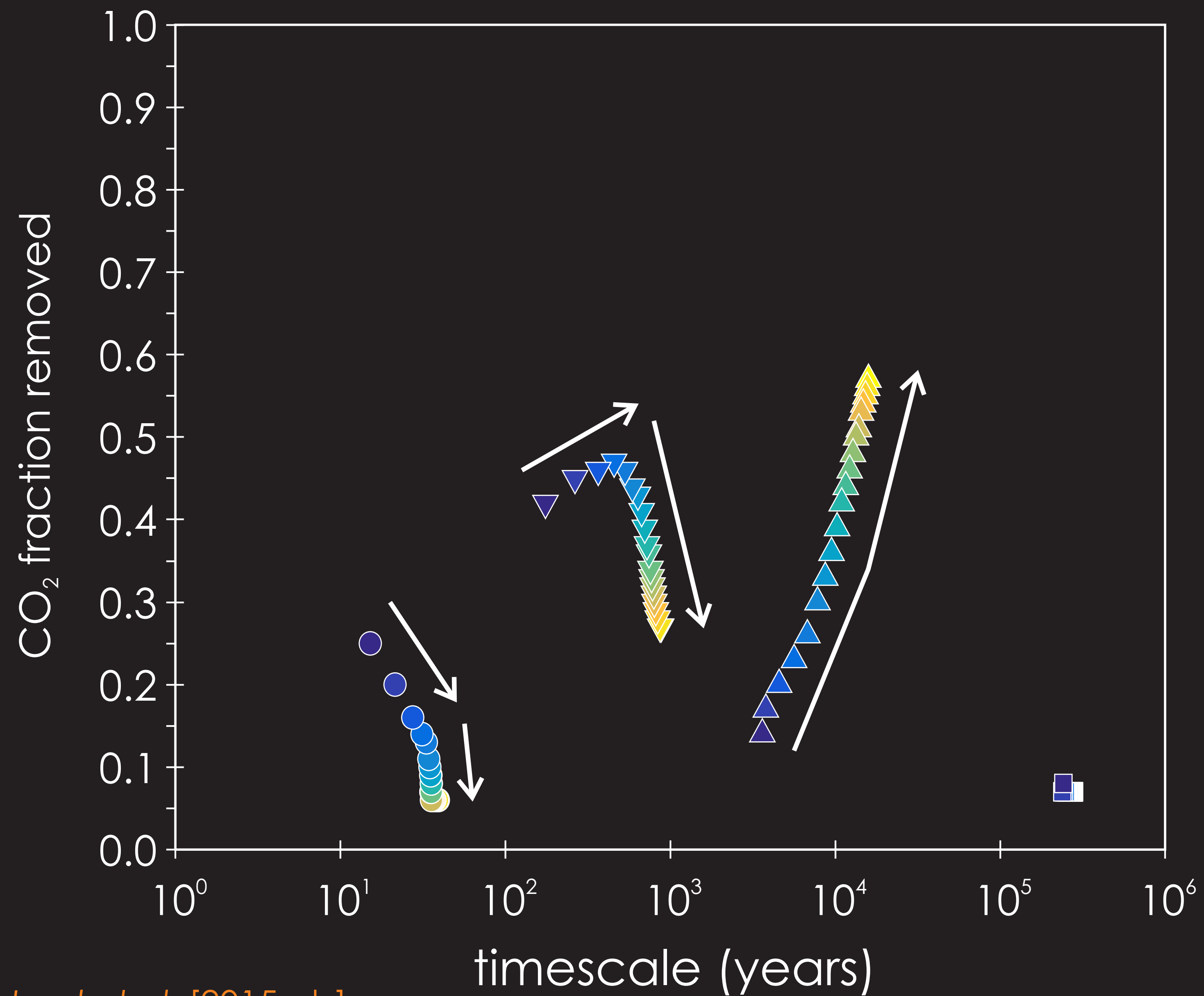
Evidence for climate-CO_2 weathering feedback?



From: *Hoffman and Schrag* [2002]



An impulse response function for the 'long tail' of $CO_{2(excess)}$ – IMPLICATIONS



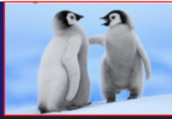
With increasing total CO_2 emissions, the response time of all sinks (bar silicate weathering) lengthen, and the shorter time-scale two weaken at the expense of the ~10,000 year $CaCO_3$ burial process.

Elevated atmospheric pCO_2 hence becomes more persistent as the main short-term CO_2 feedbacks weaken.

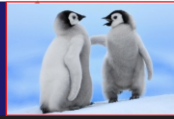
The majority of carbon removal beyond ~10,000 PgC is removed only on time-scales exceeding 10,000 years.

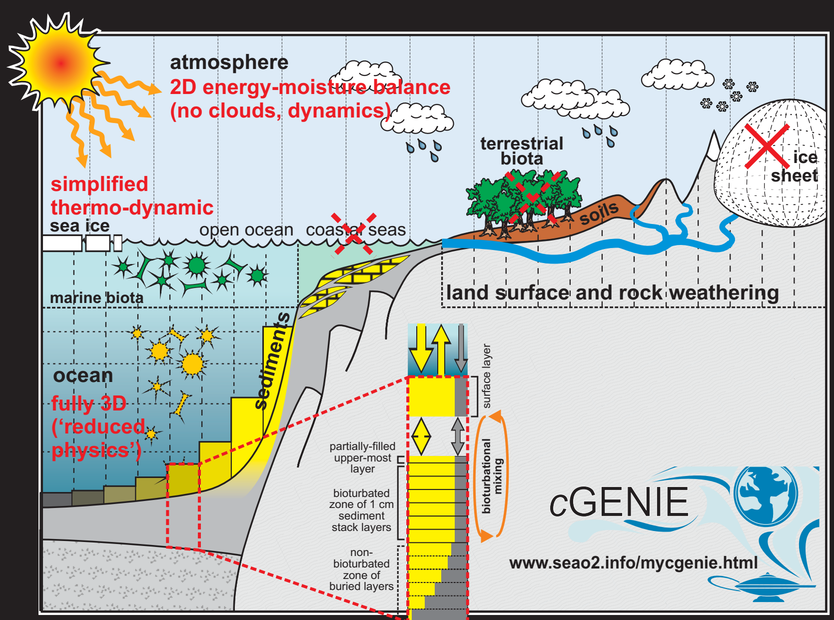
Lord et al. [2015a,b]

Melting Antarctica

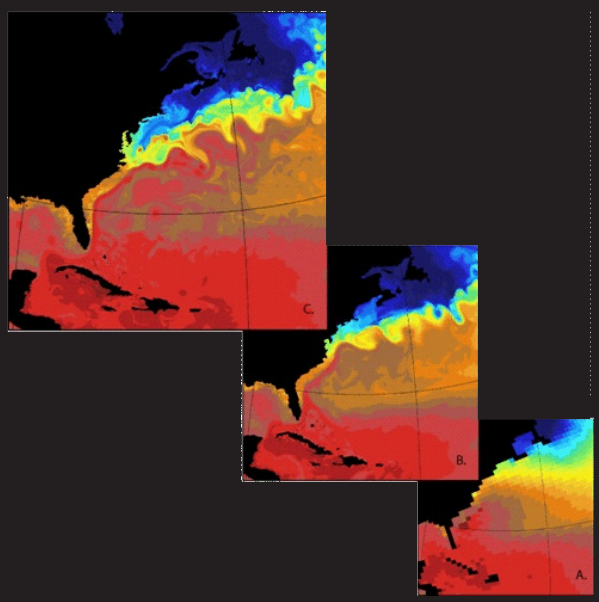


Melting Antarctica

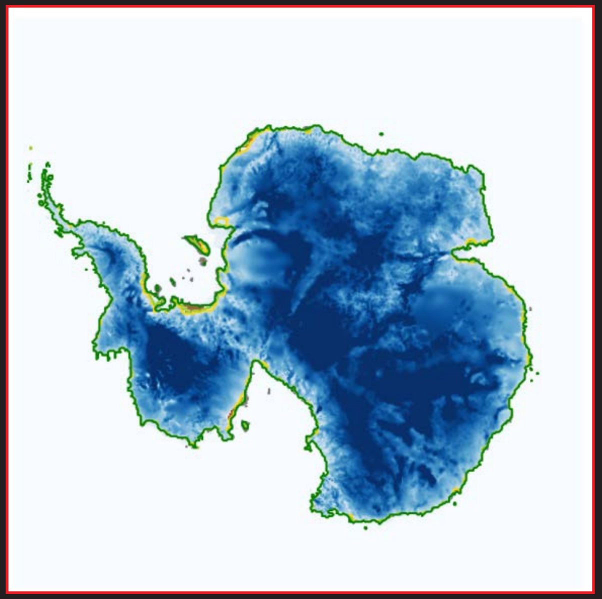




Earth system model
(CO_2 and mean SST trajectories)



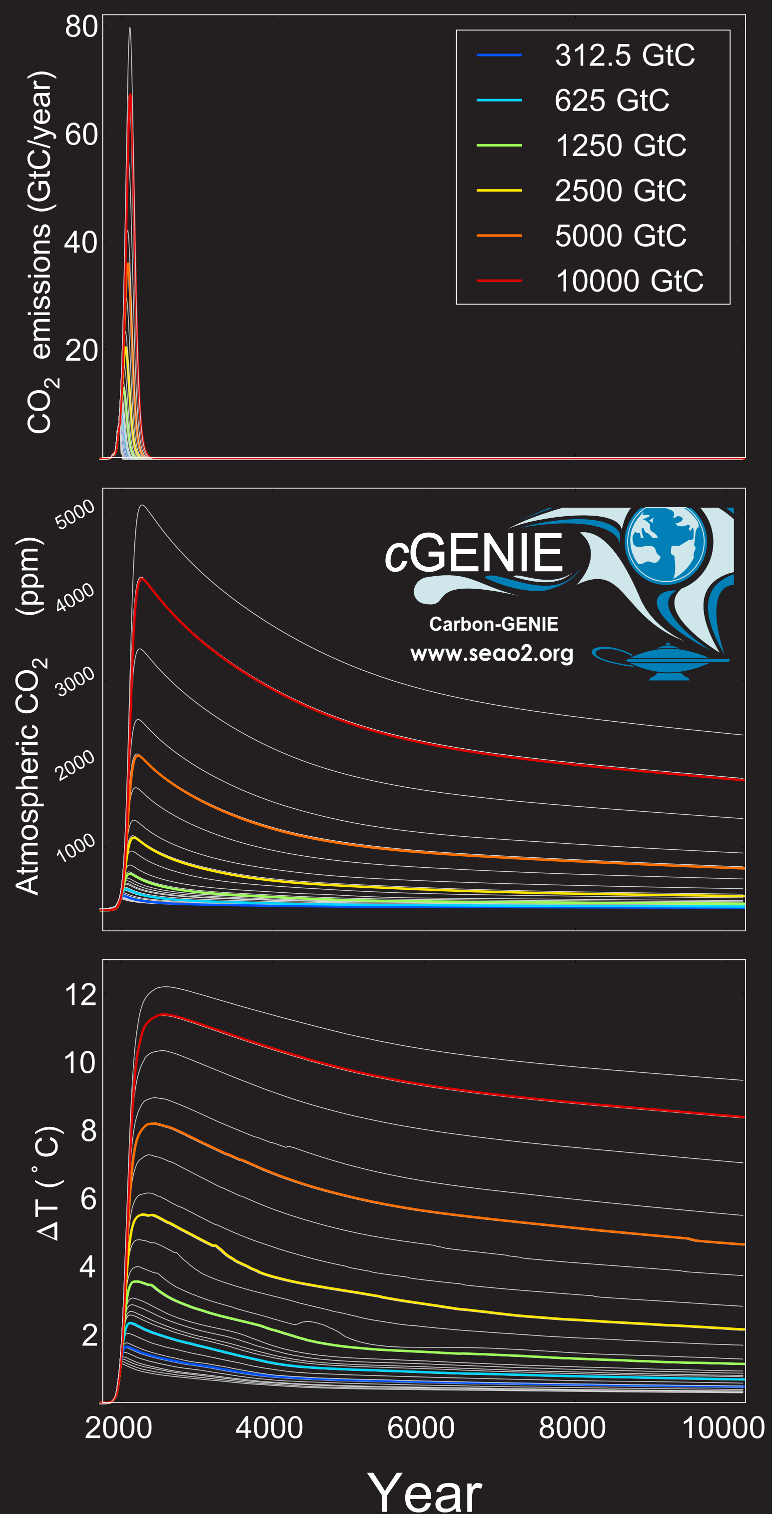
Downscaling
(SO SST and regional climate)



Ice sheet model

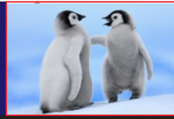
Winkelmann et al. [2015] (*Science Advances*)

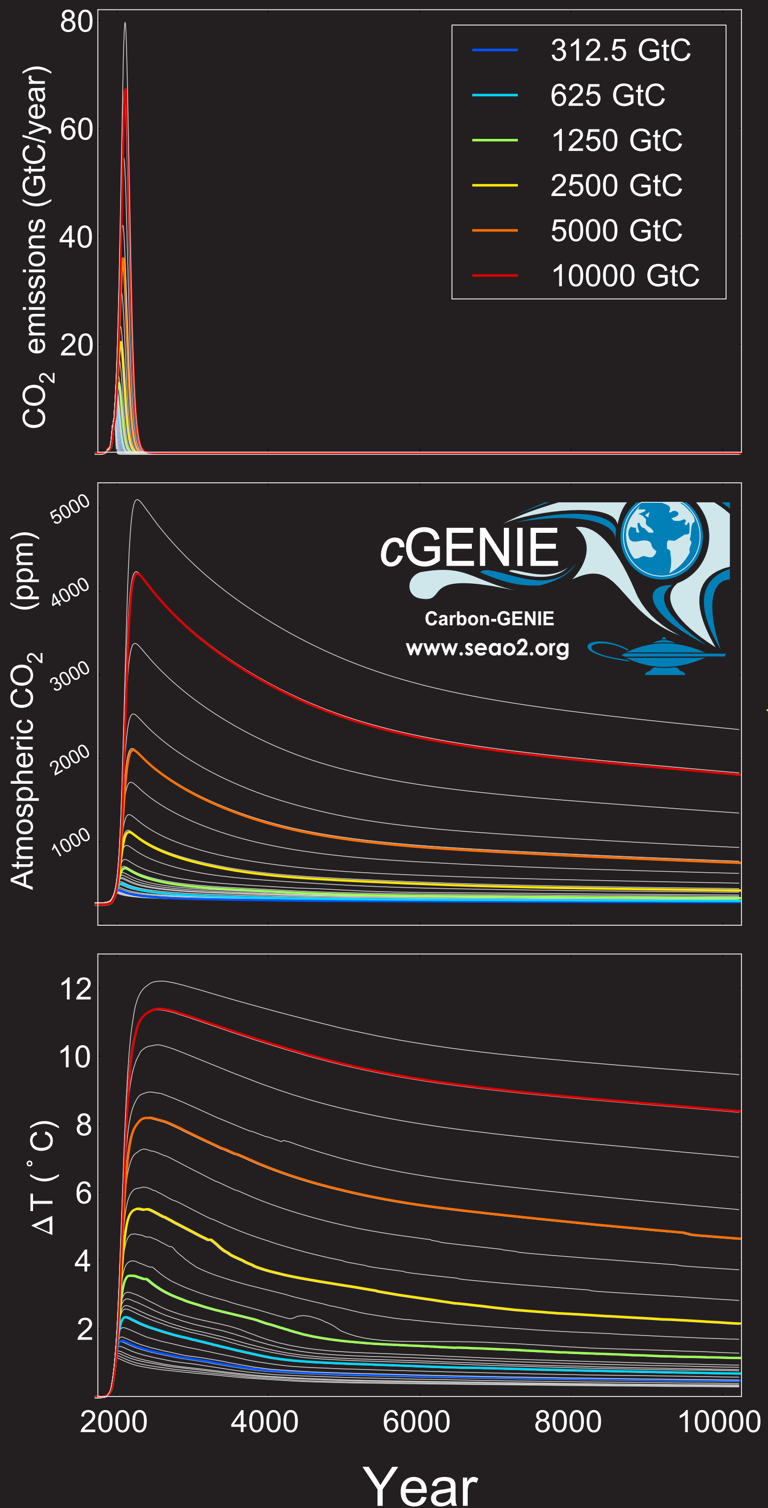
Melting Antarctica

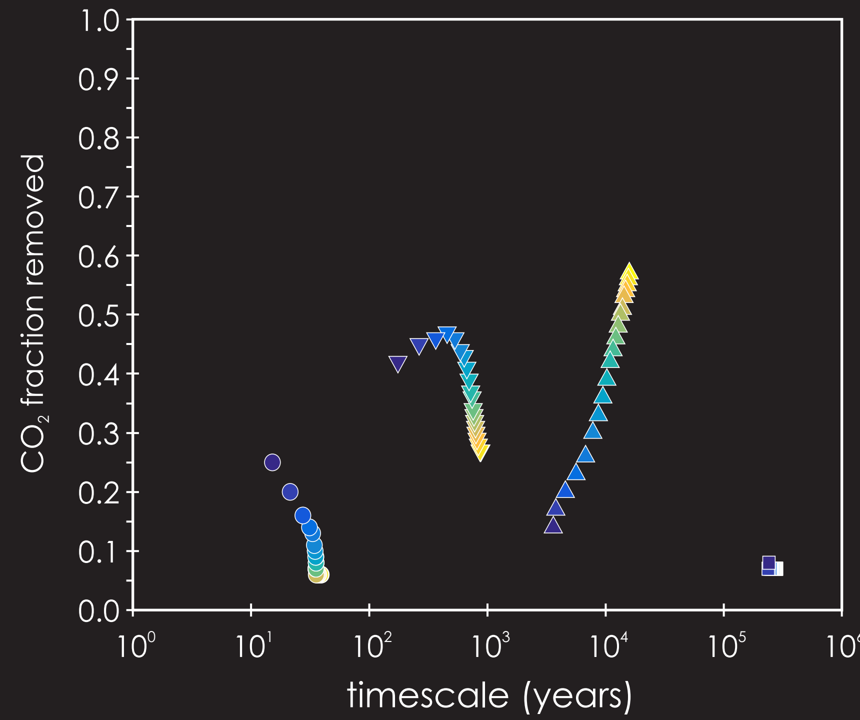


Winkelmann et al. [2015] (*Science Advances*)

Melting Antarctica

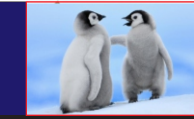


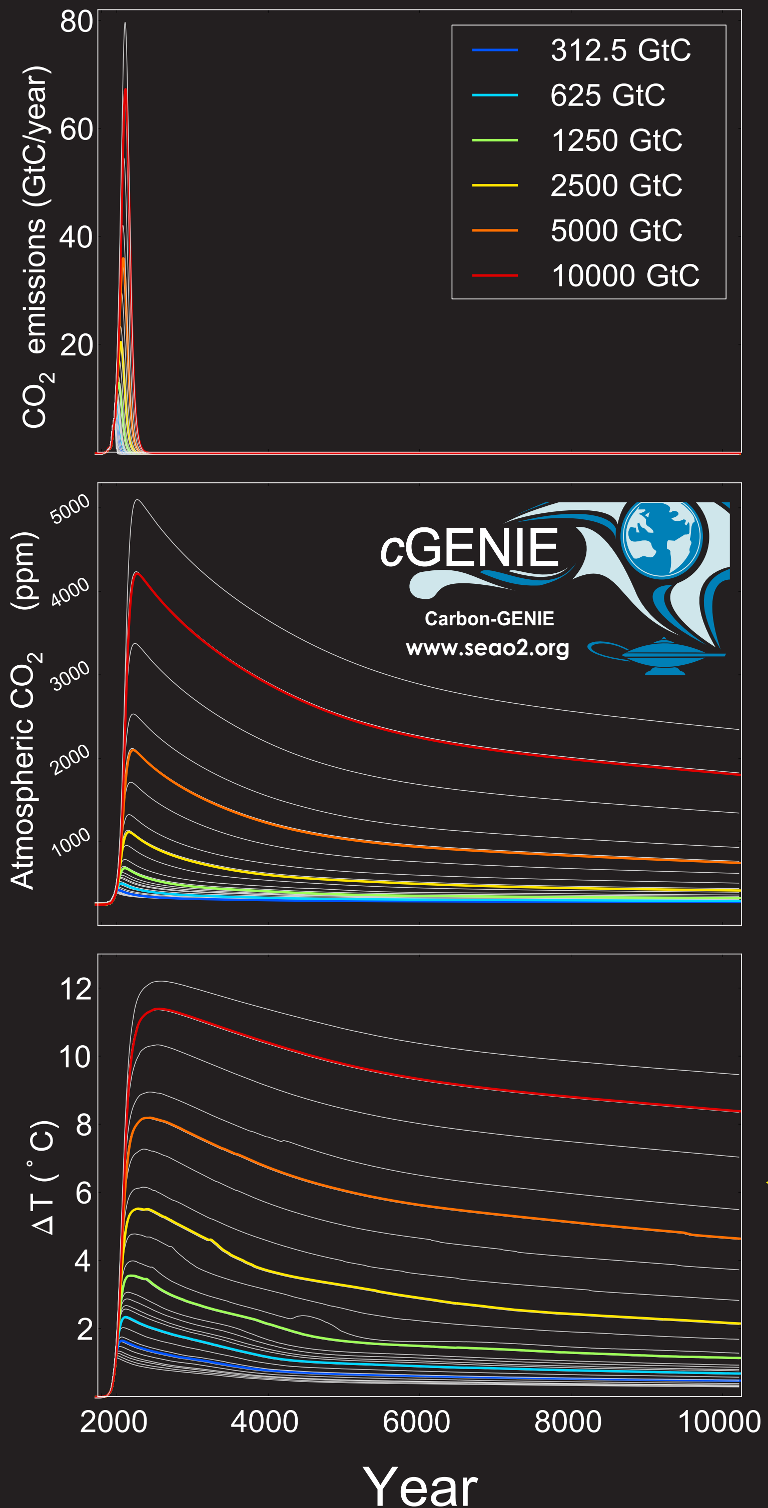




Winkelmann et al. [2015] (*Science Advances*)

Melting Antarctica

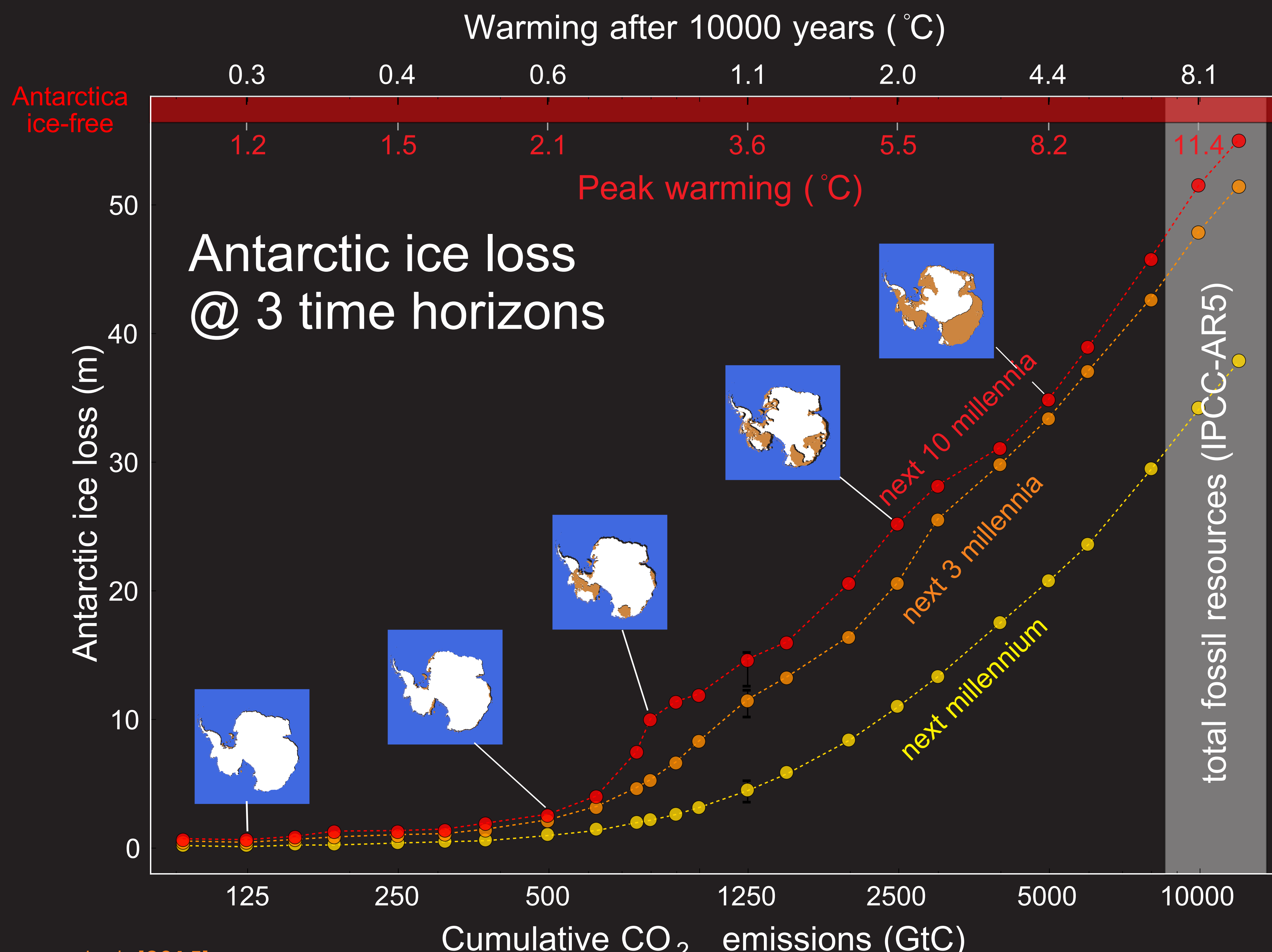




$$\Delta F \propto \ln(C/C_o)$$

Winkelmann et al. [2015] (*Science Advances*)

Melting Antarctica



Winkelmann et al. [2015]

Enhanced weathering (CO_2 removal geoengineering)

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Enhanced weathering (CO_2 removal geoengineering)

granite ≈

SiO_2 = 72%

...

CaO = 1.8%

...

MgO = 0.7%

...

basalt ≈

SiO_2 = 50%

...

CaO = 10%

...

MgO = 10%

...

Enhanced weathering (CO_2 removal geoengineering)

~ plagioclase + pyroxene (+olivine)

Enhanced weathering (CO_2 removal geoengineering)

~ olivine + pyroxene

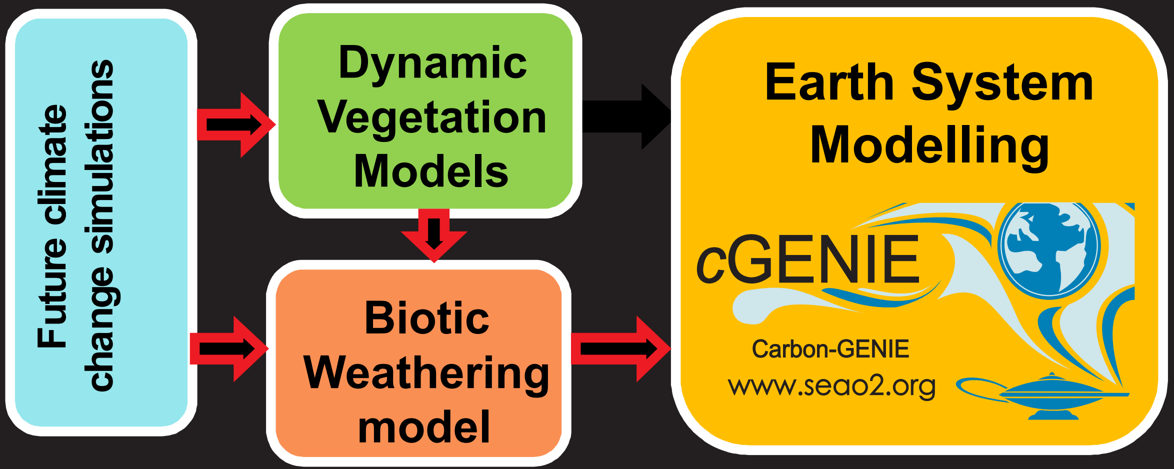
Harzburgite

~ plagioclase + pyroxene (+olivine)

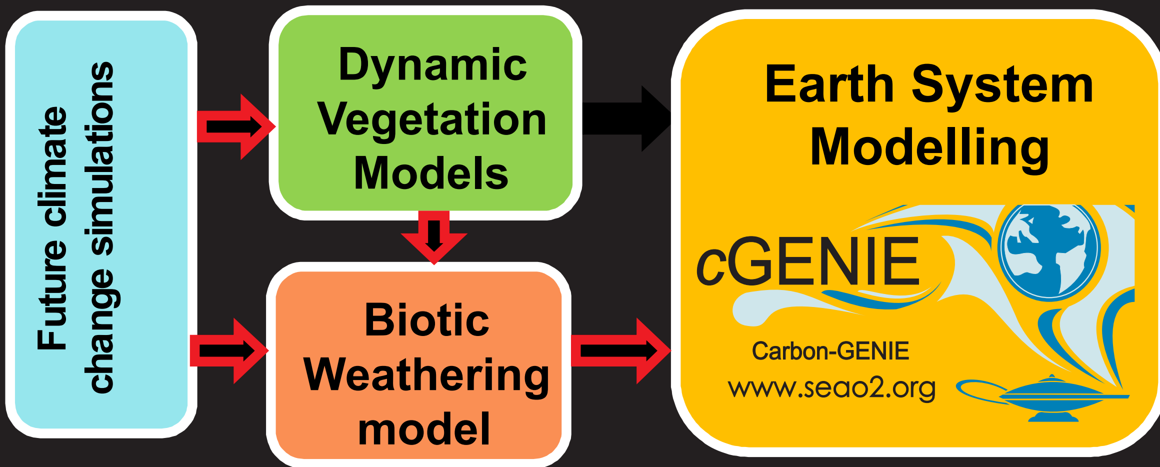
>90% olivine: $(Mg^{+2}, Fe^{+2})2SiO_4$

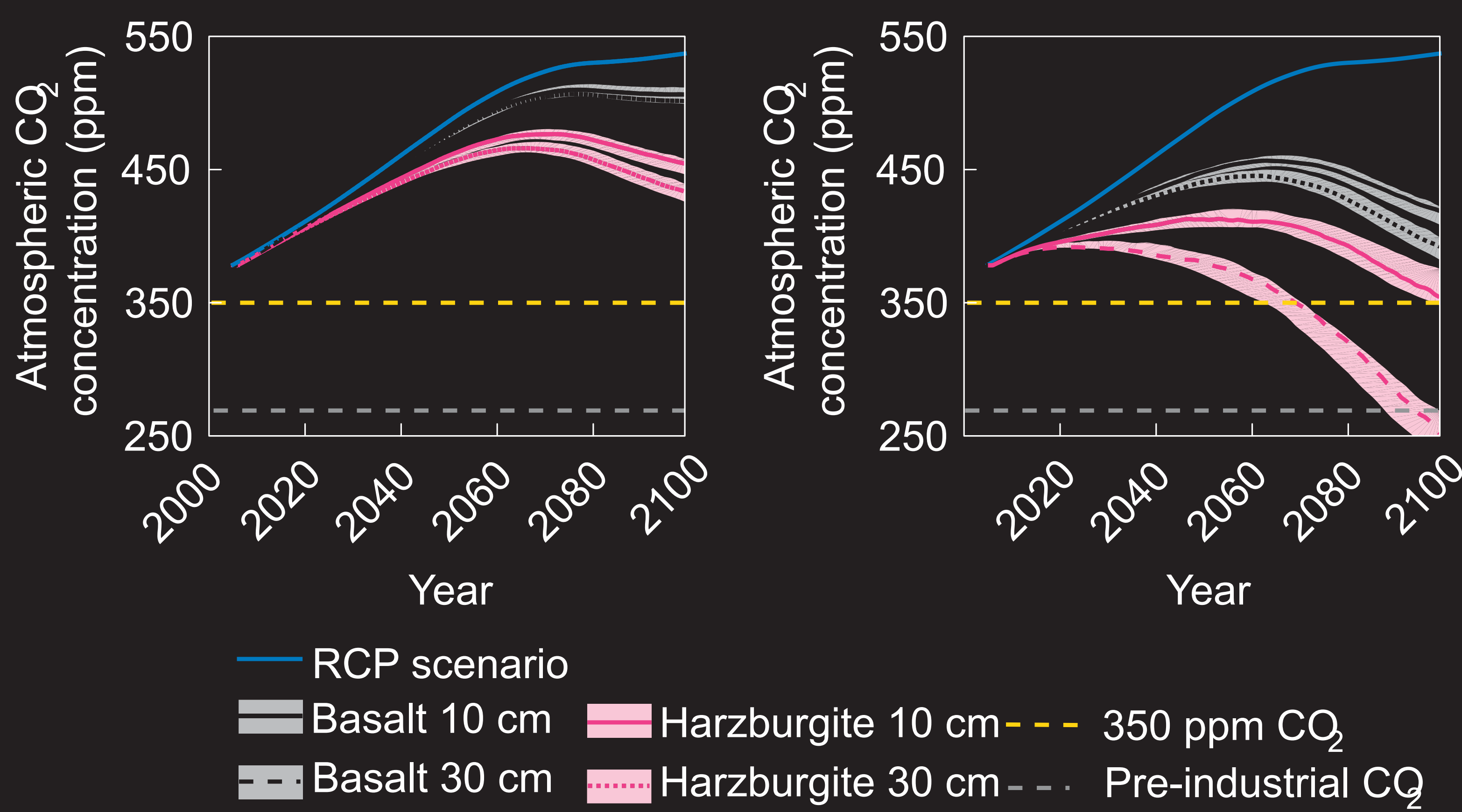
Dunite

Enhanced weathering (CO_2 removal geoengineering)



Enhanced weathering (CO_2 removal geoengineering)





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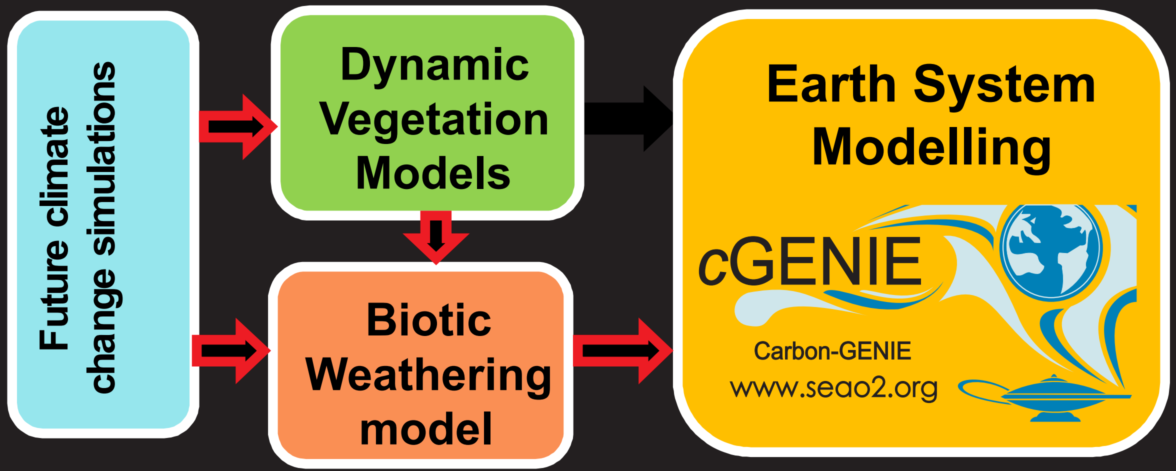

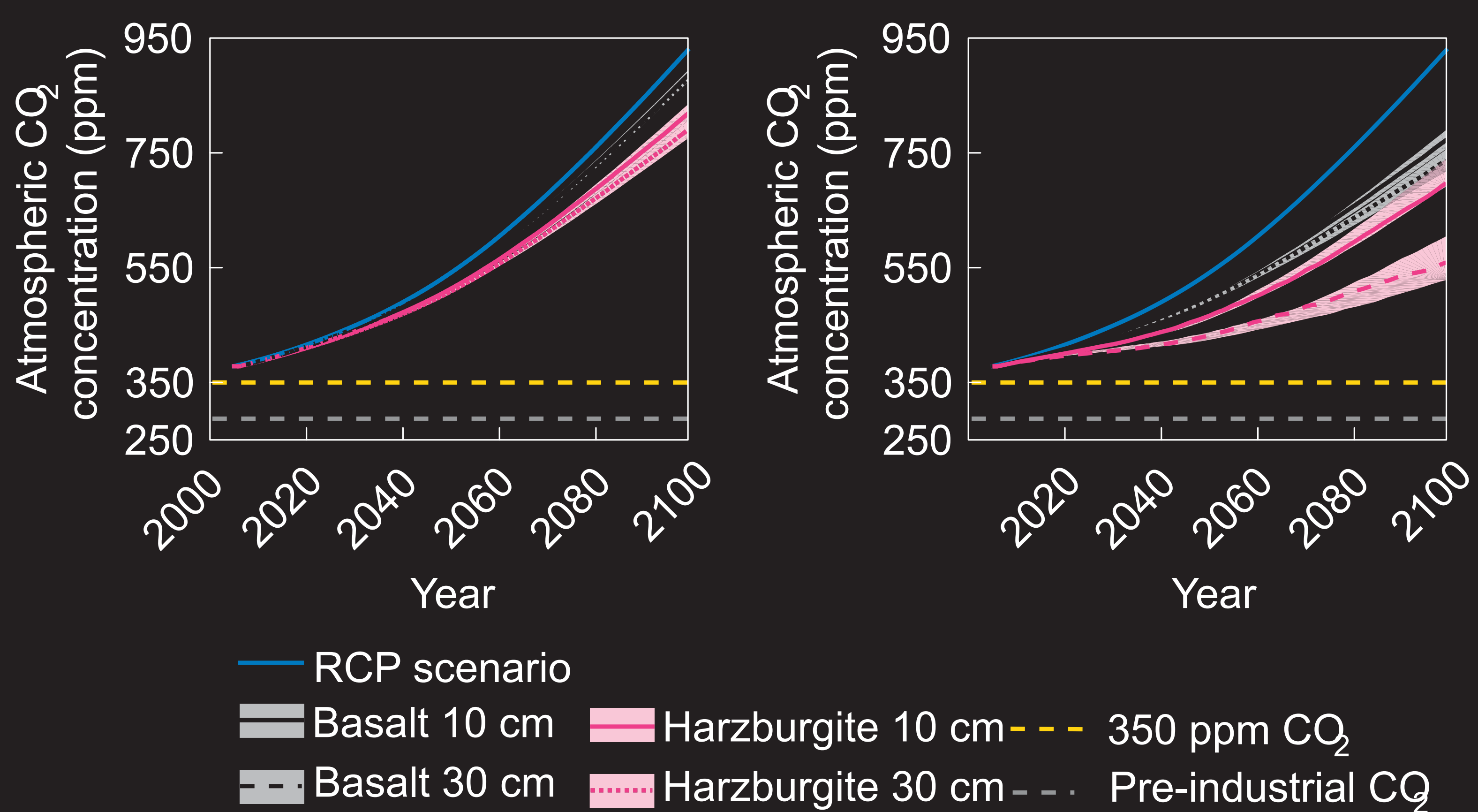

Enhanced weathering (CO_2 removal geoengineering)

Current global oil consumption = $90{,}136\times10^{3}$ barrels per day

1.0 barrel = 159 l
= 159×10^{3} cm^{3}

$\Rightarrow$ oil consumption
= 5.23×10^{15} cm^{3} $year^{-1}$
= 5.23 km^{3} $year^{-1}$

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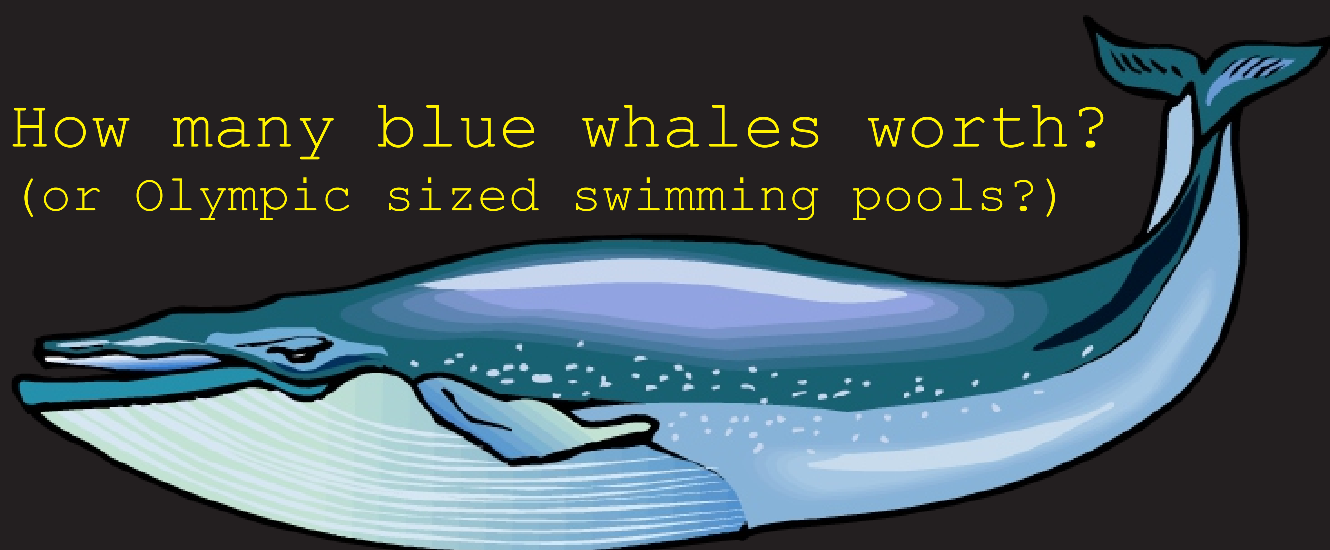

How many blue whales worth?
(or Olympic sized swimming pools?)

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= 159×10^3 cm^3

⇒ oil consumption
= 5.23×10^{15} cm^3 $year^{-1}$
= 5.23 km^3 $year^{-1}$

How many Yosemite Valleys?
(equivalent volume)

Enhanced weathering (CO_2 removal geoengineering)

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1.0 barrel = 159 l
= 159×10^3 cm^3

⇒ oil consumption
= 5.23×10^{15} cm^3 $year^{-1}$
= 5.23 km^3 $year^{-1}$

Yosemite Valley (Wikipedia):
1,200m deep × 1,600m across, 12.0 km long
⇒
volume = 1.2×1.6×12.0
= 23.0 km^3

How many Yosemite Valleys? (equivalent volume)

Cats, clays, carbon sequestration, collaborators, and CA$H

Thanks to:

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Ellen Thomas [Yale]; *Sandy Kirtland Turner* [UCR], *et al.*
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Lyla Taylor and David Beerling [Sheffield], *et al.*

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