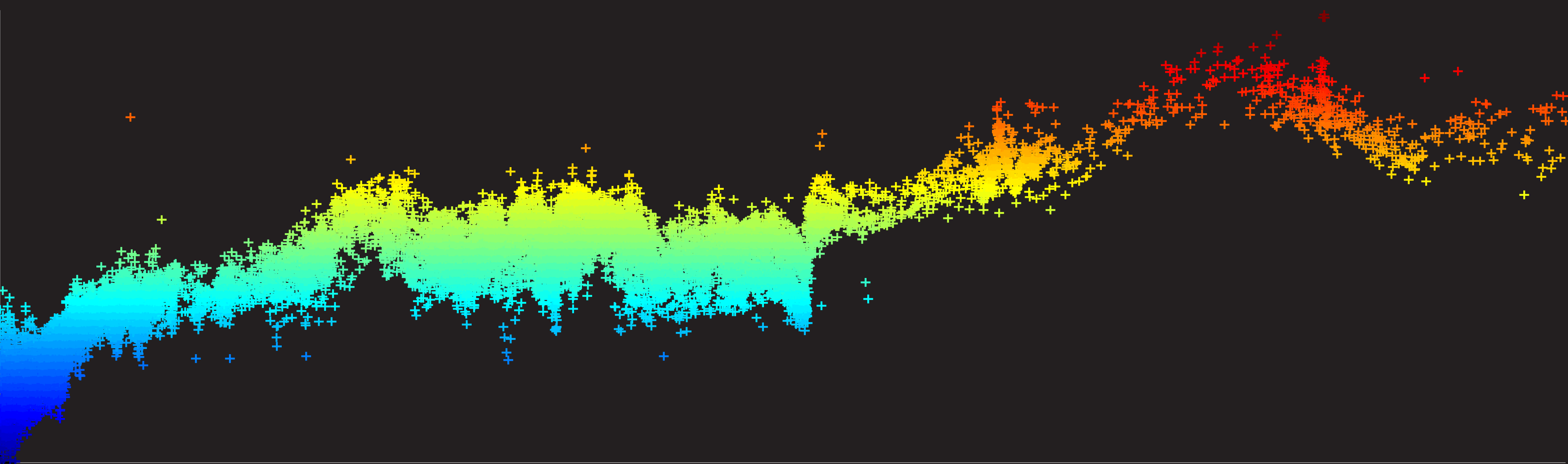
Placing data constraints on the long-term evolution of CO_2 and climate

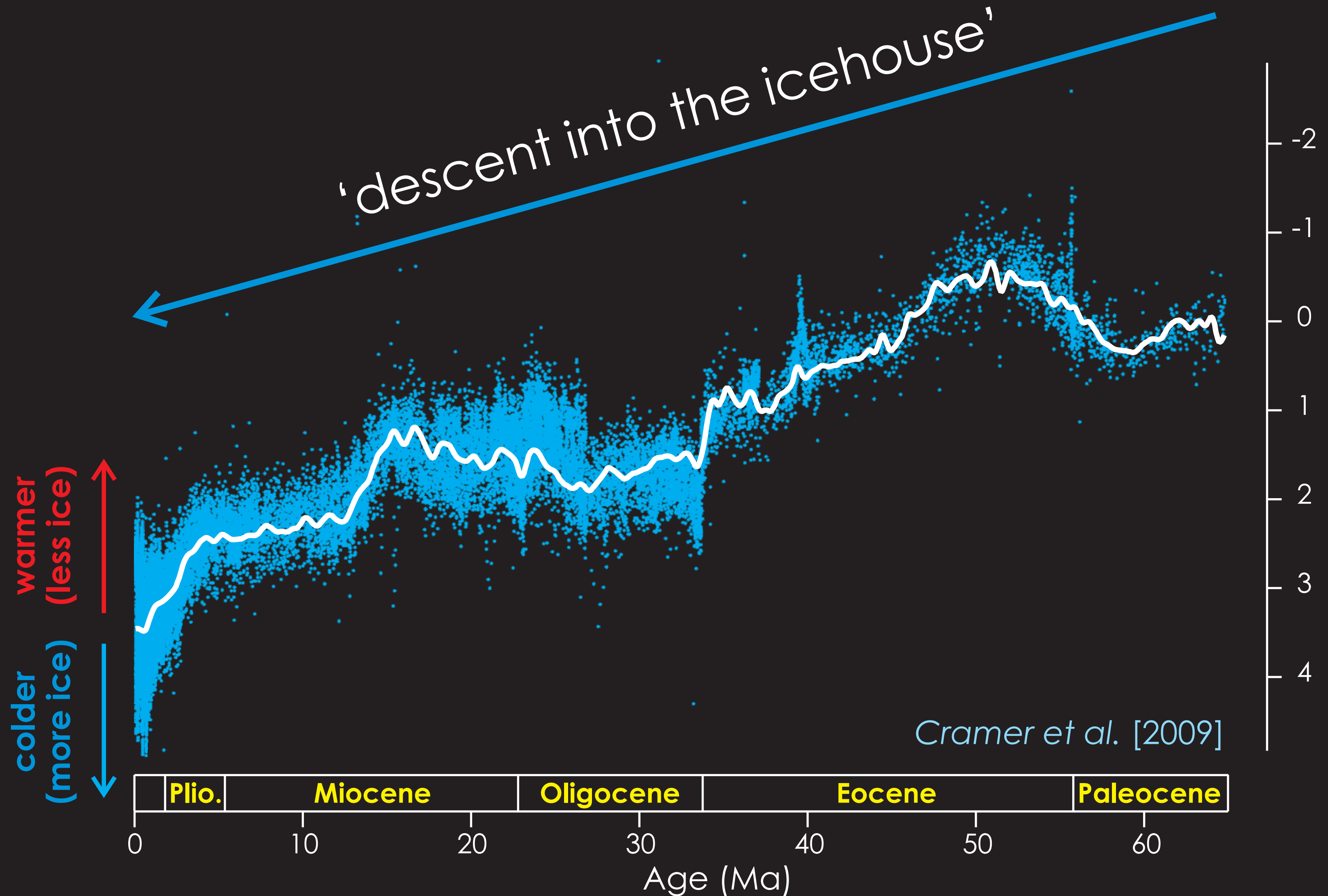
aka: 'Death of a proxy'

Andy Ridgwell

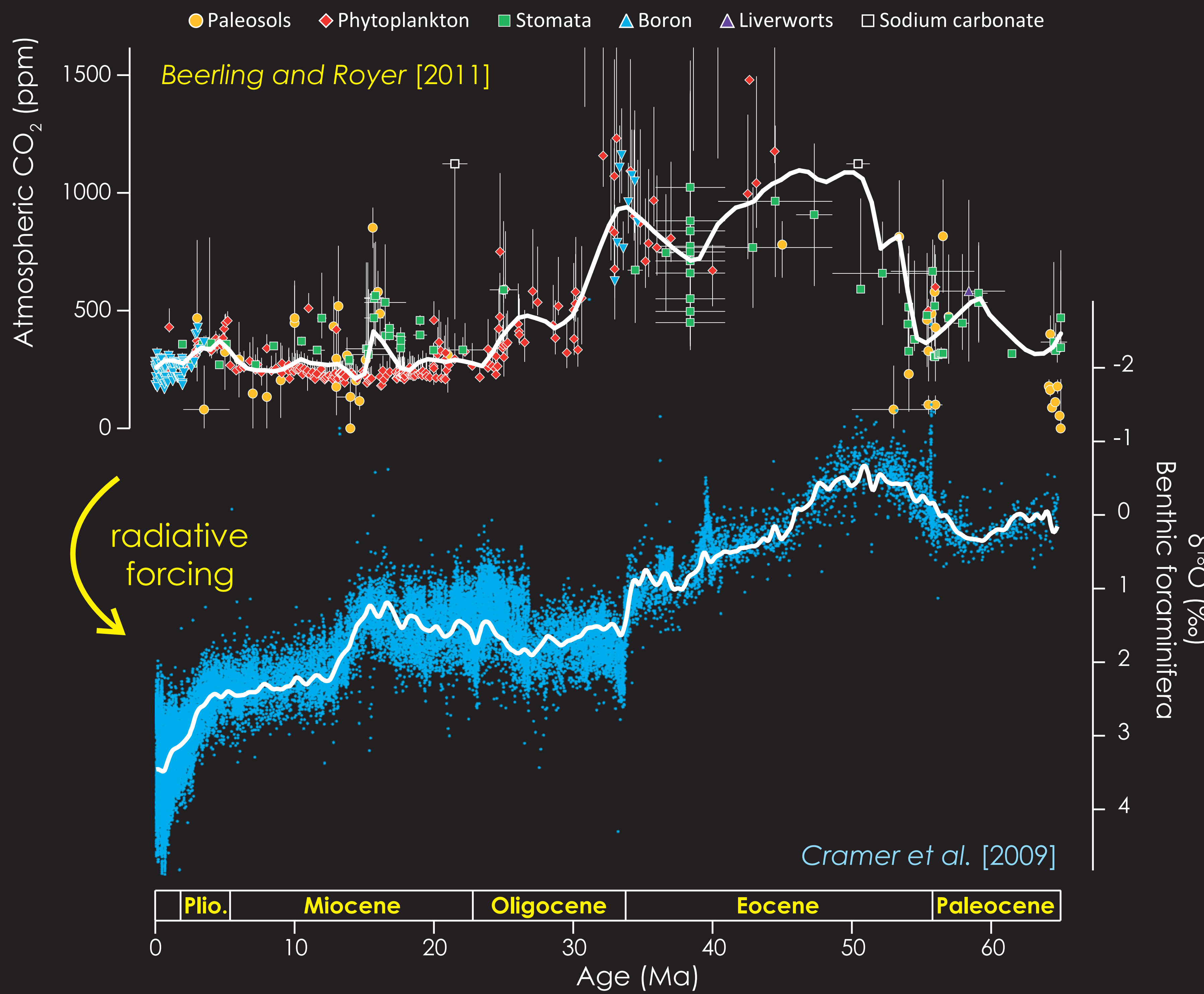
University of Bristol



What regulates Cenozoic climate?

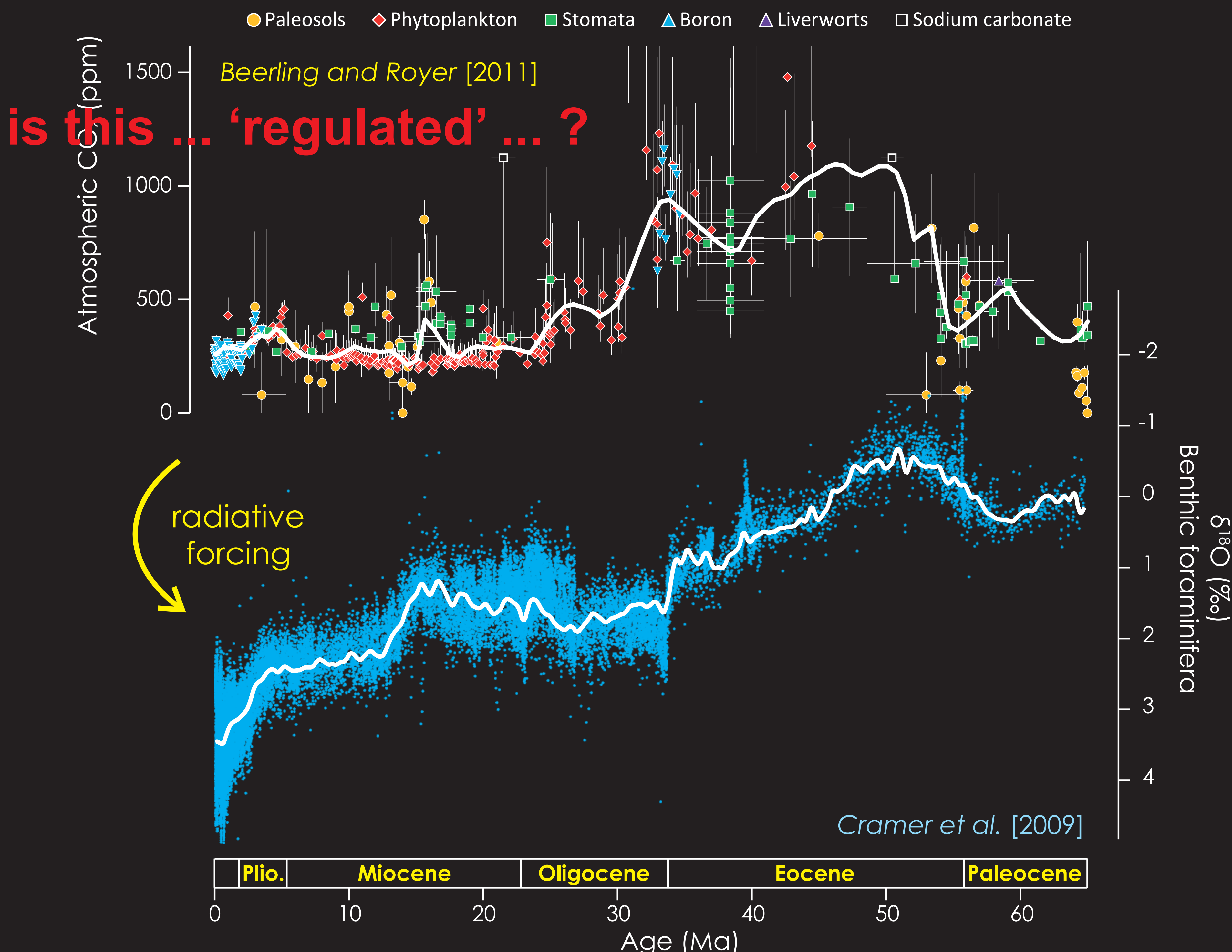


What regulates Cenozoic climate carbon cycling?



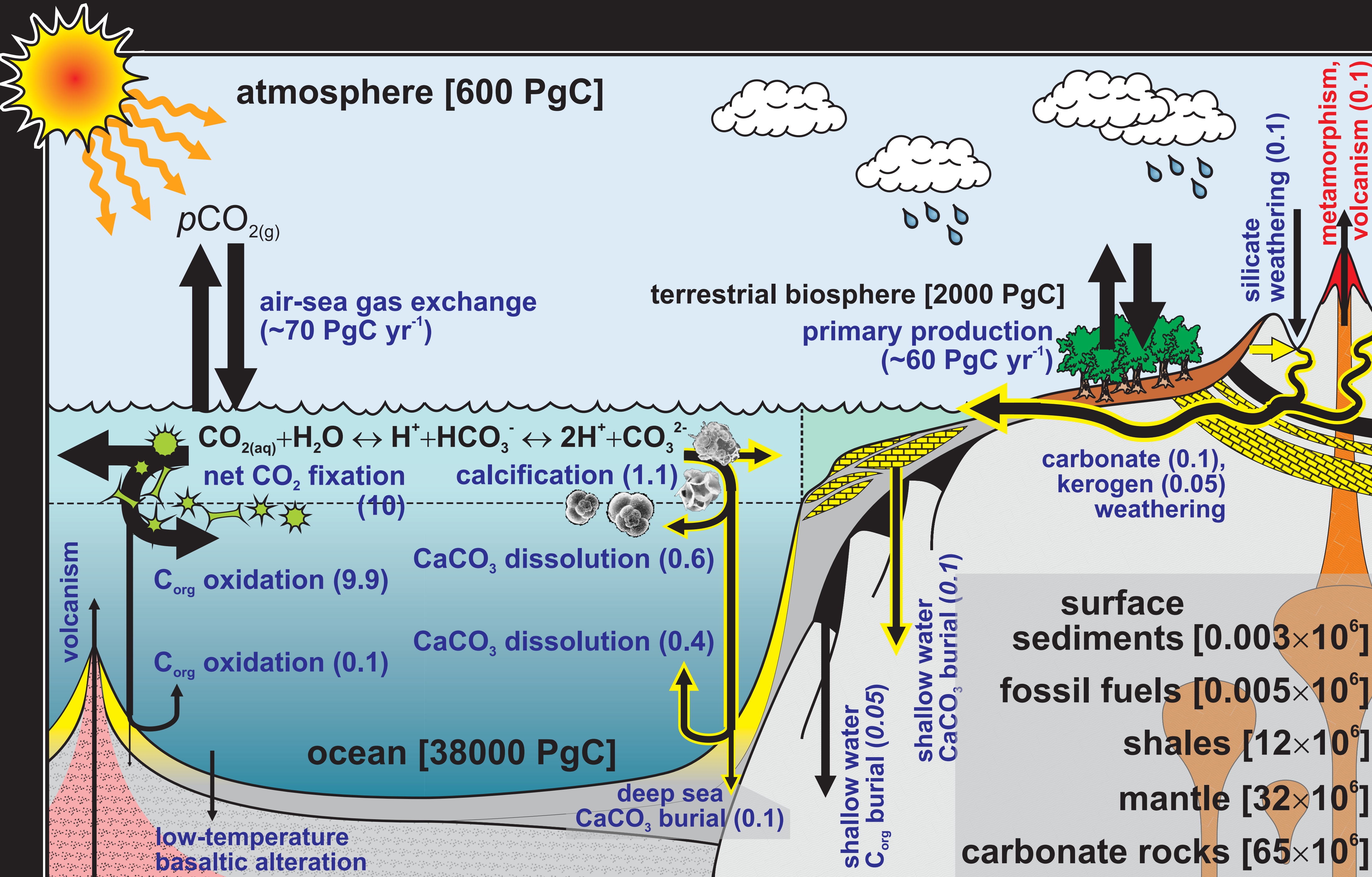
What regulates Cenozoic ~~climate~~ carbon cycling?

Co-evolution of Life and the Planet

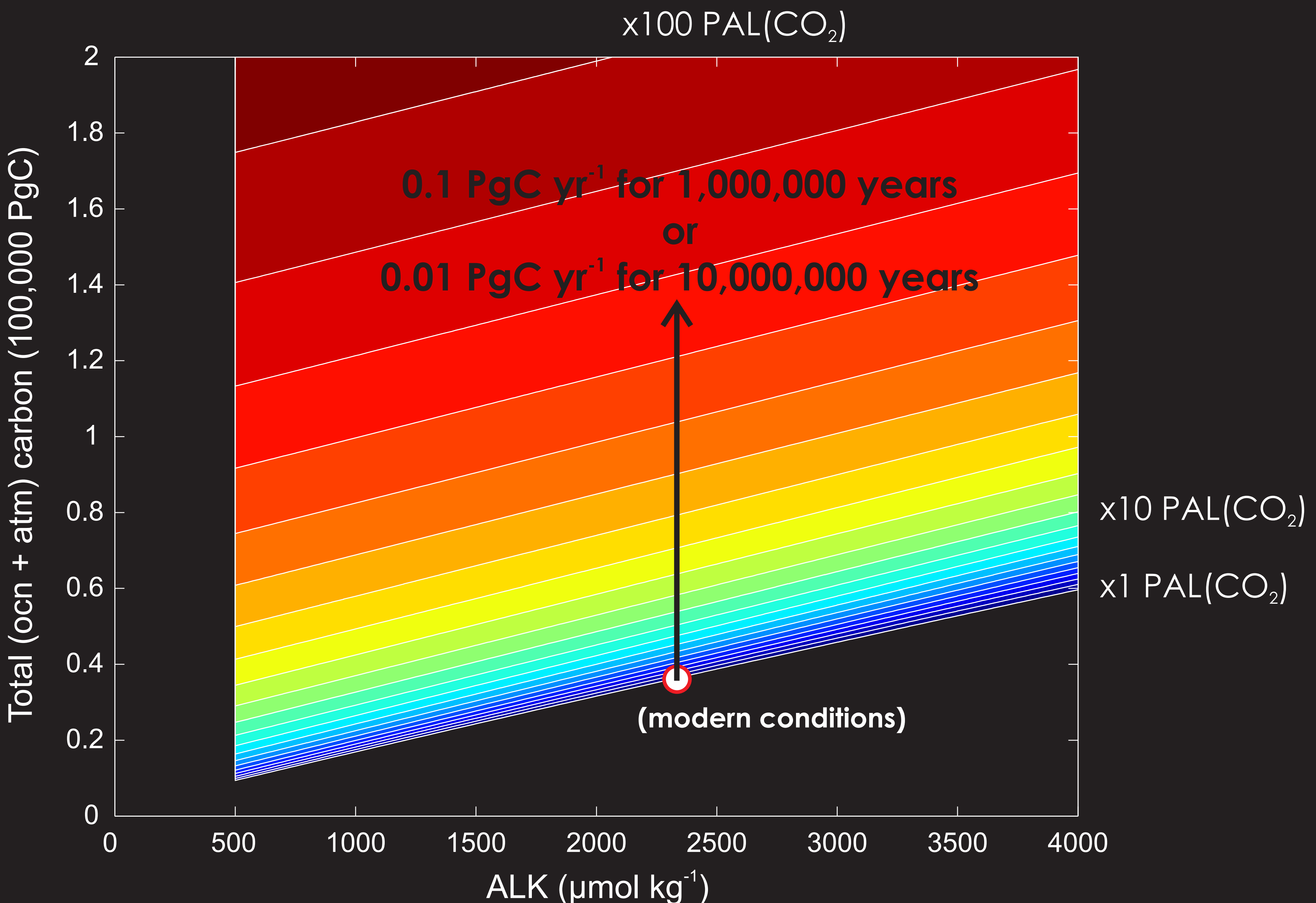


What regulates Cenozoic ~~climate~~ carbon cycling?

Co-evolution of Life and the Planet



What regulates Cenozoic ~~climate~~ carbon cycling?



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

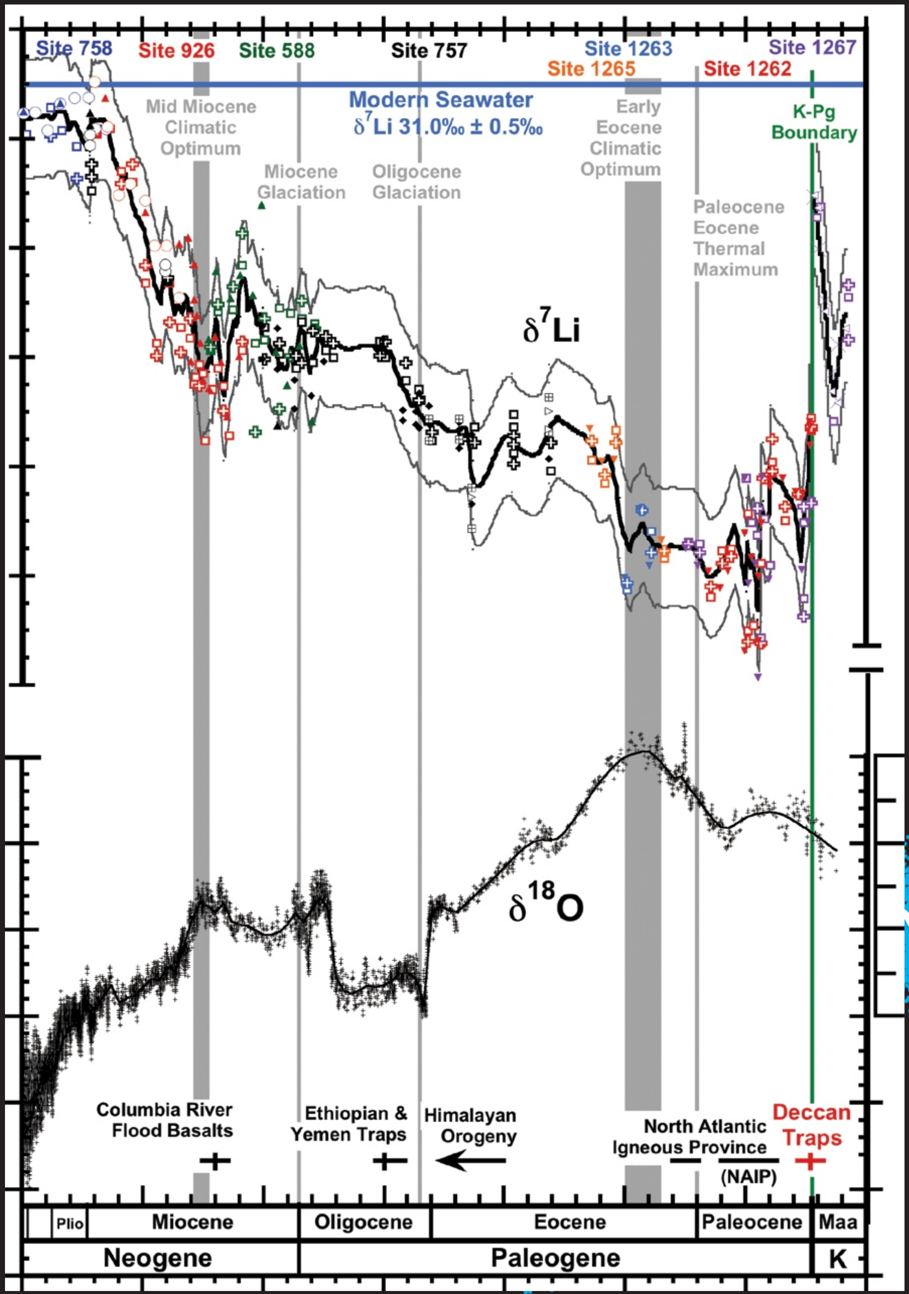
It can be seen that in (2) + (3), that the CO_2 removed (from the atmosphere) during weathering, is returned upon carbonate precipitation (and burial). In (1) + (3) (silicate weathering) CO_2 is permanently removed to the geological reservoir. This CO_2 must be balanced by mantle (/volcanic) out-gassing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

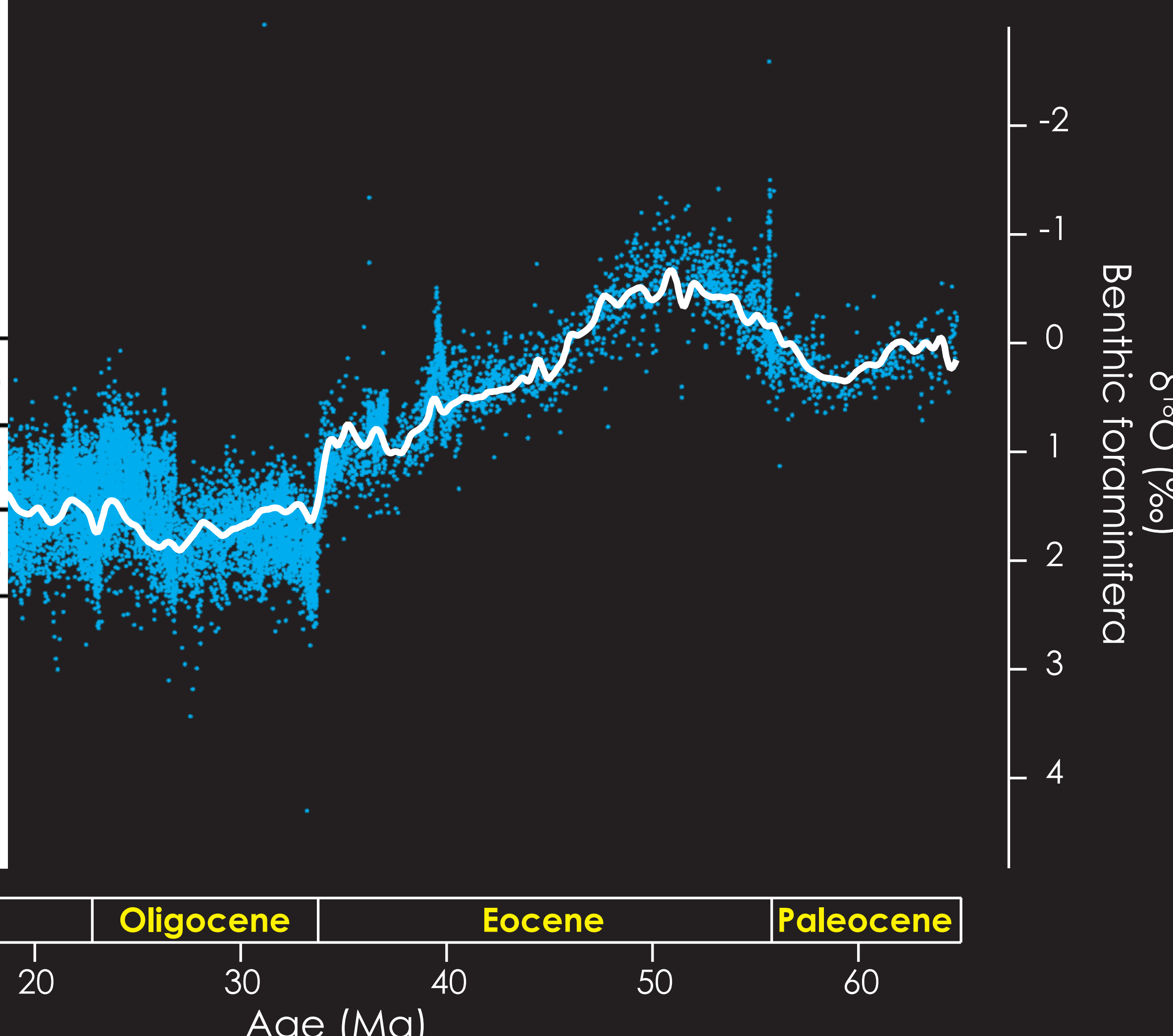
Furthermore, the rate of silicate weathering should scale with climate. Hence a ca. 100 kyr time-scale **silicate weathering feedback** is formed:

higher pCO_2 → higher temperatures (and rainfall) → higher weathering rates → 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.)

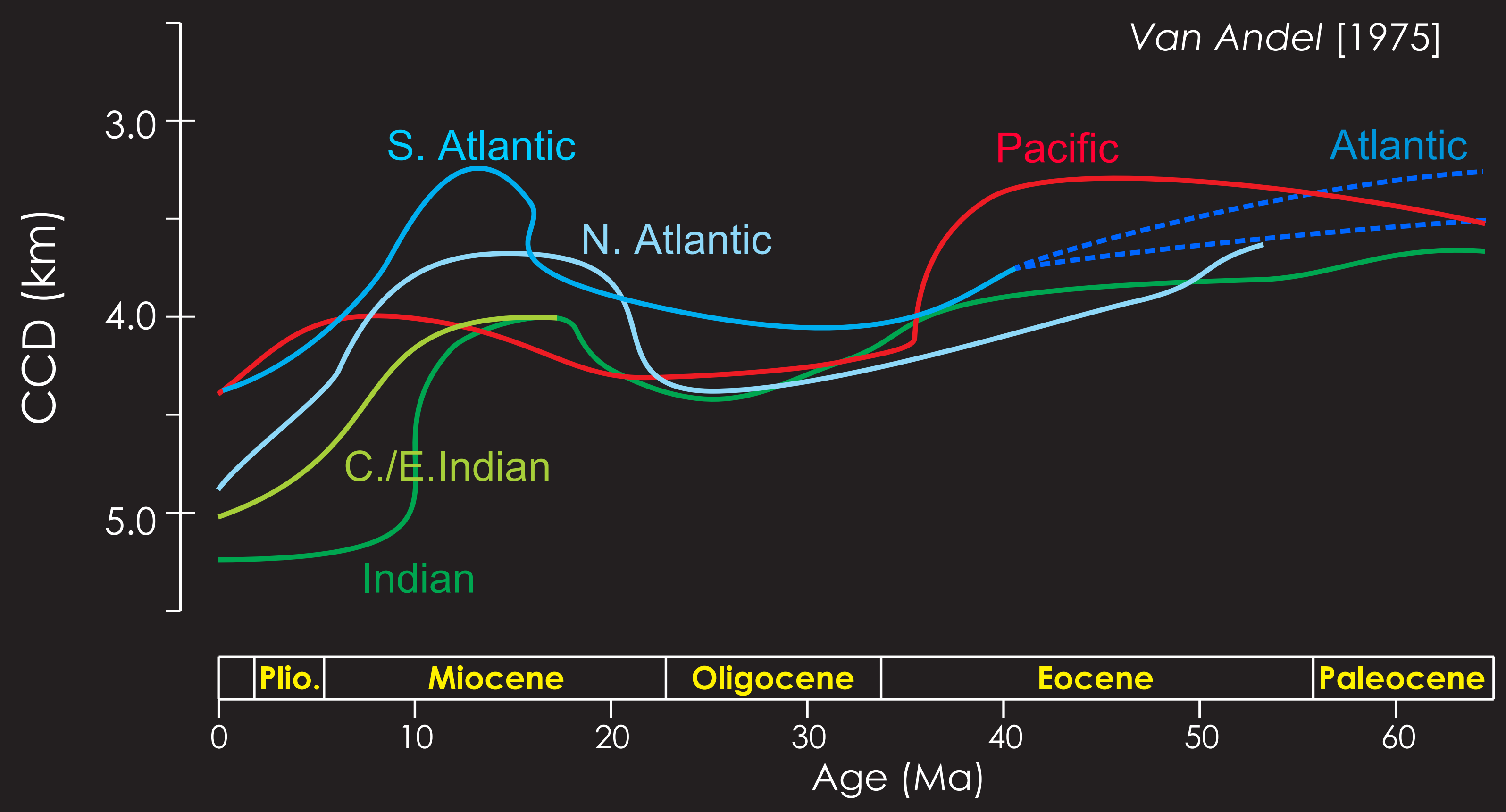
Constraints on weathering: Li isotopes



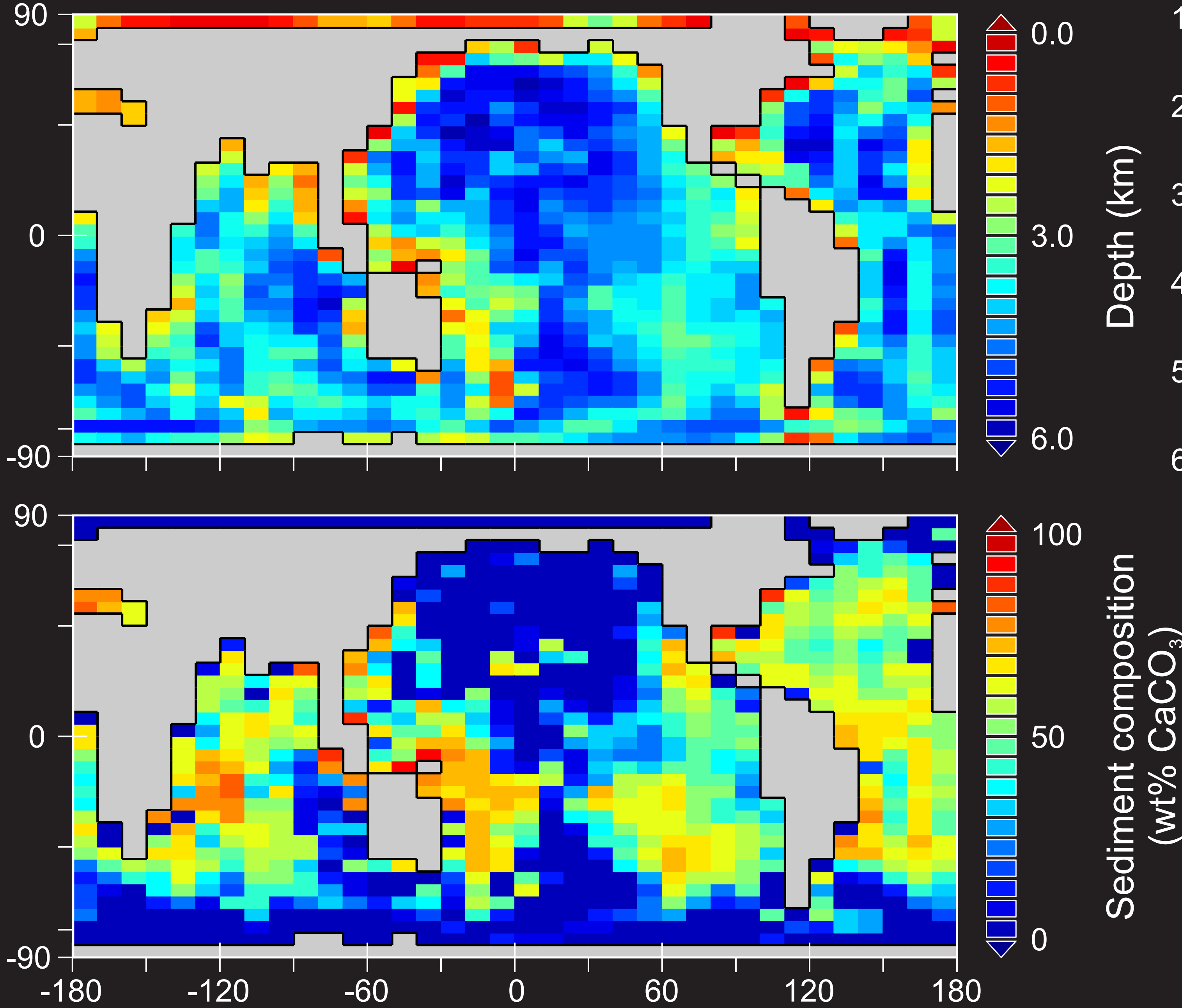


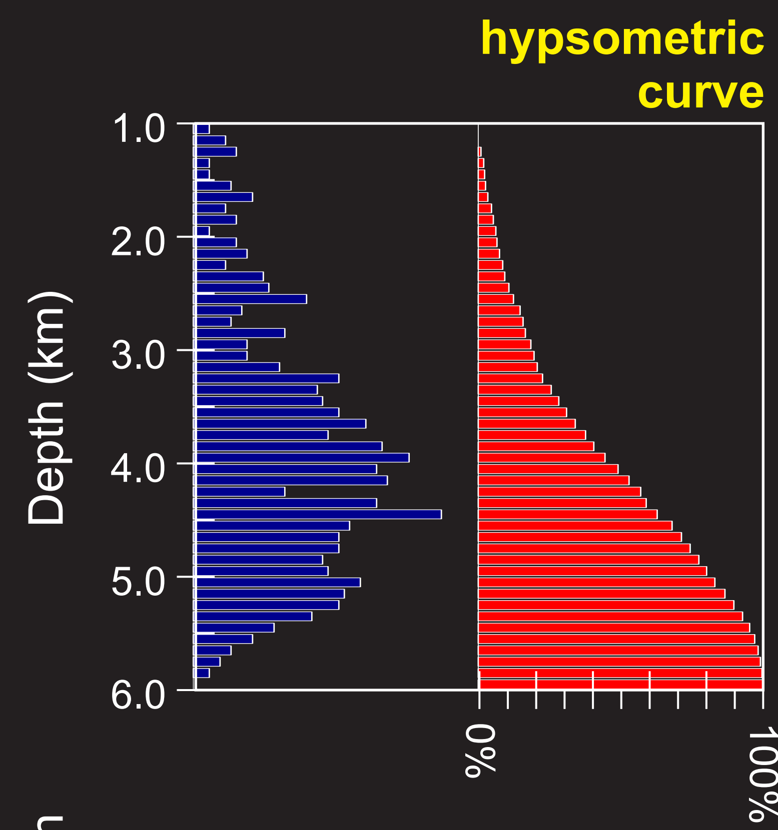
Froelich and Misra [2014]

The Carbonate Compensation Depth ('CCD')



Carbon cycle and CCD dynamics ... in models





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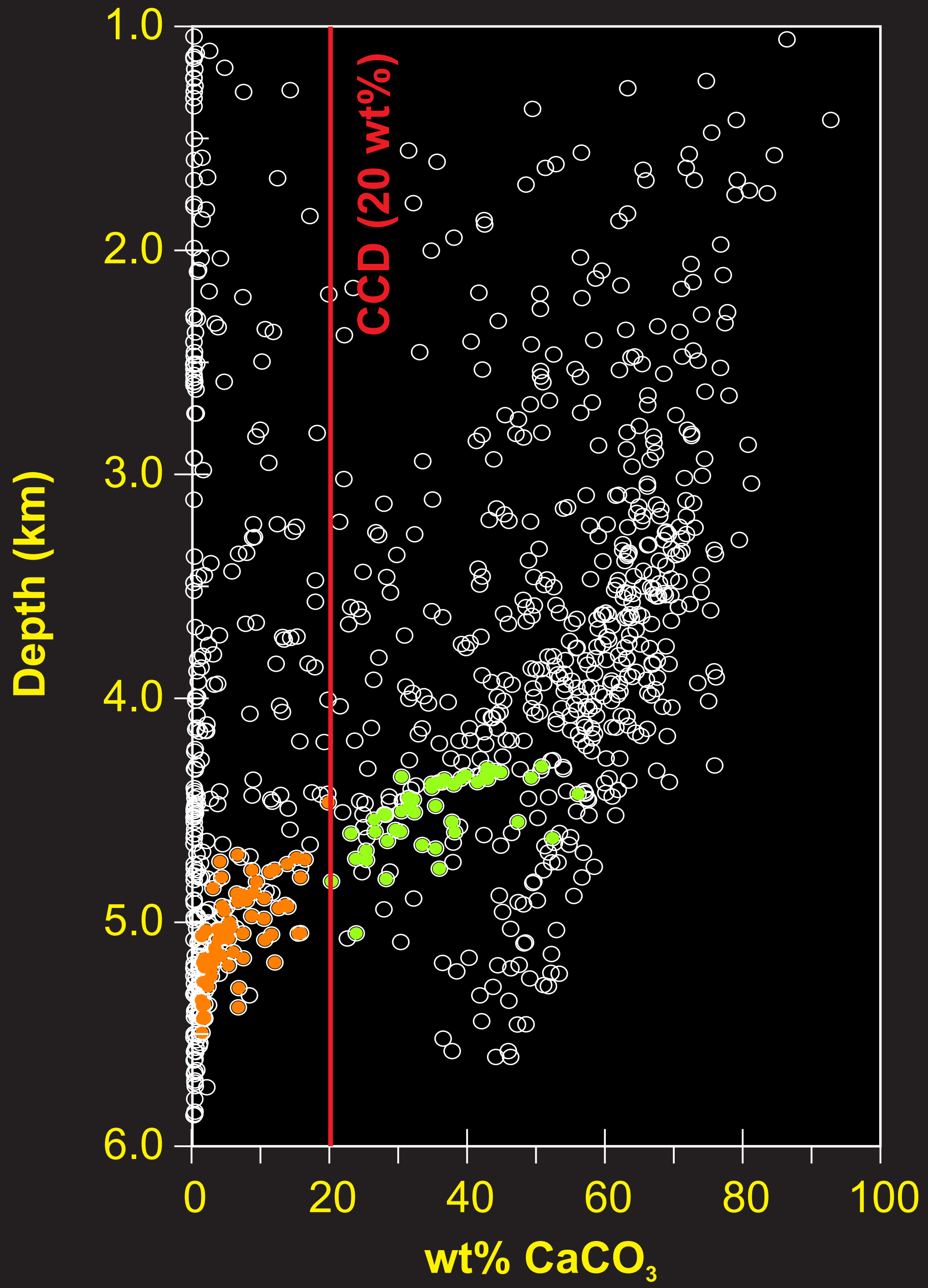

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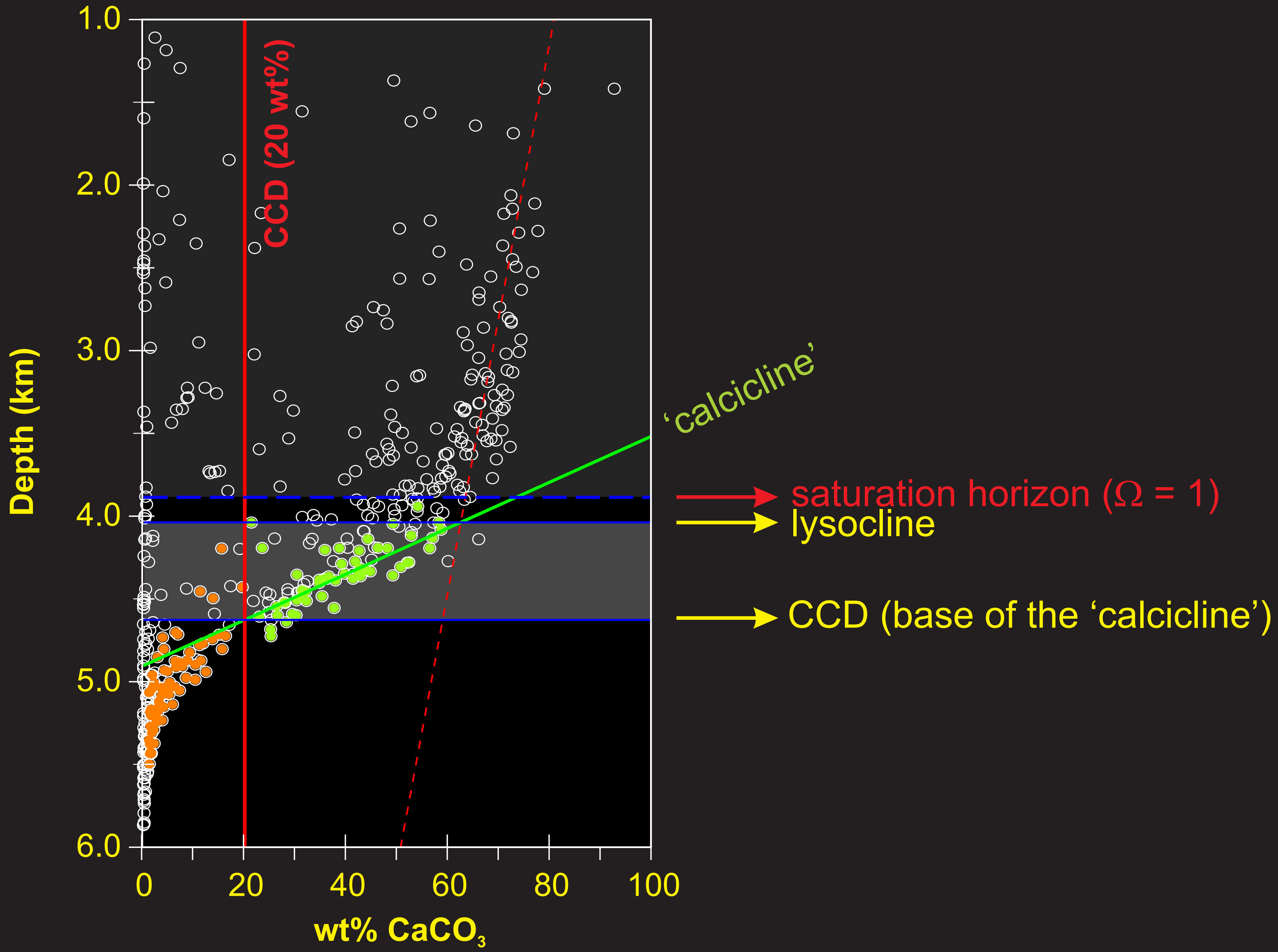
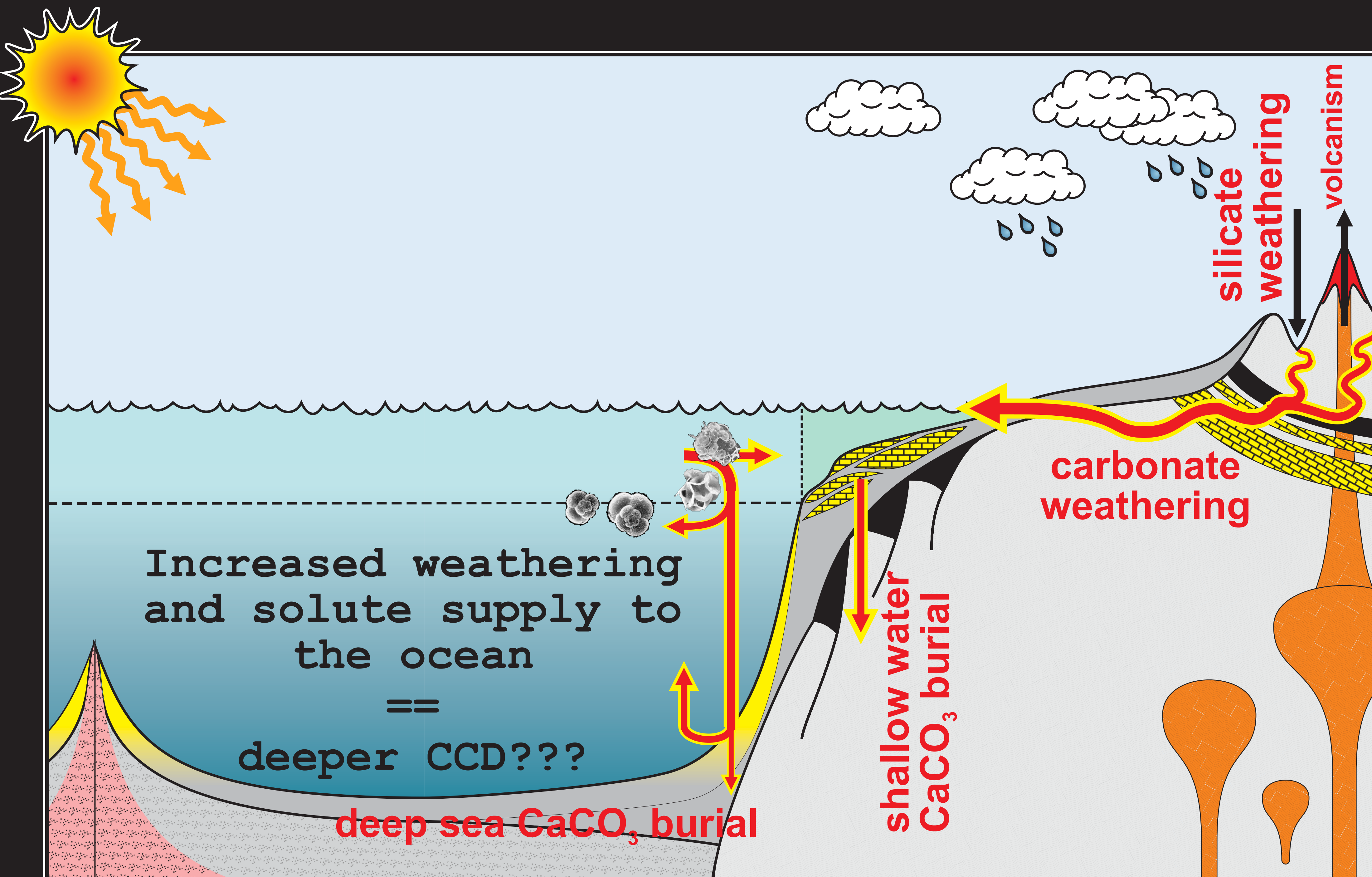


Constraining global carbon cycling with the CCD



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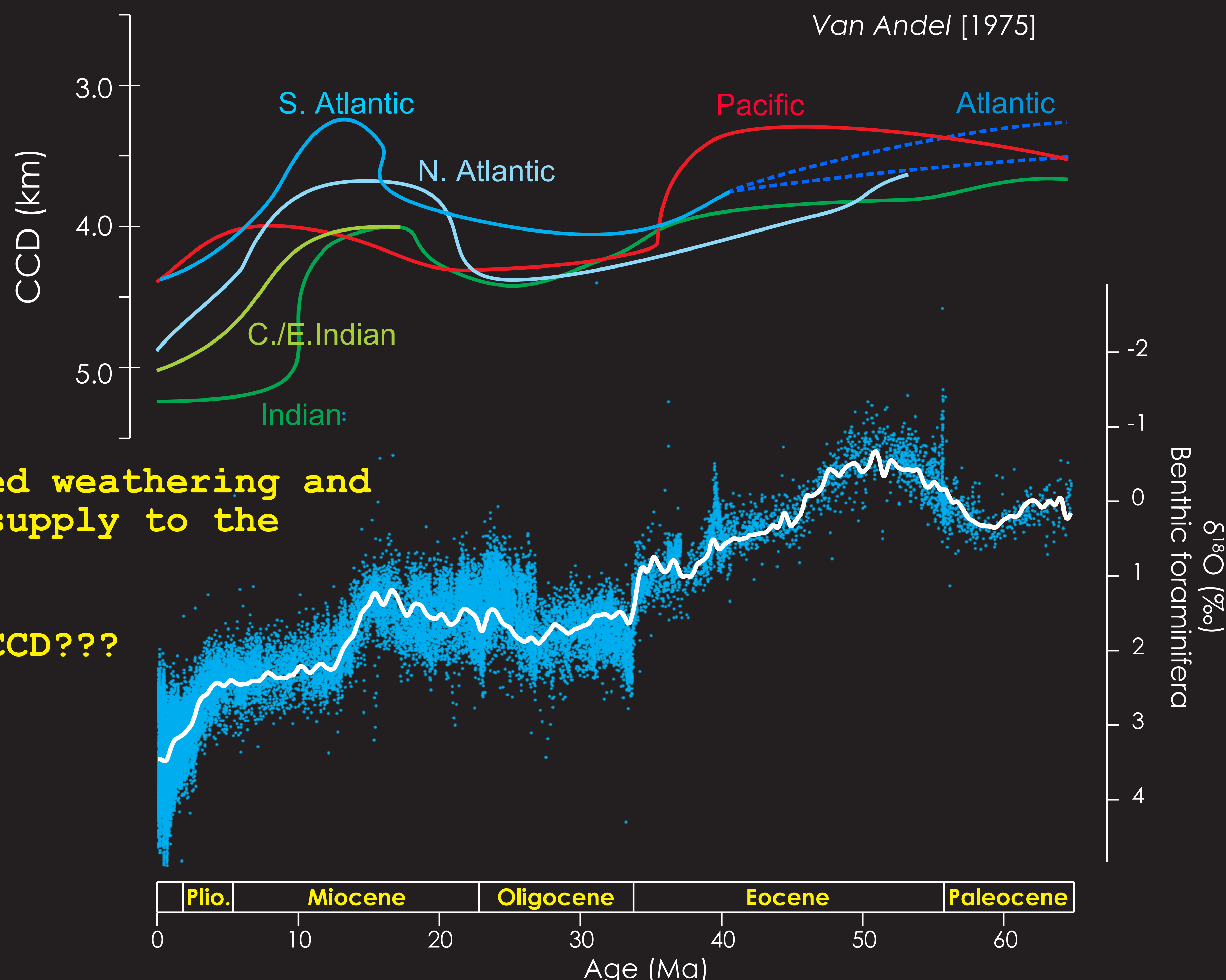
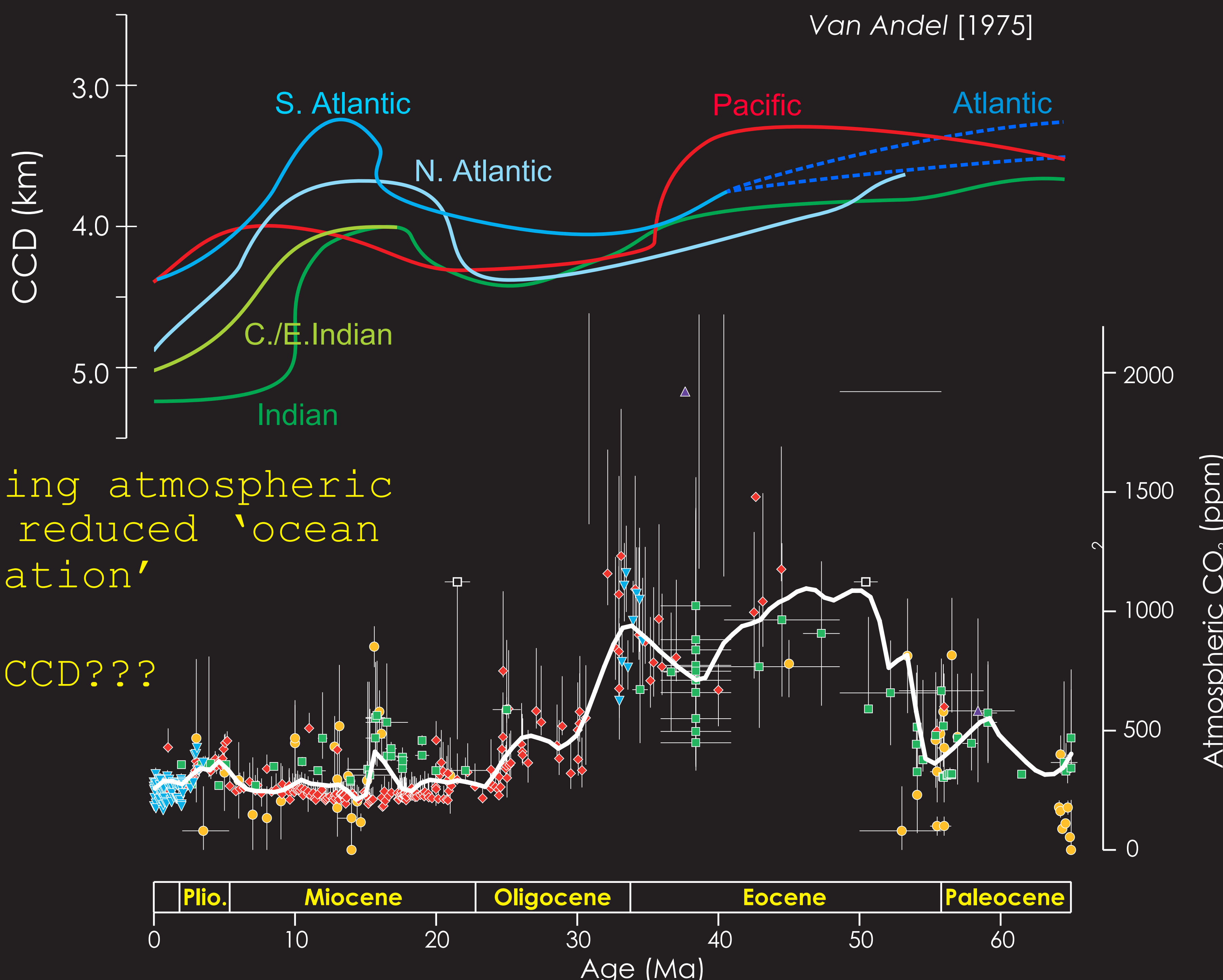


Increased weathering and solute supply to the ocean
==
deeper CCD???

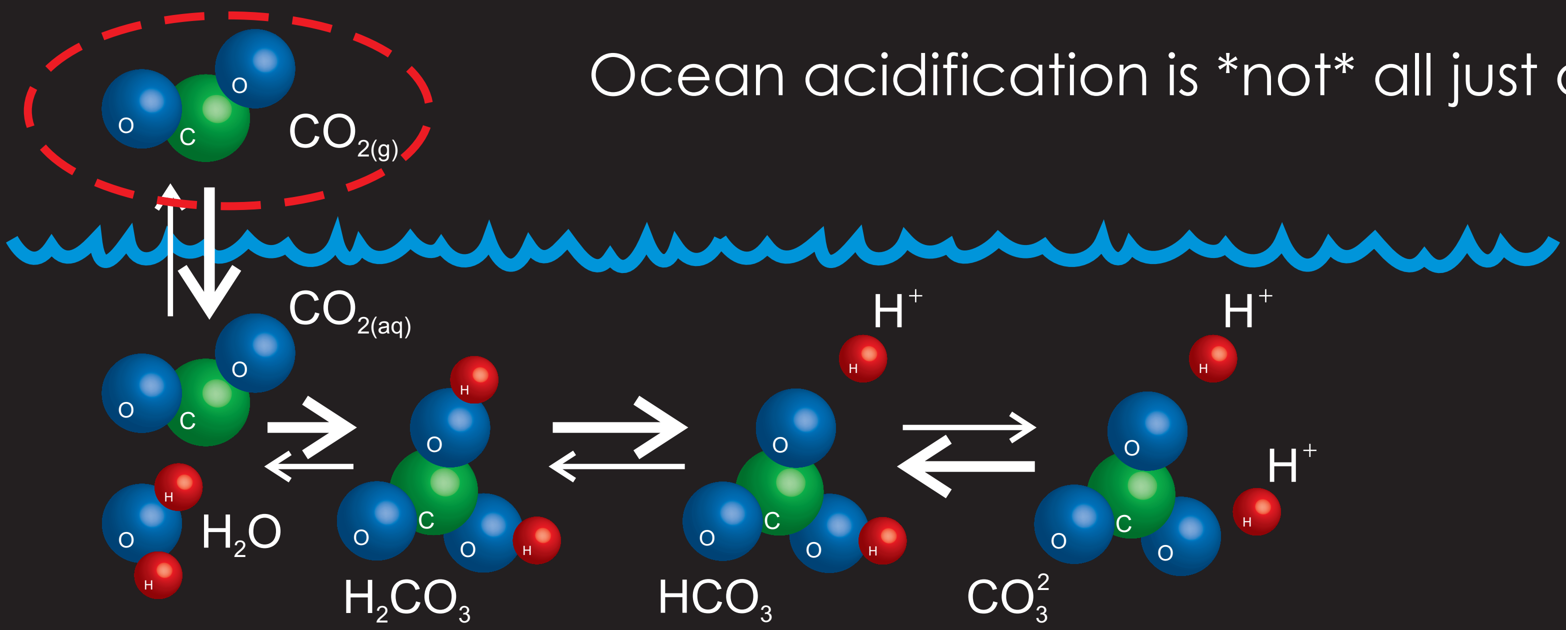
Constraining global carbon cycling with the CCD



Decreasing atmospheric CO_2 and reduced 'ocean acidiciation'
==
deeper CCD???

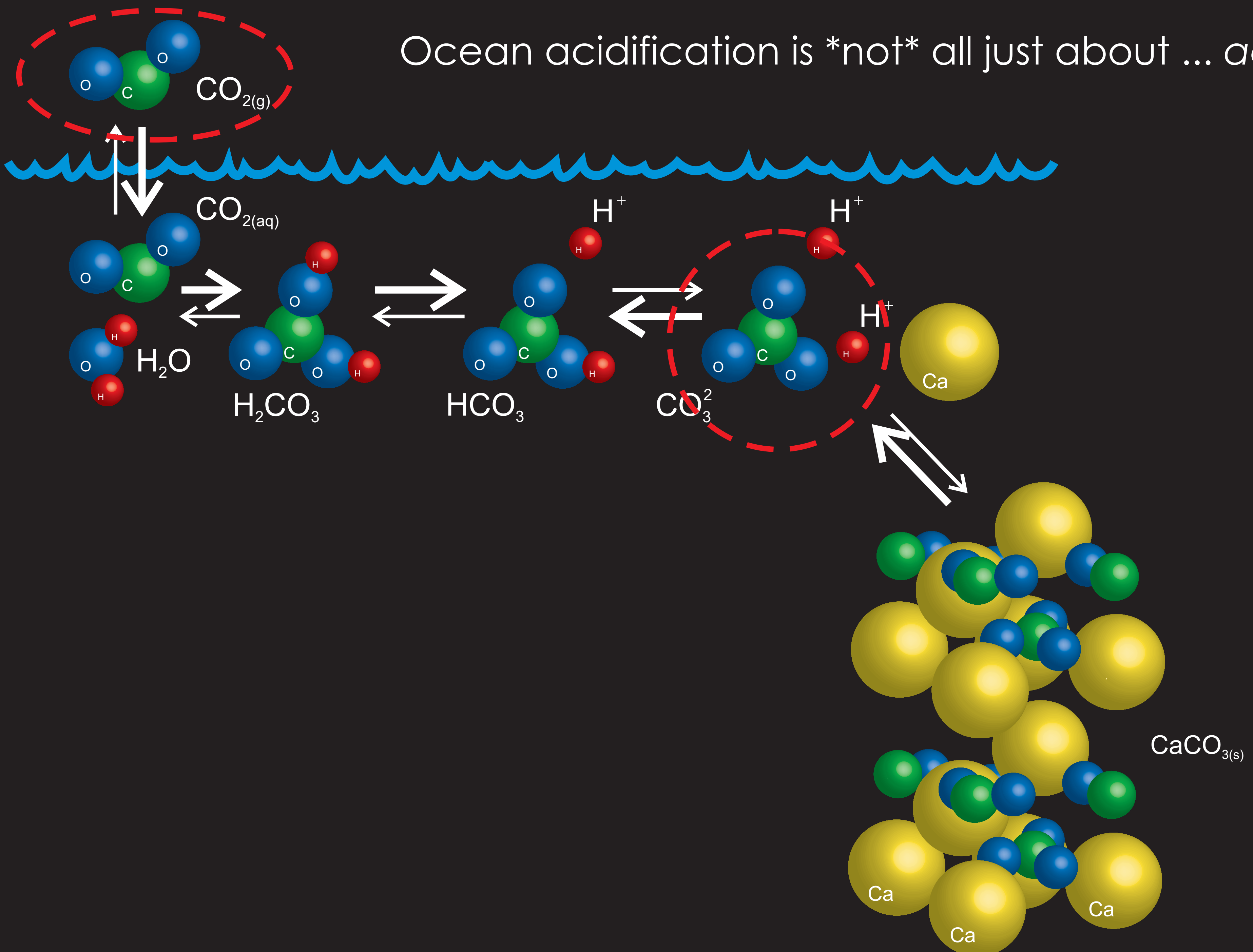
The Carbonate Compensation Depth ('CCD')

Ocean acidification is *not* all just about ...



The Carbonate Compensation Depth ('CCD')

Ocean acidification is *not* all just about ... *acidification*.



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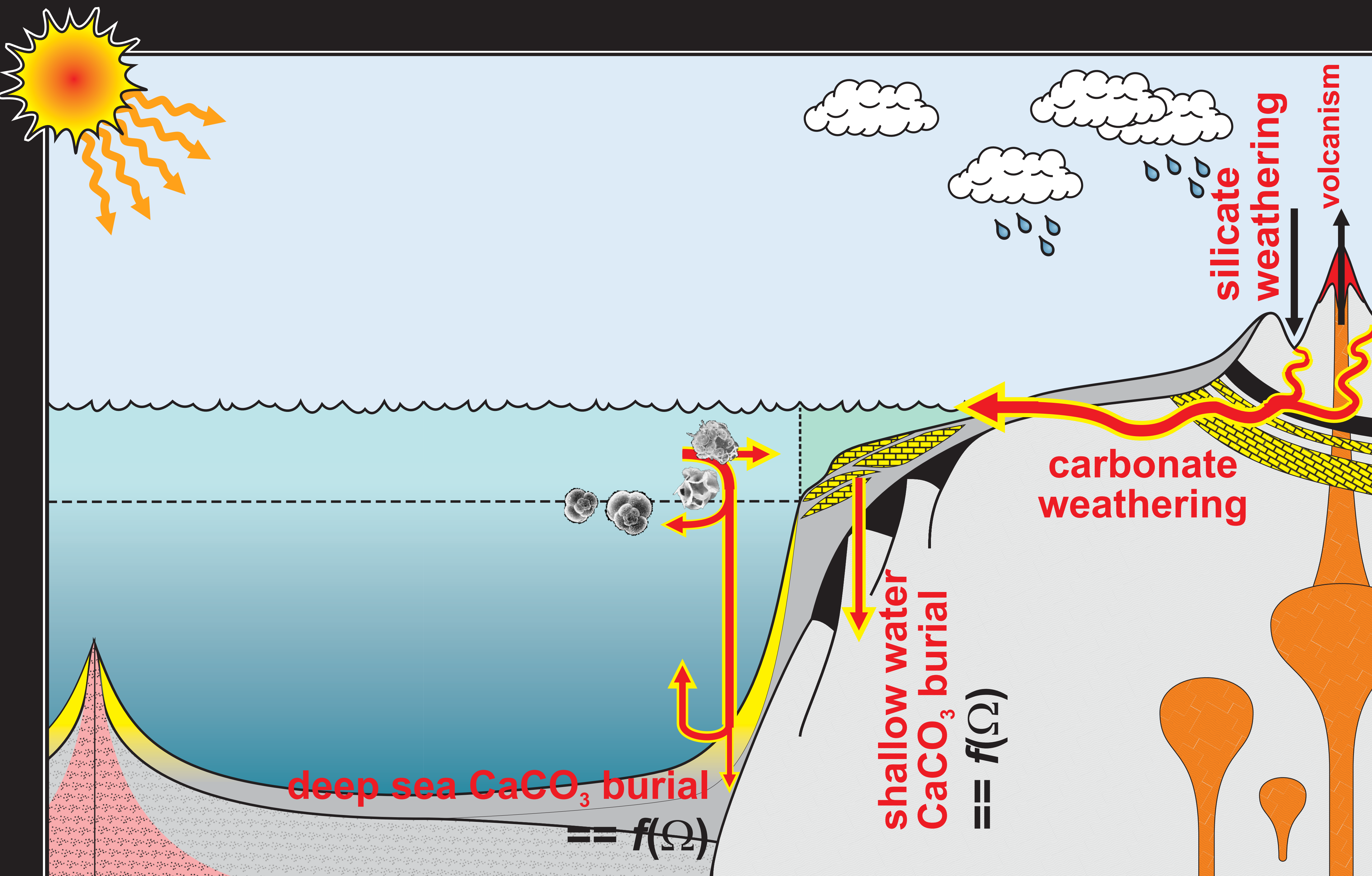
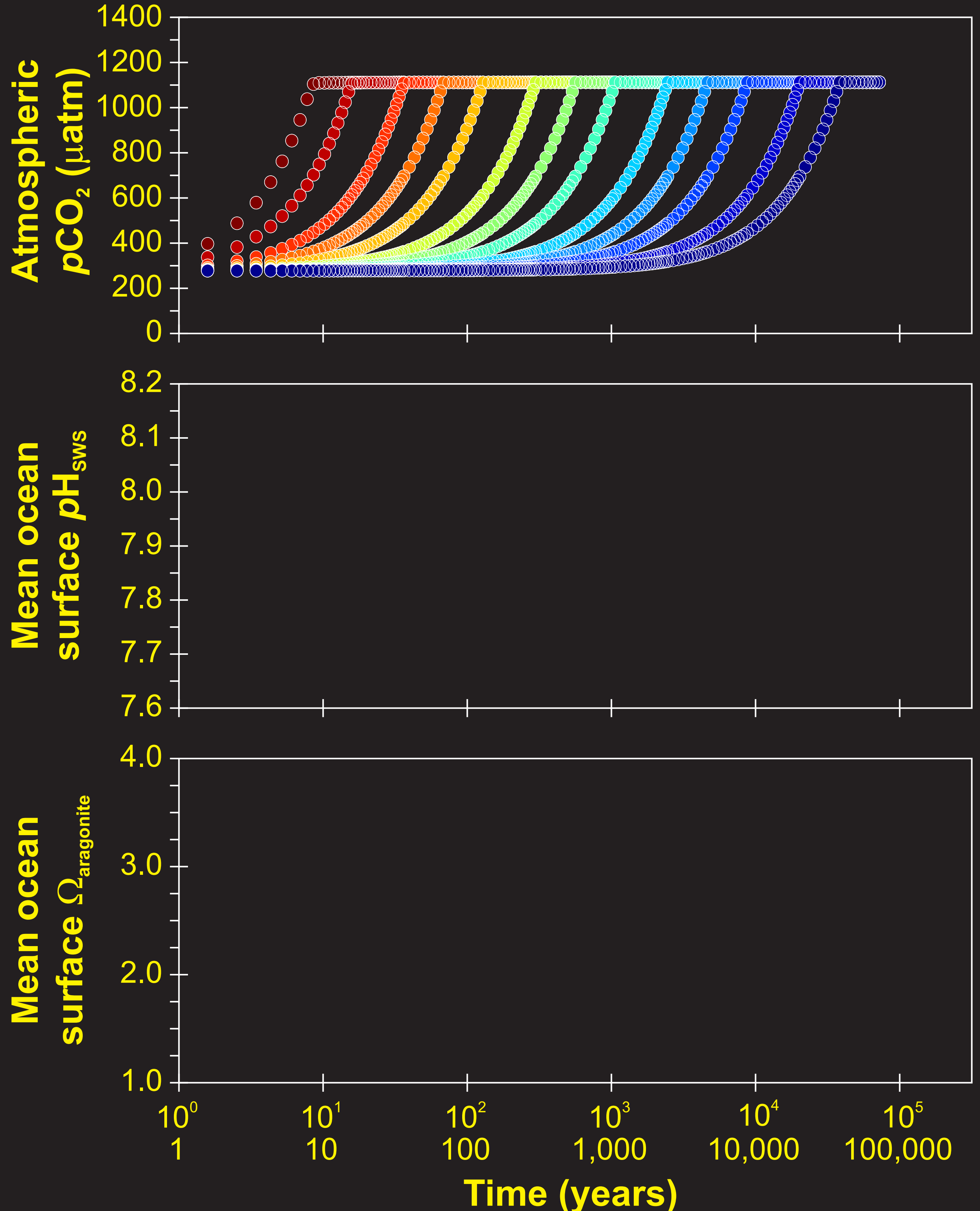




anon model

```
! 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)

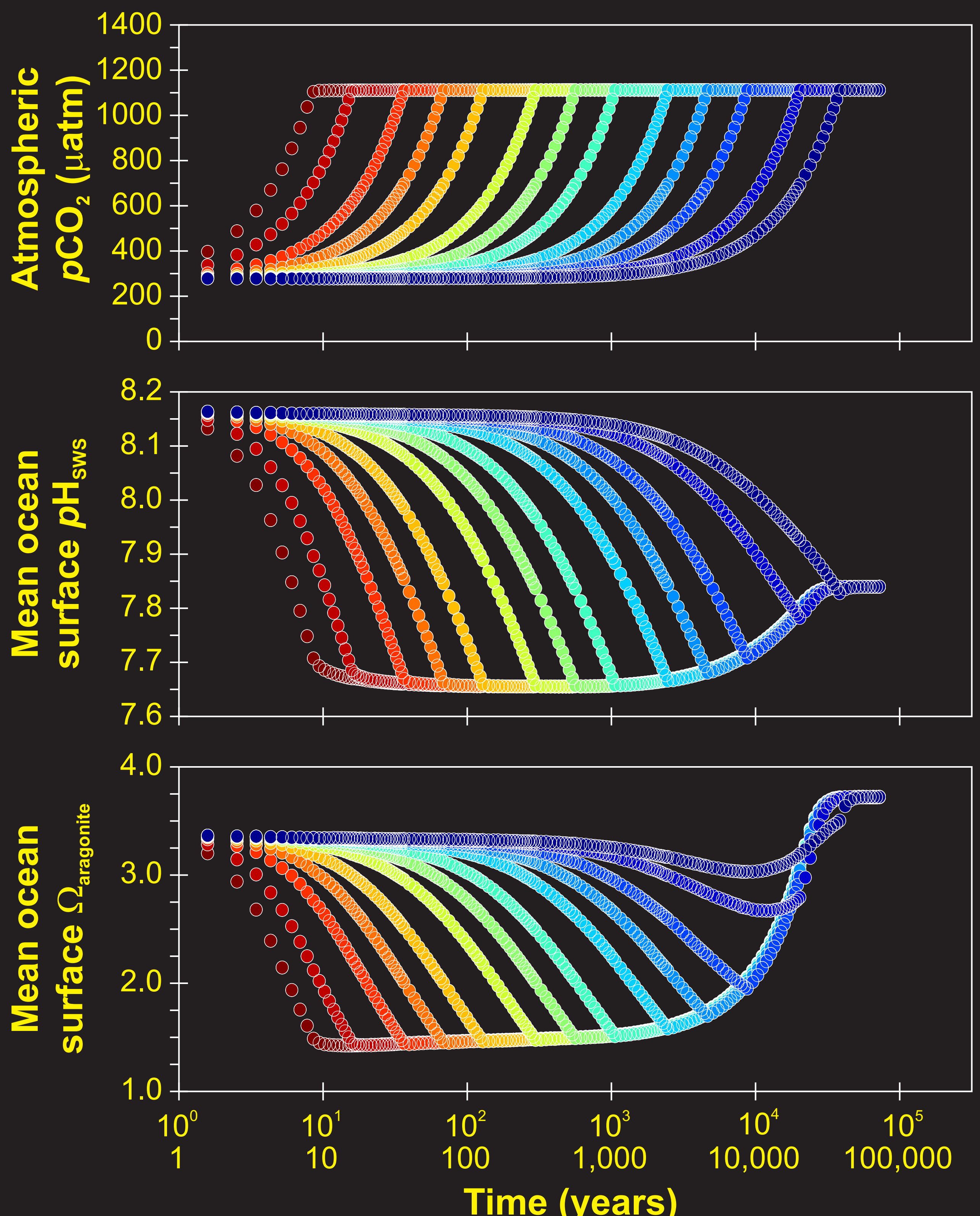
loc_conc_CO3 = &
& ( &
&   loc_ALK_DIC*dum_carbconst(icc_k) -
dum_DIC*dum_carbconst(icc_k) - &
&   4.0*loc_ALK_DIC + loc_zed &
& ) &
& /(2.0*(dum_carbconst(icc_k) - 4.0))

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
```

Hönisch et al. [2012]



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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 &
& ) &
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loc_H1 =
dum_carbconst(icc_k1)*loc_conc_CO2/loc_conc_
HCO3

loc_H2 =
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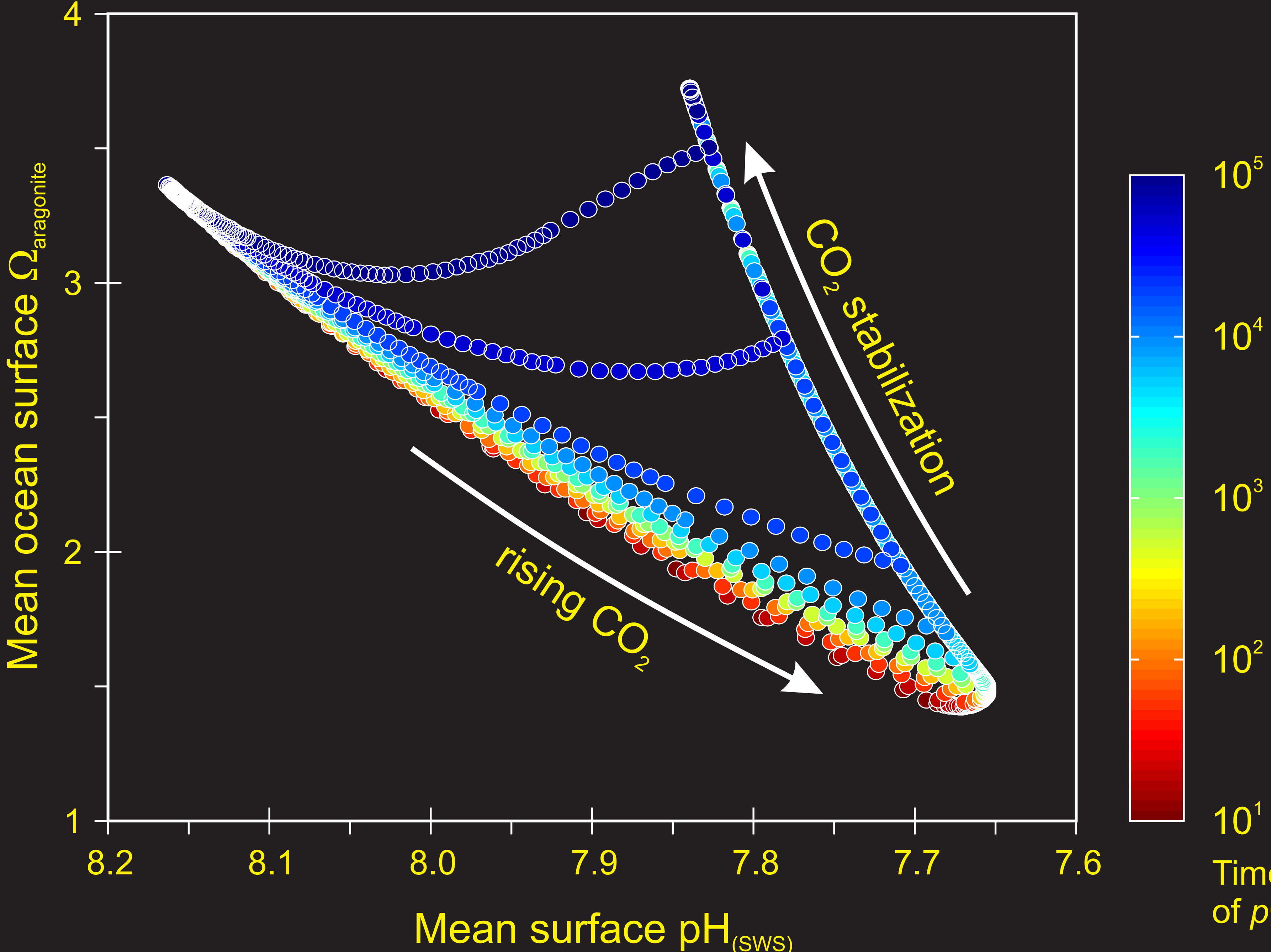
_CO3
```

Hönisch et al. [2012]

Constraining global carbon cycling with the CCD



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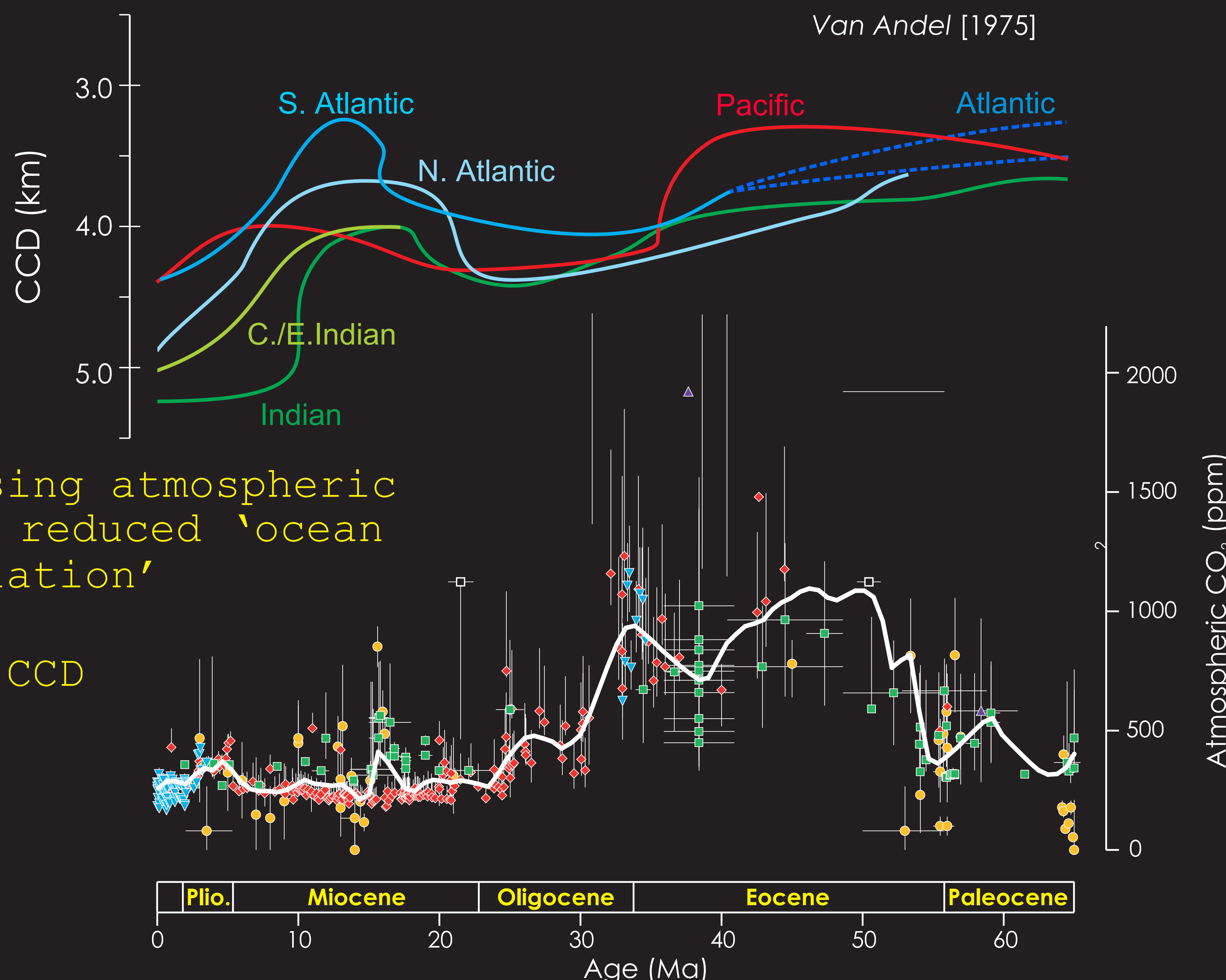

Decreasing atmospheric CO_2 and reduced 'ocean acidiciation'
/=
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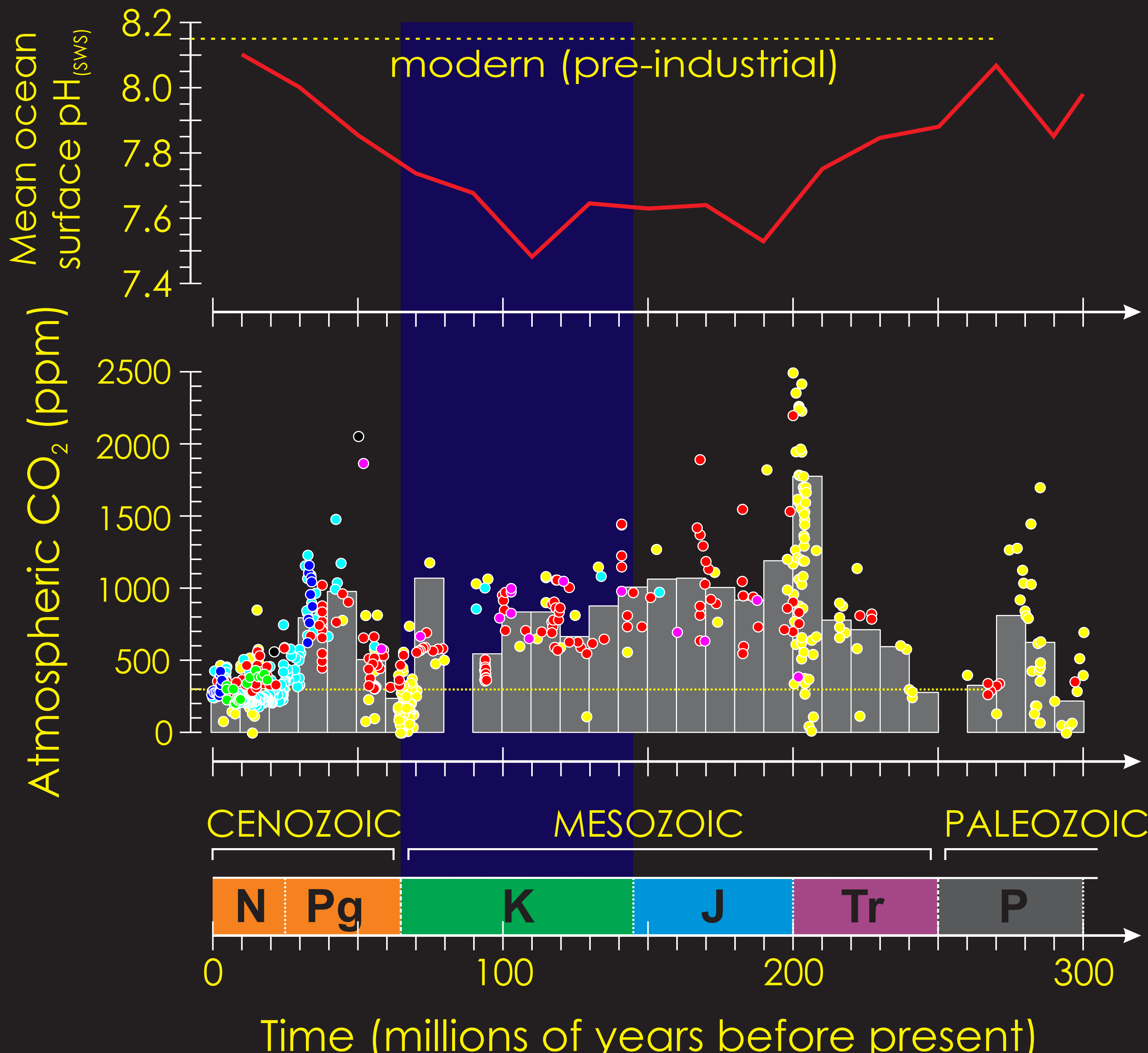

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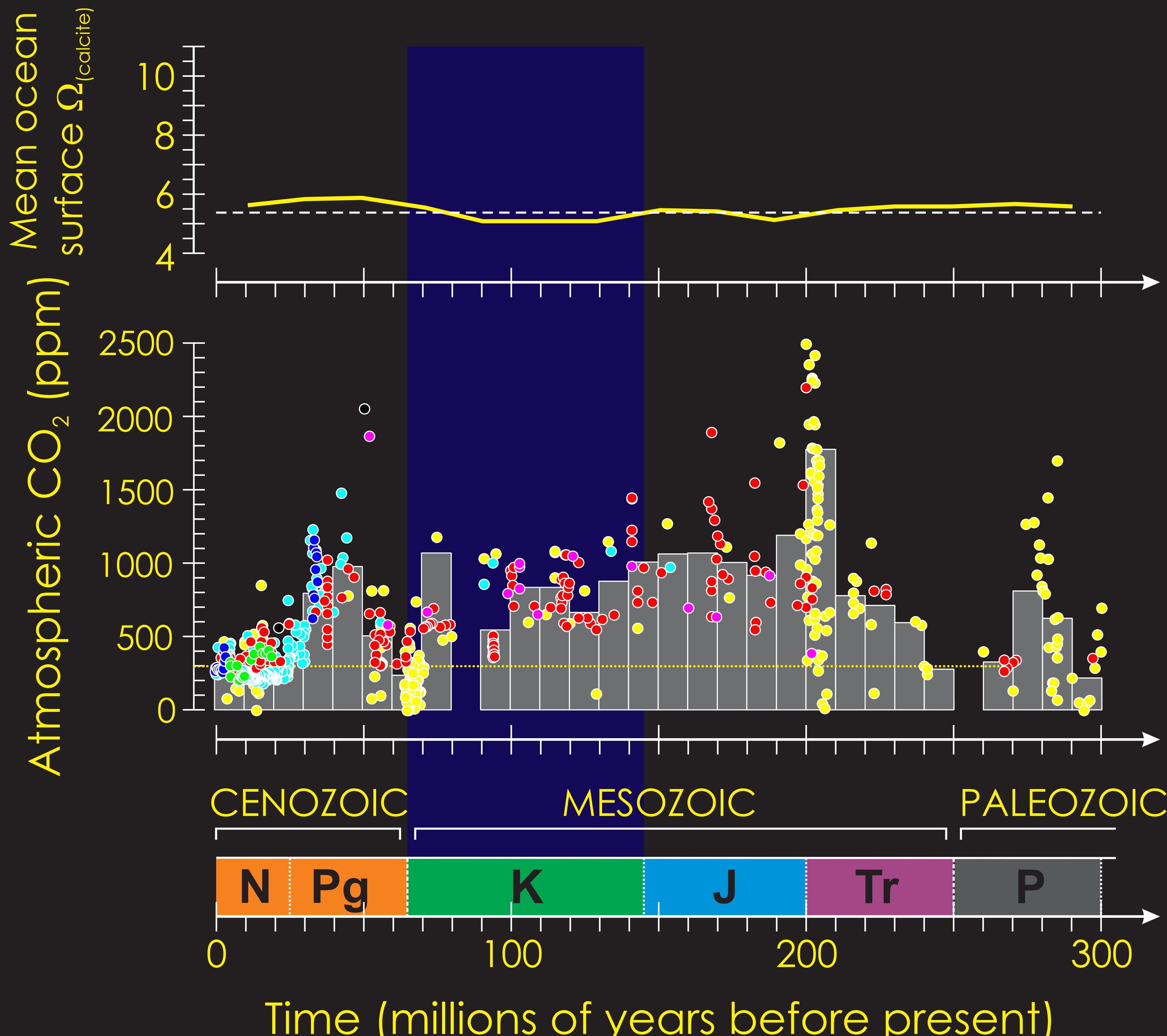

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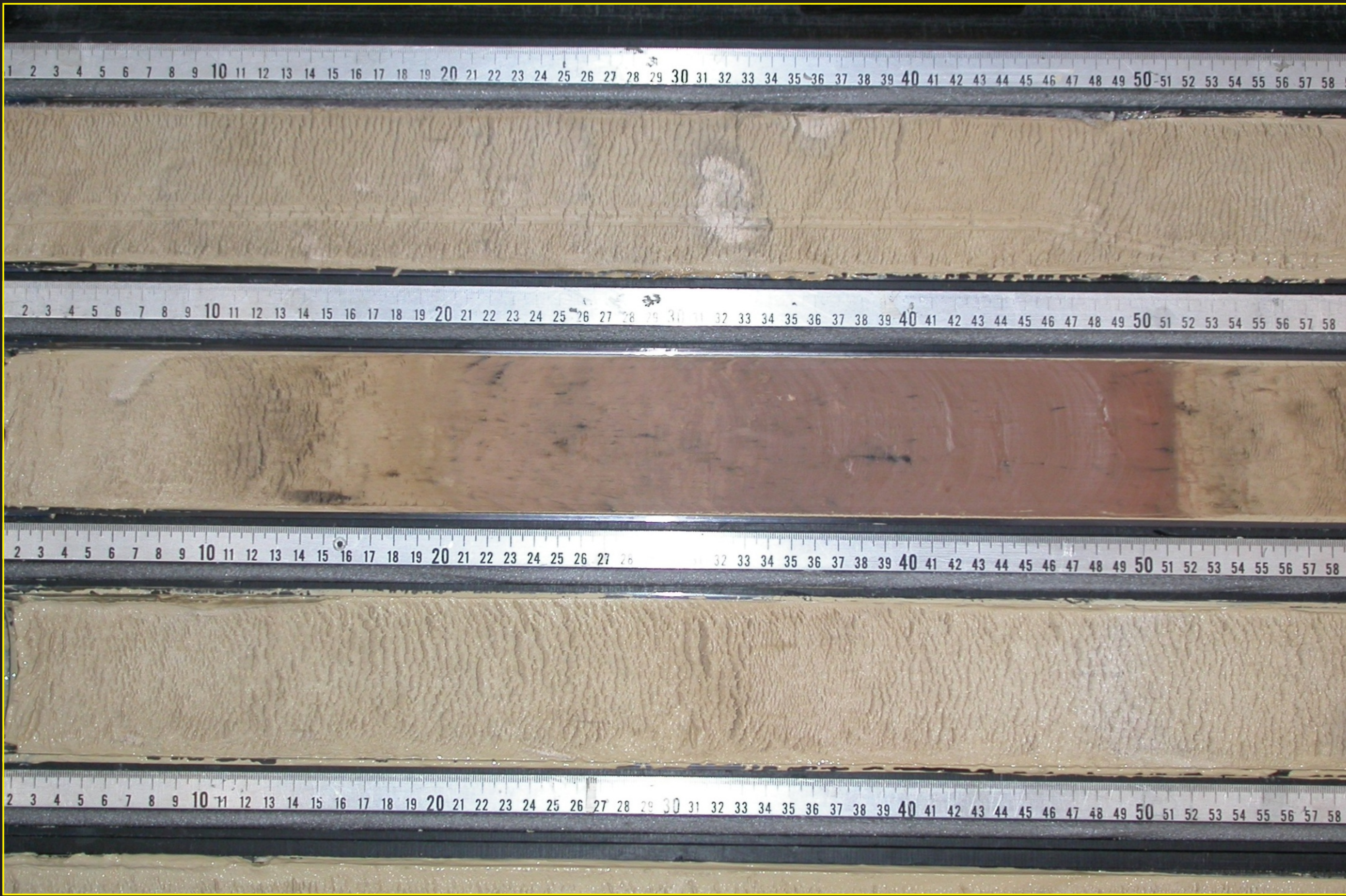
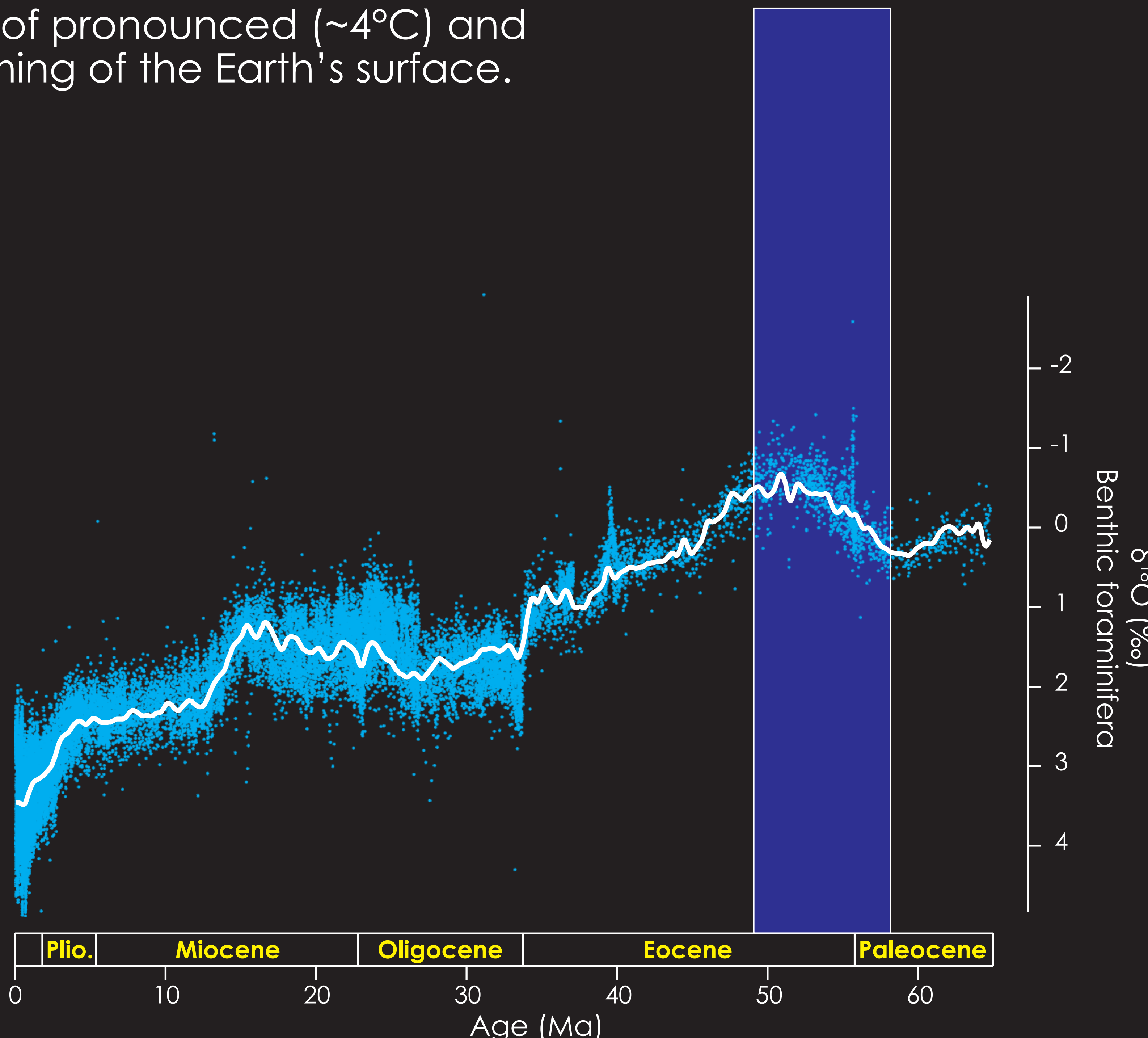


Sediments spanning the Palaeocene-Eocene boundary recovered from ODP Leg 208 (Walvis Ridge)
Picture courtesy of Dani Schmidt (University of Bristol)

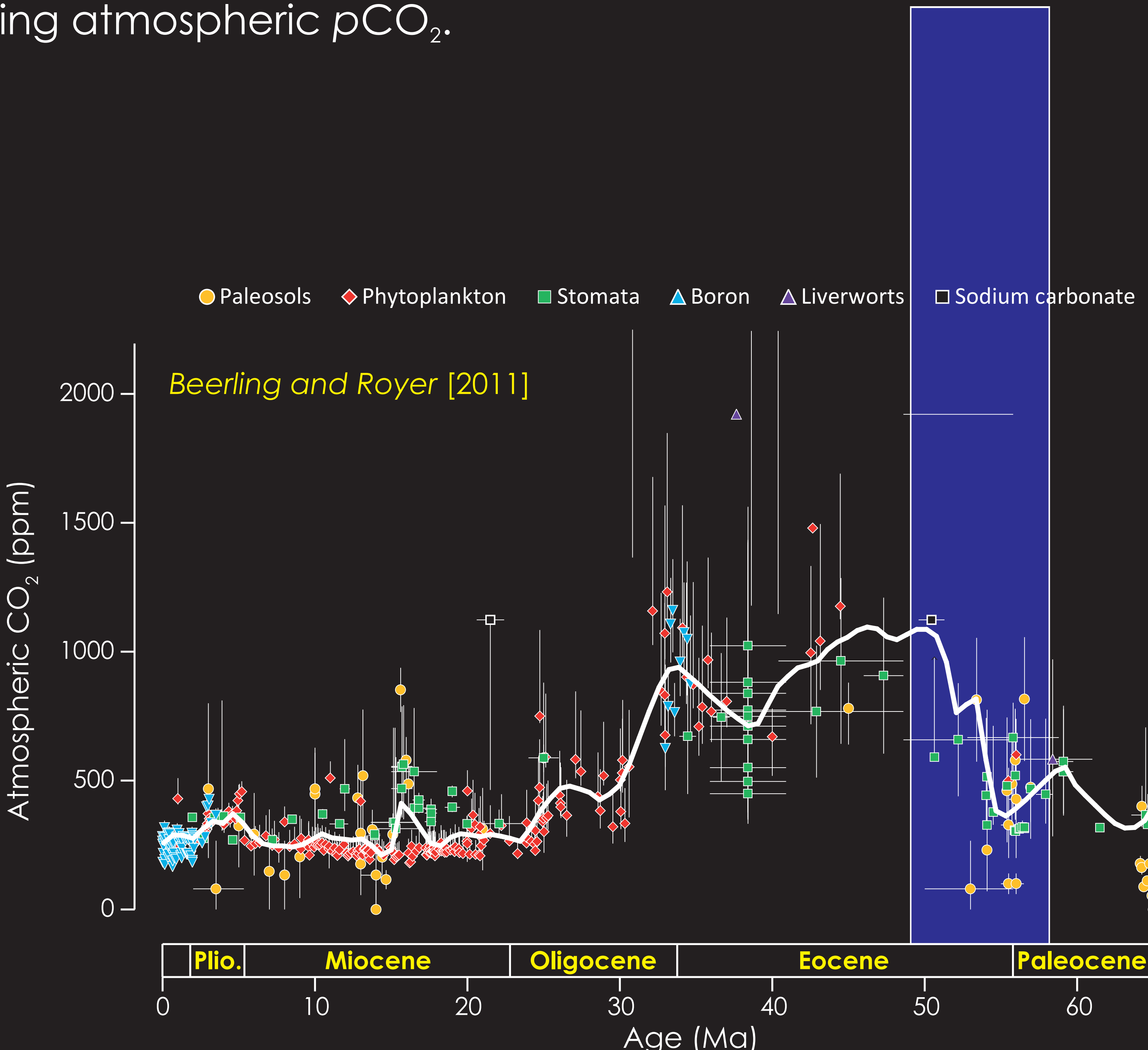
Late-Paleocene Early-Eocene ('LPEE')

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



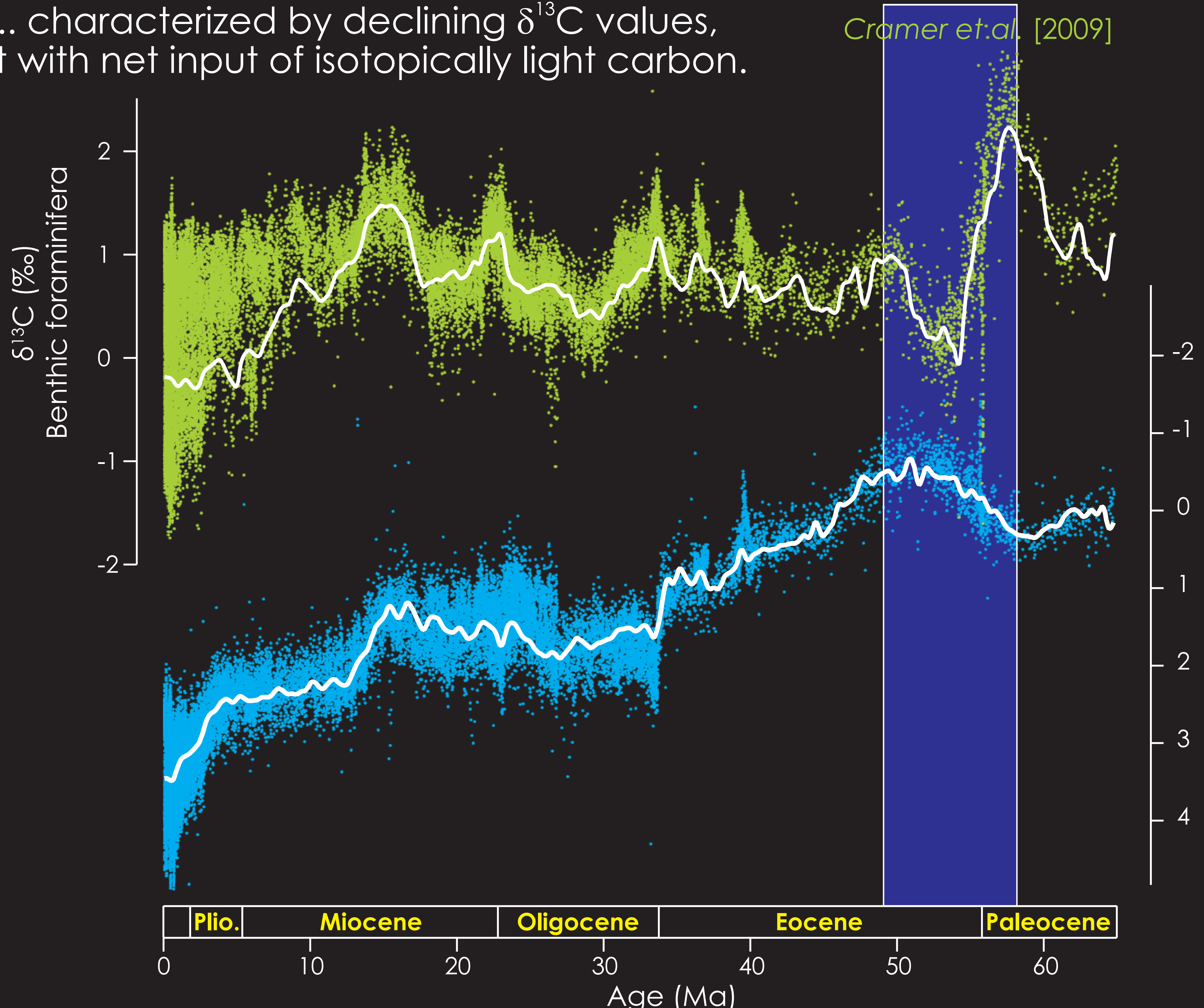
Late-Paleocene Early-Eocene

✓ Increasing atmospheric pCO_2.



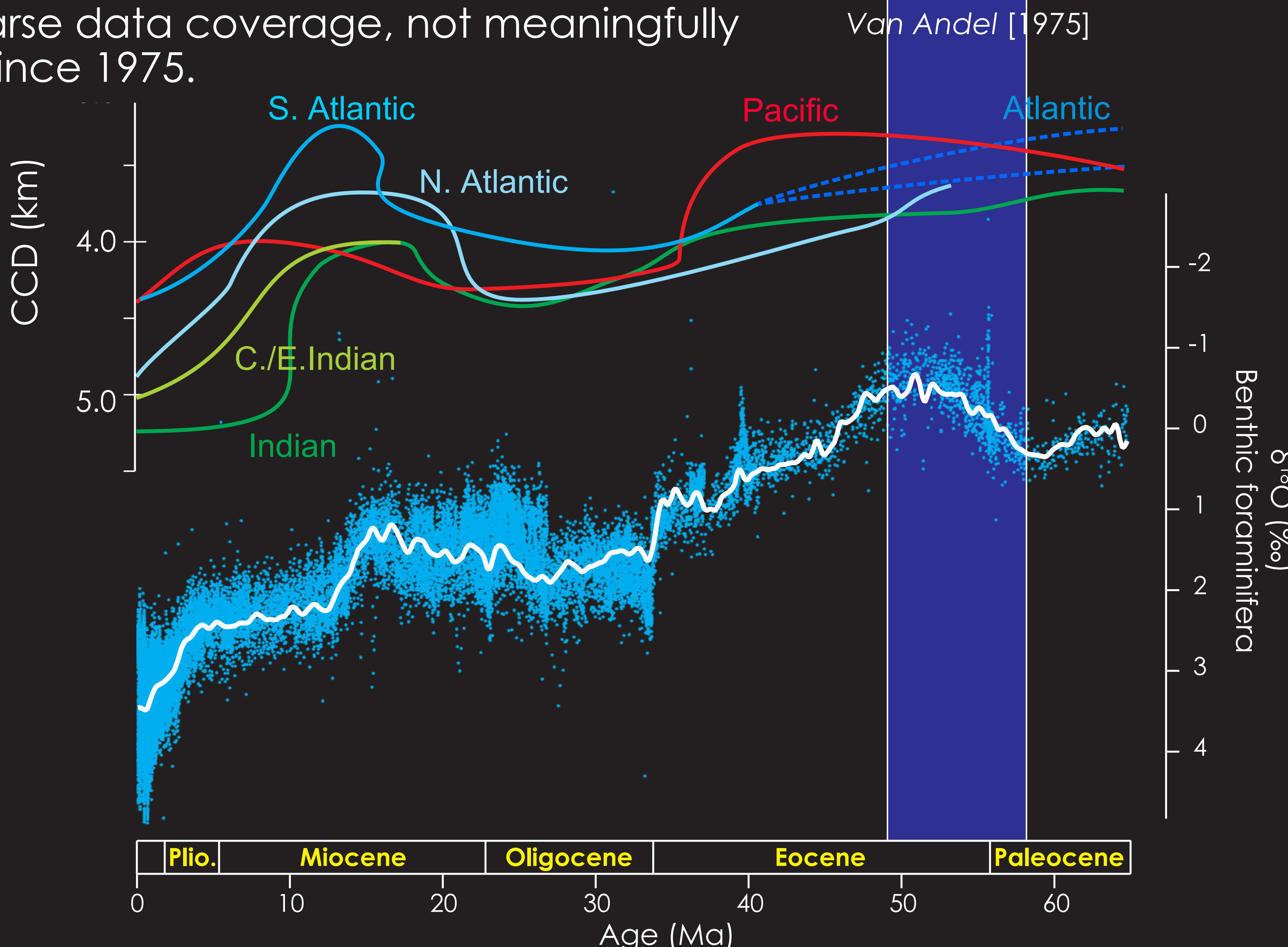
Late-Paleocene Early-Eocene

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

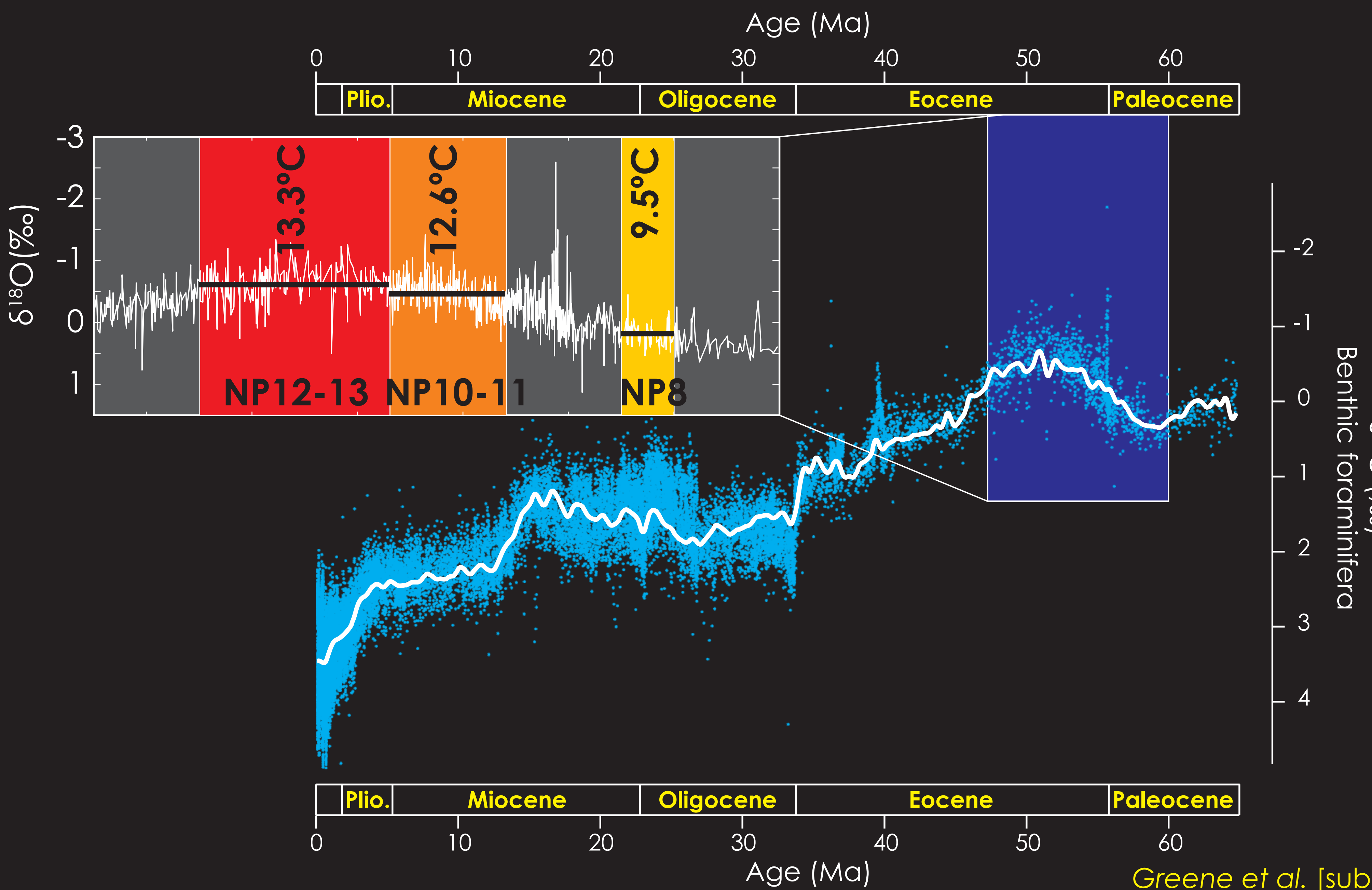


Late-Paleocene Early-Eocene

- 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.



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

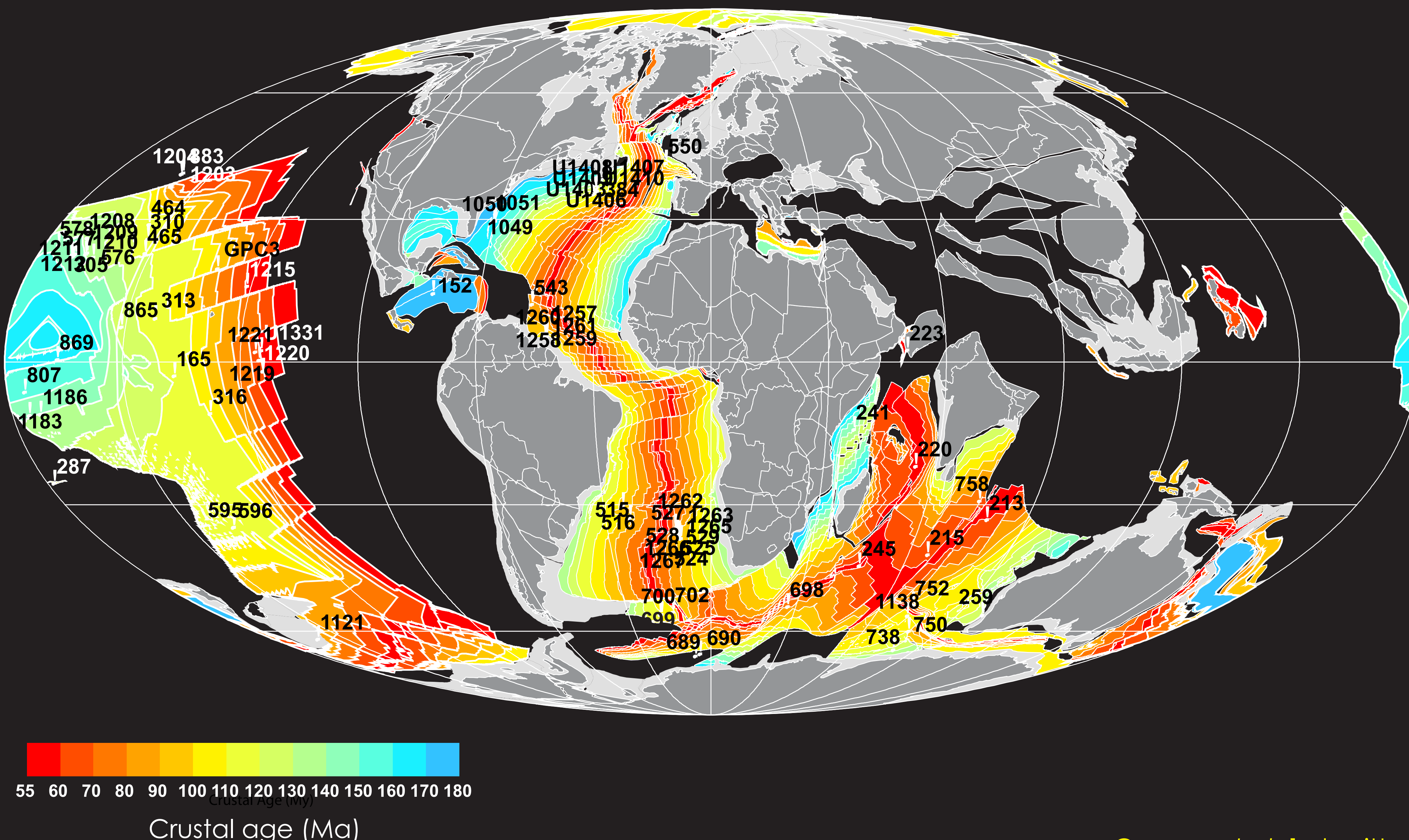


Greene *et al.* [submitted]

Late-Paleocene Early-Eocene

Co-evolution of Life
and the Planet

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



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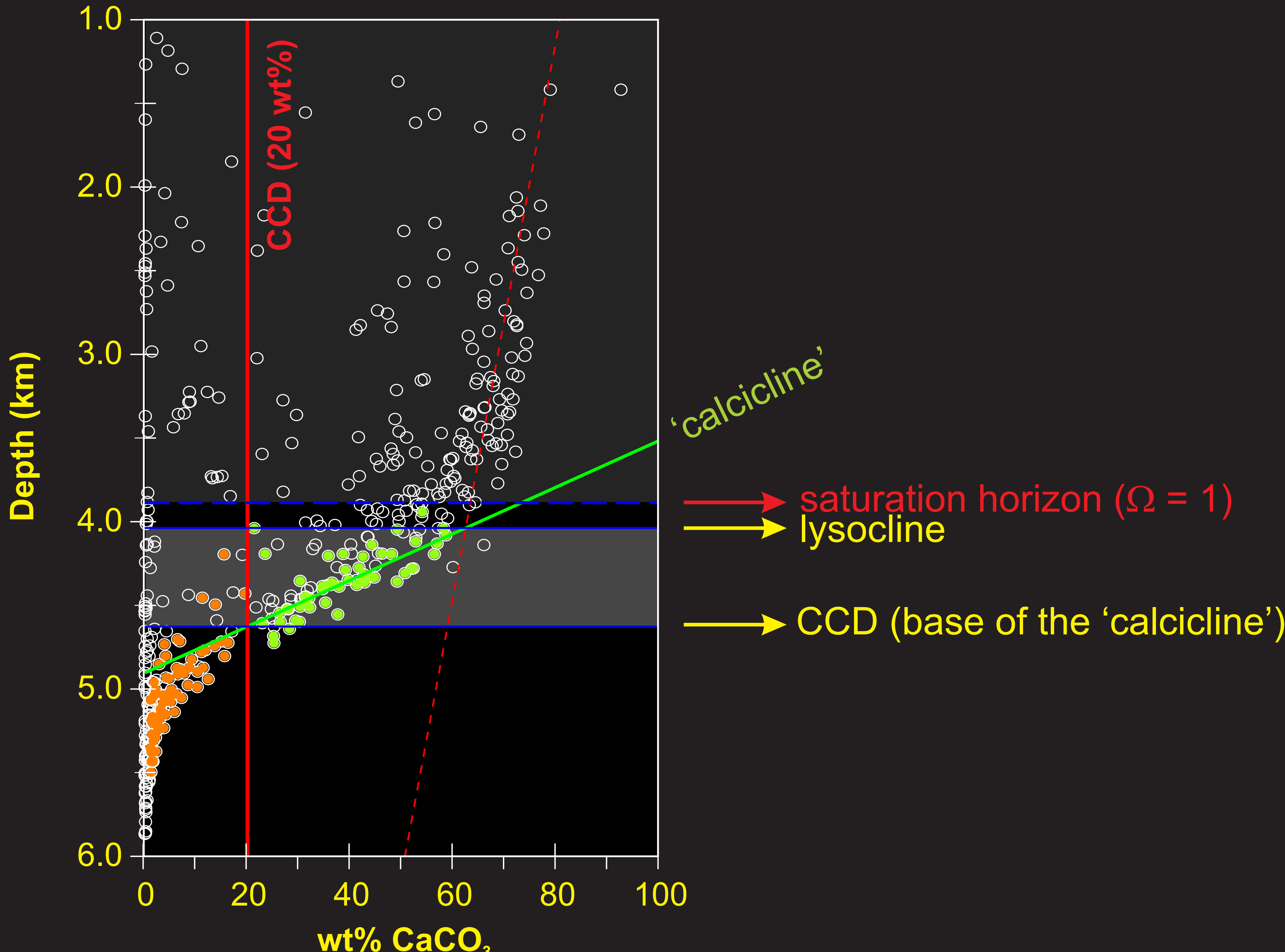

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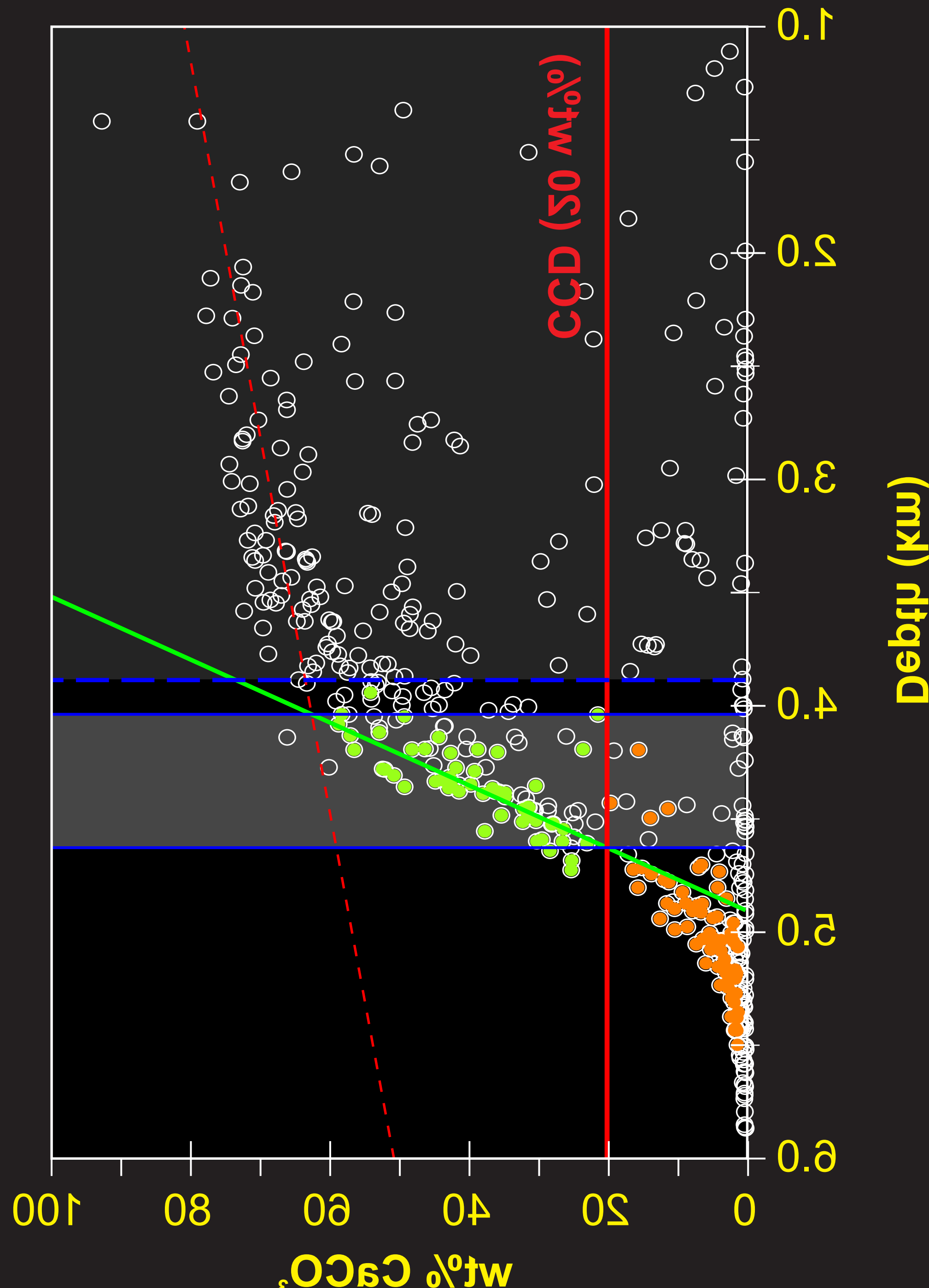
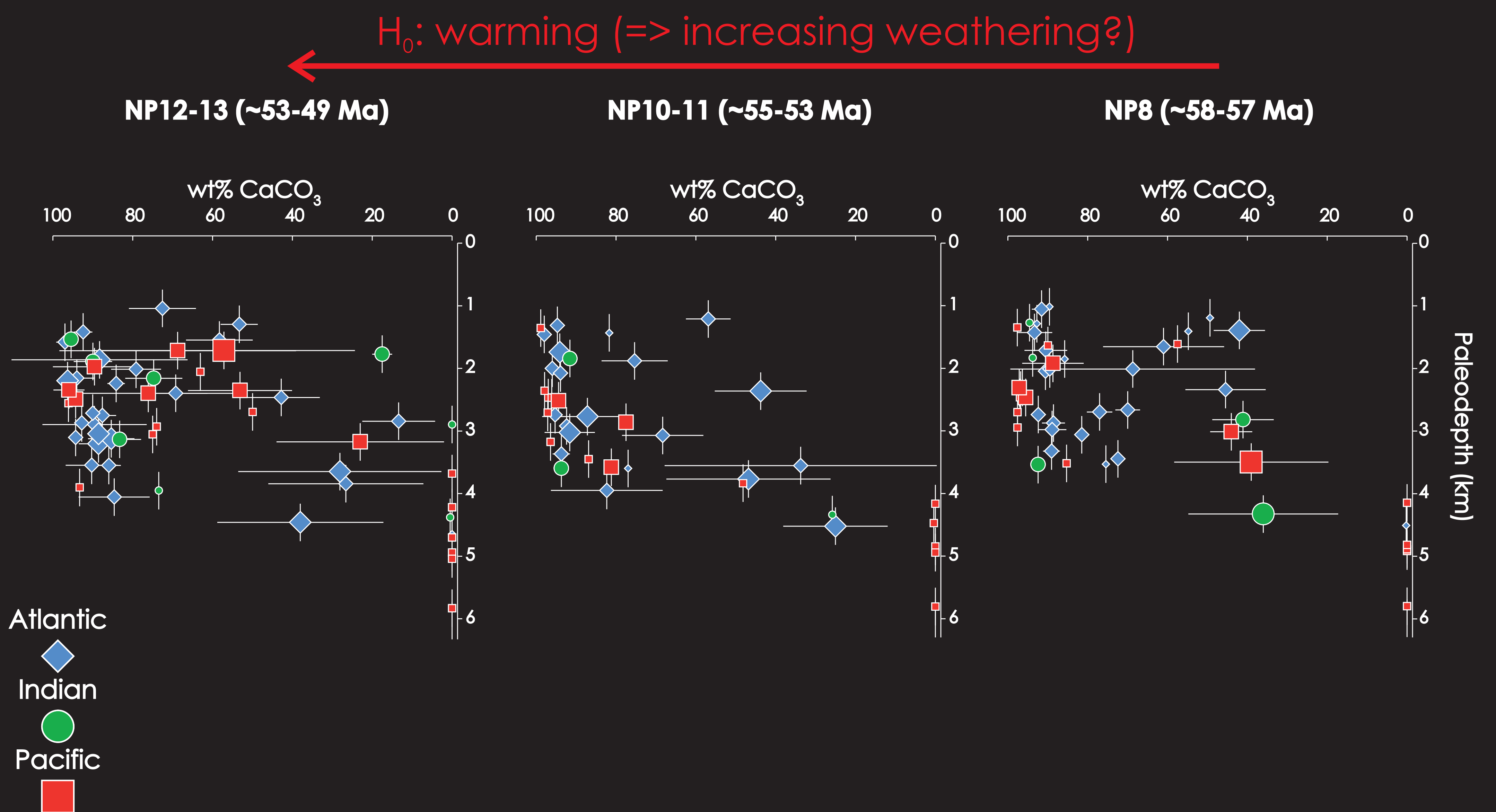


'CCD' plots.



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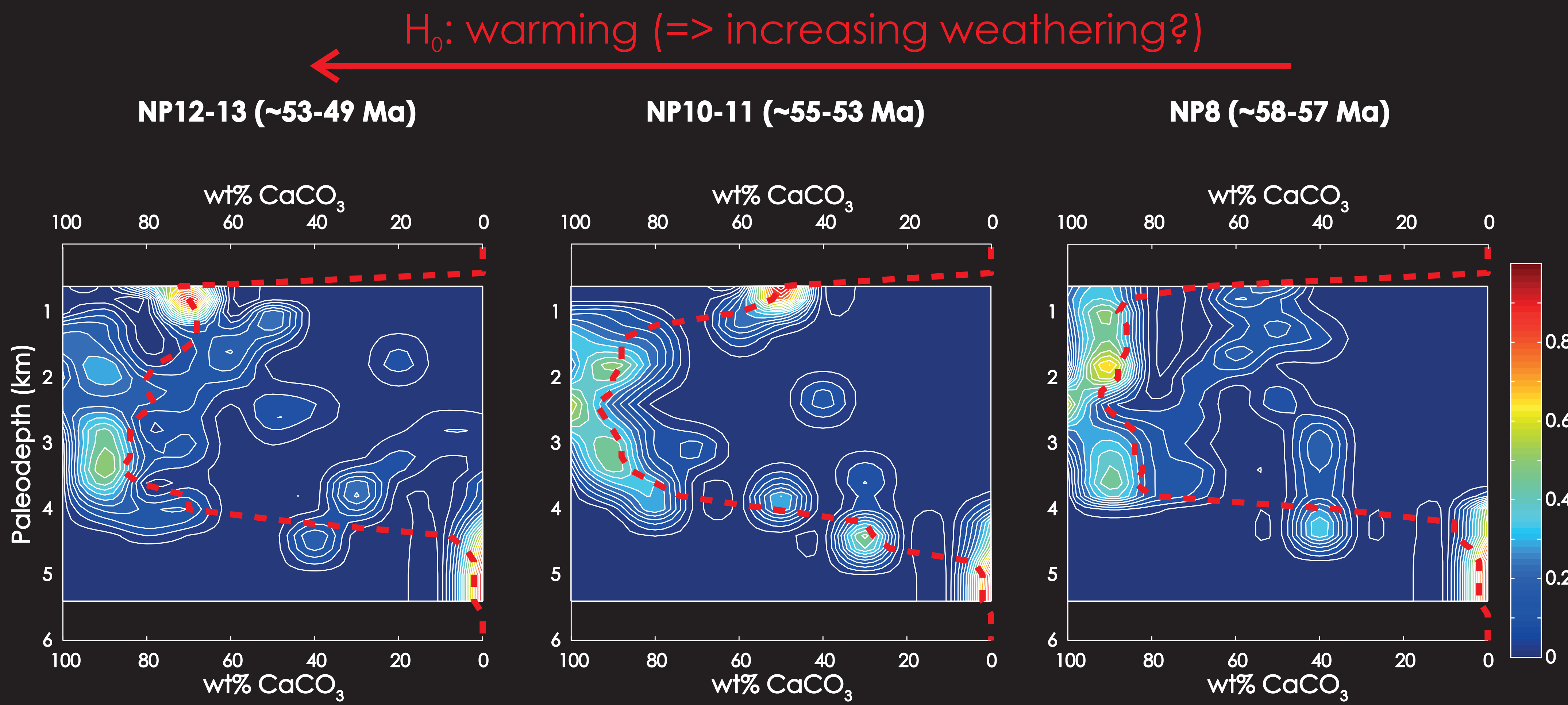

Contours are of relative data density
within a sliding time-window (and wt% bin).
Red contour delineates 50% of the data.

Greene et al. [submitted]

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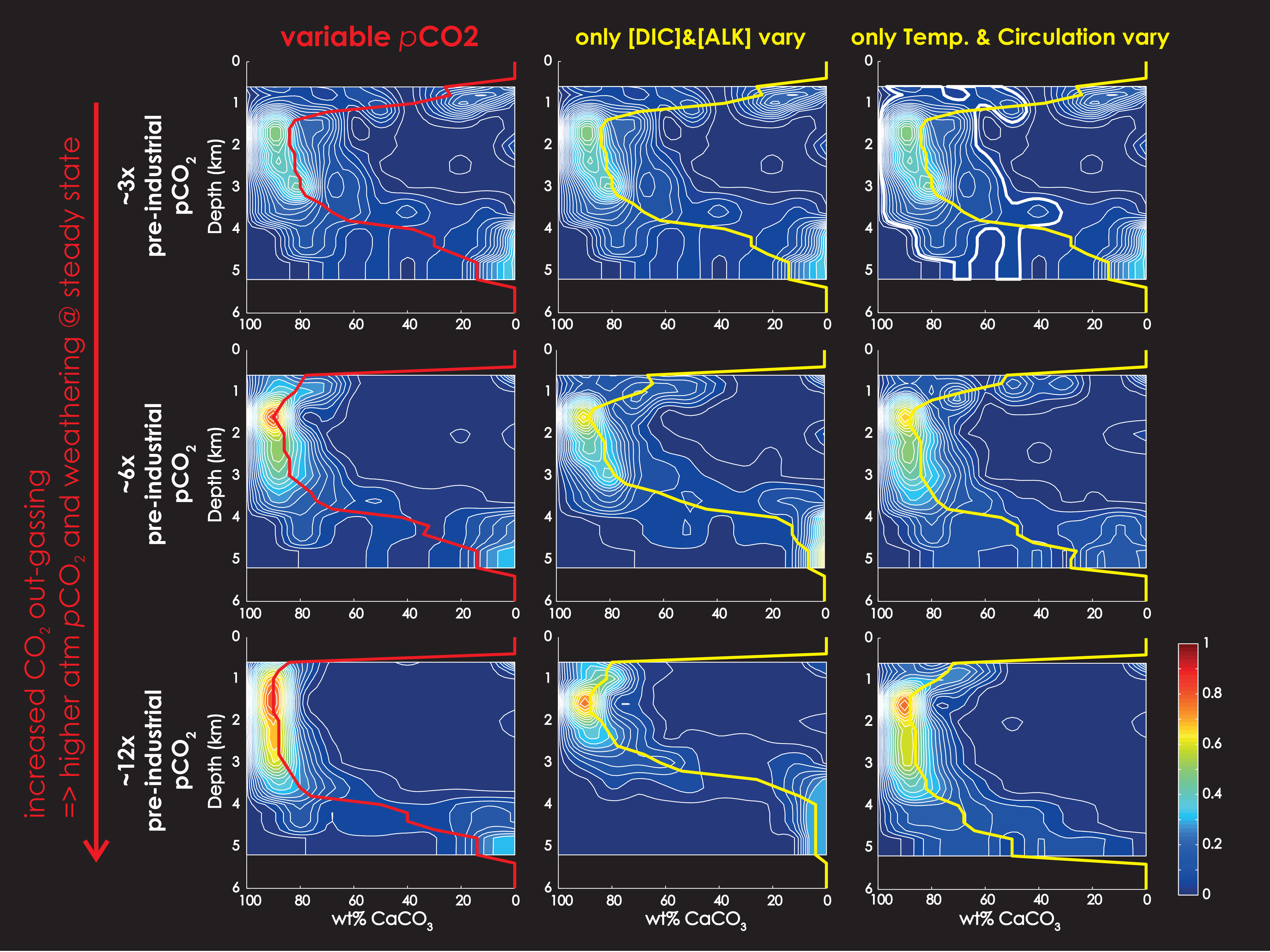
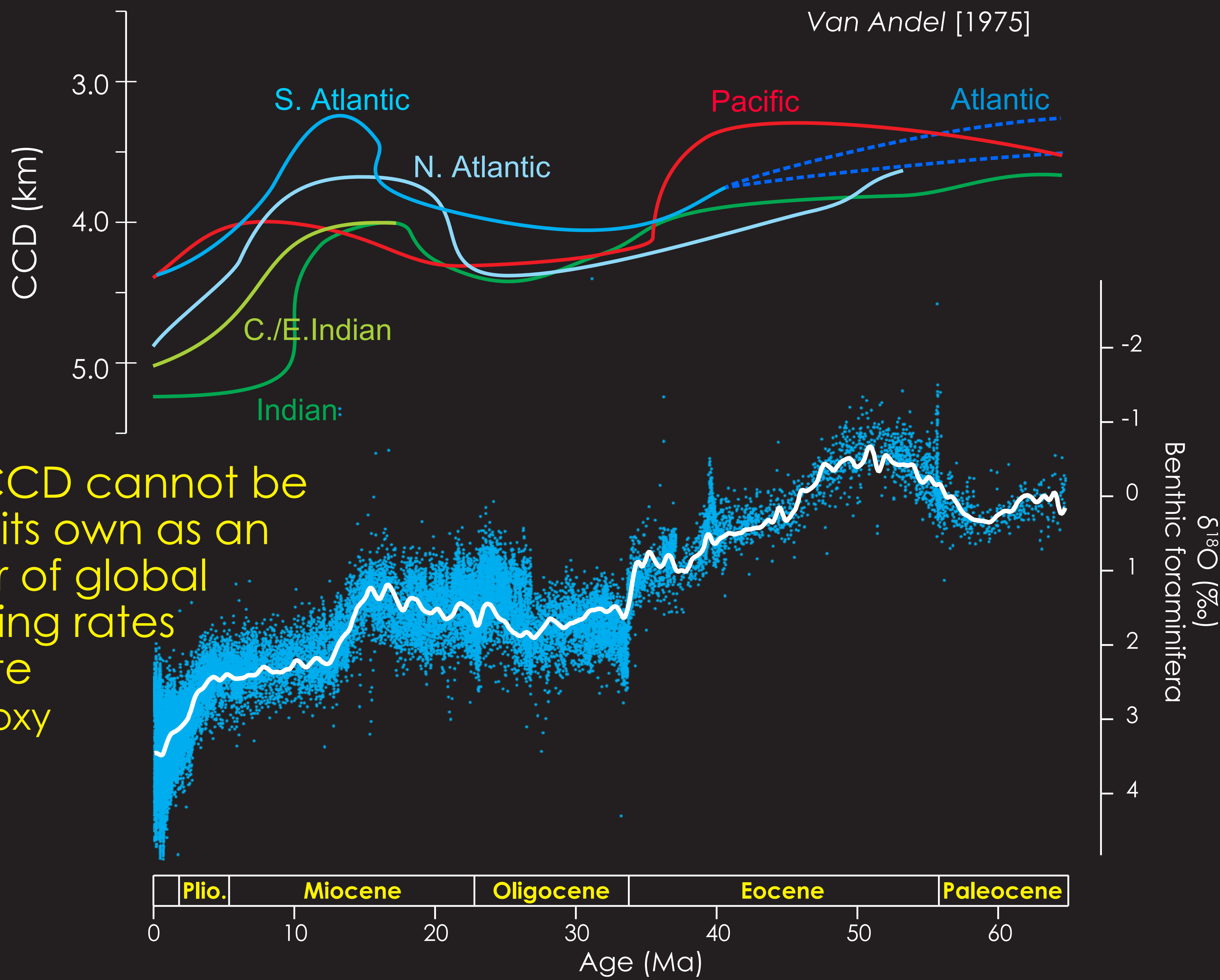


variable pCO2
only [DIC]&[ALK] vary
only Temp. & Circulation vary
increased CO_2 out-gassing
=> higher atm pCO_2 and weathering @ steady state
~3x pre-industrial pCO_2
~6x pre-industrial pCO_2
~12x pre-industrial pCO_2
Depth (km)
wt% $CaCO_3$

Constraining global carbon cycling with the CCD

Co-evolution of Life and the Planet



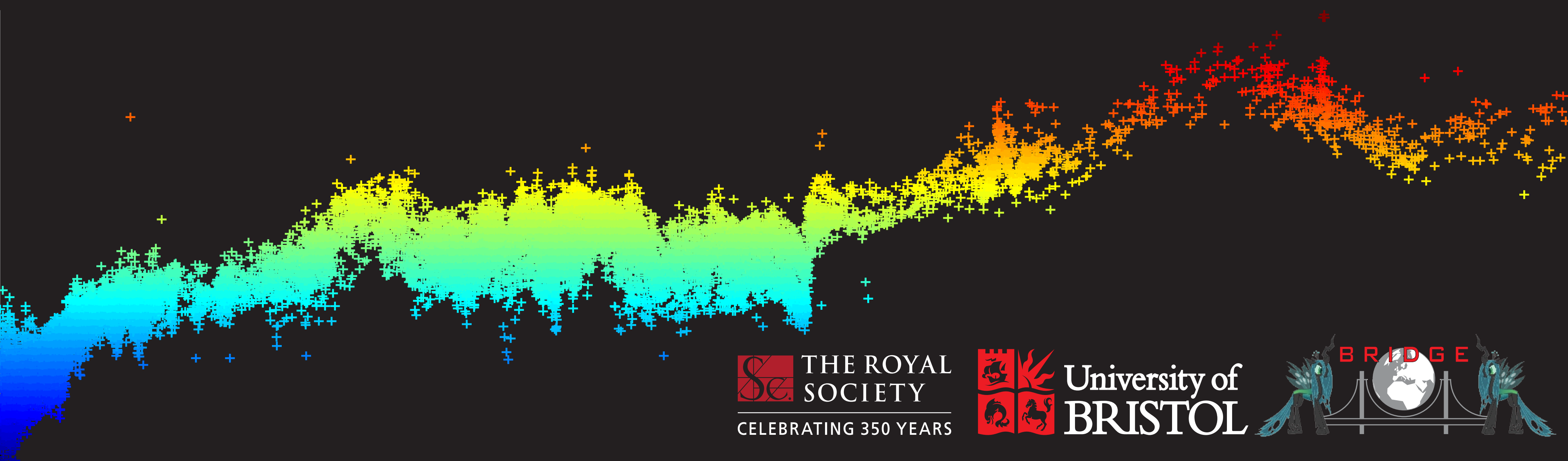
=> The CCD cannot be used on its own as an indicator of global weathering rates or climate

#deadproxy

Thanks to:

Sarah Greene, Sandy Kirtland Turner, Daniela Schmidt [Bristol]
Ellen Thomas [Yale]
Heiko Pälike [Bremen]

The Royal Society
Natural Environmental Research Council (NE/H023852/1 – 'Evolution of Carbon Cycle Dynamics')



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