What did we learn from past periods of carbon cycle perturbation in Earth history?

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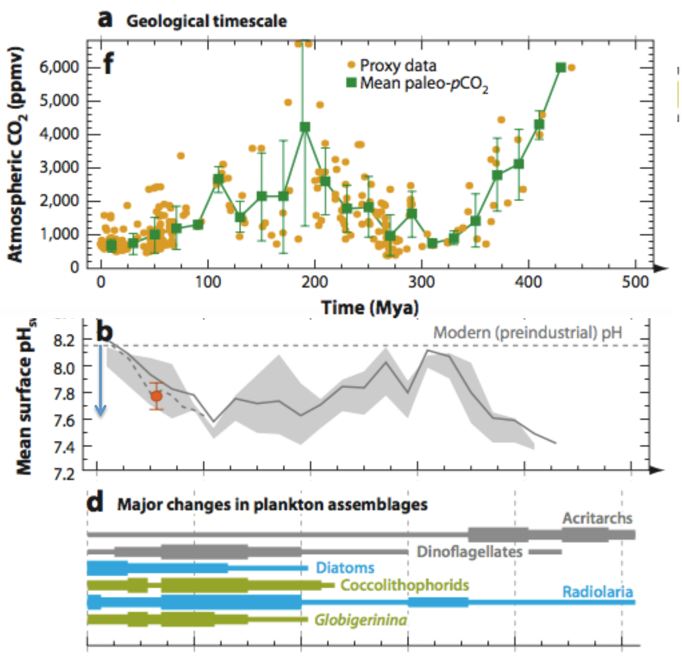
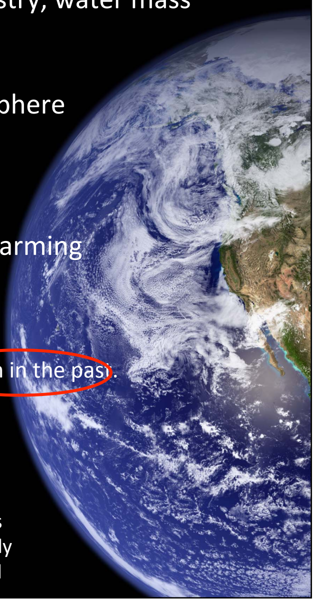


The geological context for past changes in ocean carbonate chemistry

Ocean acidification in Earth history

- Long recovery time
- Rate of change and initial conditions of the ocean are important
- Mass extinctions occurred
- Present C emission rates are very anomalous for the Earth history



Ocean is one of the most important compartment of the climate and life systems. It is fundamental to characterize as precisely as possible its major parameters (temperature, salinity, carbonate chemistry, water mass circulation etc.)

Ocean can absorb 1000 times the heat as the atmosphere (> heat capacity)
The ocean is the largest CO_2-reservoir.

Over 80% of the increase of heat caused by global warming is going into the ocean

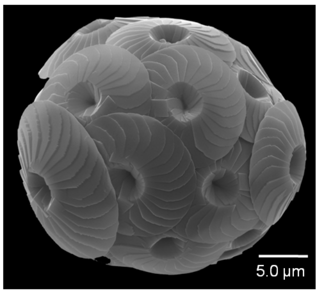
We need to increase our knowledge of the ocean today and the evolution of the physical state of the ocean in the past.

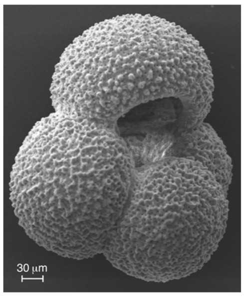
1) Direct observations
2) Satellite data

Paleoclimatologists use past climate archives, physical or chemical parameters of the environment are recorded indirectly in material mainly derived from biological activity

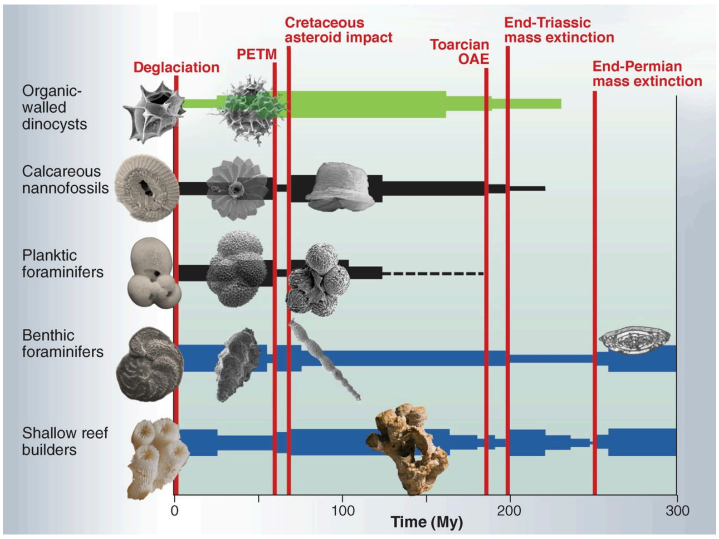
Why "paleo"?

"…. the geologic record contains <u>long-term evidence</u> for a variety of global environmental perturbations including <u>ocean acidification</u> plus their associated biotic responses." Hönisch et al., 2012 – Science





The Geological Record of Ocean Acidification



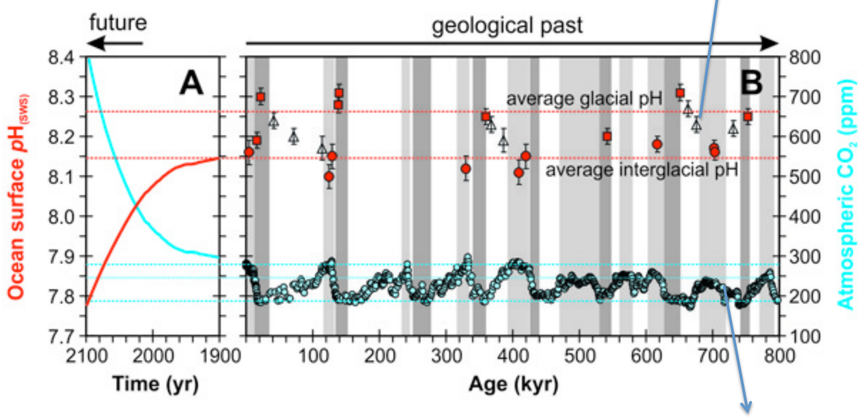
Idealized diversity trajectories of the calcareous and organic fossil lineages. Extinction and radiation suggest events of major environmental change throughout the past 300 My. Calcareous plankton is shown in black, calcareous benthos in blue, and organic fossils in green, and the line thickness indicates relative and smoothed species richness. Highlighted events (vertical red lines) have been associated with potential ocean acidification events.

Honisch et al., 2015 (*Science*)

- GLACIAL - INTERGLACIAL

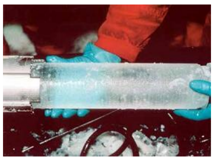
How historical and future ocean acidification compares with the geologic past

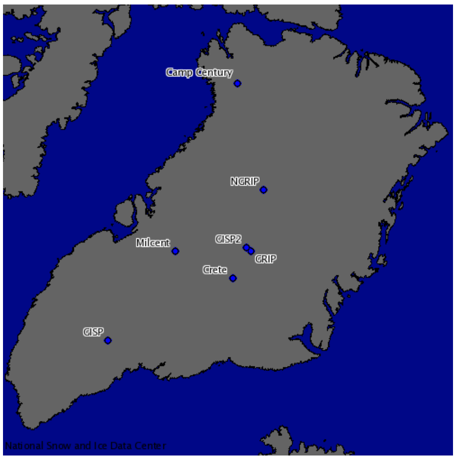
SEDIMENT CORES (CORALS)
11B CaCO3



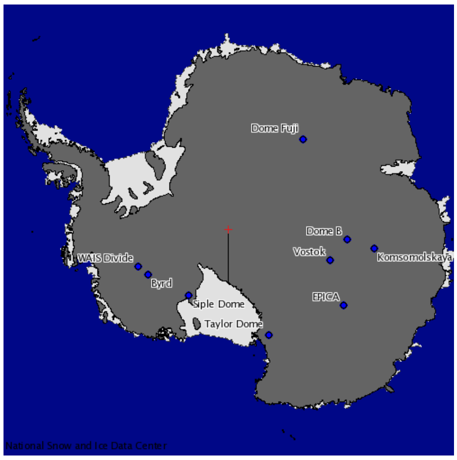
ICE CORES

Ice coring
Major Ice caps





Greenland – Northern Hemisphere



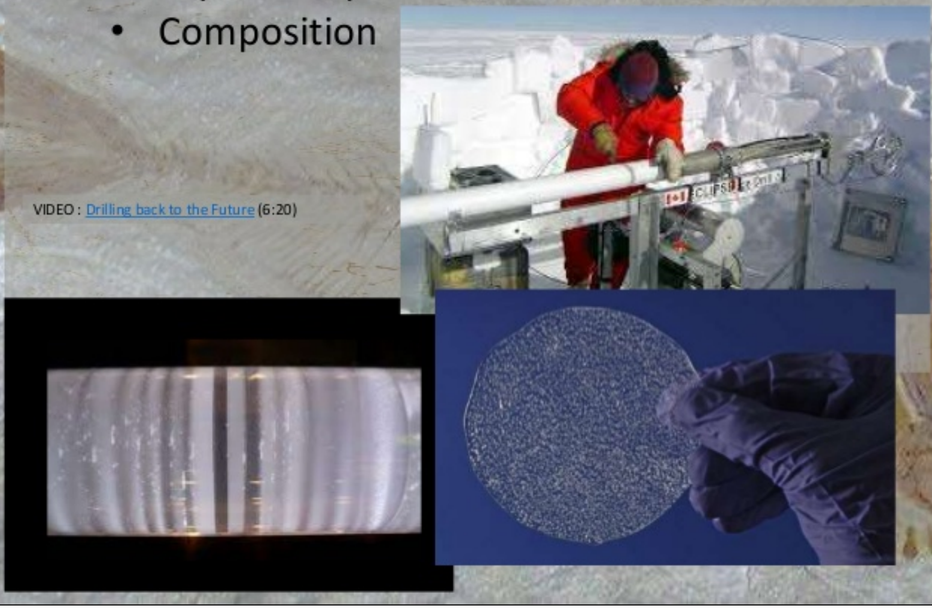
Antarctica – Southern Hemisphere

Coring in ice

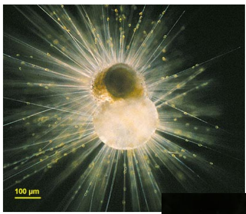
Ice core data

- Layer size, pattern, &
- Composition

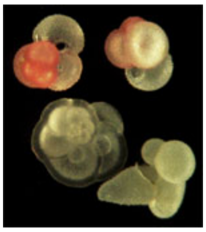
VIDEO : Drilling back to the Future (6:20)

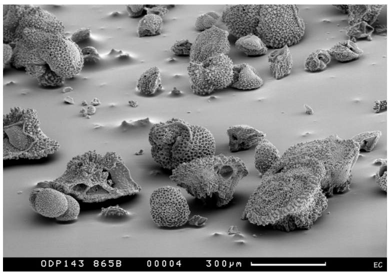


Sediment cores



From living unicellular plankton
to bottom sediment





Corals used in paleoceanography (Aragonite and calcite corals)

Two different types

Scleractinian corals	Gorgonian corals
e.g. *Porites* (tropical coral), *Lophelia* (deep-water coral) *Desmophyllum* (deep-water coral)	e.g. Keratoisis (bamboo deep-water coral)
Aragonite skeleton	Calcite/Organic skeleton
Relatively short time-series (max 200-300 years)	Long time-series (100s-1000s of years)
Fragments can be recovered in long sediment cores	May find sub-fossil individuals
Samples in cores may be millions of years old	Old samples possible but very rare
Anthropogenic and Glacial Timescale Climate reconstructions	Anthropogenic Timescale Climate reconstructions

- pH reconstructions

$\delta^{11}B$ for pH reconstructions

$B(OH)_3$ (Trigonal form) boric acid (≈80%)

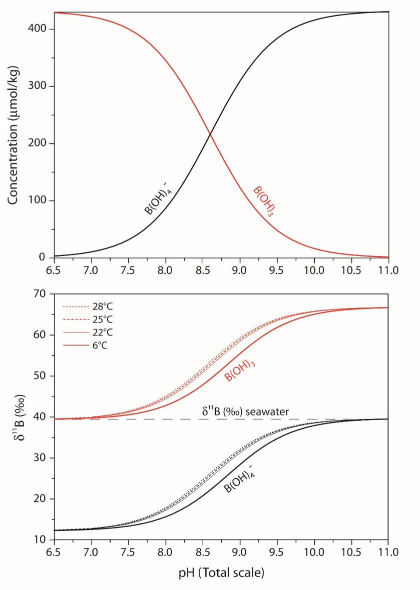
$B(OH)_4^-$ (Tetrahedral form) borate (≈20%)

Related by the acid-base equilibrium:

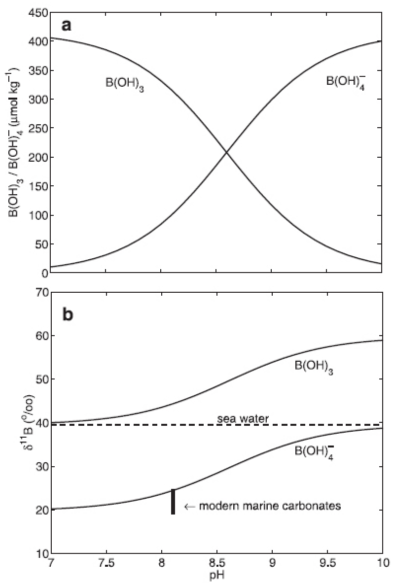
$B(OH)_3 + 2H_2O \leftrightarrow B(OH)_4^- + H_3O^+$
$^{11}B \sim 80\%$ (concentrated into $B(OH)_3$)
$^{10}B \sim 20\%$

Residence time: 9.600.000 years (calculated from the global average river input)

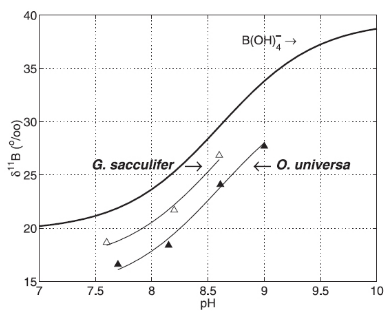
As the proportions of $B(OH)_3$ and $B(OH)_4^-$ change as a function of pH, also their isotopic composition will change
The distribution of these species is pH controlled.



$\delta^{11}B$ for pH reconstructions

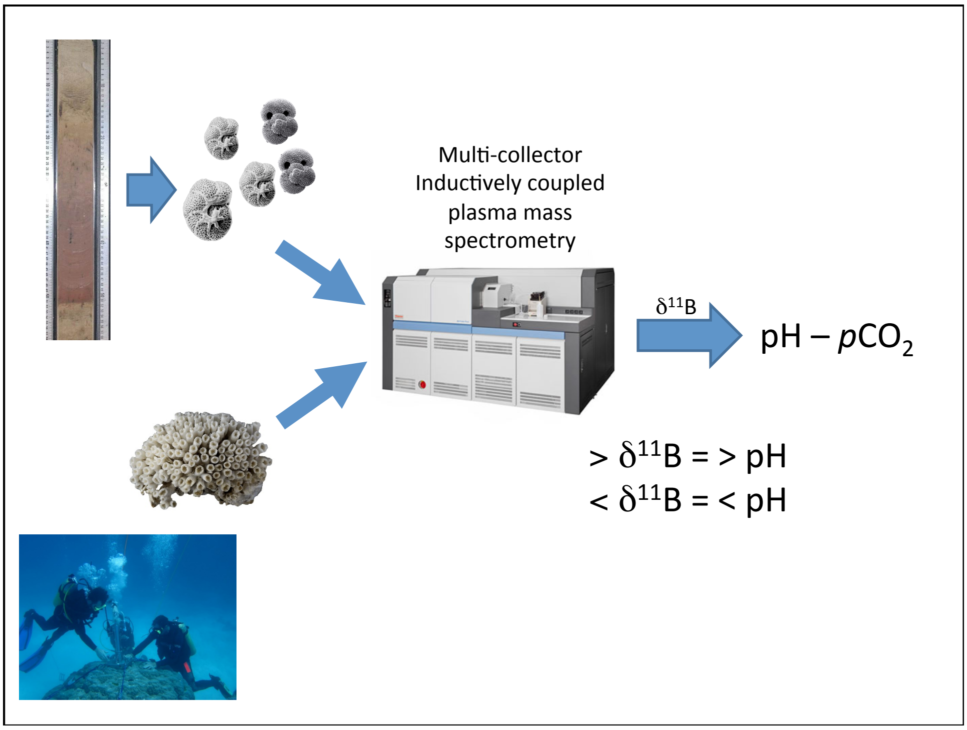


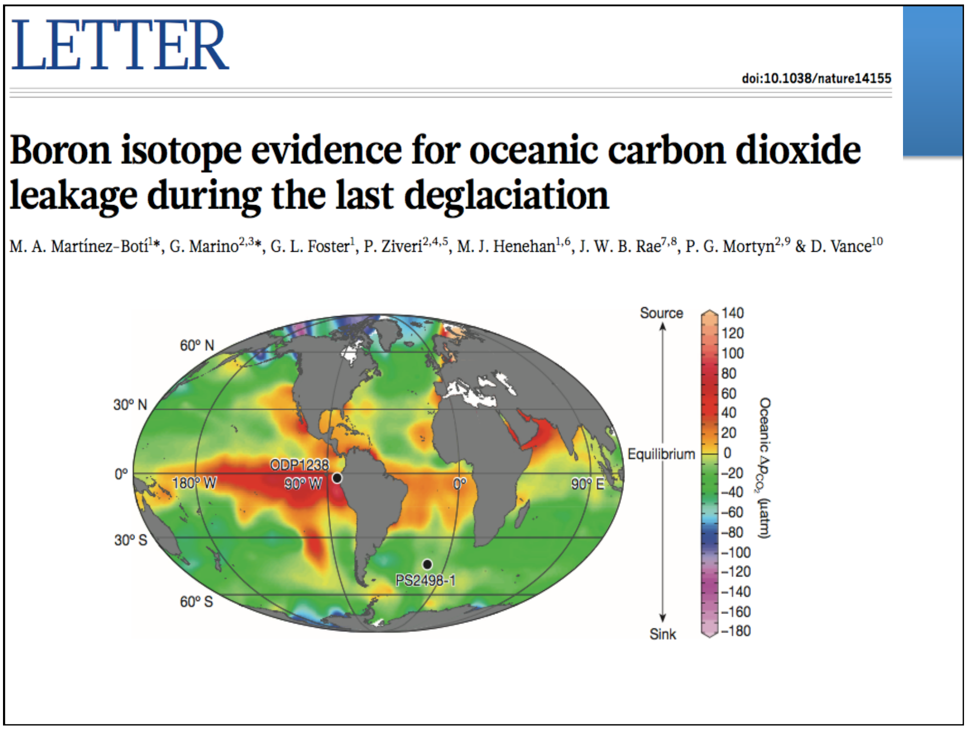
Boron concentrations in foraminifera are low (~ 10 ppm) ➔ techniques must be efficient and laboratory contamination must be carefully controlled (parts of million)



$\delta^{11}B_{carb} = \delta^{11}B_{borate\ (sea\ water)}$

Zeebe et al., 2003 – *Paleoceanography*




LETTER

doi:10.1038/nature14155

Boron isotope evidence for oceanic carbon dioxide leakage during the last deglaciation

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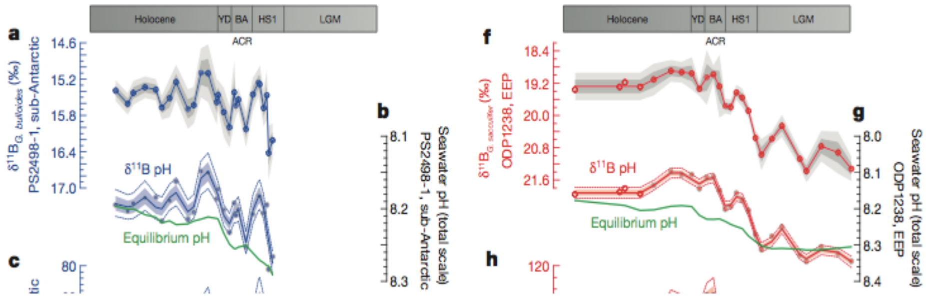
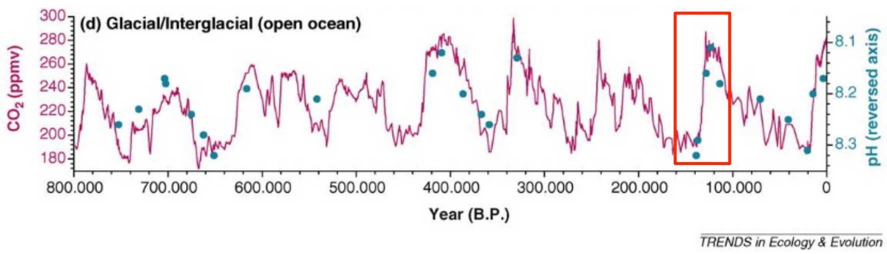
SAA and the EEP during the last deglaciation

surface waters at both locations became a significant source of carbon to the atmosphere during the last deglaciation, when the concentration of atmospheric CO_2 was increasing

SAA EEP

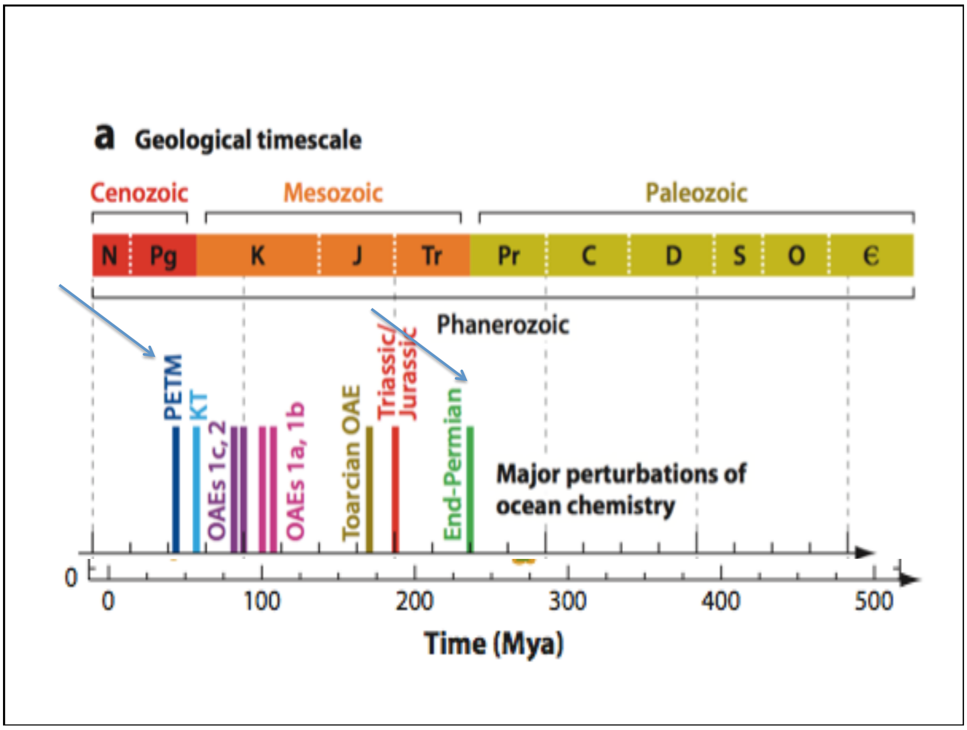


GLACIAL-INTERGLACIAL CYCLE

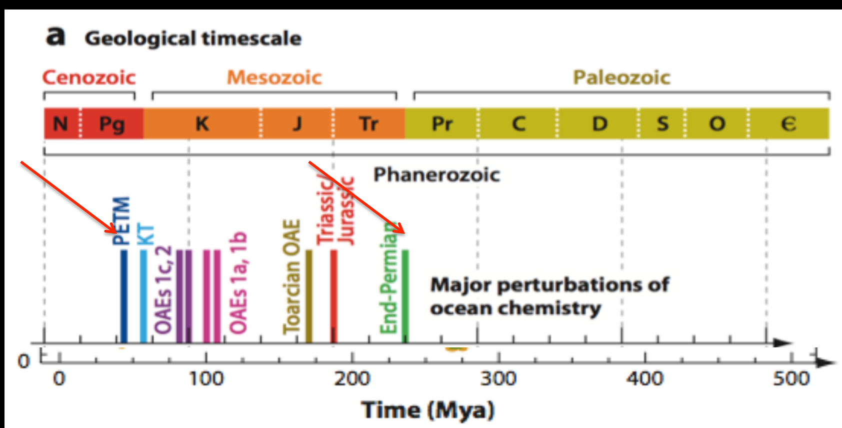


From pH 8.3 to 8.1 in 6 kyrs pH change = 0.003 units/century
Hundred time slower than today!

Pelejero et al. 2010



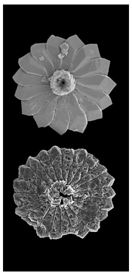
Ocean acidification: What does the past teach for the future?

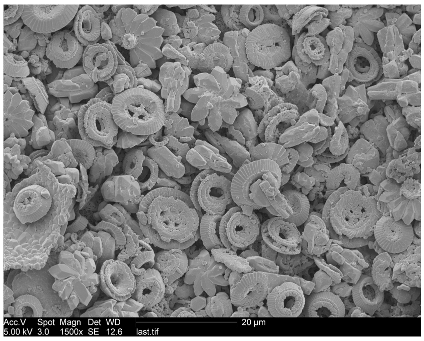


What did we learn from past ocean acidification events?

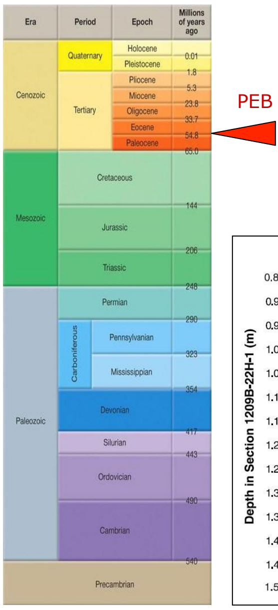
Paleocene-Eocene Thermal Maximum
(~56 Ma ago)

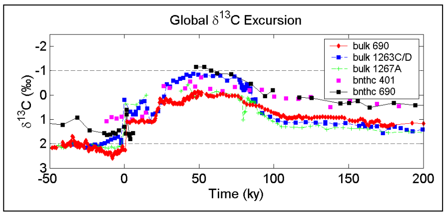
- Rapid C release - Rapid global warming
- Ocean acidification
- Long-term C sequestration

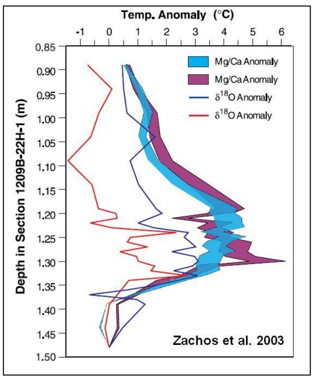


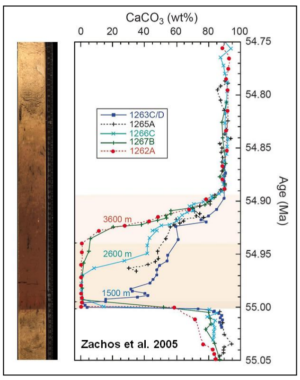


Paleocene-Eocene Thermal Maximum (PETM)







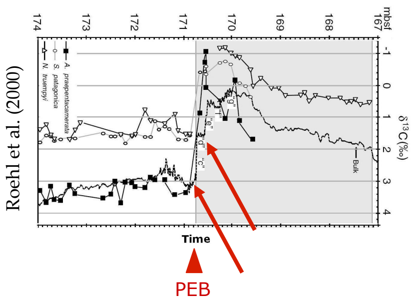


Paleocene-Eocene Thermal Maximum (PETM)

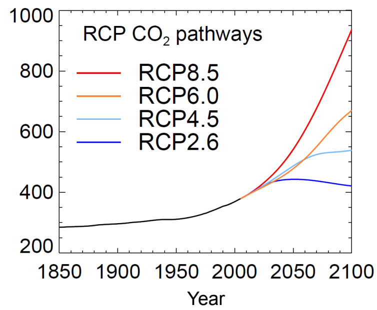
- rapid increase in atmospheric CO2 levels, attributed to the rapid release of ~2000 10^9 metric tons of carbon in the form of methane
- >50 kyr, ocean temperatures rose by 5 to 8 ºC, marine and terrestrial carbon isotope values ($\delta^{13}C$) decreased by 3 to 8 per mil
- the calcite compensation depth (CCD) in the deep sea shoaled by up to 2 km
- this massive geological carbon cycle perturbation is dwarfed by anthropogenic rates of carbon emissions [~0.2 Gt per year for PETM and 8 Gt/yr modern].
- $\delta^{13}C$ values returned to near-background levels within 110-210 kyr

What did we learn from past ocean acidification events?

PETM



Anthropocene

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2000 Pg C/2/1000 y = 1.0 Gt C y⁻¹
5000 Pg C/2/1000 y = 0.5 Gt C y⁻¹
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1954-2004: 4.8 Gt C y⁻¹
     2014: 10 Gt C y⁻¹
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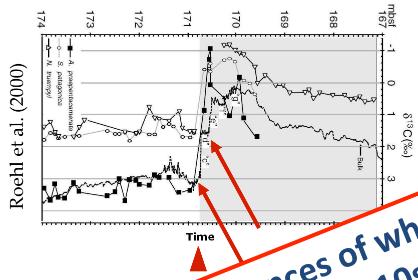
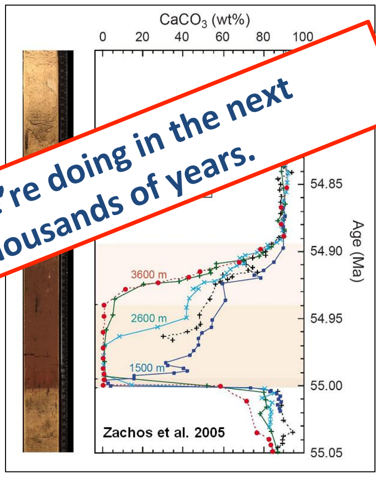
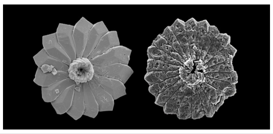
Time Scale of Carbon Input!

Paleocene-Eocene Thermal Maximum (PETM) (56 Ma)





The consequences of what we're doing in the next decades will last for 10s of thousands of years.

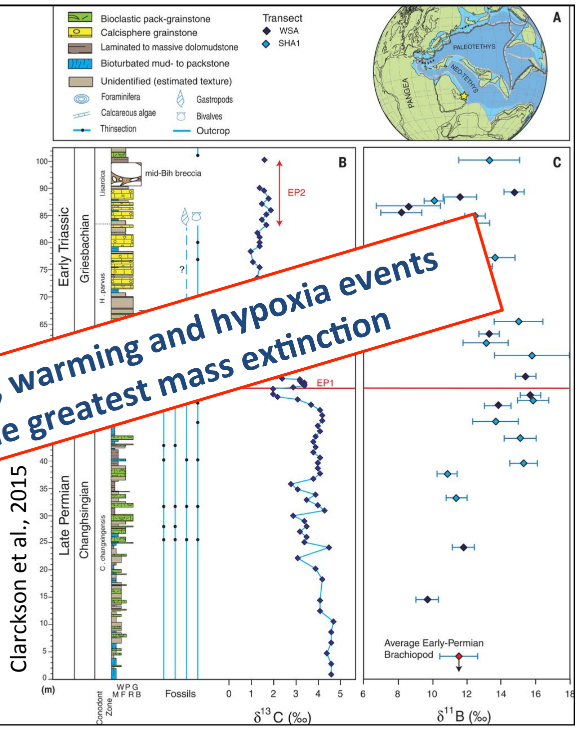


- Rapid C release - Rapid global warming
- Ocean acidification - Long-term C sequestration
- Change in pH and the rate of emission

Permo-Triassic mass extinction (252 Ma)

- Earth's most severe known extinction event.

-The recovery of life on Earth t sig tha other extinction event, possibly up to 10 million years.



ocean acidification, warming and hypoxia events occurred during the greatest mass extinction

Ocean acidification and the Permo-Triassic mass extinction

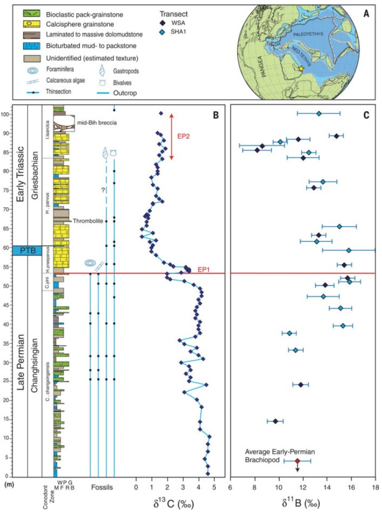


Fig. 1. Site locality and high-resolution carbon and boron isotope data. (A) Paleogeographic reconstruction for the Late Permian that formed an extensive carbonate platform. (B) Shallow water $\delta^{13}C$ record. (C) Boron isotope ($\delta^{11}B$) record.

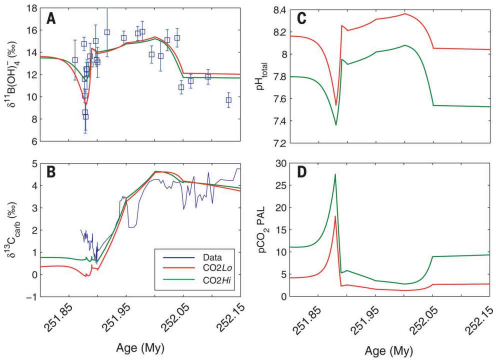
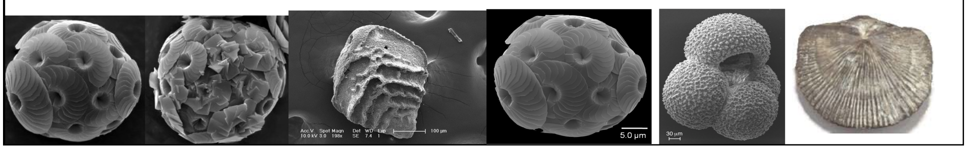


Fig. 2. Model results of carbon cycle parameters for high- and low-CO_2 end-member scenarios. (A) Model-reproduced $\delta^{11}B$ versus data. (B) Modeled $\delta^{13}C$ versus data. (C) Modeled pH envelope incorporating uncertainty of seawater B isotope composition ($\delta^{11}B_{sw}$) and dynamic temperatures. (D) Calculated atmospheric CO_2.

Clarkson et al., 2015 (*Science*)

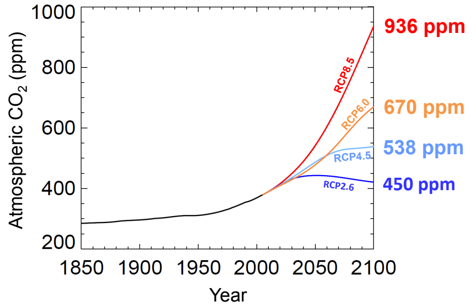
SUMMARY

- **The modern and projected rate of CO_2 emission unprecedented.**
- **OA and climate change strictly related to the rate and amount of CO_2 emission to the atmosphere.**
- **Mass extinctions in Earth's history often related to a perturbation of the carbon cycle (OA, OW, hypoxia).**
- **People should know that the consequences of what we're doing in the next decade will last for 10s of thousands of years.**

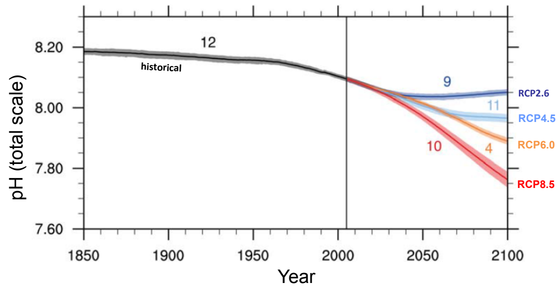


To conclude: The intensity and consequences of OA and depends on the rate of CO_2 emissions

Future atmospheric CO_2 (latest IPCC scenarios)



Intensity of ocean acidification (change in pH) varies by a factor of 3



IPCC AR5 WG1, Technical Summary (2013)