How long is 'forever'?

Geologic-climate feedbacks on atmospheric pCO_2

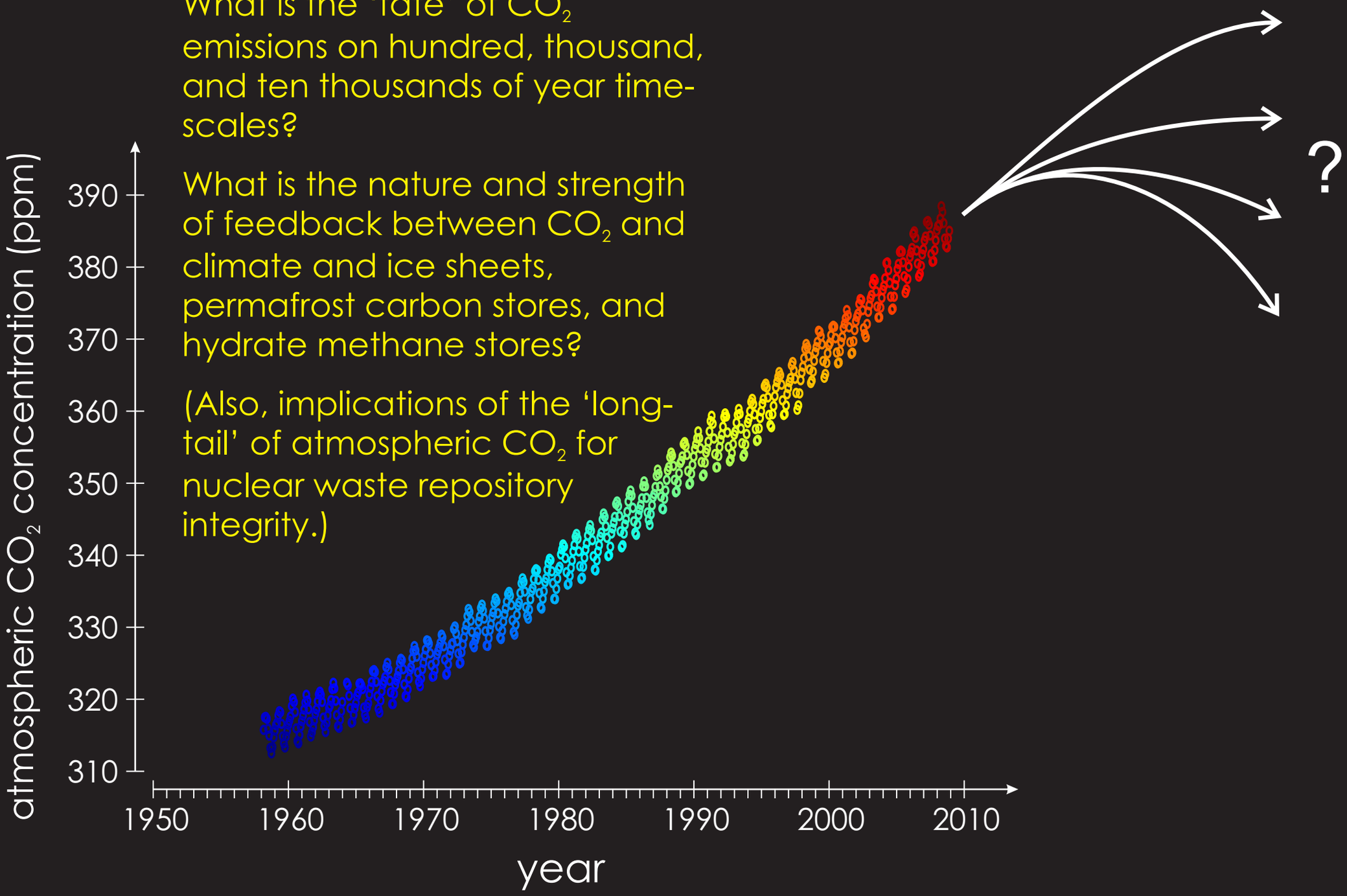
Andy Ridgwell

What regulates long-term climate evolution?

What is the 'fate' of CO_2 emissions on hundred, thousand, and ten thousands of year time-scales?

What is the nature and strength of feedback between CO_2 and climate and ice sheets, permafrost carbon stores, and hydrate methane stores?

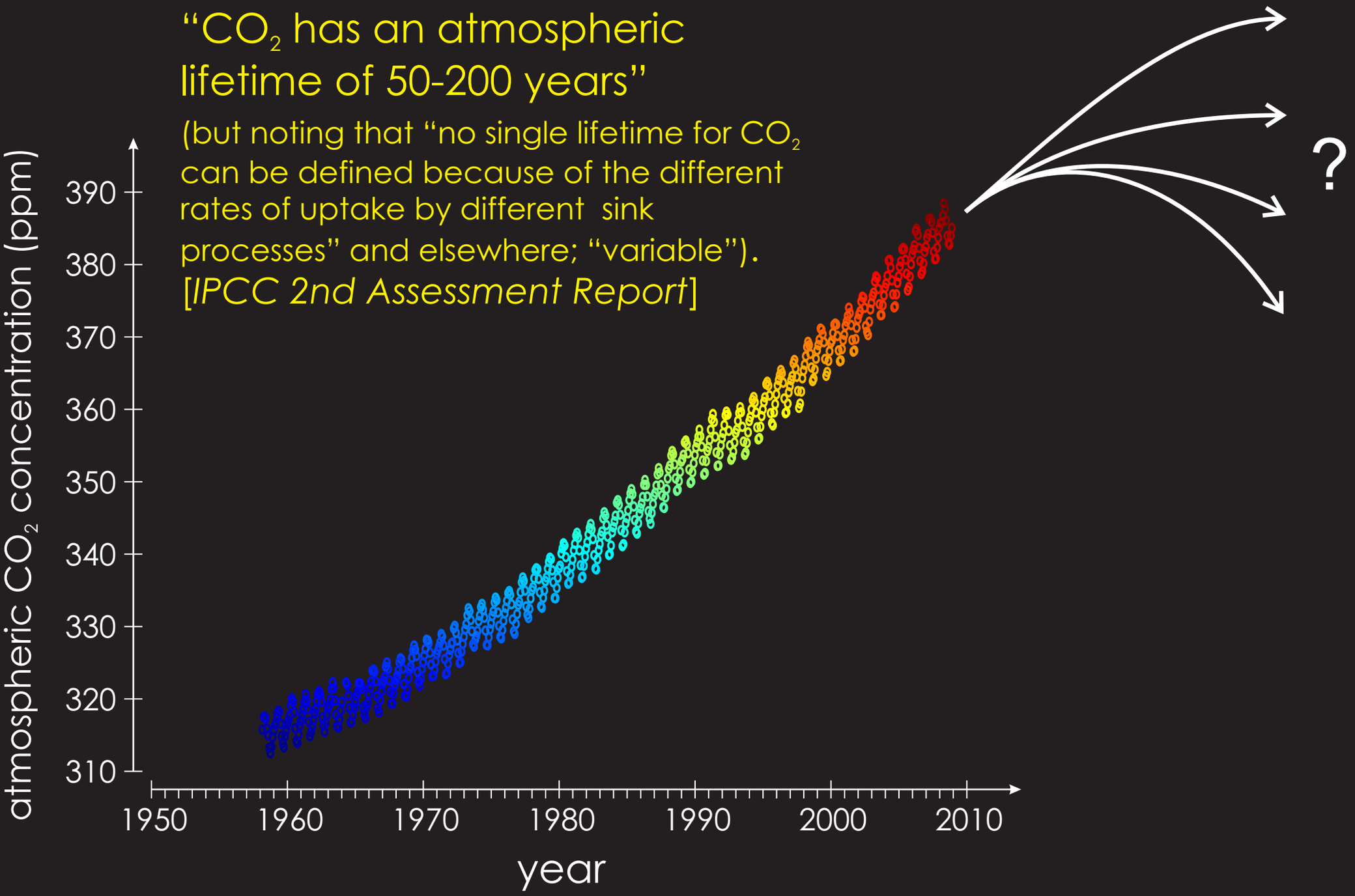
(Also, implications of the 'long-tail' of atmospheric CO_2 for nuclear waste repository integrity.)



What regulates long-term climate evolution?

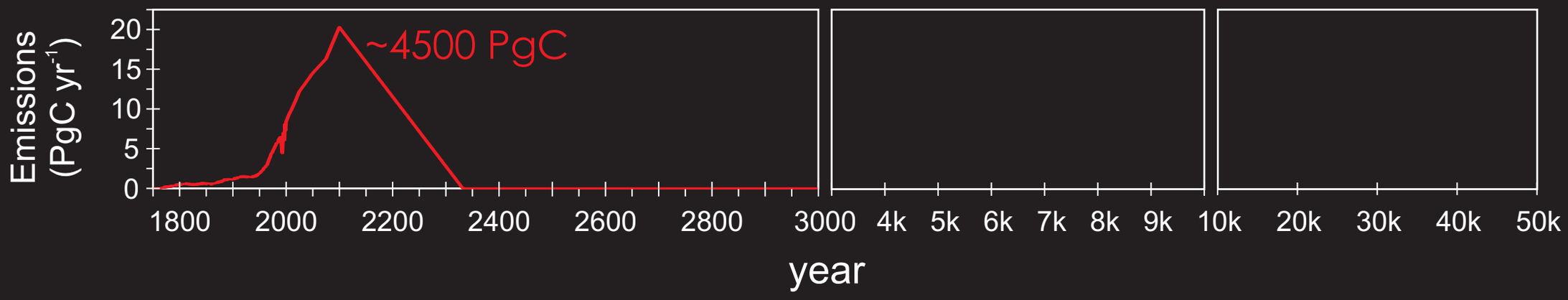
"CO_2 has an atmospheric lifetime of 50-200 years"

(but noting that "no single lifetime for CO_2 can be defined because of the different rates of uptake by different sink processes" and elsewhere; "variable"). [*IPCC 2nd Assessment Report*]



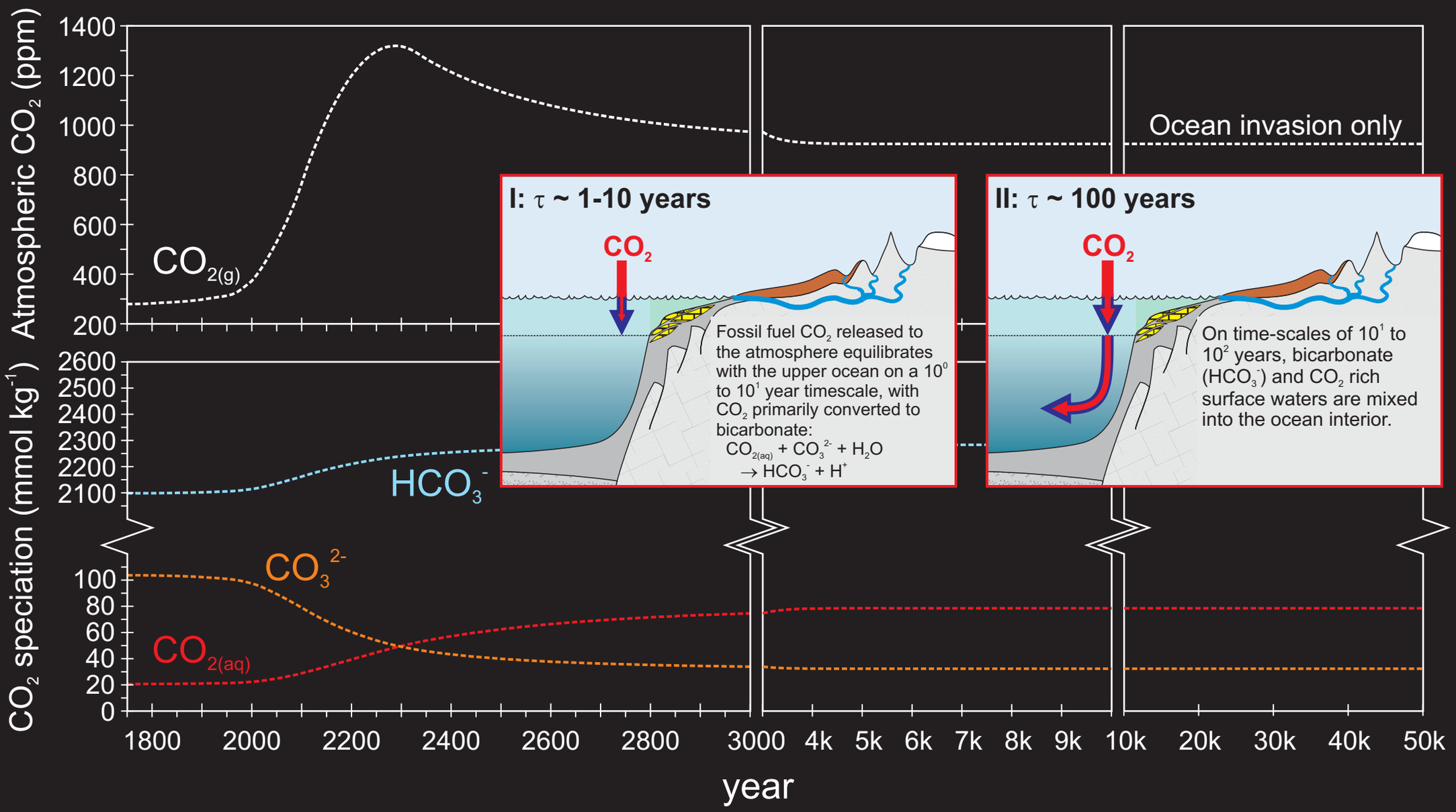
Long-term CO_2 feedback processes

Long-term CO_2 feedback processes



From: *Ridgwell and Hargreaves* [2007] (*GBC*)

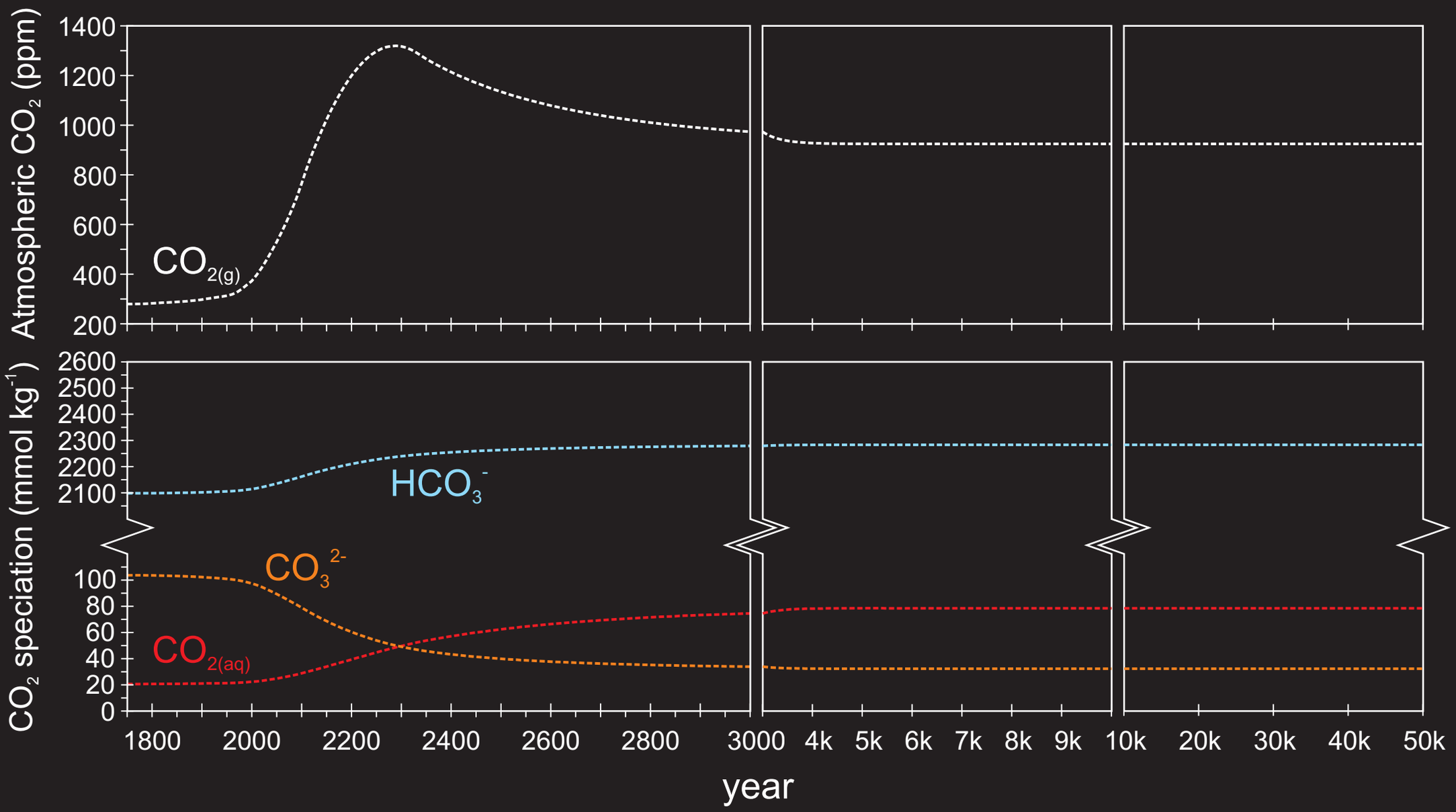
Long-term CO_2 feedback processes



From: *Ridgwell and Hargreaves* [2007] (*GBC*)

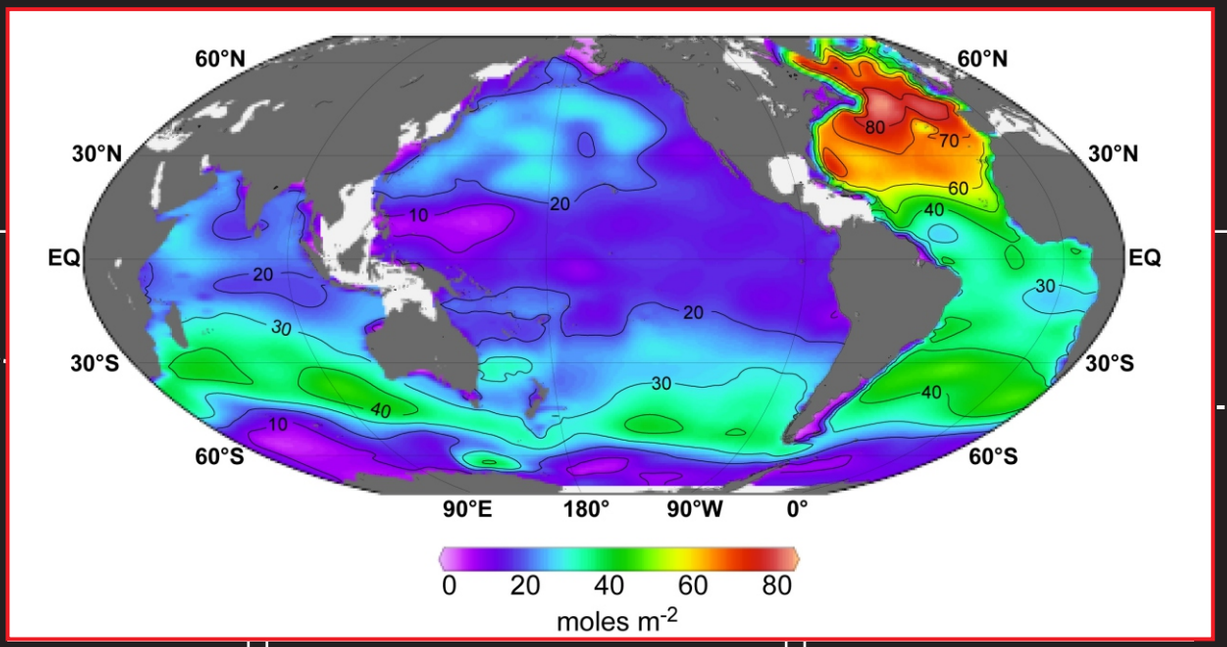
Long-term CO_2 feedback processes

evidence?



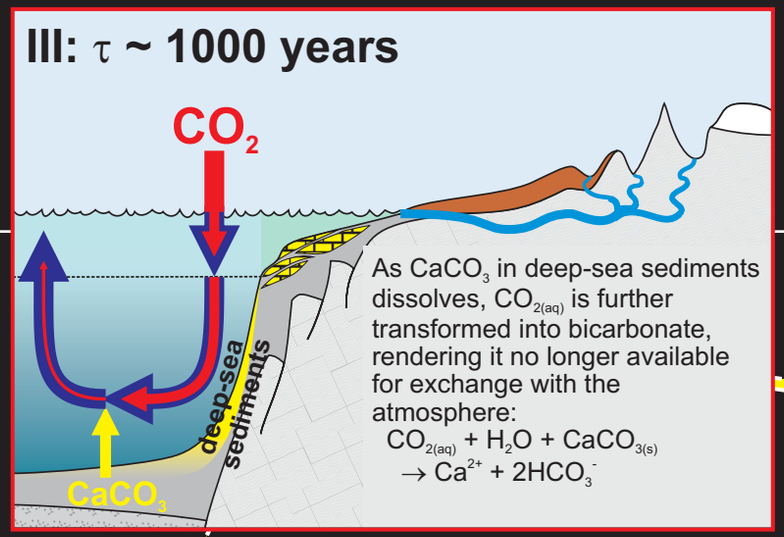
Long-term CO_2 feedback processes

evidence?



From: *Sabine et al.* [2004] (*Science*)

Long-term CO_2 feedback processes



Atmospheric CO_2 (ppm)

1400
1200
1000
800
600
400
200

$CO_{2(g)}$

Ocean invasion only

Ocean invasion + sea-floor neutralization

CO_2 speciation (mmol kg^{-1})

2600
2500
2400
2300
2200
2100

HCO_3^-

CO_3^{2-}

100
80
60
40
20
0

$CO_{2(aq)}$

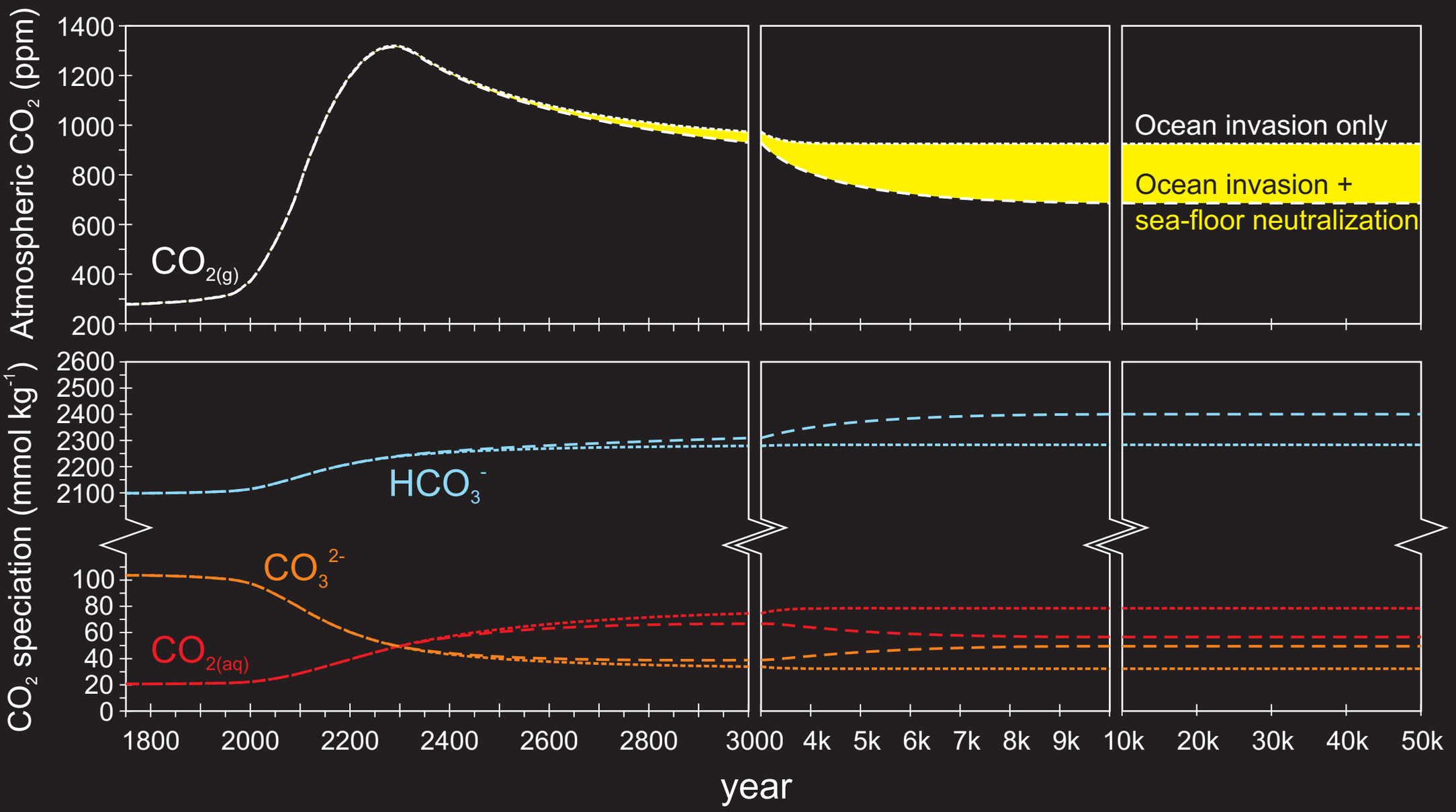
1800 2000 2200 2400 2600 2800 3000 4k 5k 6k 7k 8k 9k 10k 20k 30k 40k 50k

year

From: *Ridgwell and Hargreaves* [2007] (*GBC*)

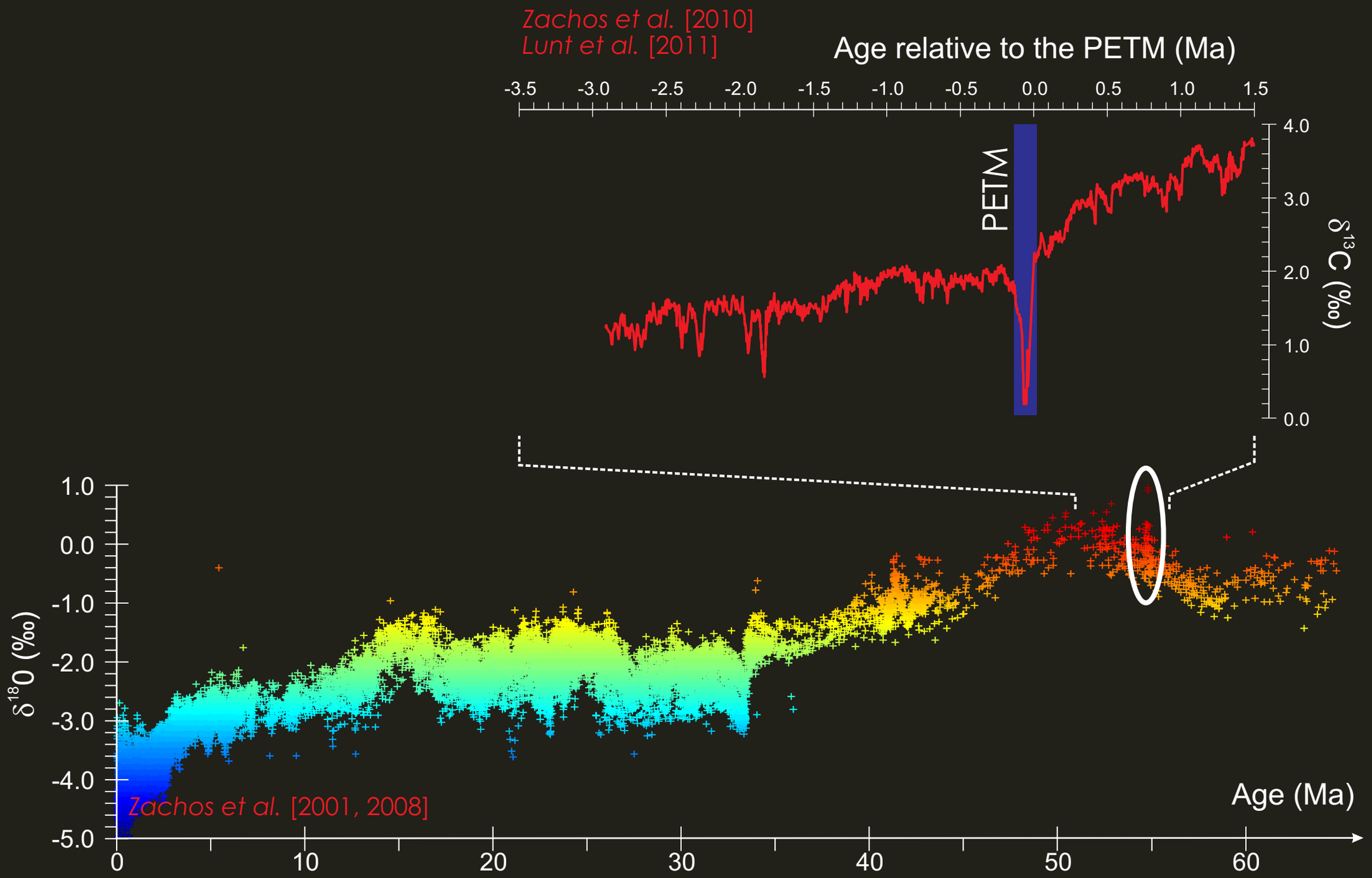
Long-term CO_2 feedback processes

evidence?

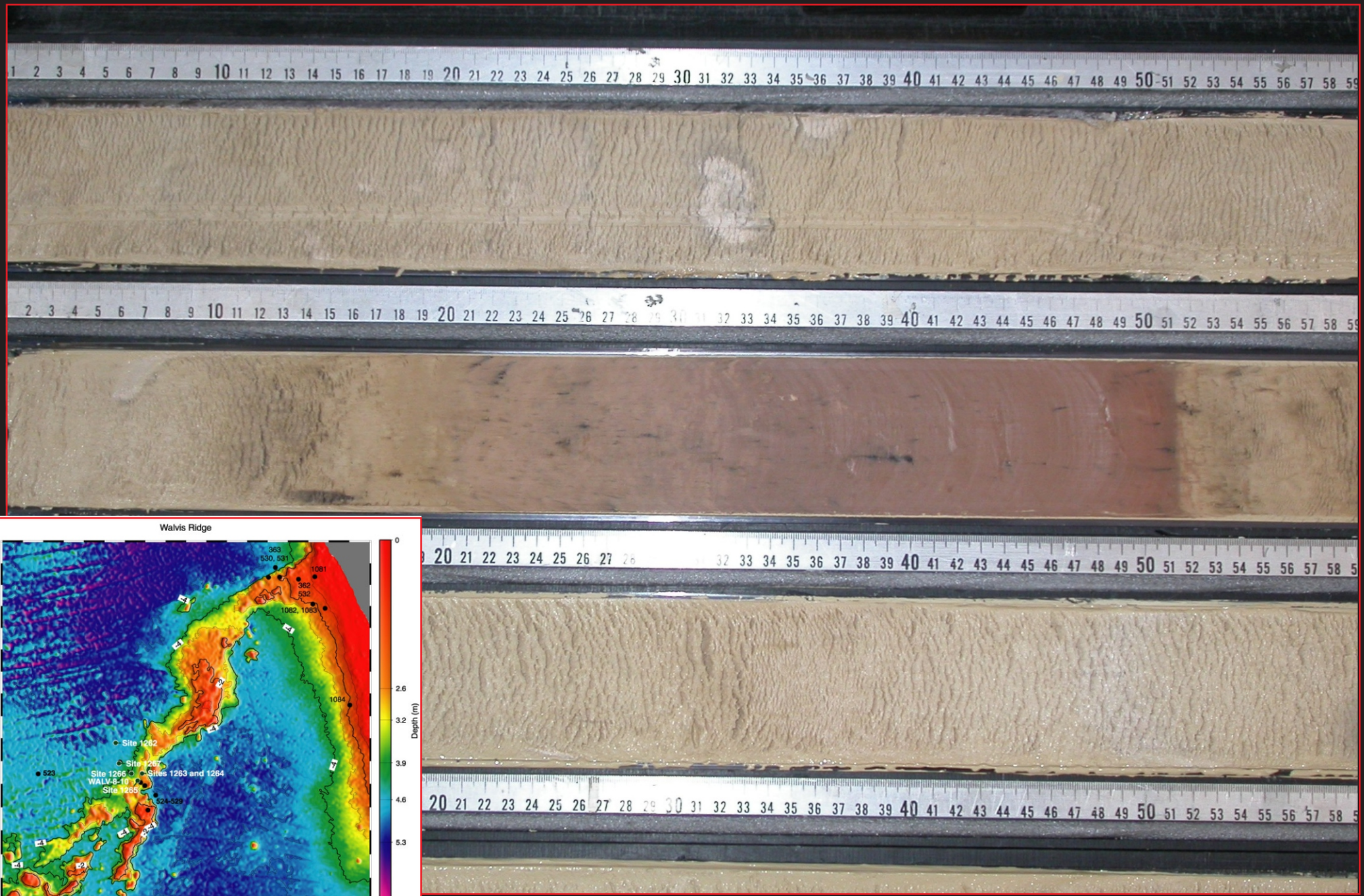


From: *Ridgwell and Hargreaves* [2007] (*GBC*)

Long-term CO_2 feedback processes

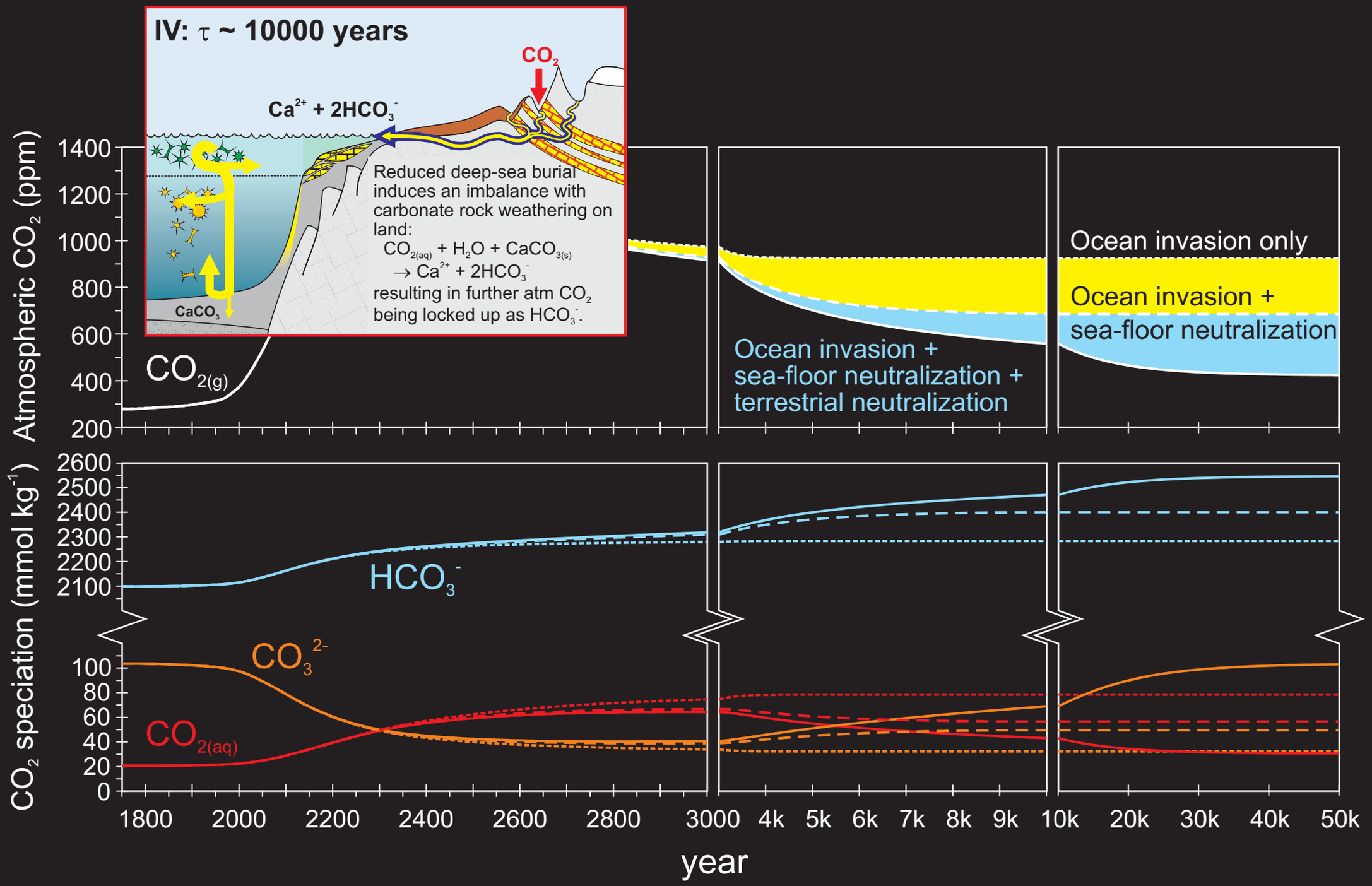


Long-term CO_2 feedback processes



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

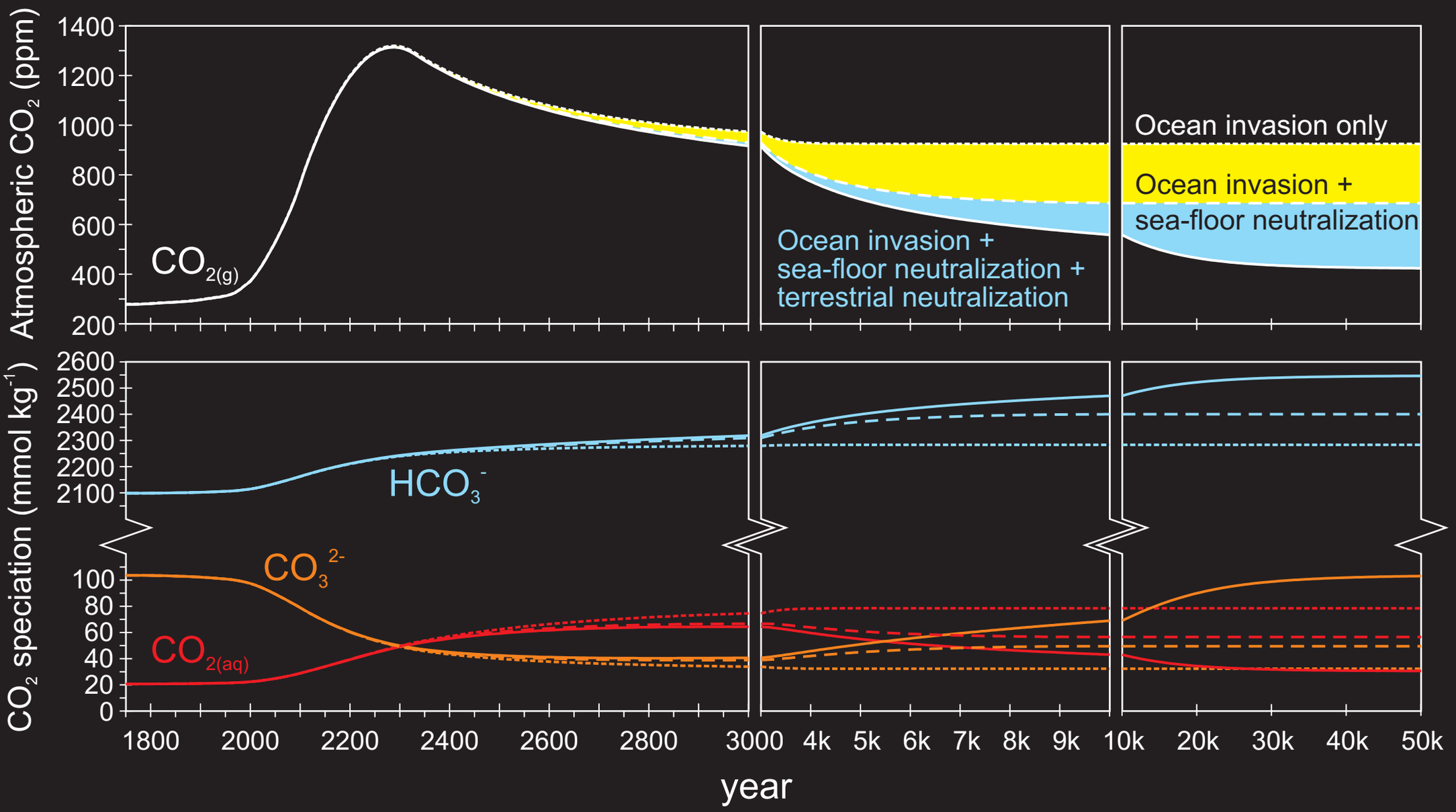
Long-term CO_2 feedback processes



From: *Ridgwell and Hargreaves* [2007] (*GBC*)

Long-term CO_2 feedback processes

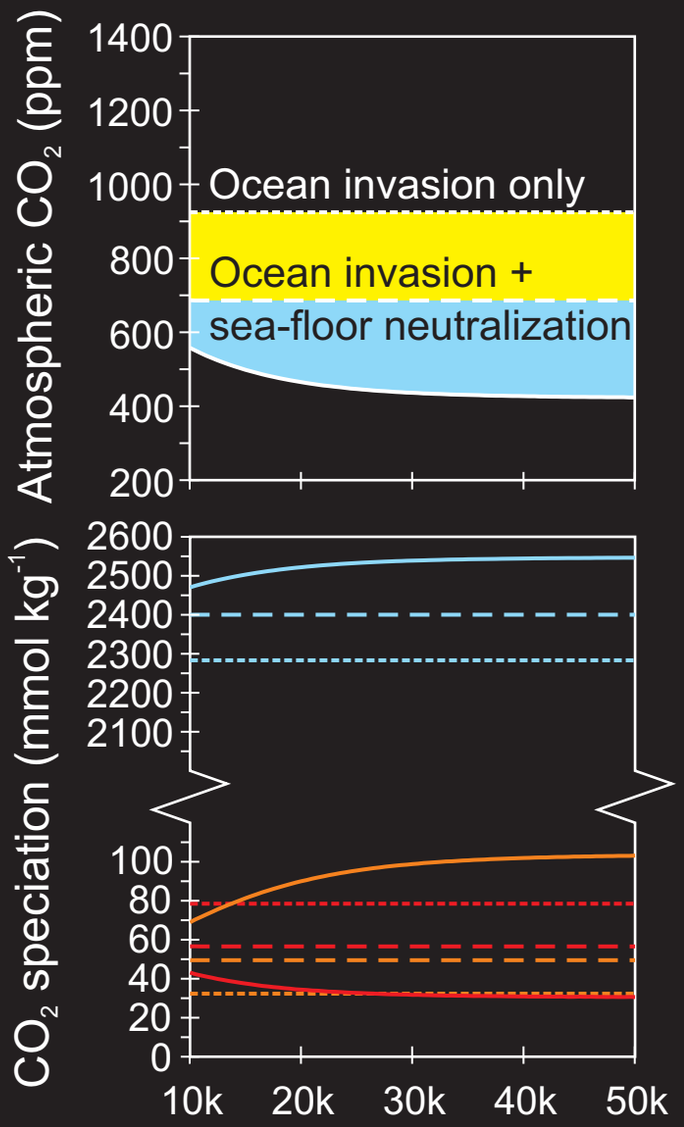
evidence?



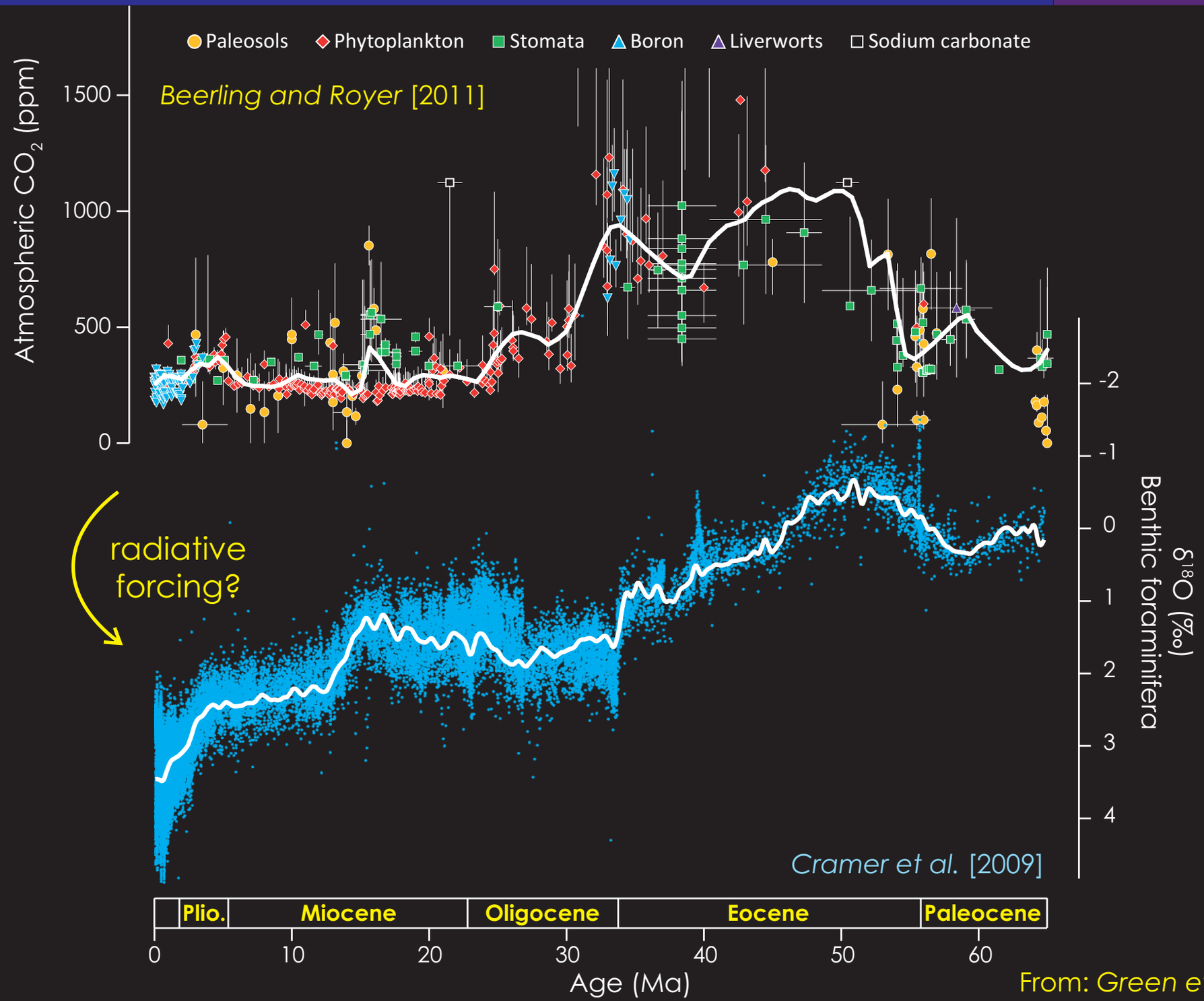
From: *Ridgwell and Hargreaves* [2007] (*GBC*)

Long-term CO_2 feedback processes

Q. Is a residual fraction of CO_2 persisting for ever ... 'OK'?

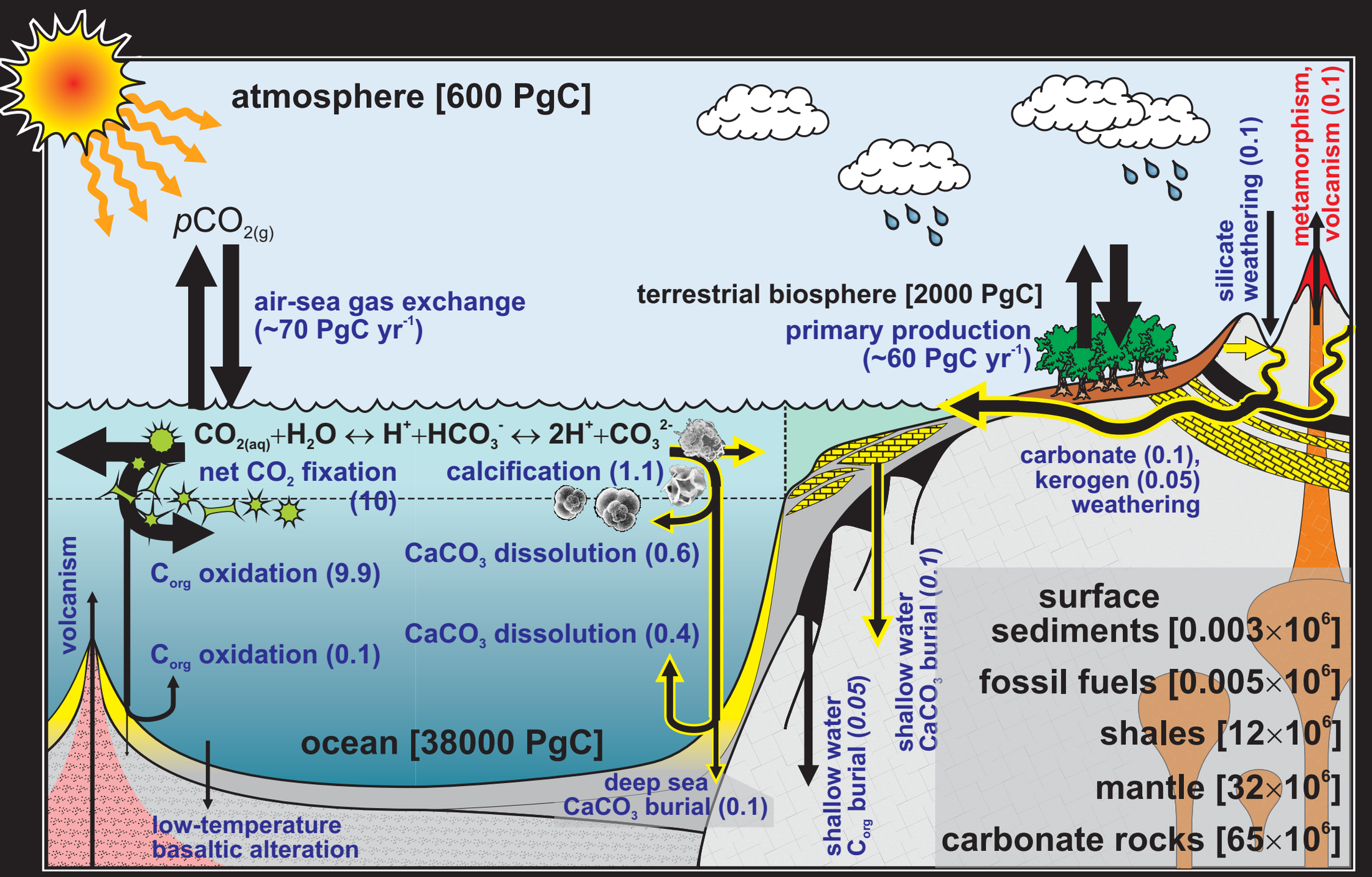


Climate-CO_2 silicate weathering feedback

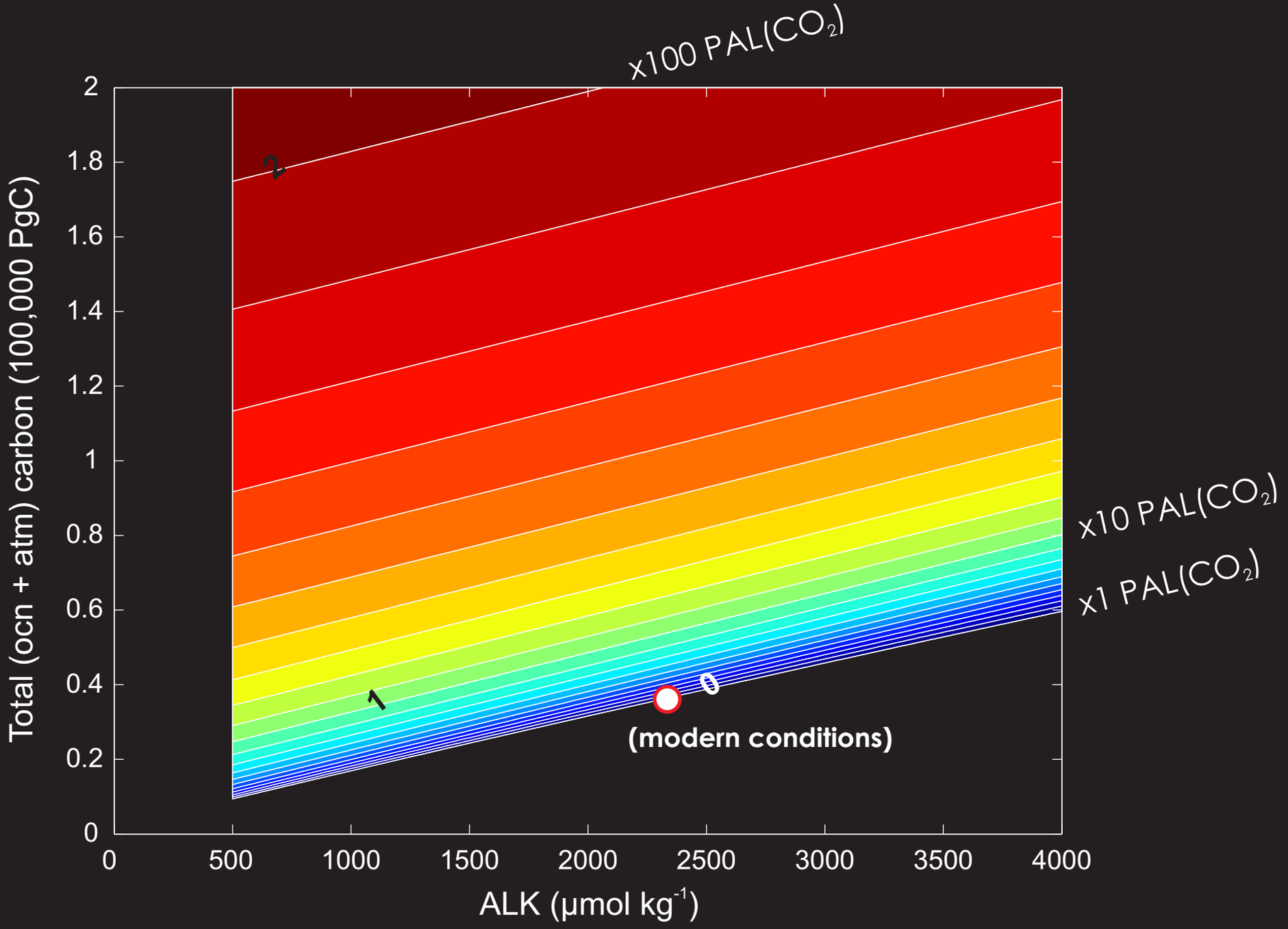


From: *Green et al.* [submitted]

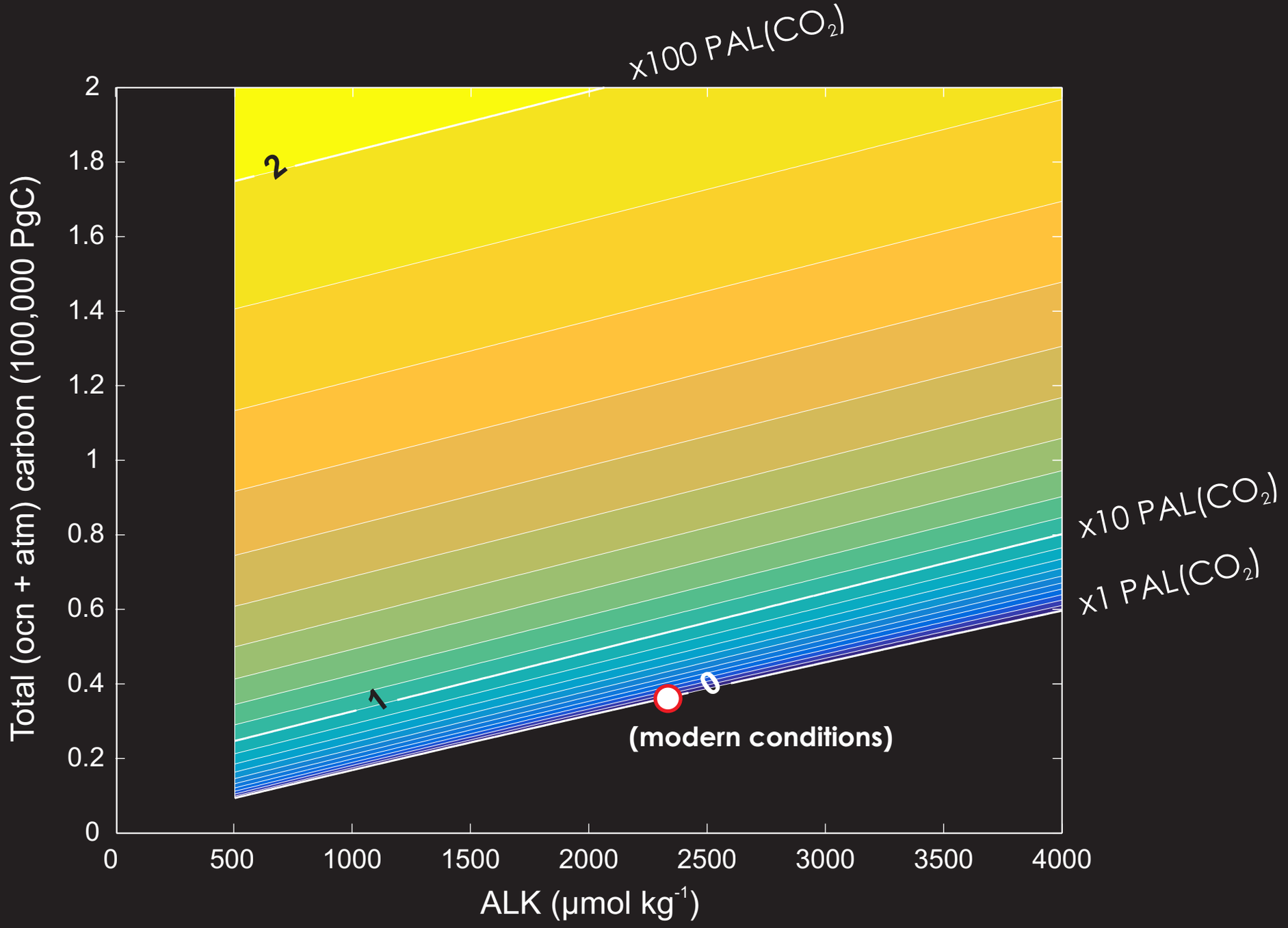
Climate-CO_2 silicate weathering feedback



Climate-CO_2 silicate weathering feedback

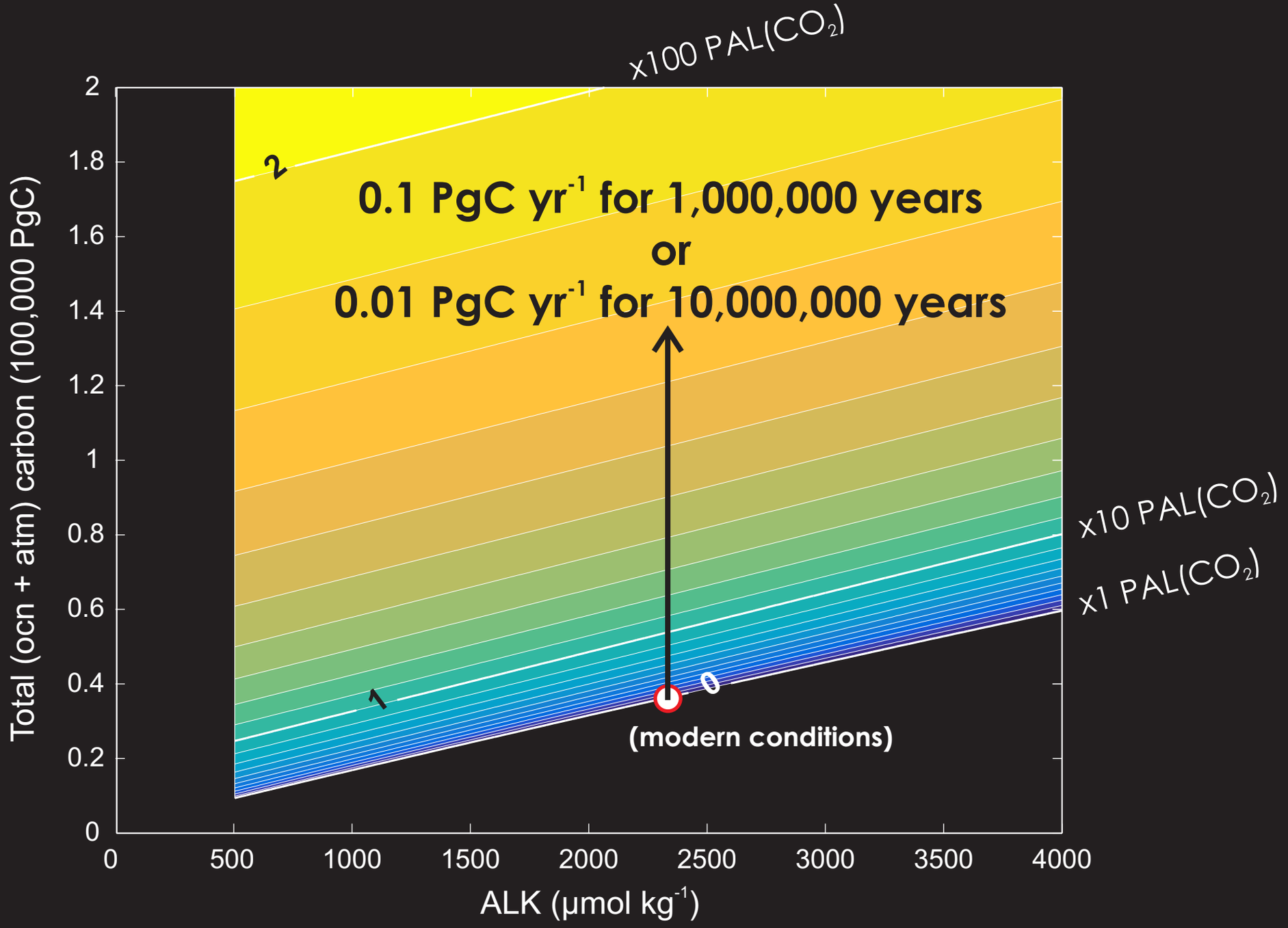


Climate-CO_2 silicate weathering feedback



see: http://www.climate-lab-book.ac.uk/2014/which-colour-scale/

Climate-CO_2 silicate weathering feedback



see: http://www.climate-lab-book.ac.uk/2014/which-colour-scale/

Climate-CO_2 silicate weathering feedback

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

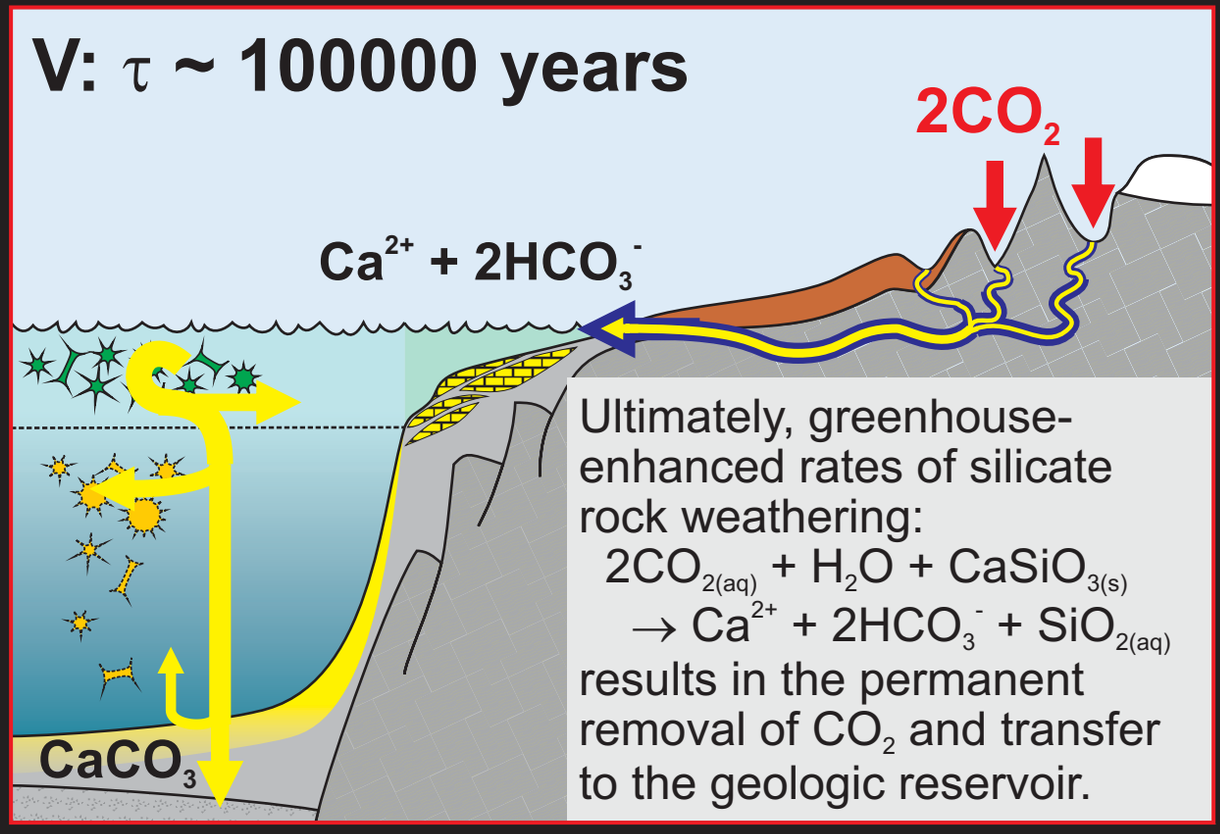
It can be seen that in (2) + (3), that the CO_2 removed (from the atmosphere) during weathering, is returned upon carbonate precipitation (and burial). In (1) + (3) (silicate weathering) CO_2 is permanently removed to the geological reservoir. This CO_2 must be balanced by mantle (/volcanic) out-gassing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

Furthermore, the rate of silicate weathering should scale with climate. Hence a ca. 100 kyr time-scale **silicate weathering feedback** is formed:

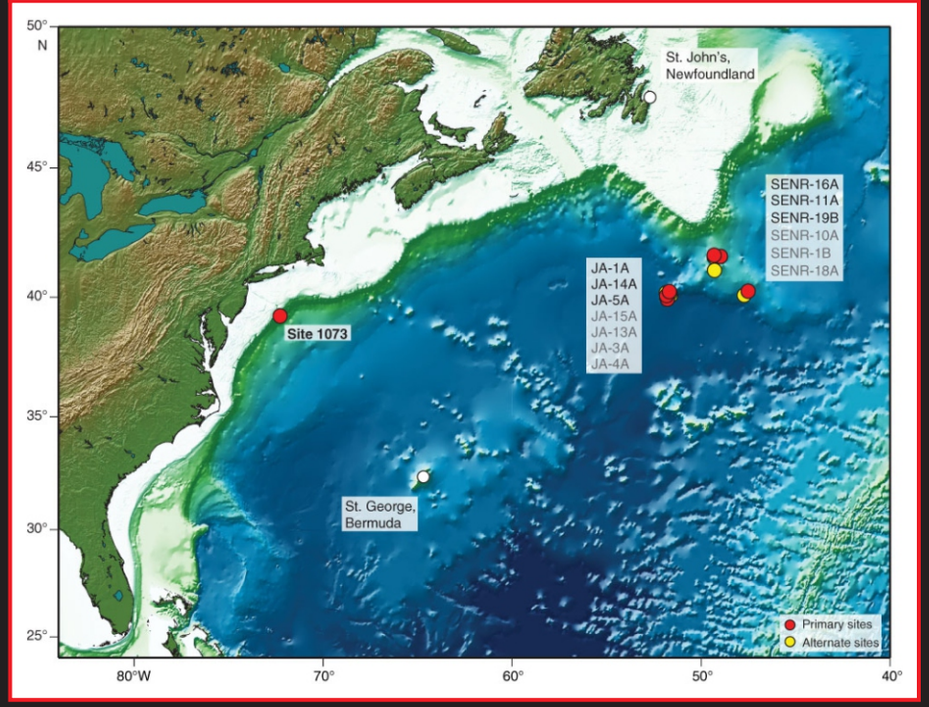
higher pCO_2 $\rightarrow$ higher temperatures (and rainfall) $\rightarrow$ higher weathering rates $\rightarrow$ lower pCO_2

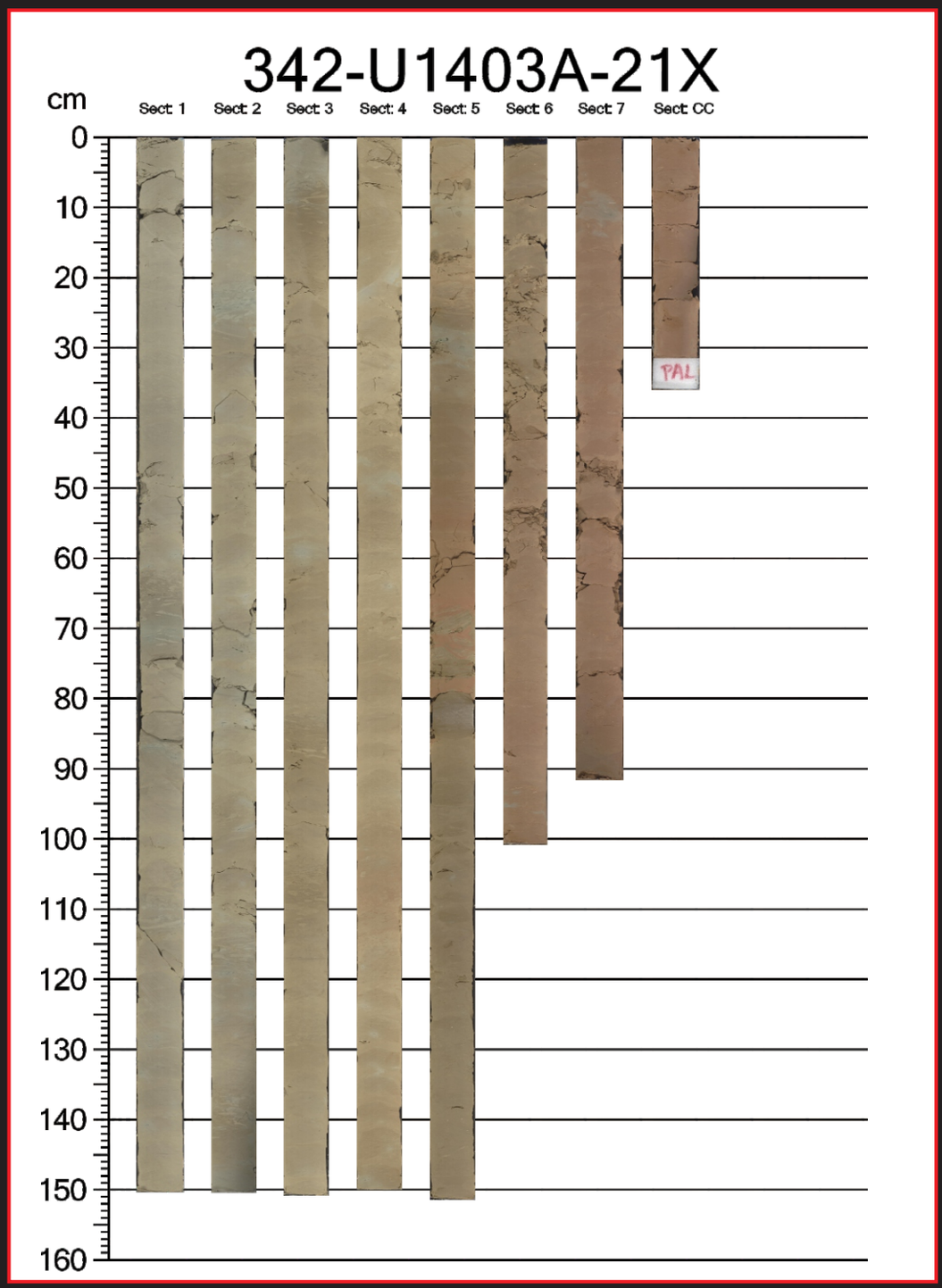
(A regulating feedback system linking CO_2 and climate with ocean productivity and oxygenation, and organic carbon burial, can also be formulated but not discussed further here.)

evidence?


V: τ ~ 100000 years
2CO2
Ca2+ + 2HCO3-
CaCO3
Ultimately, greenhouse-enhanced rates of silicate rock weathering:
2CO2(aq) + H2O + CaSiO3(s)
→ Ca2+ + 2HCO3- + SiO2(aq)
results in the permanent removal of CO2 and transfer to the geologic reservoir.

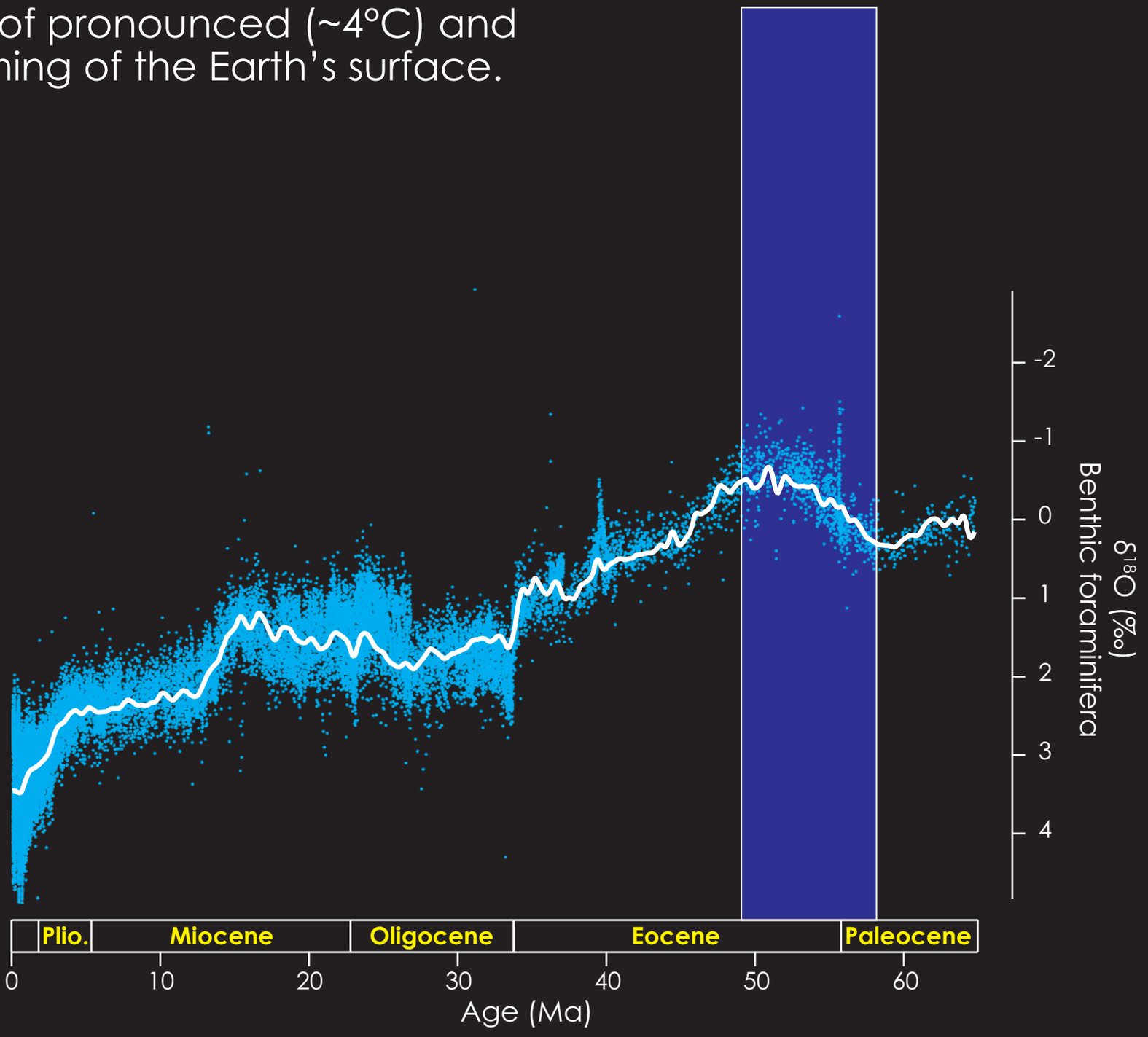
Long-term CO_2 feedback processes





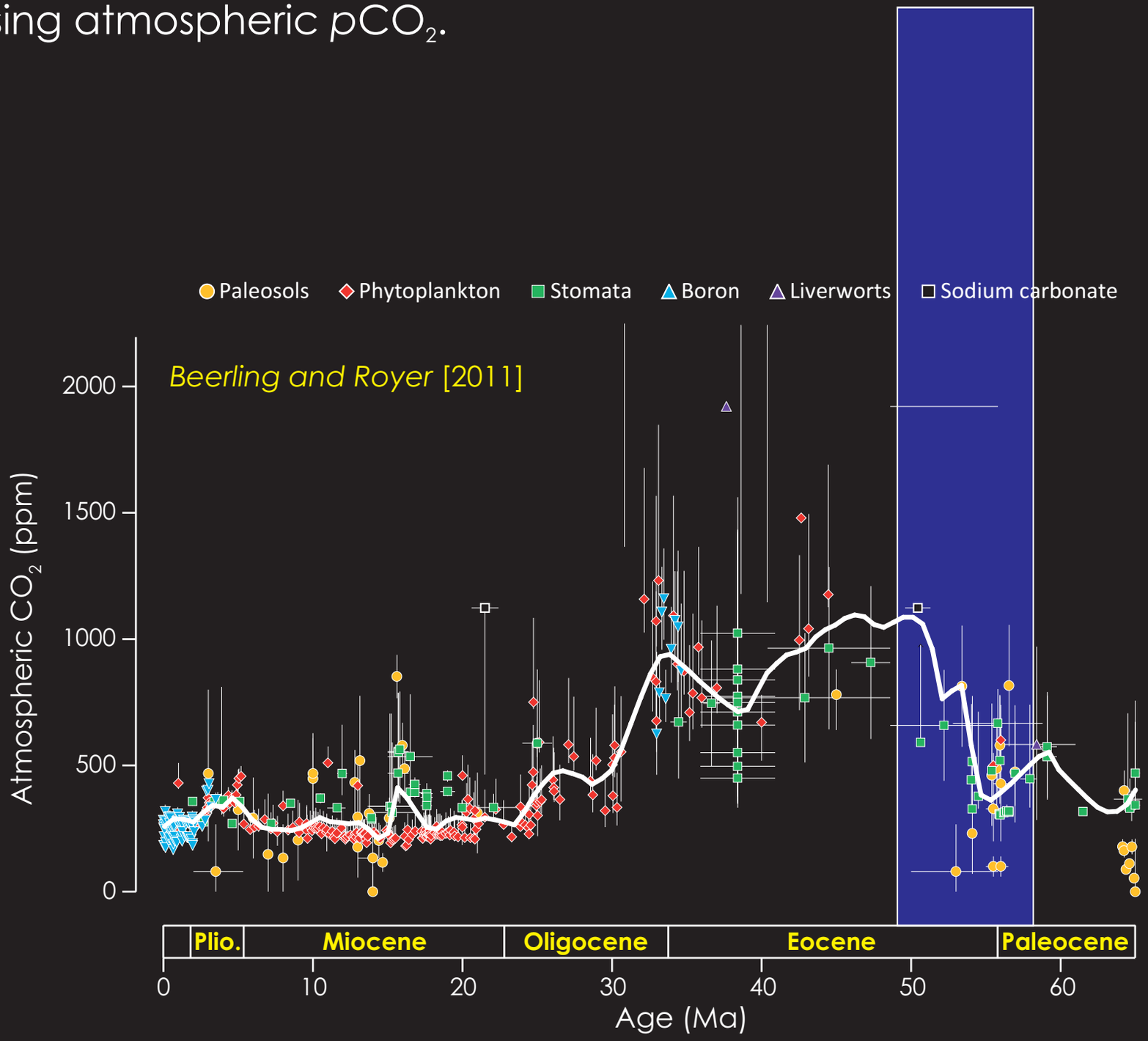
Evidence for climate-CO_2 weathering feedback

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



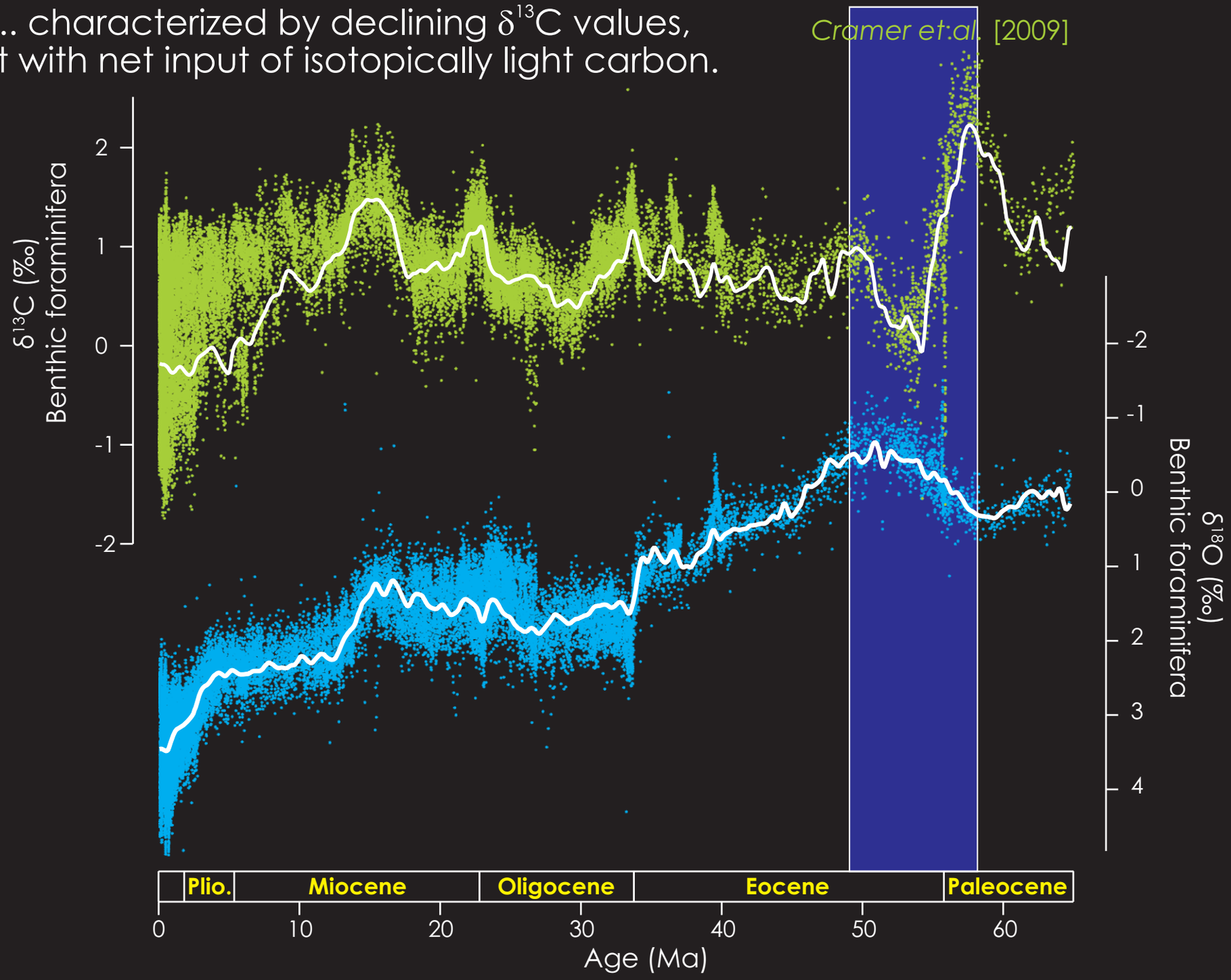
Evidence for climate-CO_2 weathering feedback

✓ Increasing atmospheric pCO_2.



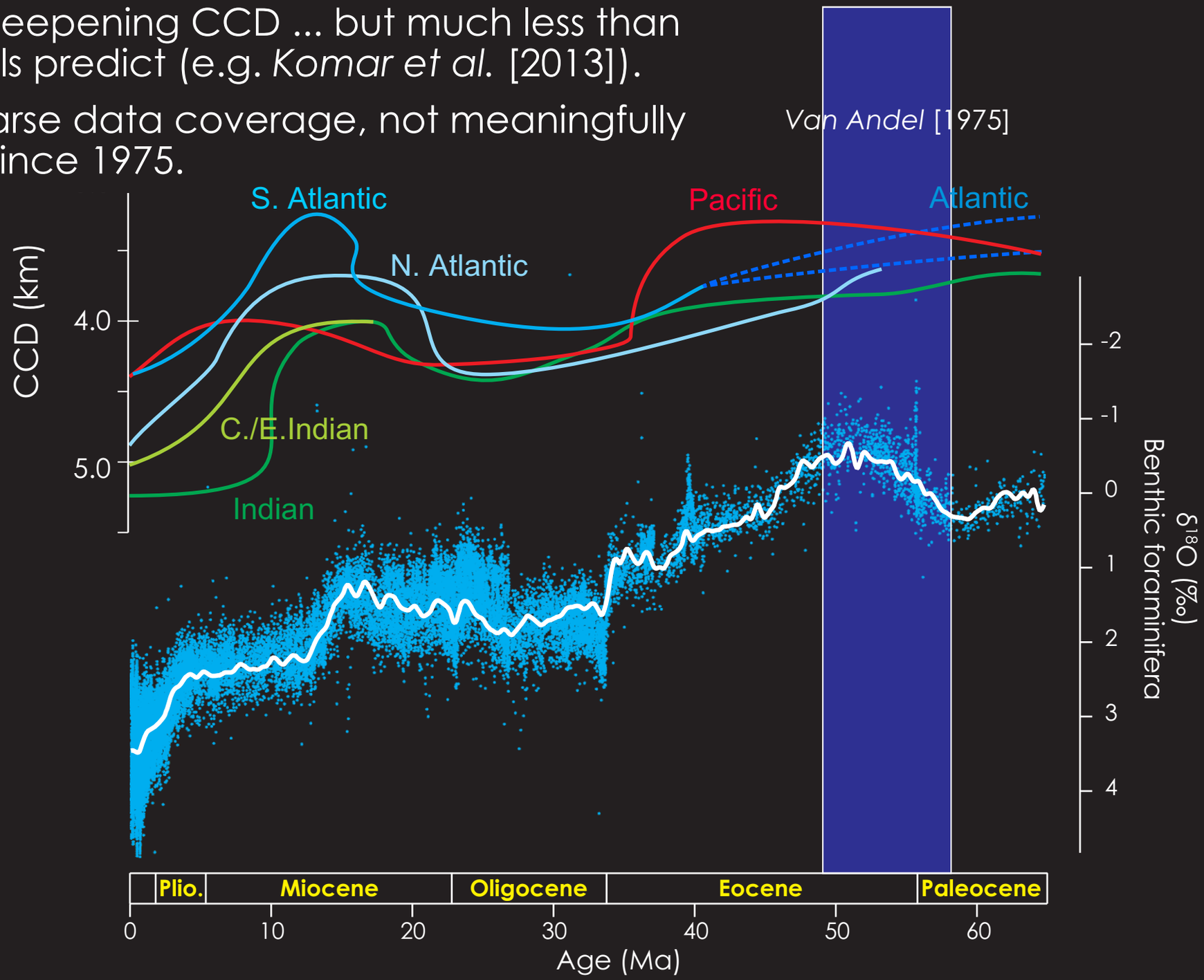
Evidence for climate-CO_2 weathering feedback

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

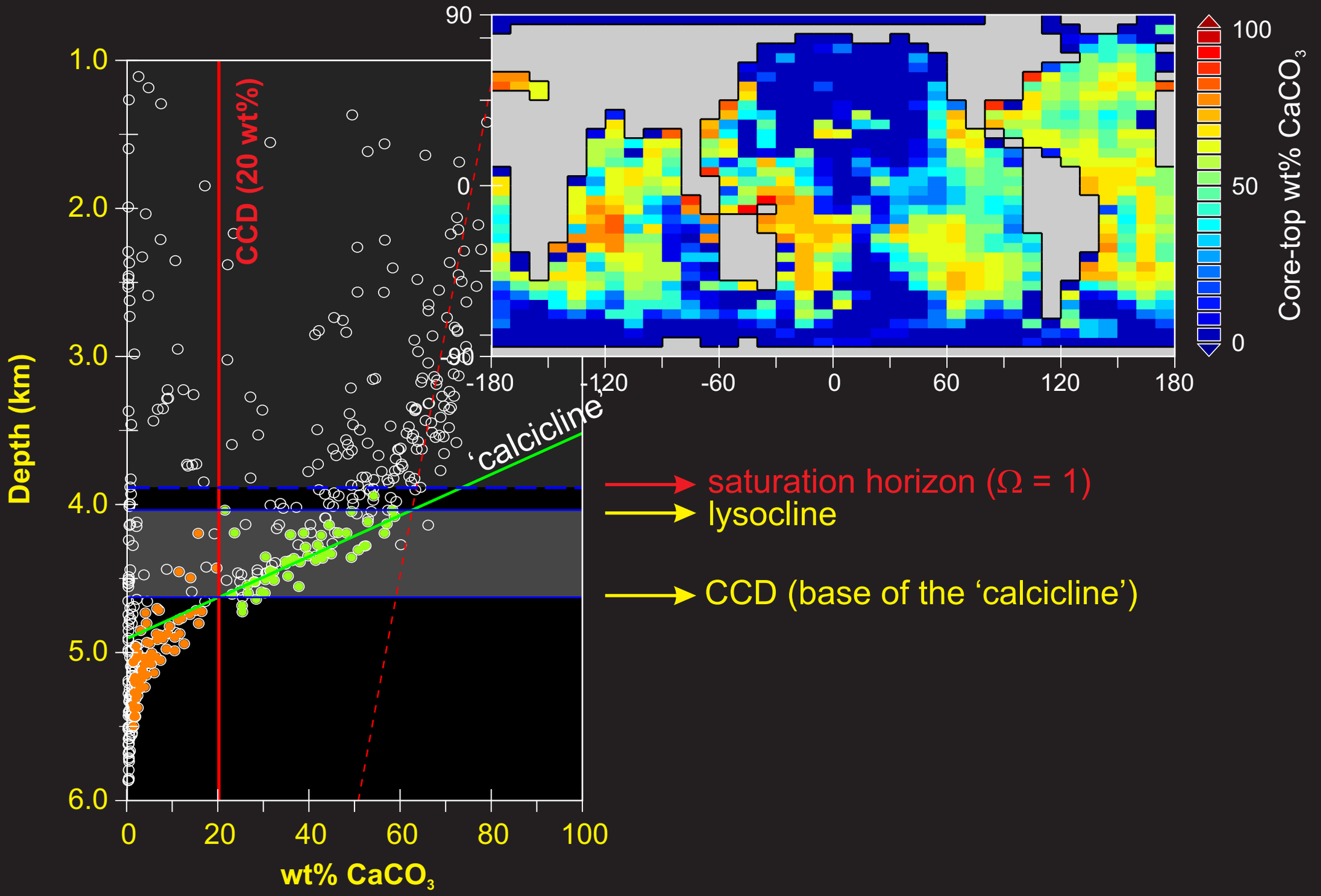


Evidence for climate-CO_2 weathering feedback

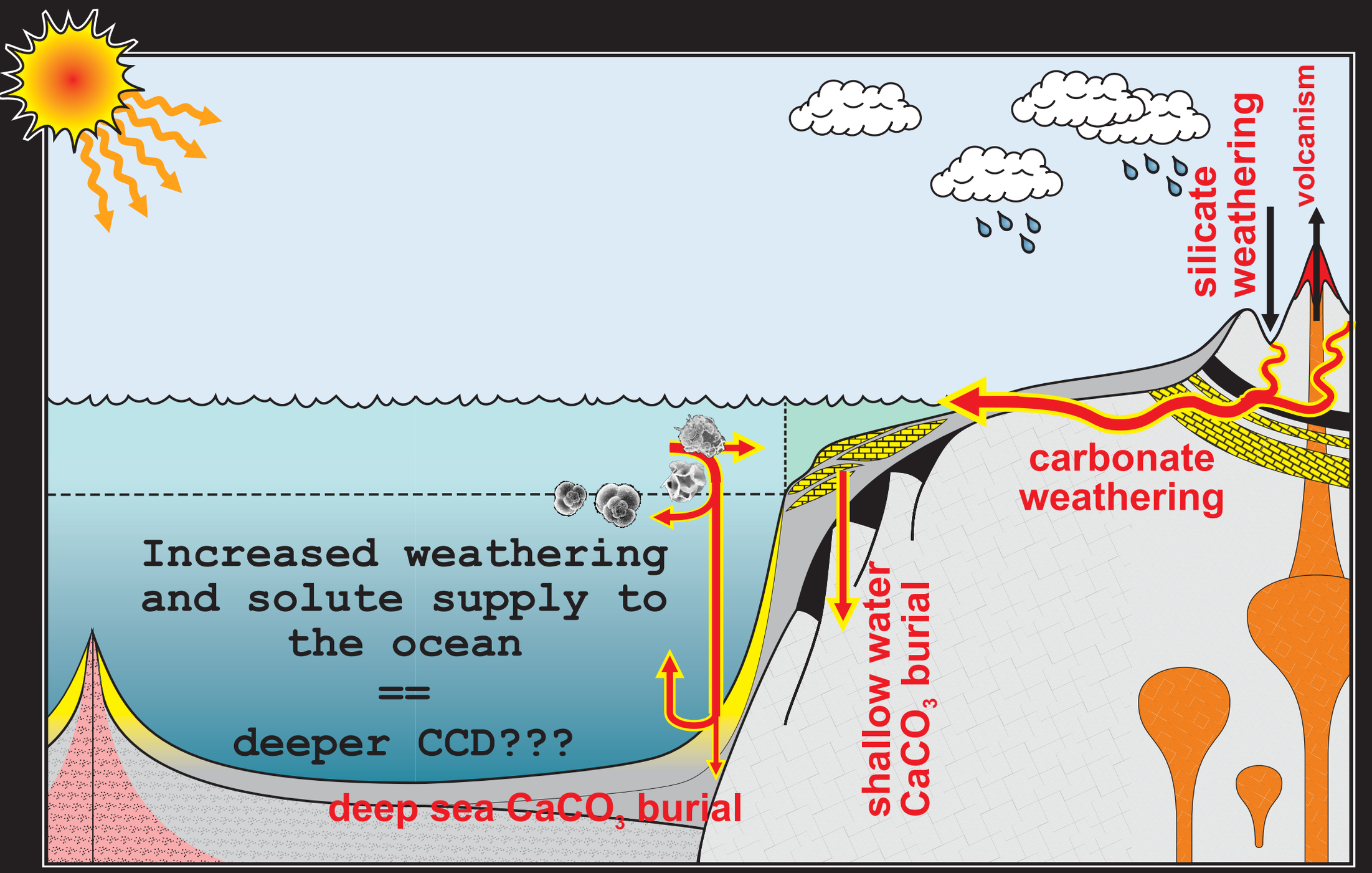
- Slightly deepening CCD ... but much less than box models predict (e.g. *Komar et al.* [2013]).
- Very sparse data coverage, not meaningfully updated since 1975.



Evidence for climate-CO_2 weathering feedback

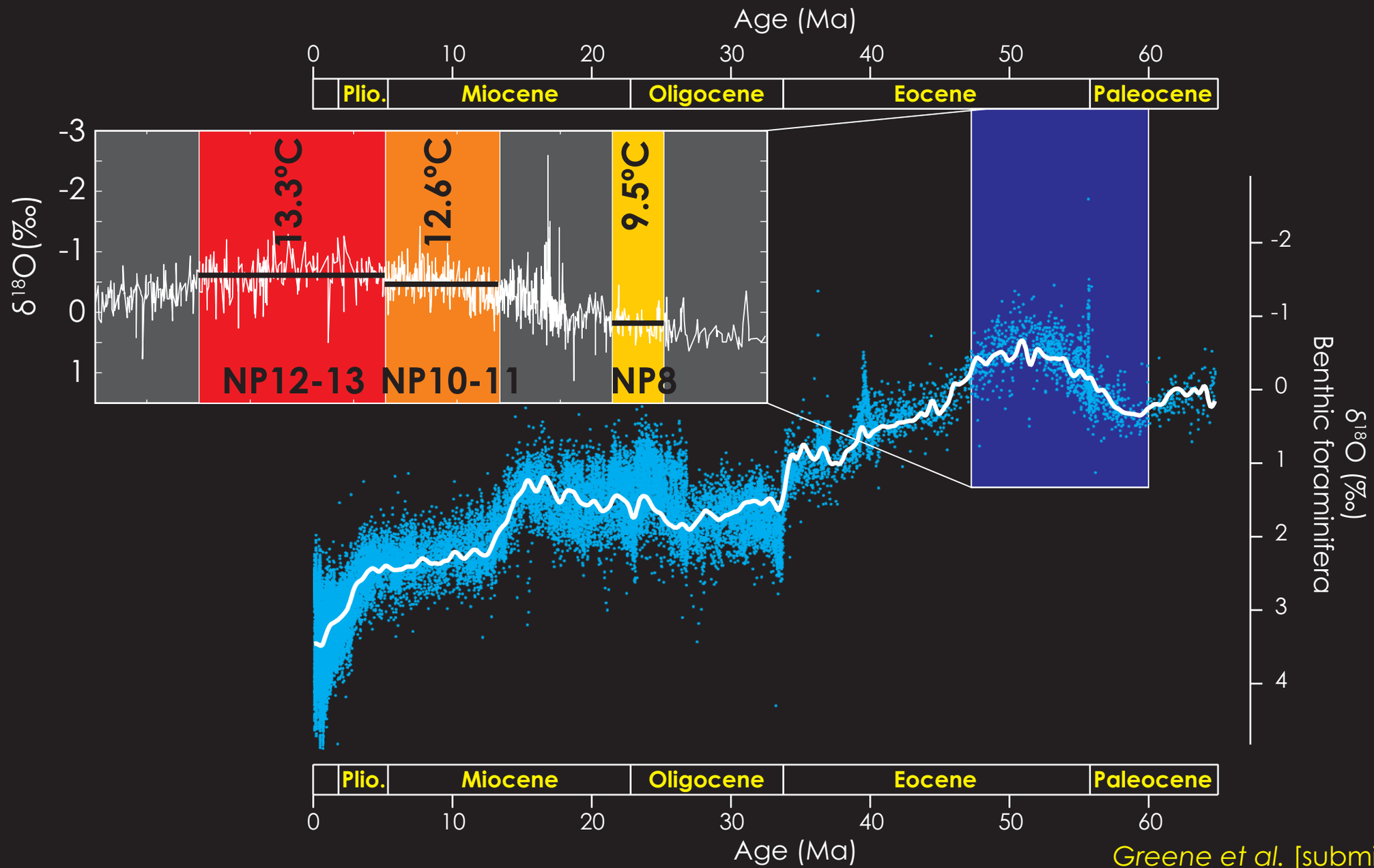


Evidence for climate-CO_2 weathering feedback



Evidence for climate-CO_2 weathering feedback

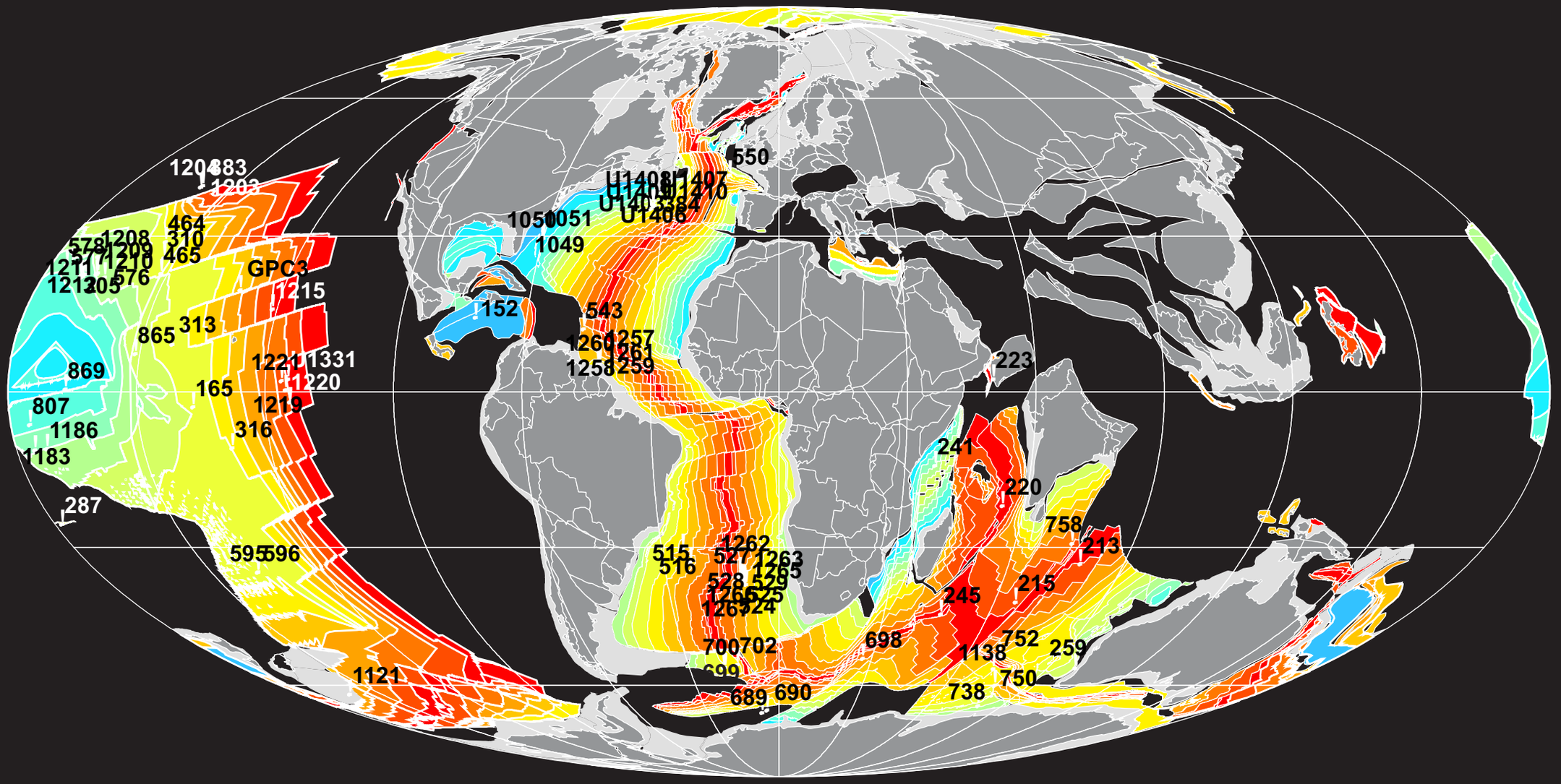
Three data slices spanning LPEE interval (and avoiding PETM).



Greene et al. [submitted]

Evidence for climate-CO_2 weathering feedback

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



55 60 70 80 90 100 110 120 130 140 150 160 170 180

Crustal age (Ma)

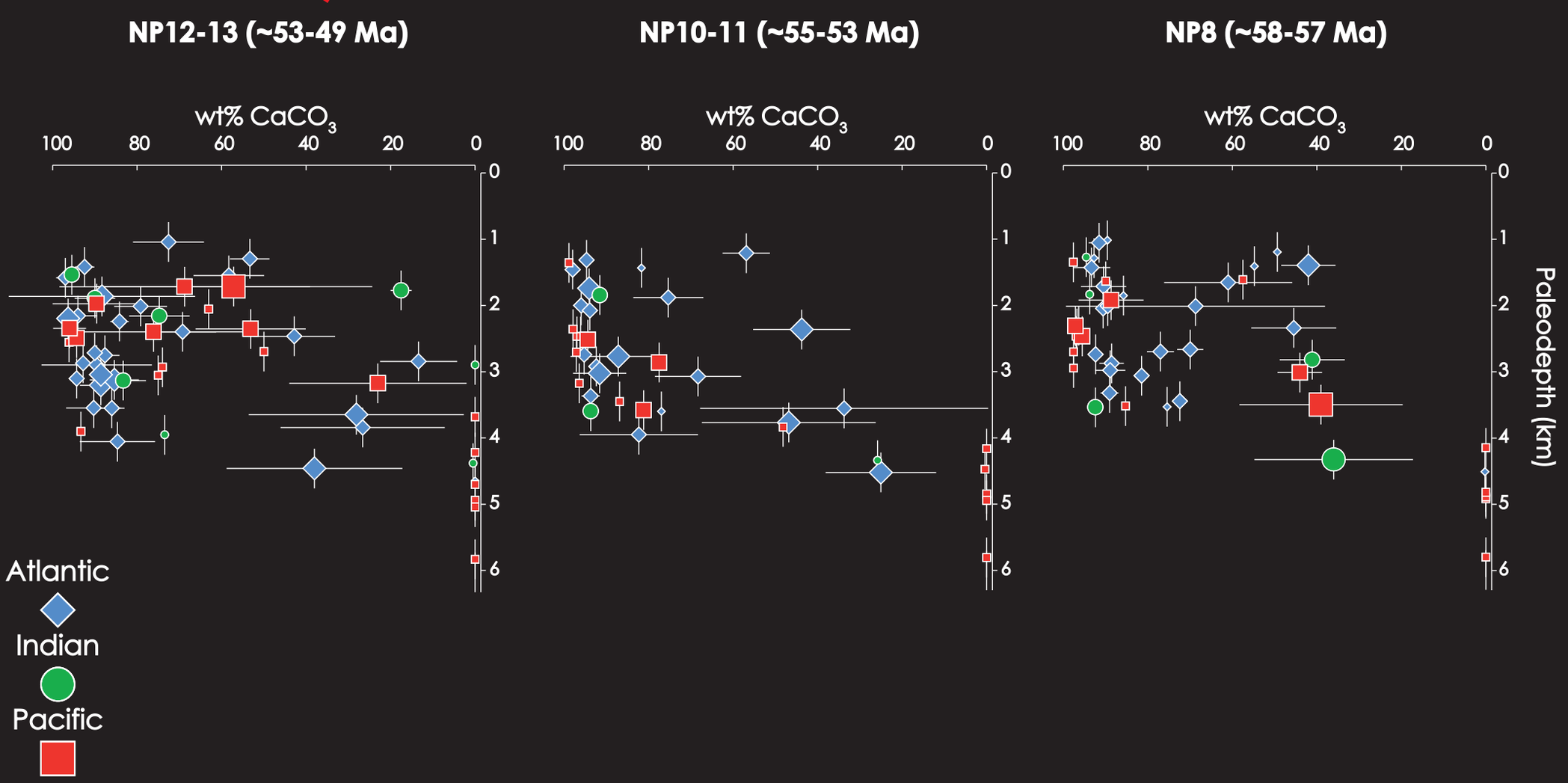
Crustal age (Ma)

Greene et al. [submitted]

Evidence for climate-CO_2 weathering feedback

'CCD' plots.

H_0: warming (=> increasing weathering?)



Greene et al. [submitted]

Evidence for climate-CO_2 weathering feedback

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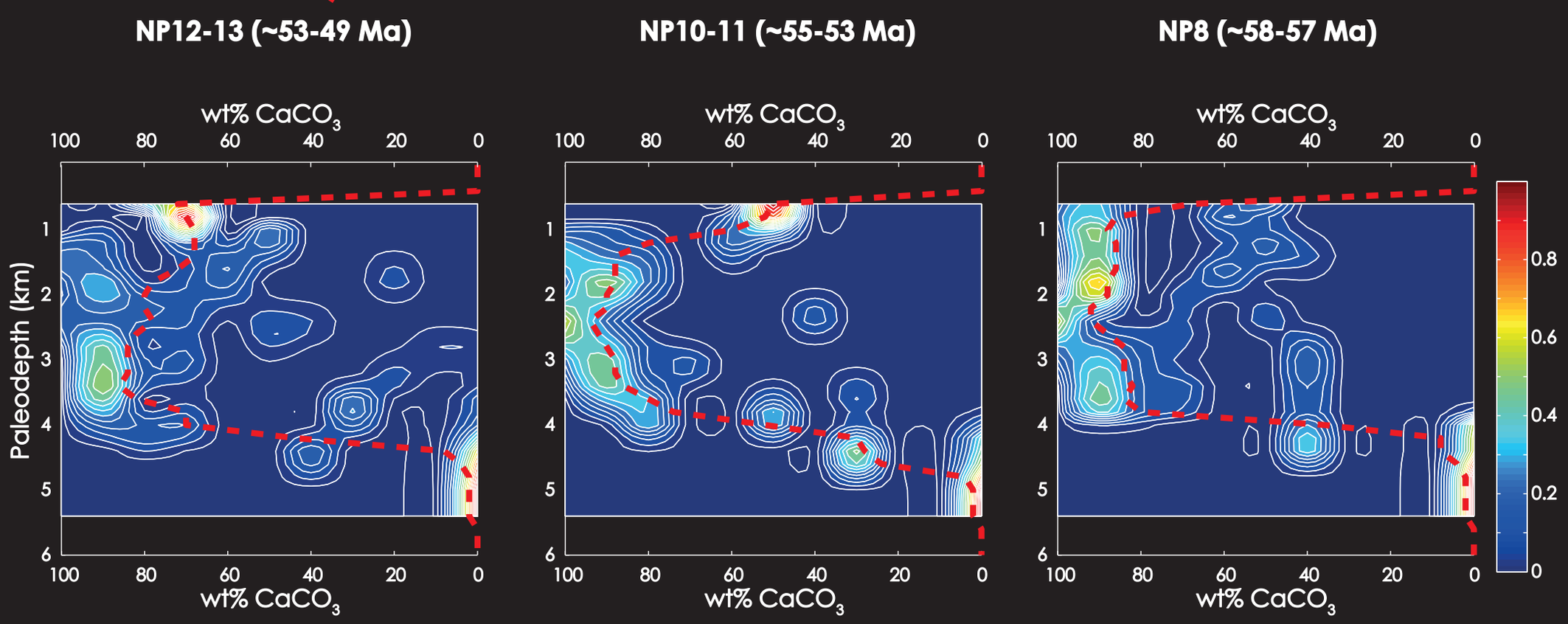
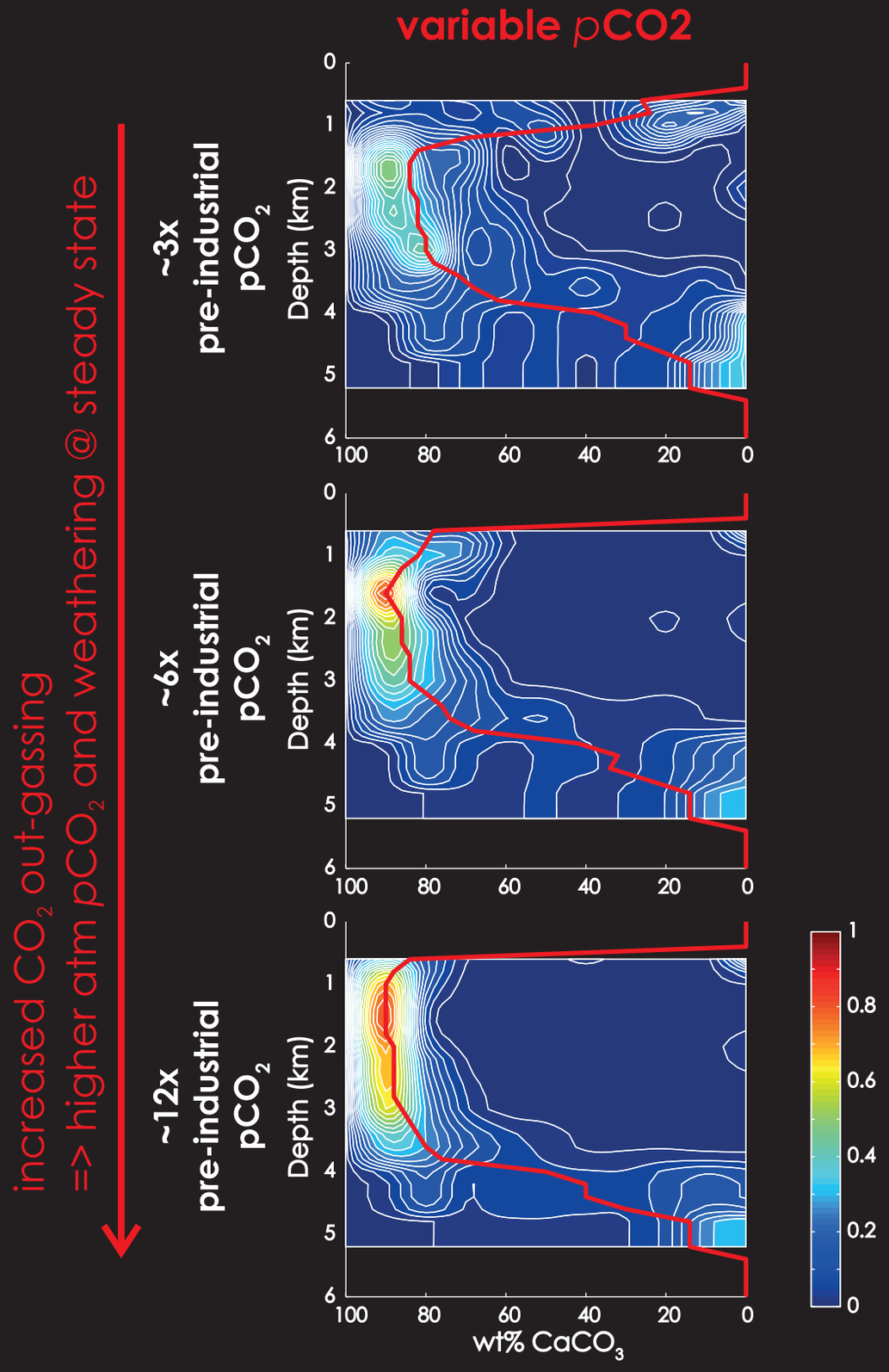
H_0: warming (=> increasing weathering?)



Contours are of relative data density
within a sliding time-window (and wt% bin).
Red contour delineates 50% of the data.

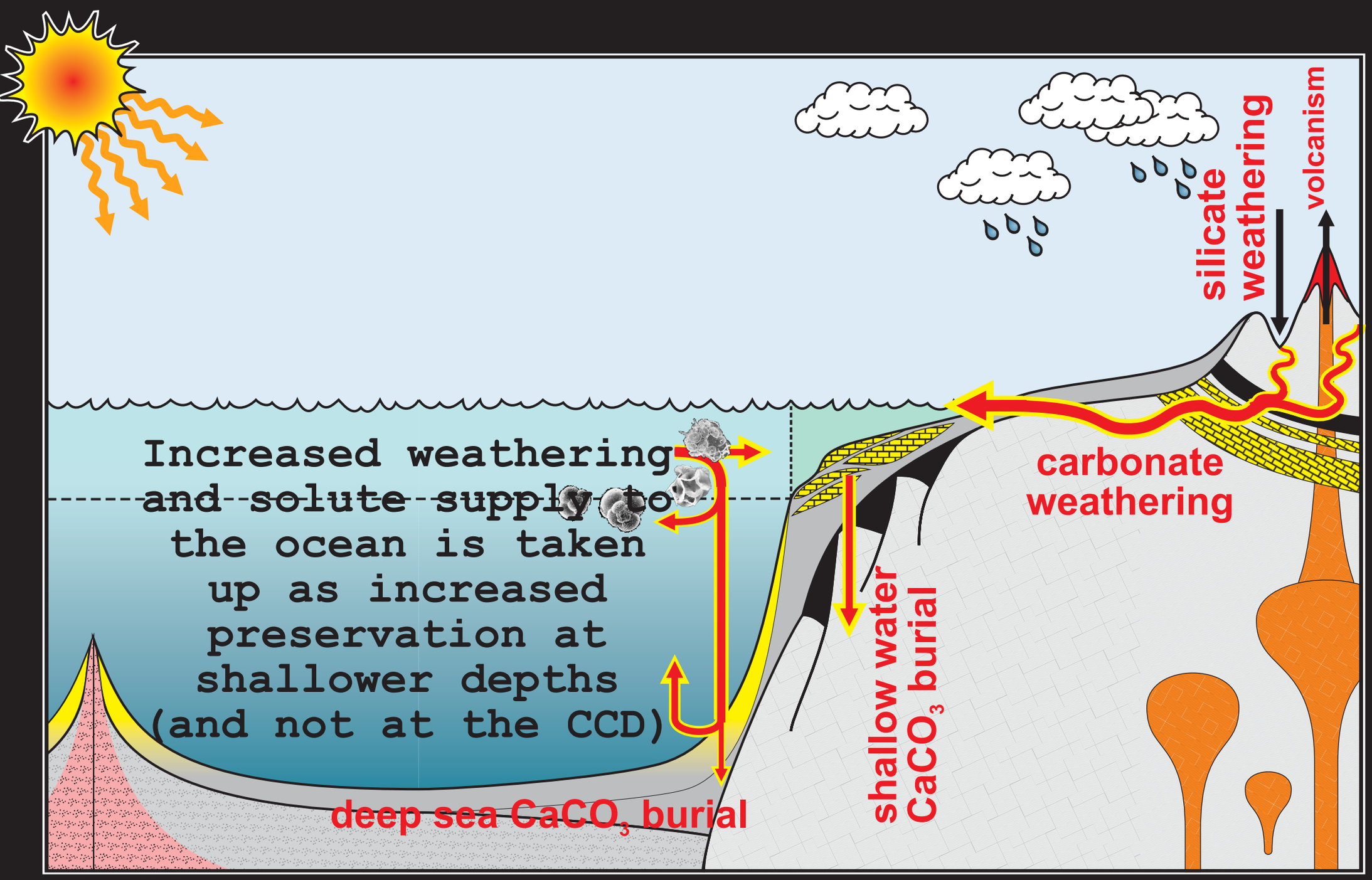
Greene et al. [submitted]



anon model

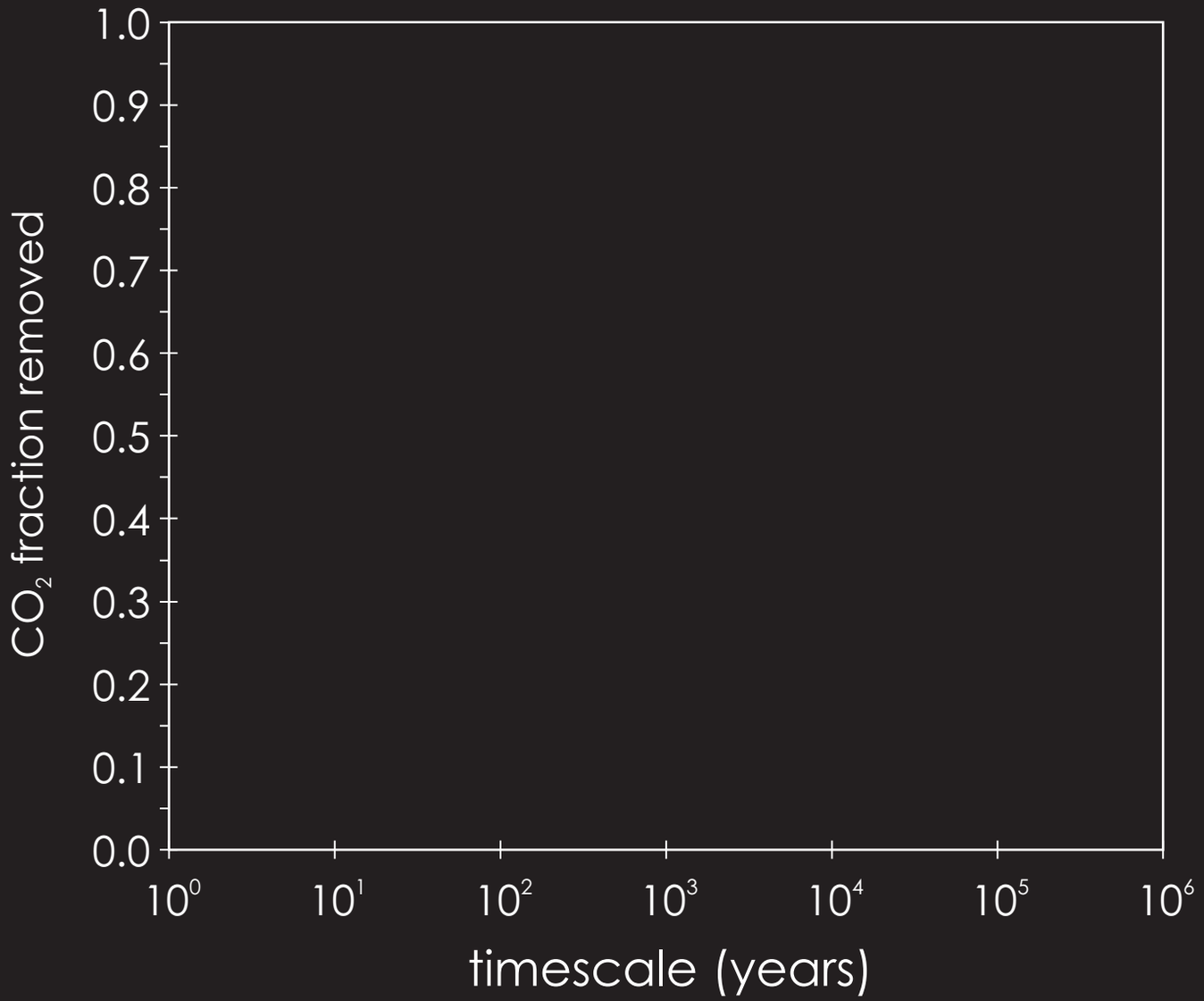
```
! calculate carbonate alkalinity

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

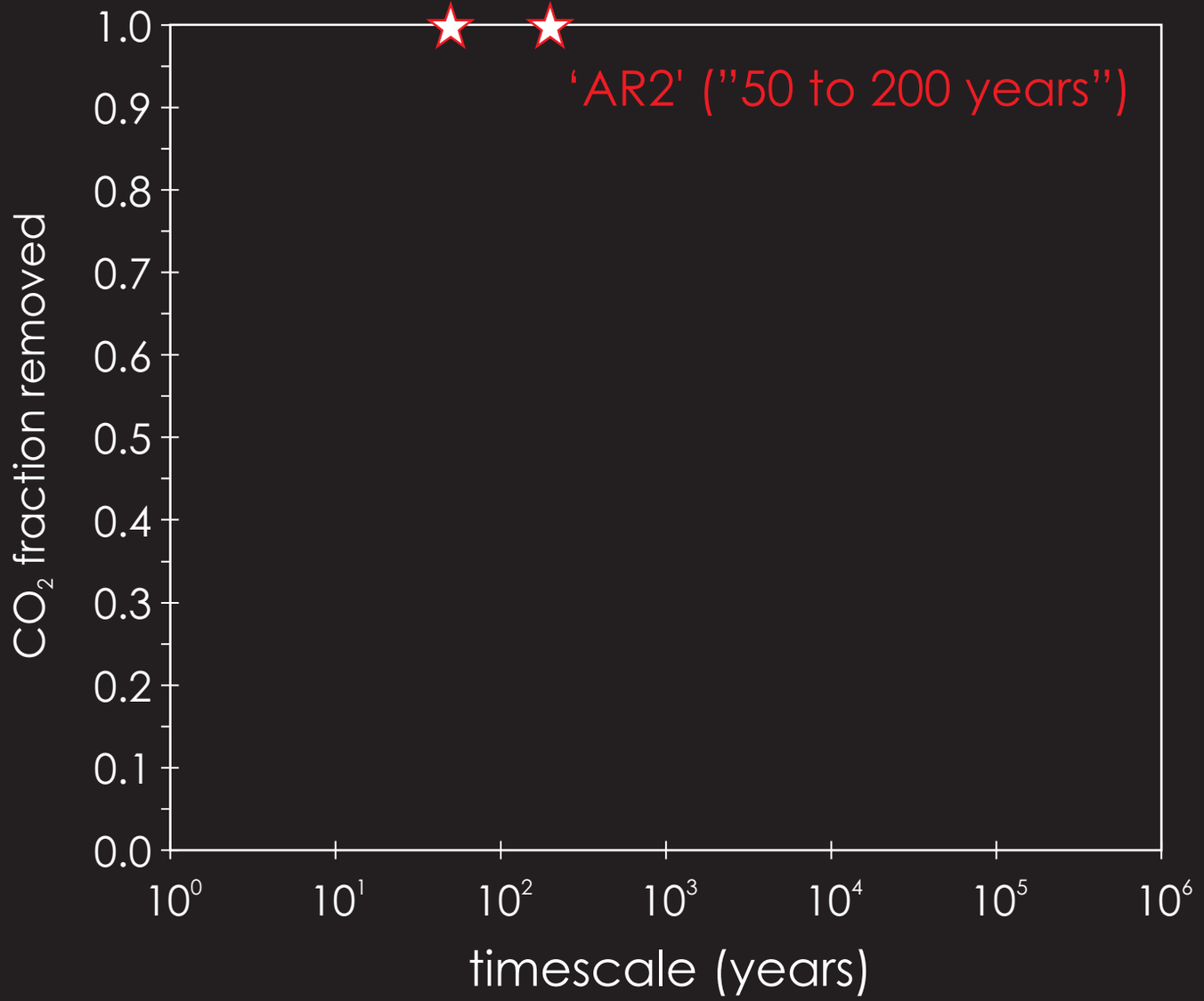


Response of carbon feedbacks to emissions

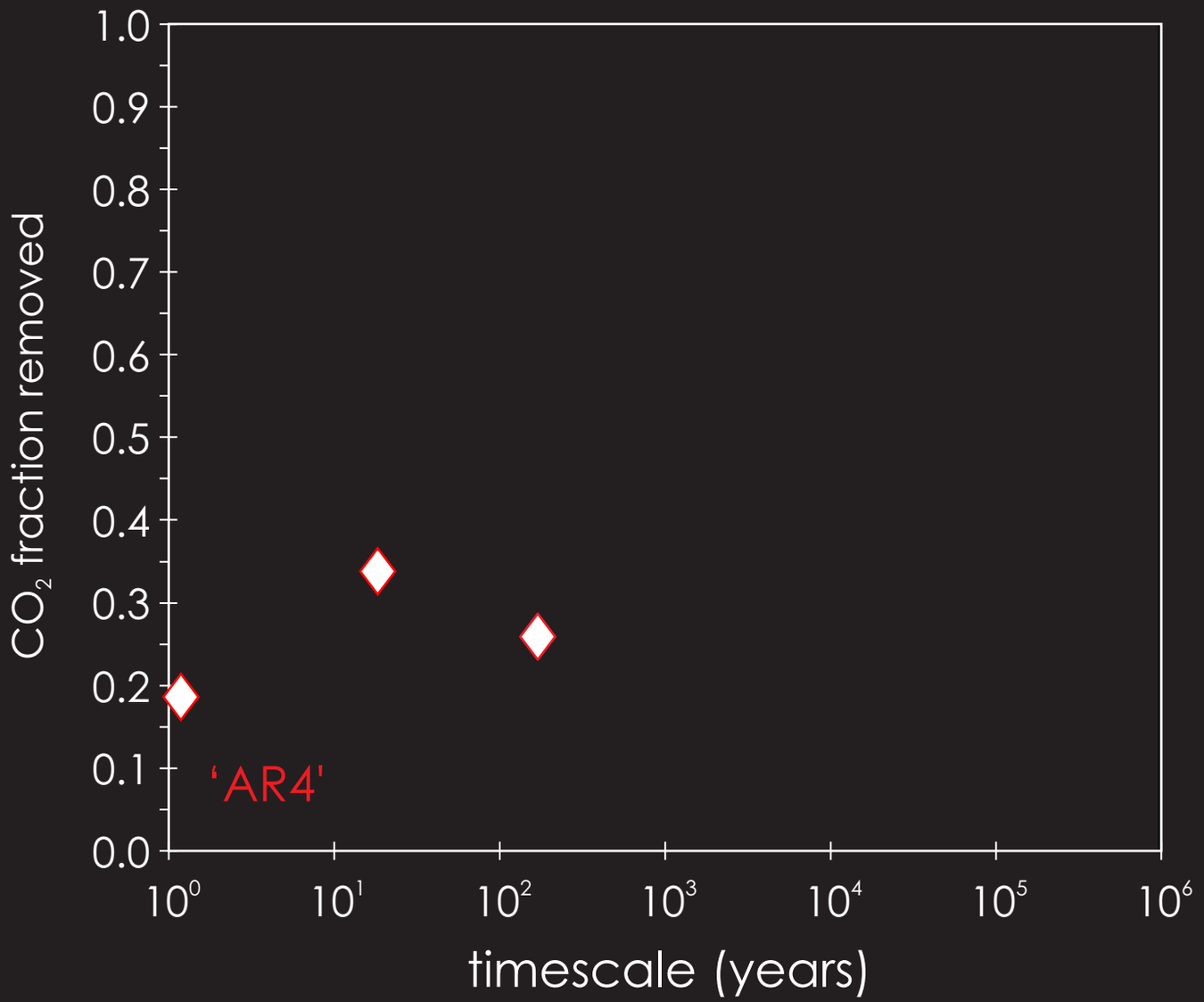
Cross-plot of the fraction of total CO_2 emissions to the atmosphere removed by a particular process (carbon sink), vs. the characteristic (e-folding) time-scale of that process (log_{10} scale).



Response of carbon feedbacks to emissions

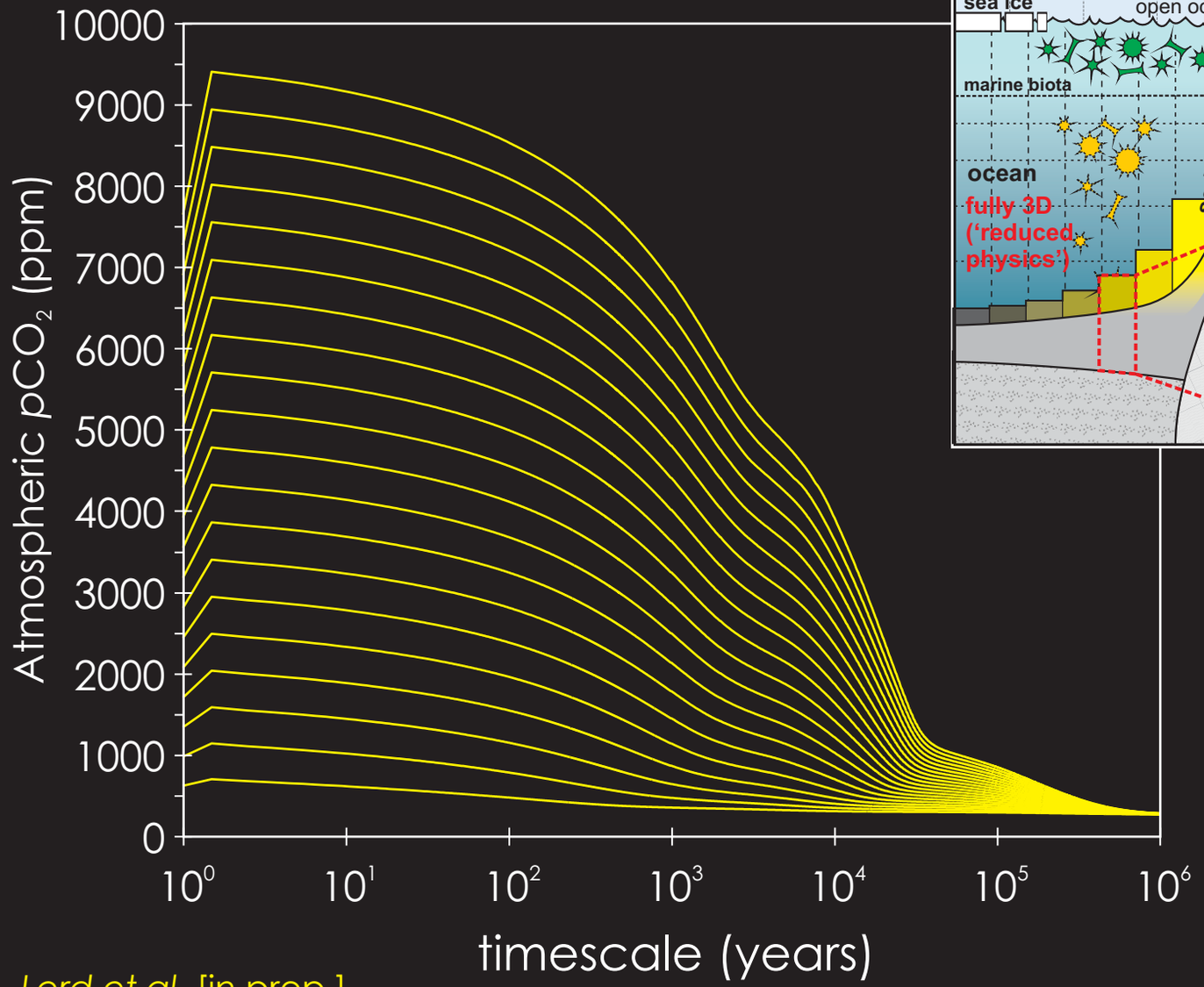


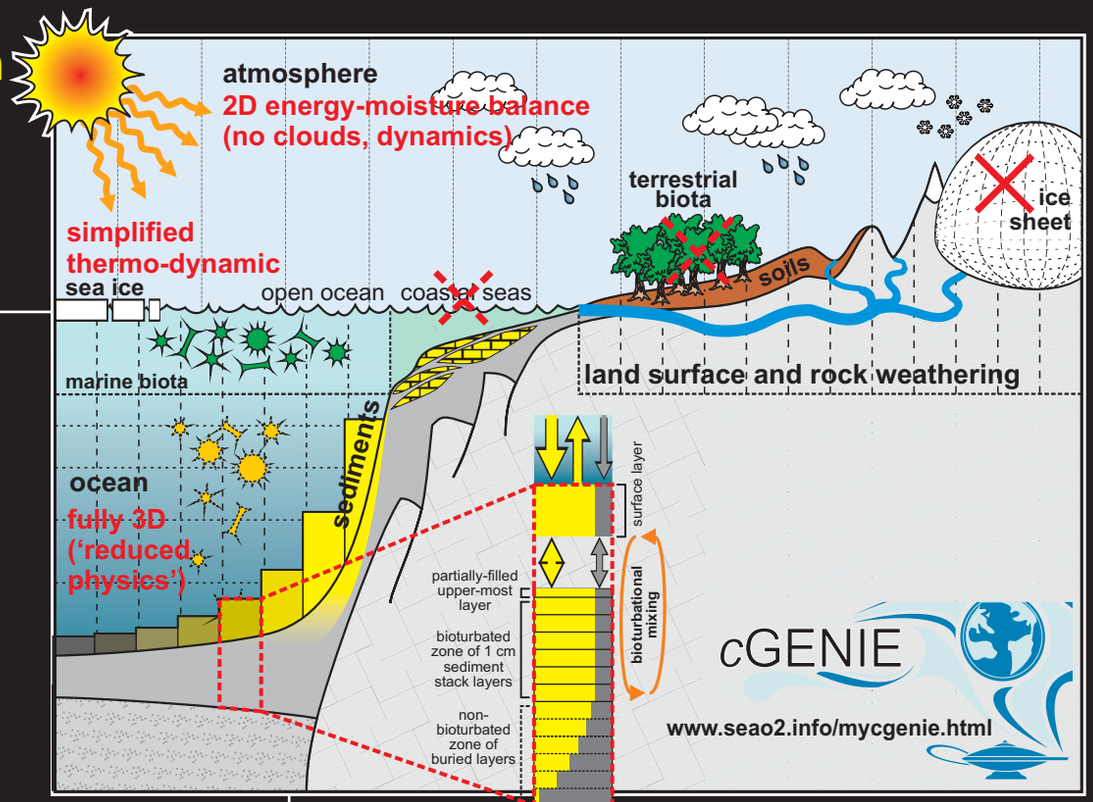
Response of carbon feedbacks to emissions



Response of carbon feedbacks to emissions

(1) Run a 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. [in prep.]

Response of carbon feedbacks to emissions

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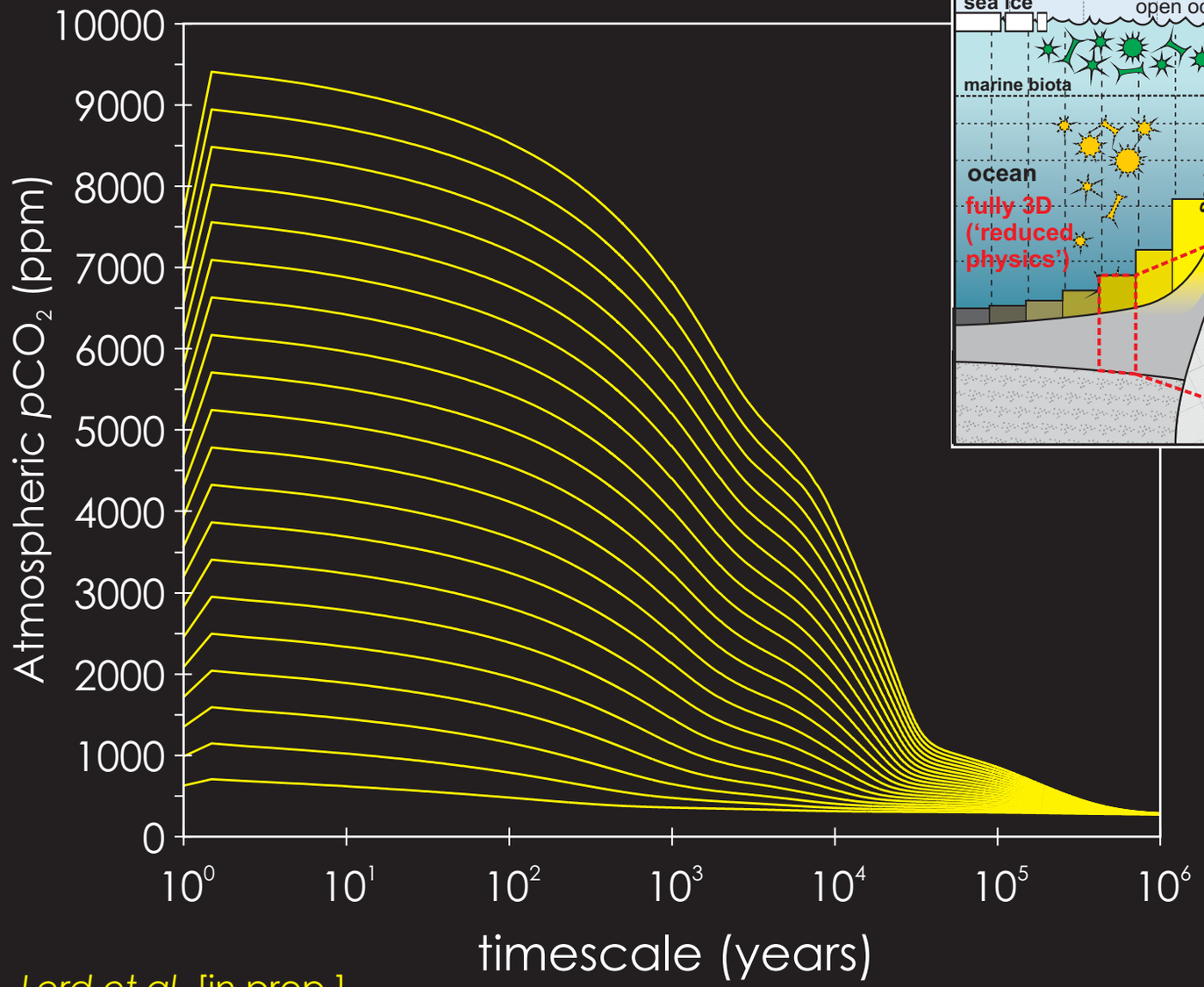
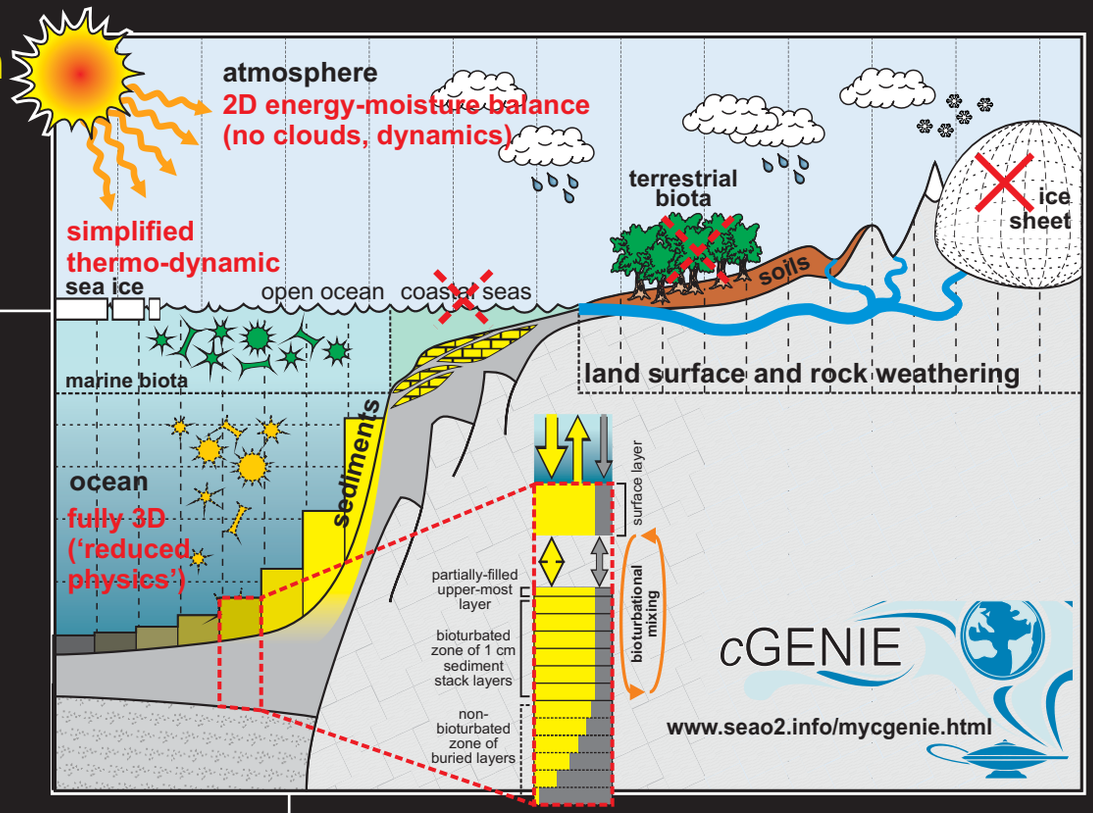




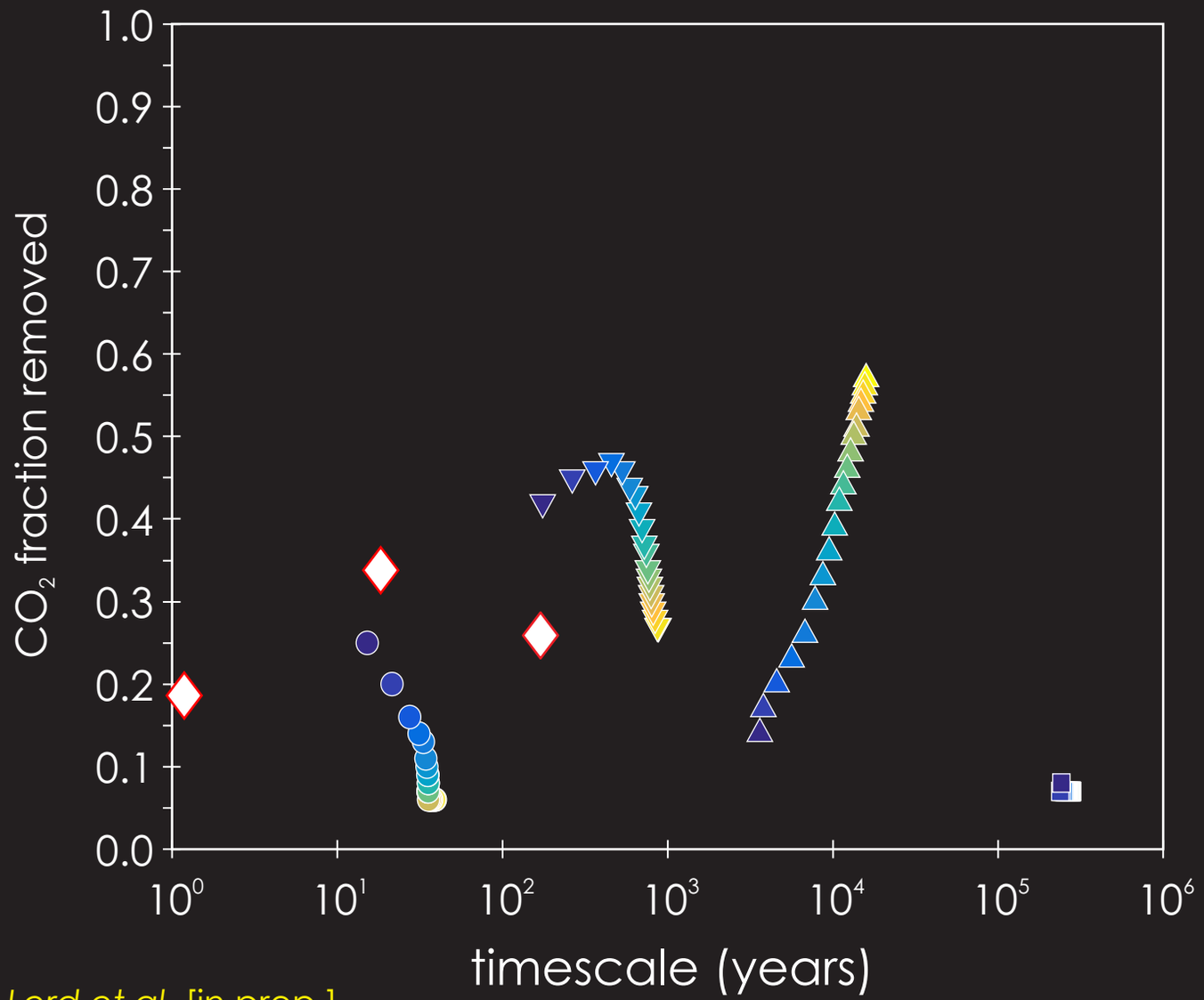
(2) Fit each CO_2 decay curve with a series (4 optimal) of exponentials. Extract the fraction of CO_2 and time-scale associated with each.

(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. [in prep.]

Response of carbon feedbacks to emissions

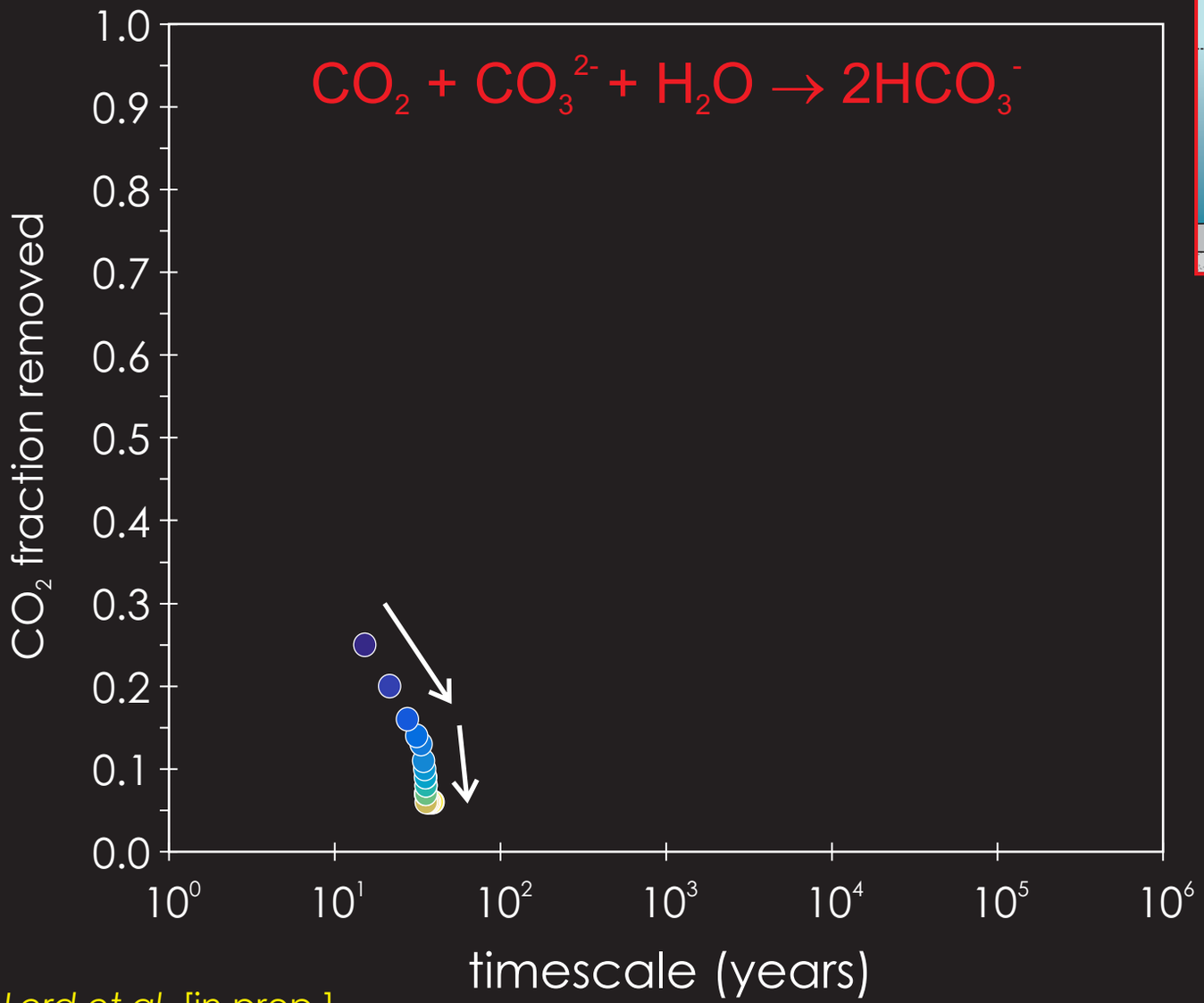
Response of fraction of CO_2 removed vs. the characteristic time-scale, as a function of total emissions, ranging from 1,000 PgC (dark blue) to 20,000 PgC (yellow).

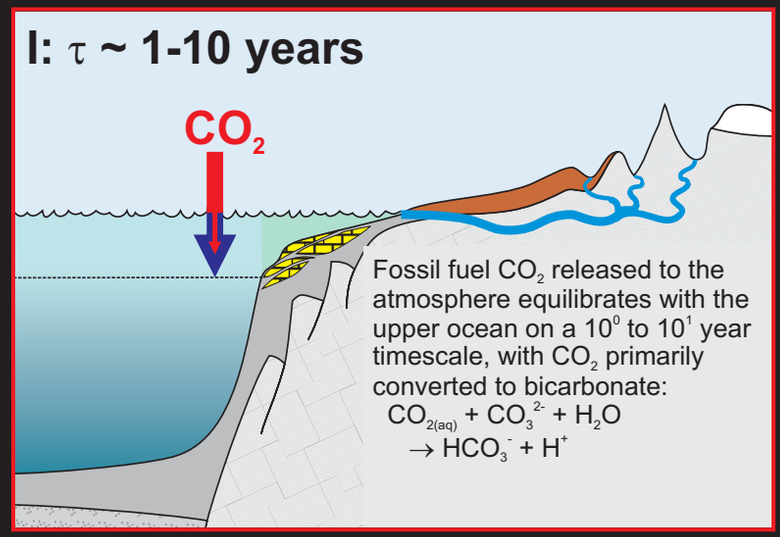


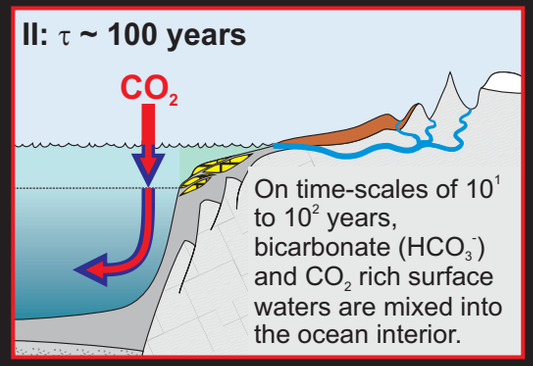
Lord et al. [in prep.]

Response of carbon feedbacks to emissions

Depletion of mixed layer carbonate buffer; ocean stratification and reduced surface mixing. Warming and reduced CO_2 solubility. Threshold reached @ ~4000 PgC?



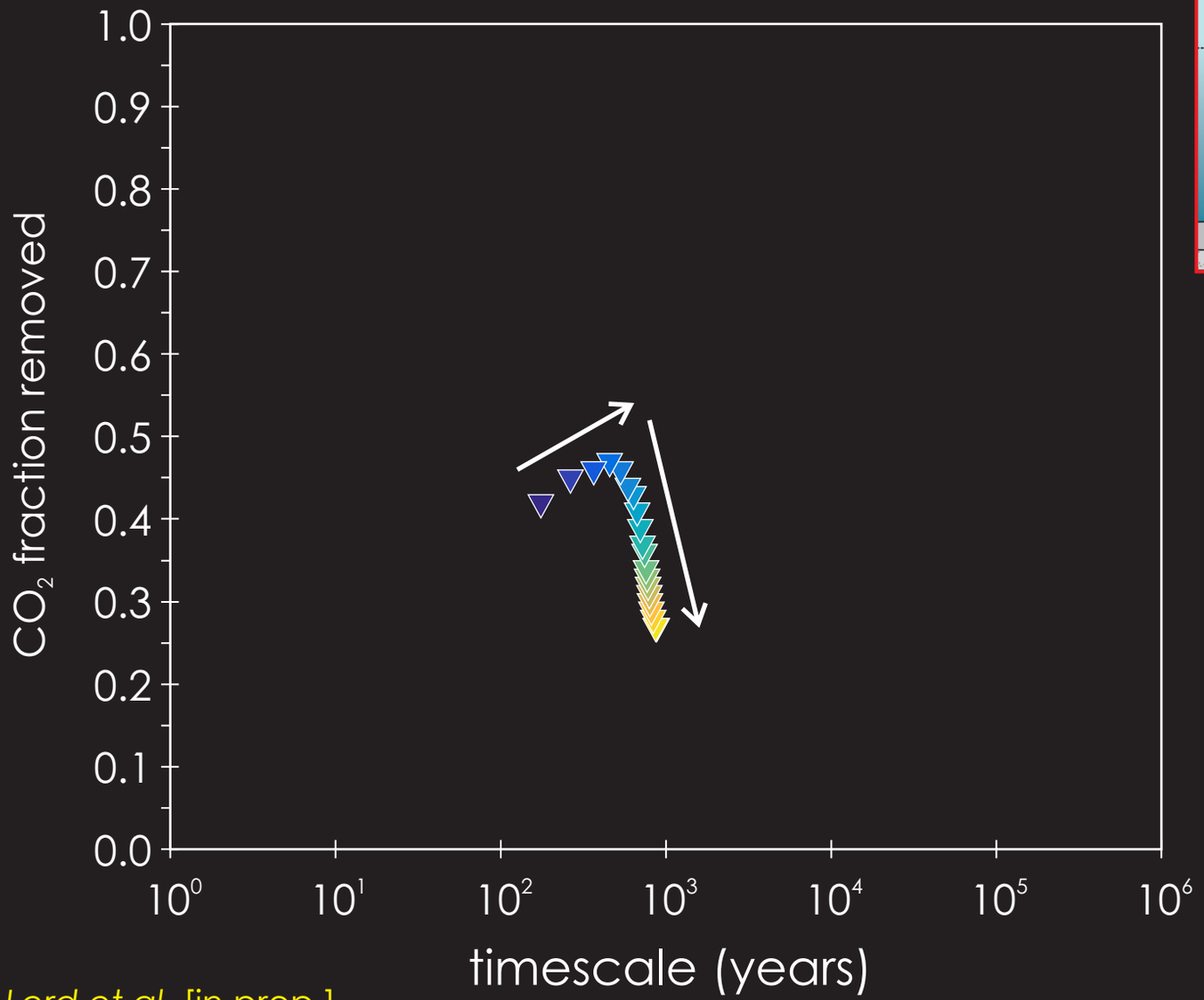


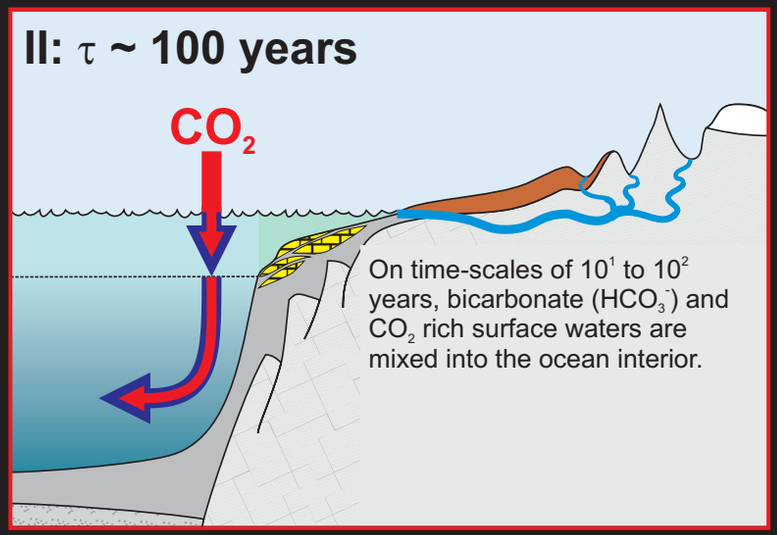


Lord et al. [in prep.]

Response of carbon feedbacks to emissions

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

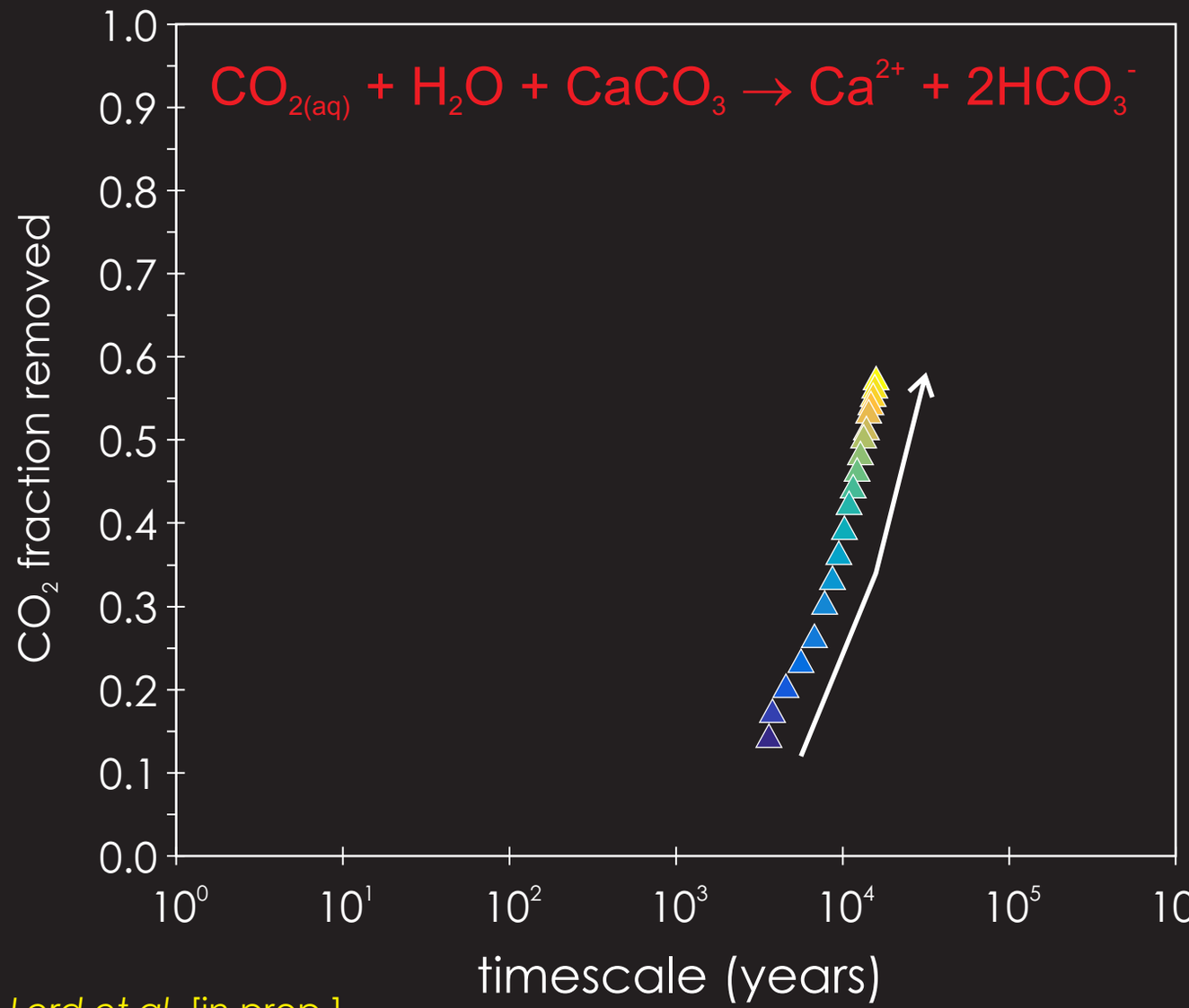


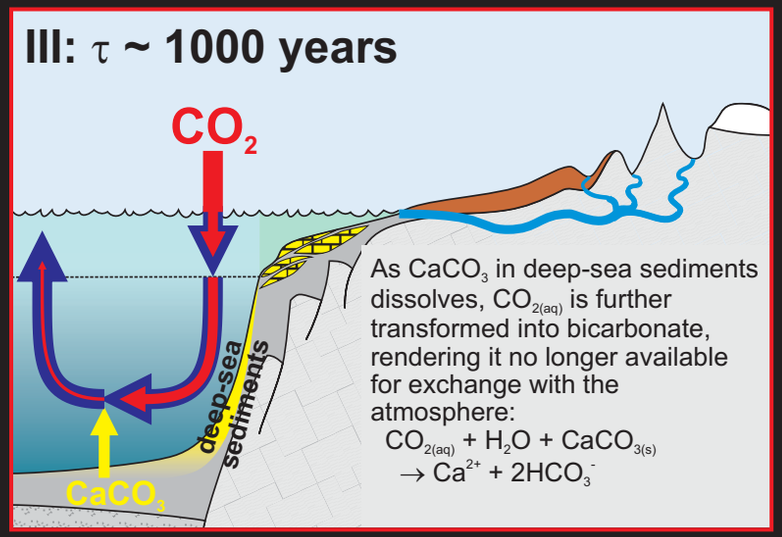


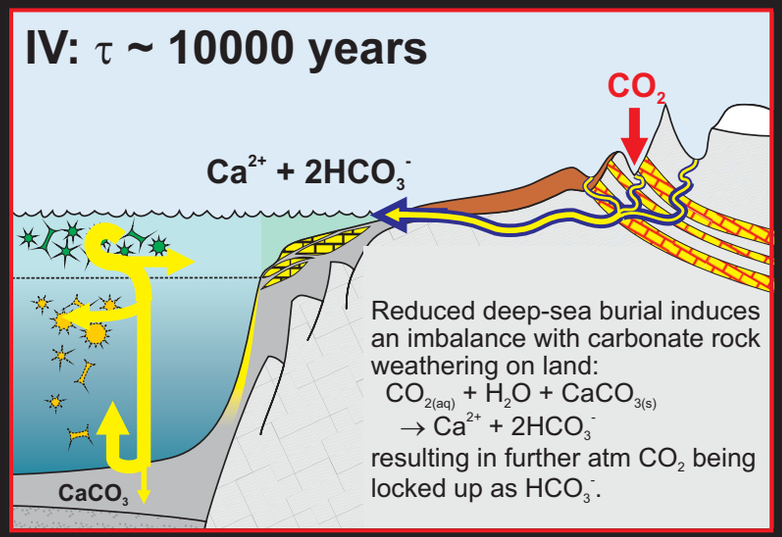
Lord et al. [in prep.]

Response of carbon feedbacks to emissions

Surface stratification and collapse of the AMOC (in this particular model).
(No obvious threshold response.)



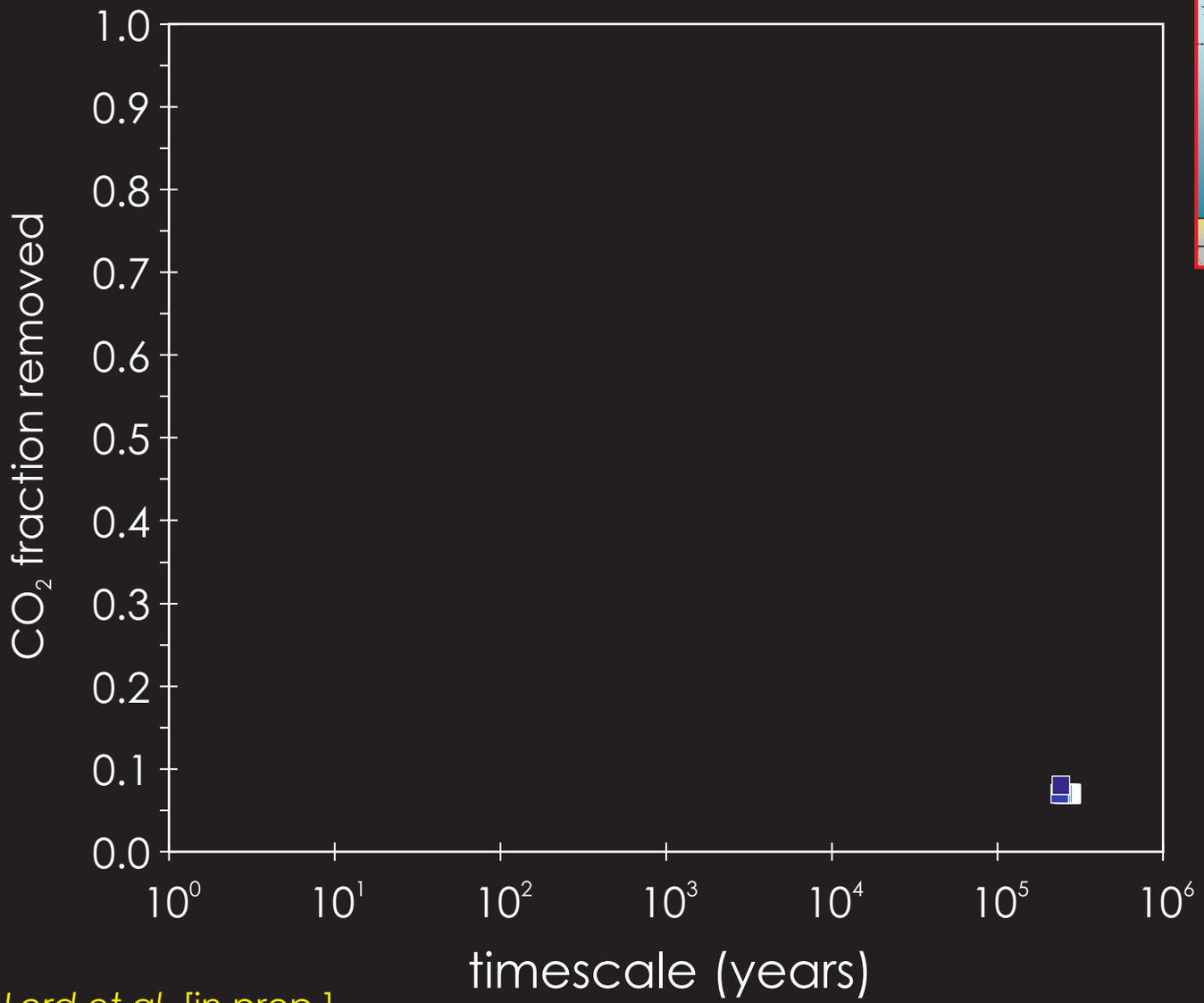




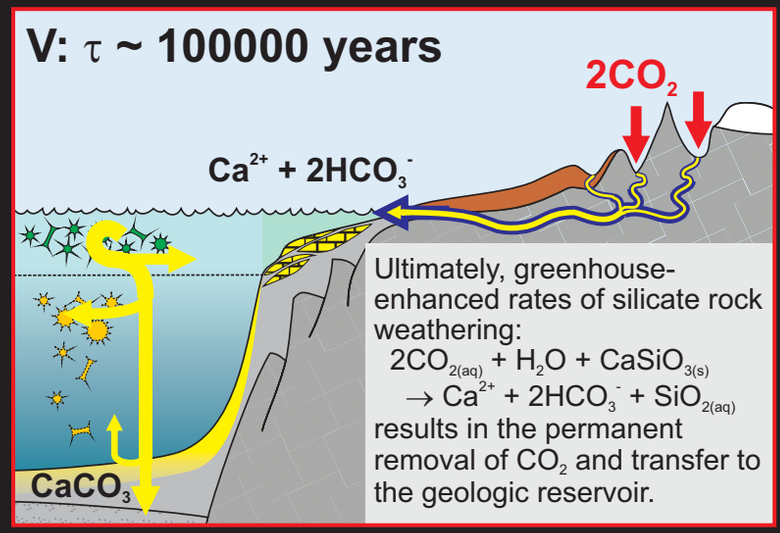
Lord et al. [in prep.]

Response of carbon feedbacks to emissions

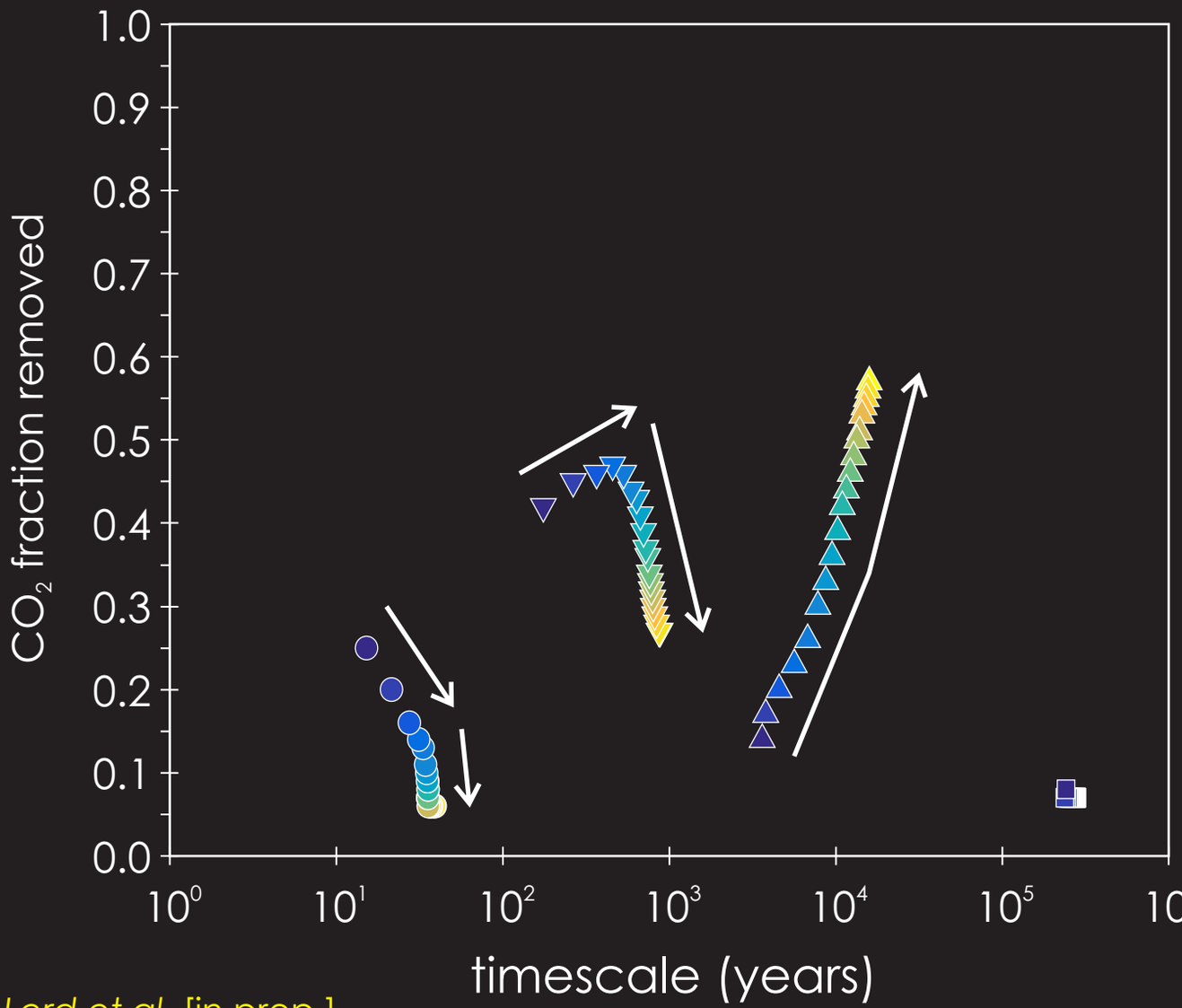
(No response!)



Lord et al. [in prep.]



Response of carbon feedbacks to emissions



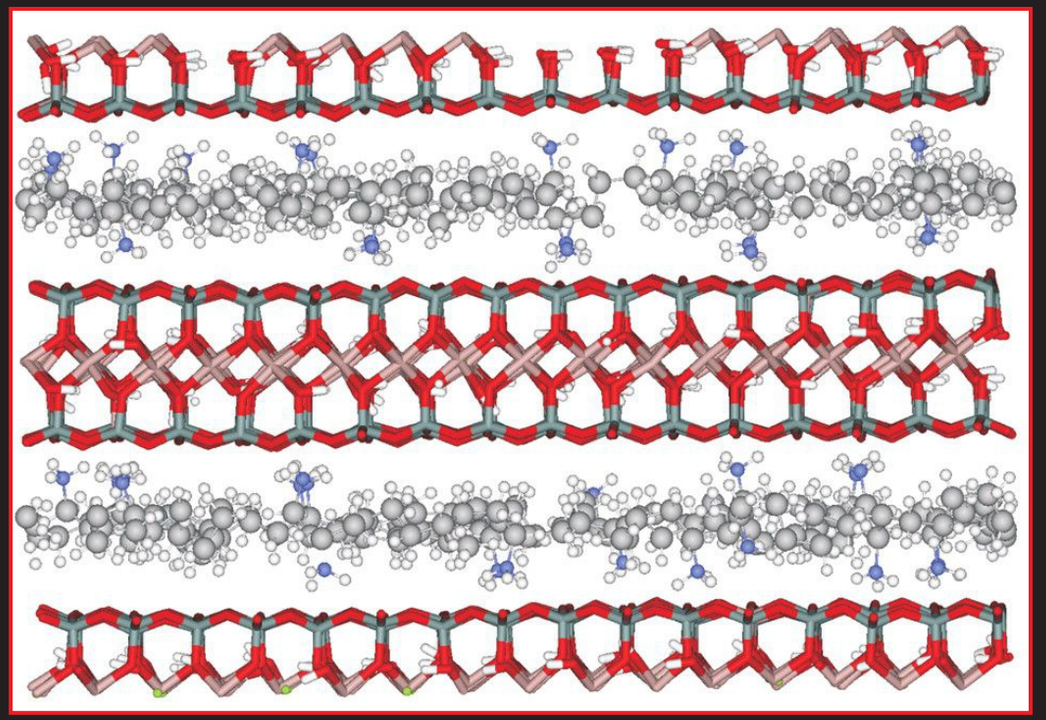
Lord et al. [in prep.]

Summary:

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 (and hence warming) will hence become more persistent as the main short-term CO_2 feedbacks weaken.

Only a (almost invariant) small fraction(~7%) of CO_2 is extremely persistent.
BUT, the majority of carbon removal beyond ~10,000 PgC is removed only on time-scales exceeding 10,000 years.
For all practical anthropogenic purposes; 'for ever'.

Cats, clays, and carbon sequestration



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