Assimilating the paleoclimate record: 'How much carbon?' (release at the PETM)

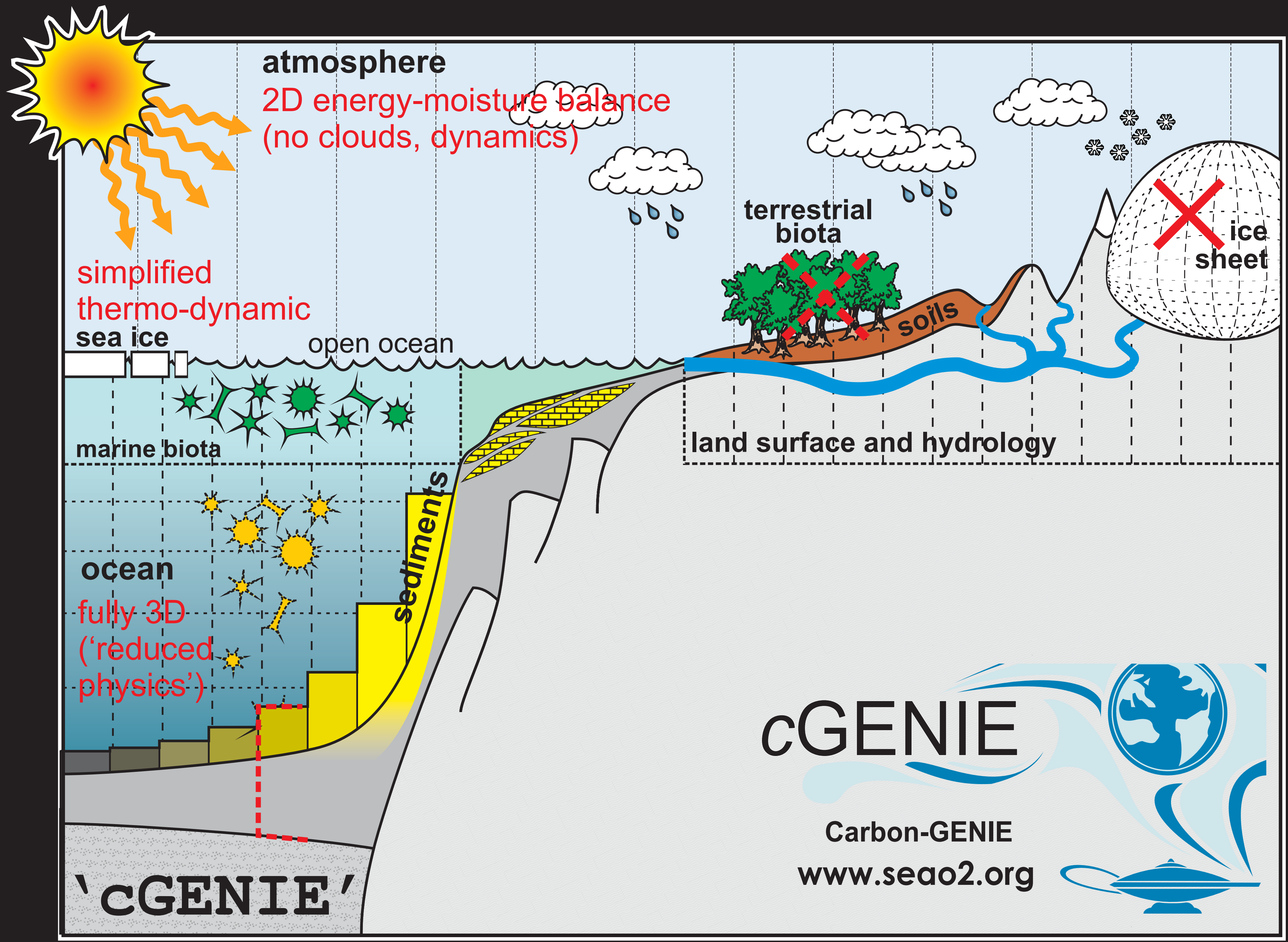
Andy Ridgwell
University of California, Riverside / University of Bristol

European Research Council
Established by the European Commission

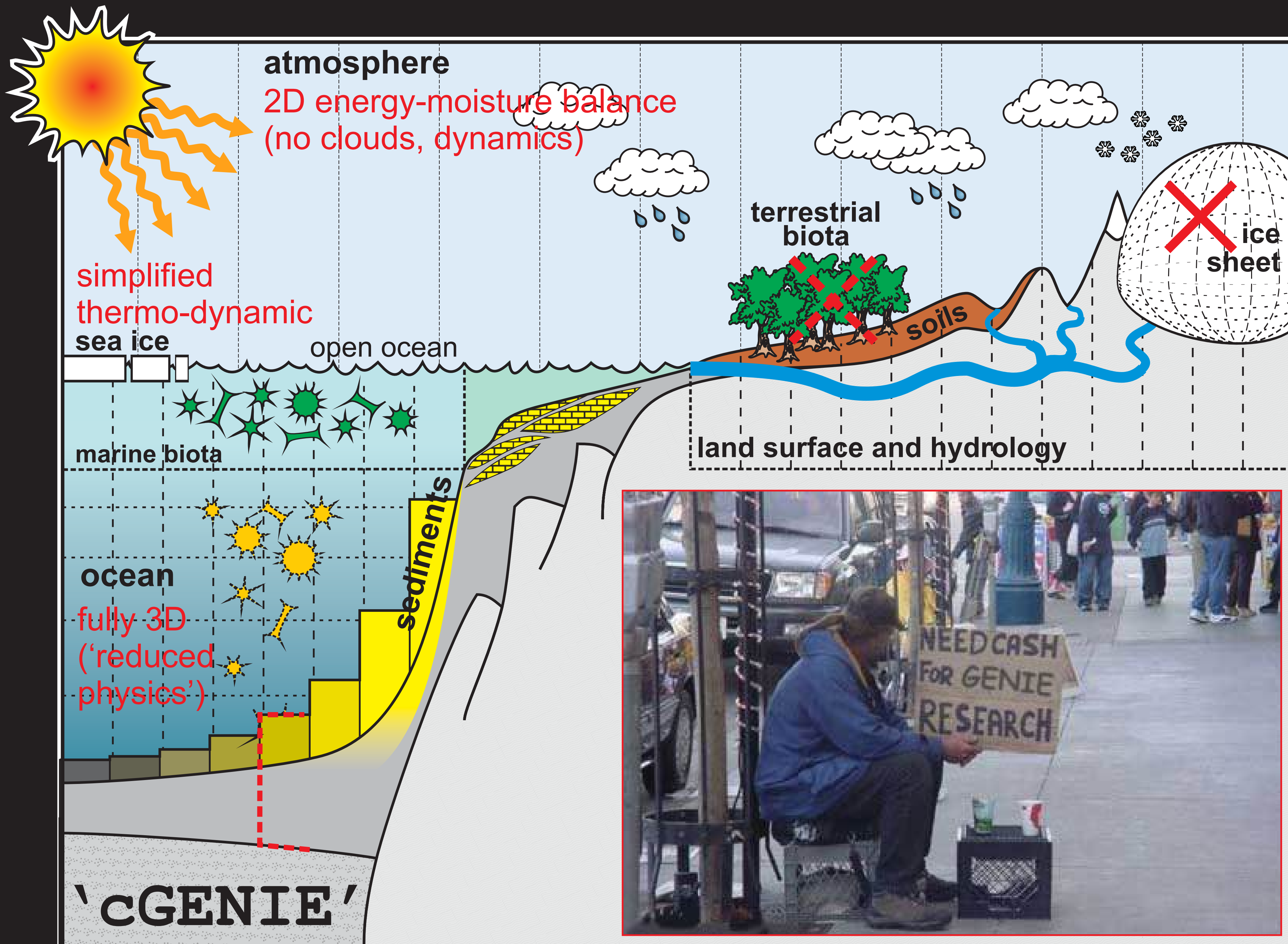
models

```
! 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
```

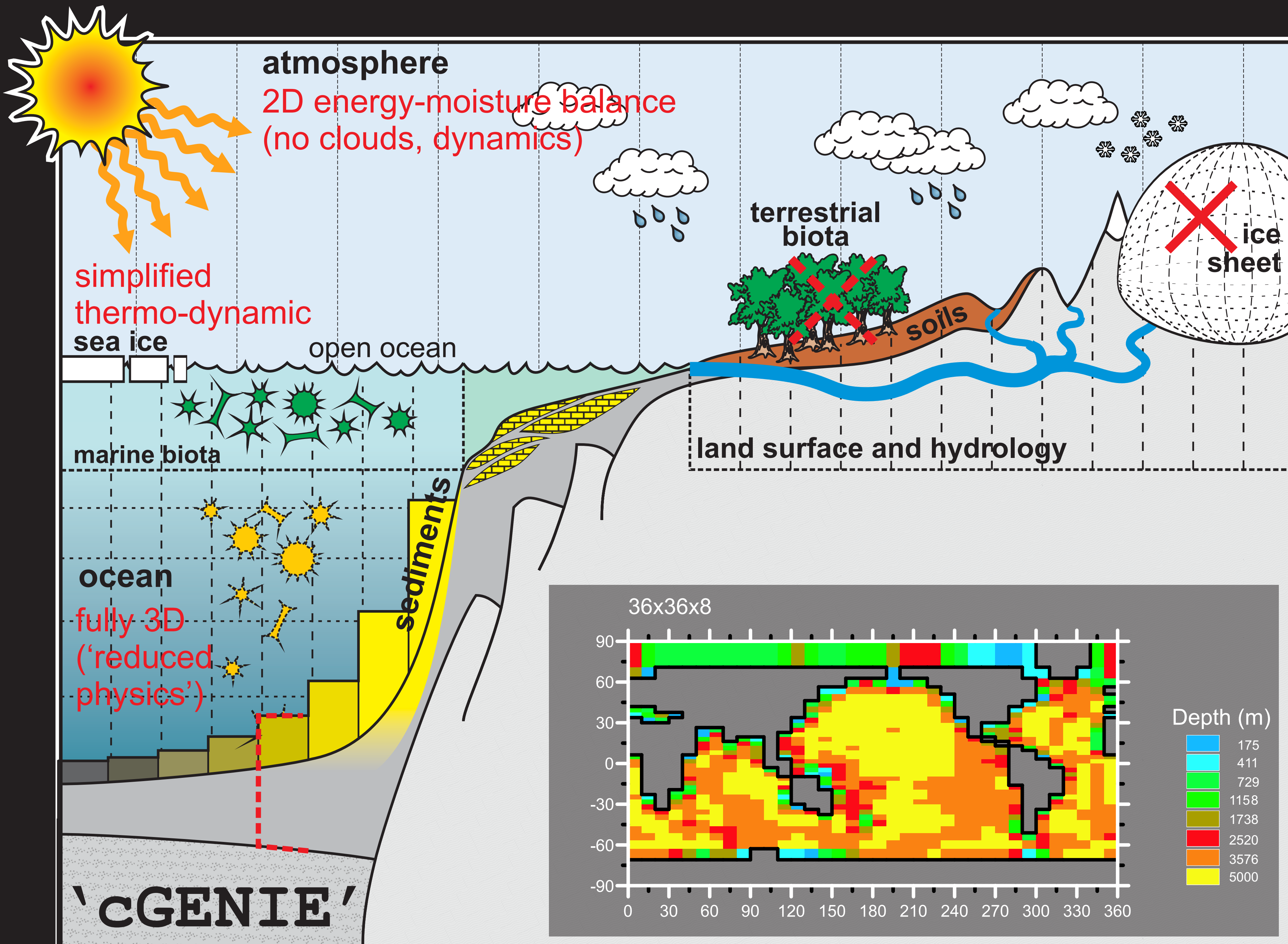
models


atmosphere
2D energy-moisture balance
(no clouds, dynamics)
simplified
thermo-dynamic
sea ice
open ocean
terrestrial
biota
ice
sheet
soils
land surface and hydrology
marine biota
ocean
fully 3D
('reduced
physics')
sediments
'cGENIE'
cGENIE
Carbon-GENIE
www.seao2.org

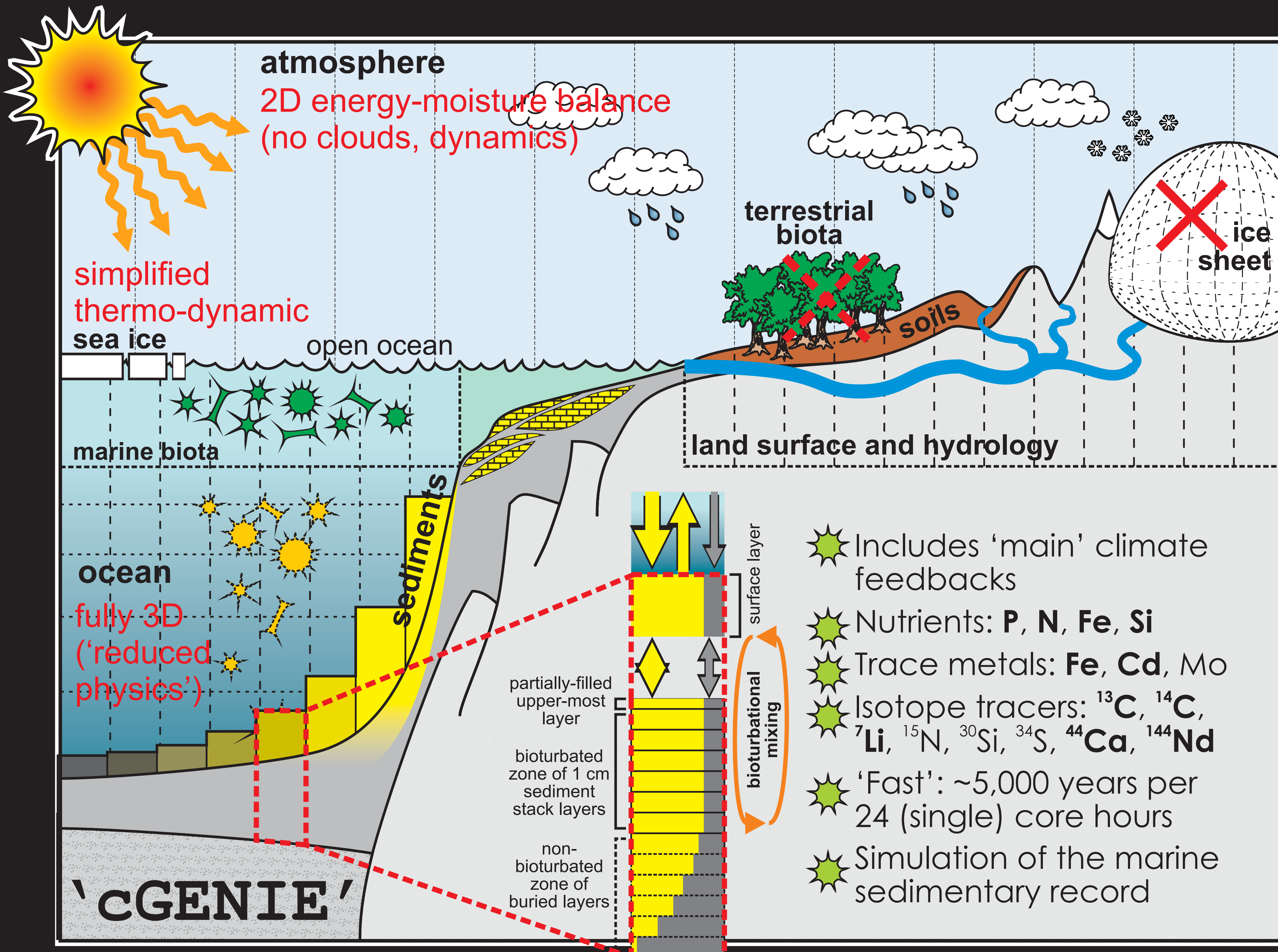
models


atmosphere
2D energy-moisture balance
(no clouds, dynamics)
simplified
thermo-dynamic
sea ice
open ocean
terrestrial
biota
soils
ice
sheet
marine biota
land surface and hydrology
sediments
ocean
fully 3D
('reduced
physics')
'cGENIE'
NEED CASH
FOR GENIE
RESEARCH

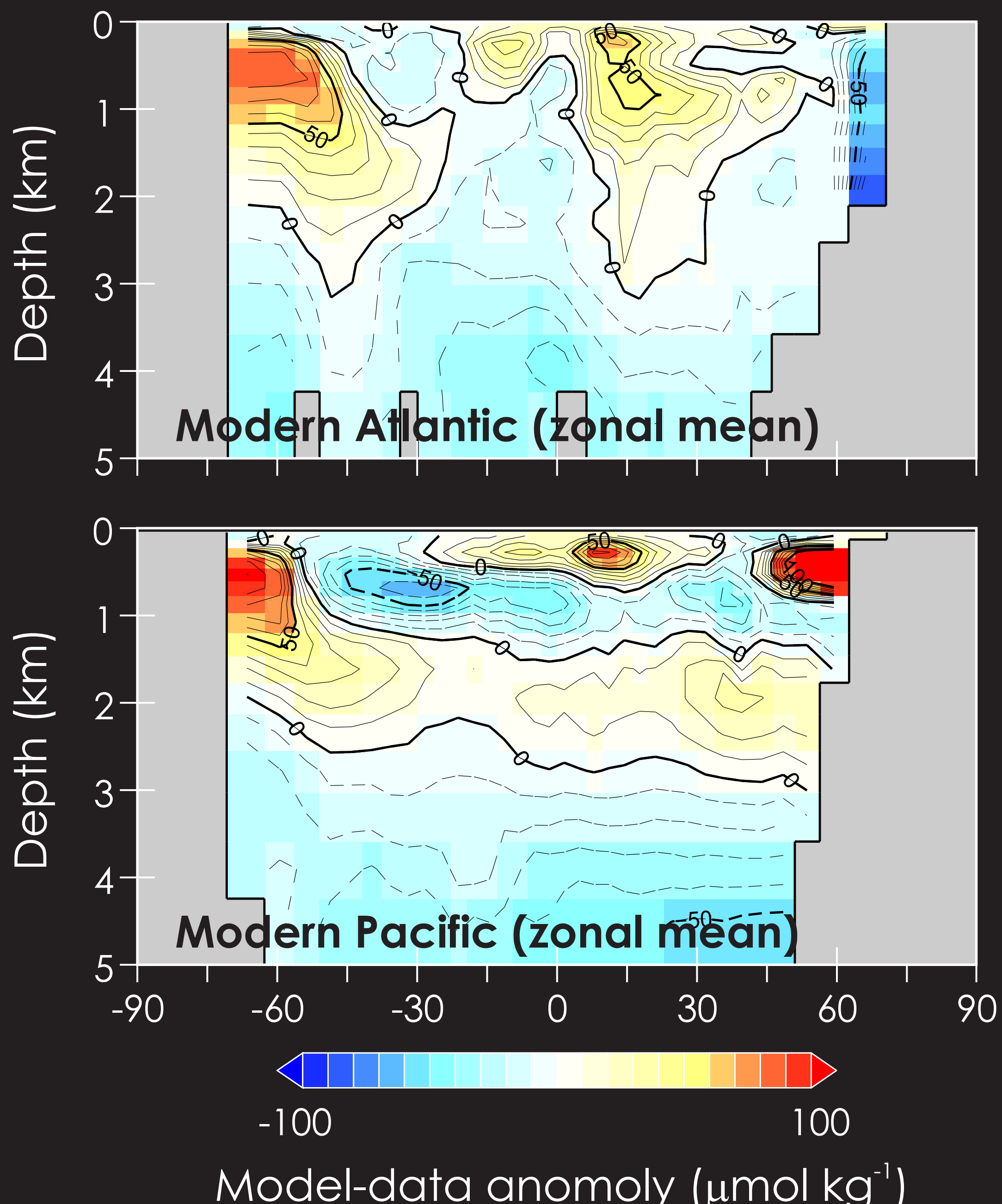
models

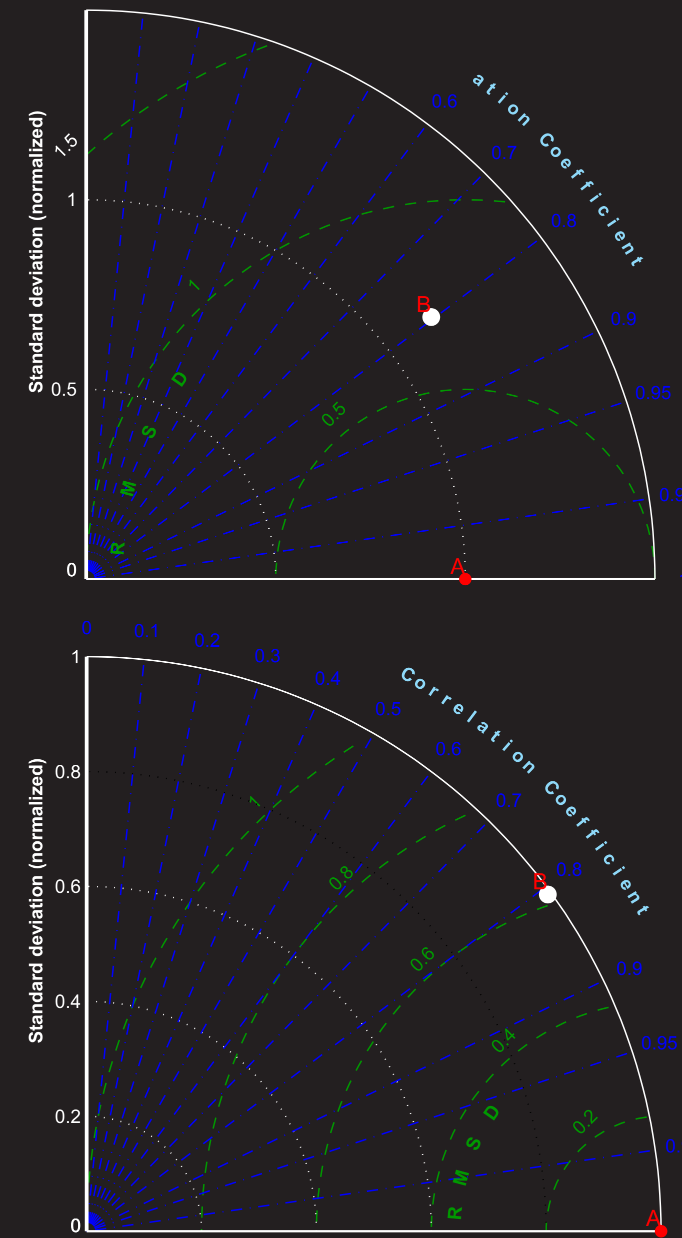

atmosphere
2D energy-moisture balance
(no clouds, dynamics)
simplified
thermo-dynamic
sea ice
open ocean
terrestrial
biota
soils
ice
sheet
marine biota
land surface and hydrology
sediments
ocean
fully 3D
('reduced
physics')
'cGENIE'
36x36x8
90
60
30
0
-30
-60
-90
0 30 60 90 120 150 180 210 240 270 300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

models


atmosphere
2D energy-moisture balance
(no clouds, dynamics)
simplified
thermo-dynamic
sea ice
open ocean
terrestrial
biota
ice
sheet
soils
marine biota
land surface and hydrology
sediments
ocean
fully 3D
('reduced
physics')
'cGENIE'
surface layer
partially-filled
upper-most
layer
bioturbated
zone of 1 cm
sediment
stack layers
non-
bioturbated
zone of
buried layers
bioturbational
mixing
Includes 'main' climate feedbacks
Nutrients: **P**, **N**, **Fe**, **Si**
Trace metals: **Fe**, **Cd**, Mo
Isotope tracers: ^{13}**C**, ^{14}**C**, ^{7}**Li**, ^{15}N, ^{30}Si, ^{34}S, ^{44}**Ca**, ^{144}**Nd**
'Fast': ~5,000 years per 24 (single) core hours
Simulation of the marine sedimentary record

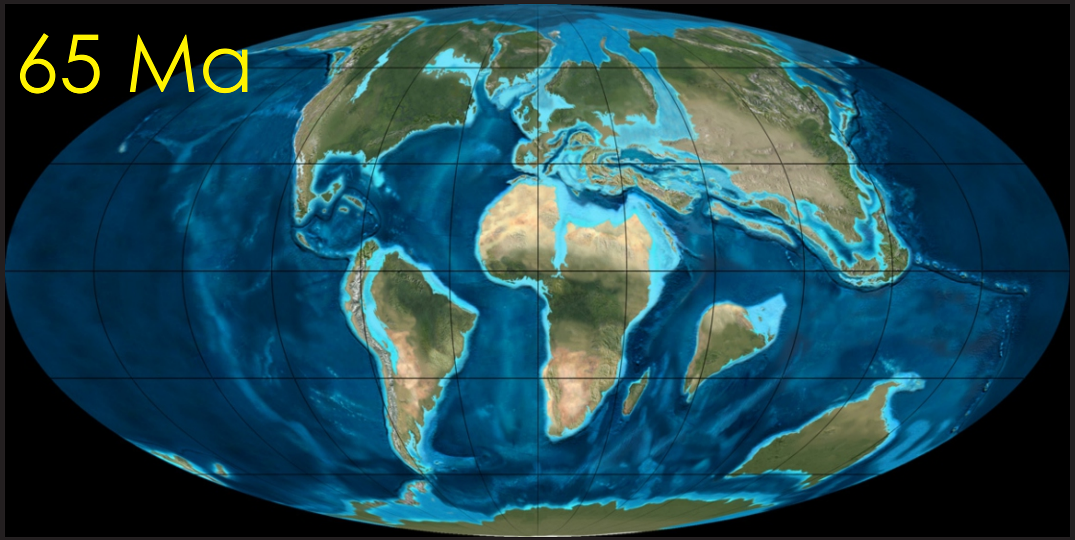
models

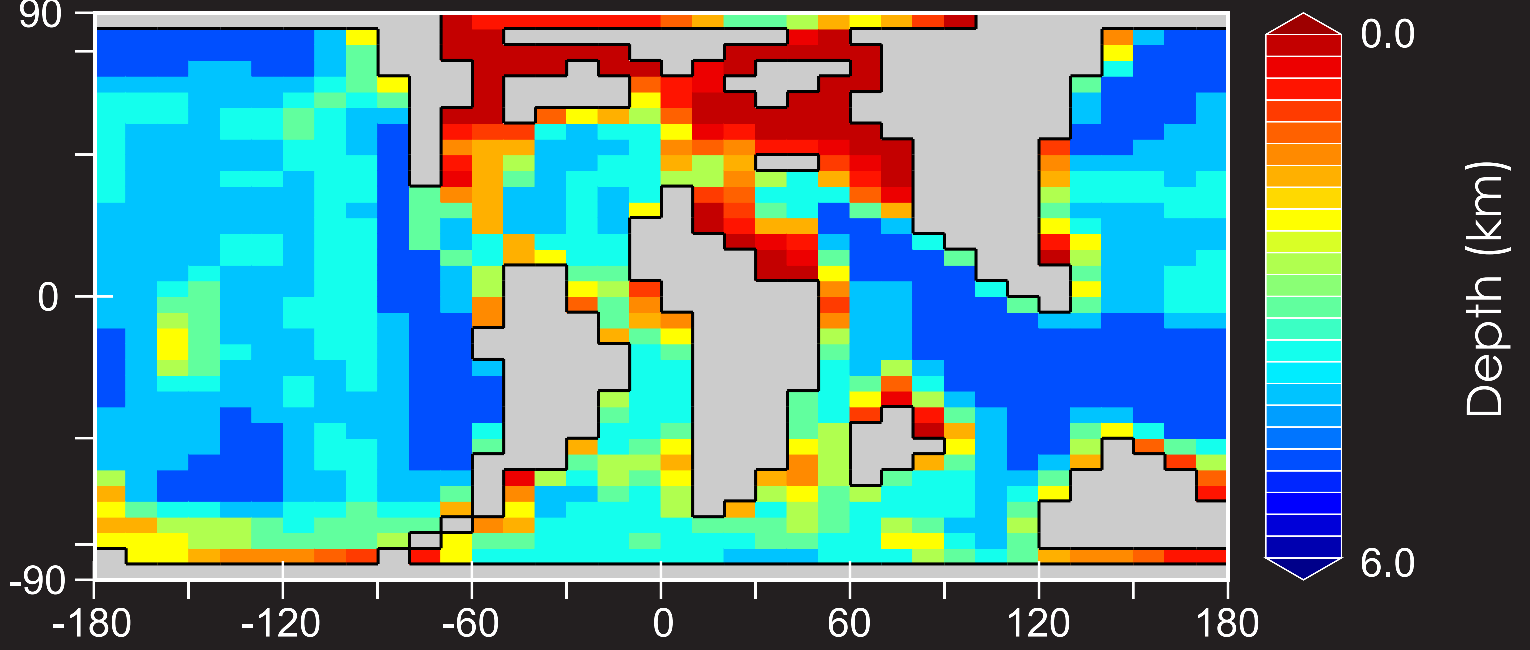




Model-data assessments can be made statistically by e.g., 'Taylor diagrams'

models in deep time



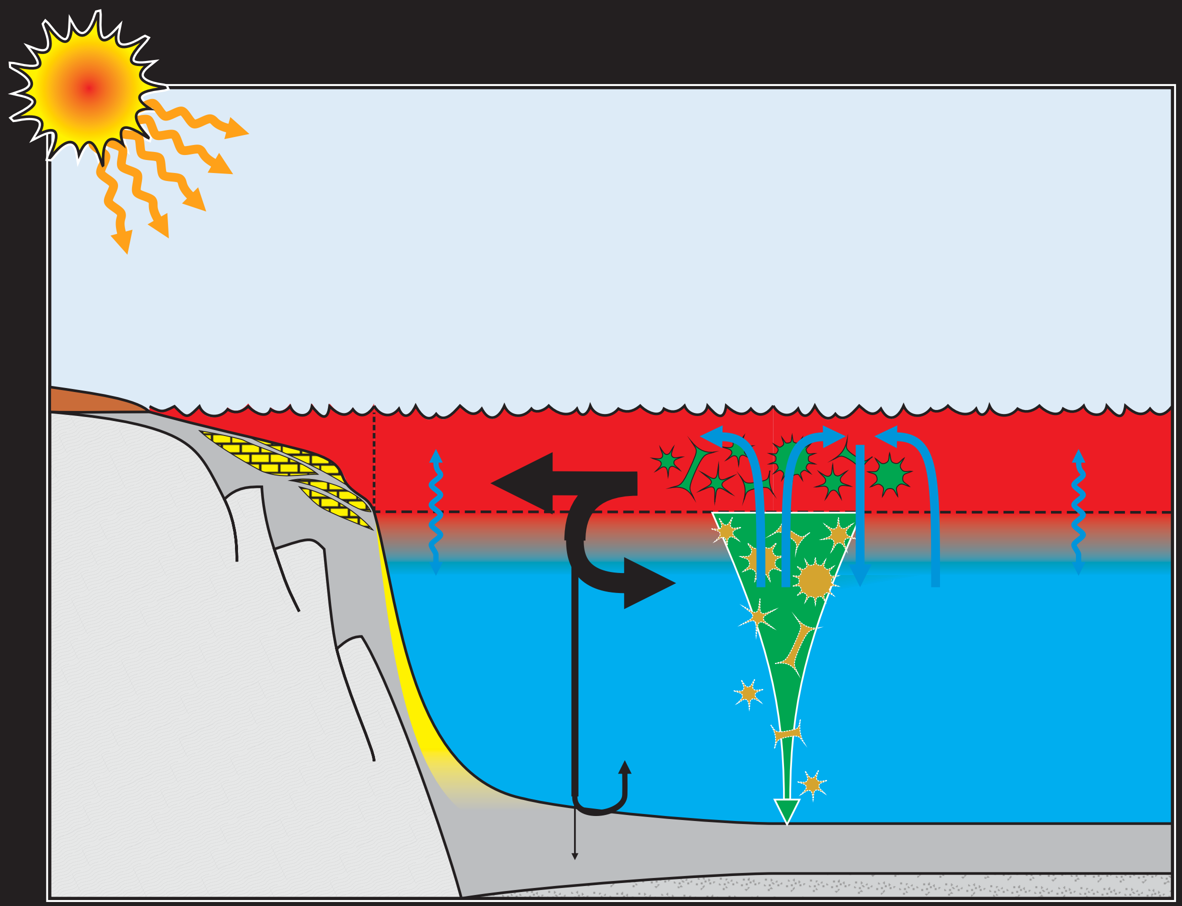


models in deep time

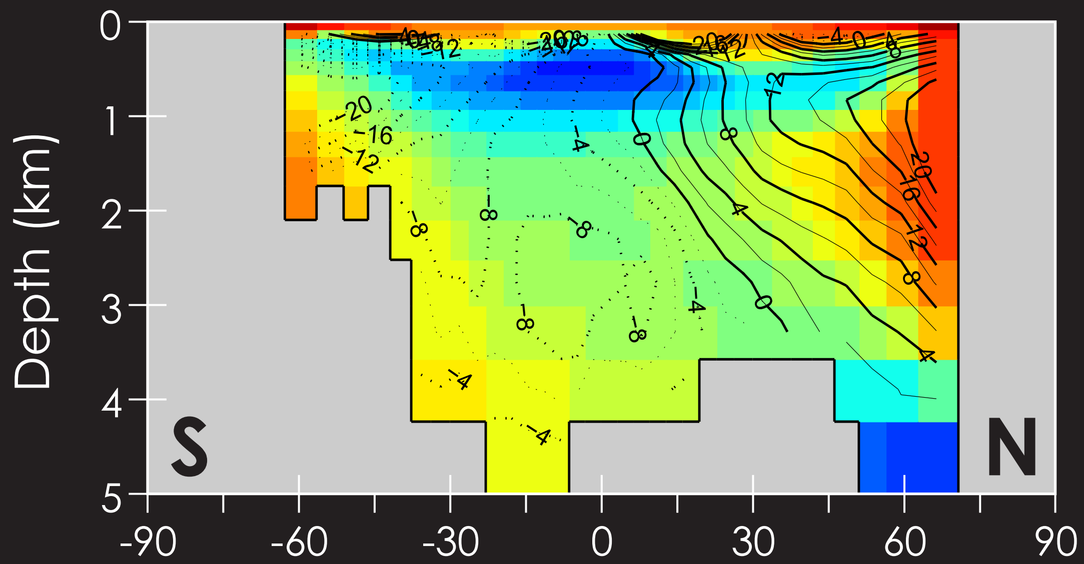
(warm == stratified) && (stratified == anoxic) == .true.

???

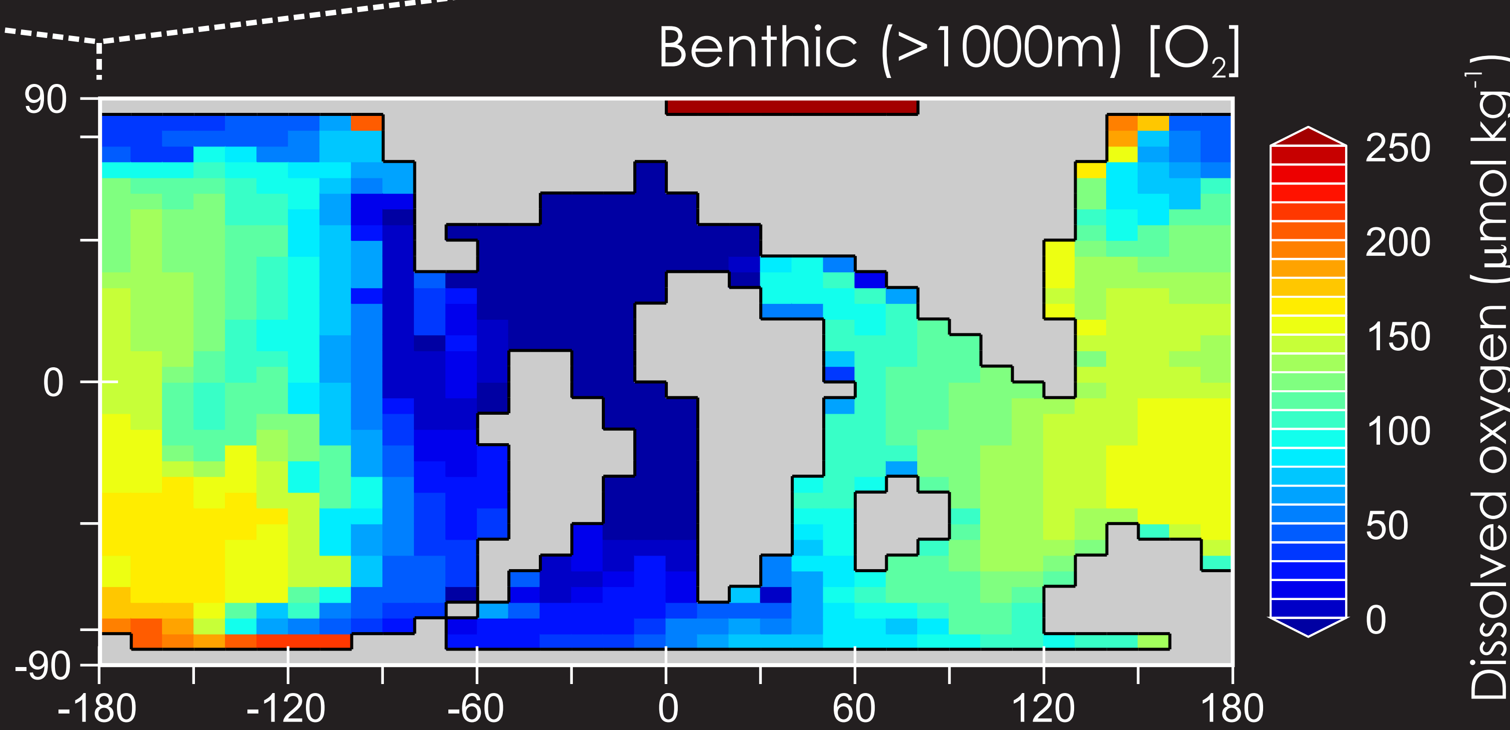
('stratified' || 'sluggish' || 'stagnant')



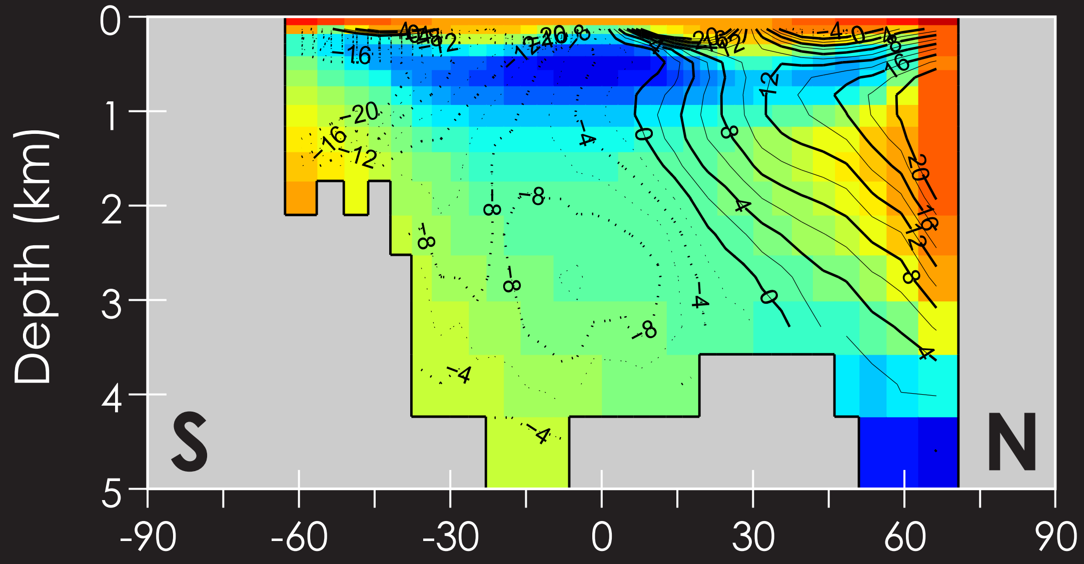
models in deep time



x4 CO_2 reference simulation

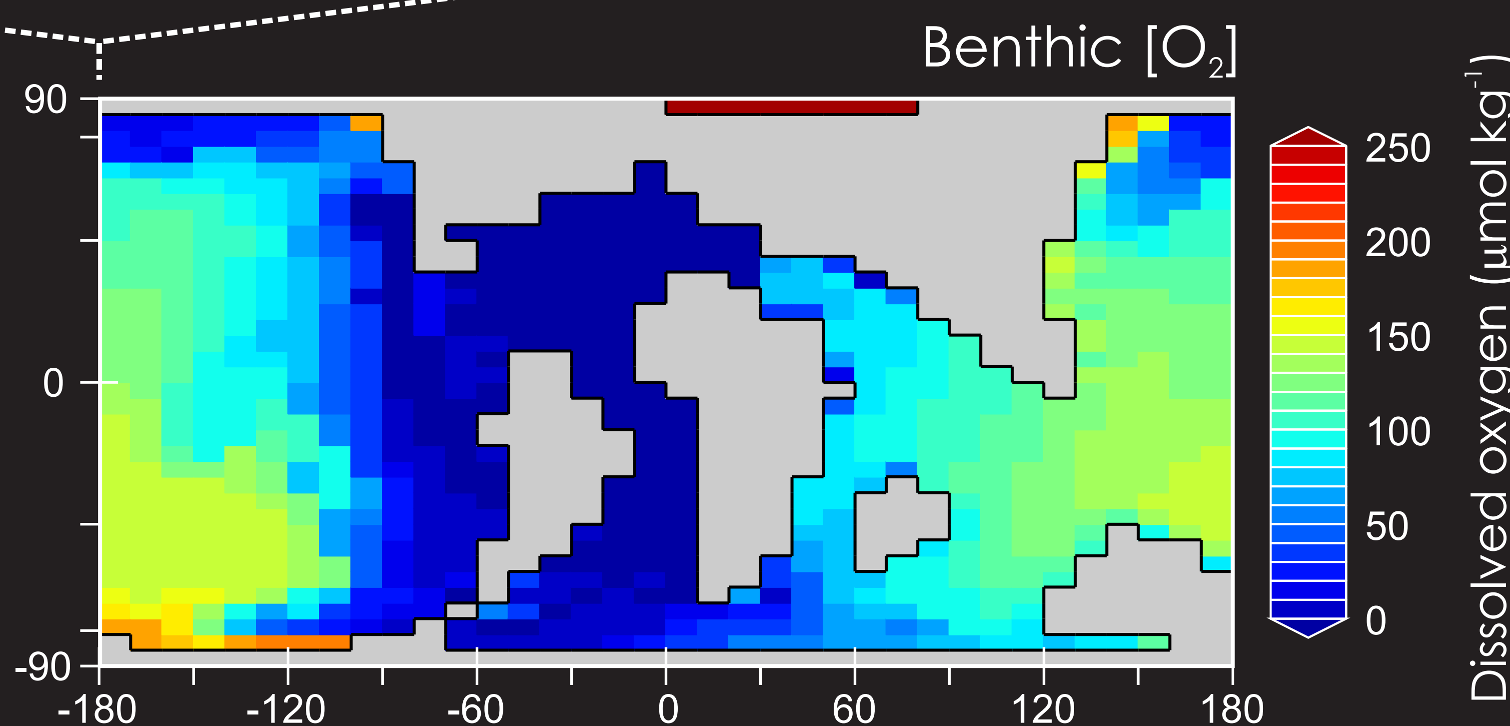


models in deep time



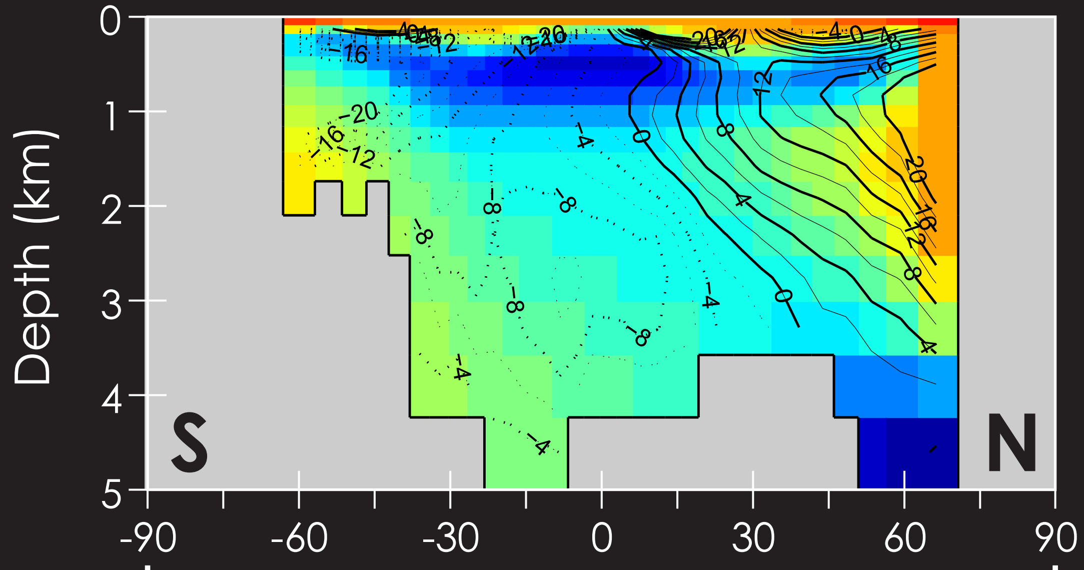
x8 CO_2 @ 10,000 yrs

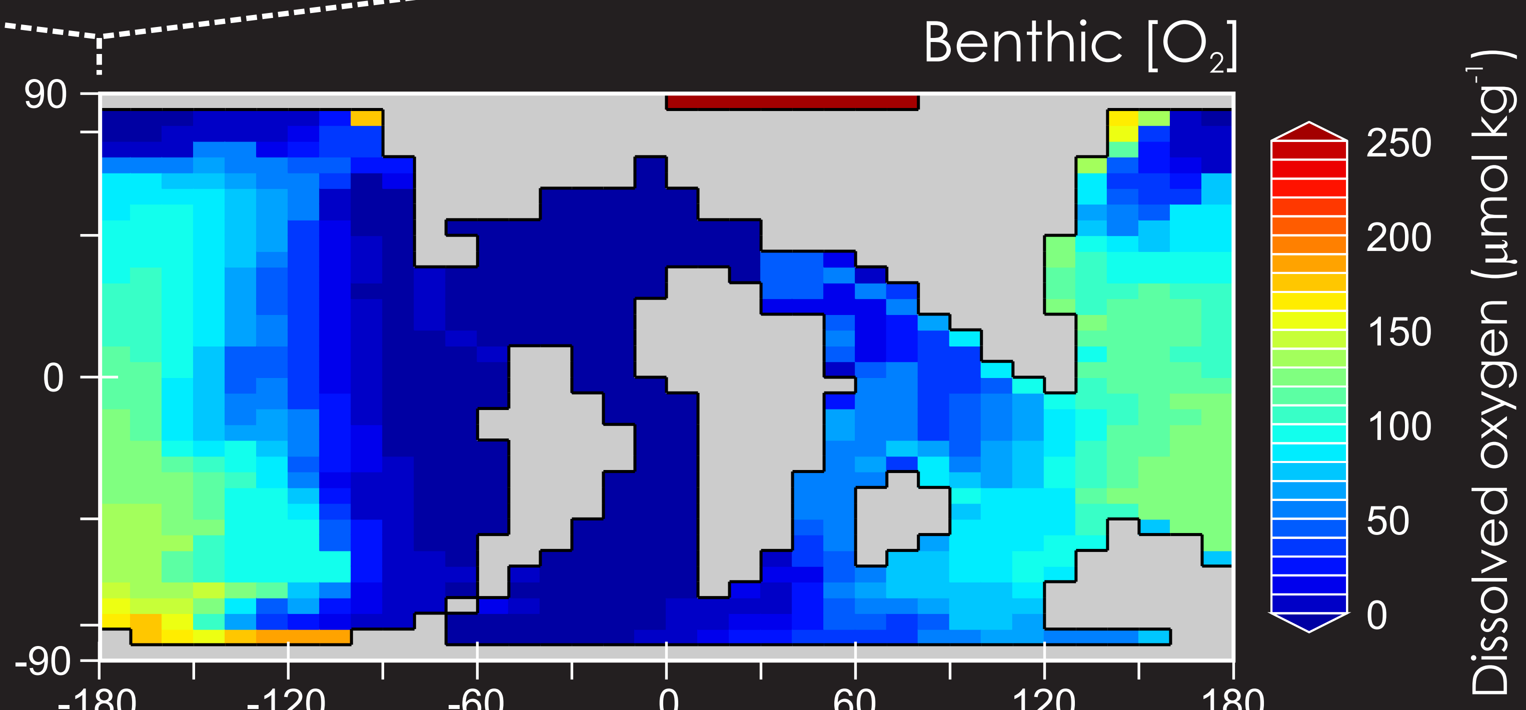
(started from end of the x4 simulation)

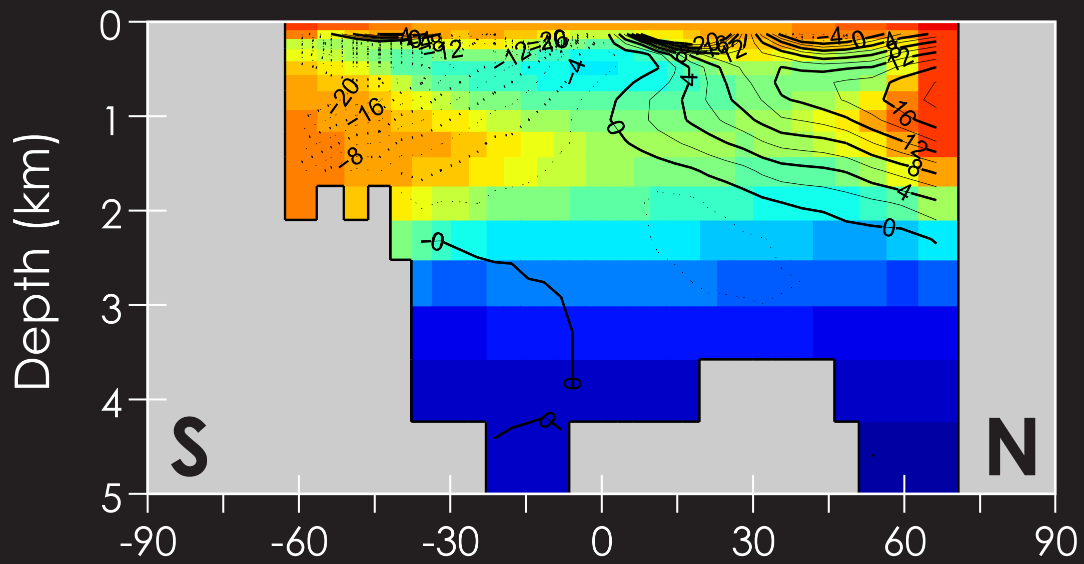


x16 CO_2 @ 10,000 yrs

(started from end of the x4 simulation)

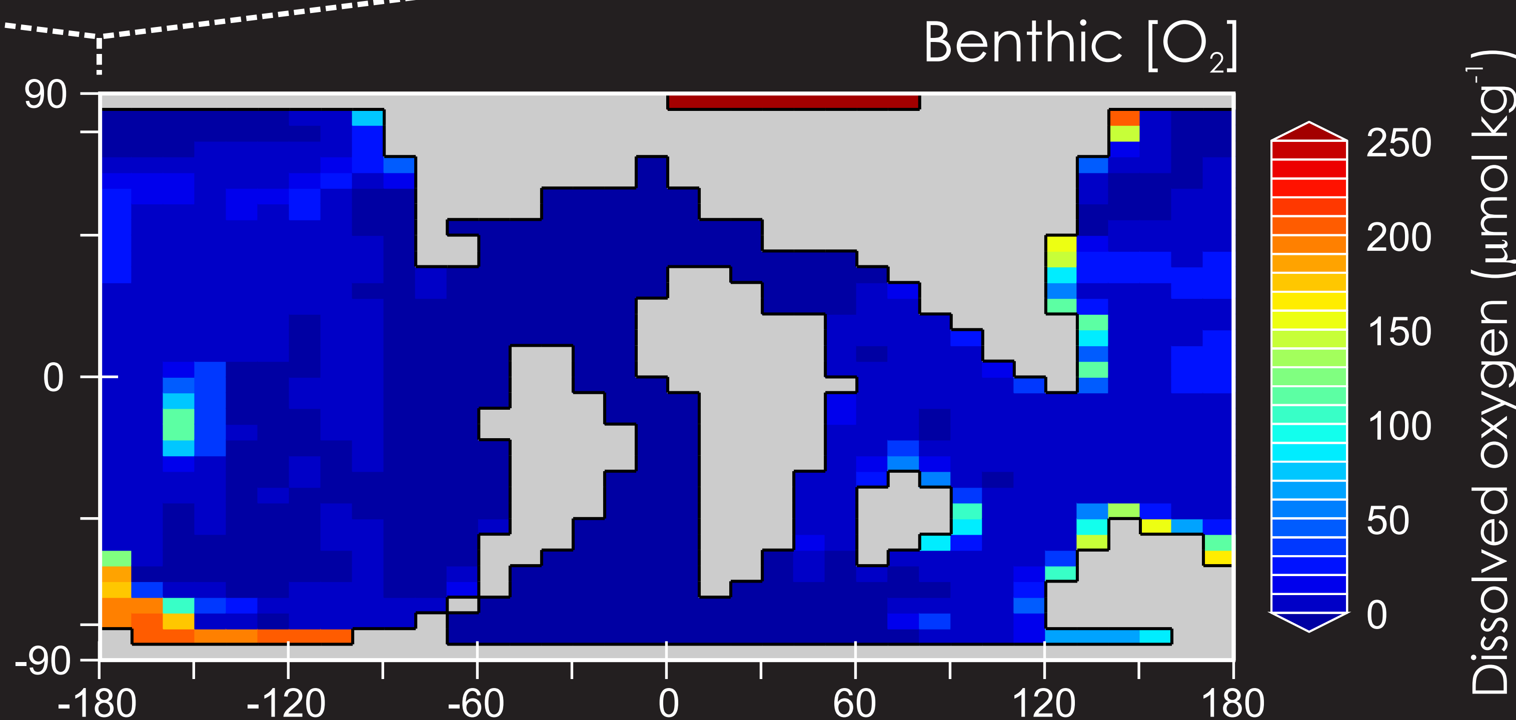


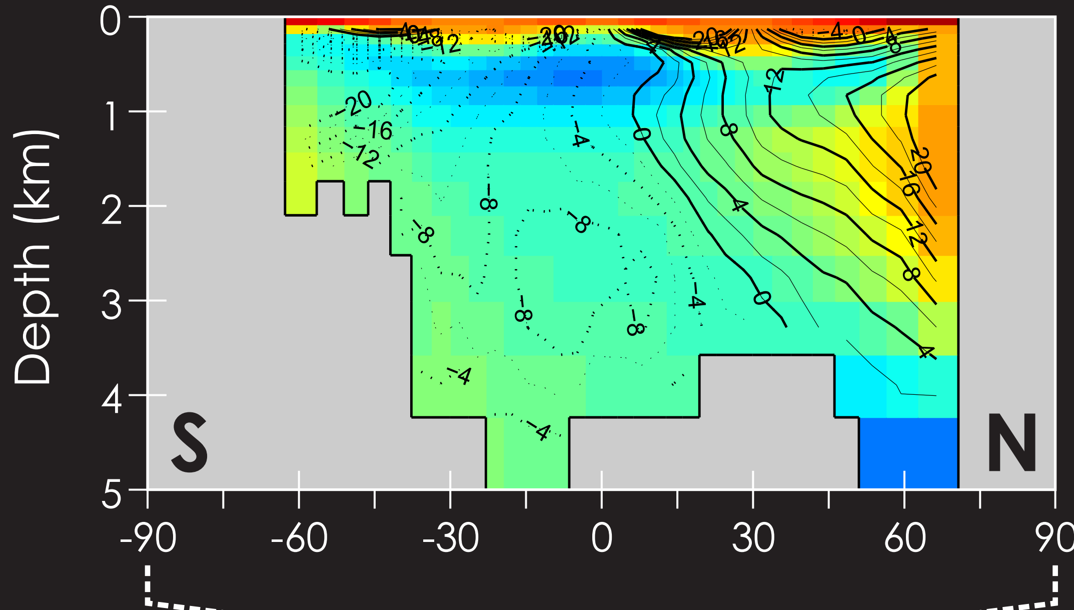




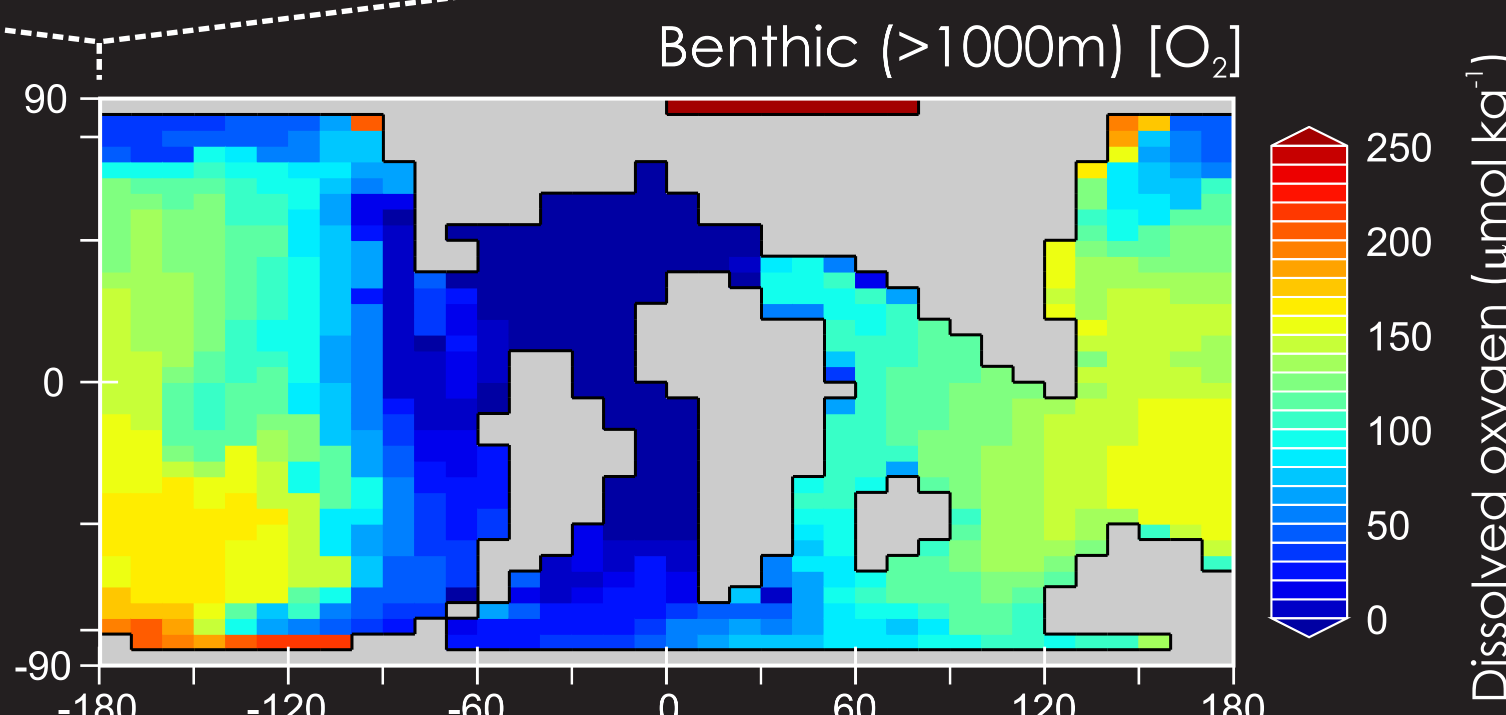
x16 CO_2 @ 2,000 yrs

(following on from a 10,000 yr x4 CO_2 spin-up)

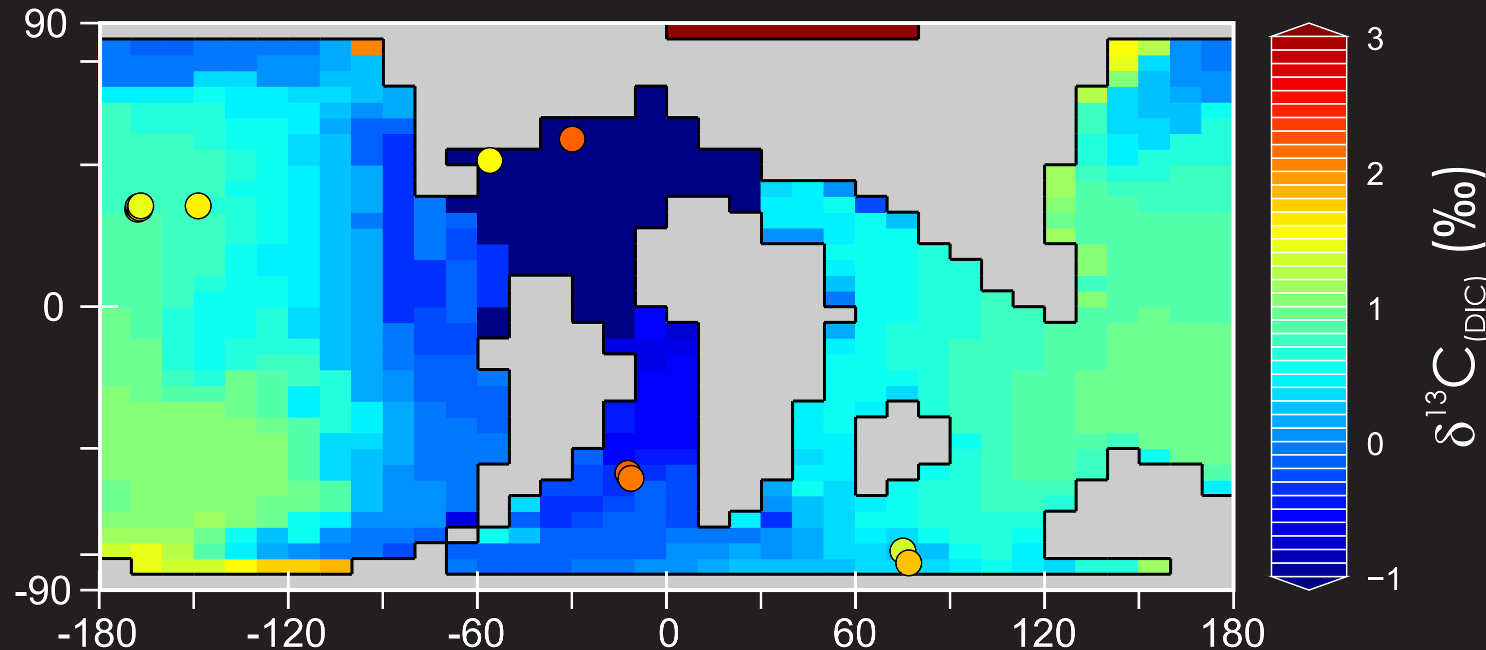




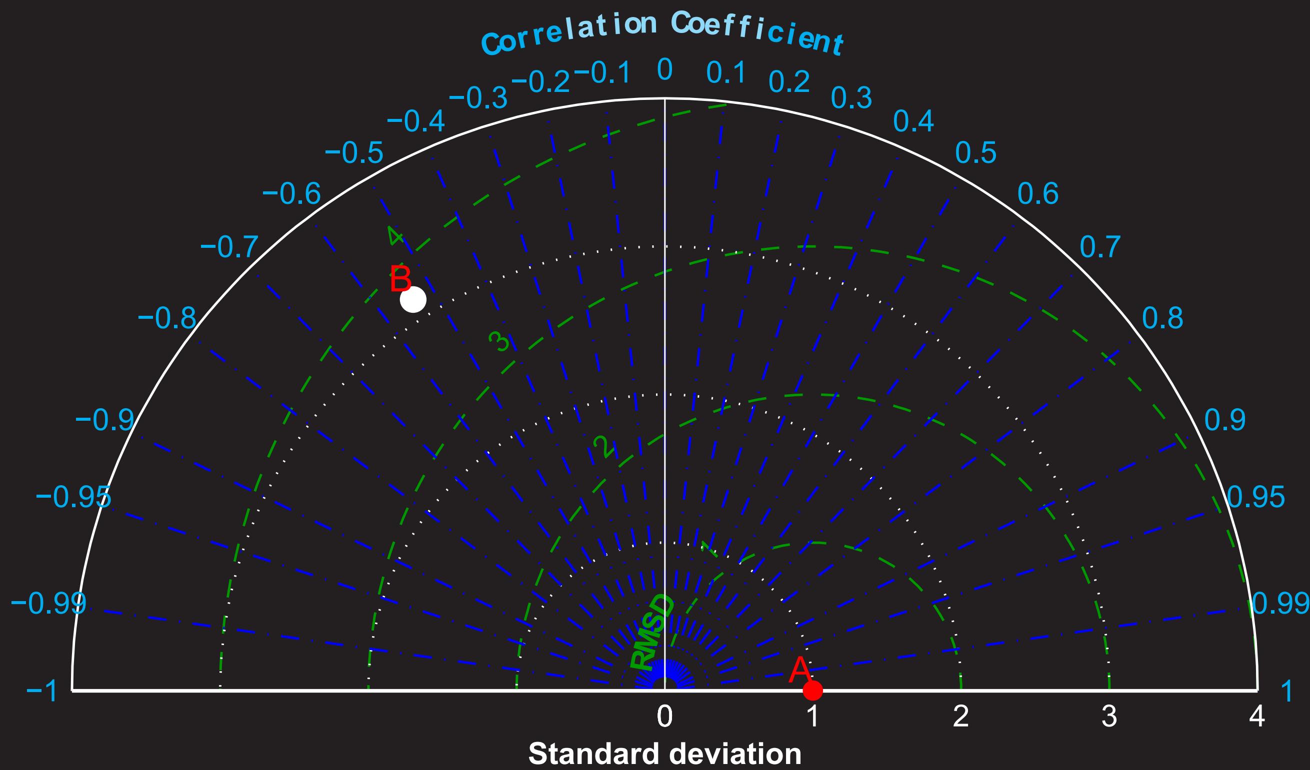
x4 CO_2 reference simulation;
latest Maastrichtian

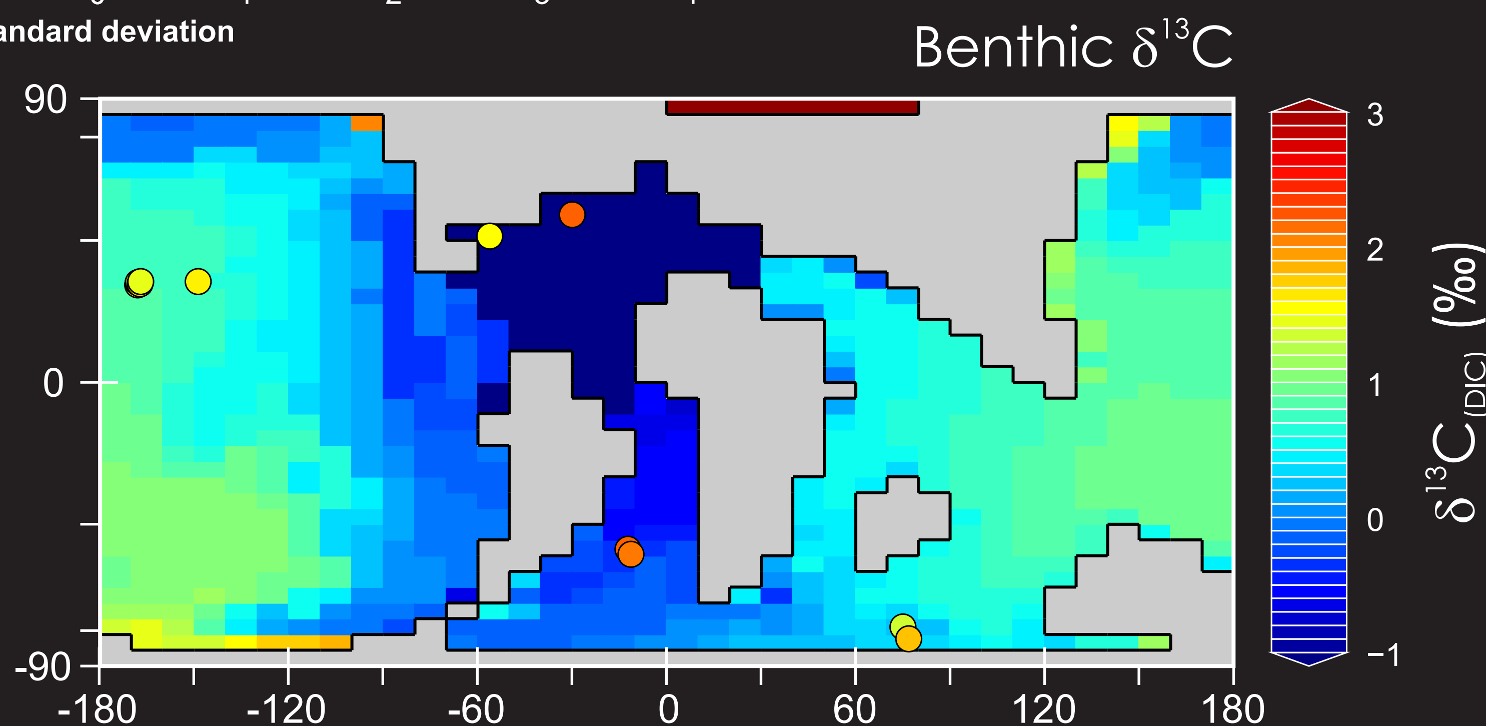


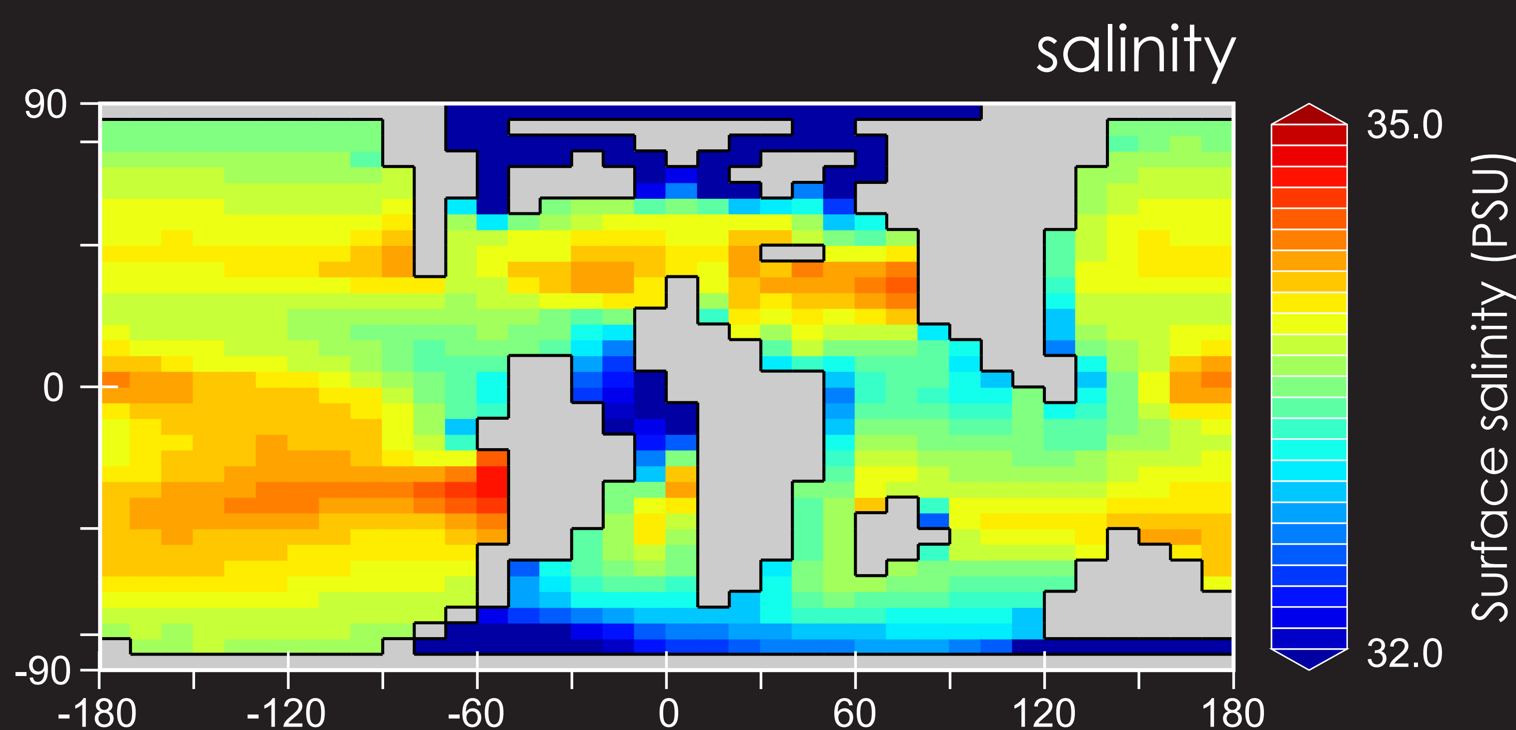
Model bottom-water $\delta^{13}C$ with benthic foraminiferal $\delta^{13}C$ overlain (Cramer '09)



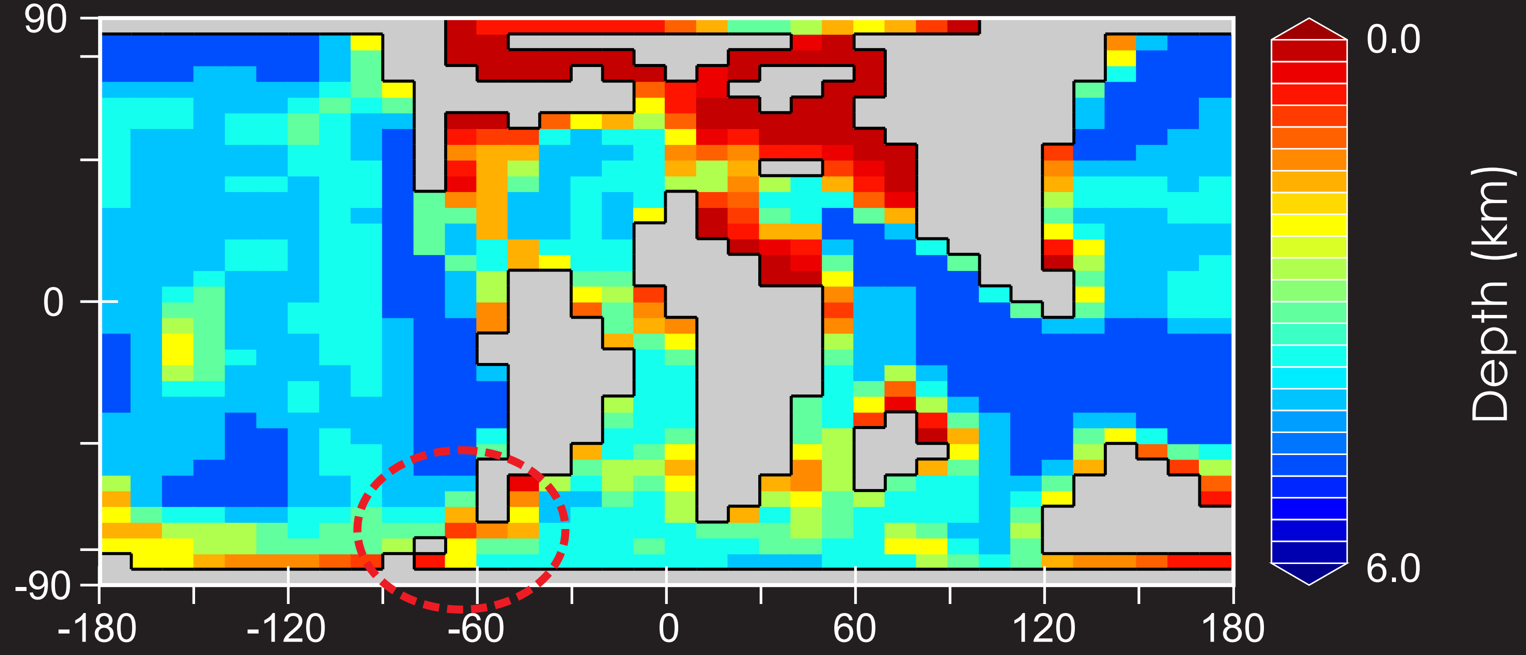
models in deep time





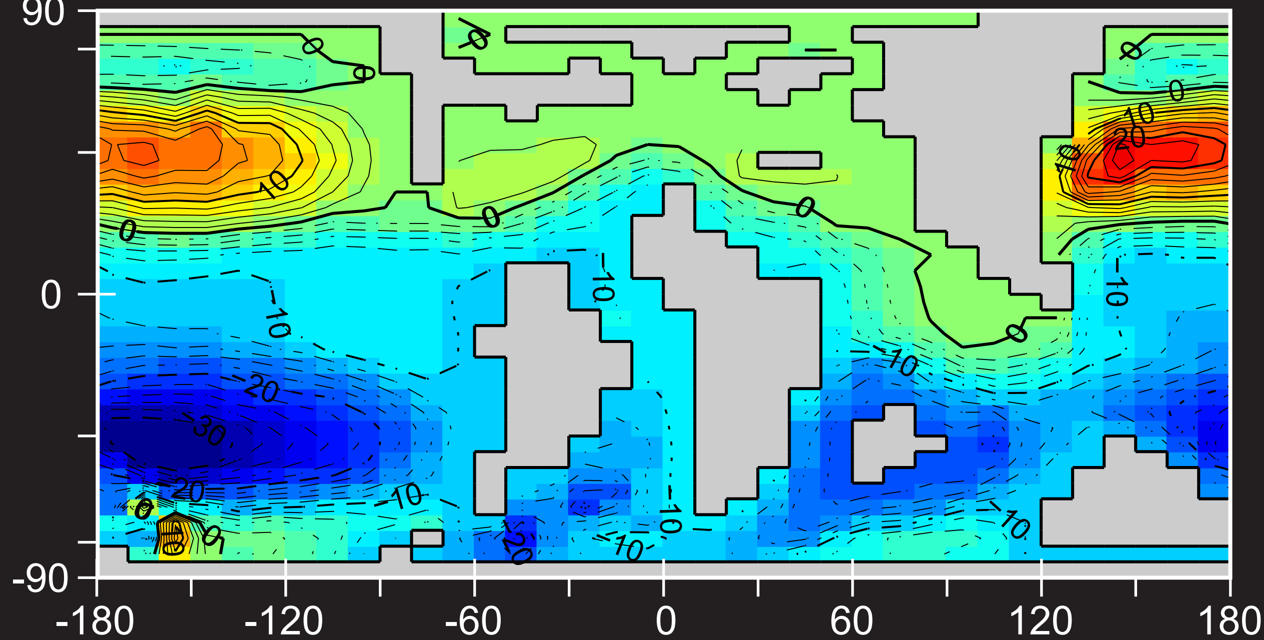

salinity
90
0
-90
-180
-120
-60
0
60
120
180
35.0
32.0
Surface salinity (PSU)

models in deep time

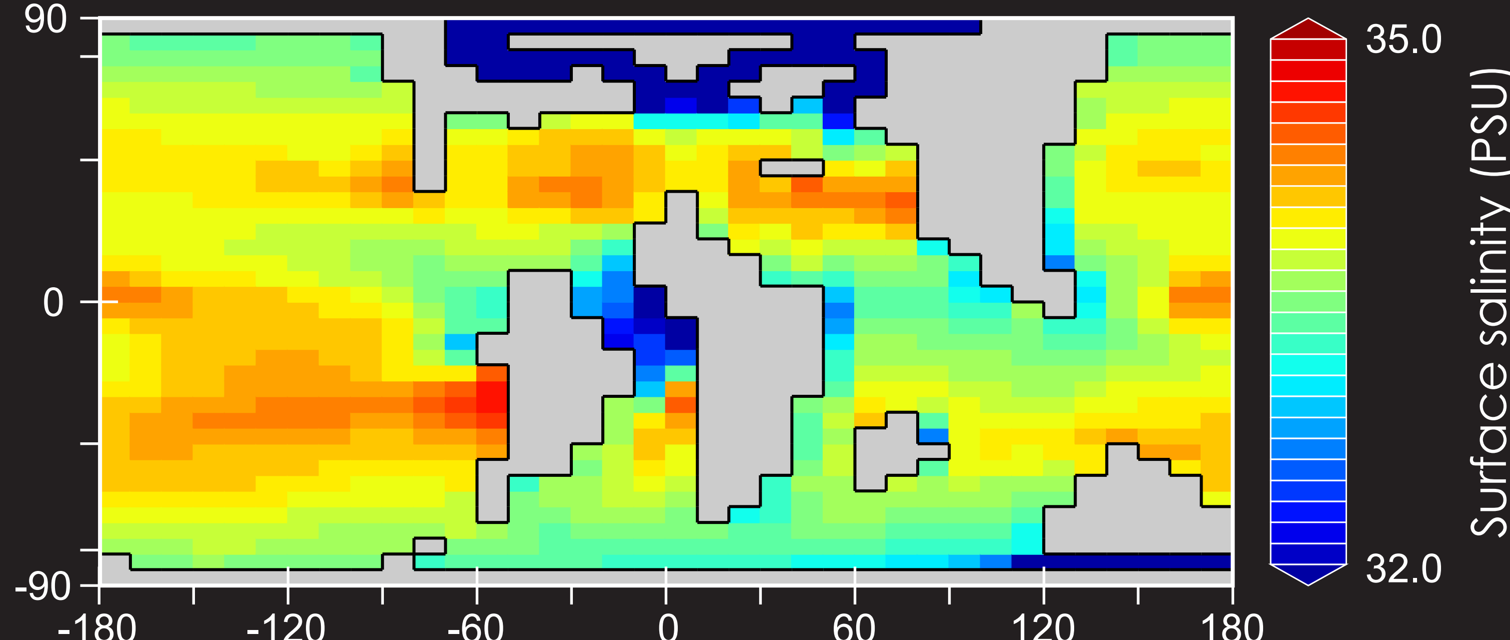


models in deep time

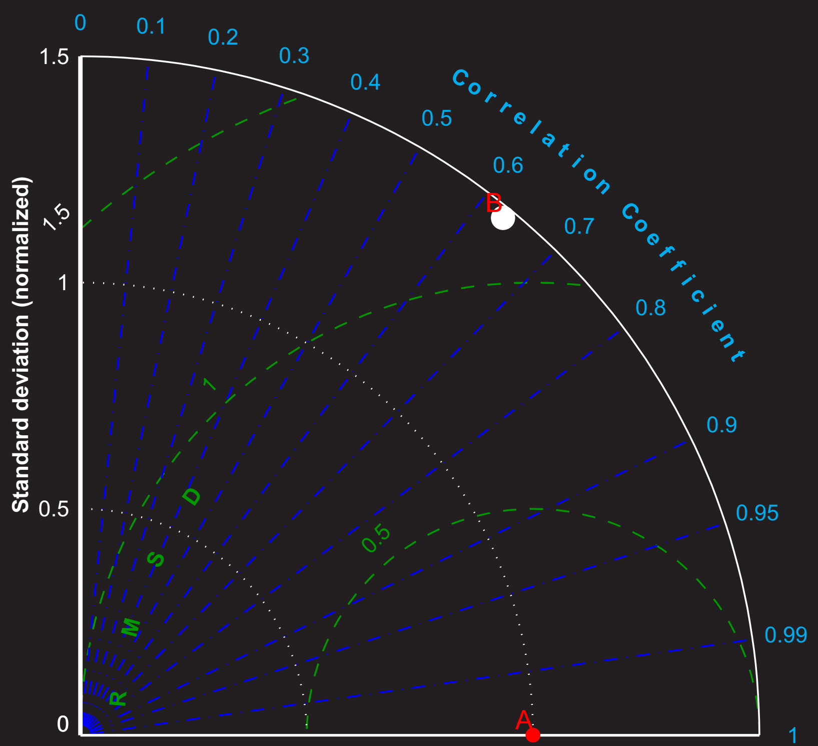
Barotropic streamfunction

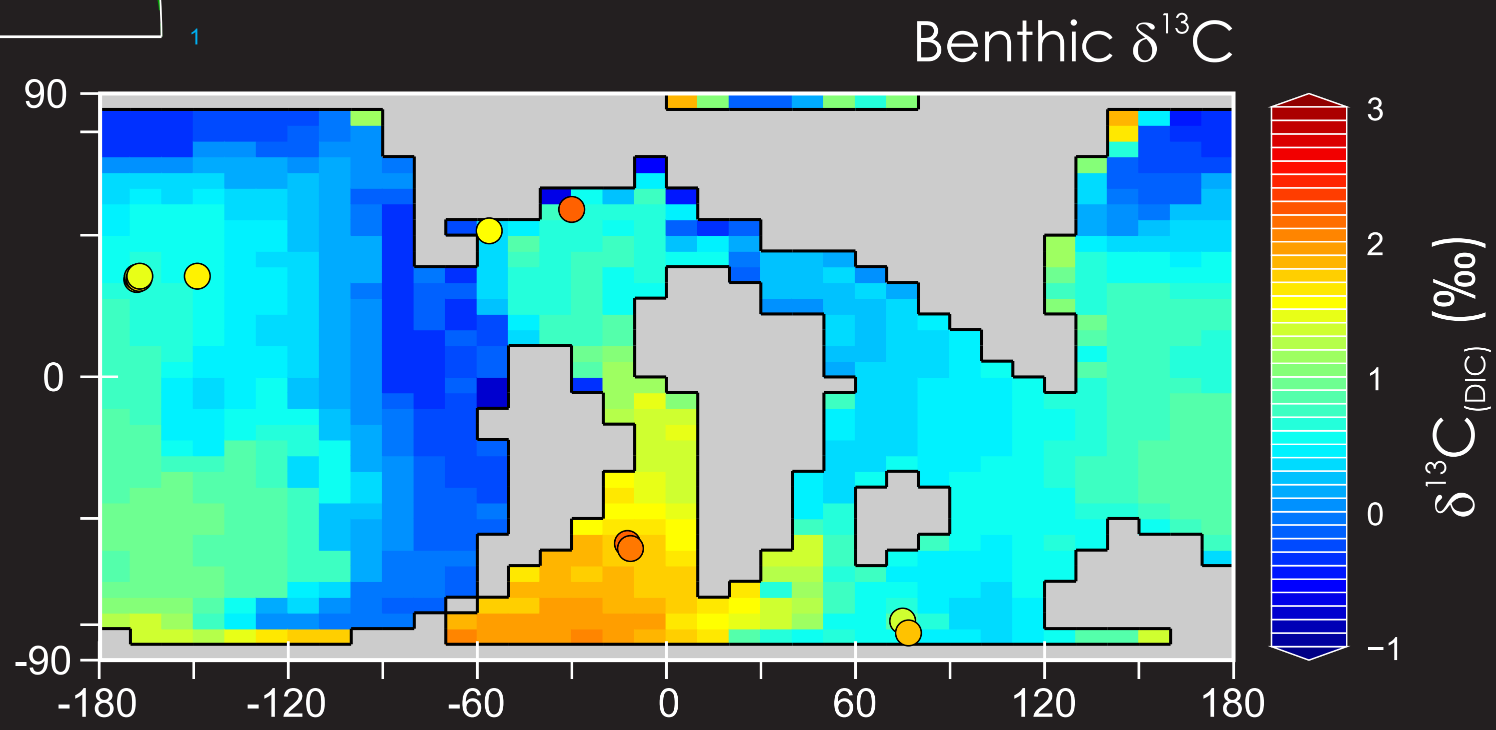


salinity

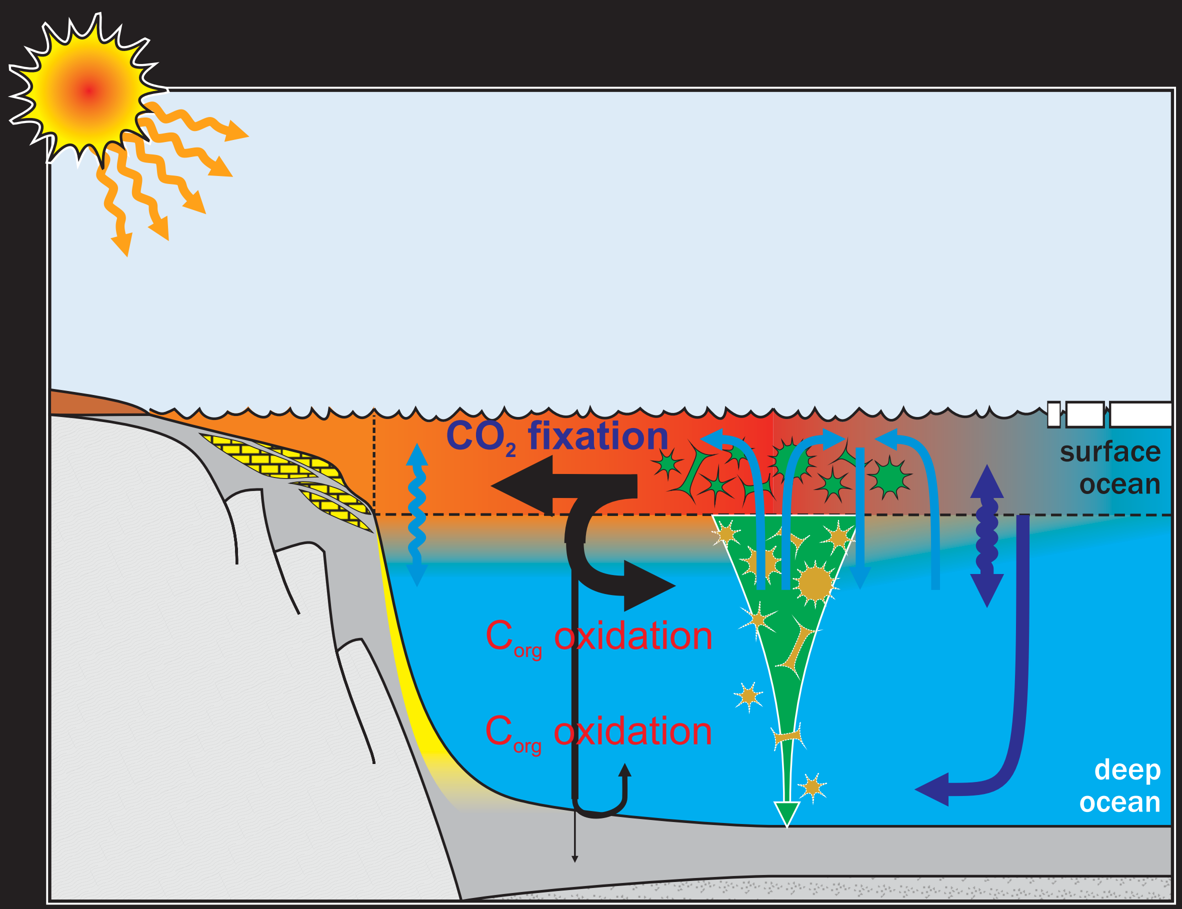


models in deep time





models in deep time ... a 'real' example

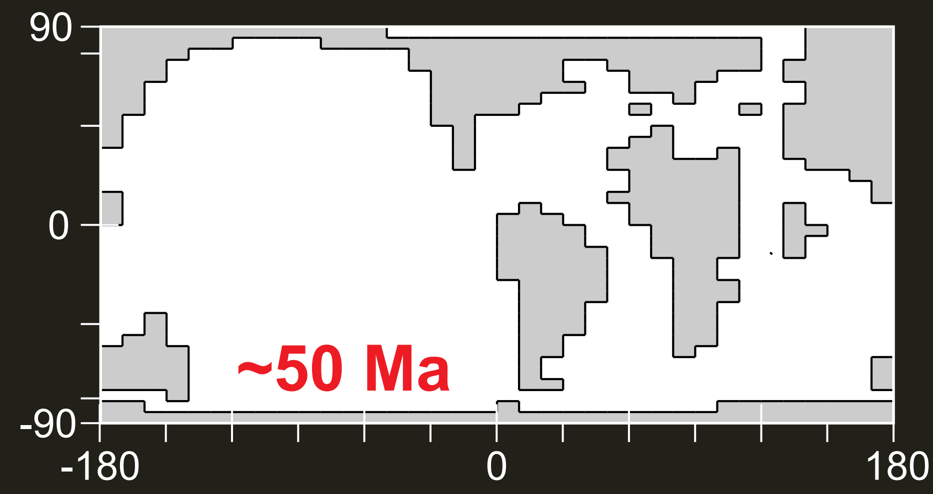


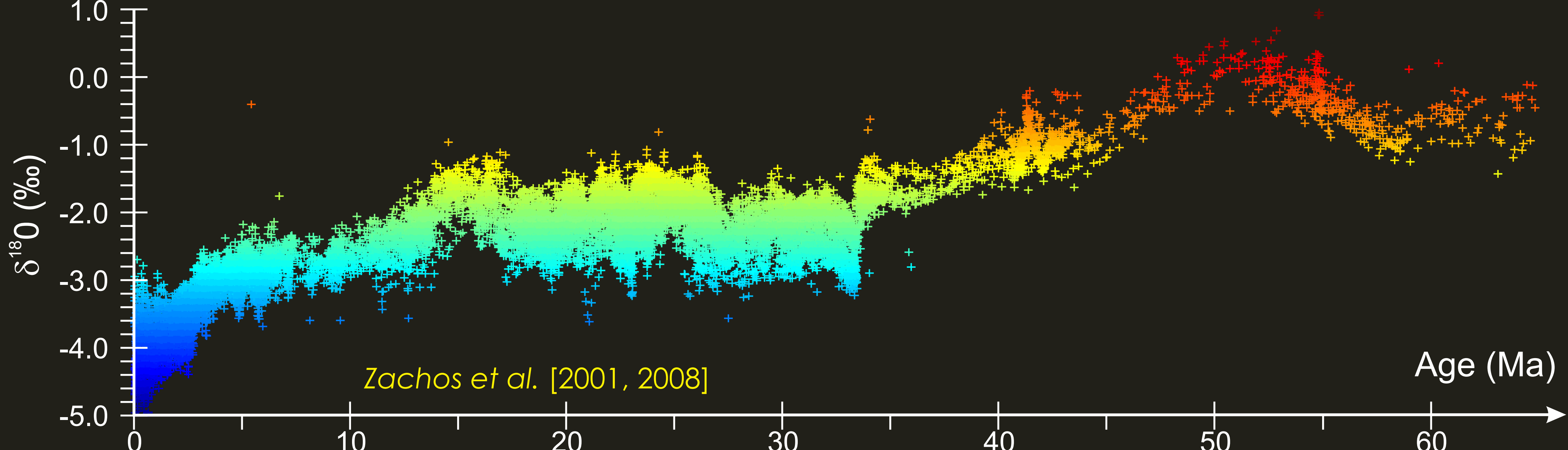
Consider the biological pump ...

How does it 'work'?

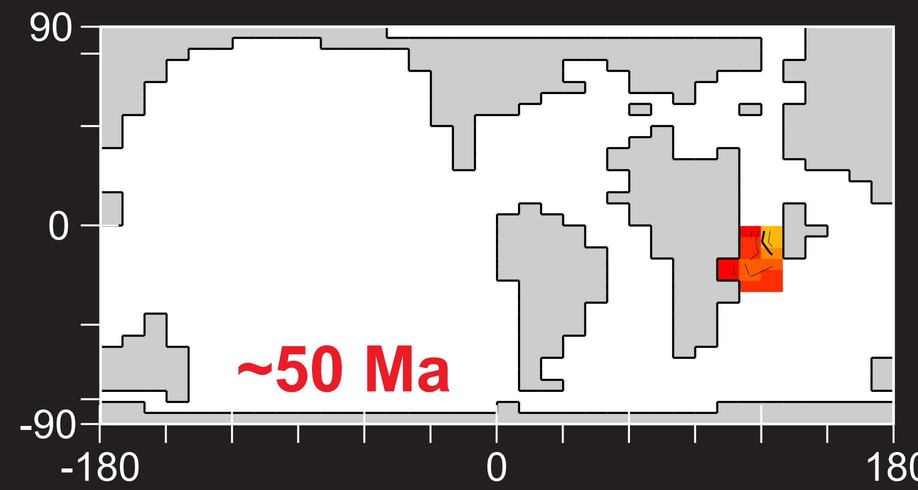
(what controls its 'efficiency'?)

models in deep time ... a 'real' example



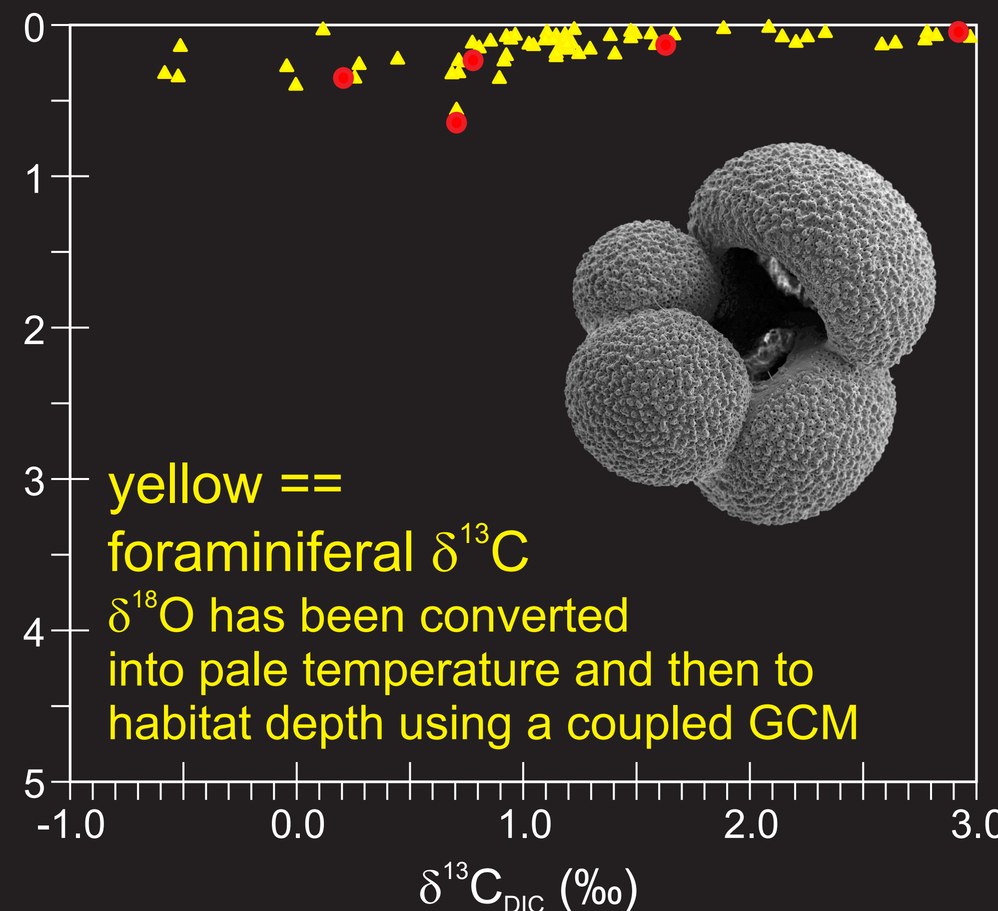


models in deep time ... a 'real' example

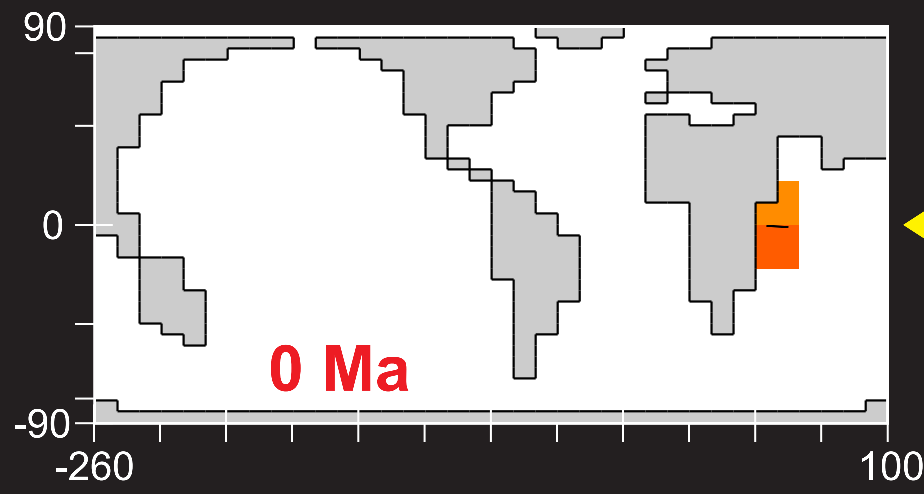


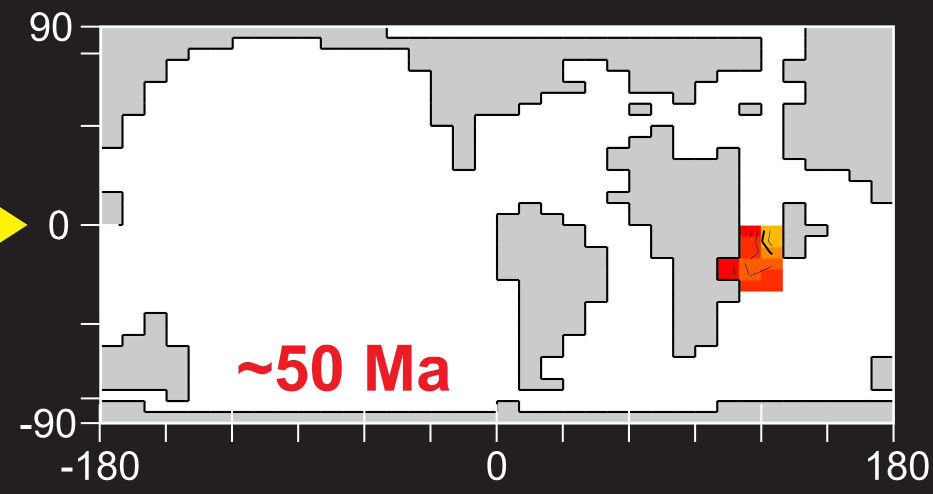
Planktic foraminiferal $\delta^{13}C$ from early Eocene Tanzania

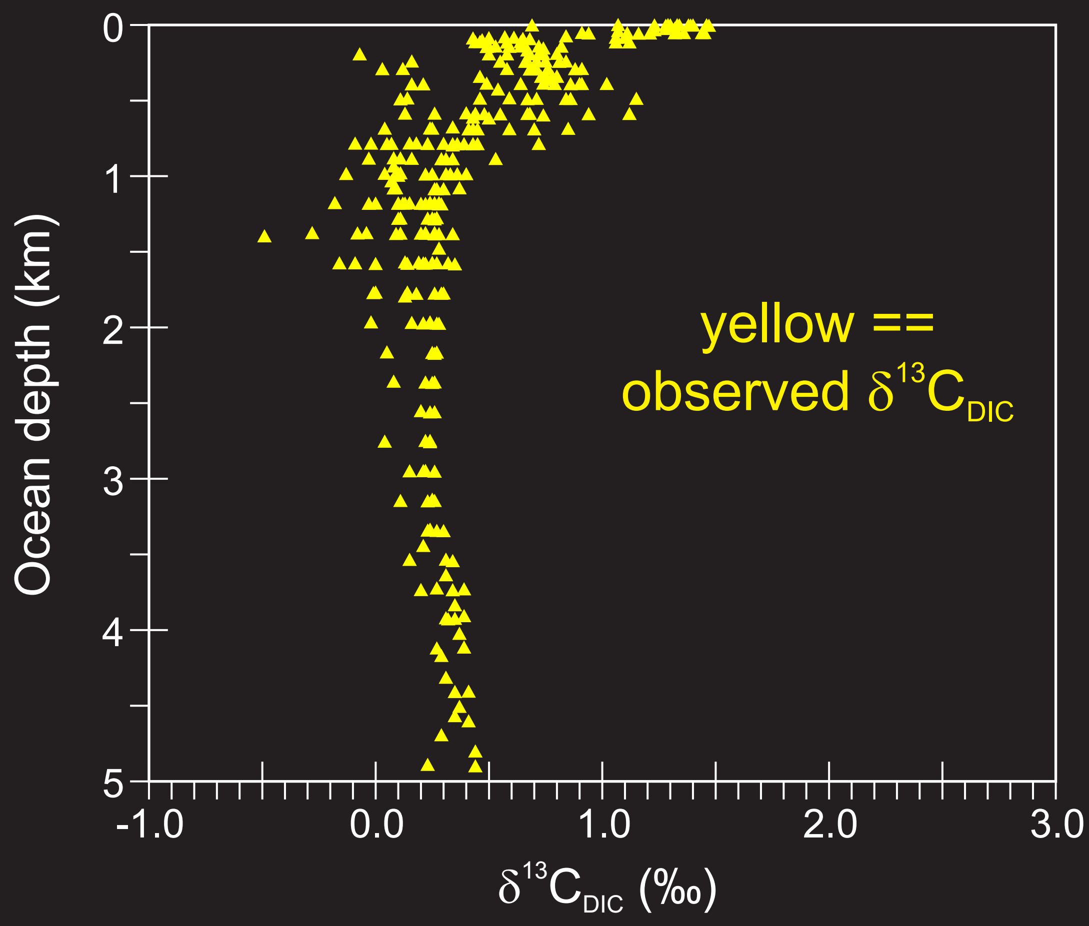
John *et al.*, Temperature-dependent remineralisation and carbon cycling in the warm Eocene oceans, *PPP* **413**, 158-166 (2014).



models in deep time ... a 'real' example

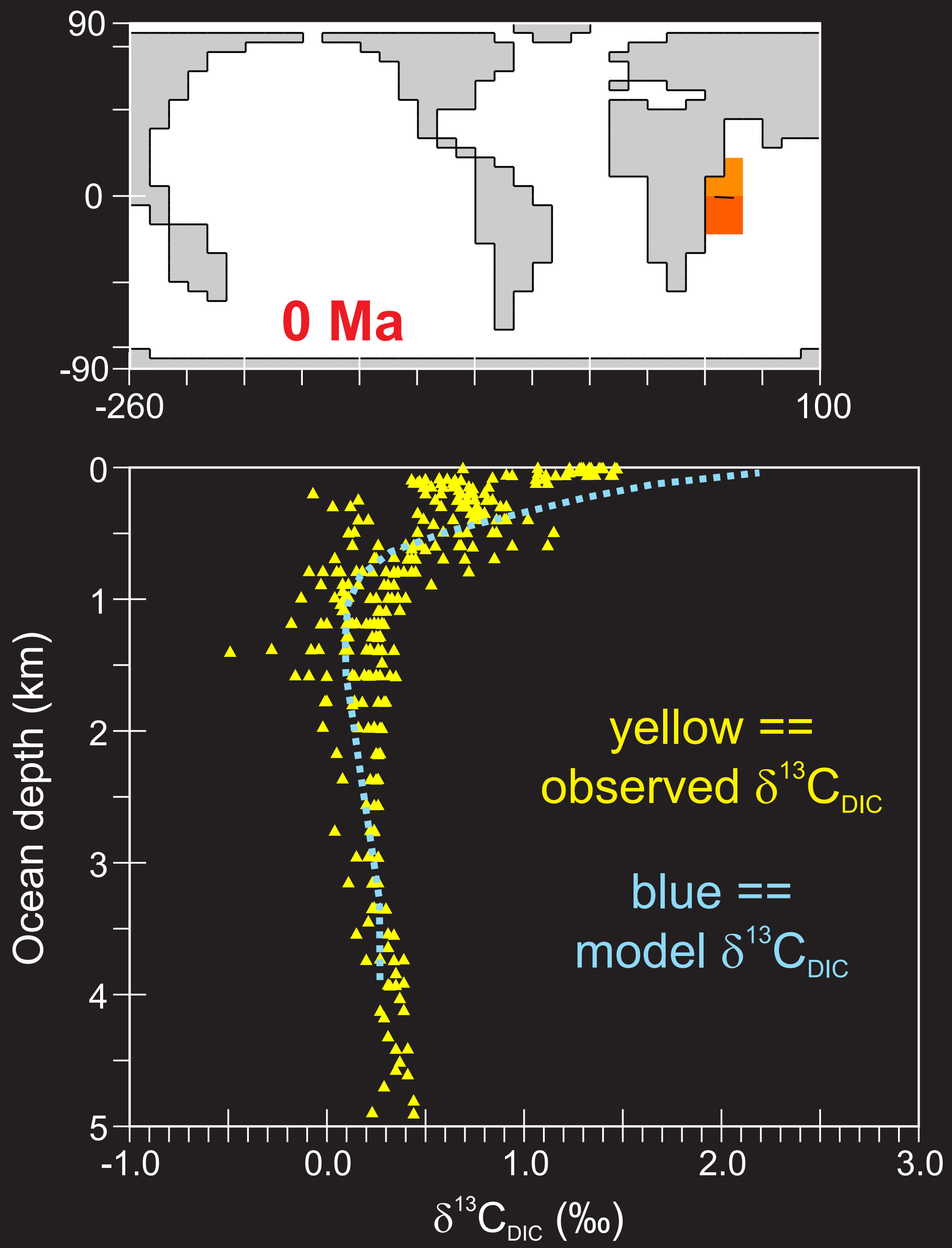




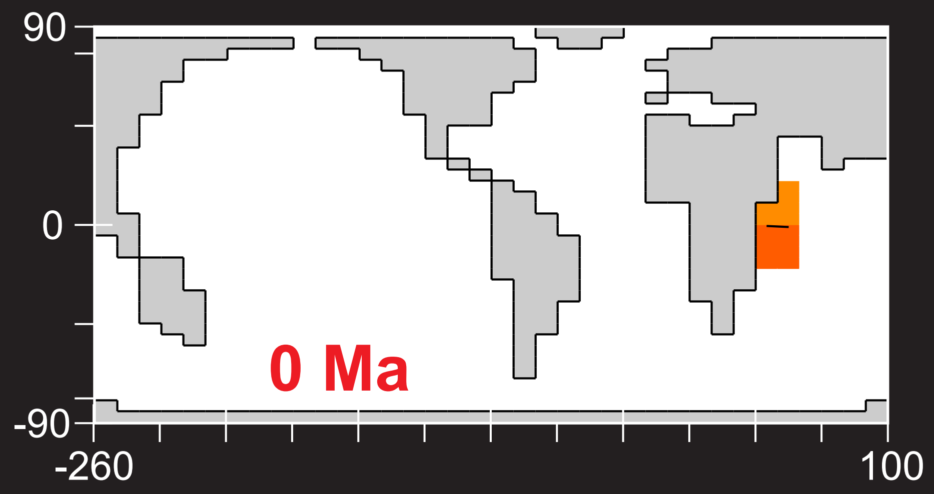


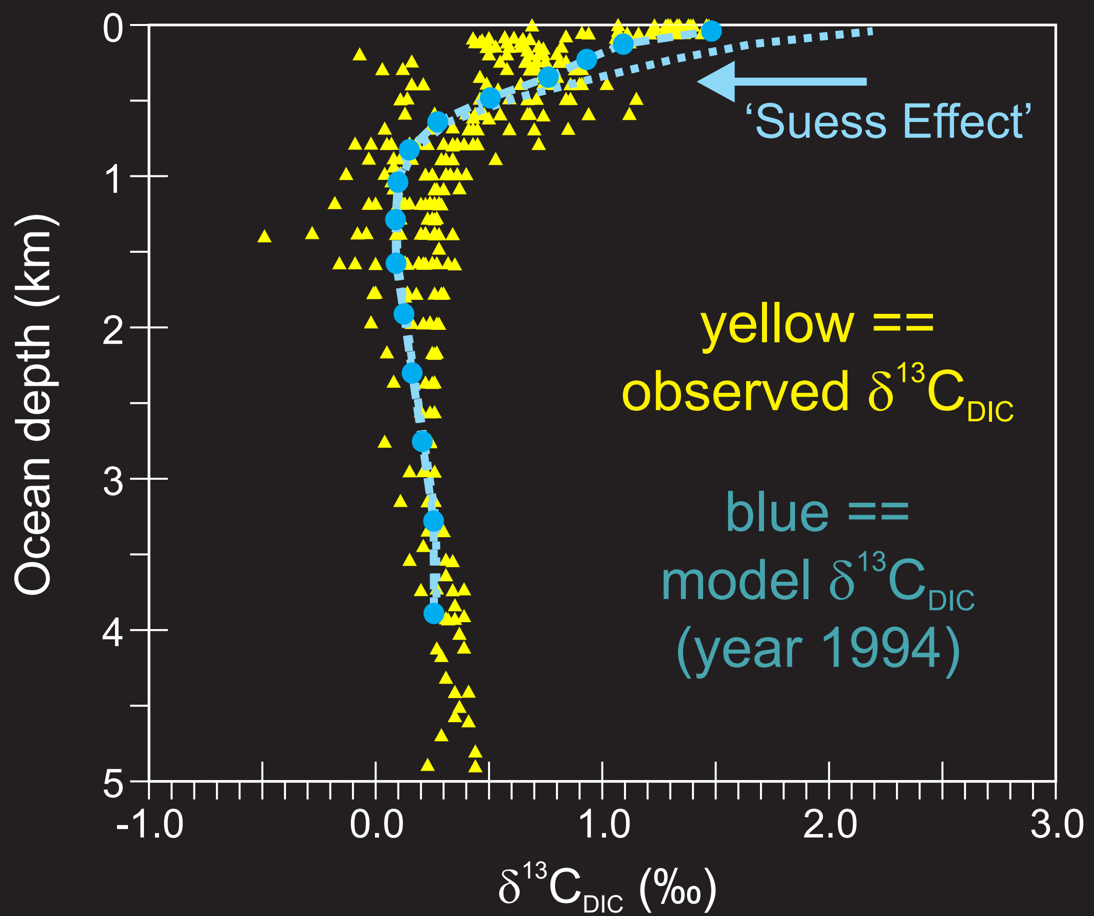
Open ocean $\delta^{13}C_{DIC}$ adjacent to modern Tanzania

models in deep time ... a 'real' example

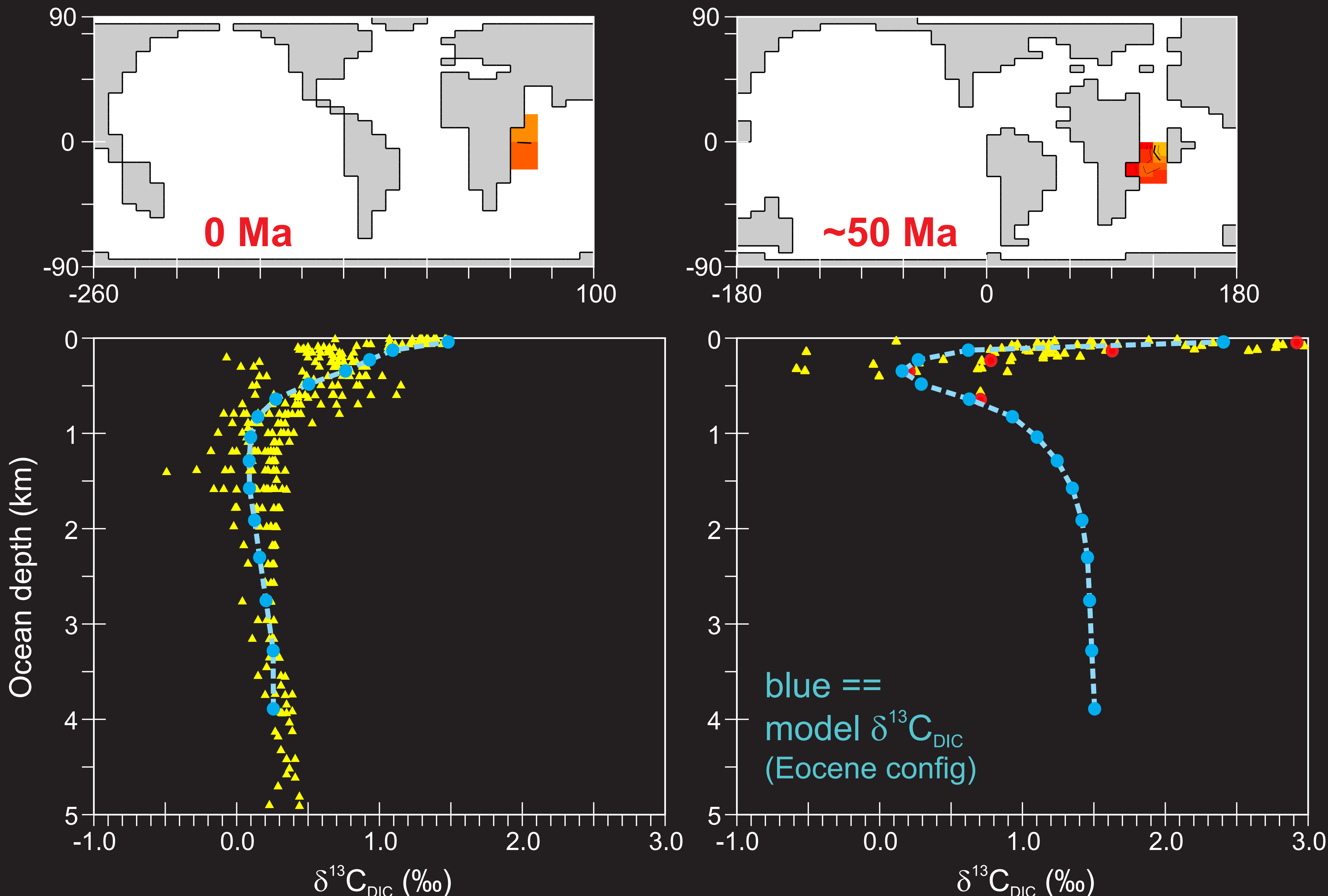


models in deep time ... a ‘real’ example

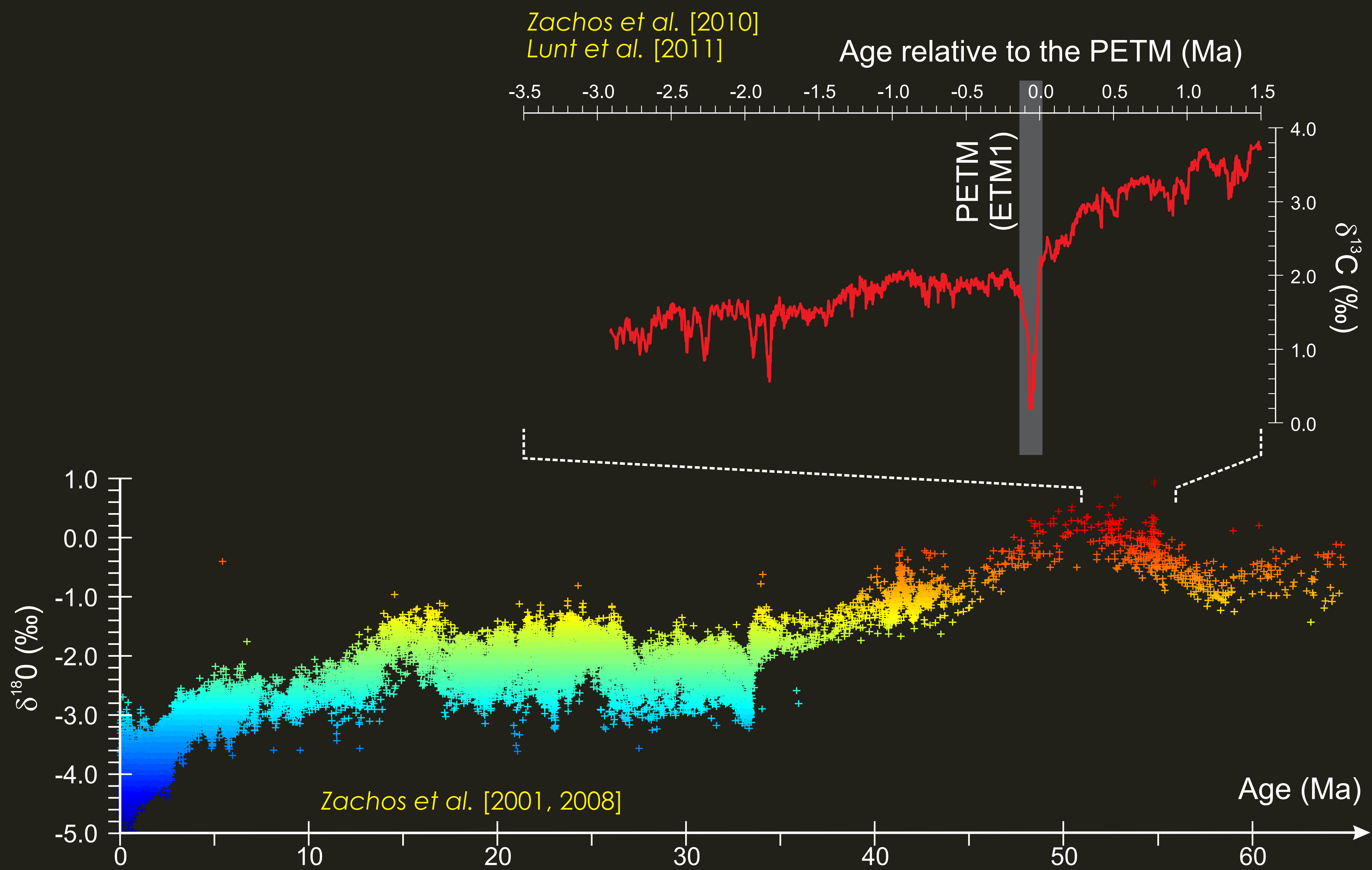




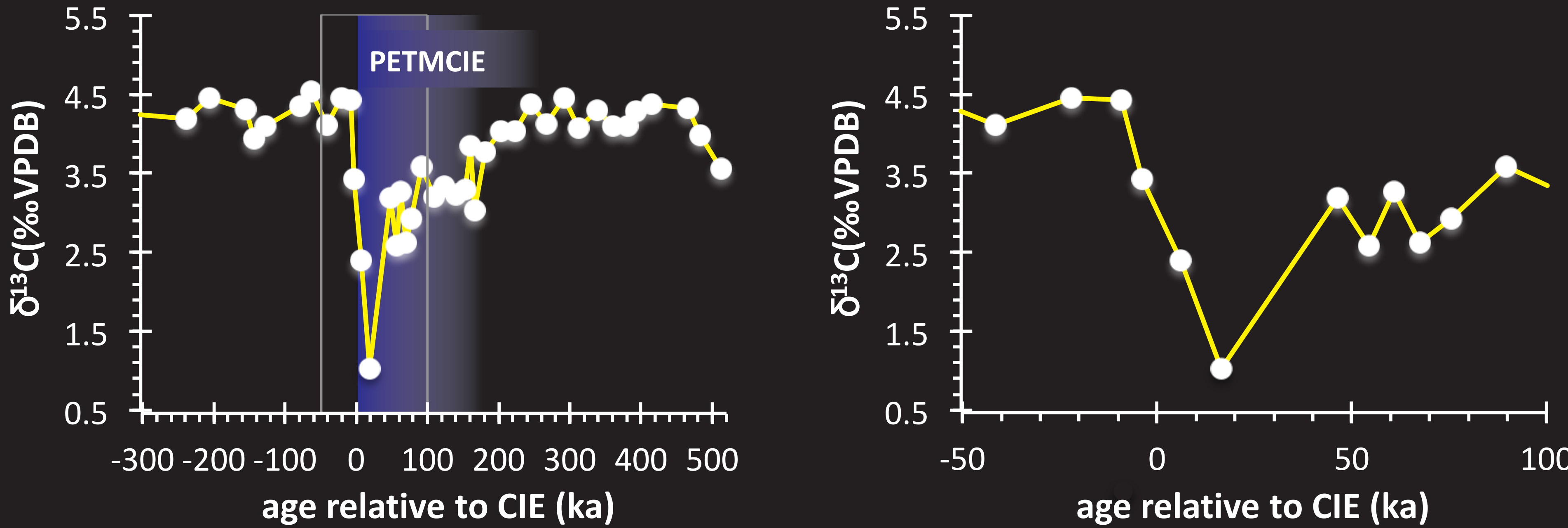
models in deep time ... a 'real' example



Background – the Paleocene-Eocene Thermal Maximum

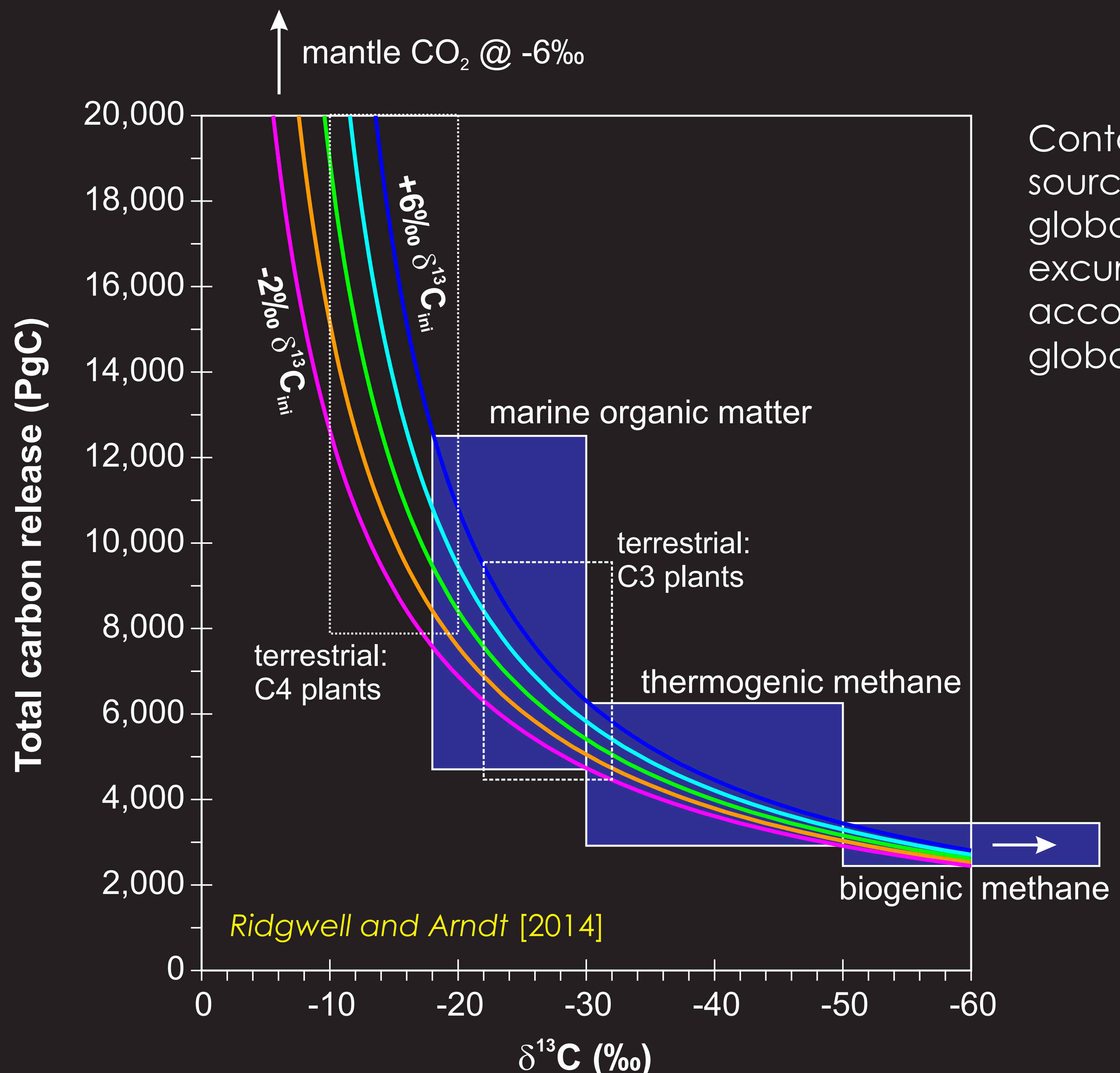


Background – 'Traditional' ($\delta^{13}C$) carbon interpretation



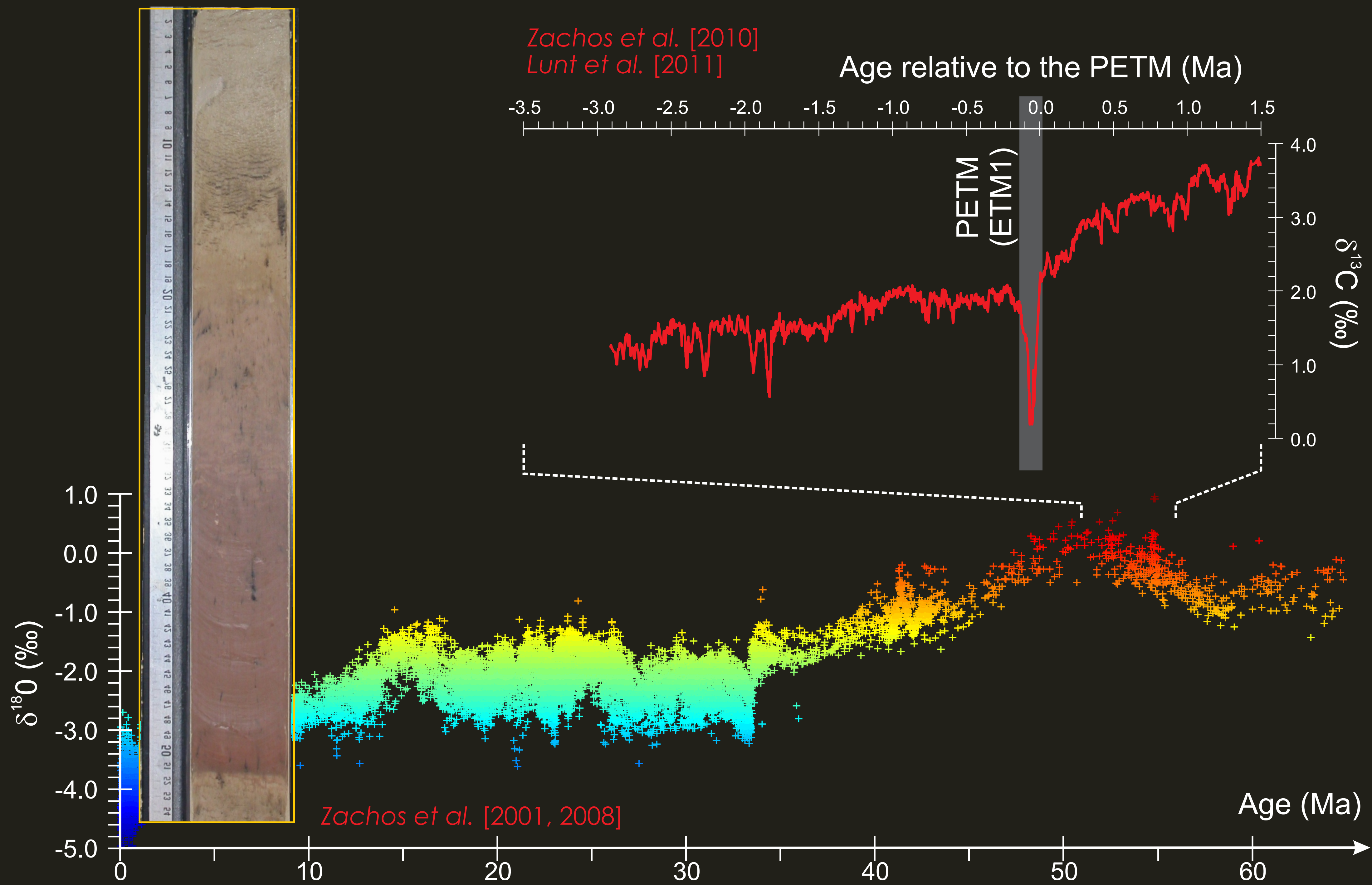
Site 401 (North East Atlantic)

Background – ‘Traditional’ (δ^{13}C) carbon interpretation

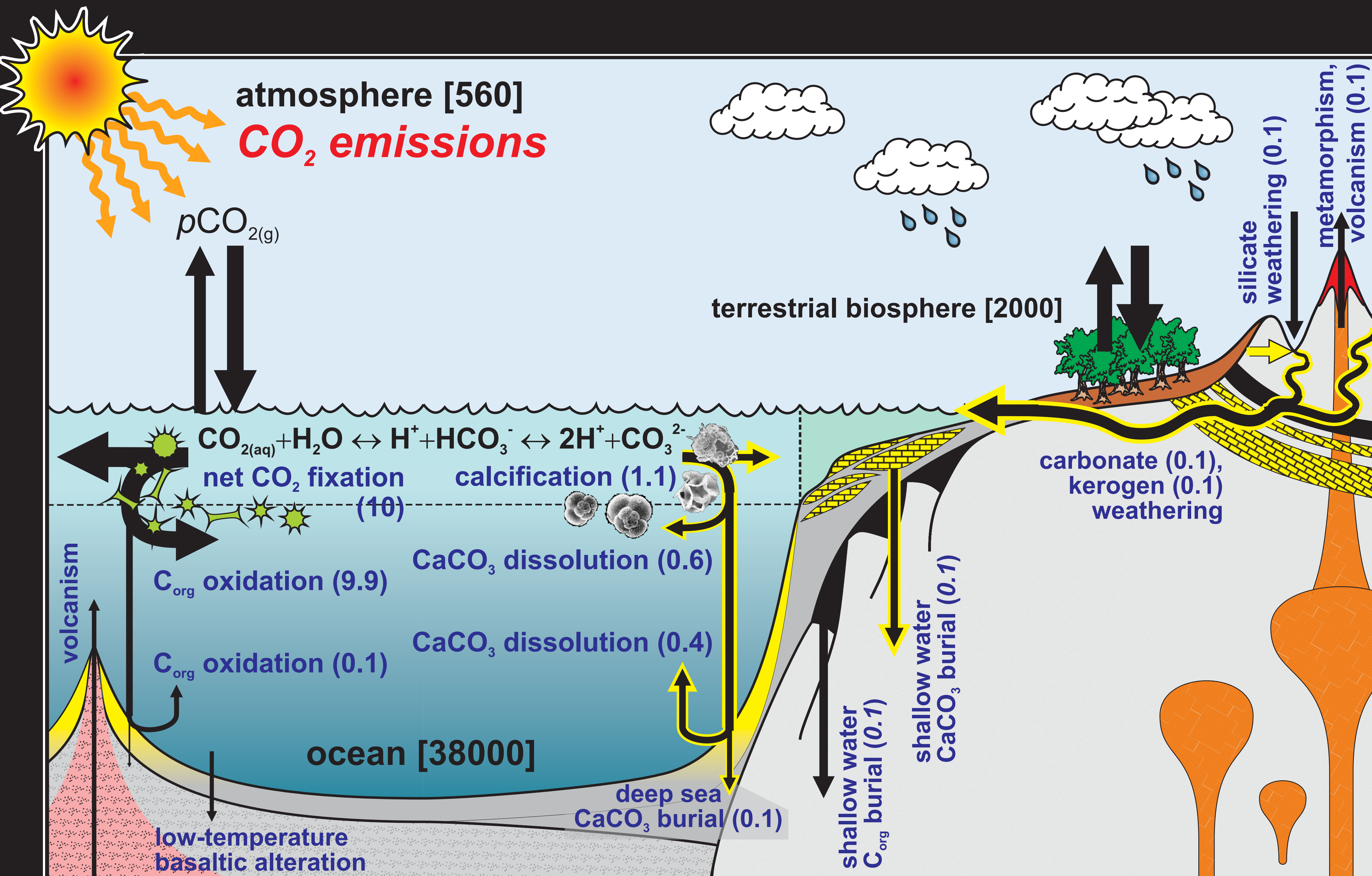


Contours of carbon release vs. source isotopic signature for a global -4‰ carbon isotopic excursion. Contours differ according to the initial mean global δ^{13}C.

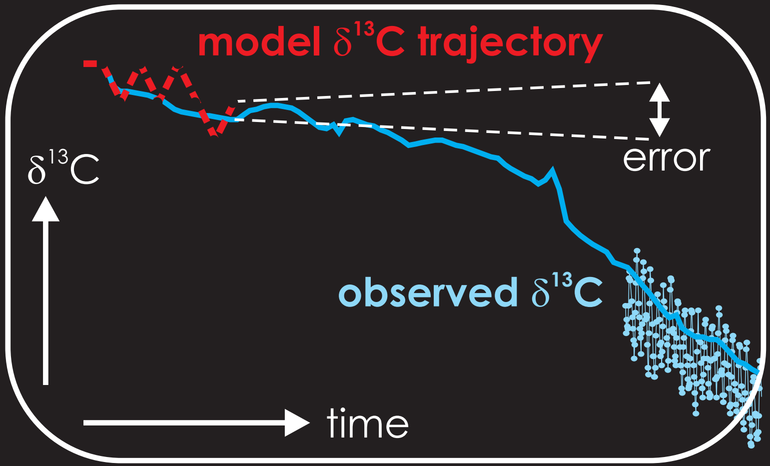
Background – ‘Traditional’ ($\delta^{13}C$) carbon interpretation



Background – 'Traditional' ($\delta^{13}C$) carbon interpretation

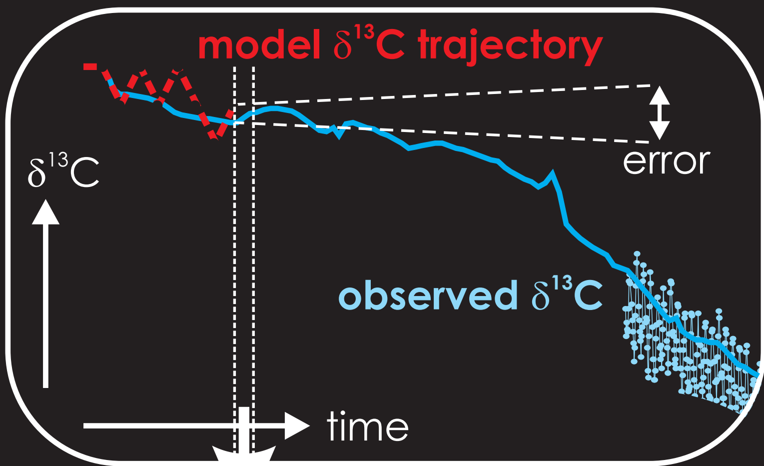


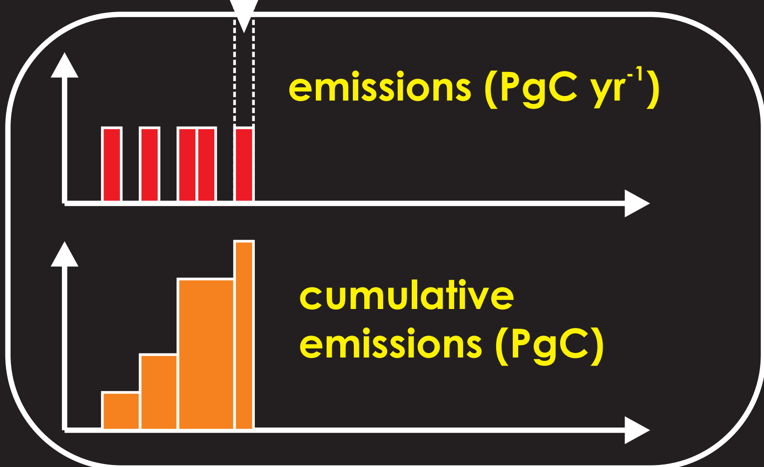
Geochemical data assimilation in deep time



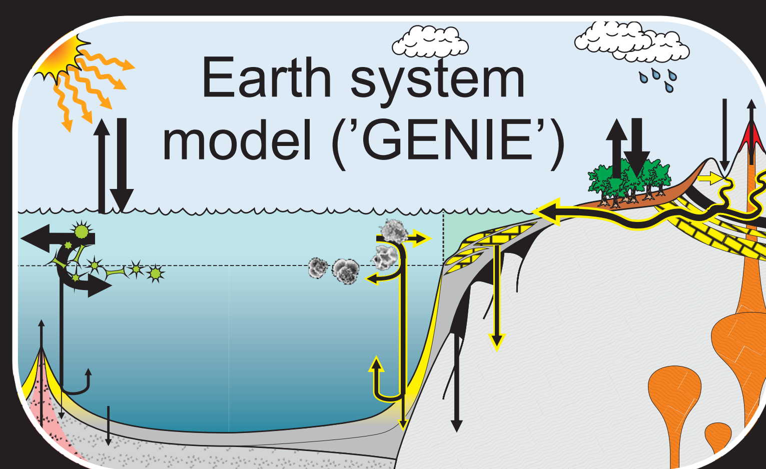
1. Calculate model-data error:
too high ⇒ emit carbon
'OK' ⇒ do nothing
(too low ⇒ remove carbon)

Geochemical data assimilation in deep time



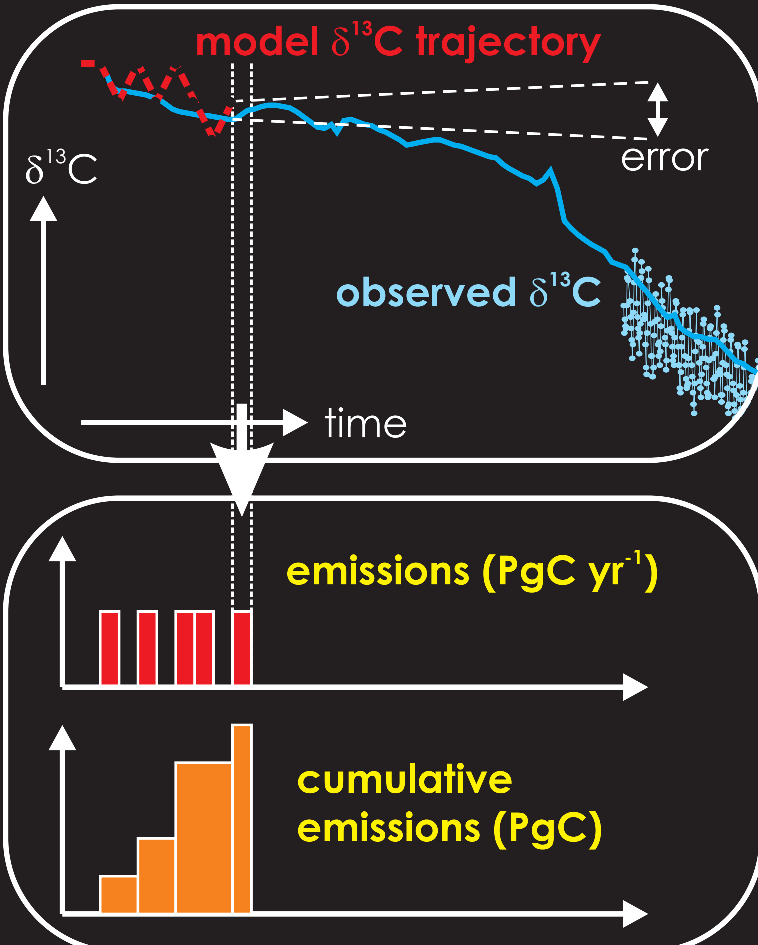


2. If CO_2 emissions required:
Add CO_2 to atmosphere
in an Earth system model

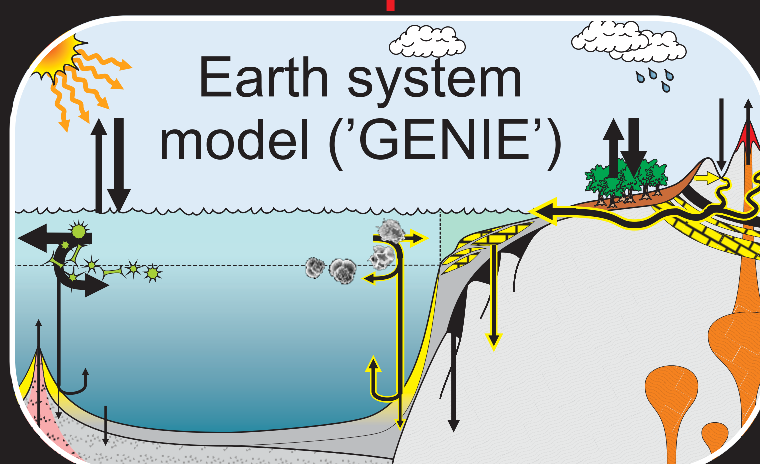


assume:
δ13C signature
of fossil fuels
for emissions

Geochemical data assimilation in deep time

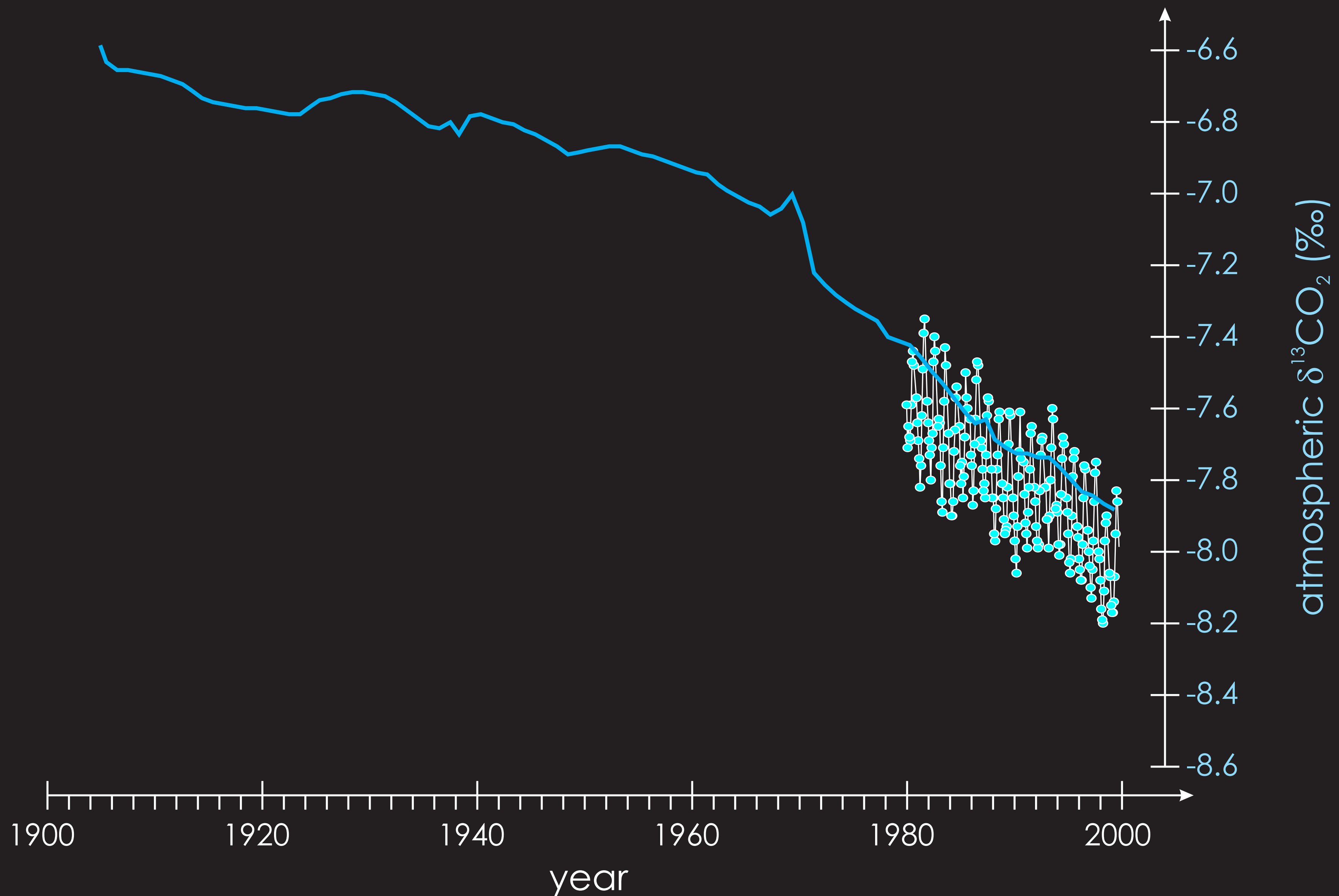


3. Calculate new atmospheric CO_2 $\delta^{13}C$ value in model
<REPEAT>

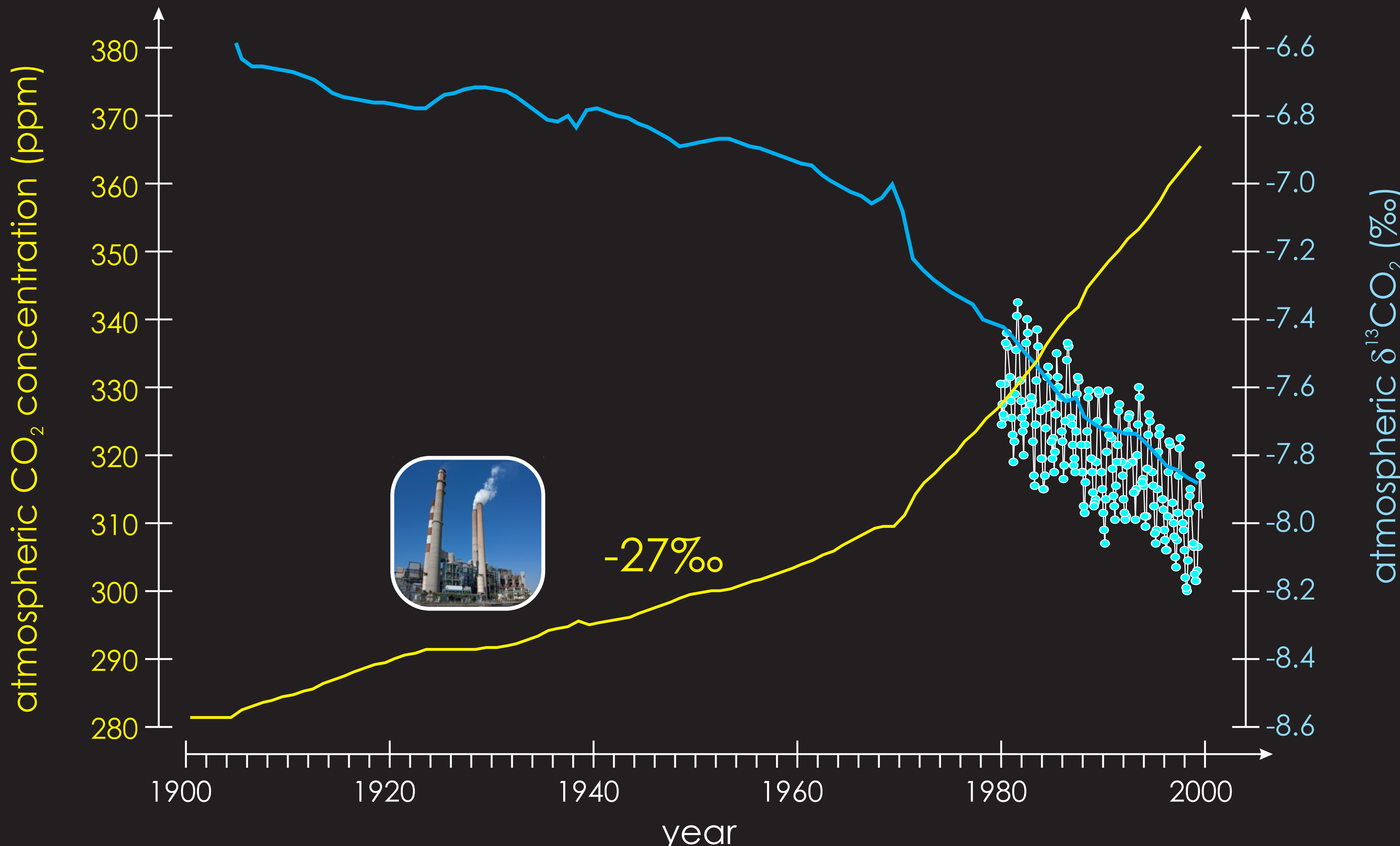


assume:
$\delta^{13}C$ signature of fossil fuels for emissions

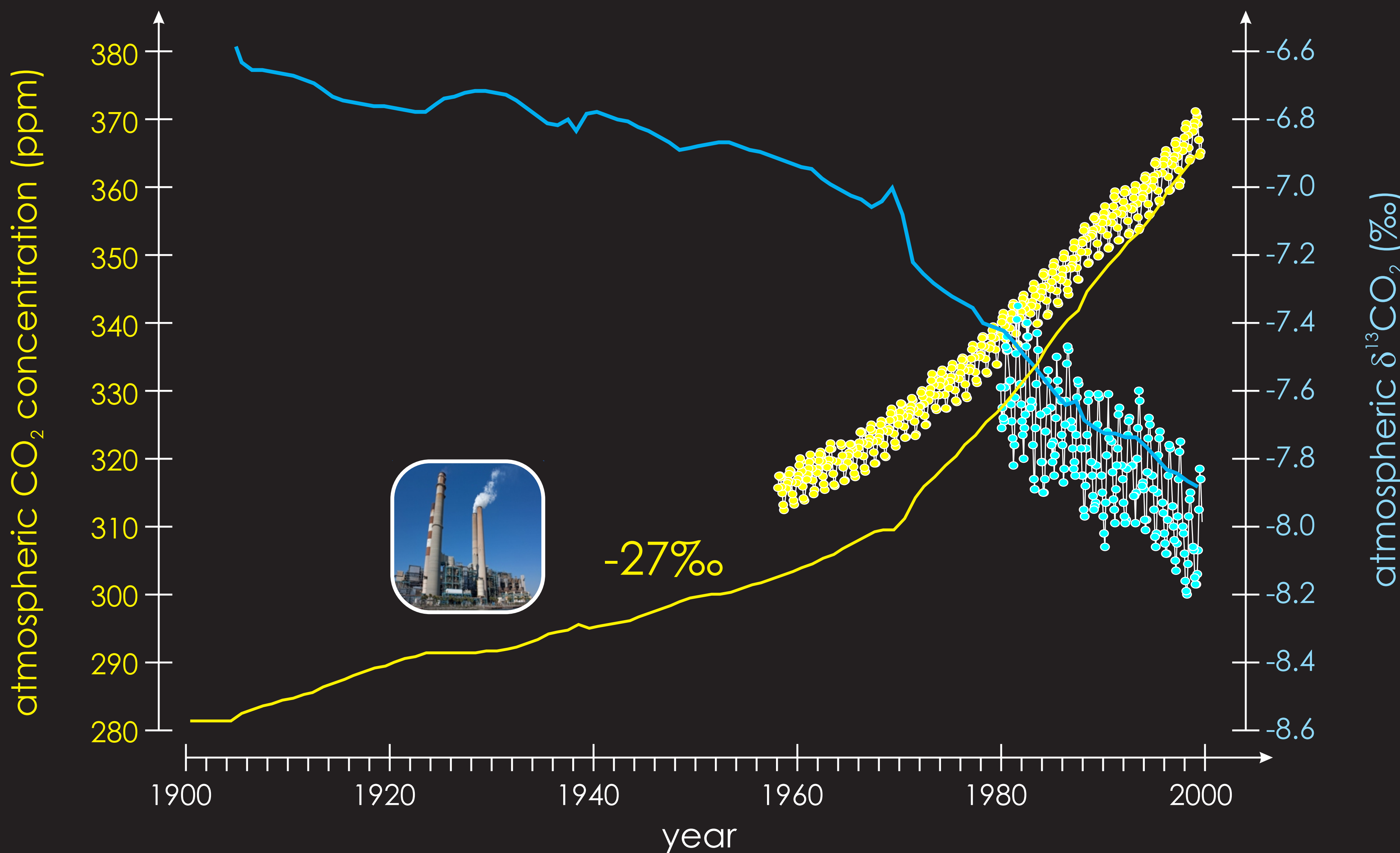
Geochemical data assimilation in deep time



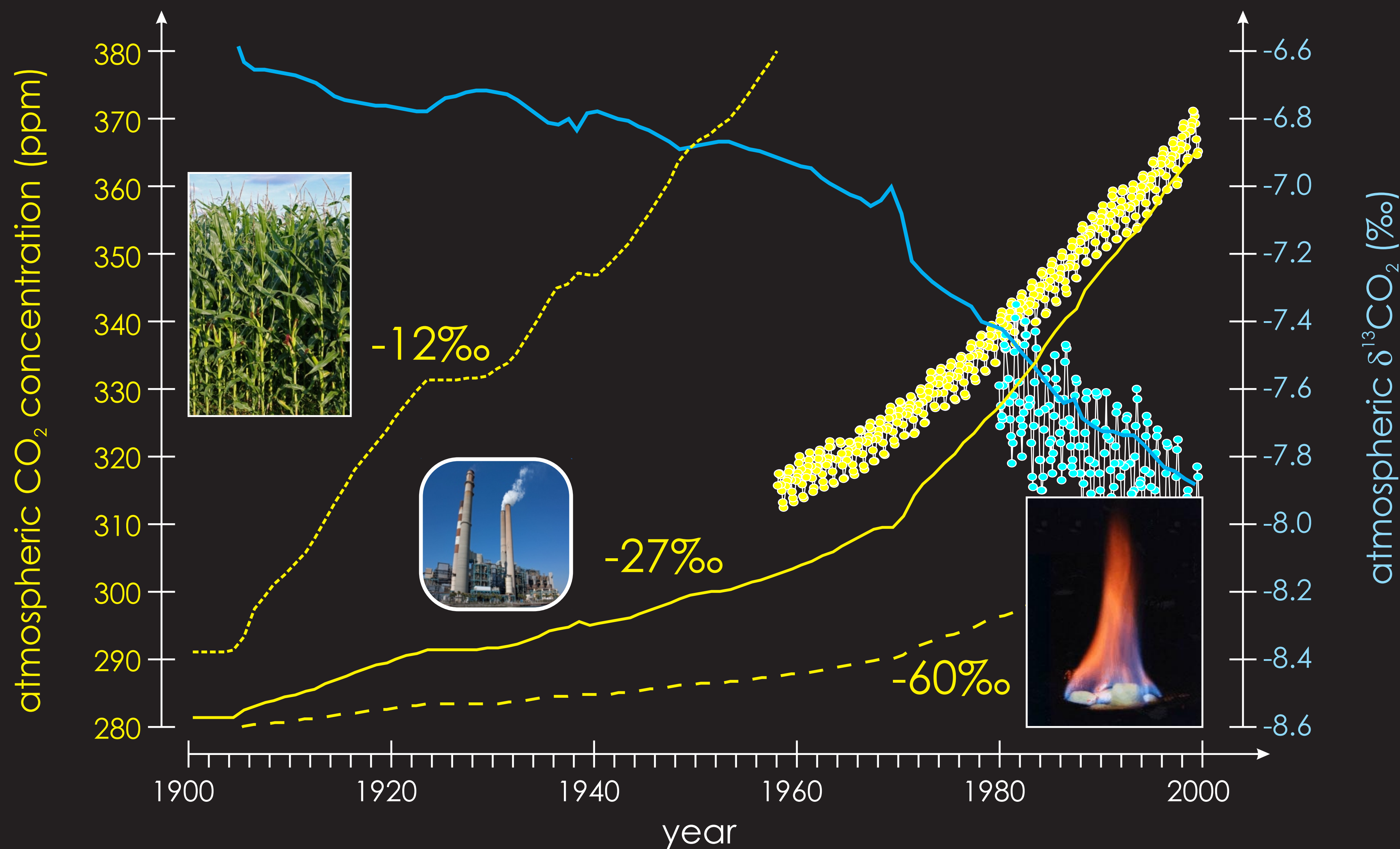
Geochemical data assimilation in deep time



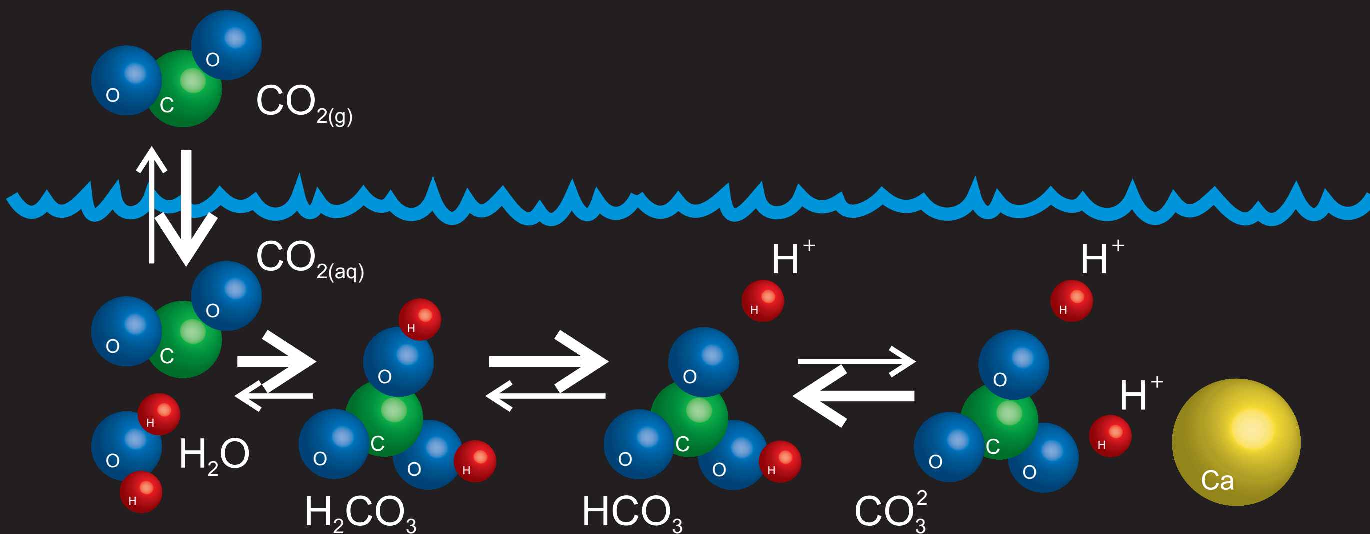
Geochemical data assimilation in deep time



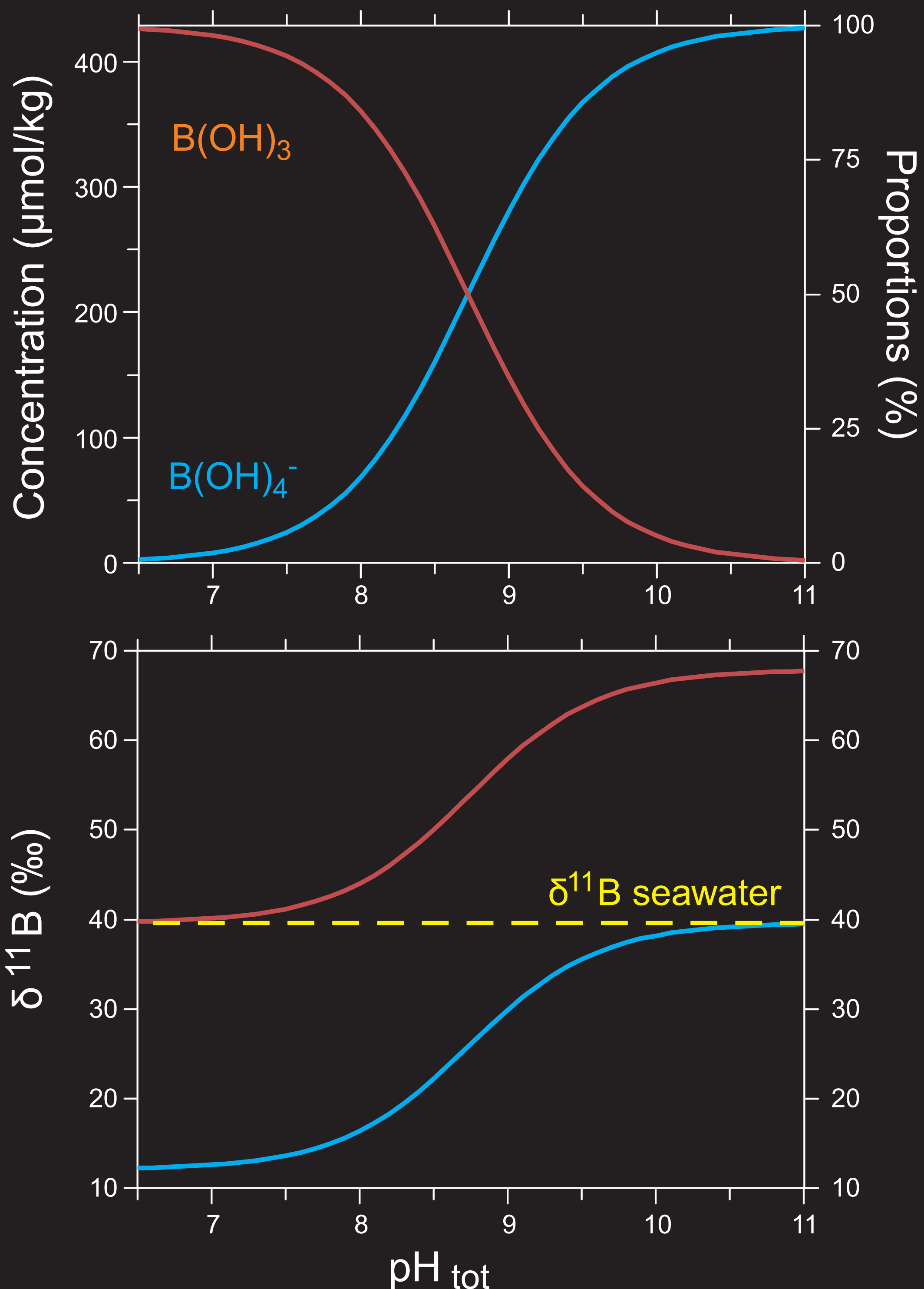
Geochemical data assimilation in deep time



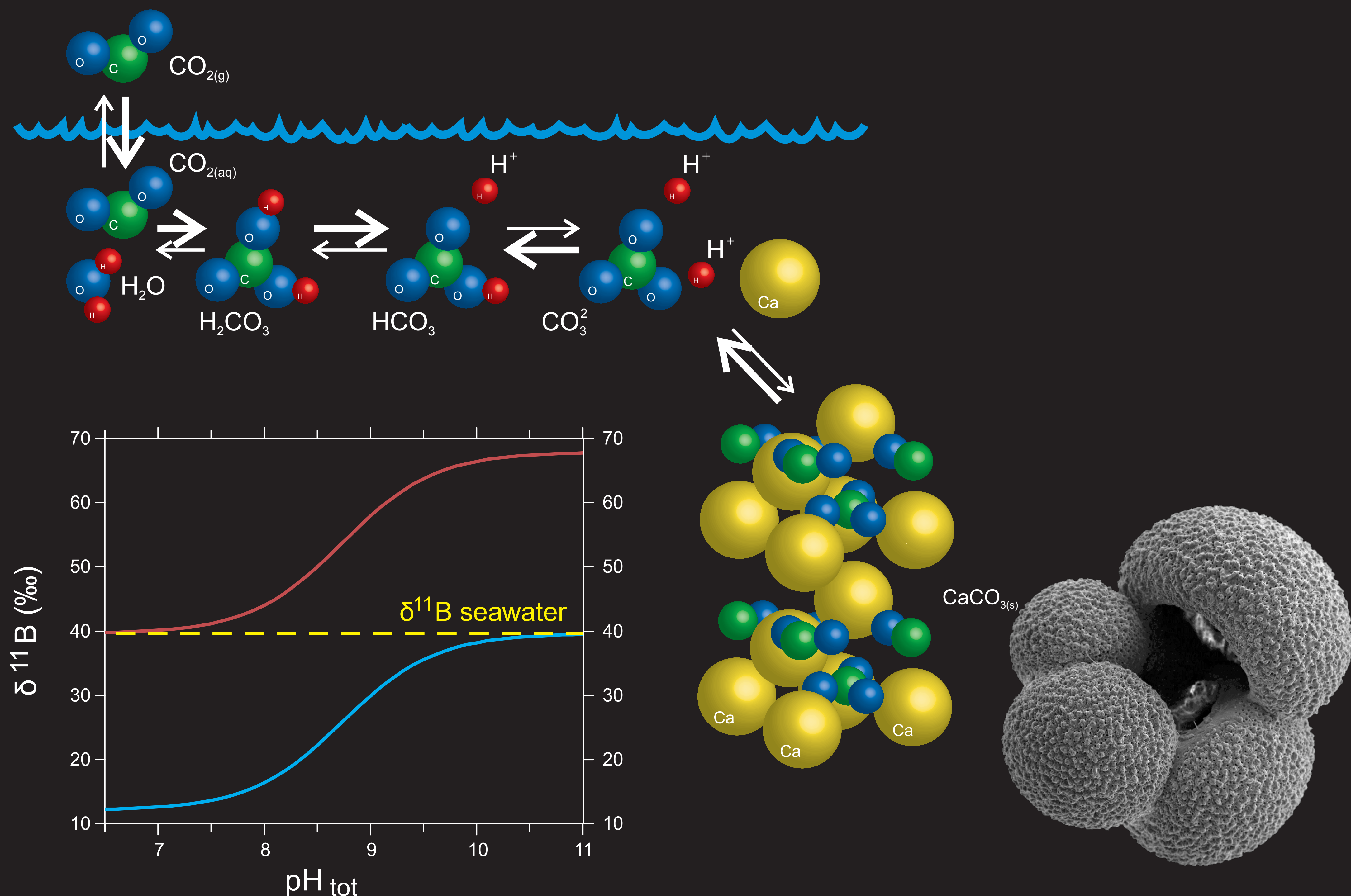
Boron, isotopes, and paleo pH



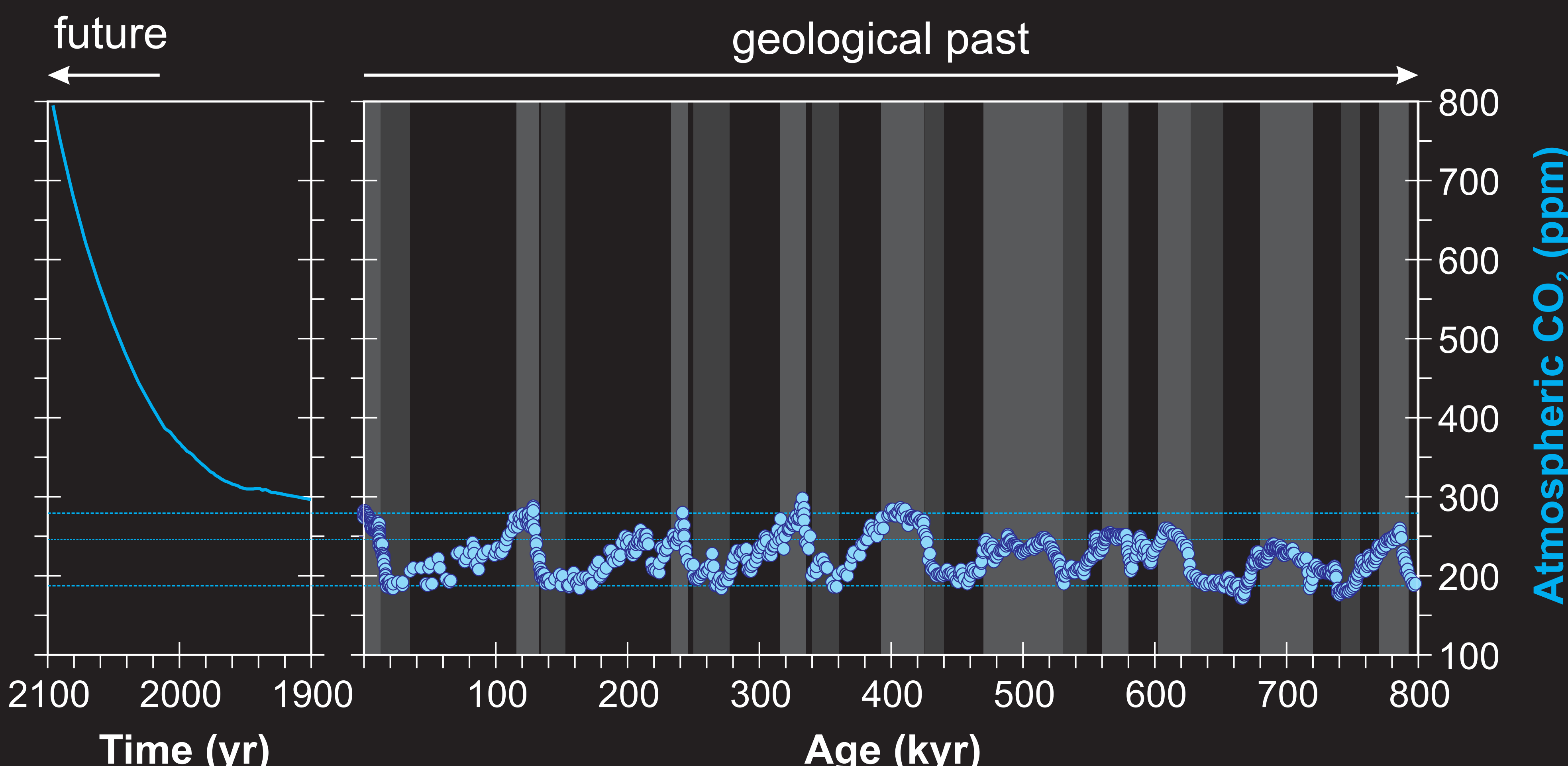
Boron, isotopes, and paleo pH



Boron, isotopes, and paleo pH

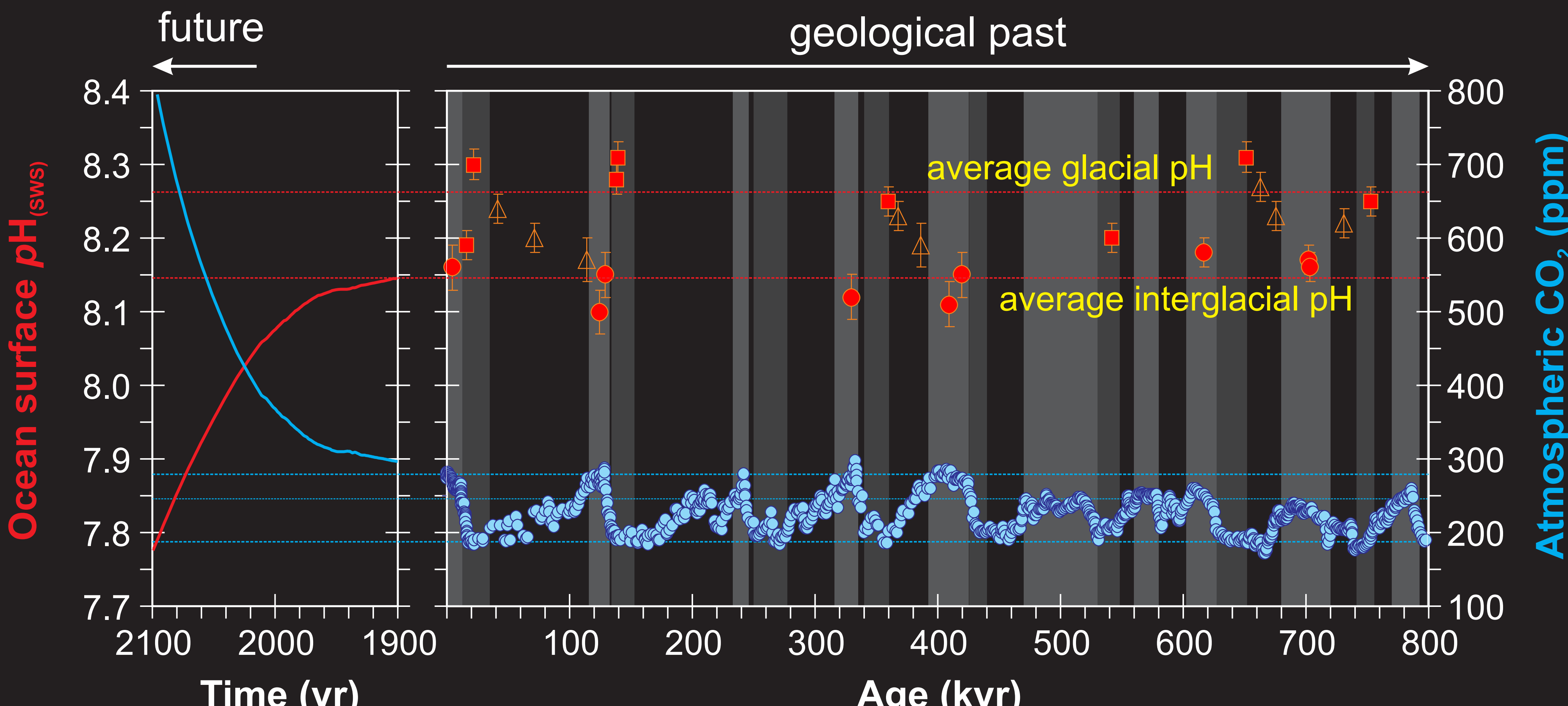


Boron, isotopes, and paleo pH



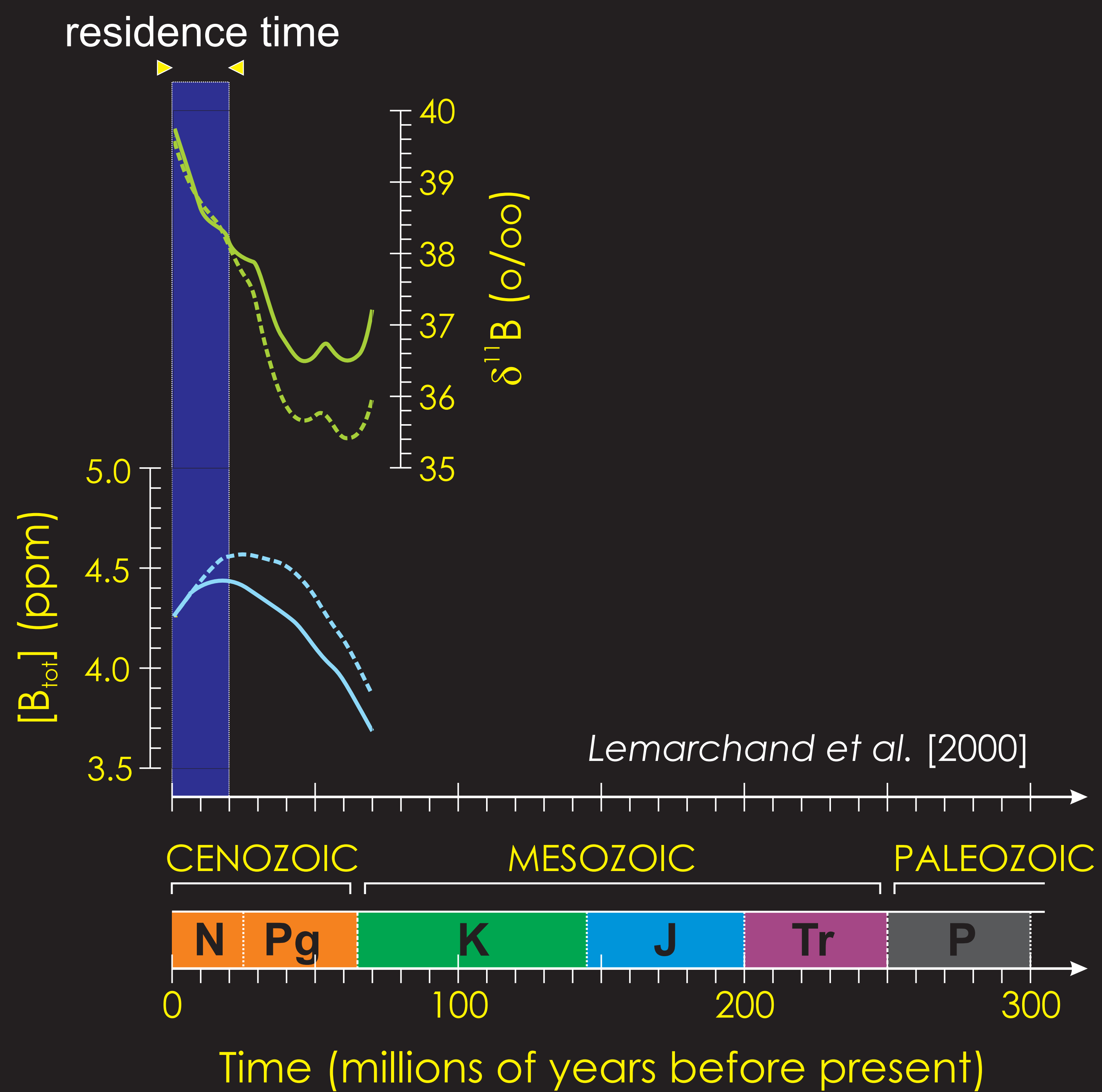
Barker and Ridgwell [2012], adapted from *Hönisch and Hemming* [2005]

Boron, isotopes, and paleo pH

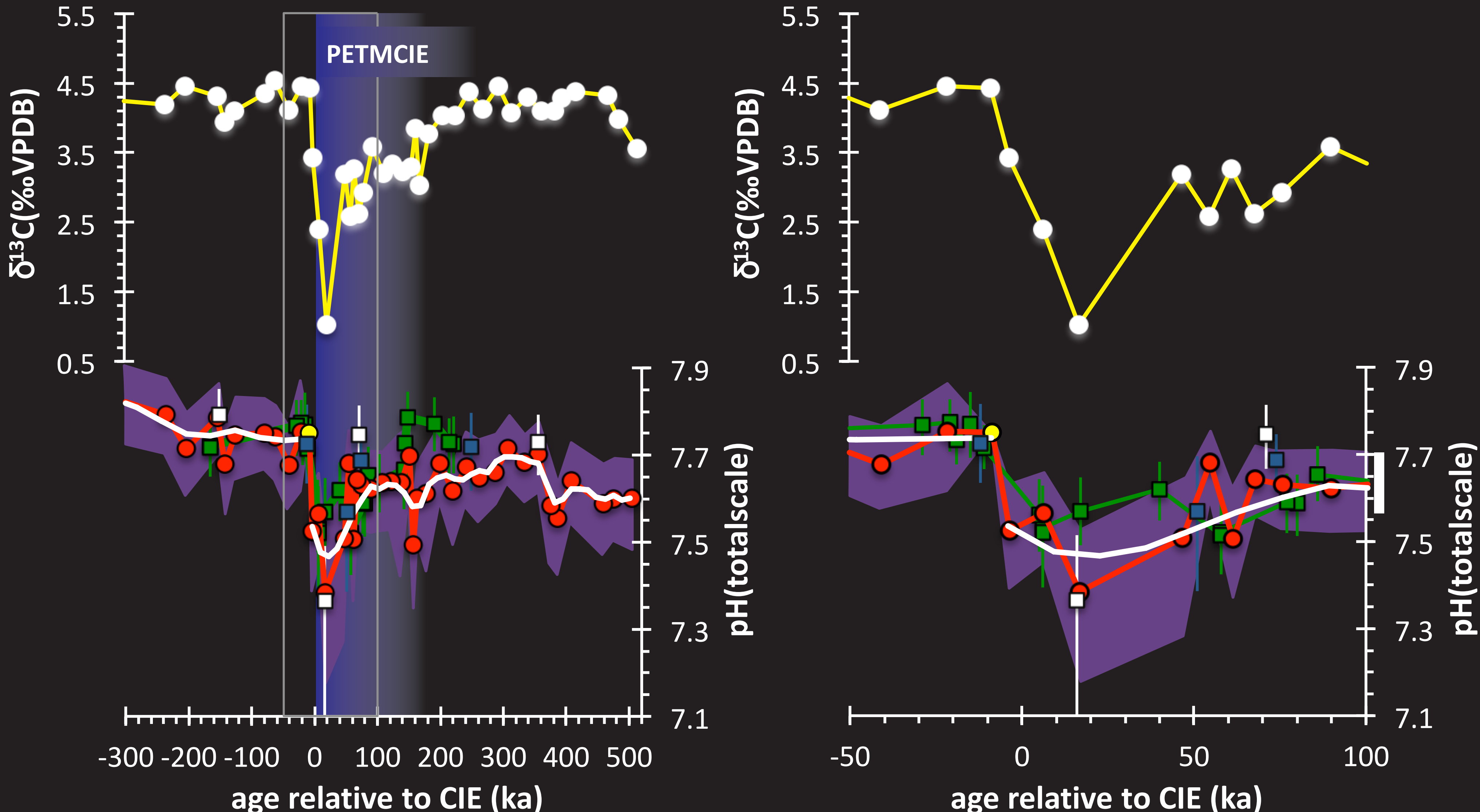


Barker and Ridgwell [2012], adapted from *Hönisch and Hemming* [2005]

Boron, isotopes, and paleo pH



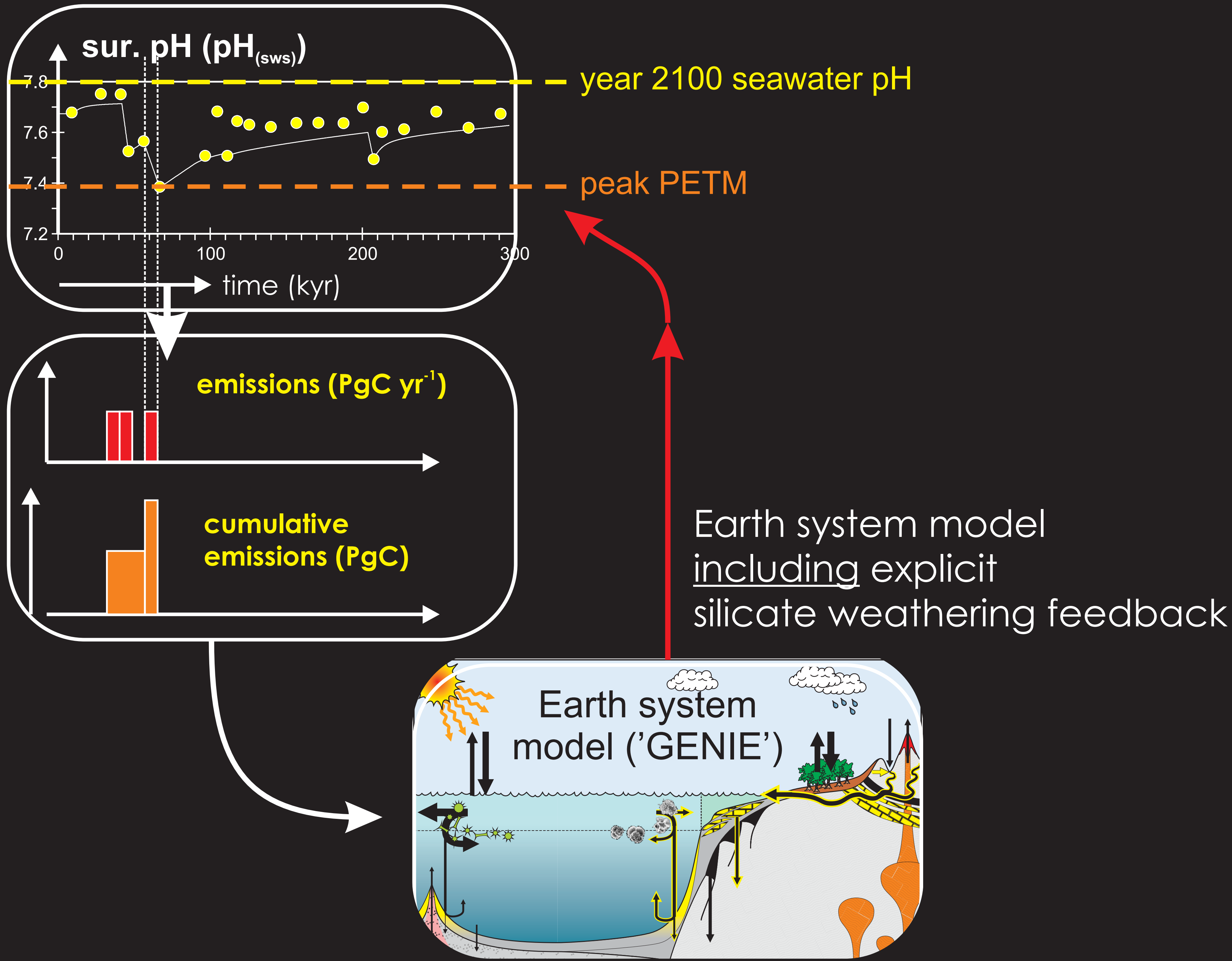
Boron, isotopes, and paleo pH



Site 401 (NE Atlantic) [unpublihed]

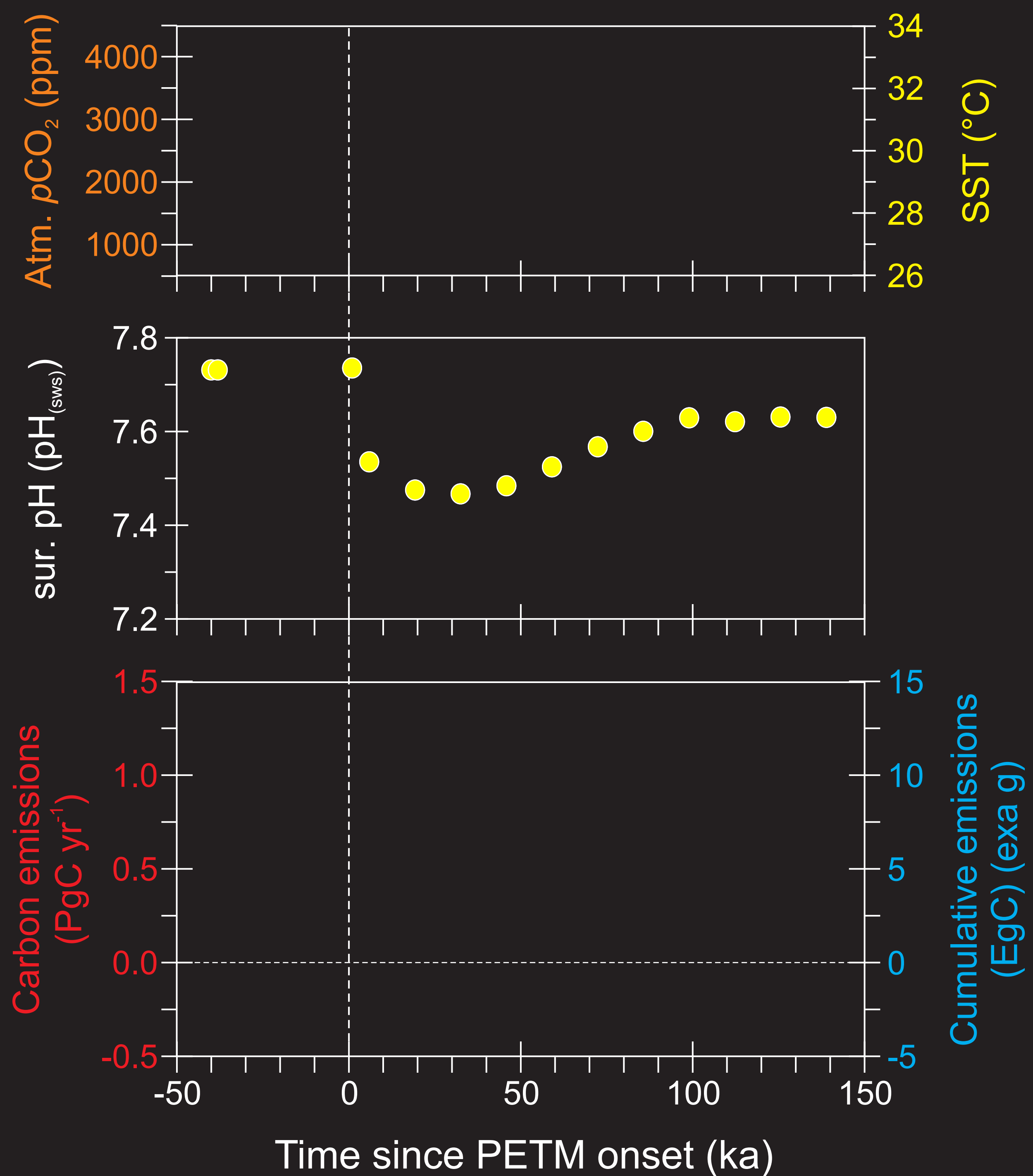
Site 865 (Eq. Pacific) Site 1263 (ES Atlantic) Site 1209 (N Pacific) [*Penman et al.*, 2014]

Assimilating surface ocean pH change (only)

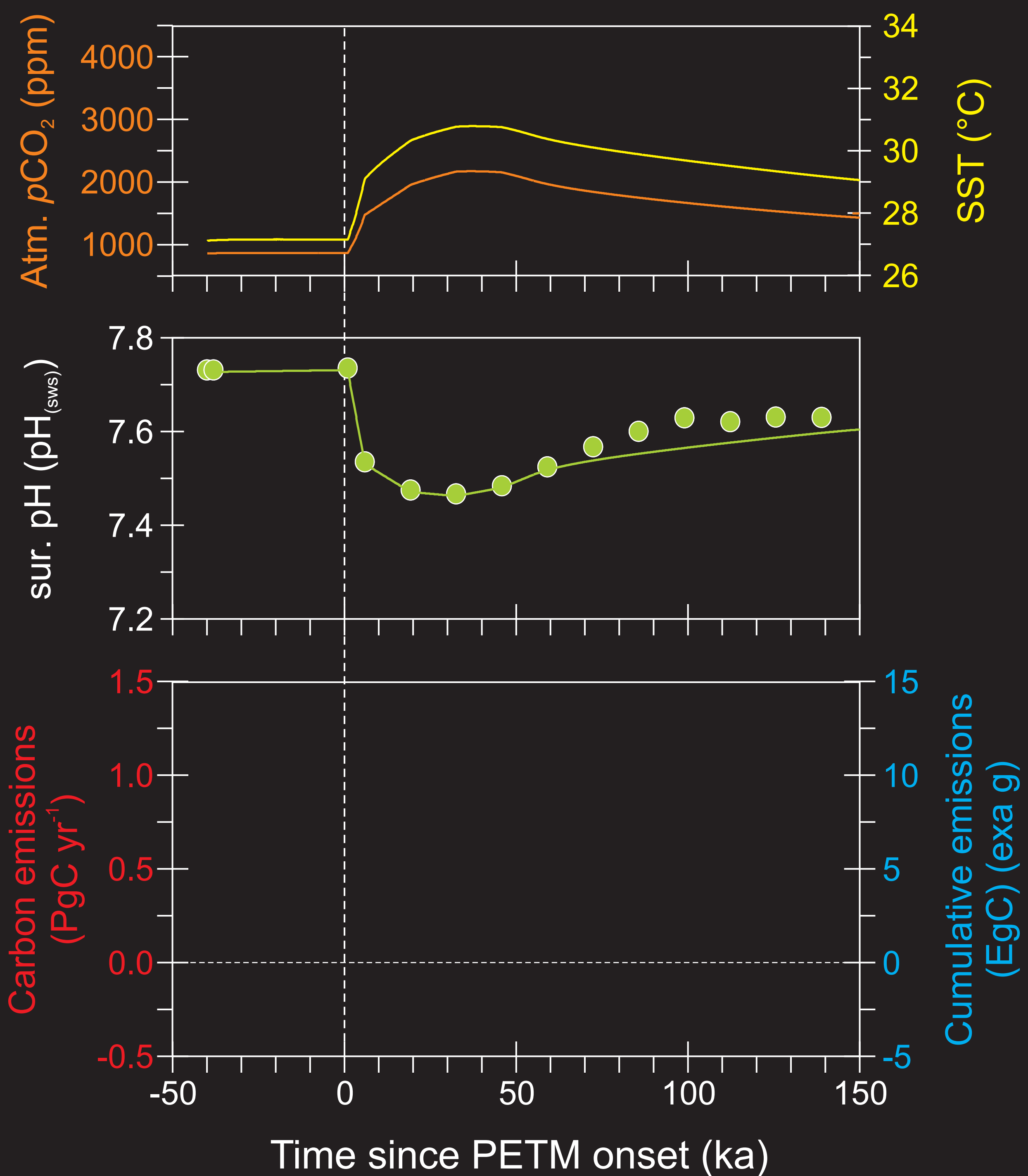


Assimilating surface ocean pH change (only)

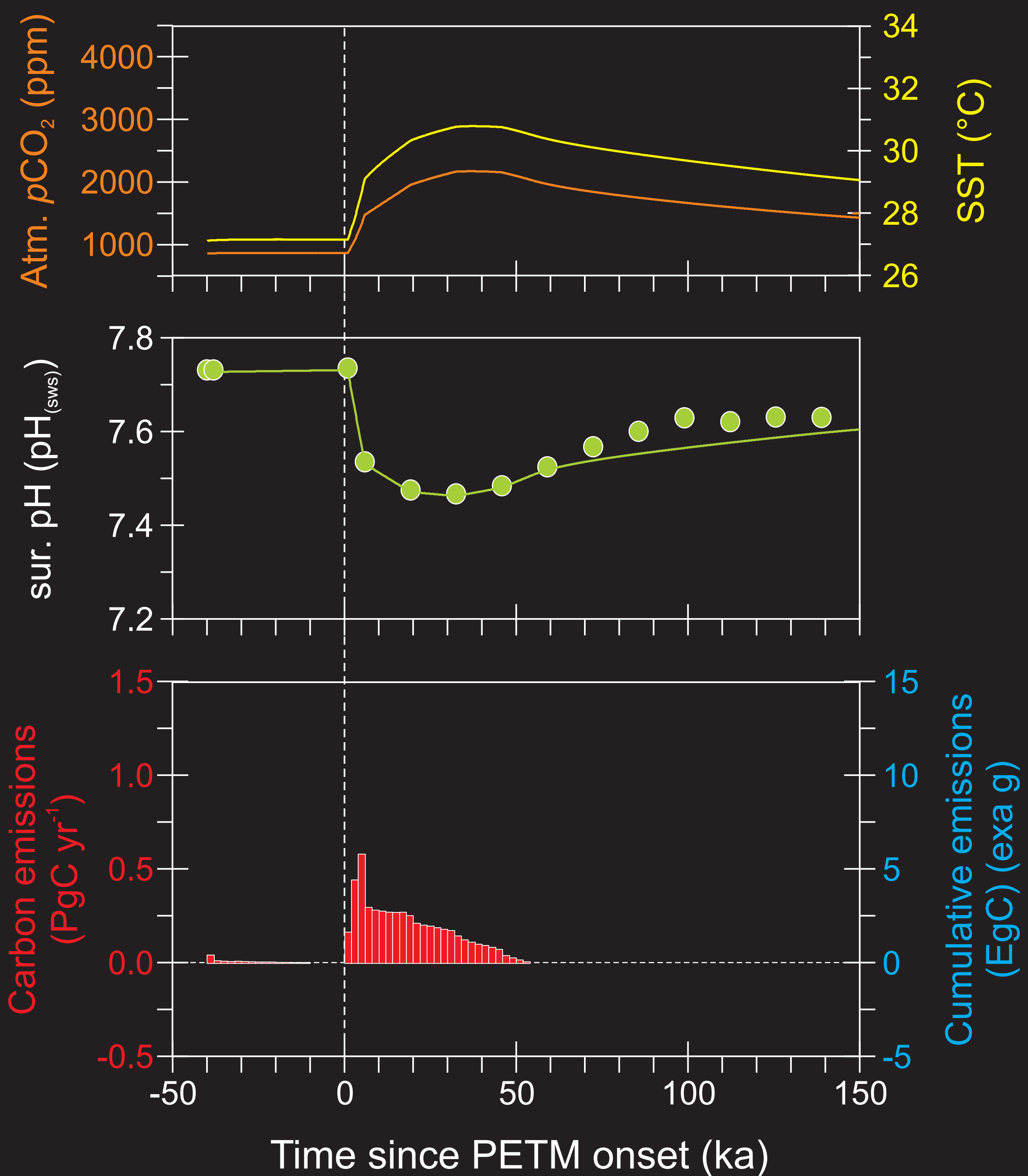
MPI:
Monday
14th Sept



Assimilating surface ocean pH change (only)

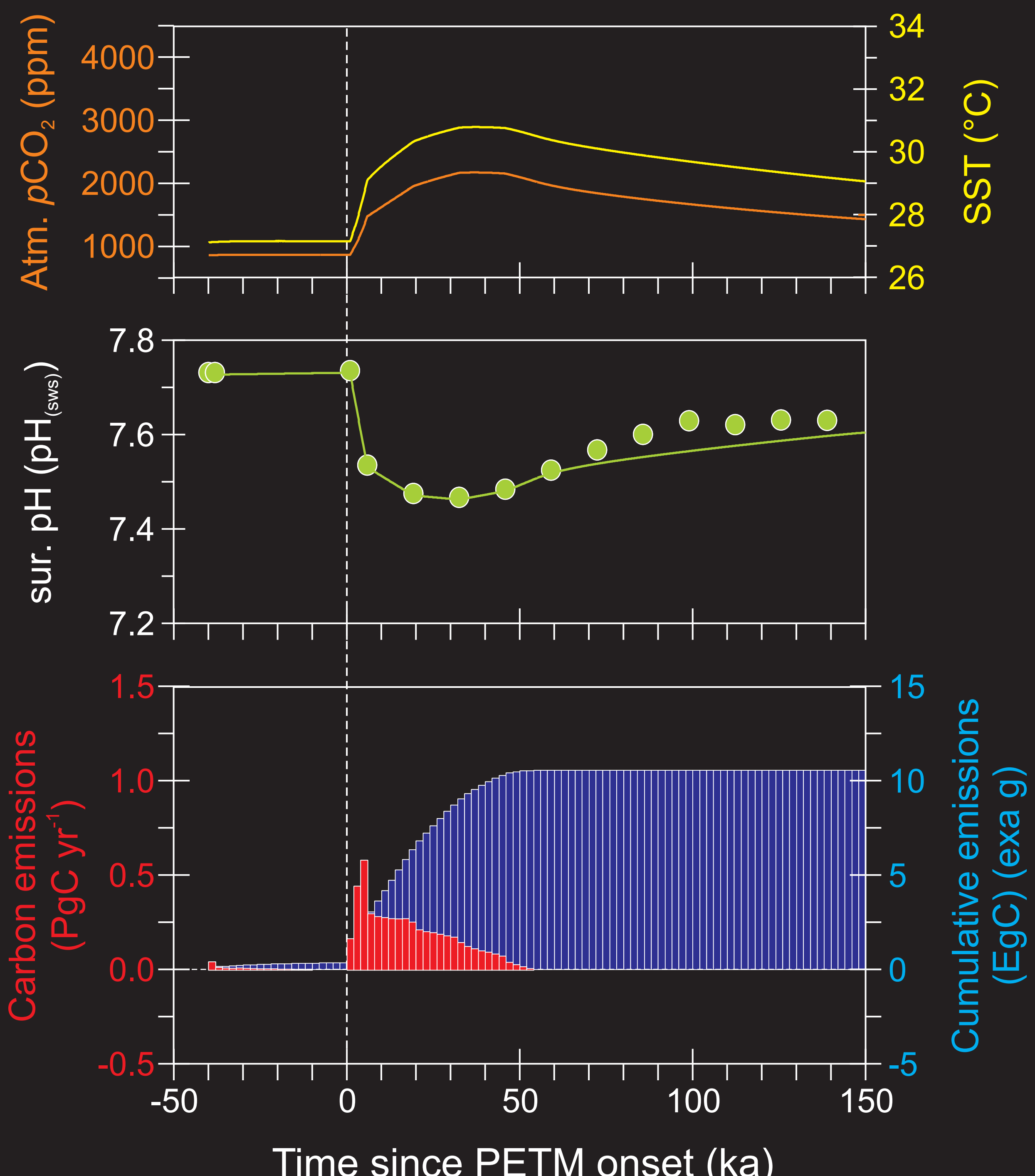


Assimilating surface ocean pH change (only)

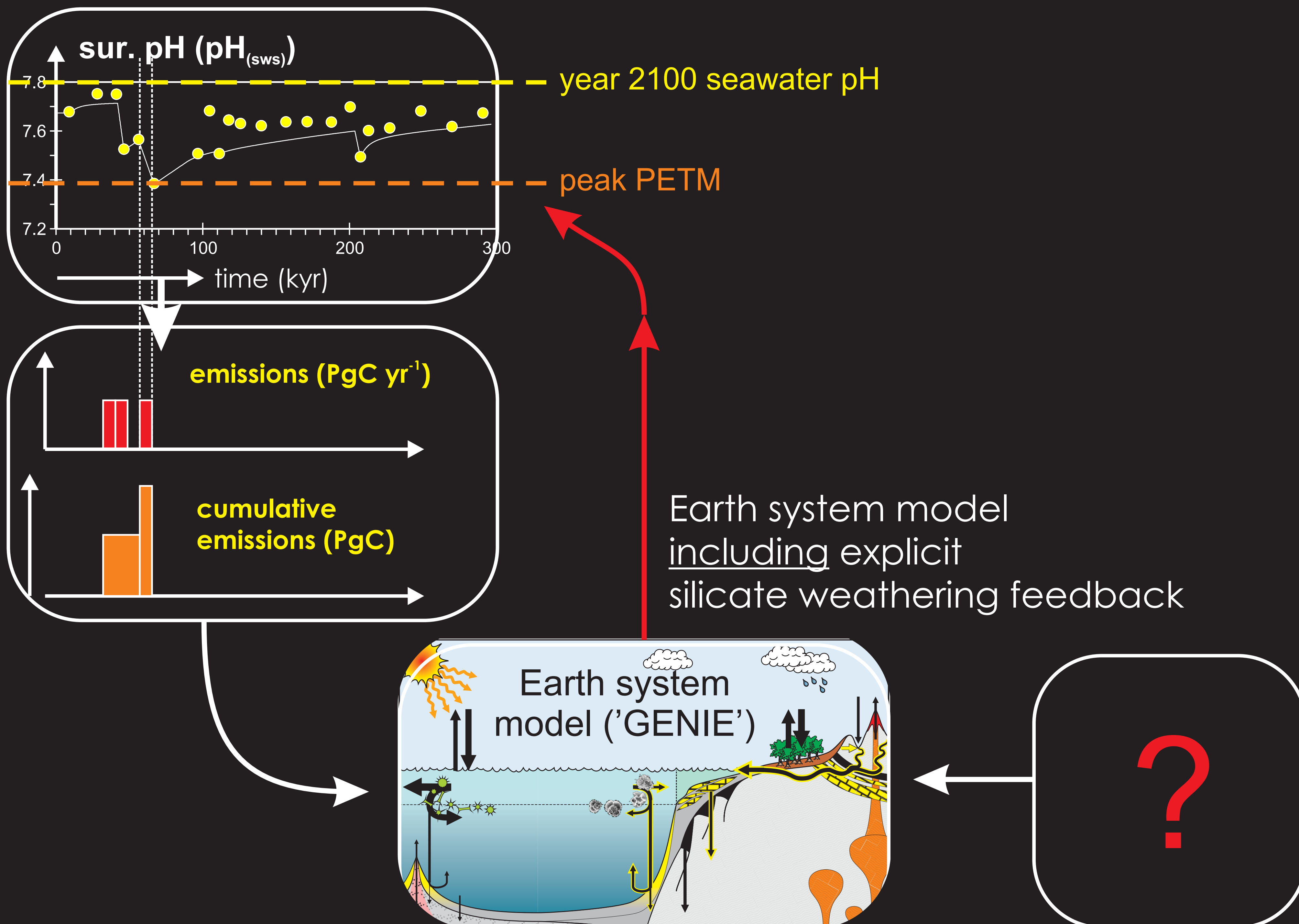


Assimilating surface ocean pH change (only)

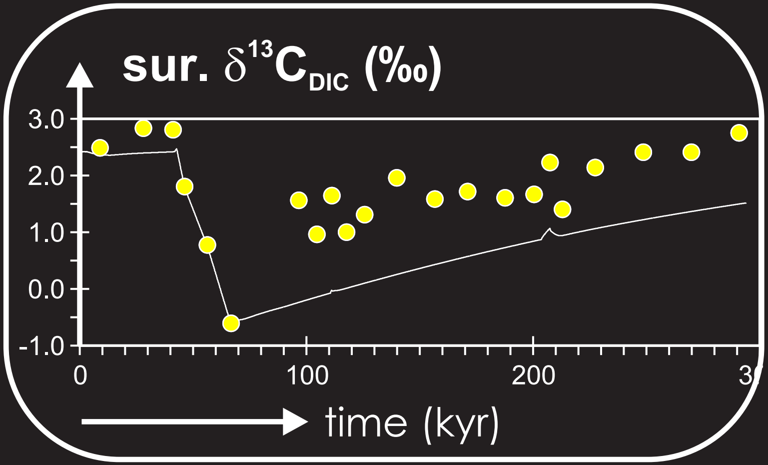
MPI:
Monday
14th Sept



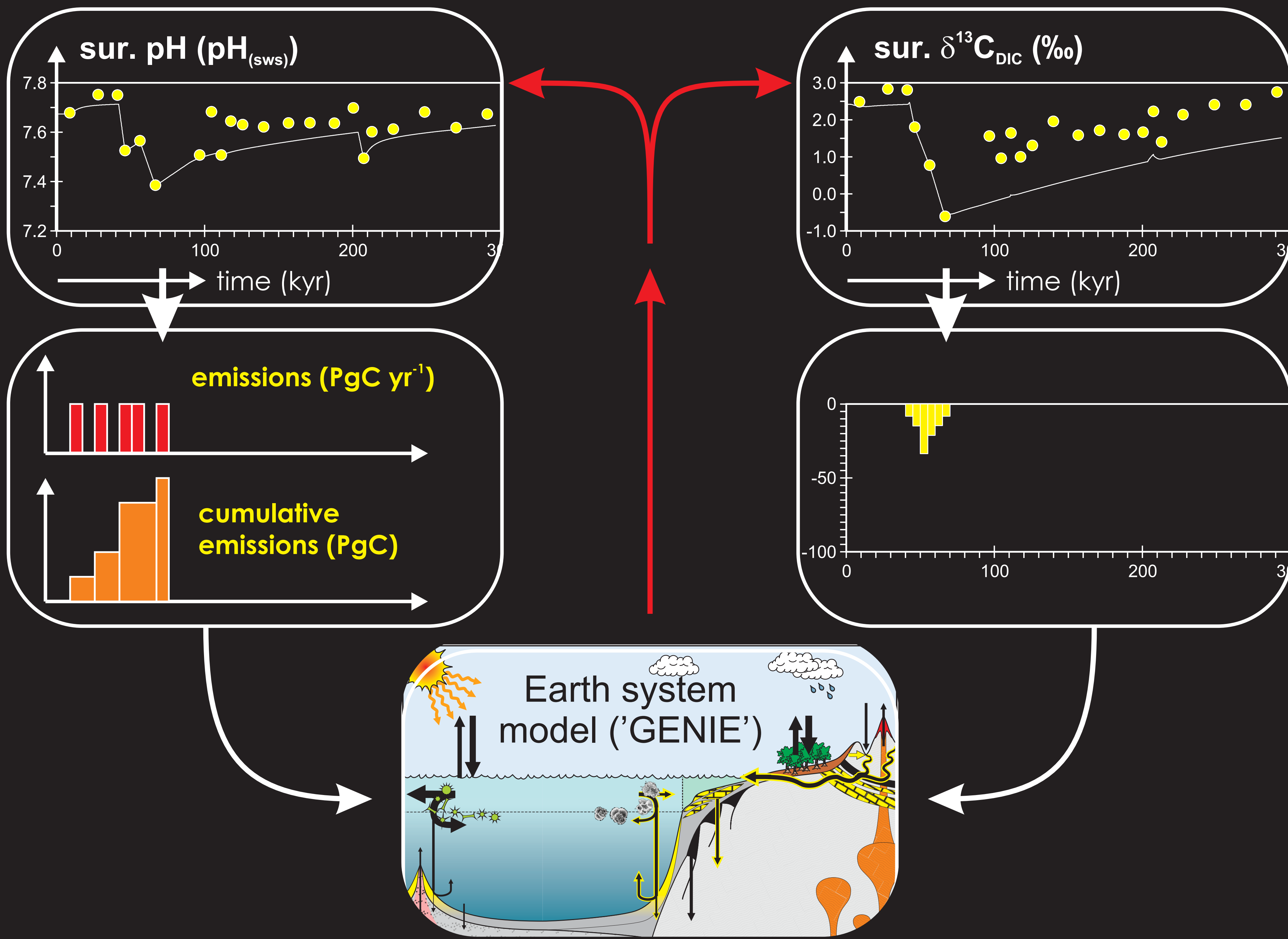
Assimilating surface ocean pH change (only)



Assimilating surface ocean pH and $\delta^{13}C$

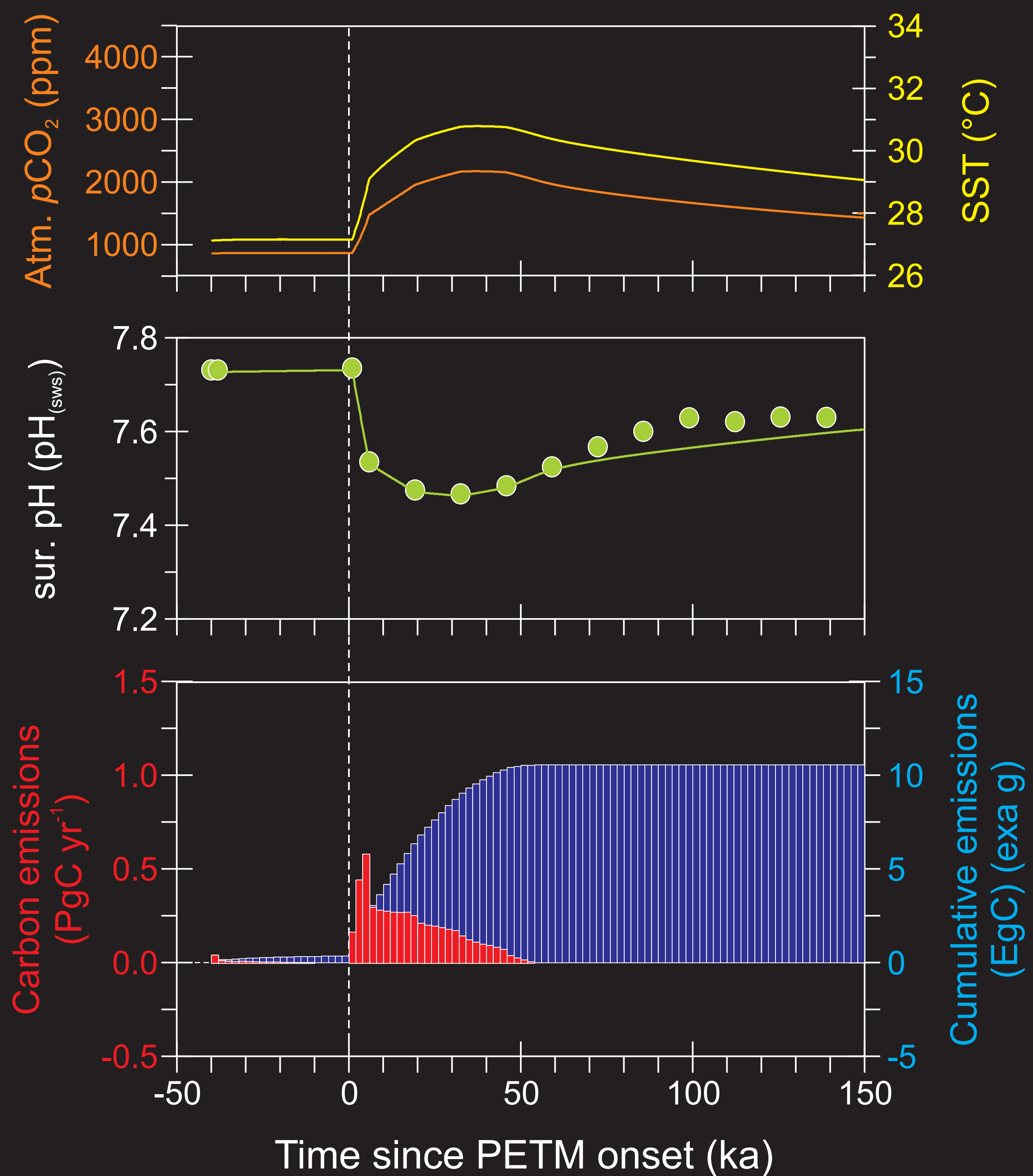


Assimilating surface ocean pH and $\delta^{13}C$



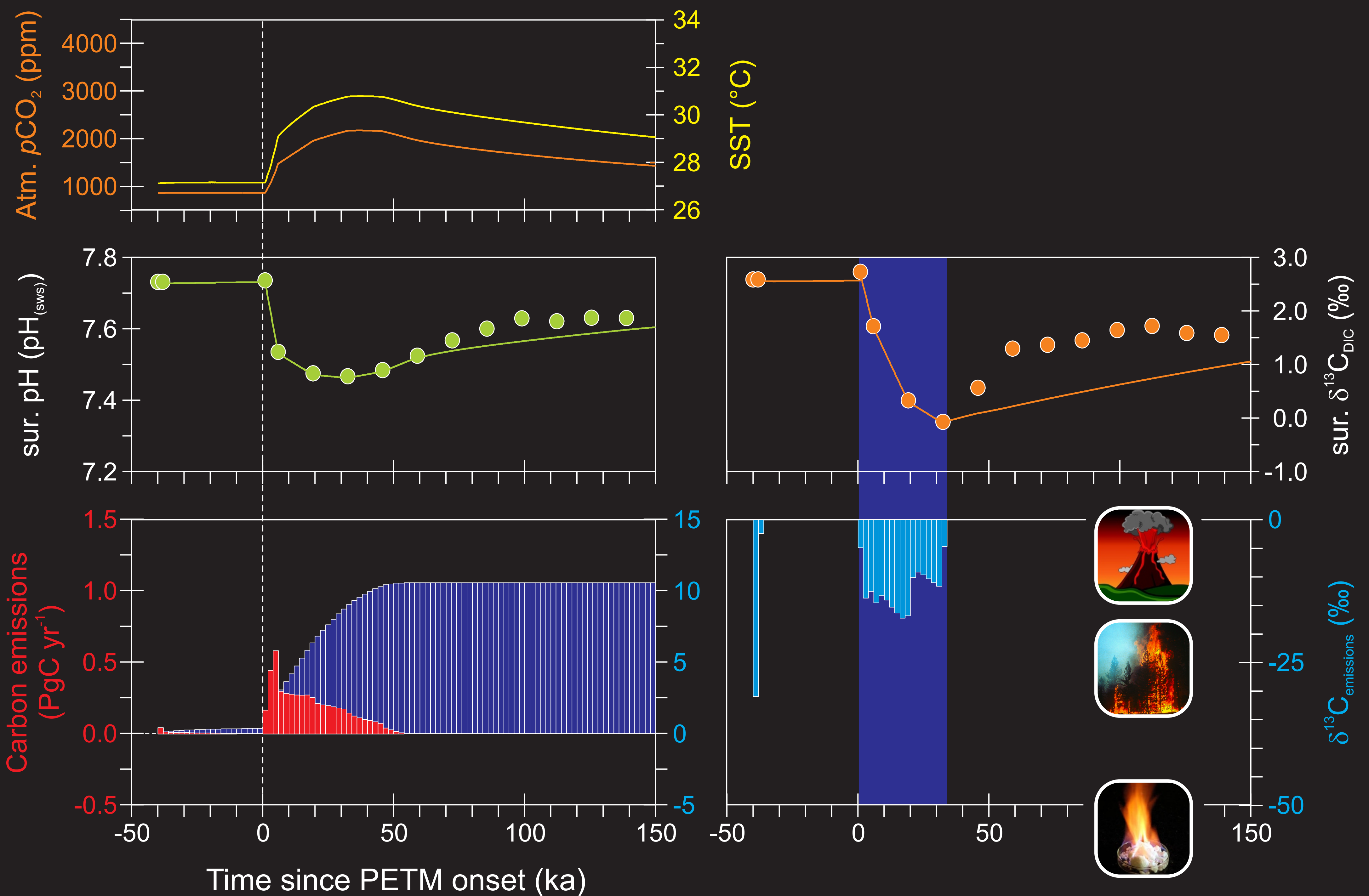
Assimilating surface ocean pH <u>and</u> $\delta^{13}C$

MPI: Monday 14th Sept



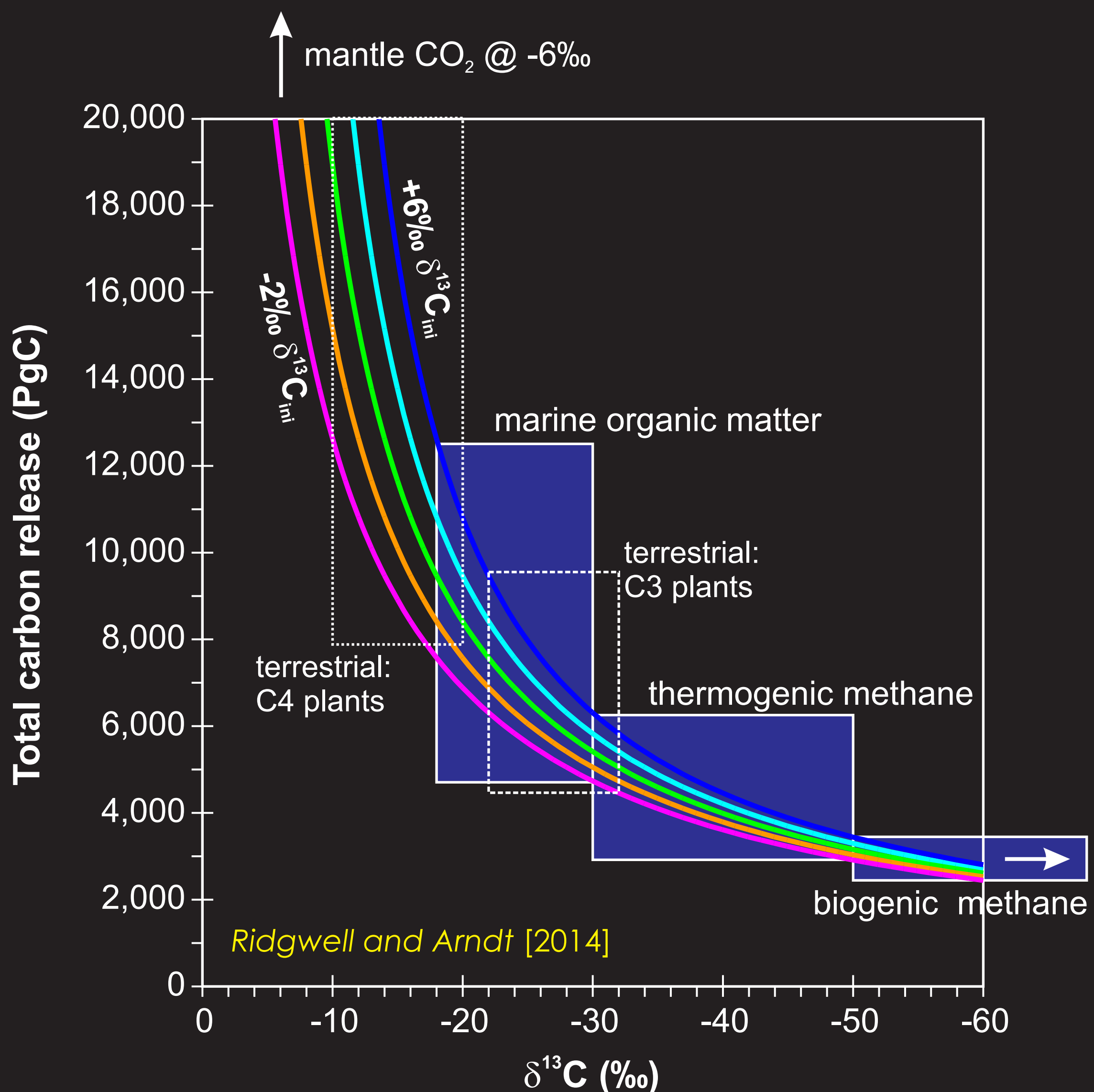
Assimilating surface ocean pH and $\delta^{13}C$

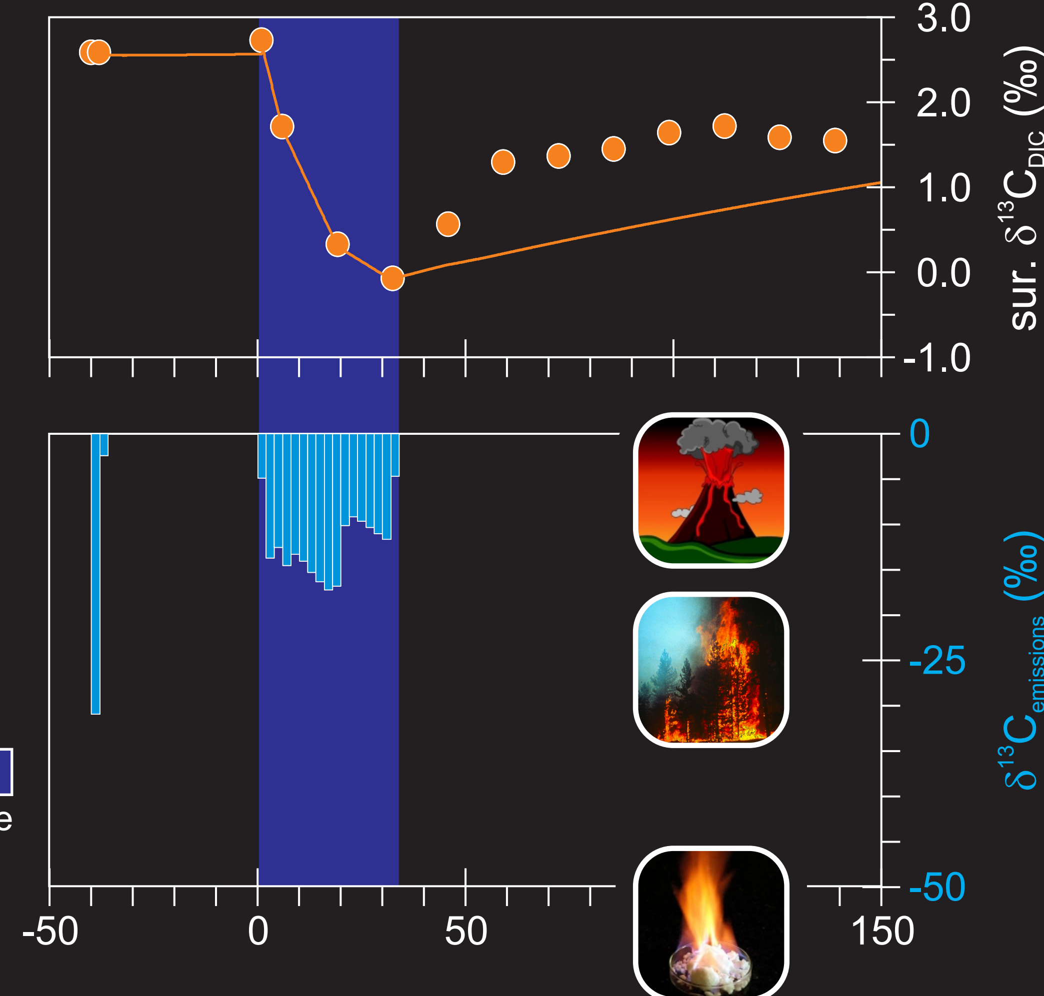
MPI:
Monday
14th Sept



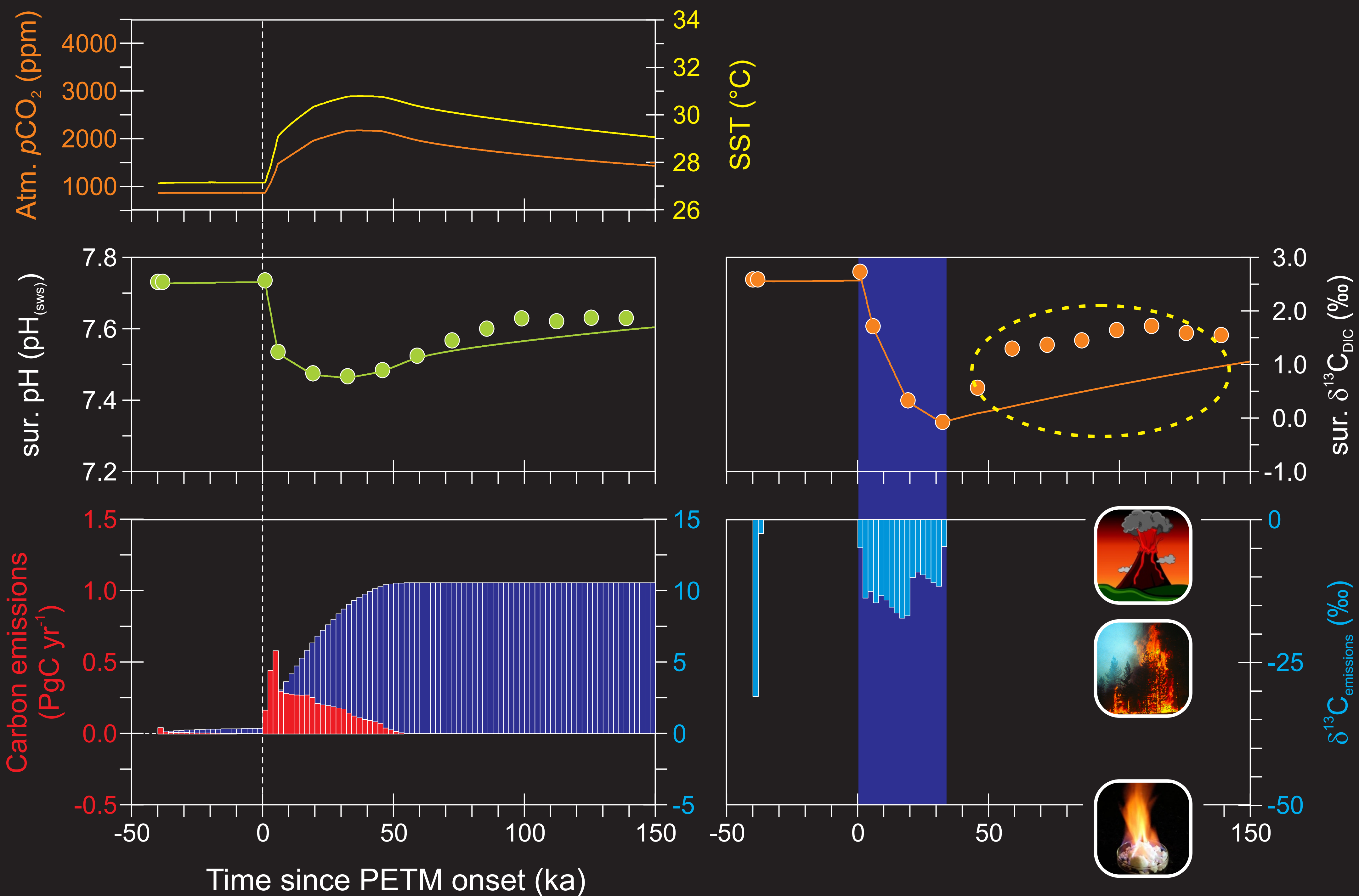
Assimilating surface ocean pH <u>and</u> $\delta^{13}C$

MPI: Monday 14th Sept

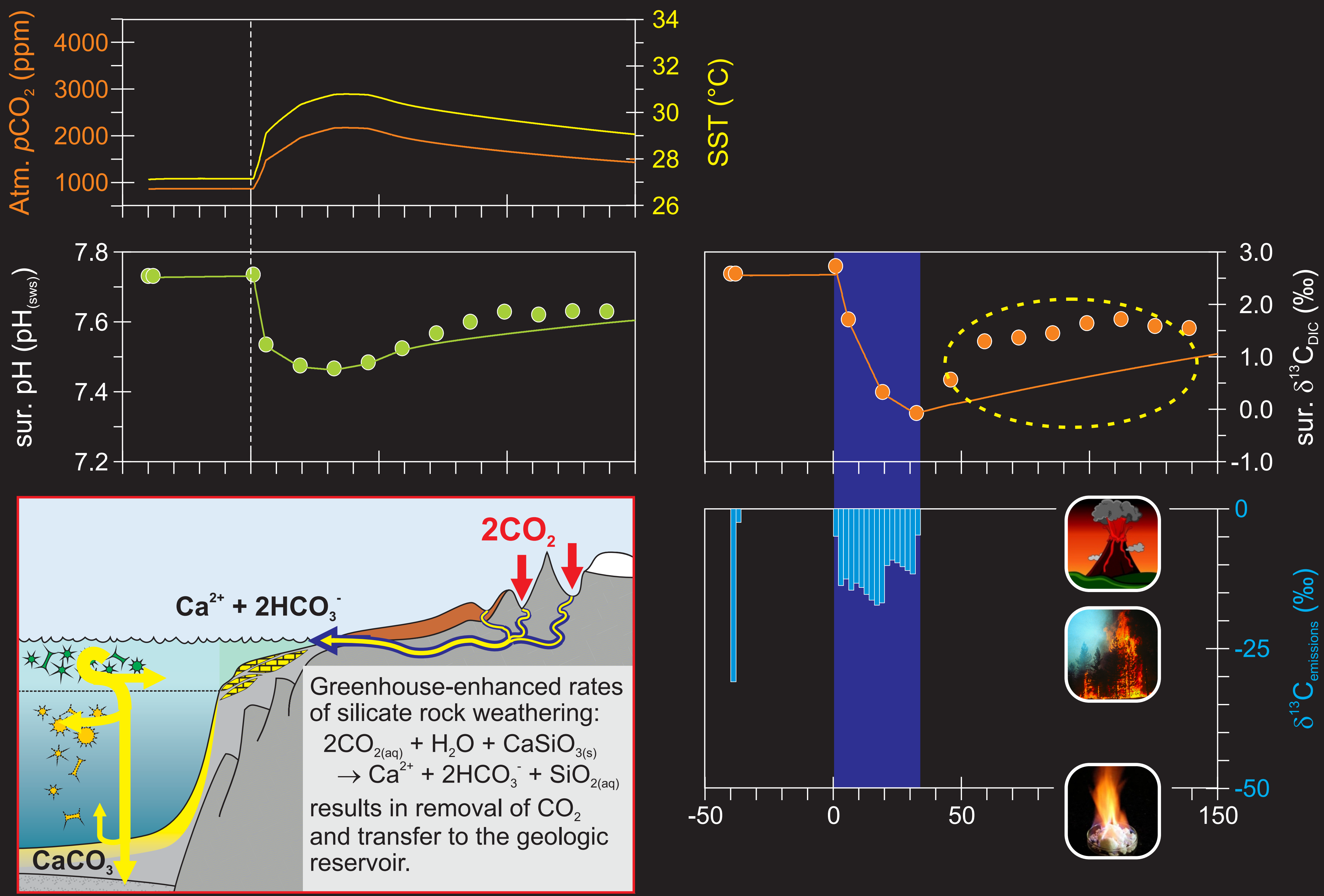




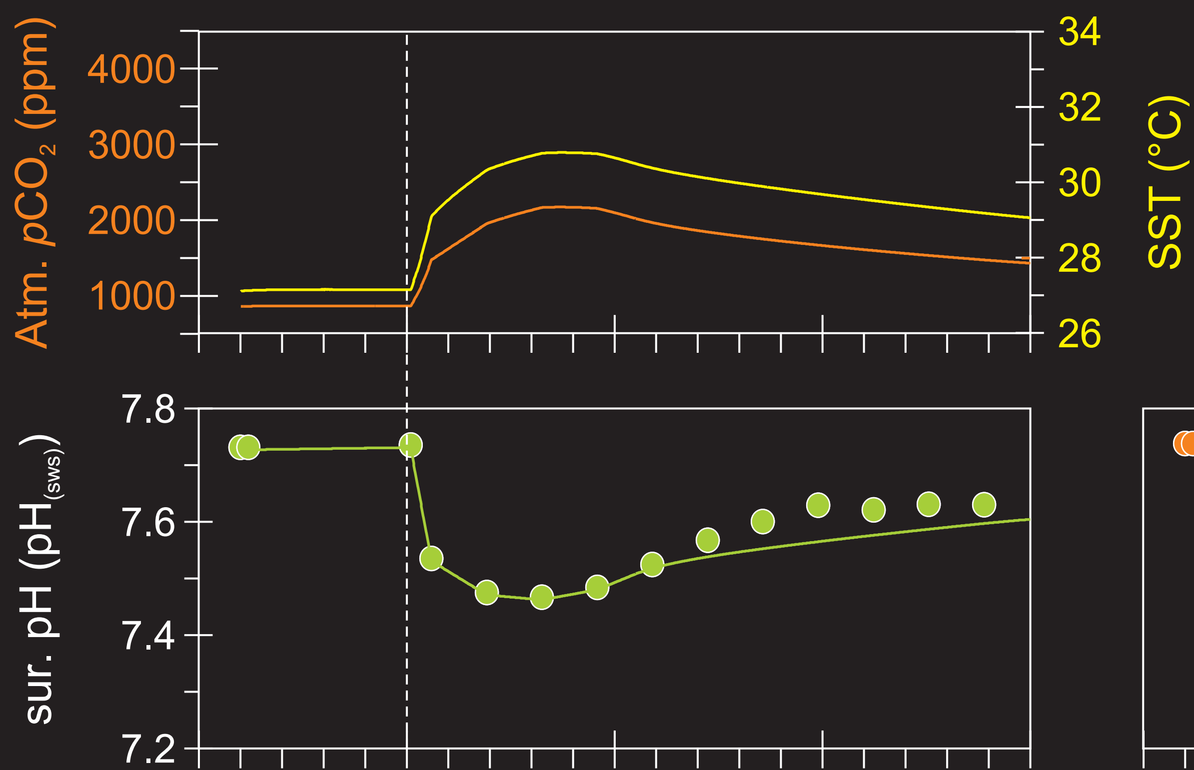
Assimilating surface ocean pH and $\delta^{13}C$

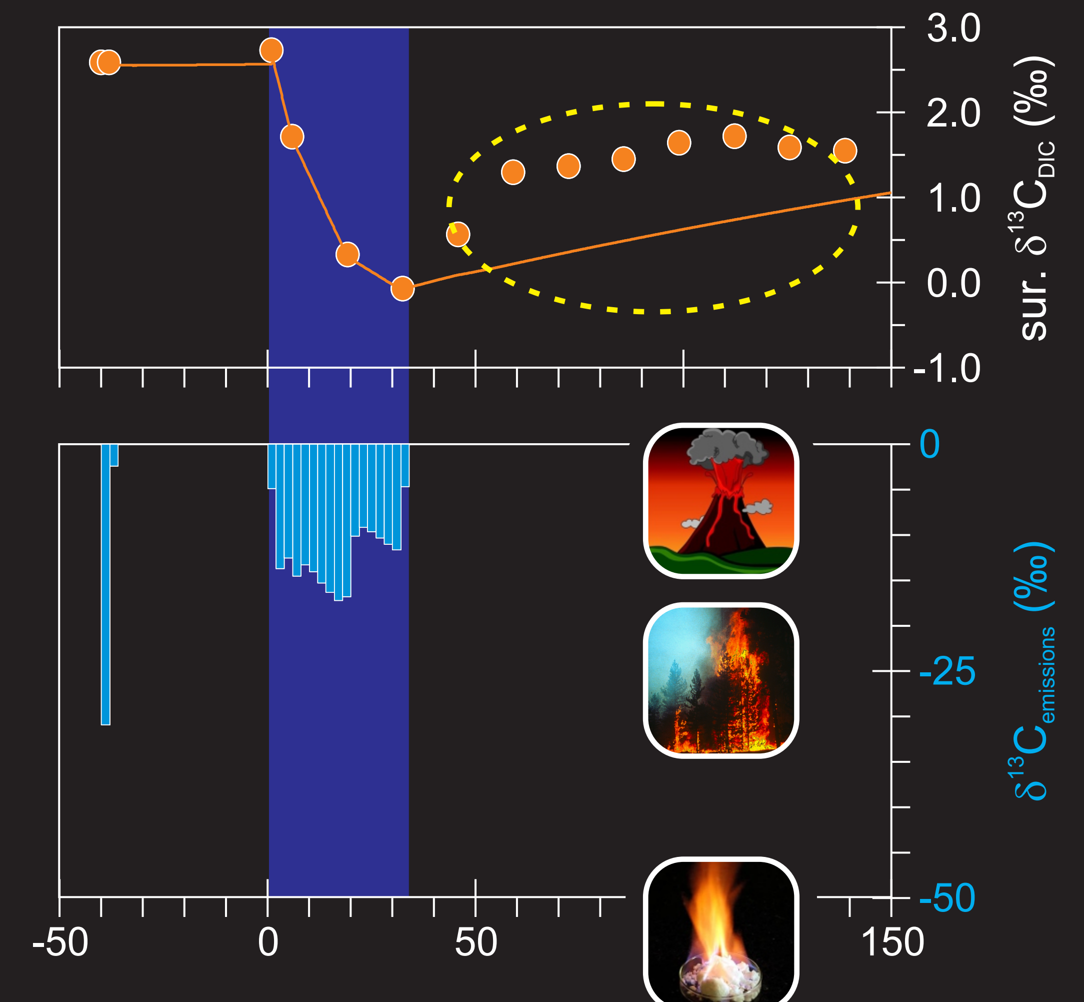


Assimilating surface ocean pH and $\delta^{13}C$



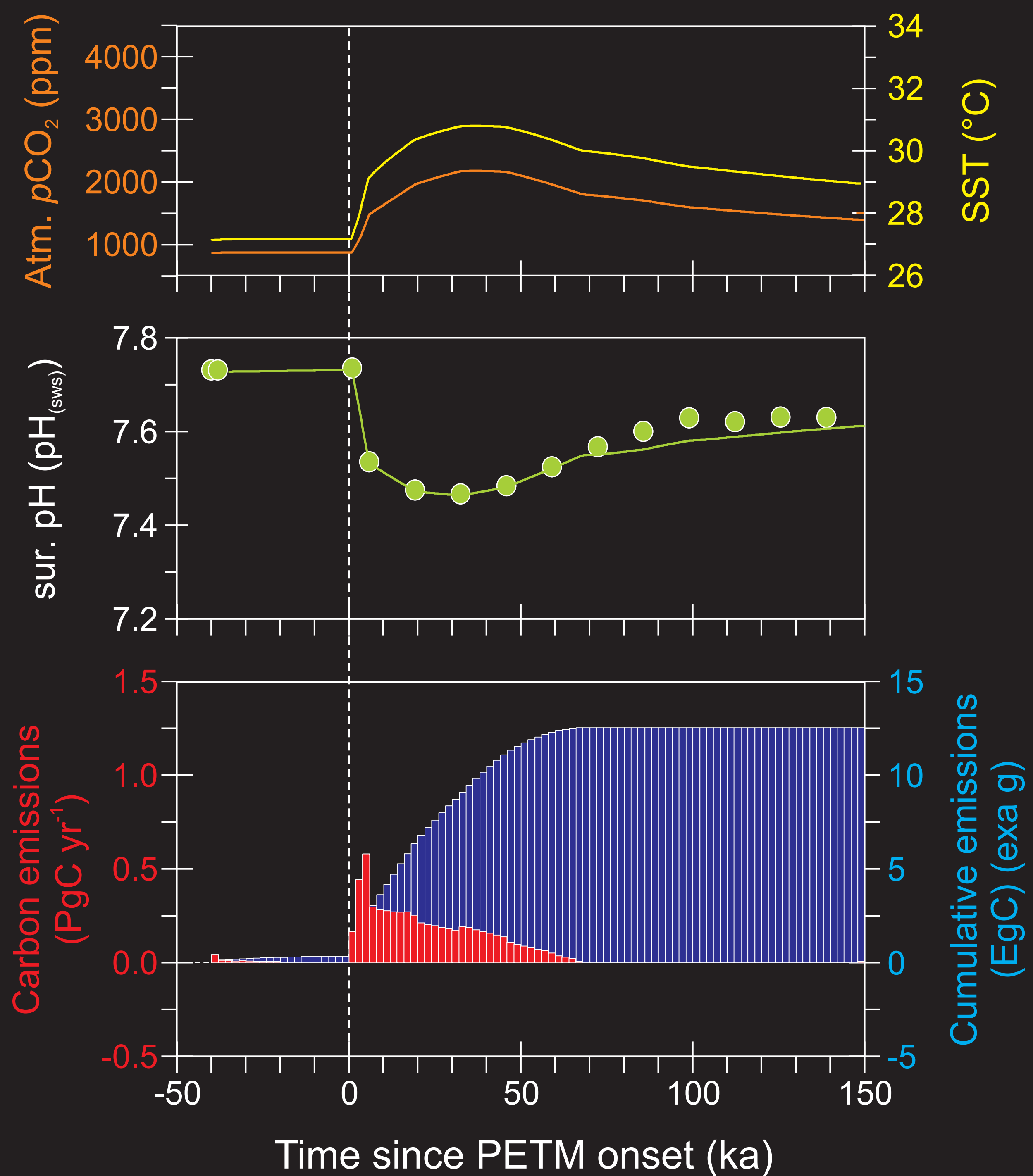
Assimilating surface ocean pH <u>and</u> $\delta^{13}C$ (#2)



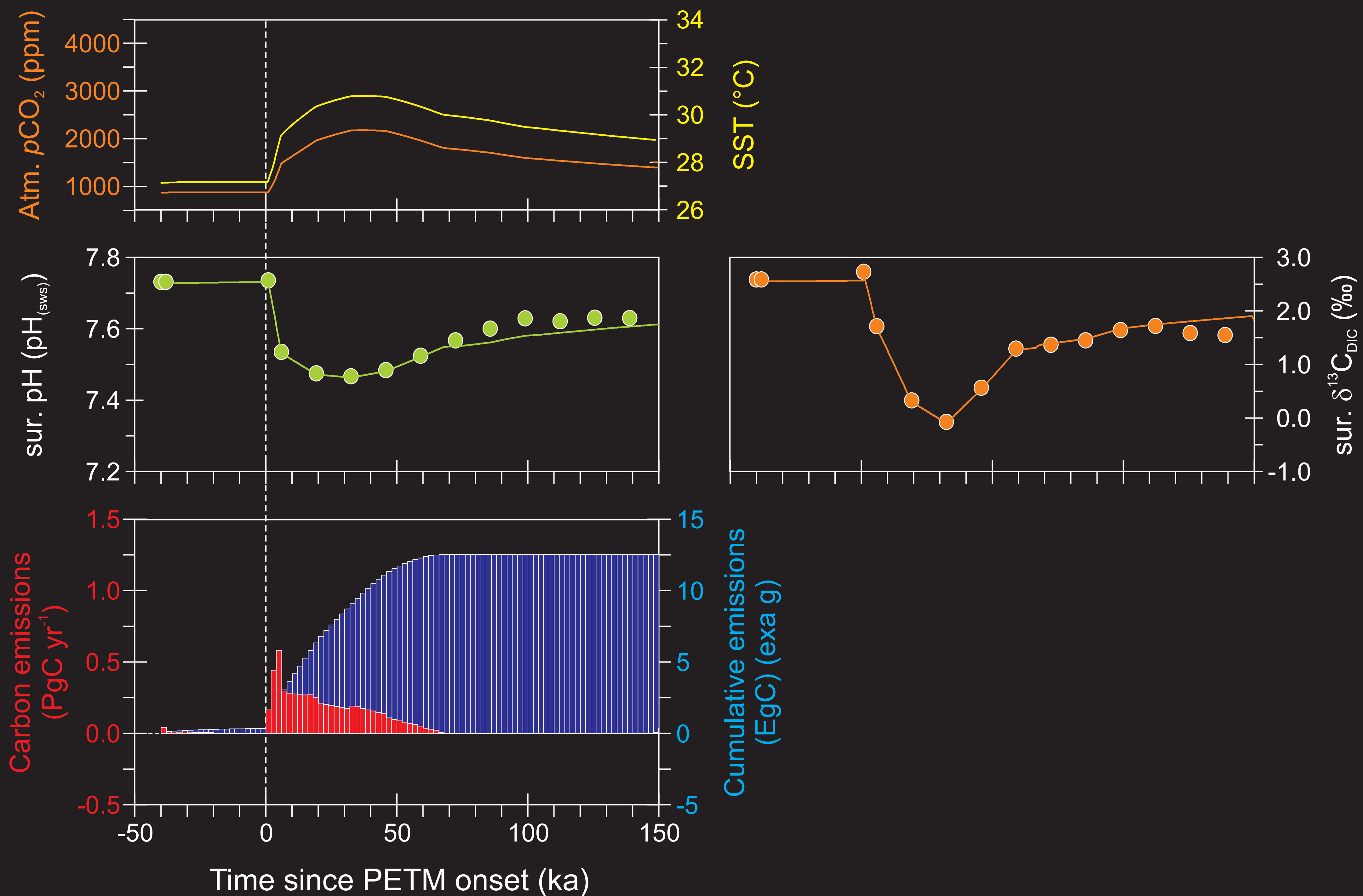


organic carbon preservation

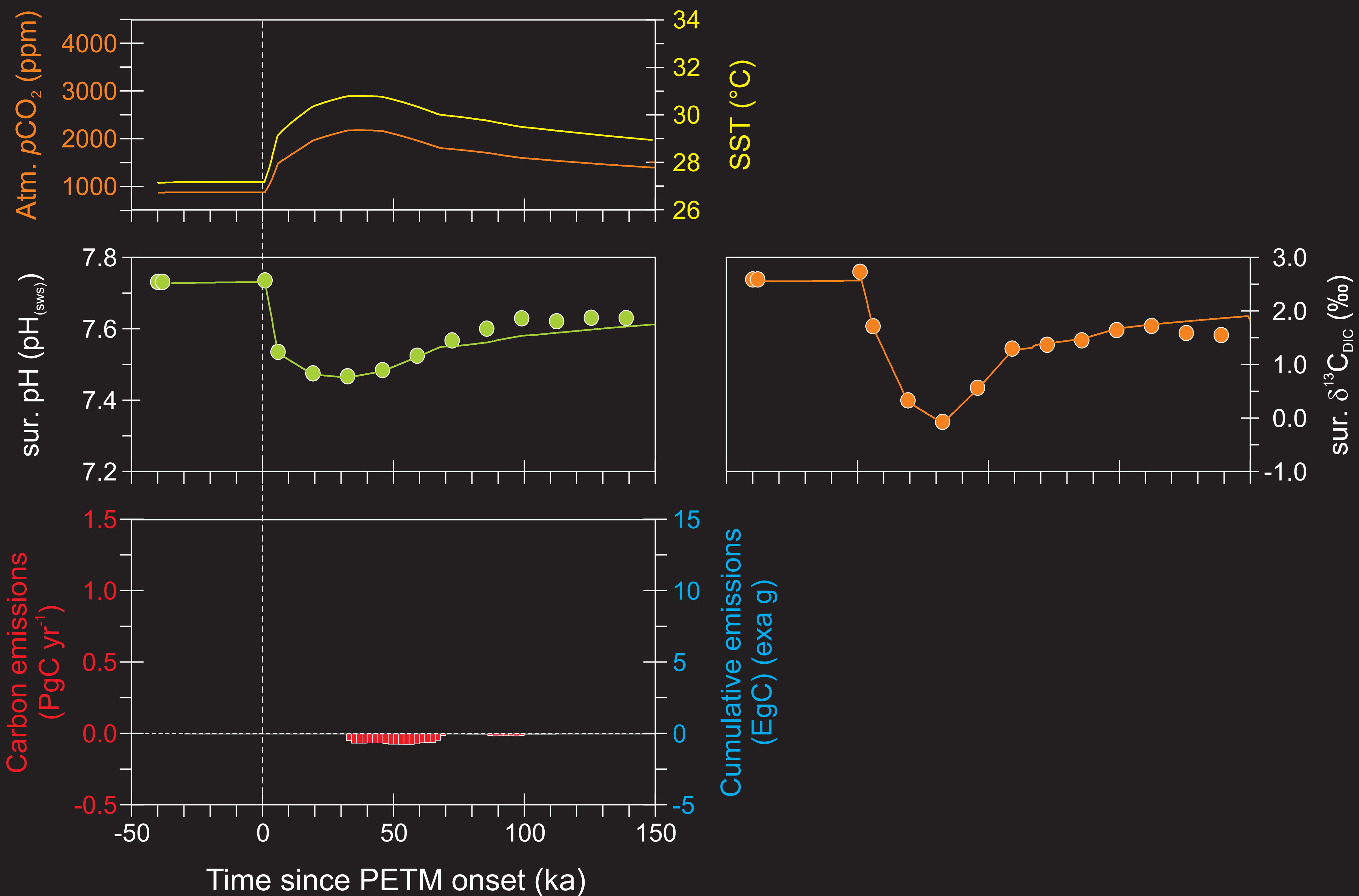
Assimilating surface ocean pH and $\delta^{13}C$ (#2)



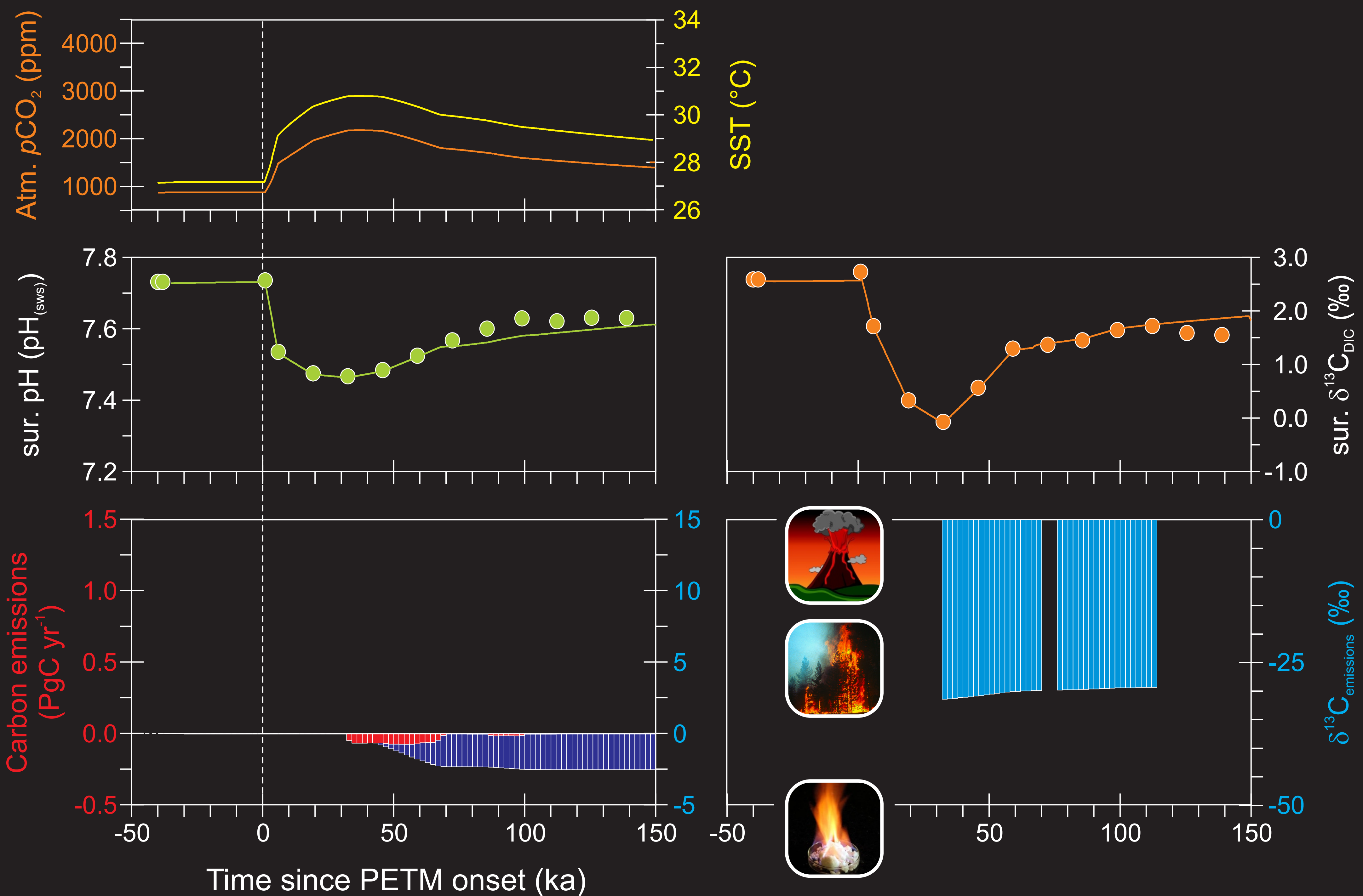
Assimilating surface ocean pH and $\delta^{13}C$ (#2)



Assimilating surface ocean pH and $\delta^{13}C$ (#2)



Assimilating surface ocean pH and $\delta^{13}C$ (#2)



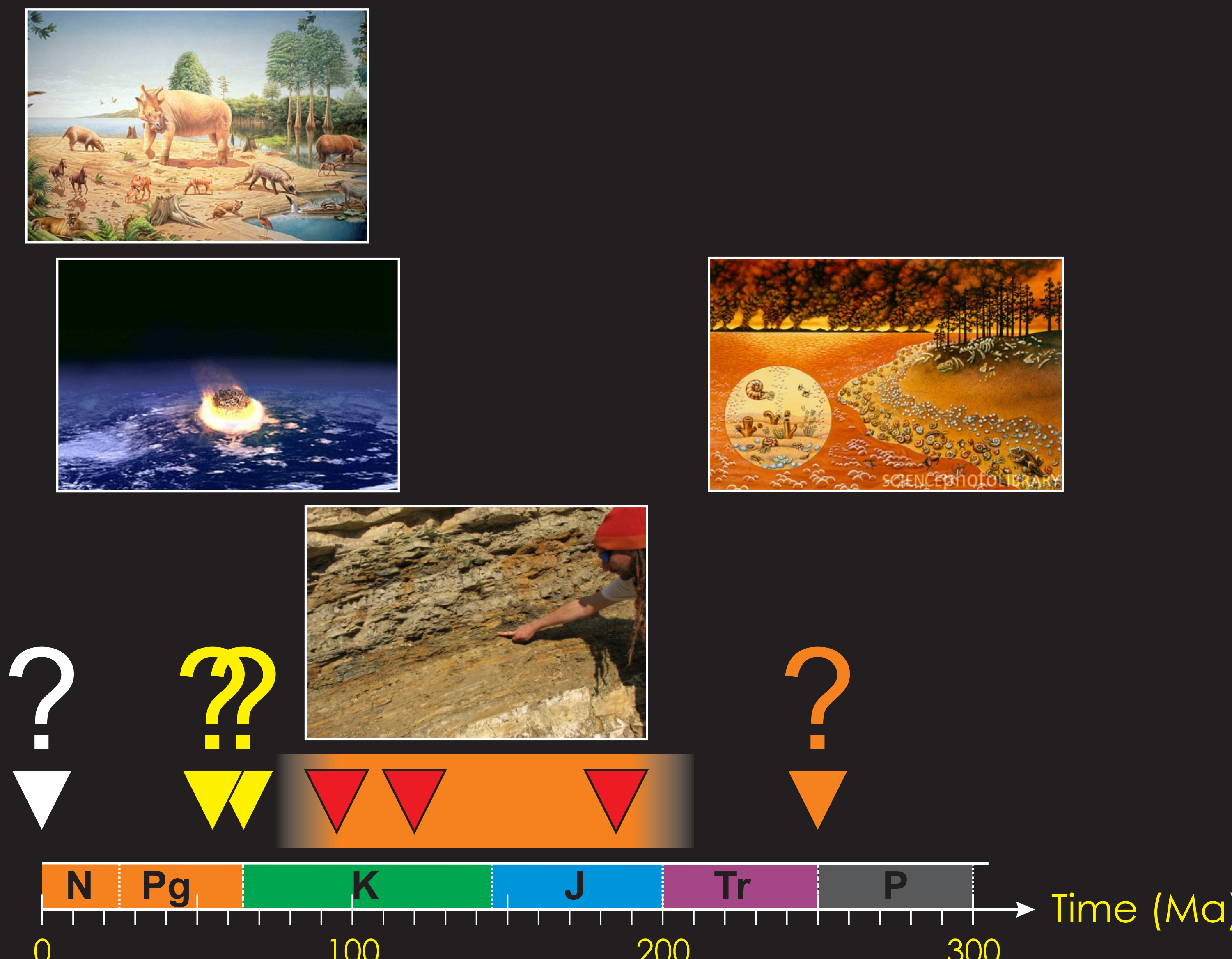
Summary

(1) Observationally-rooted and process-based understanding of the modern ocean is fundamental to applying numerical models (toys) to the past.

(2) Numerical models can be used to assimilate multiple lines of ‘secondary’ paleo evidence, and solve for ‘primary’ marine environmental parameters (turning lead into gold?).

(3) PETM warming and ocean acidification was likely primarily driven by mantle carbon input (~10,000 PgC) at rates only 5% of modern fossil fuel emissions.
Enhanced marine organic carbon burial (~2000 PgC) played a key role in the recovery from the event.

Summary



Thanks to:

Marcus Gutjahr [GEOMAR]
Philip Sexton [The Open University]
Gavin Foster [NOC]