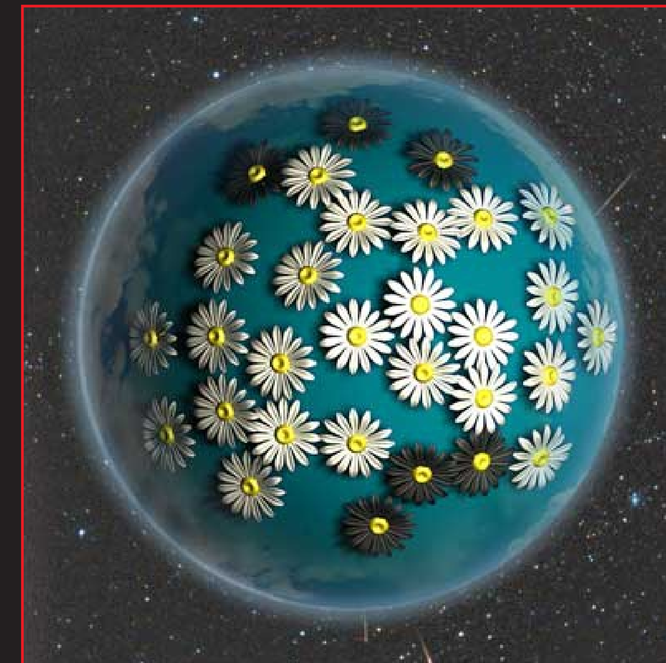
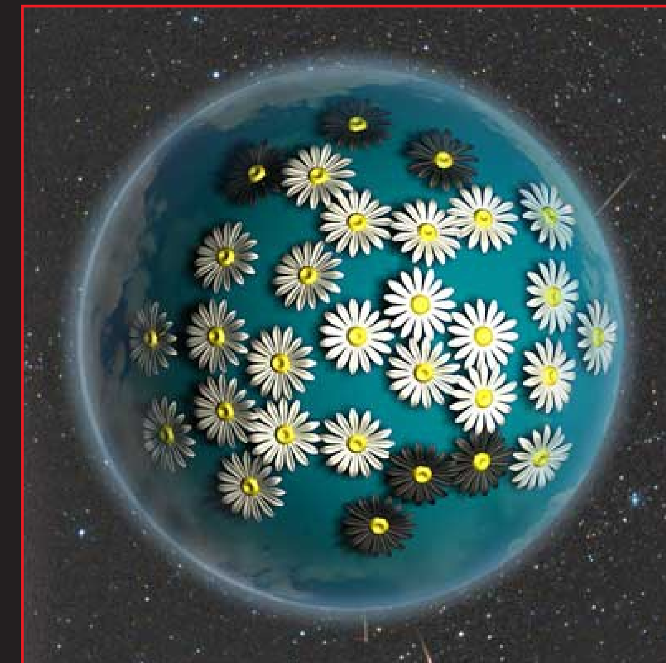
The Global Climate Thermostat: Fact, fiction, and computer models

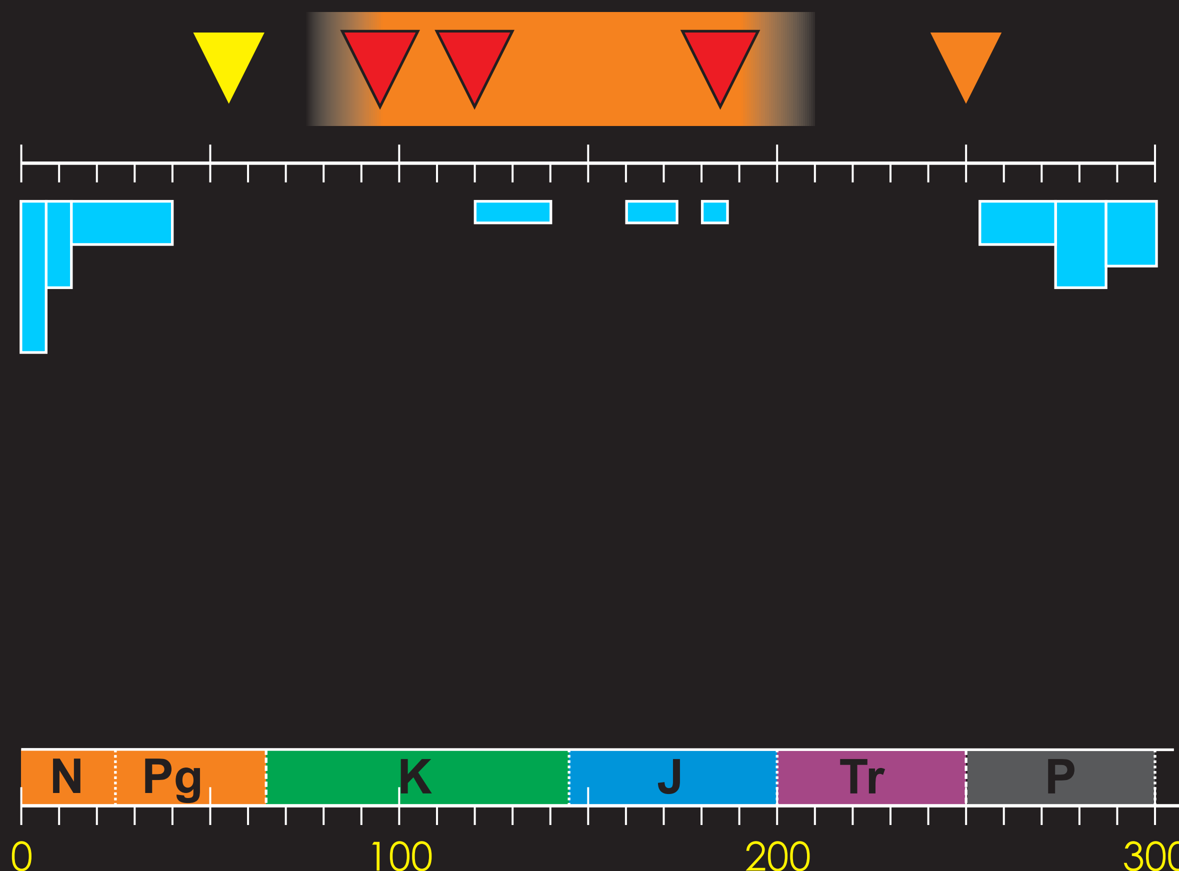
Andy Ridgwell

Regulation of global climate



Regulation of global climate

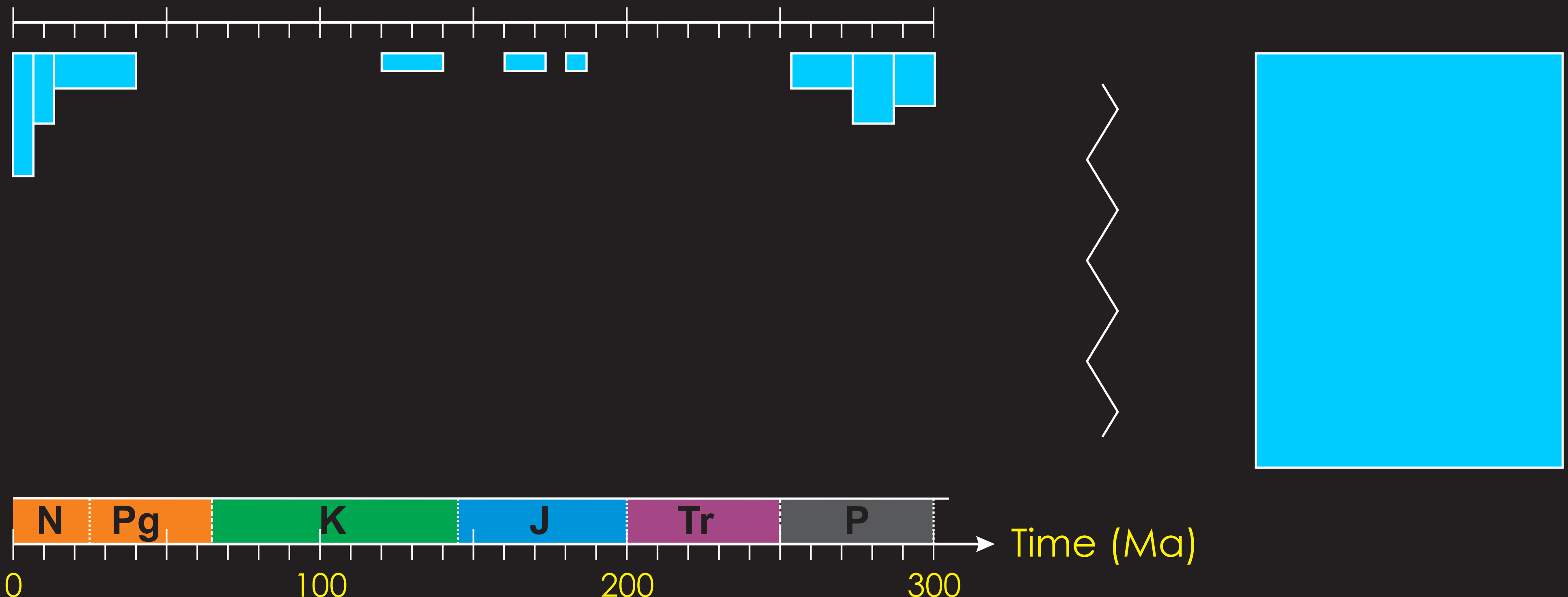




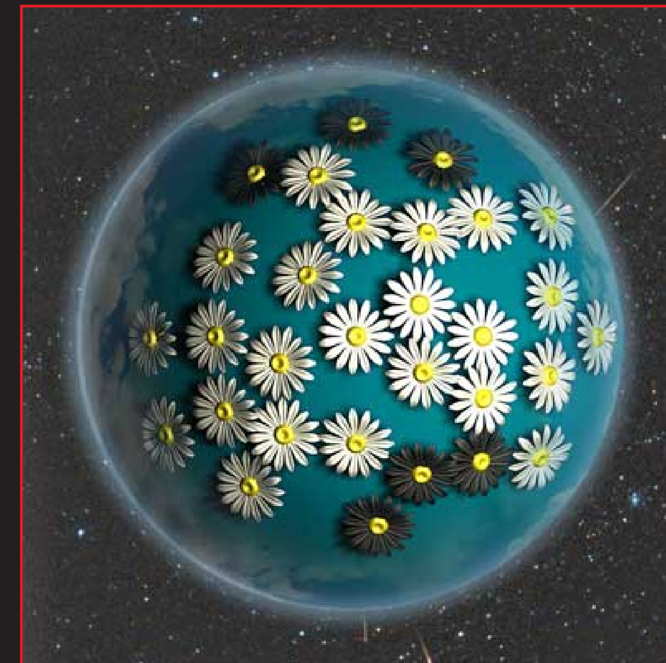
Occurrence of
ice ages (relative intensity)

source; *Crowell* [1999]

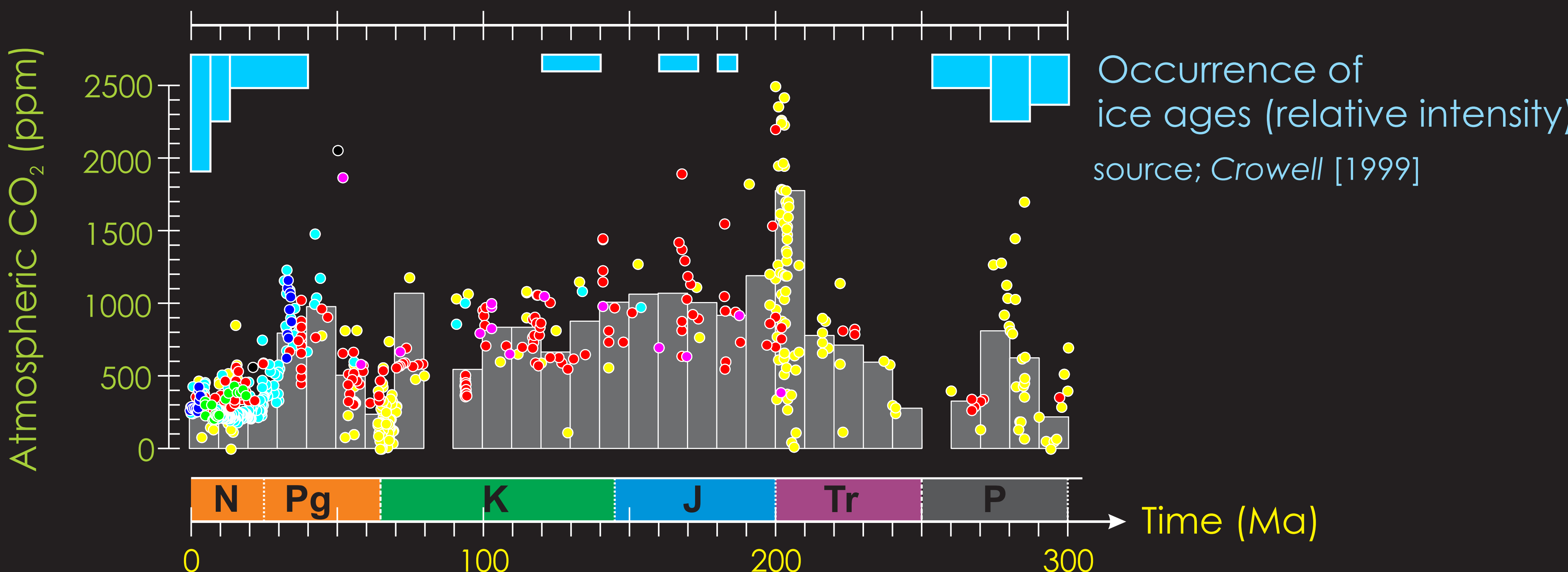
Regulation of global climate



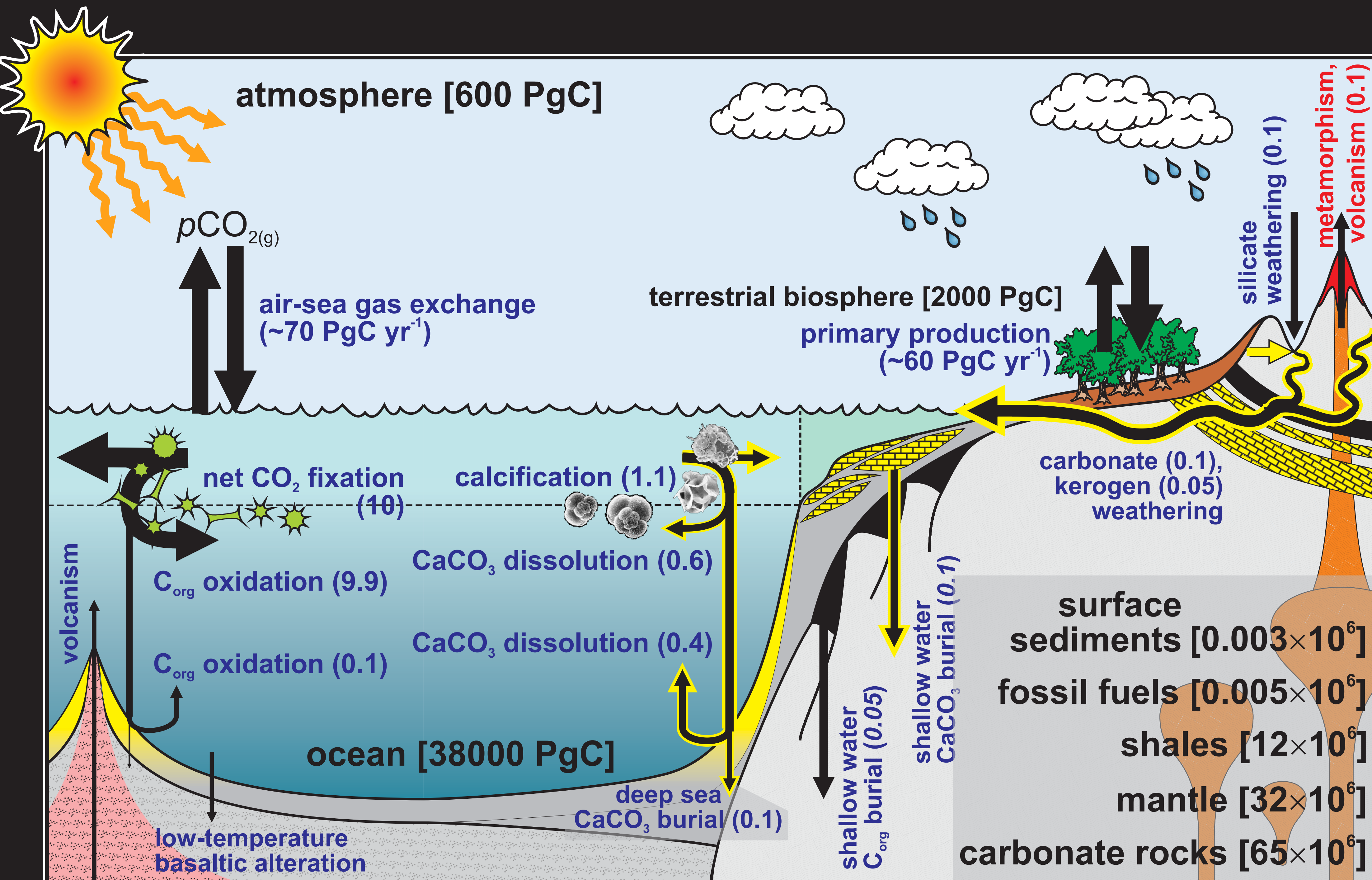
Regulation of global ~~climate~~ carbon cycling



From: *Hönisch et al.* [2012]



Regulation of global ~~climate~~ carbon cycling



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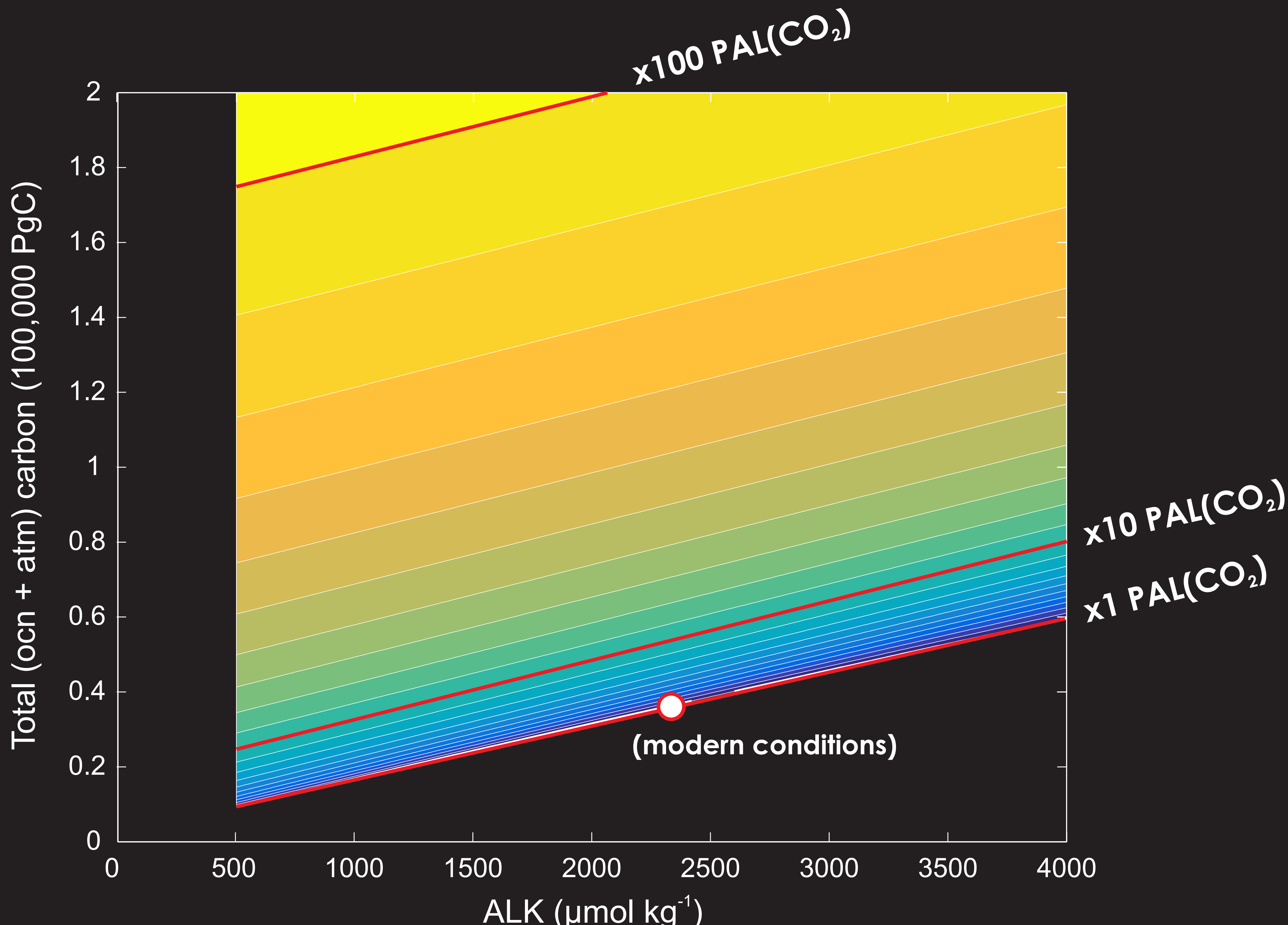
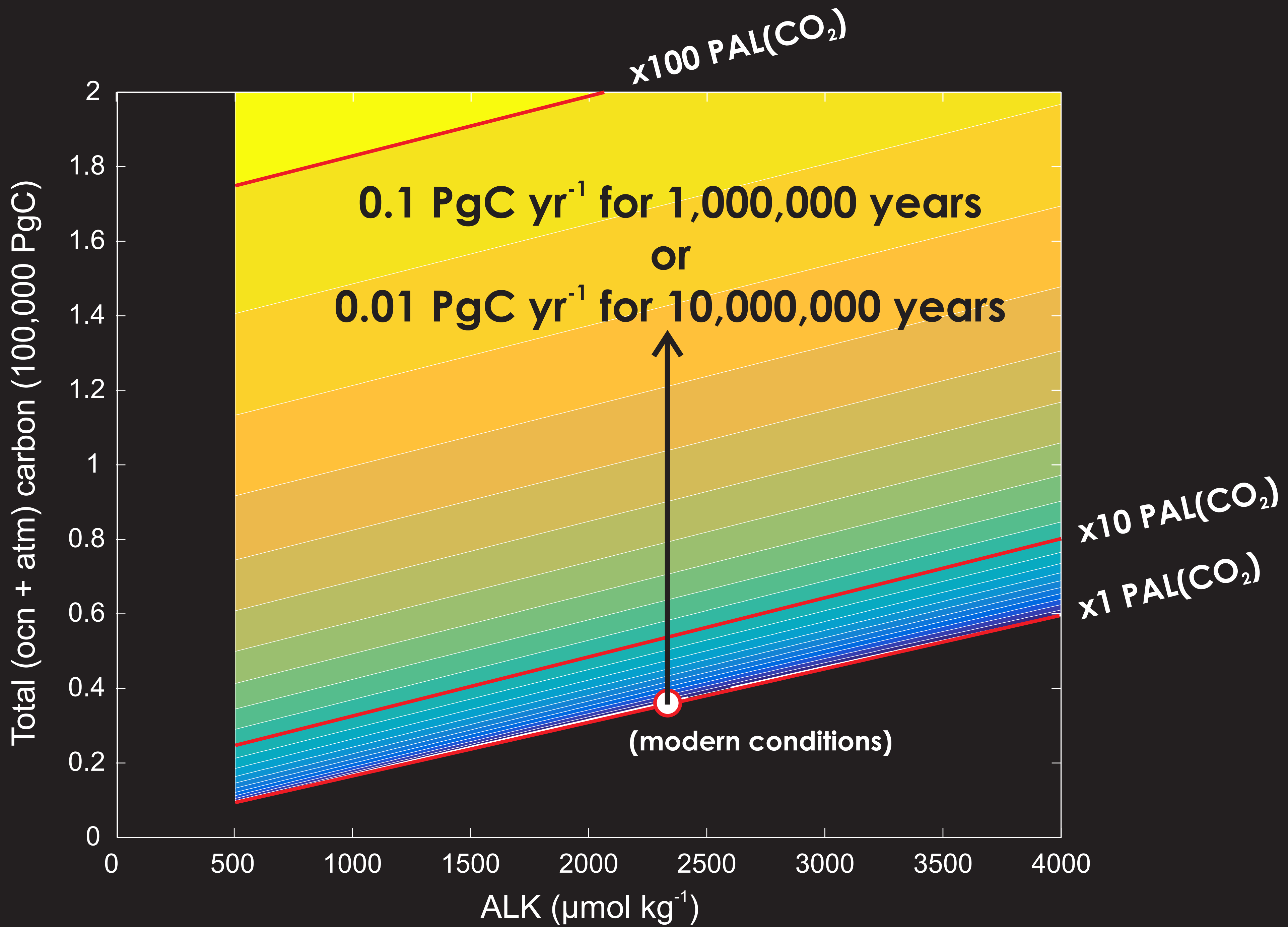


Regulation of global ~~climate~~ carbon cycling



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.

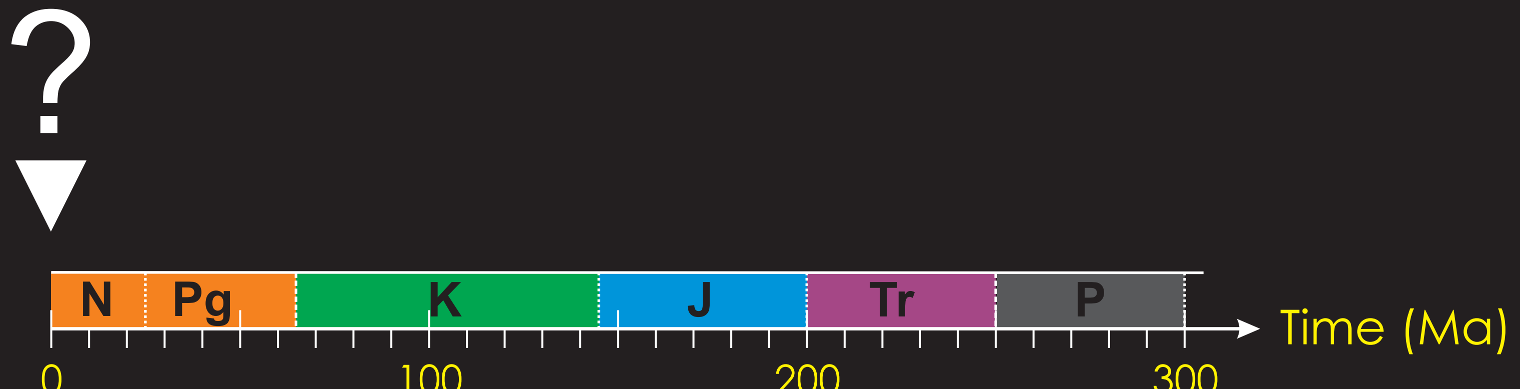
Regulation of global ~~climate~~ carbon cycling

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

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

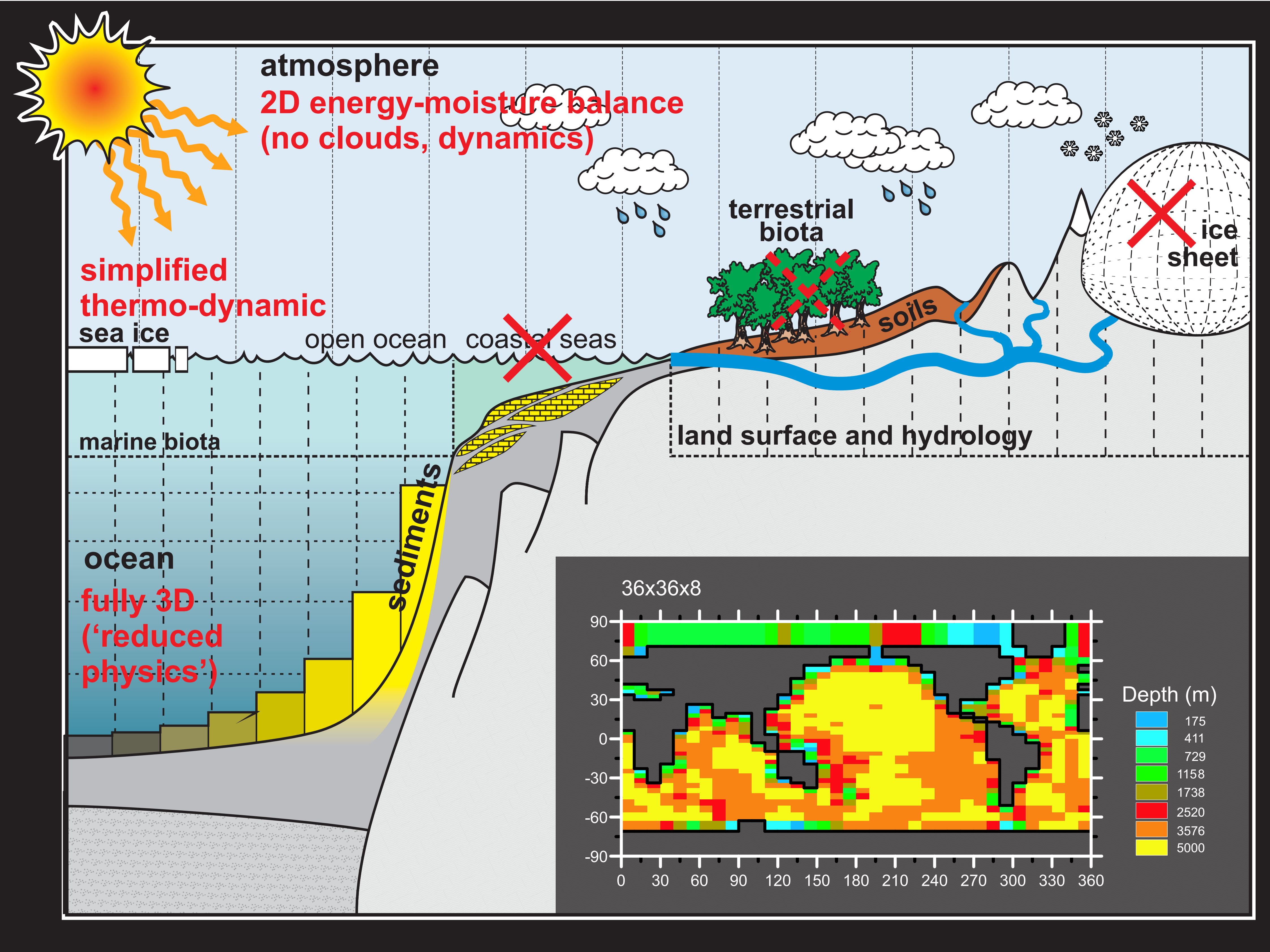
higher pCO_2 → higher temperatures (& rainfall) → higher weathering rates → lower pCO_2

Outline



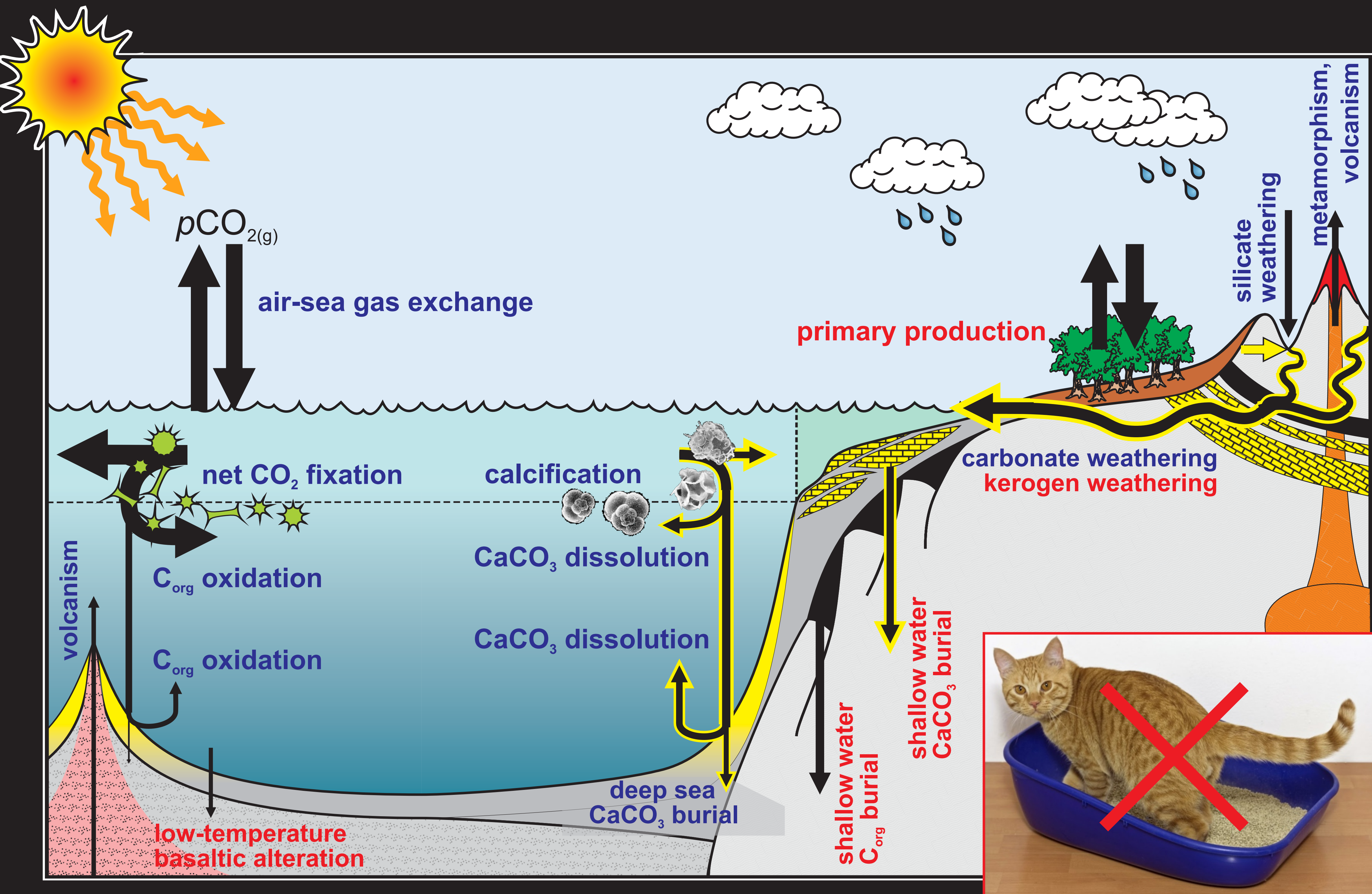
lies, damn lies, and computer models

```
! 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
```



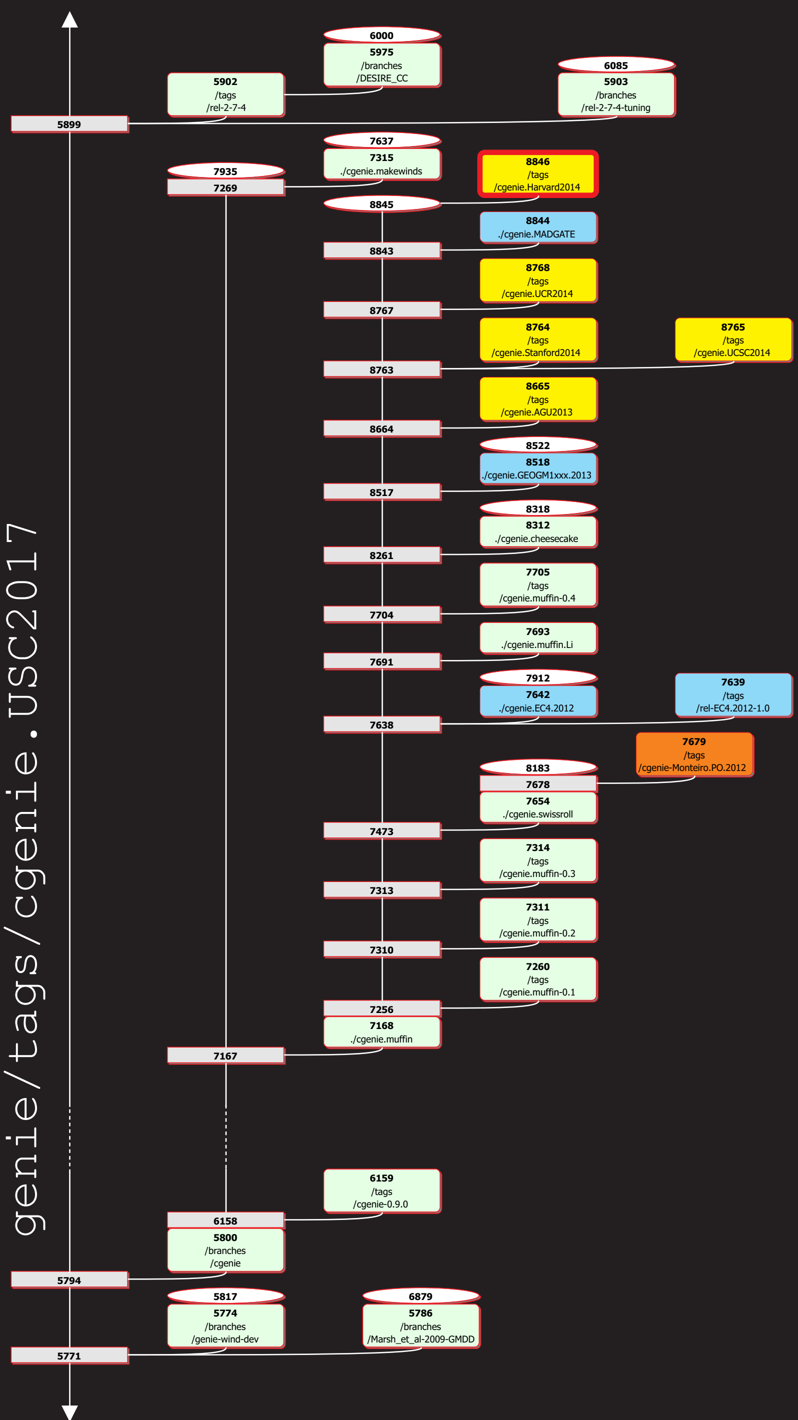
atmosphere
2D energy-moisture balance
(no clouds, dynamics)
terrestrial
biota
ice
sheet
simplified
thermo-dynamic
sea ice
open ocean
coastal seas
soils
marine biota
land surface and hydrology
sediments
ocean
fully 3D
('reduced
physics')
36x36x8
Depth (m)
175
411
729
1158
1738
2520
3576
5000
90
60
30
0
-30
-60
-90
0
30
60
90
120
150
180
210
240
270
300
330
360

lies, damn lies, and computer models



lies, damn lies, and computer models

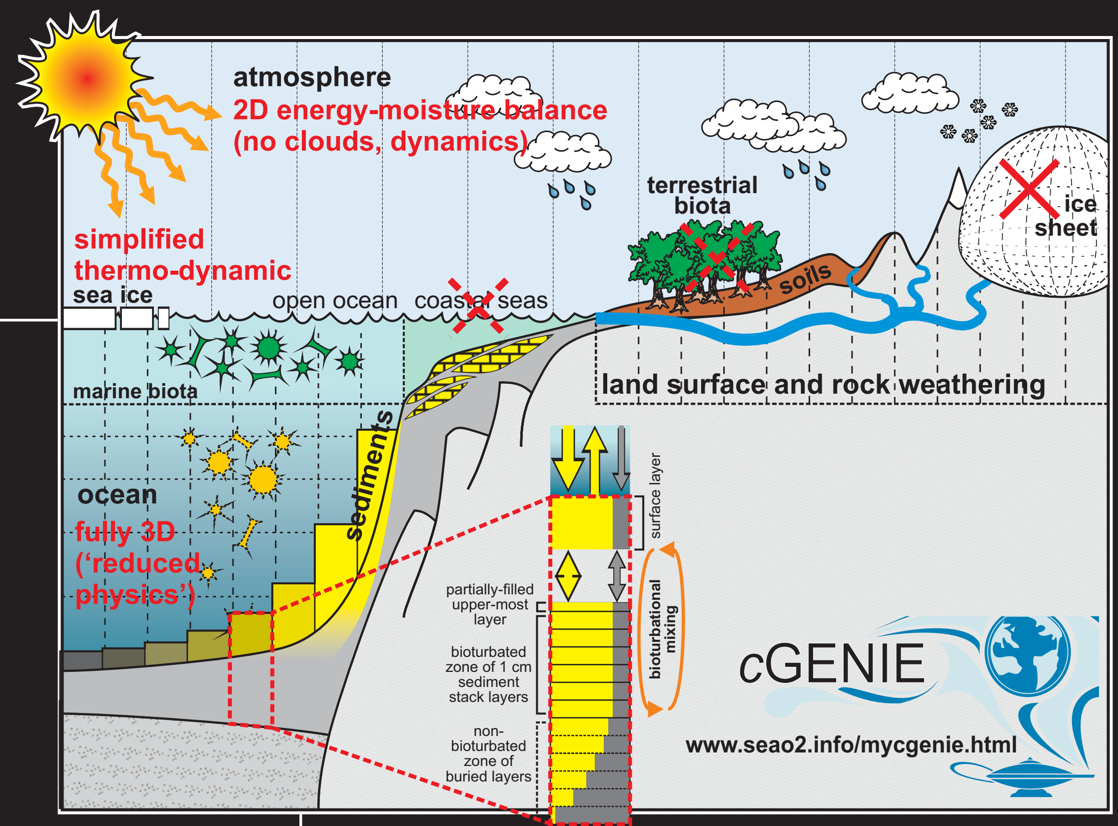
https://svn.ggy.bris.ac.uk/subversion/genie/tags/cgenie.USC2017

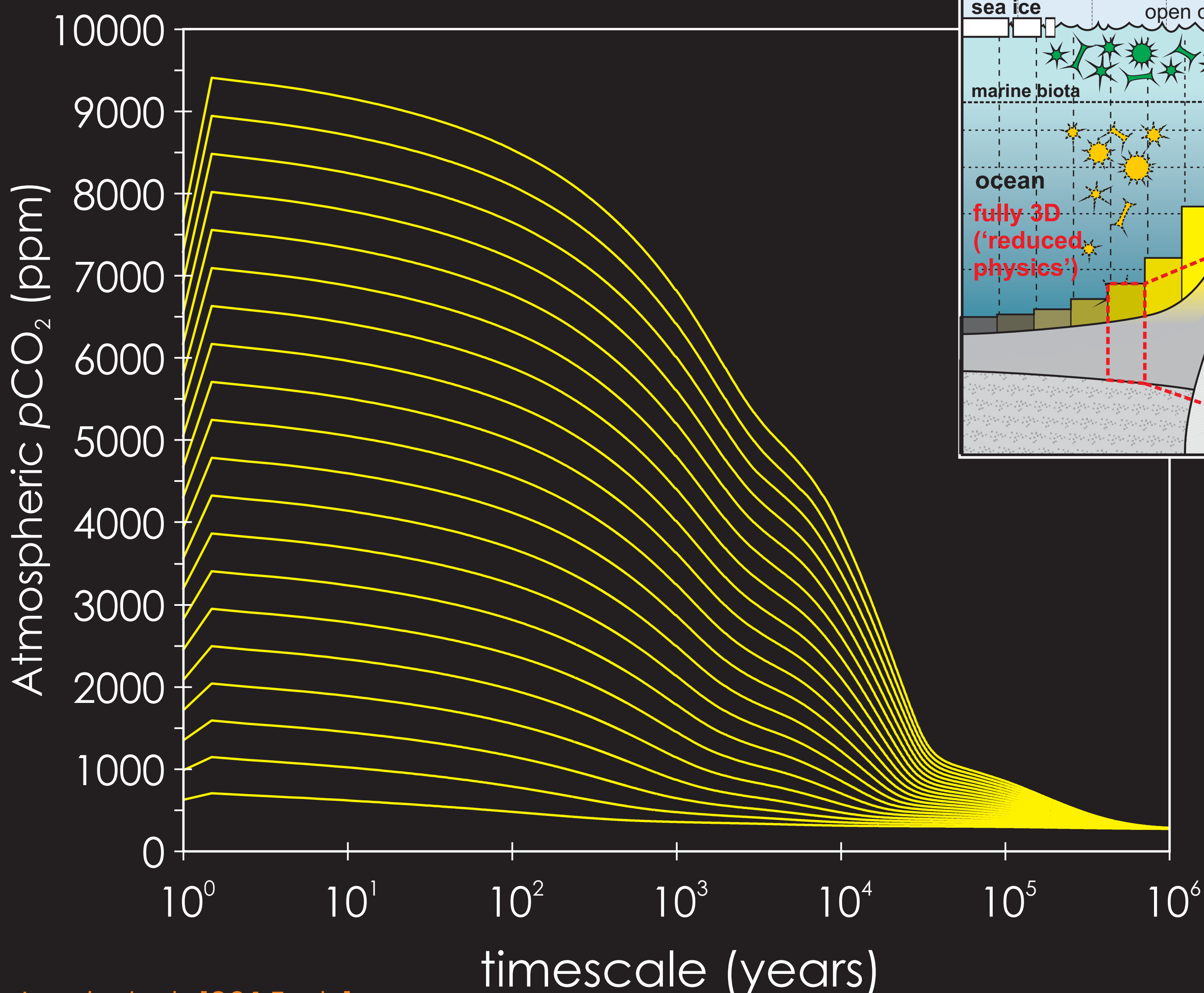


http://www.seao2.info/misc_usc2017.html

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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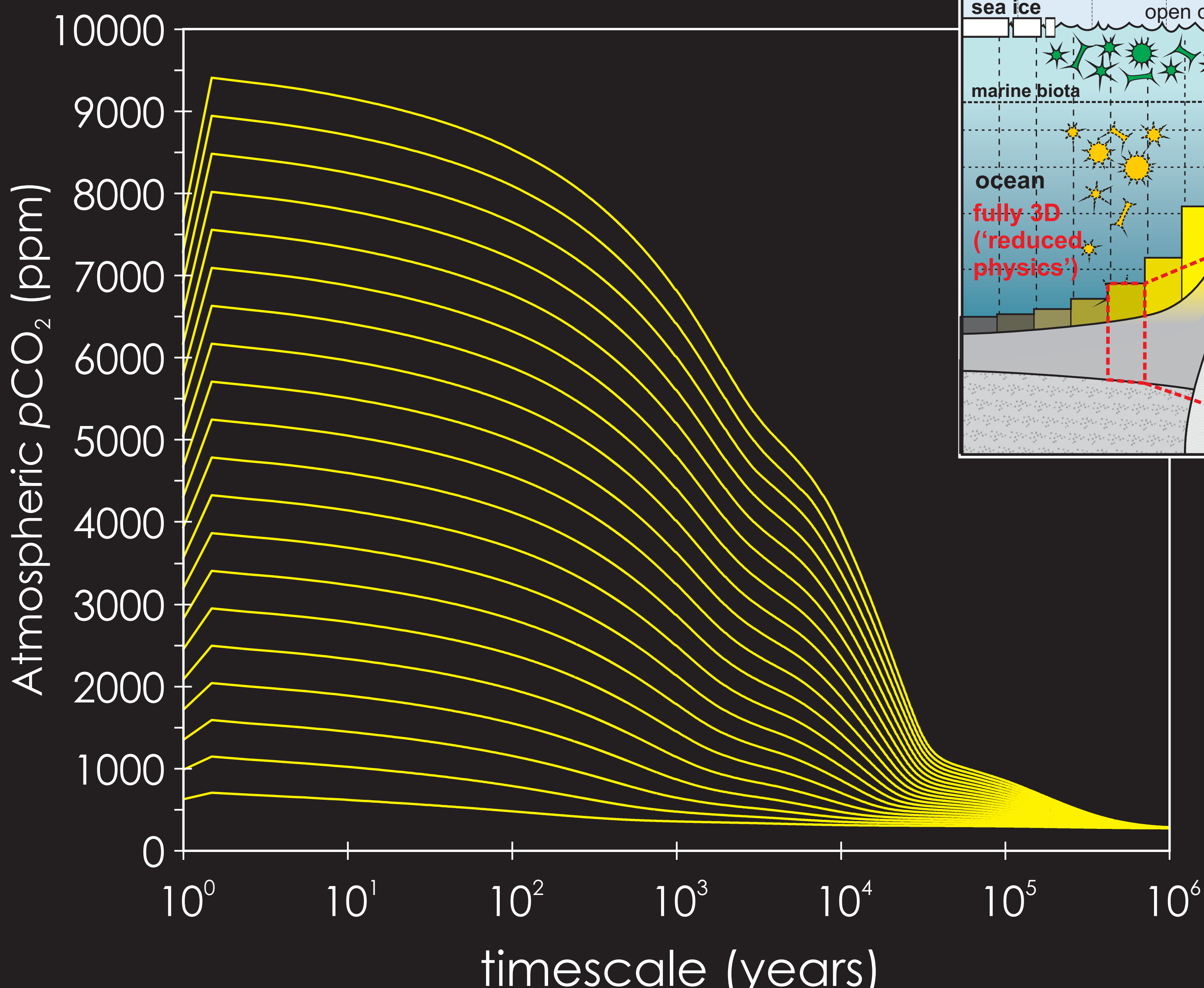
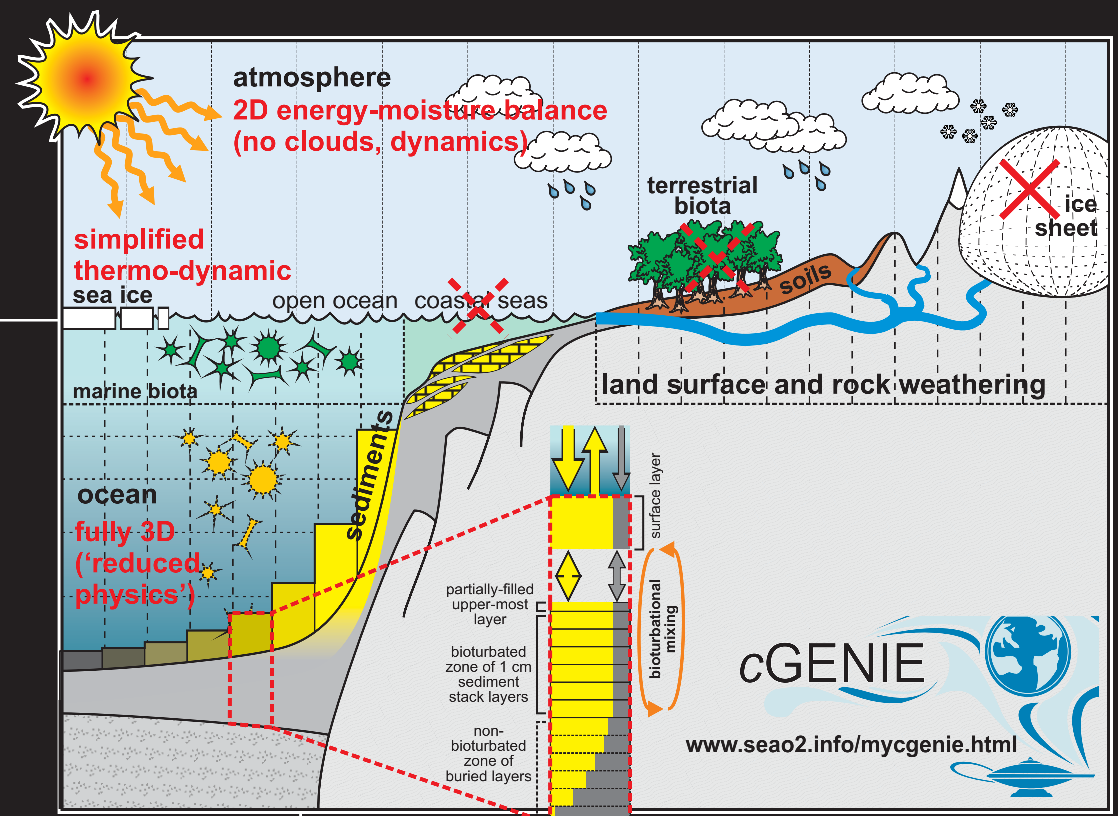




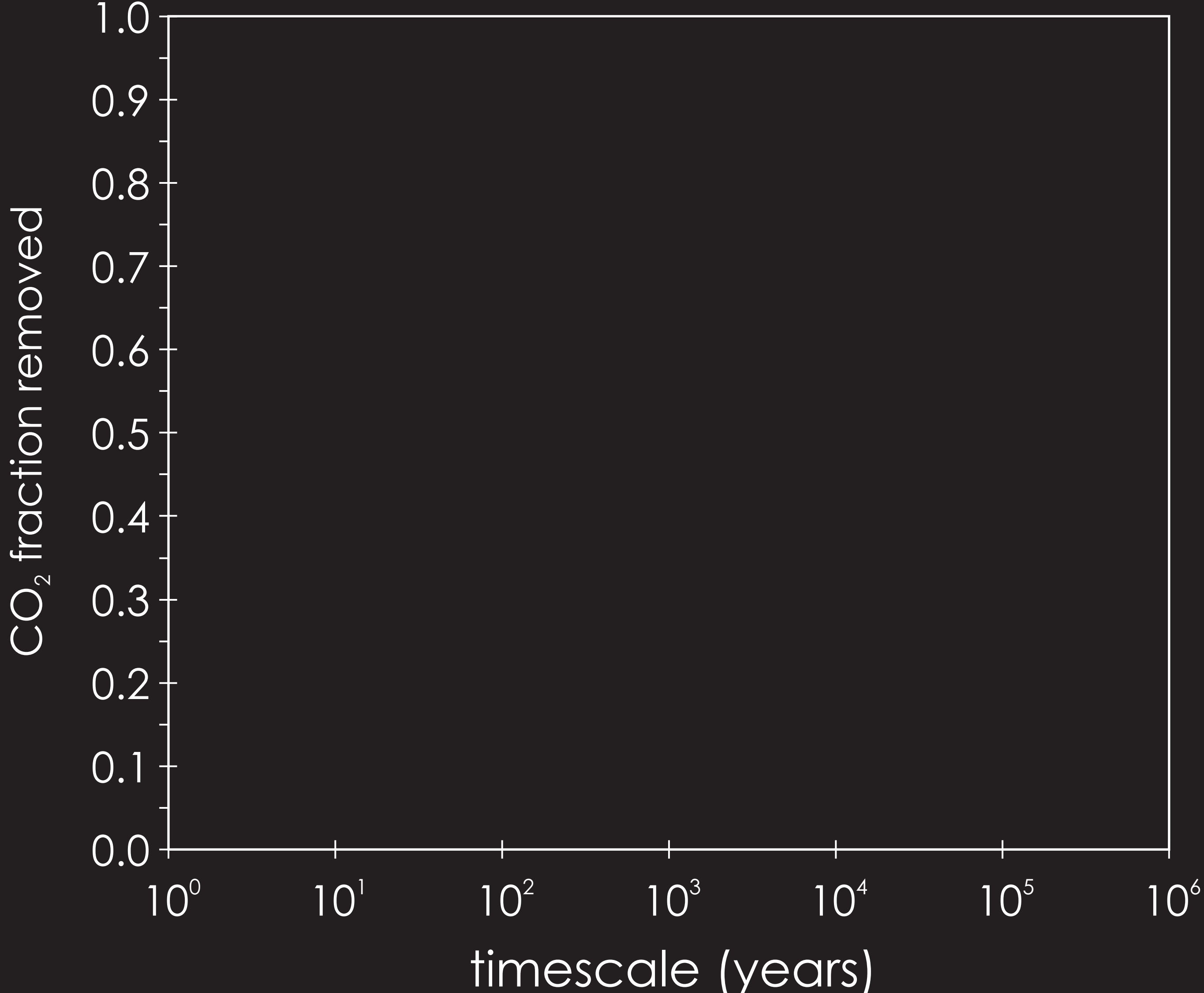
(2) Fit each CO_2 decay curve with a series (4 optimal) of exponentials. Extract the fraction of CO_2 and time-scale associated with each.

(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 $CO_{2(excess)}$

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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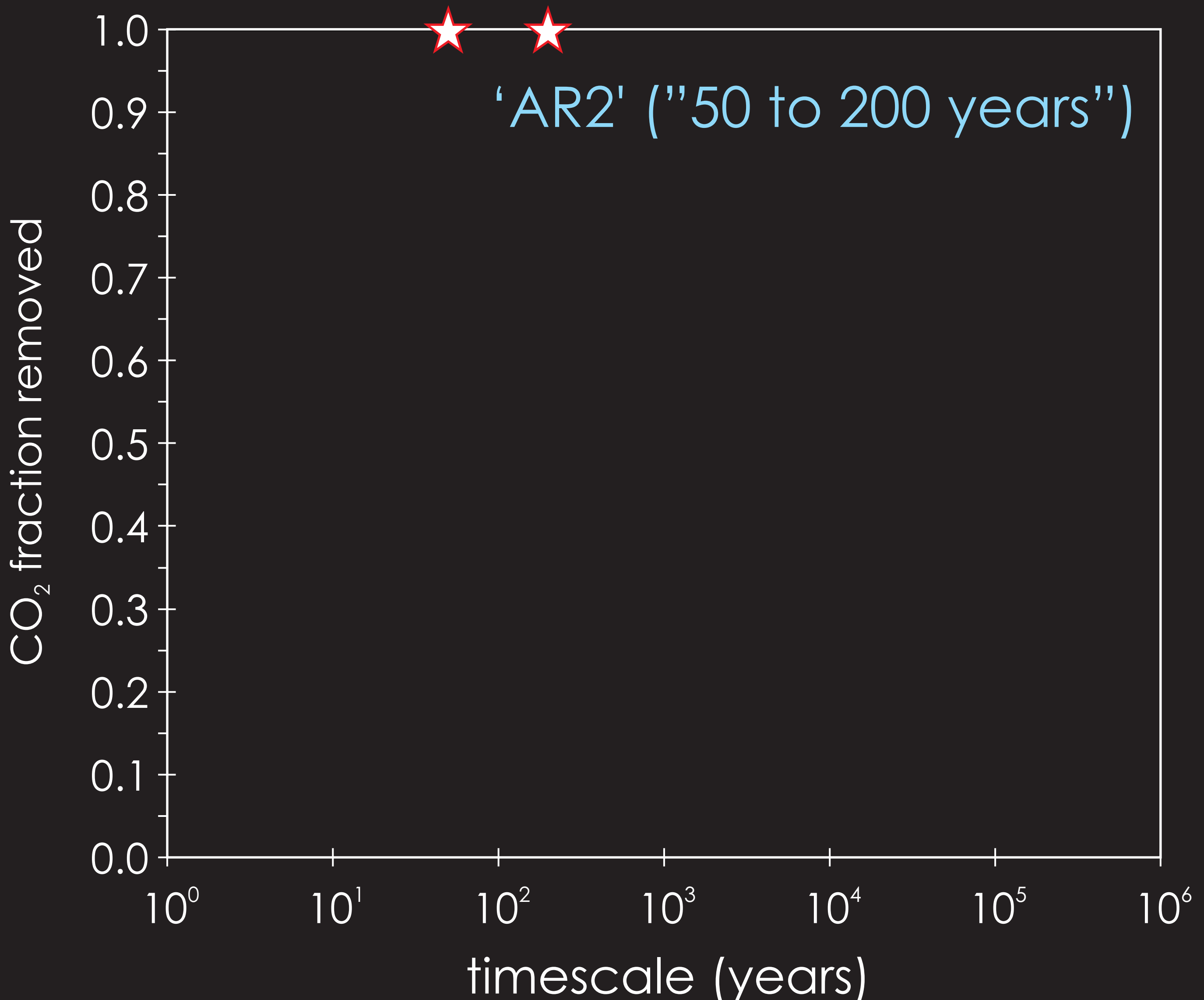

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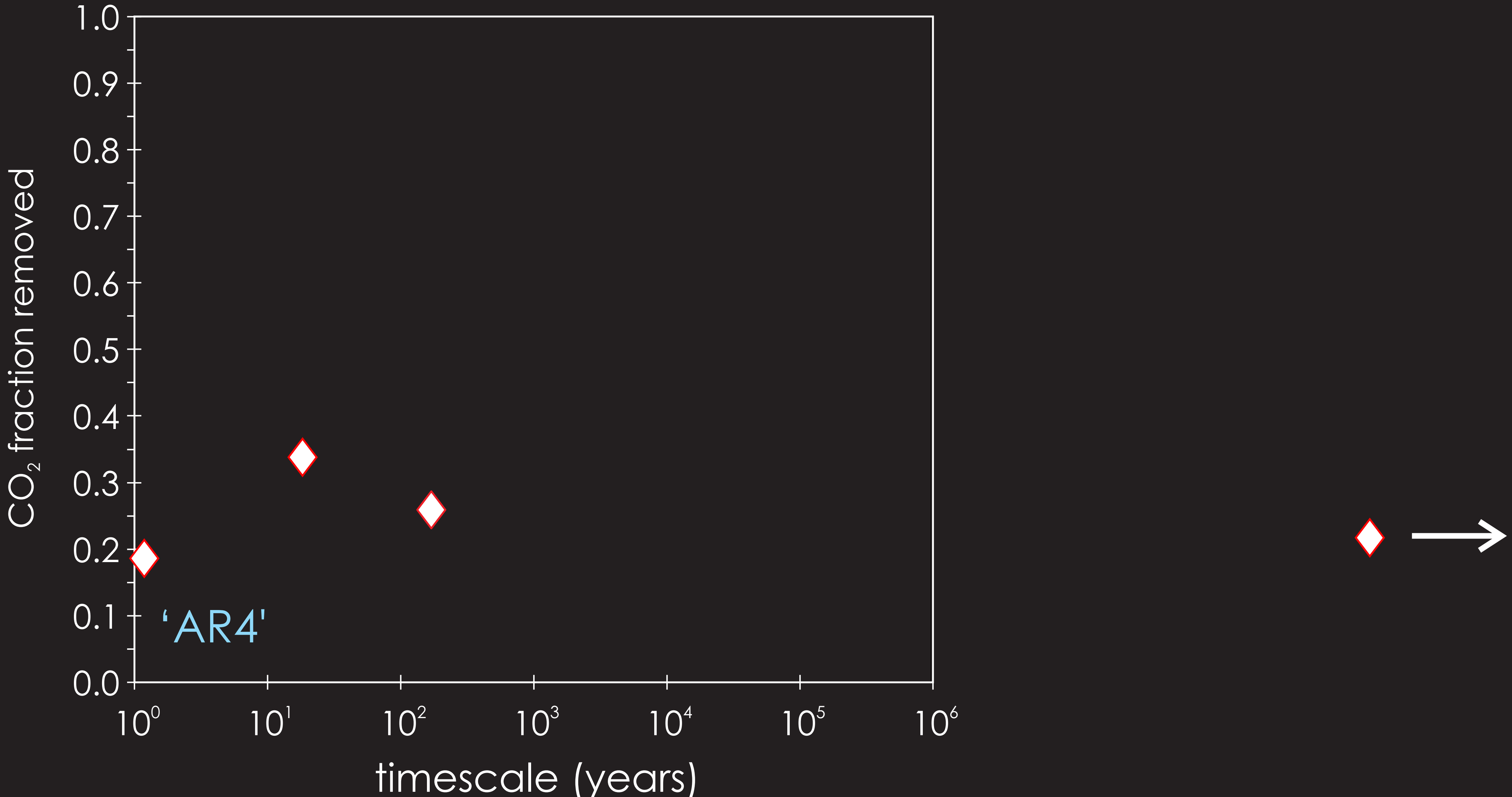
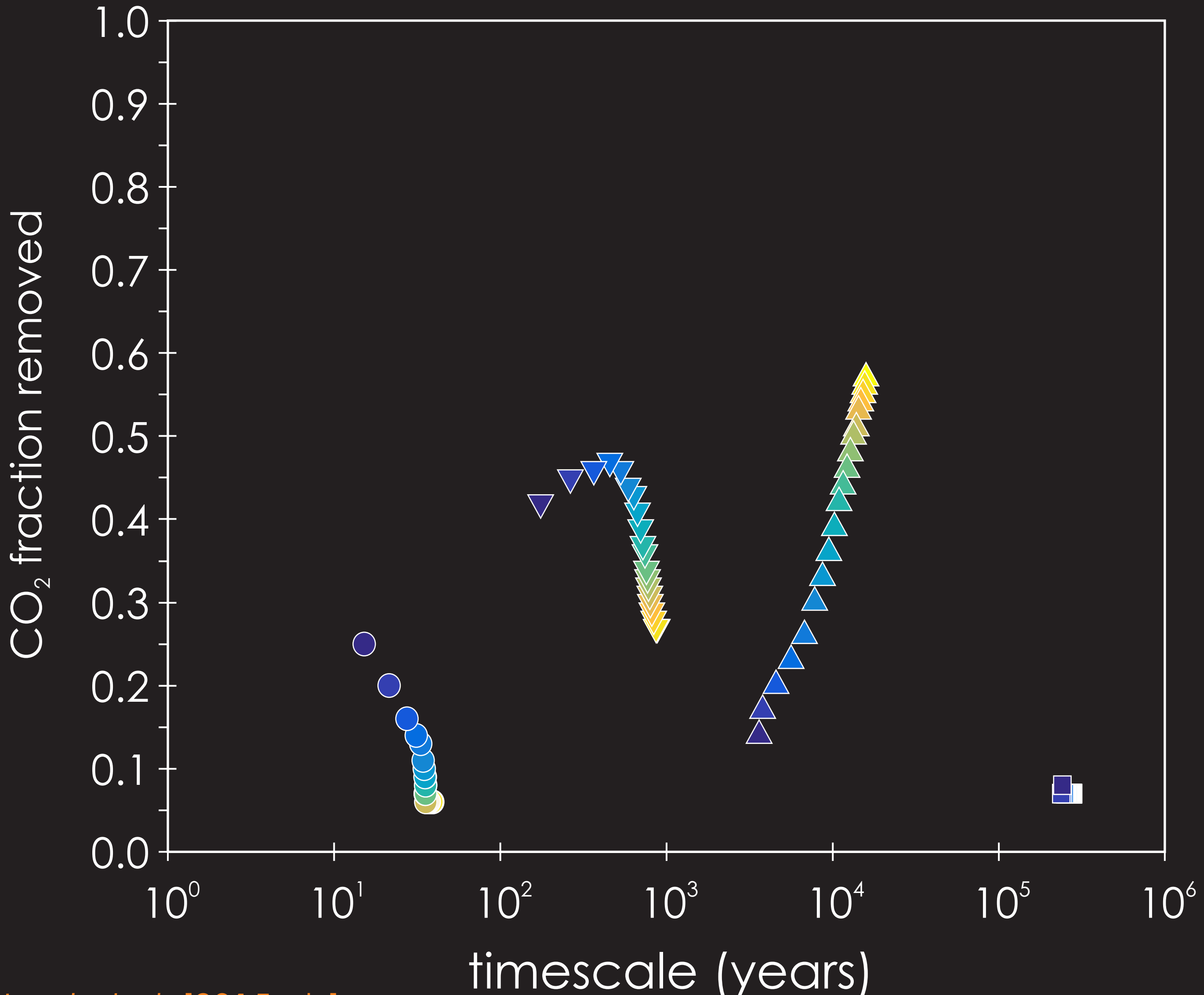


Impulse response function analysis of the 'long tail' of $CO_{2(excess)}$

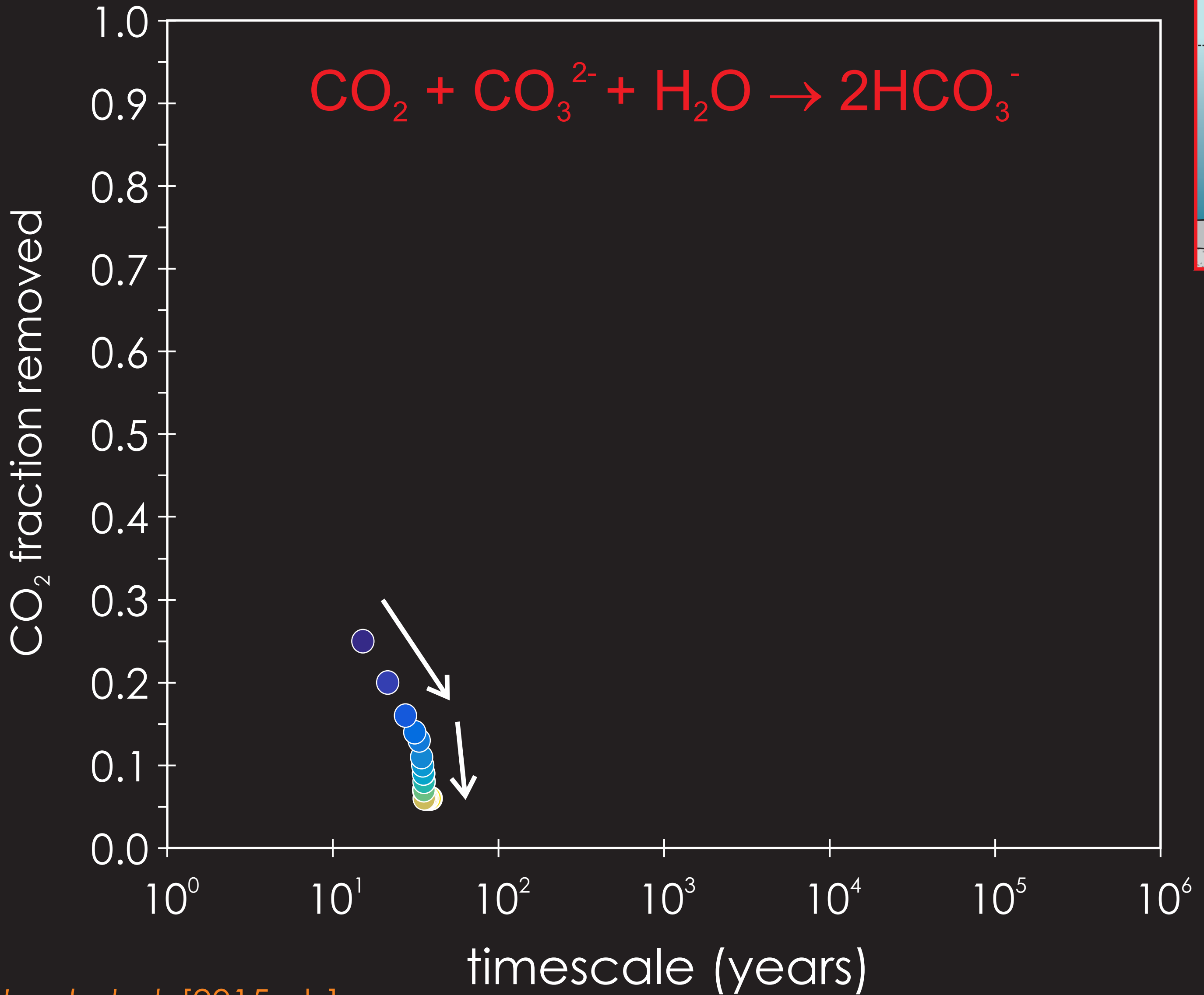
Response of fraction of CO_2 removed vs. the characteristic time-scale, as a function of total emissions, ranging from 1,000 PgC (dark blue) to 20,000 PgC (yellow).

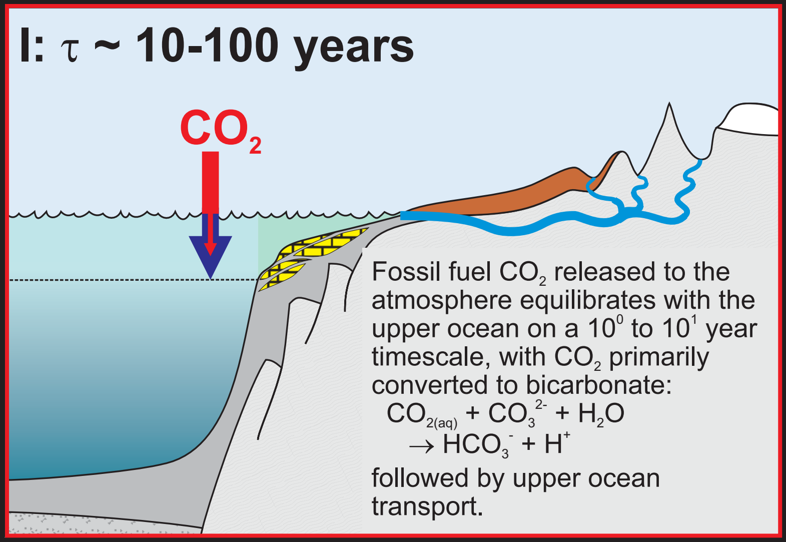


Lord et al. [2015a,b]

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.

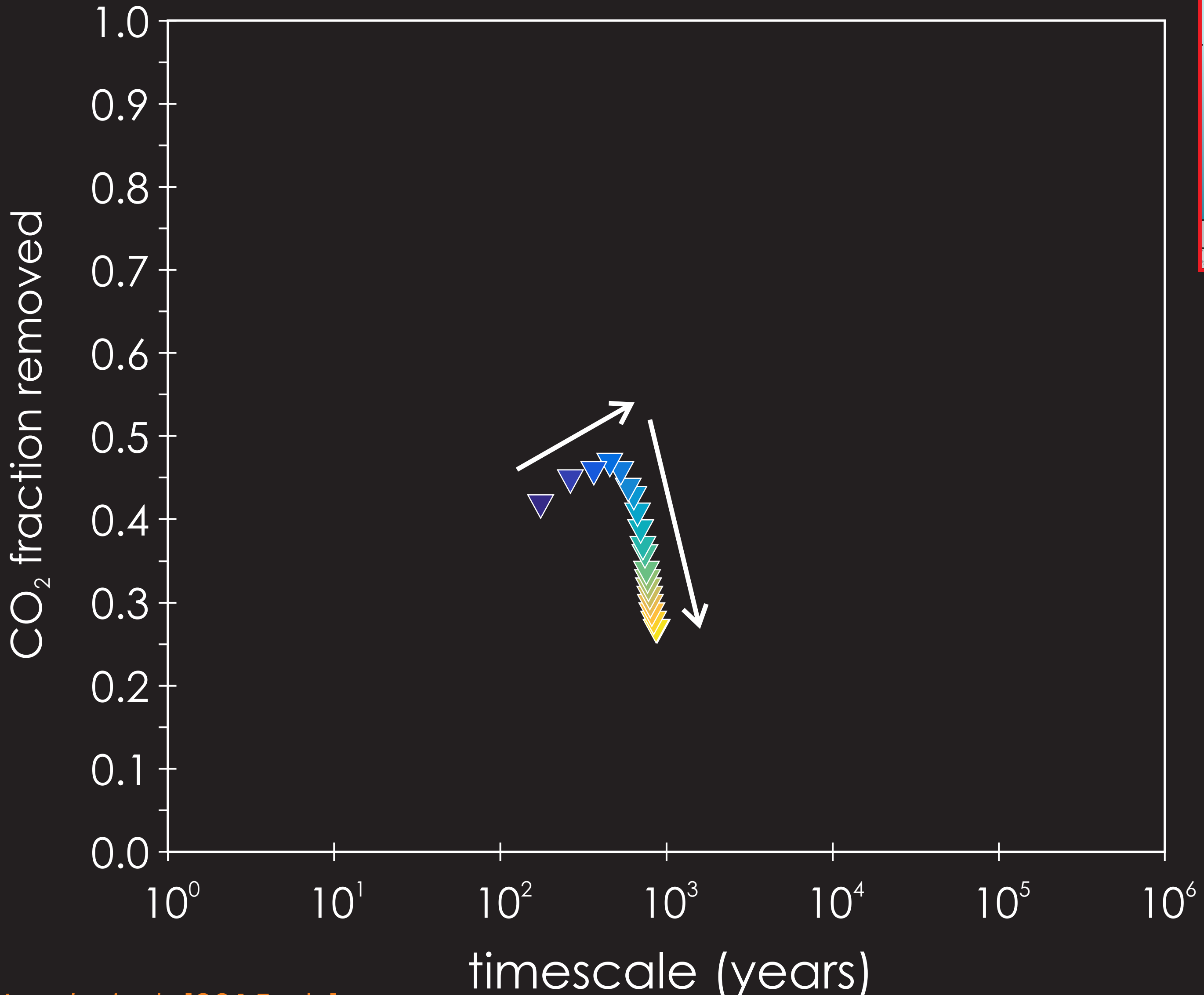


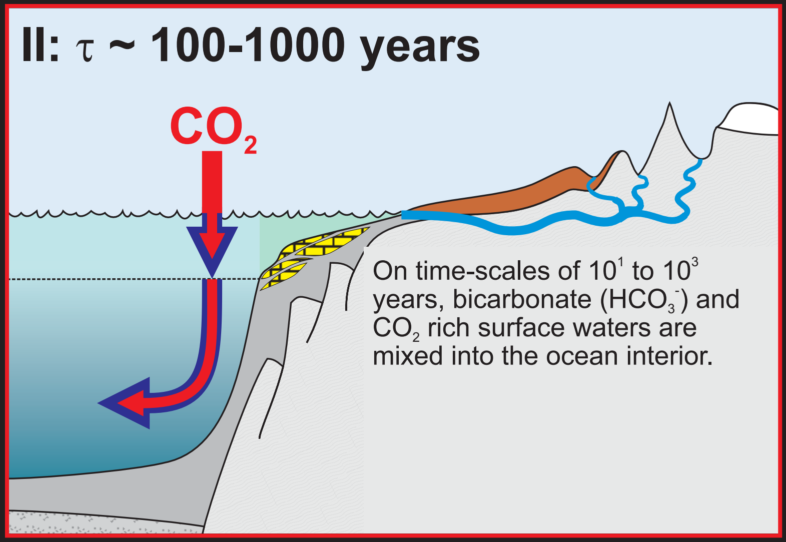


Lord et al. [2015a,b]

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?

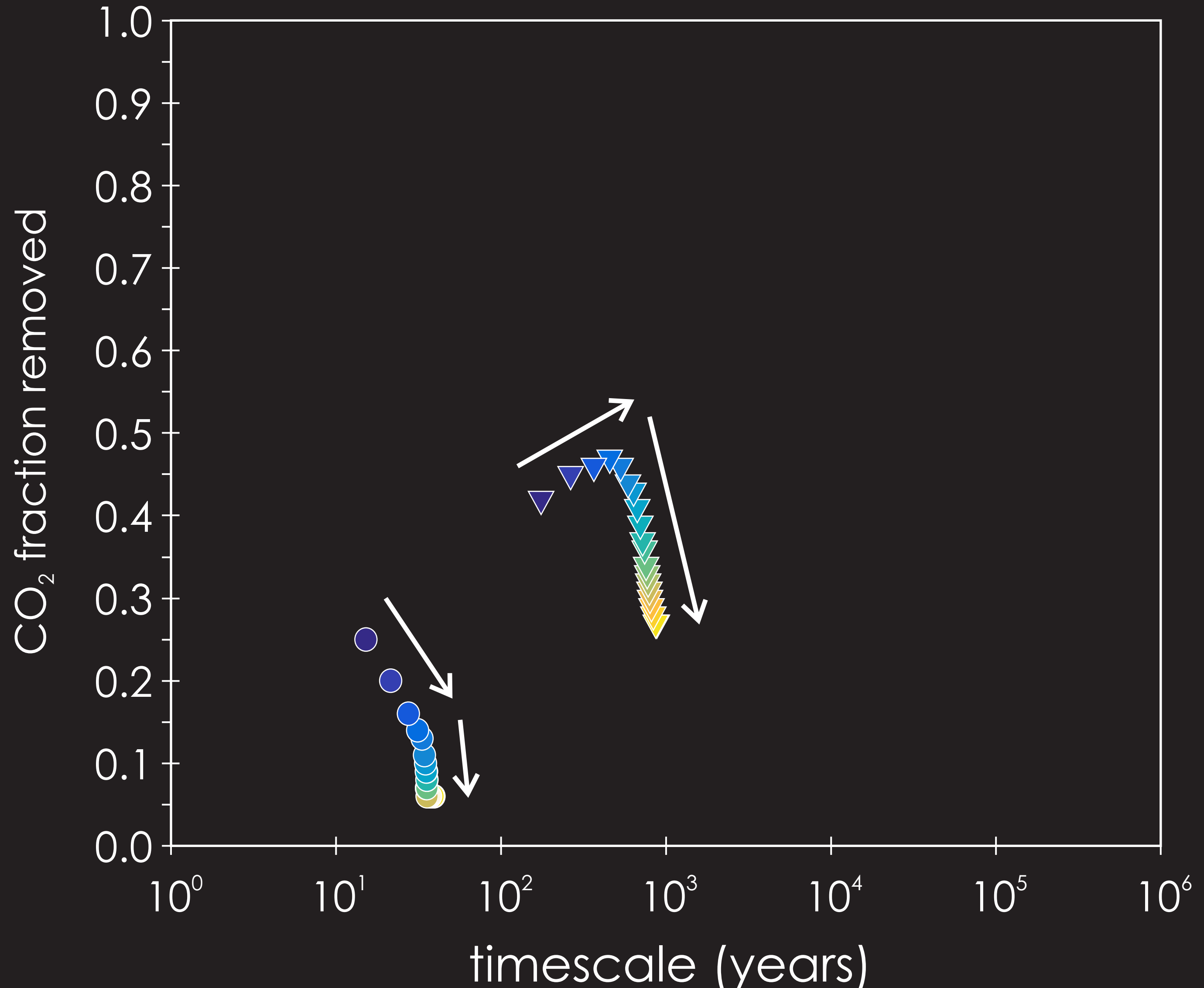




Lord et al. [2015a,b]

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

evidence?



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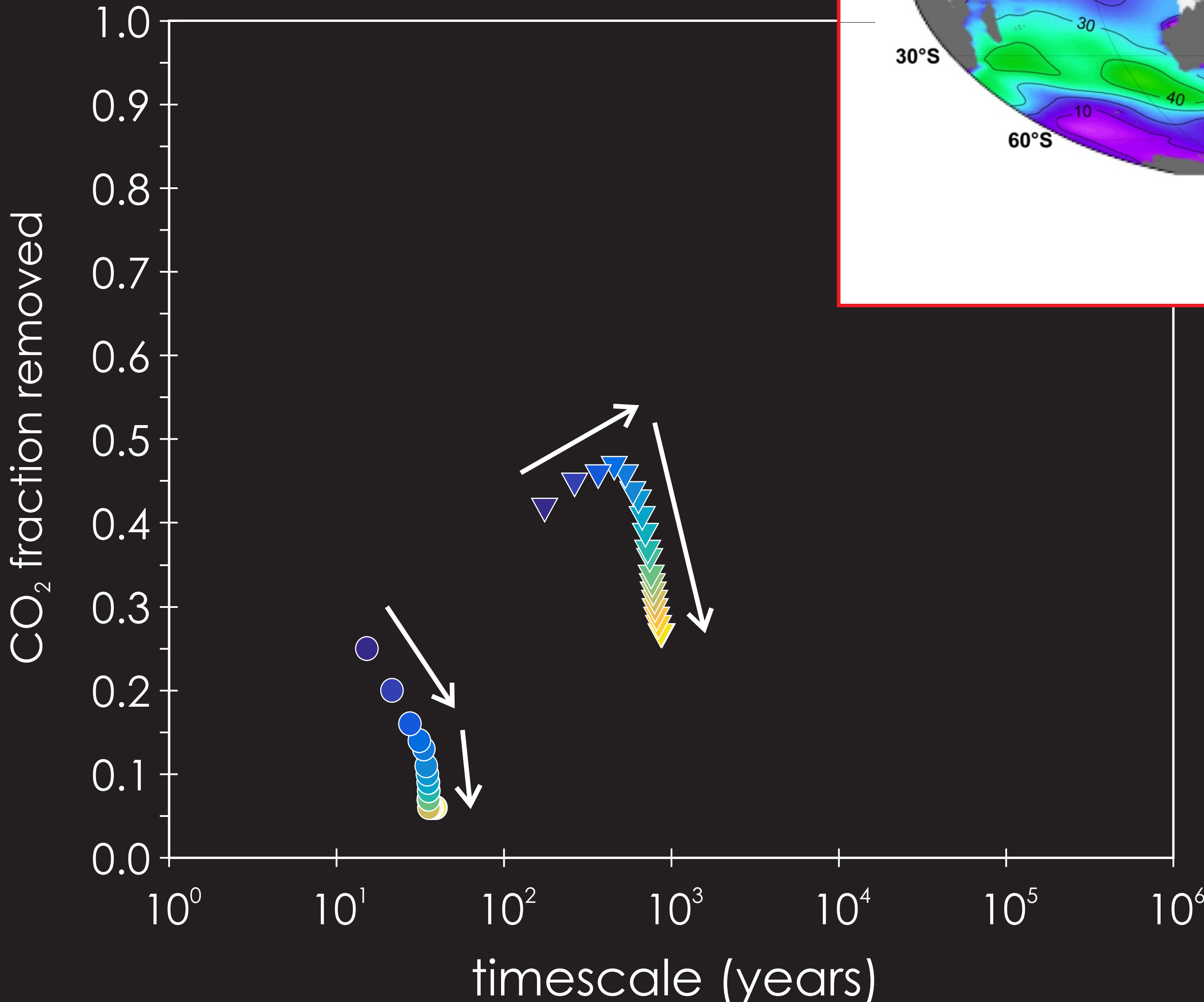
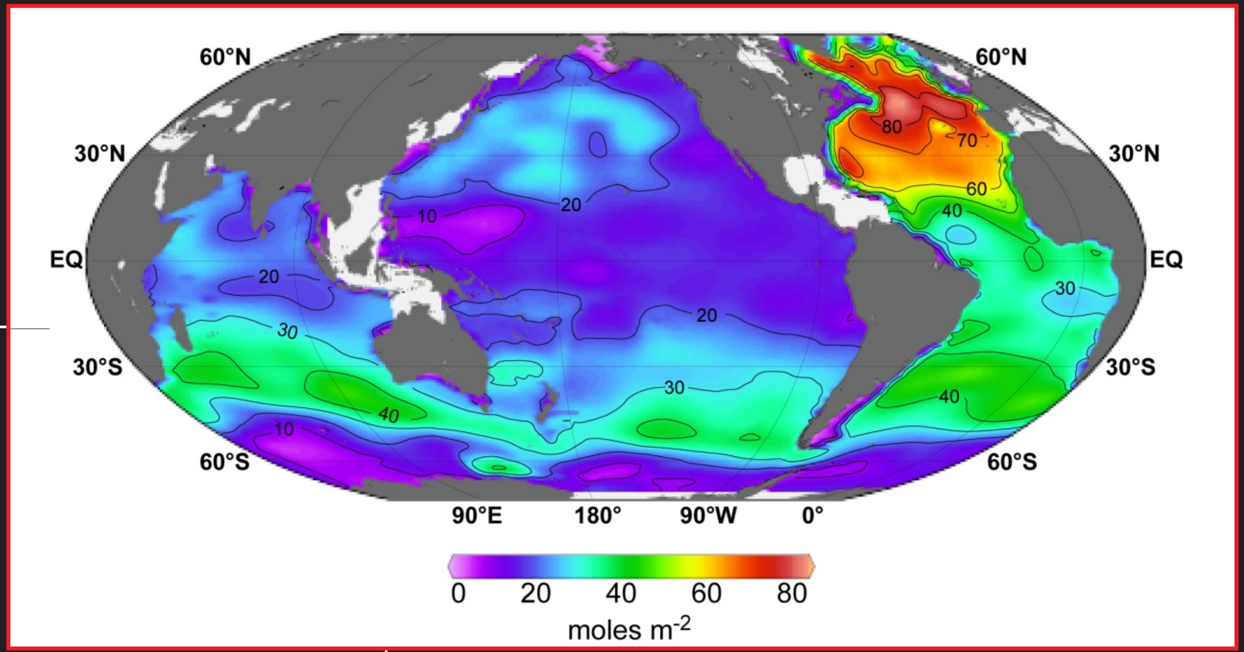
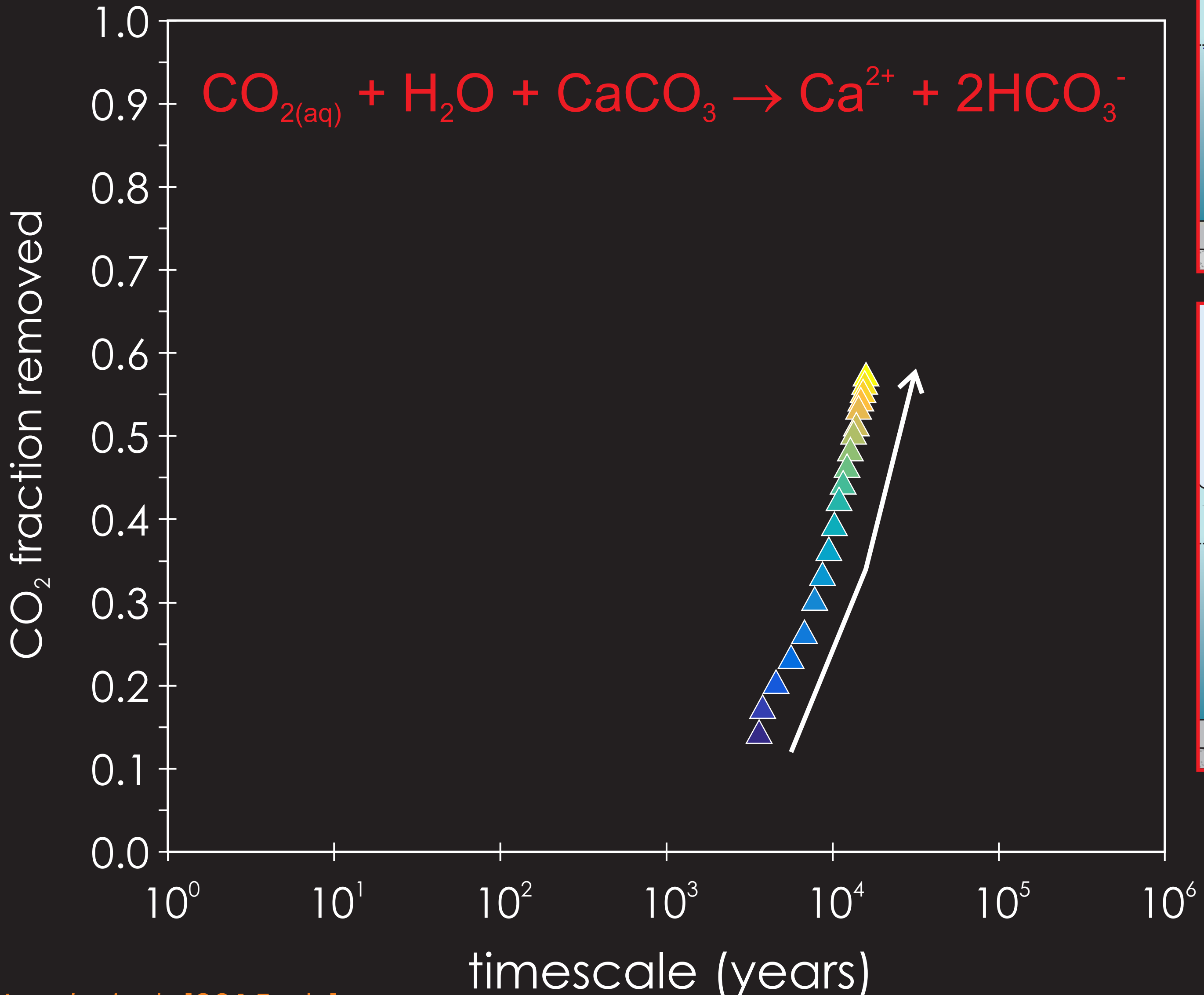
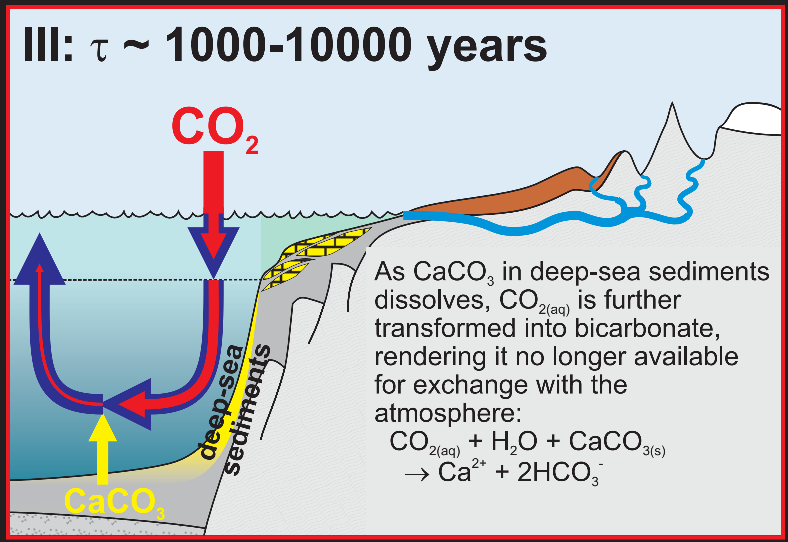


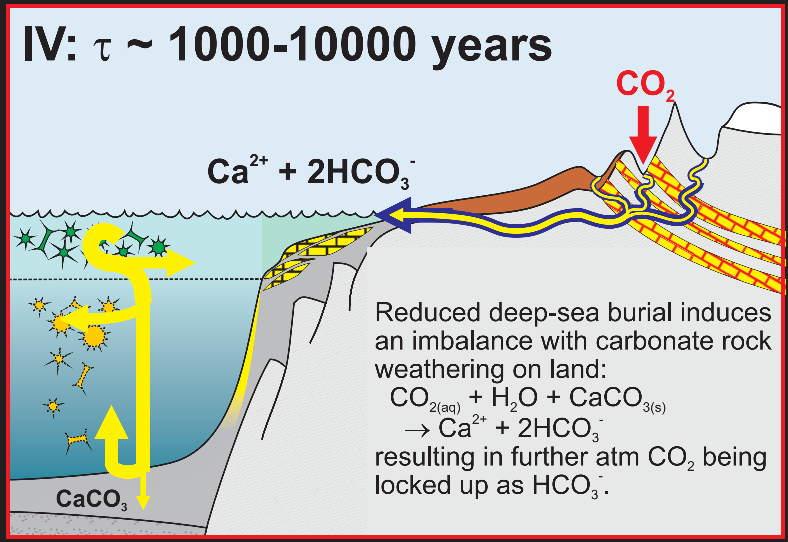


Impulse response function analysis of the 'long tail' of $CO_{2(excess)}$

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



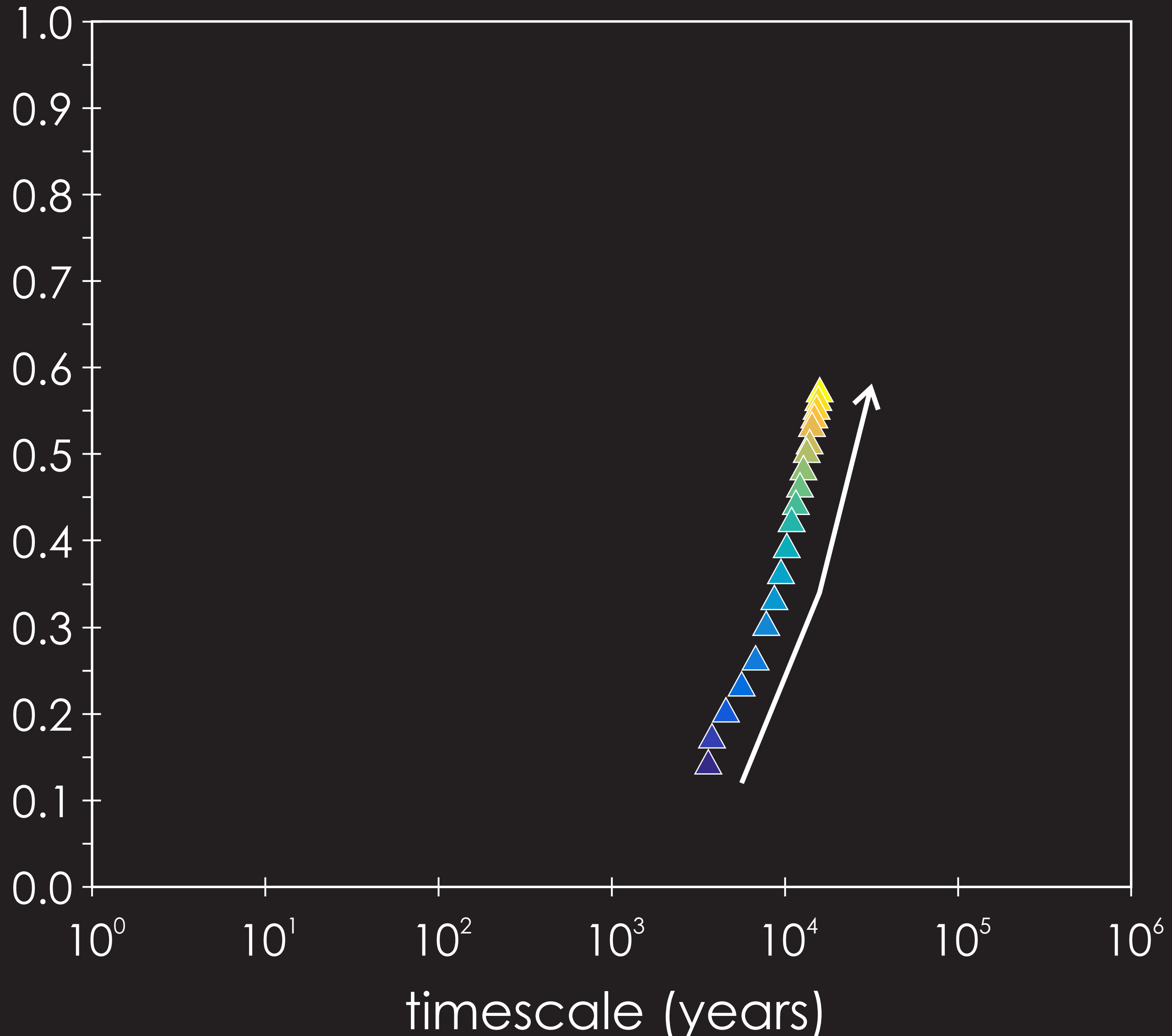




Lord et al. [2015a,b]

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

evidence?



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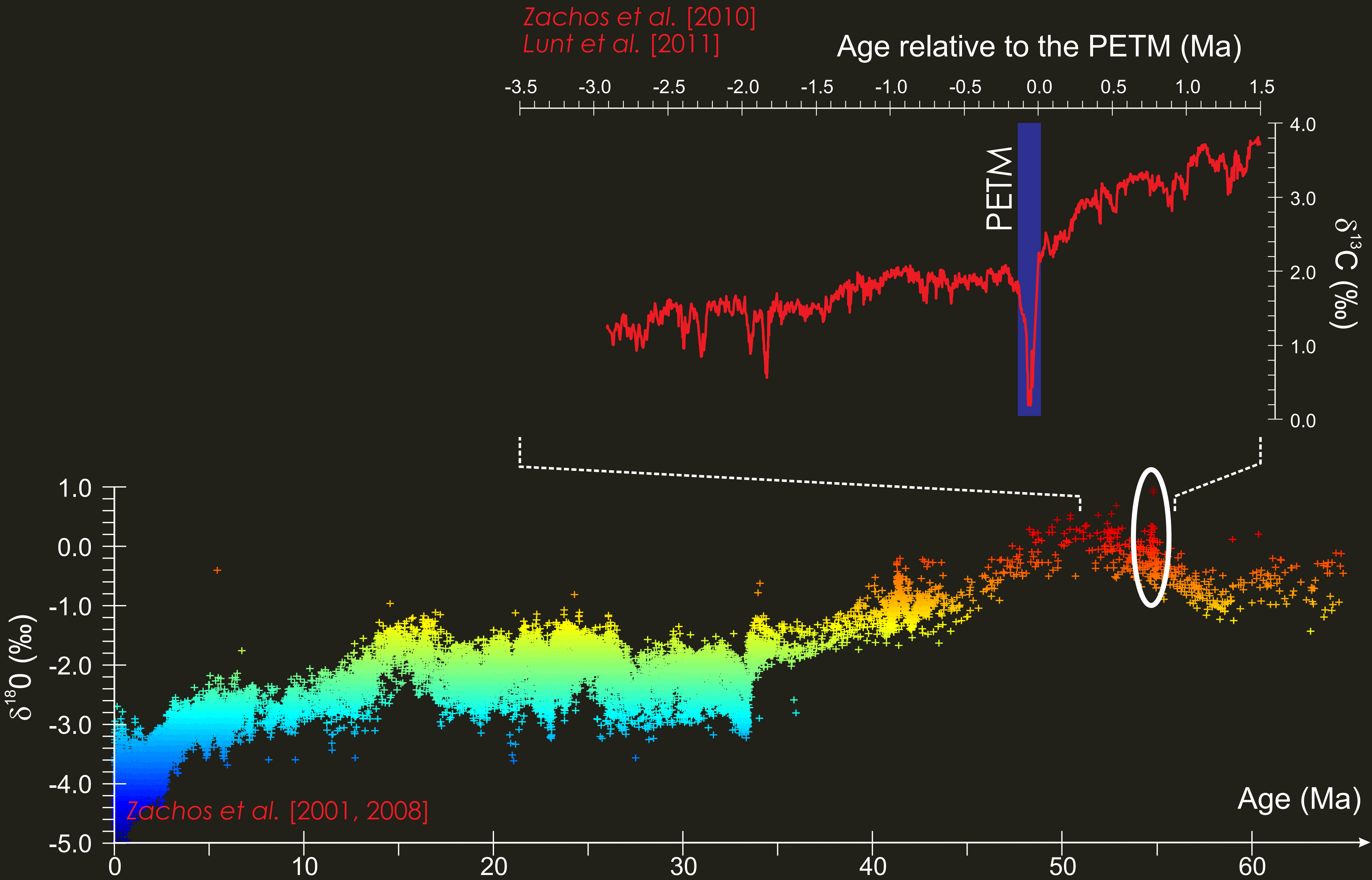
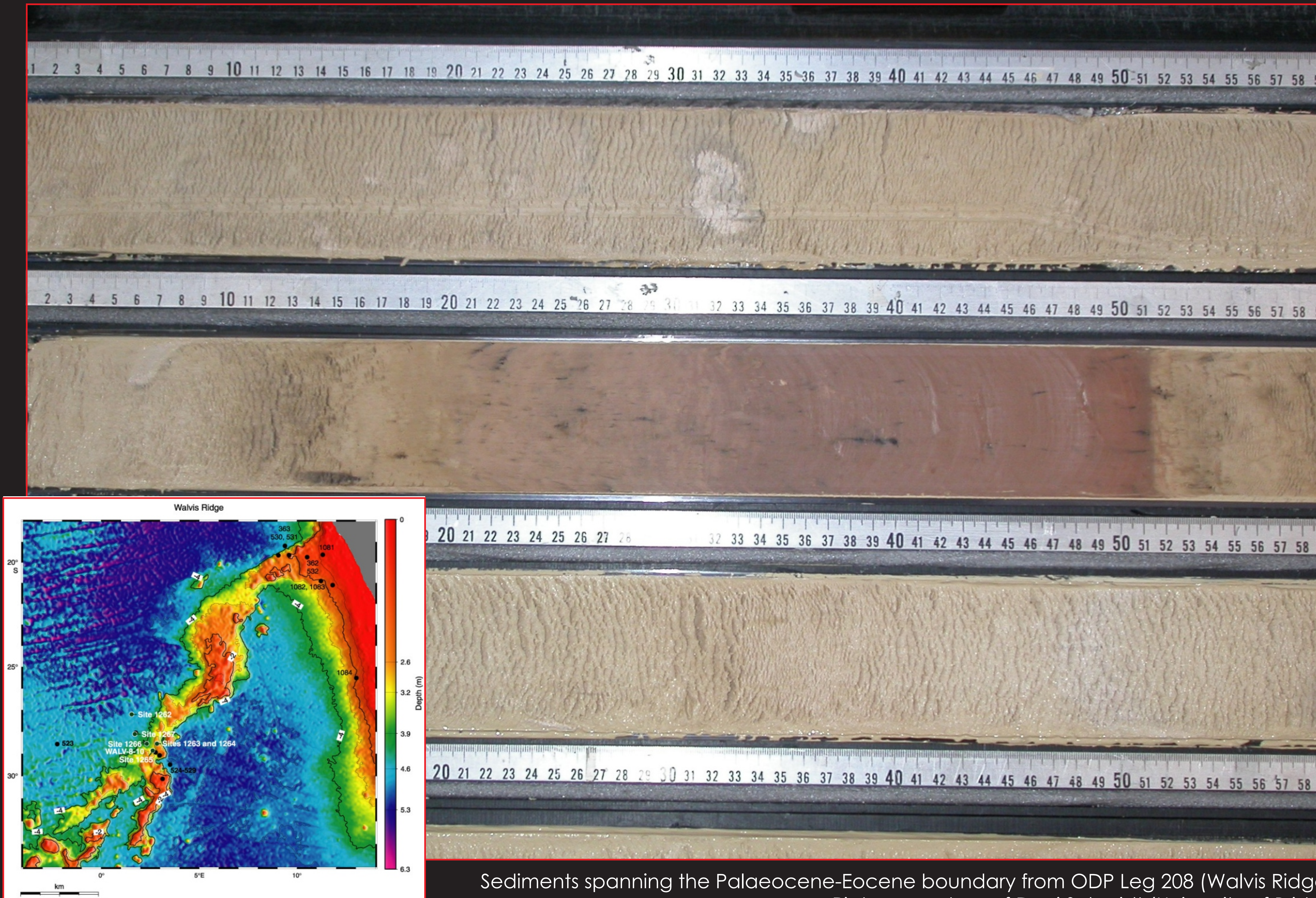


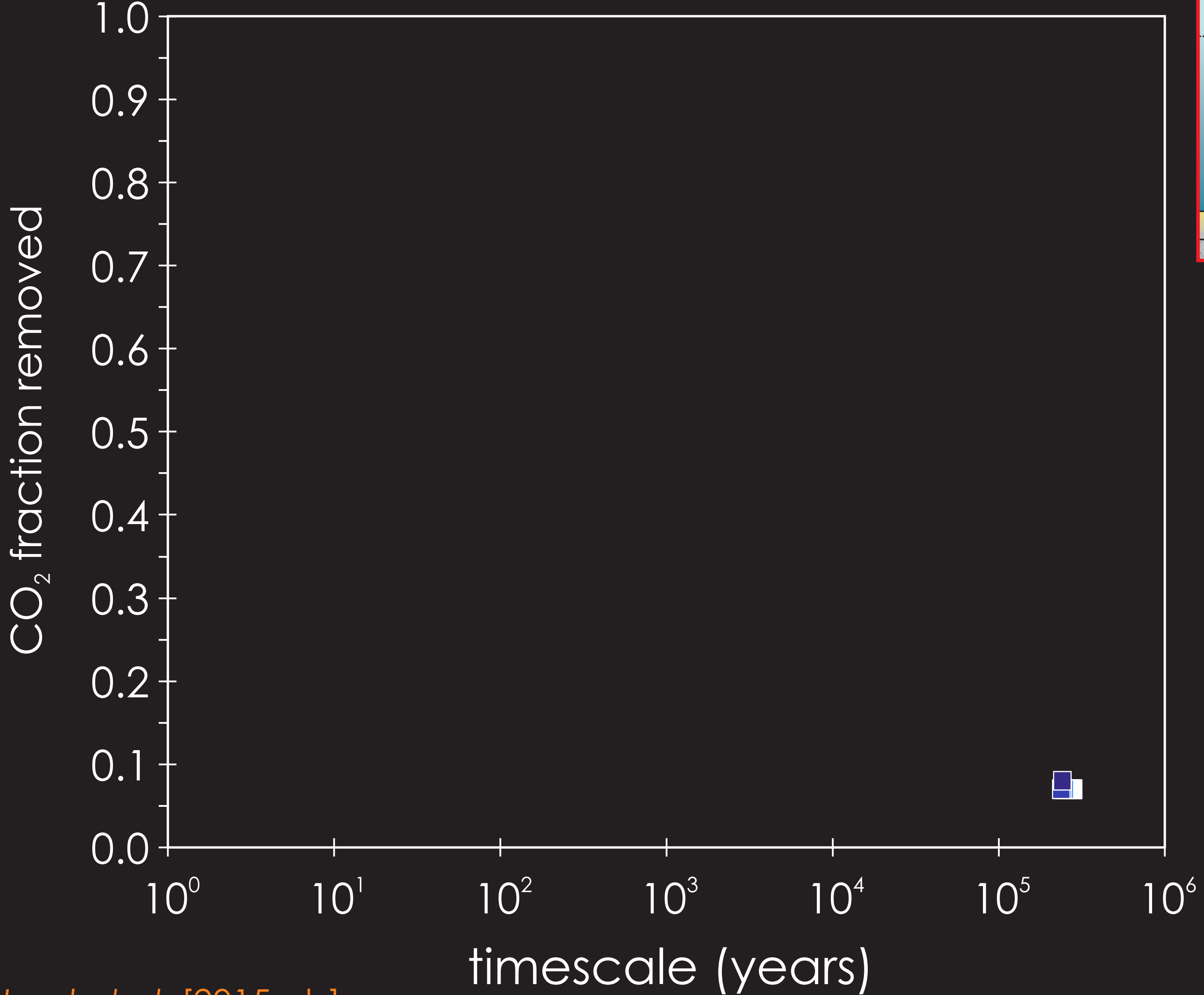
Impulse response function analysis of the 'long tail' of $CO_{2(excess)}$

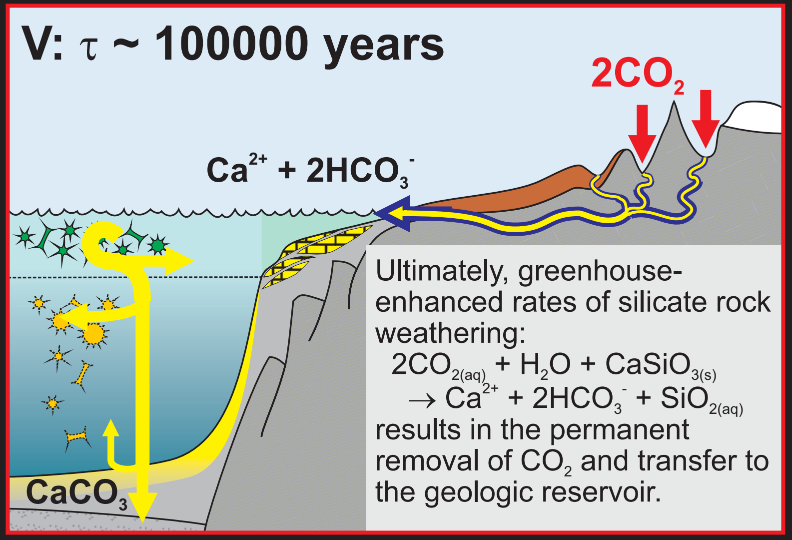


Sediments spanning the Palaeocene-Eocene boundary from ODP Leg 208 (Walvis Ridge)
Picture courtesy of Dani Schmidt (University of Bristol)

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

Silicate weathering (no time-scale response!).

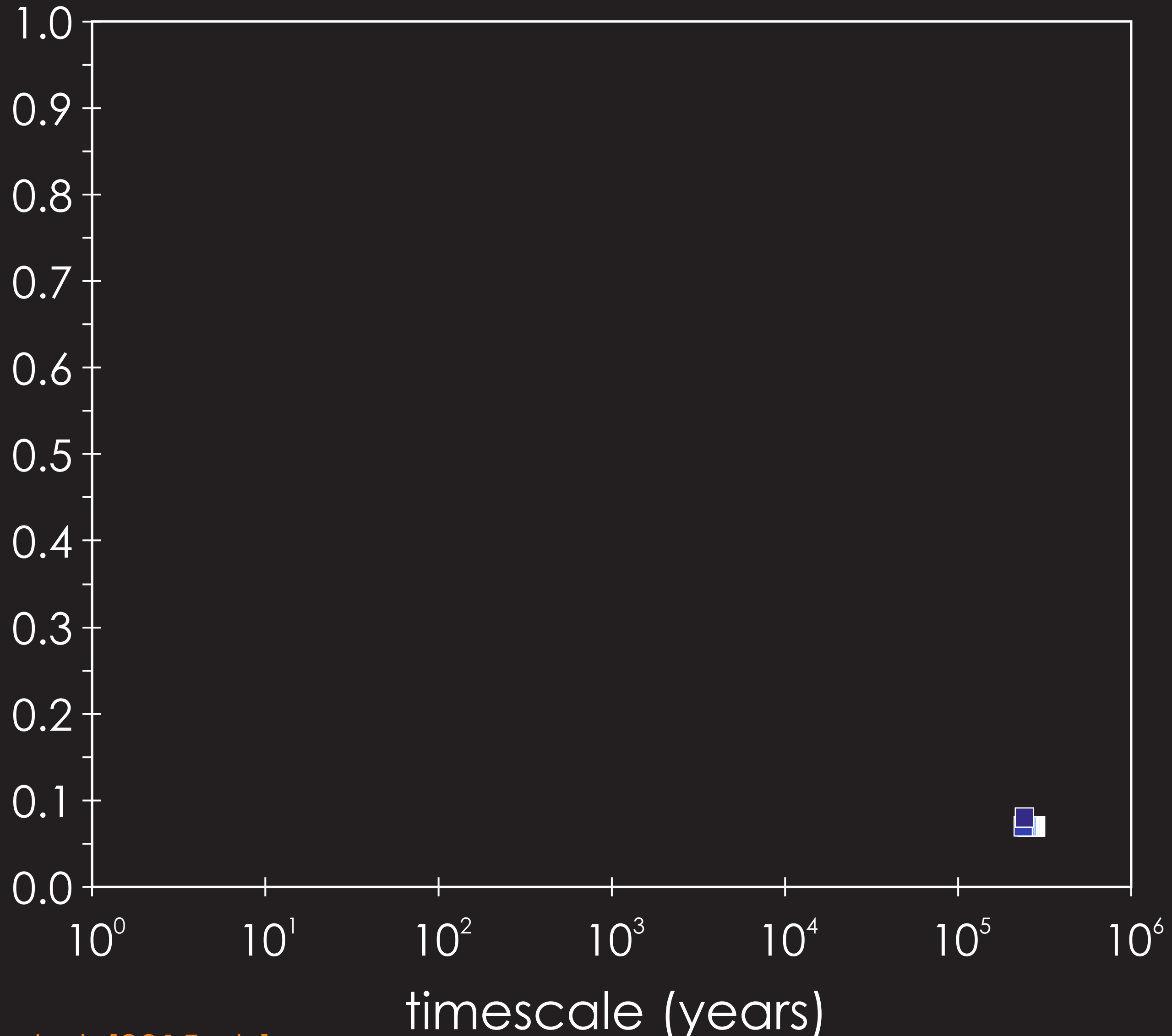




Lord et al. [2015a,b]

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

evidence?



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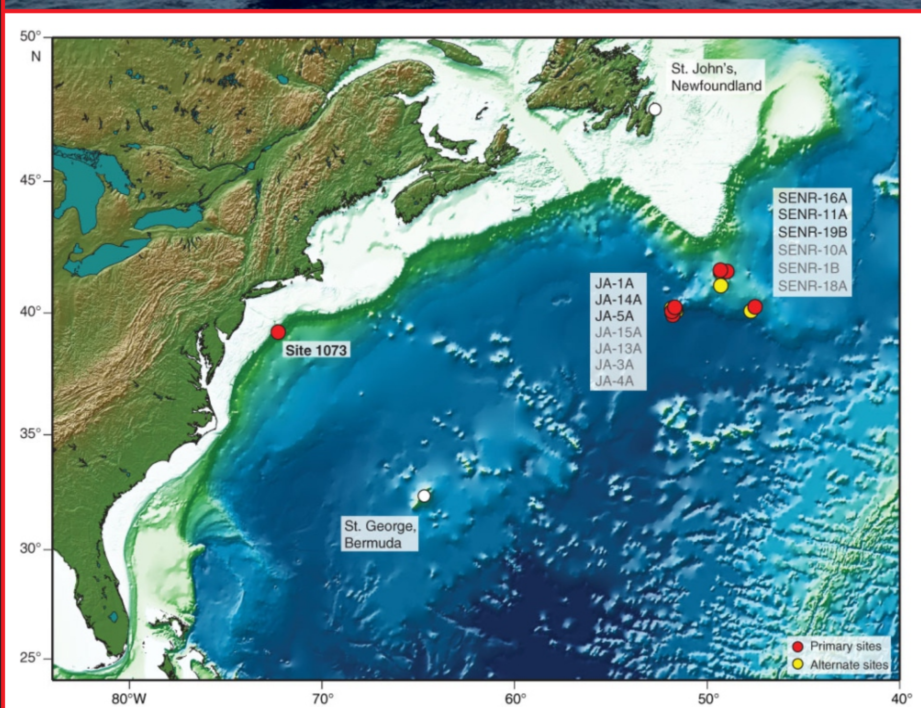
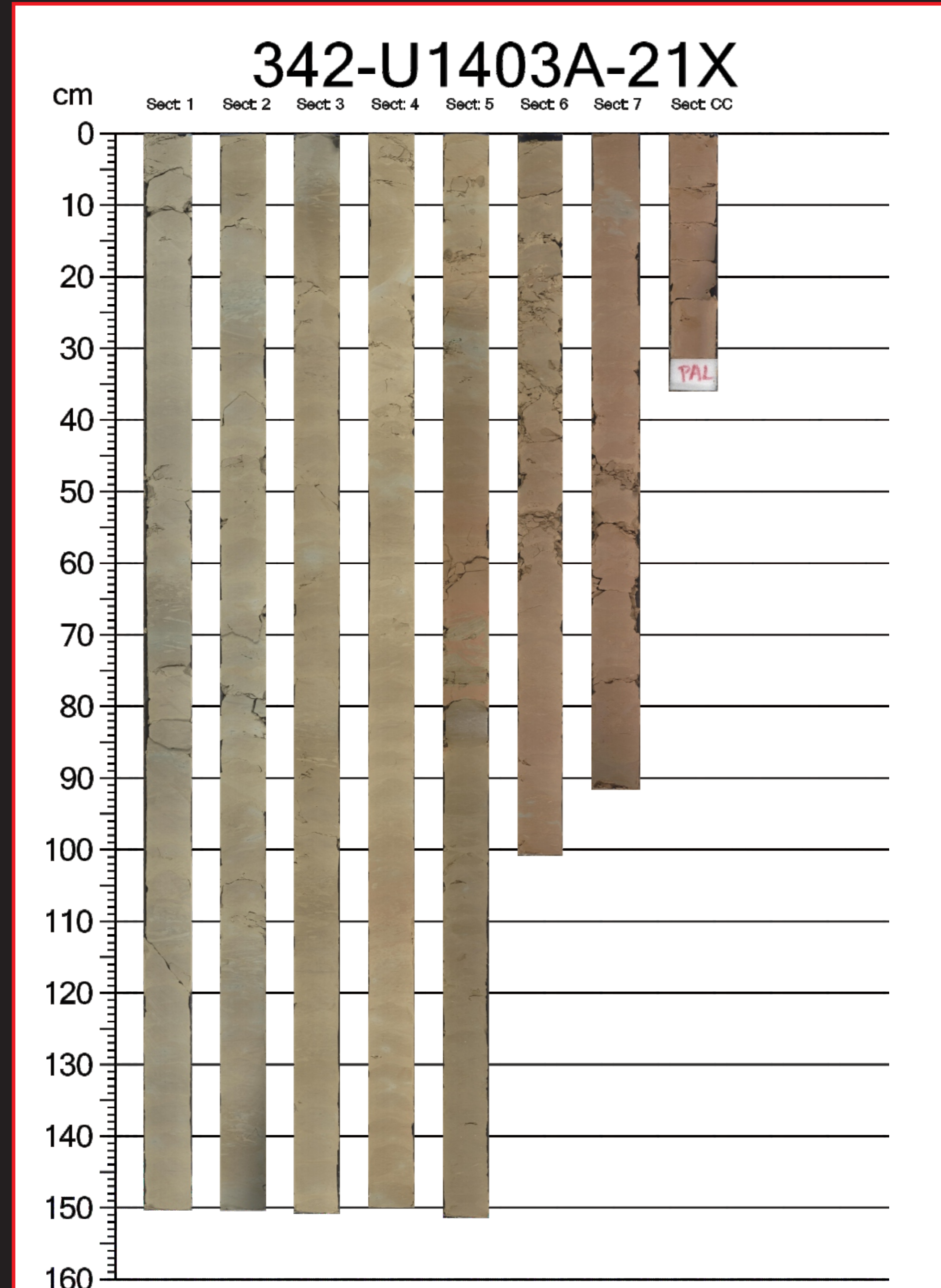
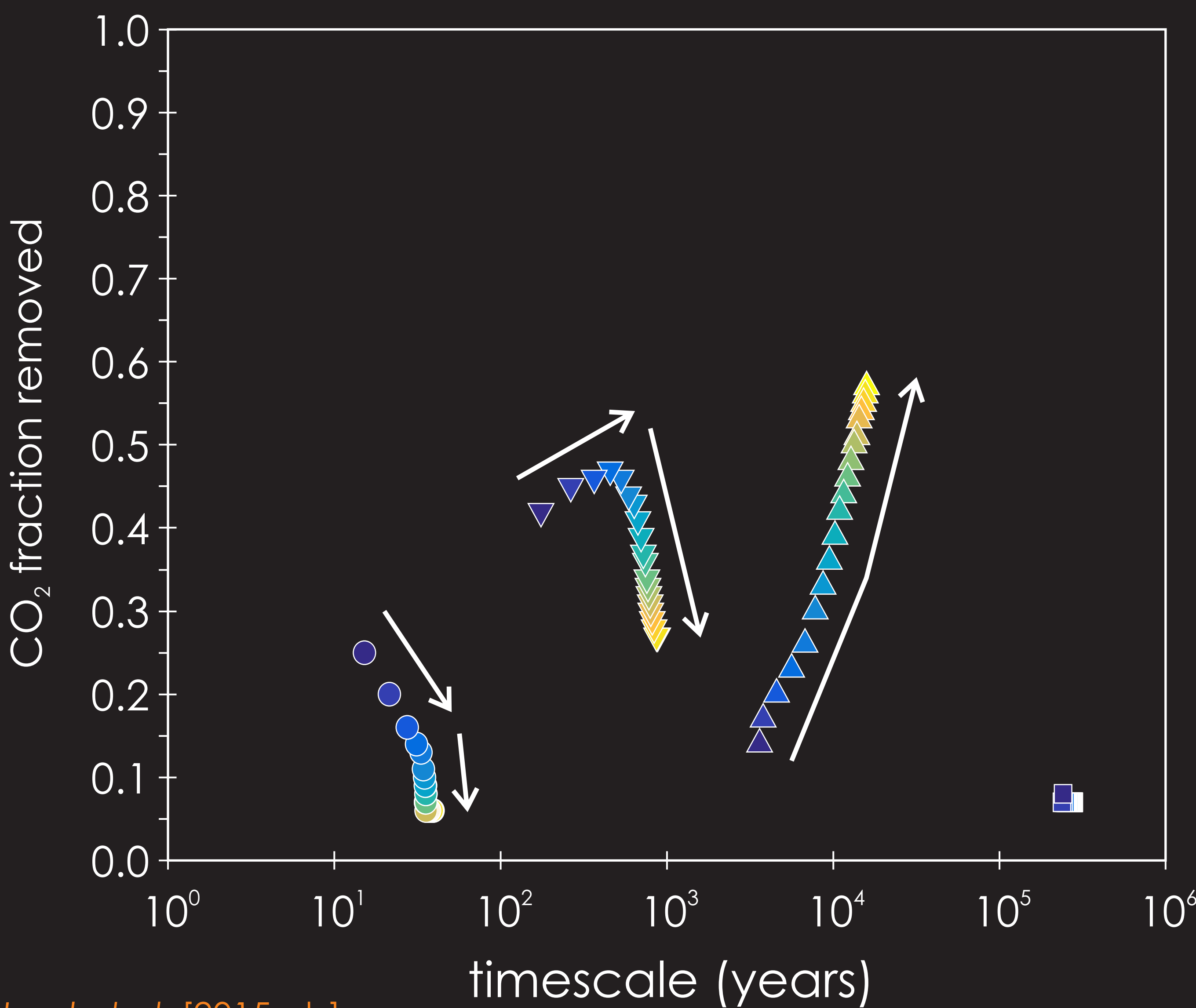




An impulse response function for the 'long tail' of $CO_{2(excess)}$ – IMPLICATIONS



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.

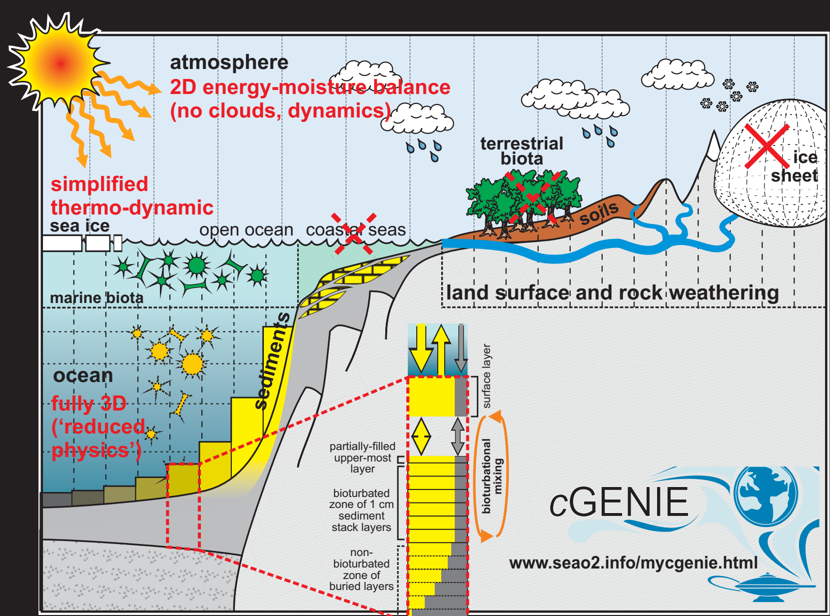
Elevated atmospheric pCO_2 hence becomes more persistent as the main short-term CO_2 feedbacks weaken.

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

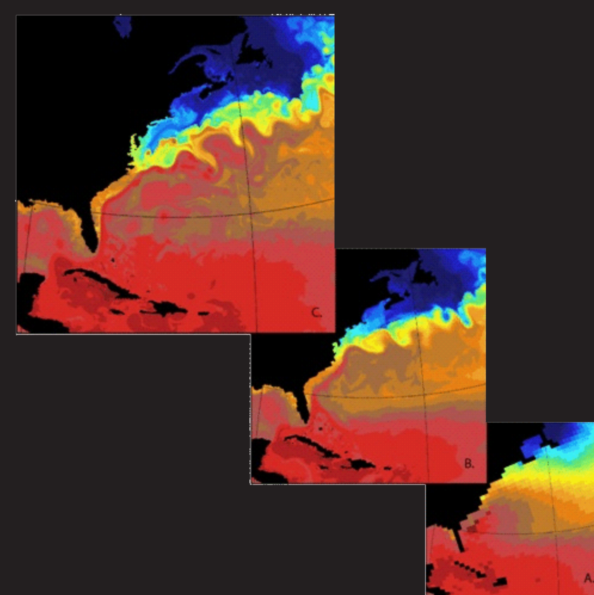
Lord et al. [2015a,b]

Melting Antarctica

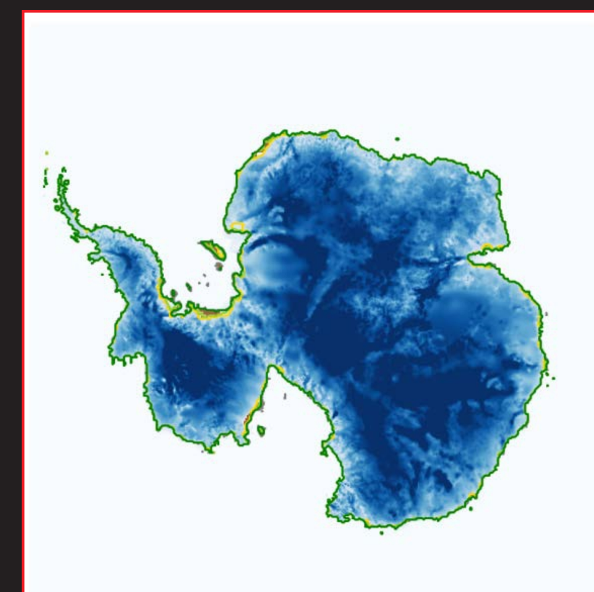
Melting Antarctica



Earth system model
(CO_2 and mean SST trajectories)



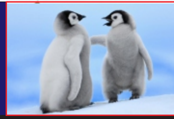
Downscaling
(SO SST and regional climate)

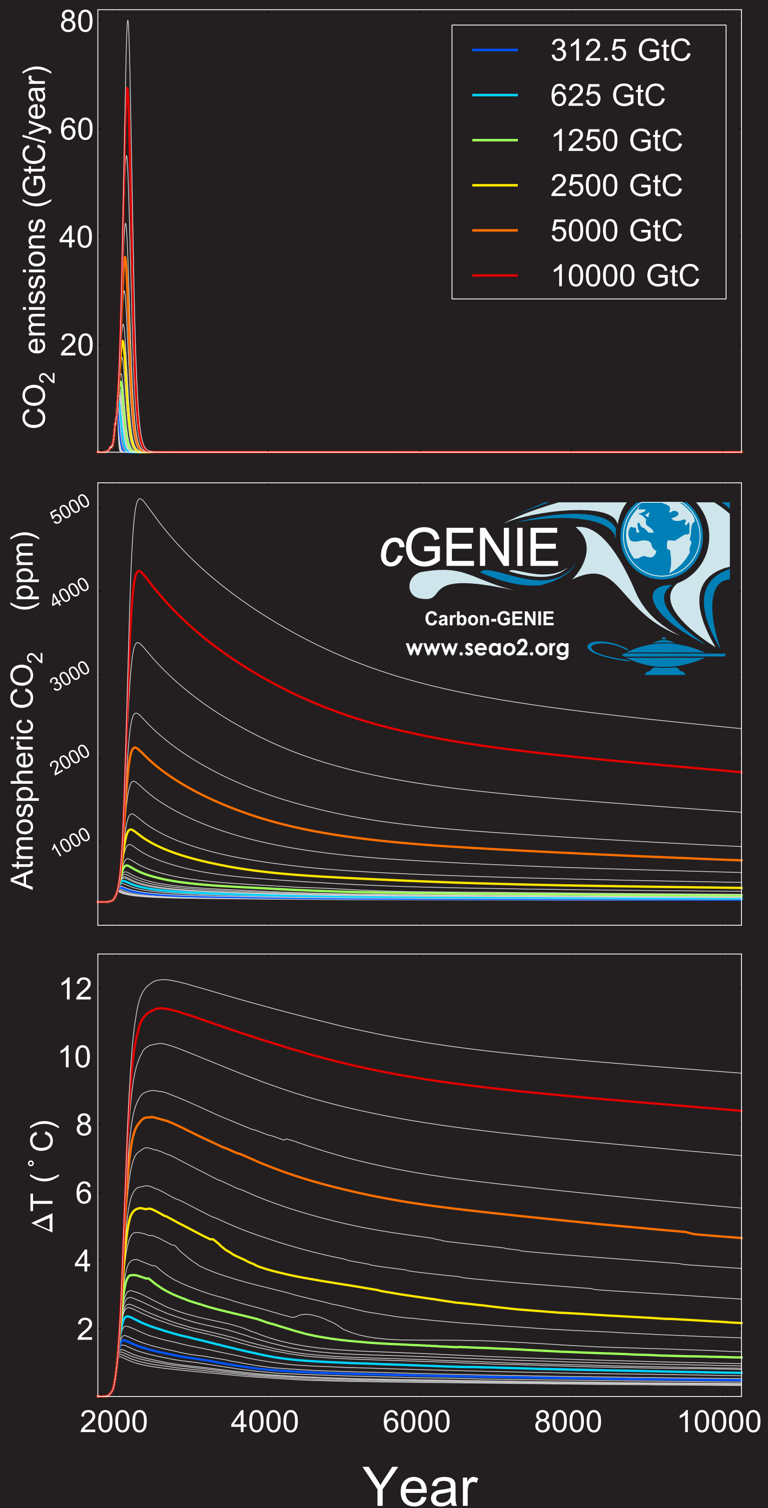


Ice sheet model

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

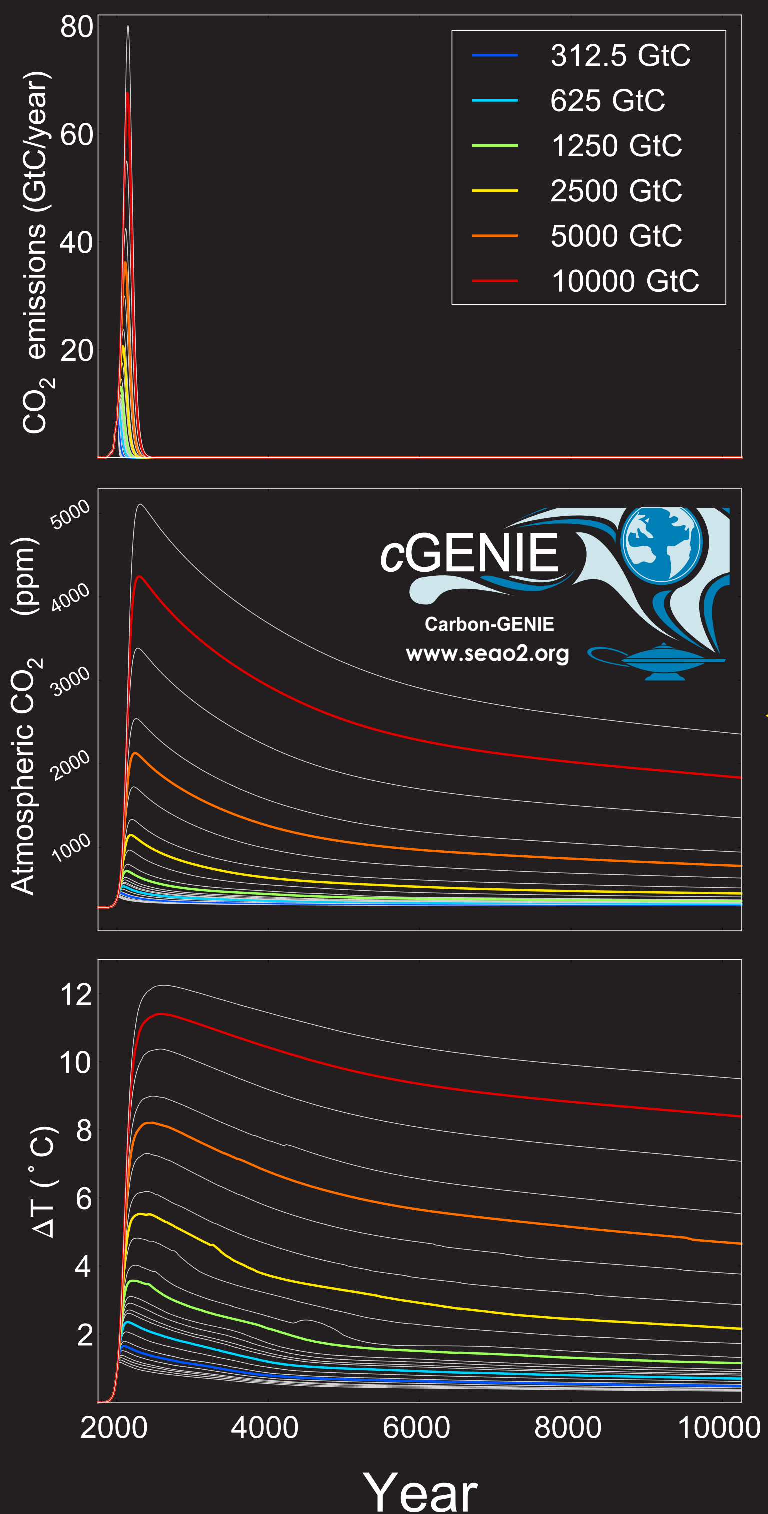
Melting Antarctica

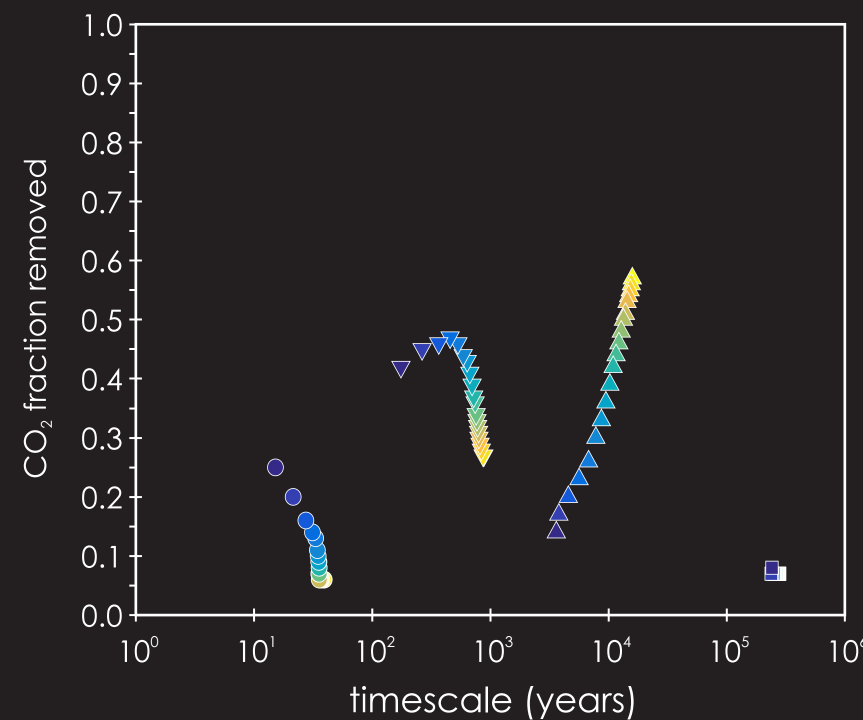




Winkelmann et al. [2015] (*Science Advances*)

Melting Antarctica





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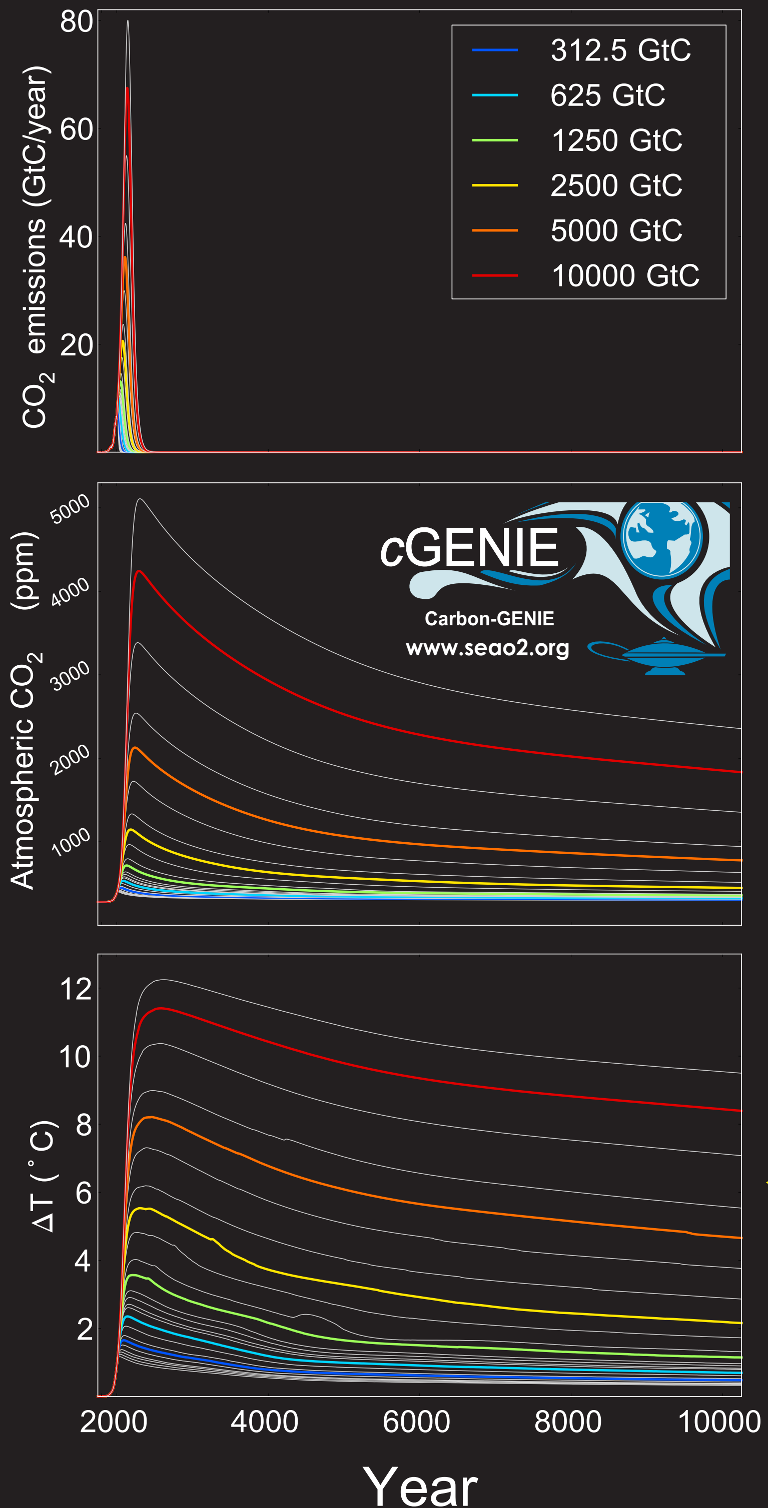
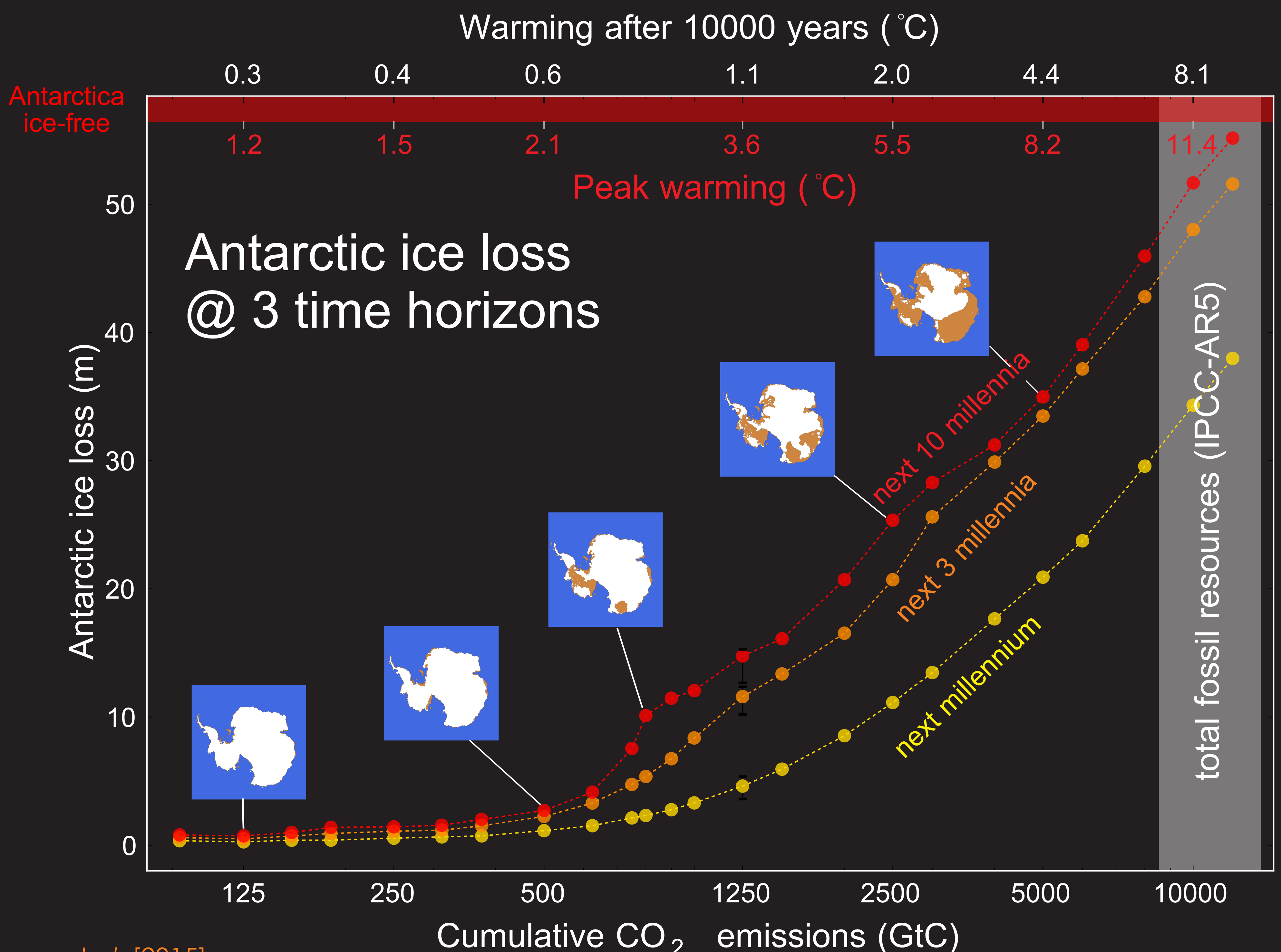
Melting Antarctica



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

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

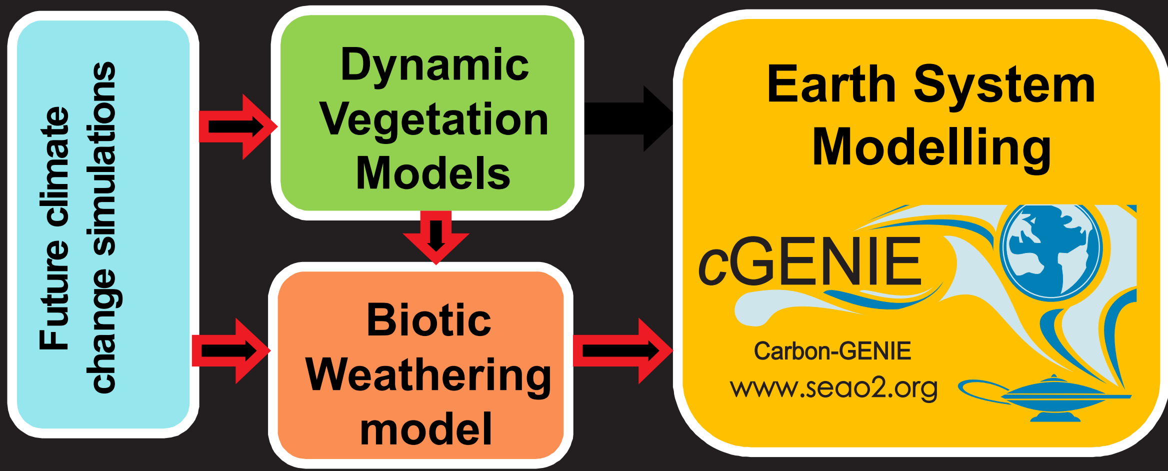
Harzburgite

~ plagioclase + pyroxene (+olivine)

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

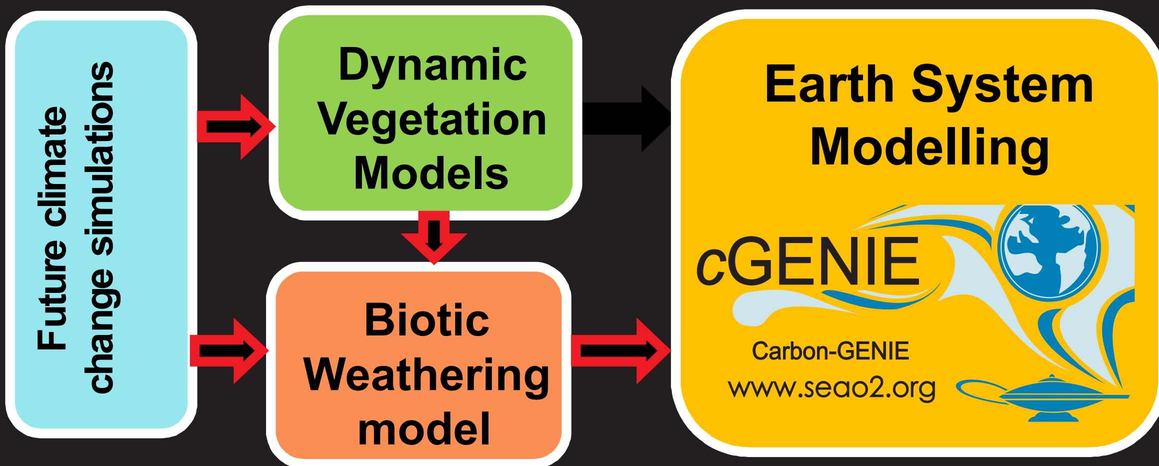
Dunite

Enhanced weathering (CO_2 removal geoengineering)

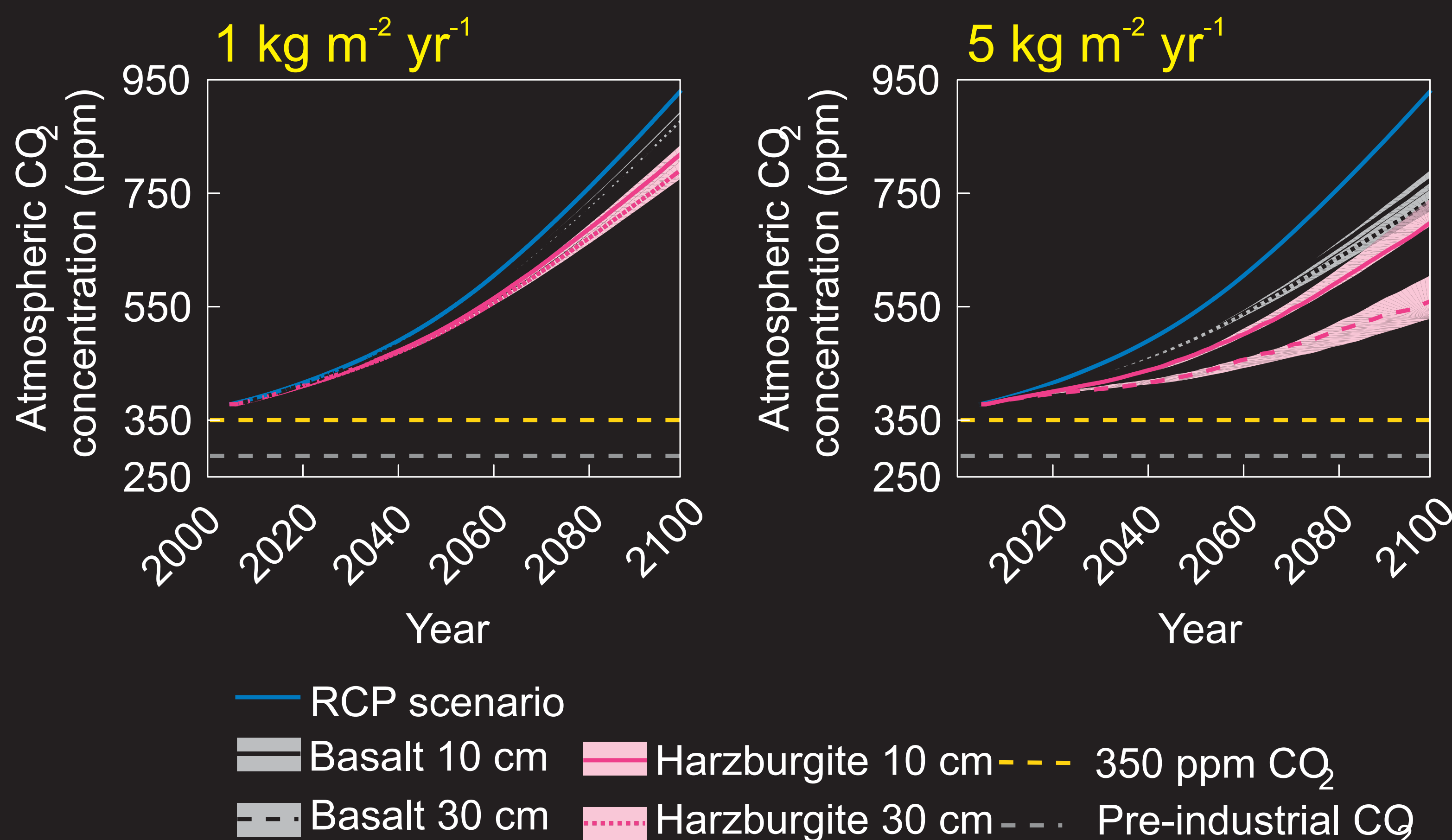


Taylor et al. [2015]
(Nature Climate Change)

Enhanced weathering (CO_2 removal geoengineering)

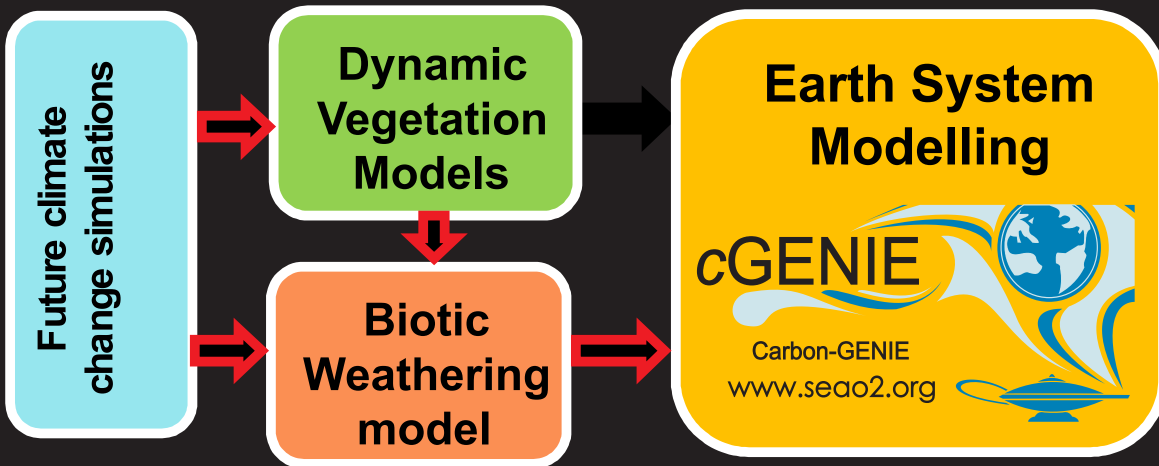


Taylor et al. [2015] (Nature Climate Change)



Ground rock application over $20{\times}10^3$ km^2 of tropical climatic 'hotspots'

Enhanced weathering (CO_2 removal geoengineering)



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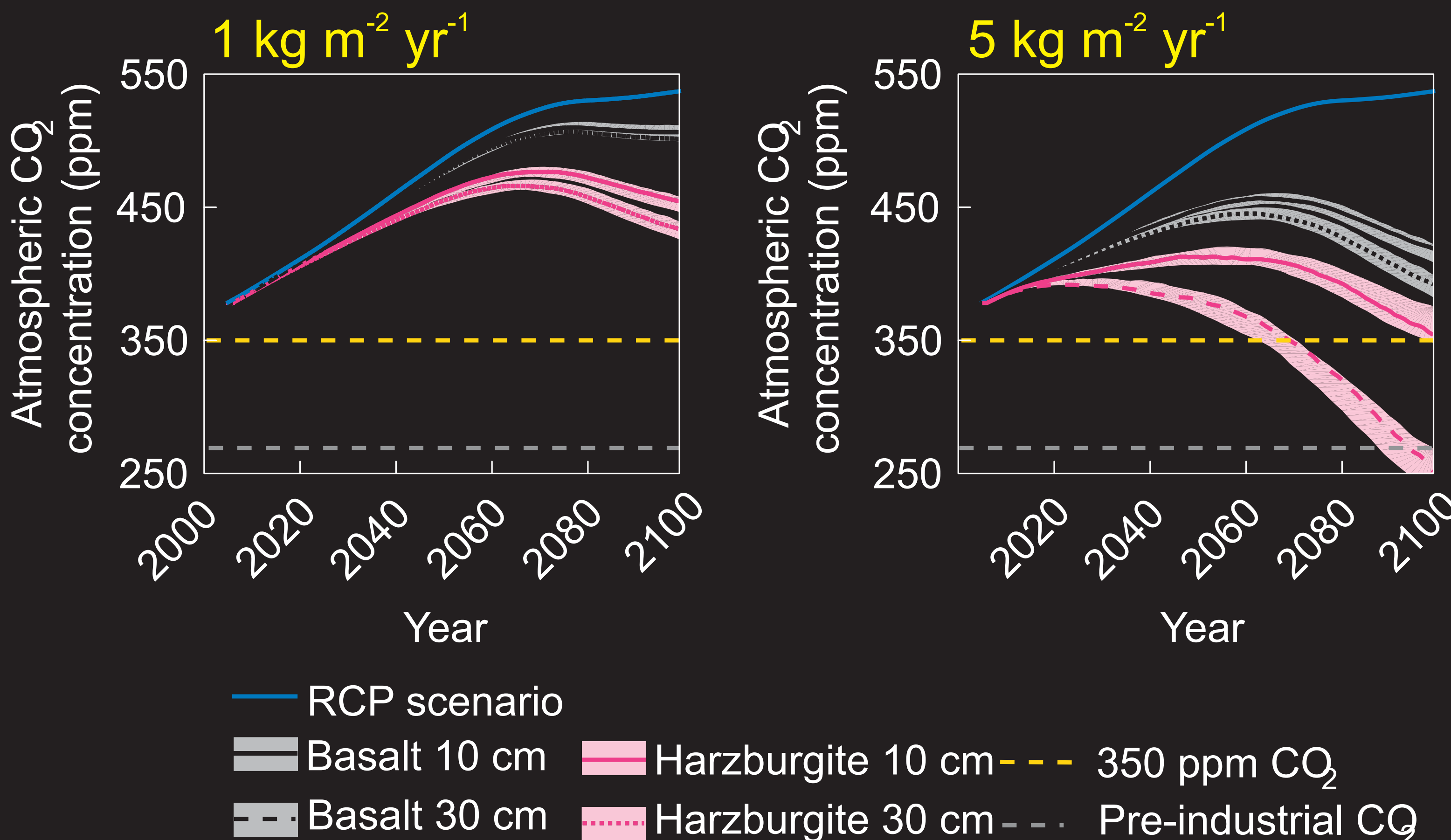

Ground rock application over $20{\times}10^3$ km^2 of tropical climatic 'hotspots'

Enhanced weathering (CO_2 removal geoengineering)

Current global oil consumption = $90{,}136 \times 10^3$ barrels per day

1.0 barrel = 159 l
= 159×10^3 cm^3

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

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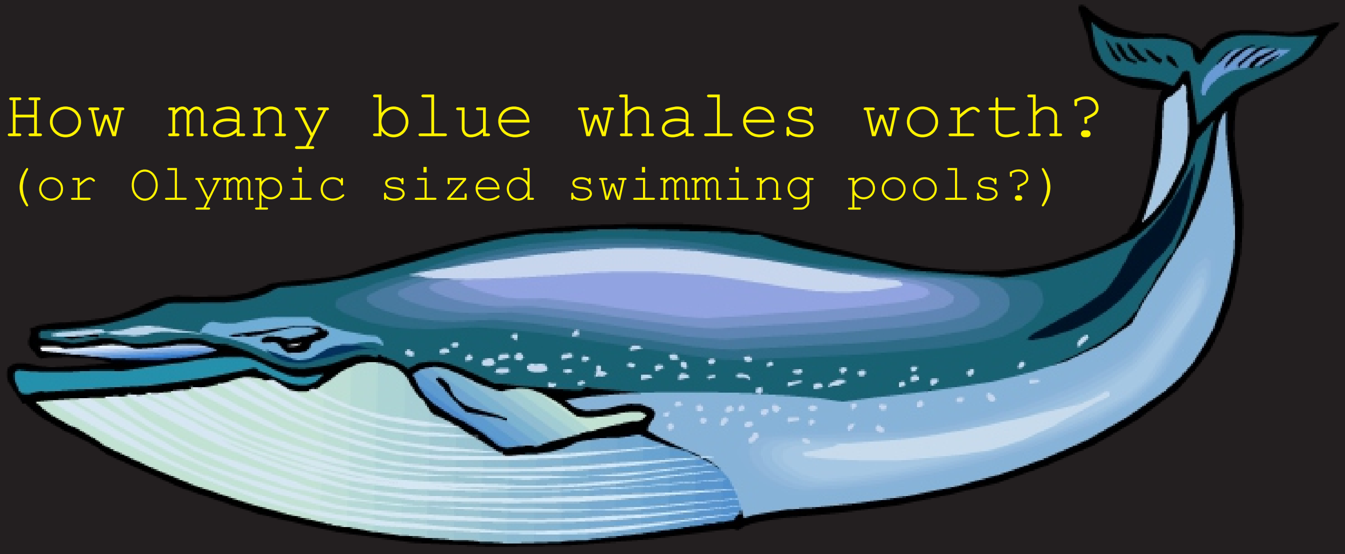
How many blue whales worth?
(or Olympic sized swimming pools?)



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How many Yosemite Valleys?
(equivalent volume)

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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, collaborators, and cold hard CA$H

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

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