Från växthus till ishus och en extrem klimathändelse

The Cenozoic greenhouse to icehouse and an extreme global warming event

By Dr. Helen Coxall

Dina lärare

Dr. Helen Coxall
Lecturer/ Docent in
Marine Micropalaeontology

My Research: reconstructing ocean and climate changes during the past 70 million years (using microscopic marine fossils and geochemistry).

Snowball Earth-hypotesen

Förra veckan:

Under geologisk tid regleras Jordens temperatur av:

- Solenergi
- Kemisk vittring
- Kontinentaldrift
- Oceanbottenspridning
- Bergkedjesbildning

Vad hänt med Jordens temperaturreglering under Snowball Earth?

Bild: BBC

Ditt schema

18/1. Geologin bakom klimatsystemet – Alasdair Skelton

25/1. Från växthus till ishus och en extrem klimathändelse – Helen Coxall

1/2. Den pågående istiden – Sarah Greenwood

8/2. Snowball Earth-hypotesen – Alasdair Skelton

15/2. Sedimentologiska argument för och emot hypotesen – Otto Hermelin

22/2

1/3. r

Skelt

8/3.

Skelt

15/3 nder

de senaste årmiljonerna? – Martin Jakobsson – 15/3

23-25/3 eller 27-29/3. Exkursion till Islay, Skottland

5/4. Kan en Snowball Earth händer igen? – Alasdair Skelton

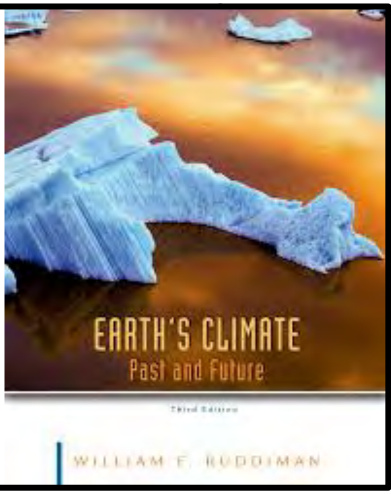
19/4. Tentamen

Course textbook reading

Earth's Climate: Past and Future, Ruddiman, 2013, W.H. Freeman, 3rd ed.

ISBN: 9781429255257:

Chapters 6 and 7, Zachos et al., 2001; 2008



Outline

To understand the significance of Snowball Earth we have to understand the wider range of climate variability on Earth:

- Trends in Earth's climate over the past 800 million years: ***greenhouse* and *icehouse* climate modes** (tectonic scale climate variability), **the $\delta^{18}O$ proxy**

STUDY THE RECENT GEOLOGICAL PAST WHERE DETAILS ARE BEST RECORDED

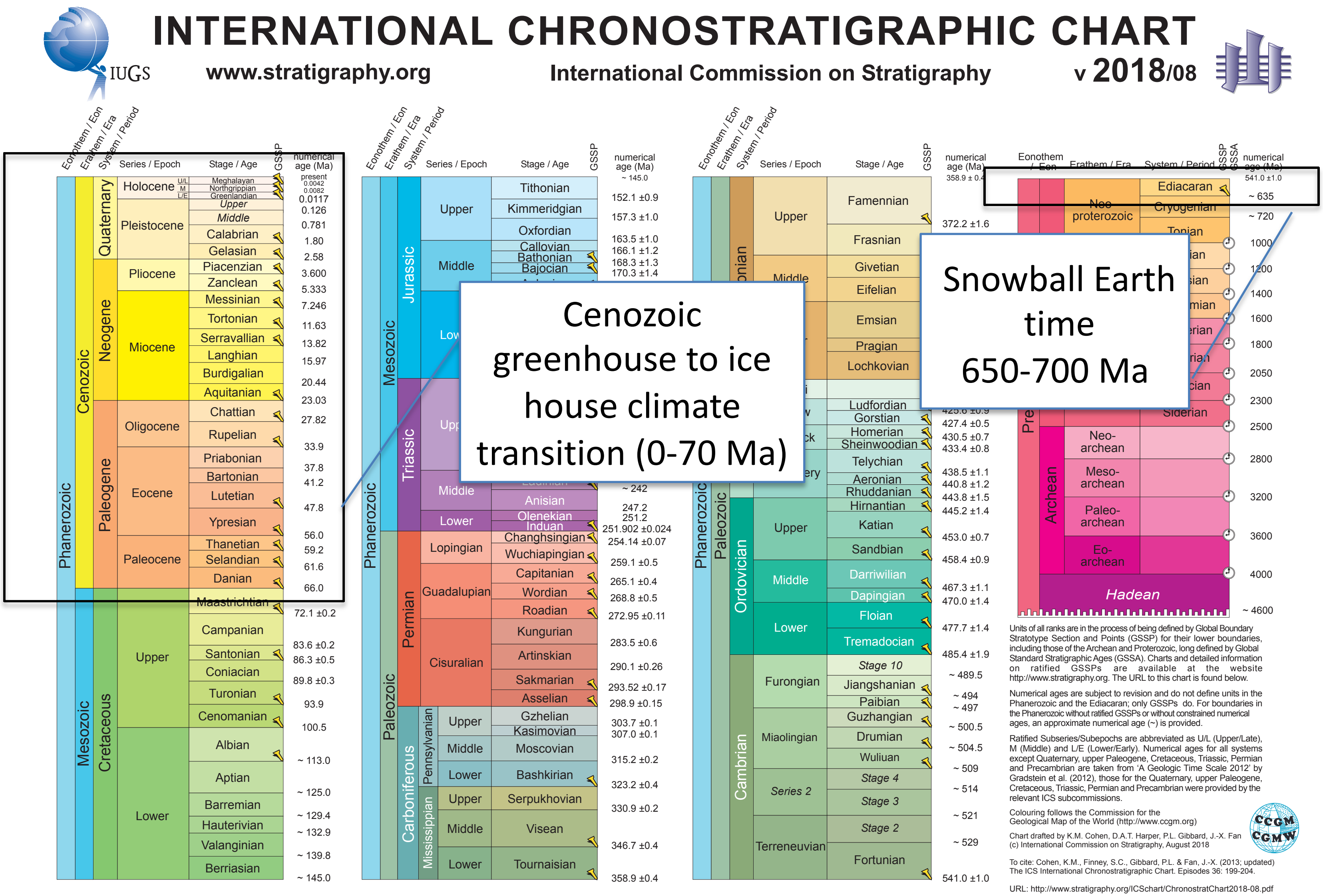
- Earth's **last global greenhouse**; (orbital scale climate variability) evidence, cause.

- **An extreme climate warming event**: warming, ocean acidification & carbon release *(sound familiar?)* 56 million years ago

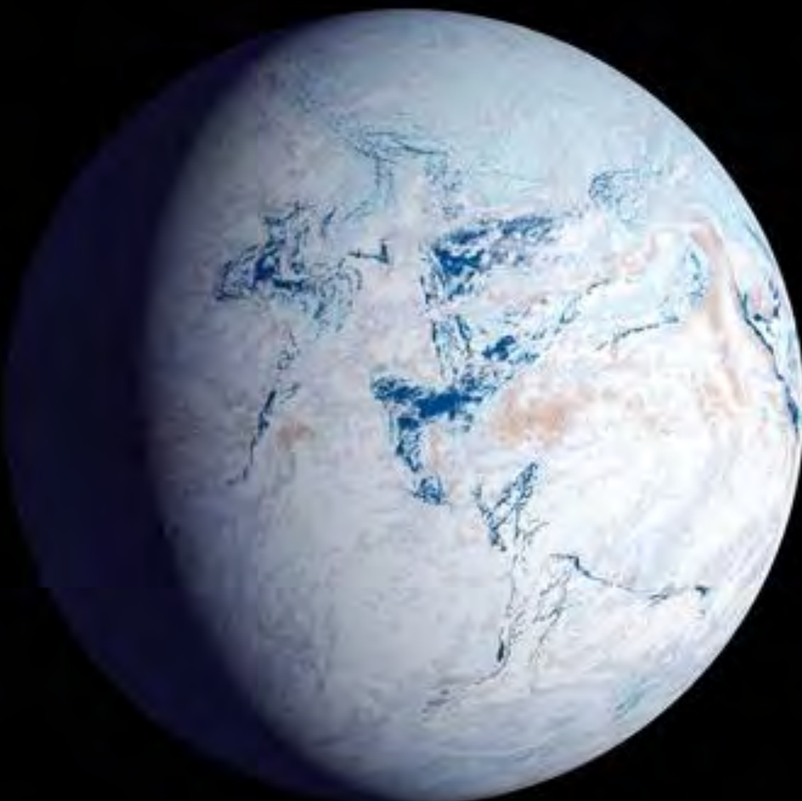
- End of the last greenhouse climate, shift into the **modern icehouse**
  -Stage 1: cooling & **glaciation of Antarctica** 34 million years ago
  -Stage 2: more global cooling and **glaciation of the northern hemisphere** 2-5 million years ago.

- Conclusions: climate modes over geological time and evidence for the principal **driving forces of climate** from key examples

Setting the scene: geologic time



How can we know the climate and temperature in the geological past?



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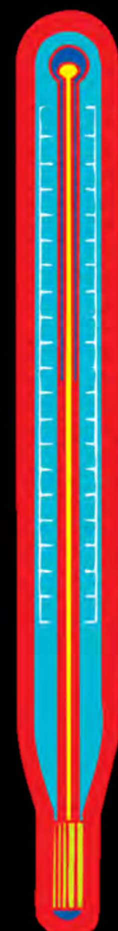

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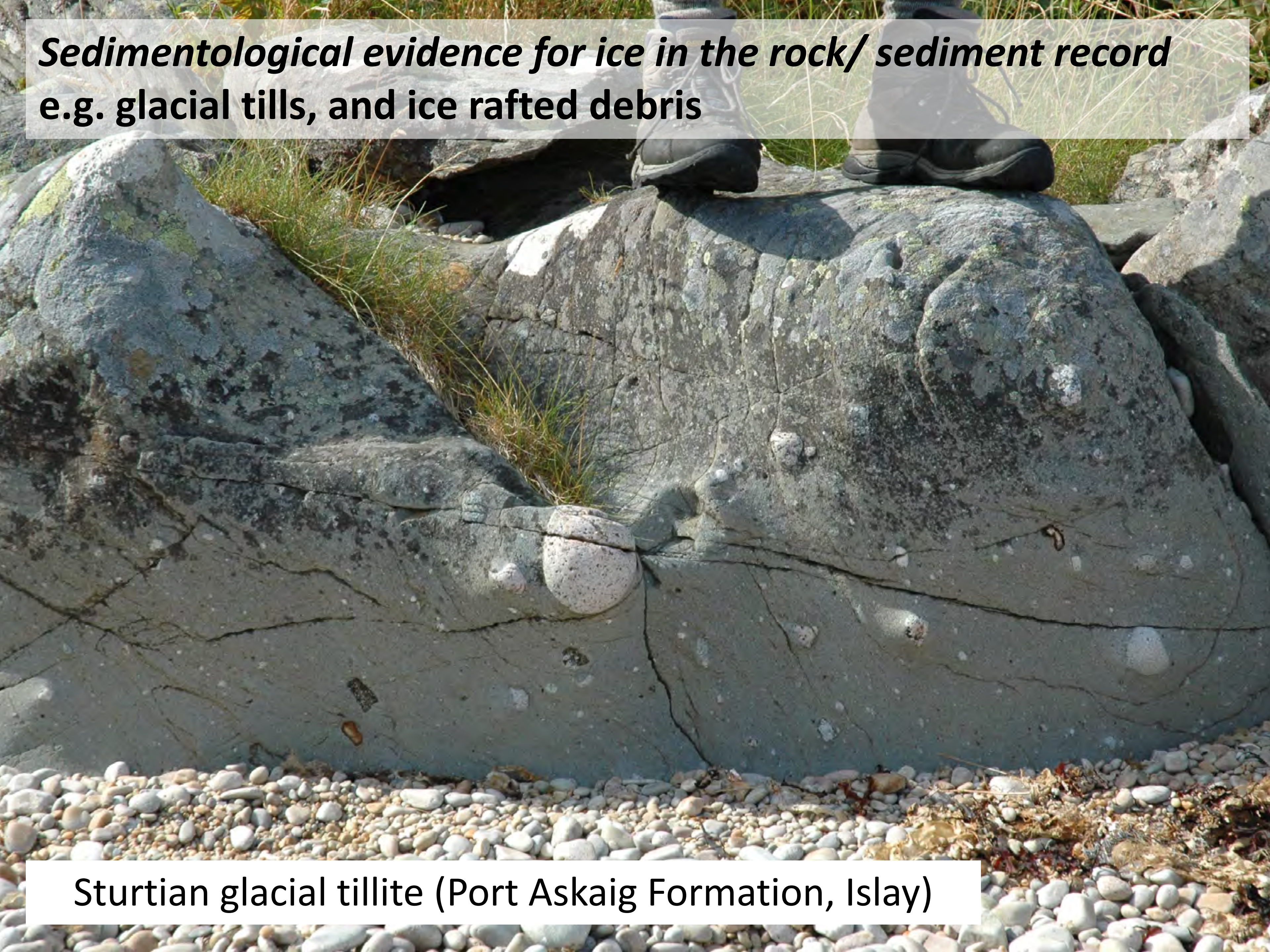
The $\delta^{18}O$ proxy for past temperature on Earth

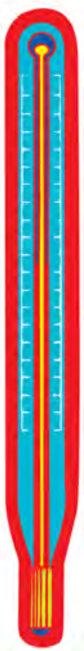
Fossils of Tropical Vegetation in the Arctic:

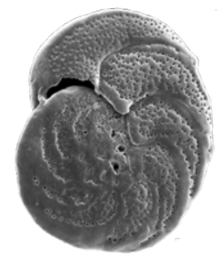
- Fossil leaf of a tropical breadfruit tree found in the Arctic


Sedimentological evidence for ice in the rock/ sediment record
e.g. glacial tills, and ice rafted debris
Sturtian glacial tillite (Port Askaig Formation, Islay)

Geochemical evidence: the δ^{18}O proxy for past temperature on Earth

δ^{18}O (oxygen stable isotope ratios) measured in minerals, and fossil skeletons and shells preserved in the geological record is used as a palaeothermometer.

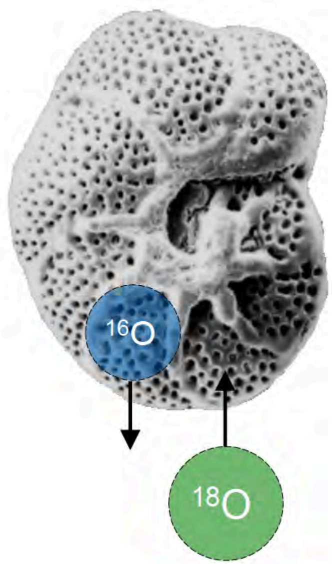


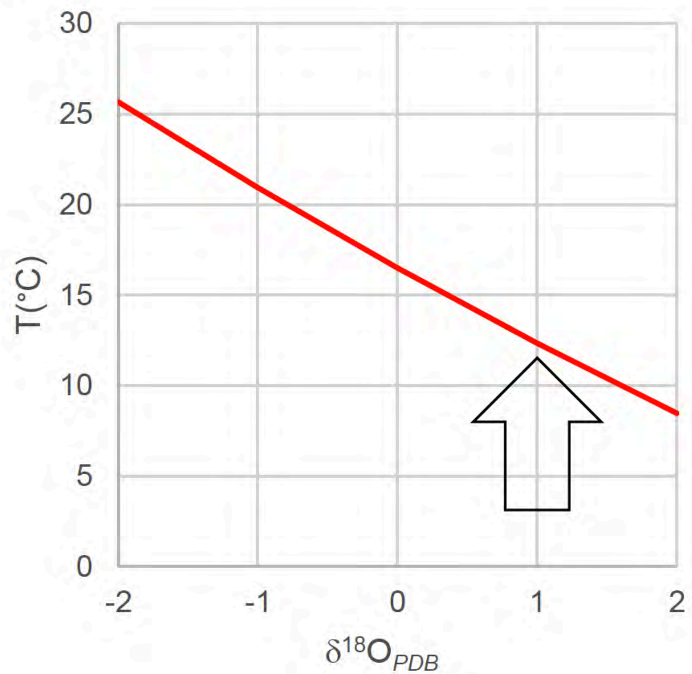


All made of **$CaCO_3$**

The method is based on the principal that there is a temperature controlled fractionation of oxygen stable isotopes (^{18}O & ^{16}O) into calcium carbonate.

Isotopisk fraktionering





$\delta^{18}O$ temperature equation

Epstein et al. (1953)

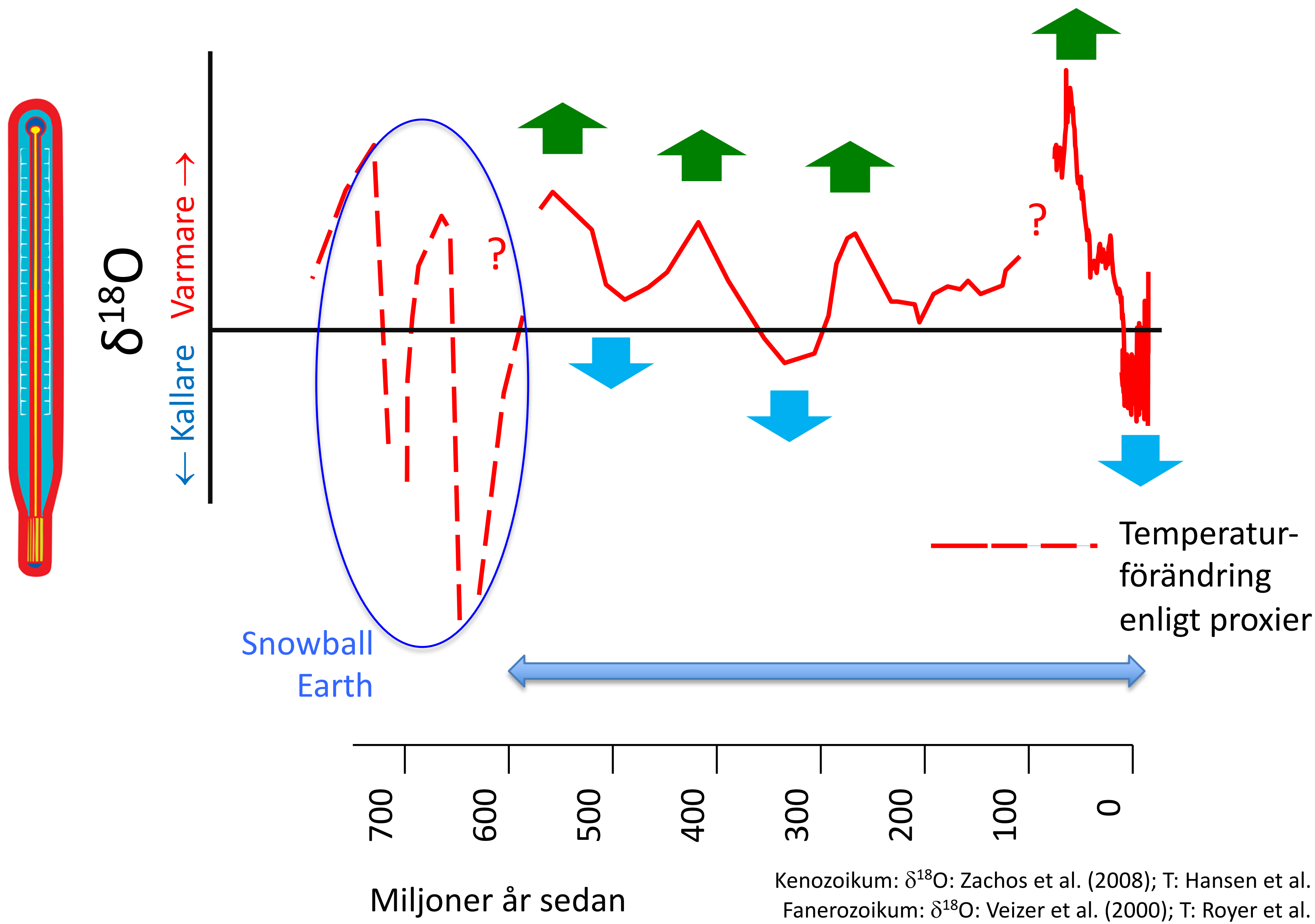
$$T = 16{,}5 - 4{,}3[\delta^{18}O_{PDB}] + 0{,}146\ [\delta^{18}O_{PDB}]^2$$

Bild: UCL

<u>In isotopically identical waters</u>, calcite ($CaCO_3$) shells precipitated in:

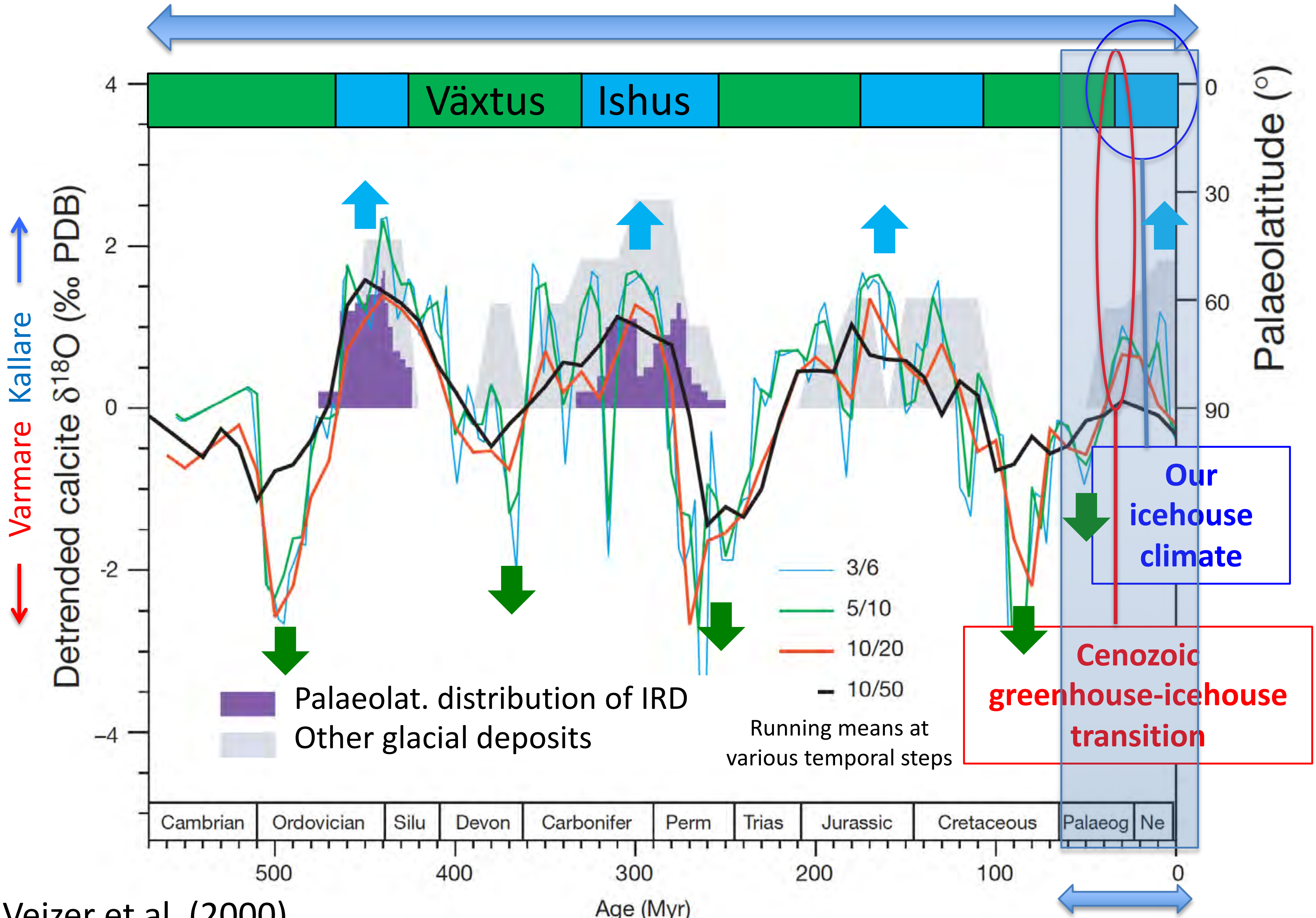
- **-cold** water have relatively **high $\delta^{18}O$**
- **-warm water** have relatively **low $\delta^{18}O$**

Temperaturförändring under geologisk tid



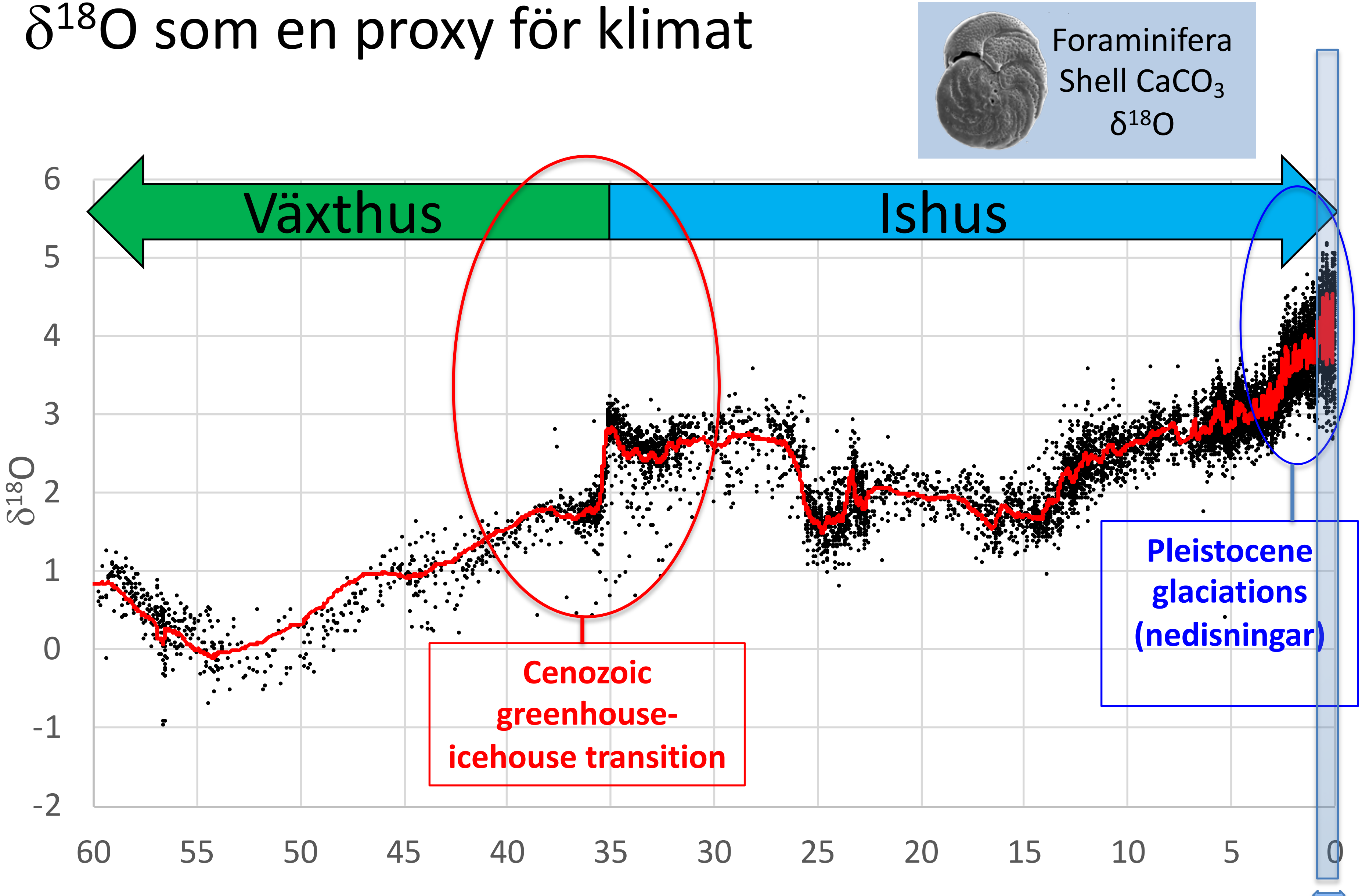
Kenozoikum: $\delta^{18}O$: Zachos et al. (2008); T: Hansen et al. (2013)
Fanerozoikum: $\delta^{18}O$: Veizer et al. (2000); T: Royer et al. (2004)
Neoproterozoikum: $\delta^{13}C$: Halverson et al. (2005)

$\delta^{18}O$ som en proxy för klimat



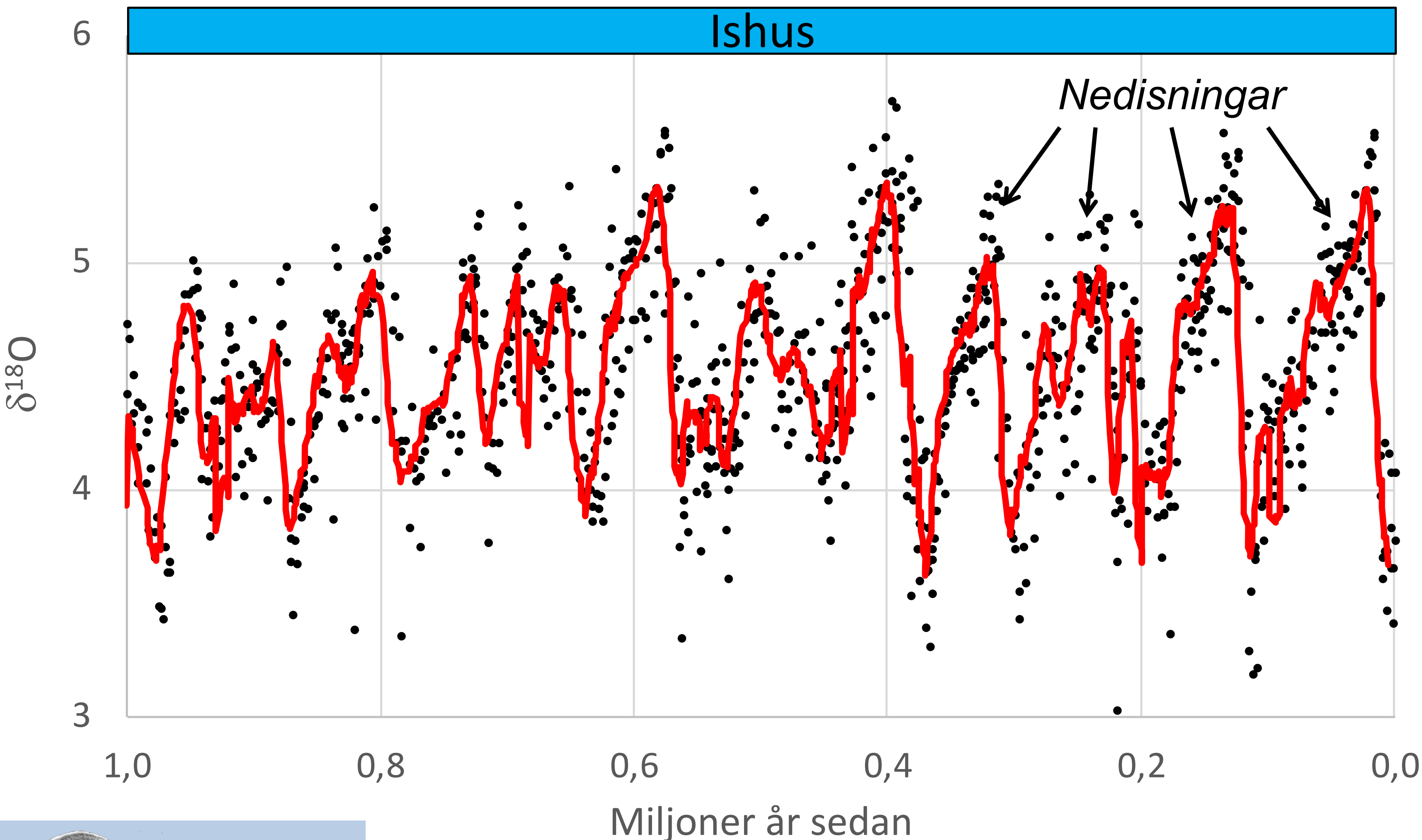
Veizer et al. (2000)

$\delta^{18}O$ som en proxy för klimat



Zachos et al. (2008)

$\delta^{18}O$ som en proxy för klimat



Foraminifera
Shell $CaCO_3$
$\delta^{18}O$

Zachos et al. (2008)

STUDY THE RECENT GEOLOGICAL PAST WHERE DETAILS ARE BEST RECORDED

Where do the most detailed and continuous *δ¹⁸O curves* for the Cenozoic come from? Answer: Foraminifera (microscope shell-building marine plankton)

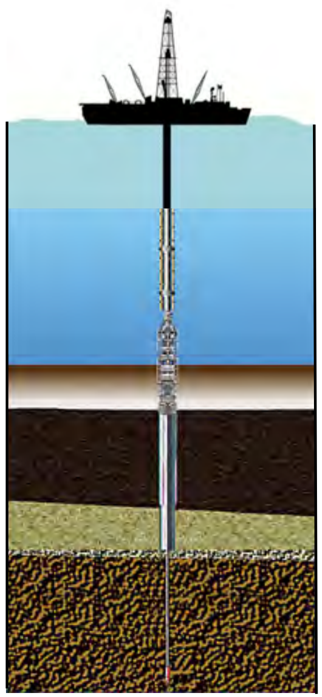
Foraminifera shell $CaCO_3$ (calcium carbonate)

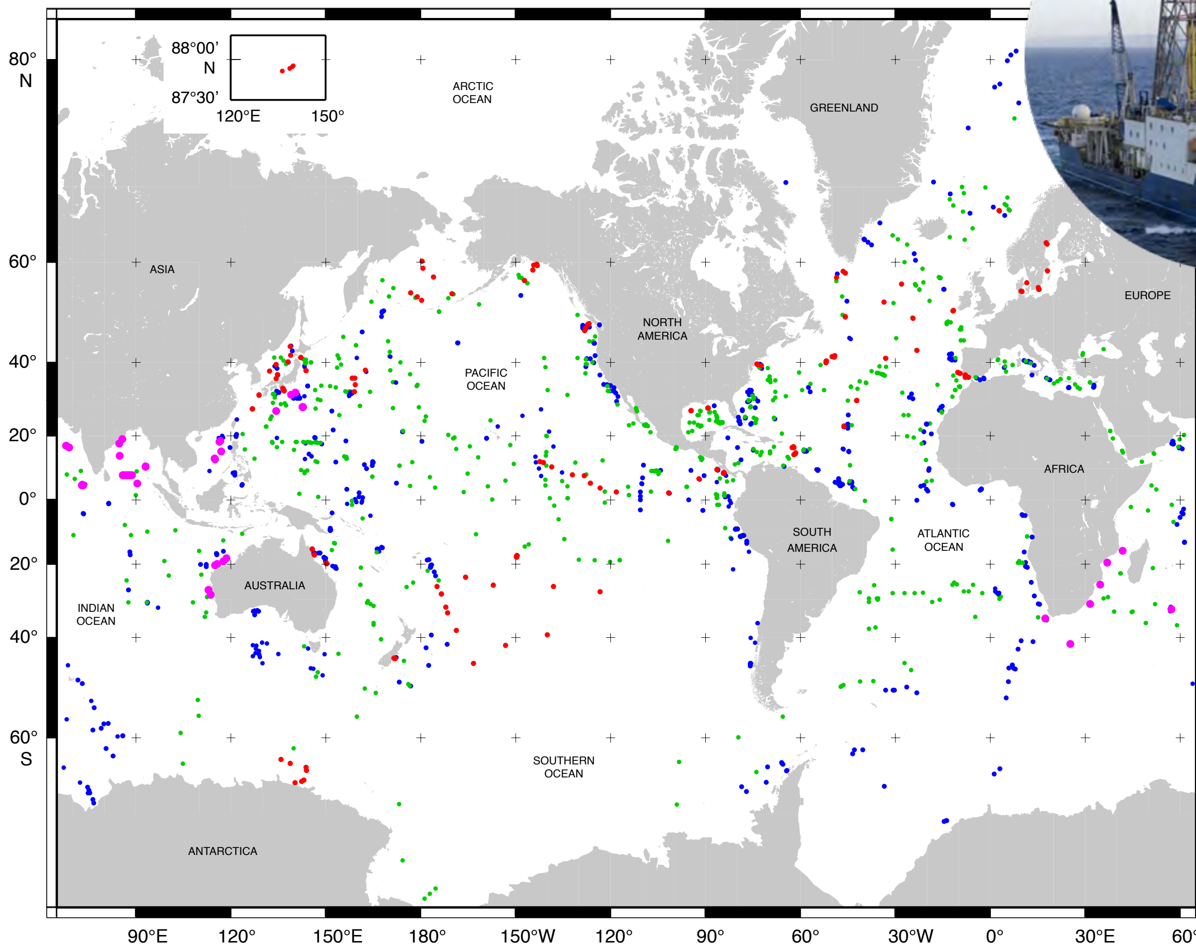
1. ***$\delta^{18}O$*** *($^{18}O/^{16}O$) reflects ocean temperature* ***AND*** *the amount of ice stored on land in glaciers (glaciers store ^{16}O), when the foram was alive (i.e. the isotopic composition of seawater).*

2. ***$\delta^{13}C$*** *($^{13}C/^{12}C$) reflects global carbon cycling (^{12}C taken up during photoshynthesis), when the foram was alive.*

Where does 0-65 Ma foraminifera $\delta^{18}O$ data come from?

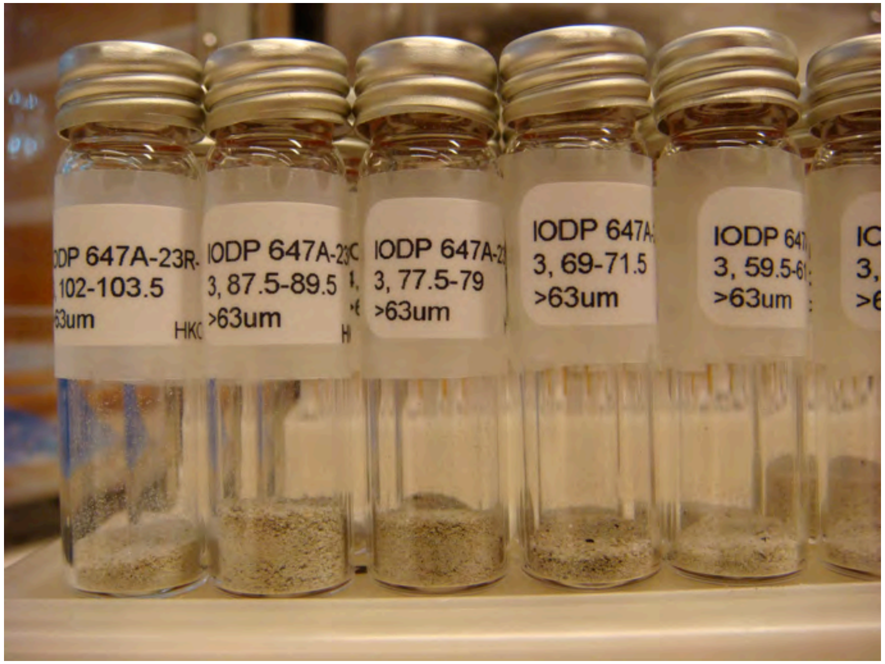
Answer: Deep sea sediments cores

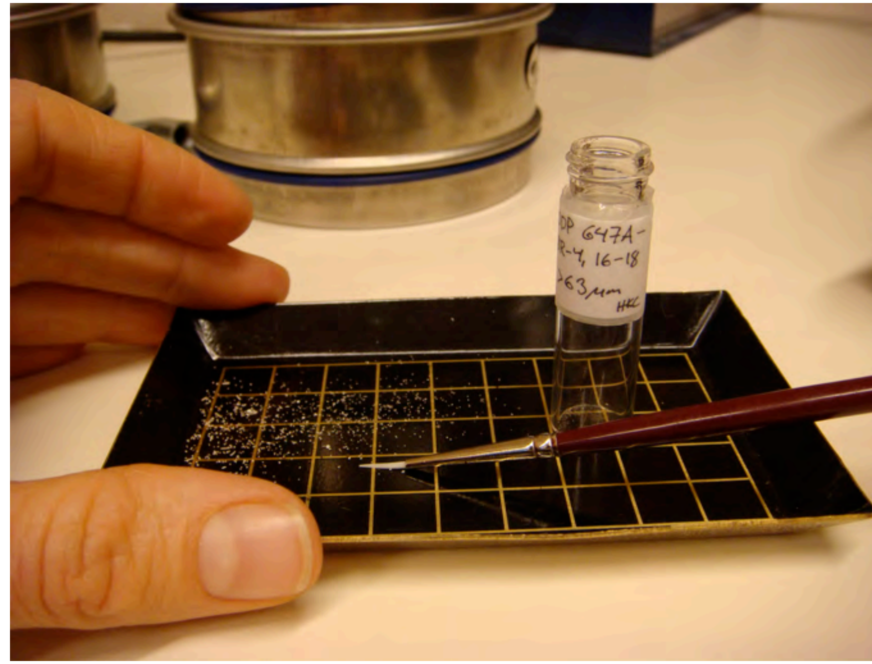


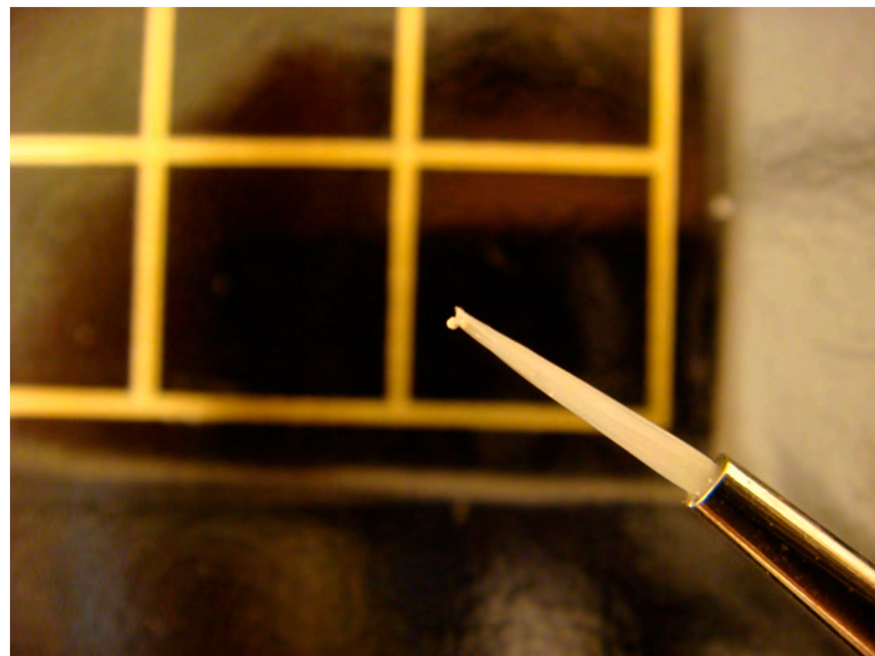


DSDP Legs 1–96 (•), ODP Legs 100–210 (•), IODP Expeditions 301–348 (•), IODP Expeditions 349–361 (•)


Fossil foraminifera shells from deep sea
Sediments: our 'time machine at the seafloor'
Bio- carbonates, foraminifera:
$CaCO_3$
1 mm

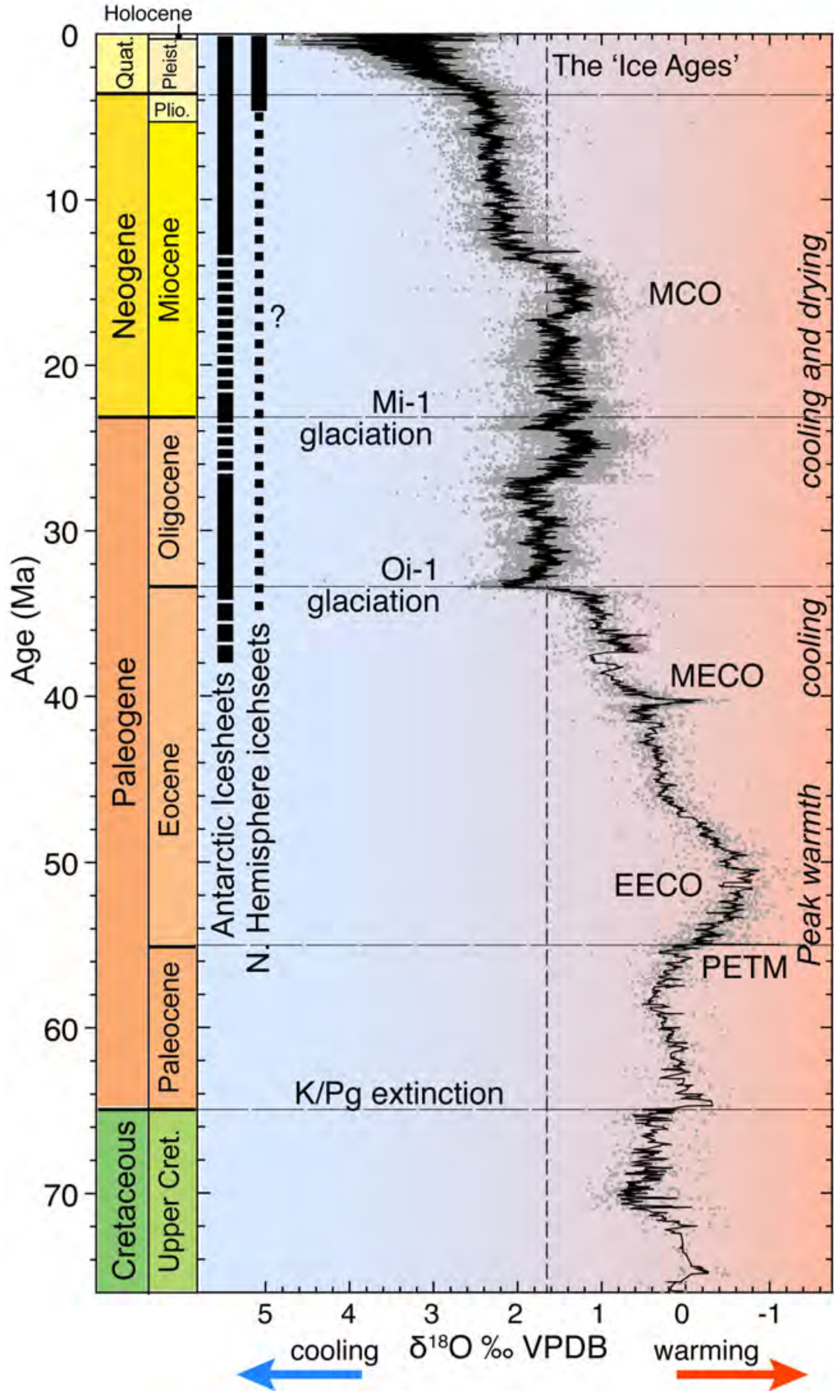

DP 647A-23R-
102-103.5
3um
HKC
IODP 647A-2
3, 87.5-89.5
>63um
IODP 647A-2
3, 77.5-79
>63um
IODP 647A
3, 69-71.5
>63um
IODP 64
3, 59.5-61
>63um


P 647A-
R-4, 16-18
>63μm
HKC



The Cenozoic deep sea δ¹⁸O climate curve

Also known as the 'Zachos Curve' after the scientist James Zachos,



Modified from Zachos et al., 2001, 2008; Cramer et al., 2009.

Measured on thousands of samples of seafloor-living (benthic) foraminifera from all over the world's oceans

James Zachos,

University of California
Santa Cruz

Summary points 1.

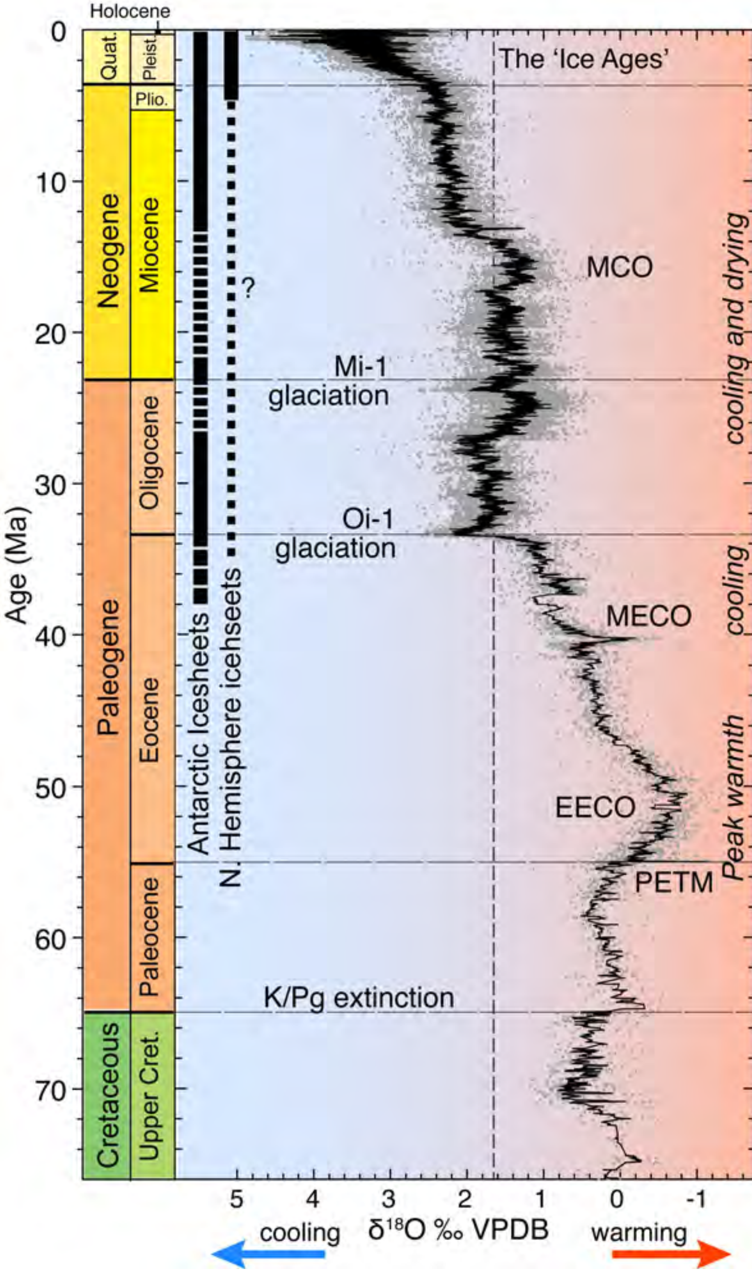
- Over its history the Earth has alternated between warm '**greenhouse'** and colder '**icehouse'** climate modes, lasting 10s to up to ~100 million years.

- We are **now in an icehouse mode** that started 34 million years ago.

- Under an icehouse climate, ice and glaciers exist in polar regions. The size of these glaciers changes giving times of stronger and weaker glaciation: we are currently in an **interglacial**.

- It is much easier to find geological evidence for the past 100 million years. So we can ask more detailed questions such as:
  Are greenhouse conditions caused by high CO_2*?*
  Why did the Earth shift into an icehouse state?

The early Cenozoic greenhouse climate

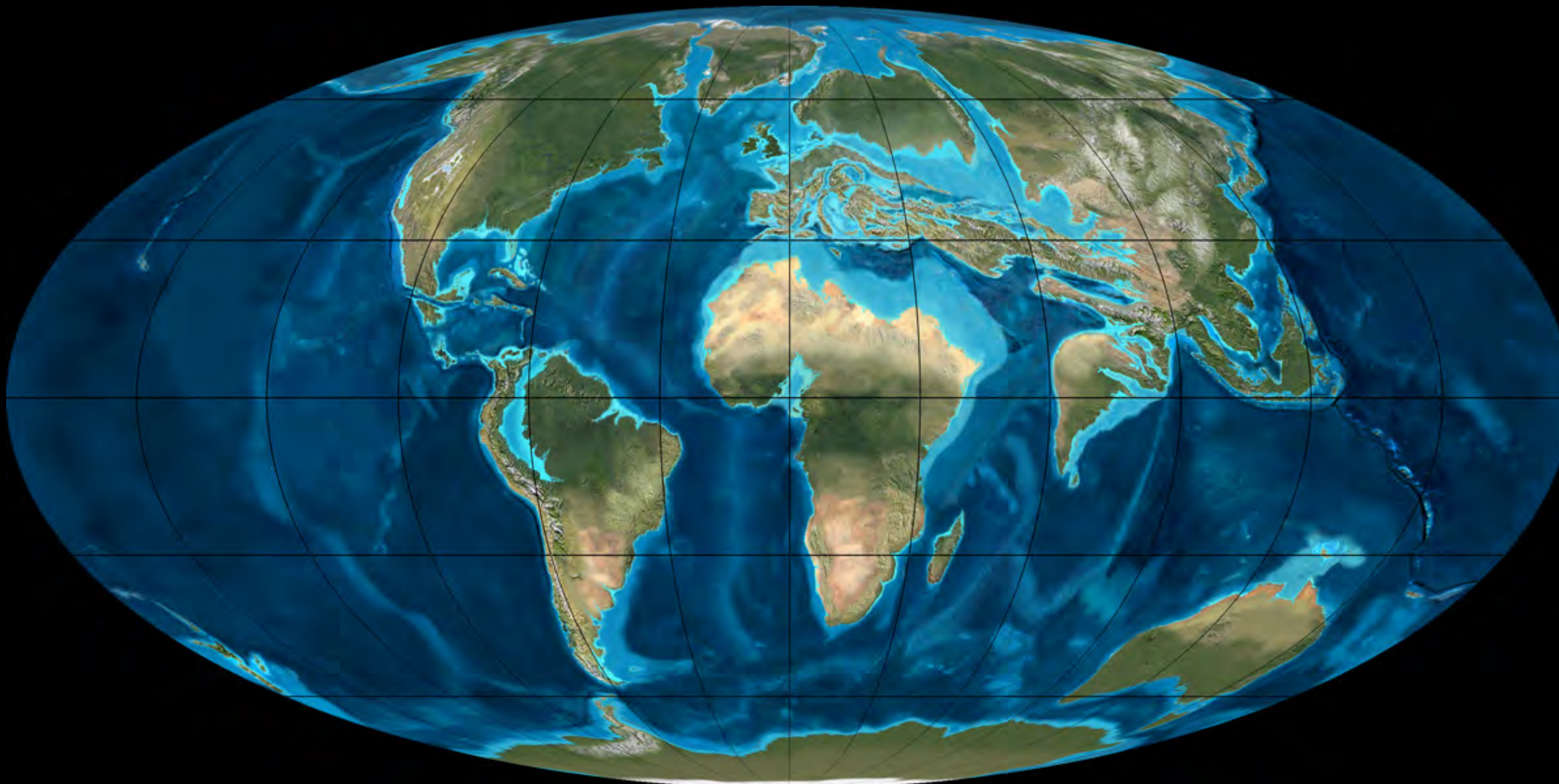


$\delta^{18}O$ evidence tells us that the deep ocean, and therefore Earth was much warmer than today.

Cenozoic climatic from deep sea $\delta^{18}O$ (Zachos et al., 2001, 2008; Cramer et al., 2009).

Artists impression of an Eocene forest 40 Ma: Image from Pin

Eocene greenhouse climate geography



Similar to modern with some important differences:

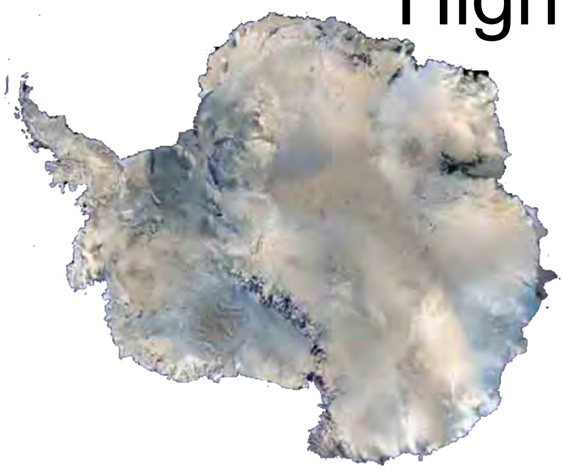
- Antarctica still attached to S. America (no Antarctic Circum- Polar Current; ACC)
- Water flows from the Atlantic to Pacific across the Panama seaway
- Water flowed from the Indian Ocean to the Atlantic through the Tethys seaway

Maps: *Ron Blakely, NAU Geology:* http://cpgeosystems.com/rect_globe.html

Climate evidence from other sources?

- Distribution of fossil and sediment types and the Earth?
- Lets look at the north and south pole.

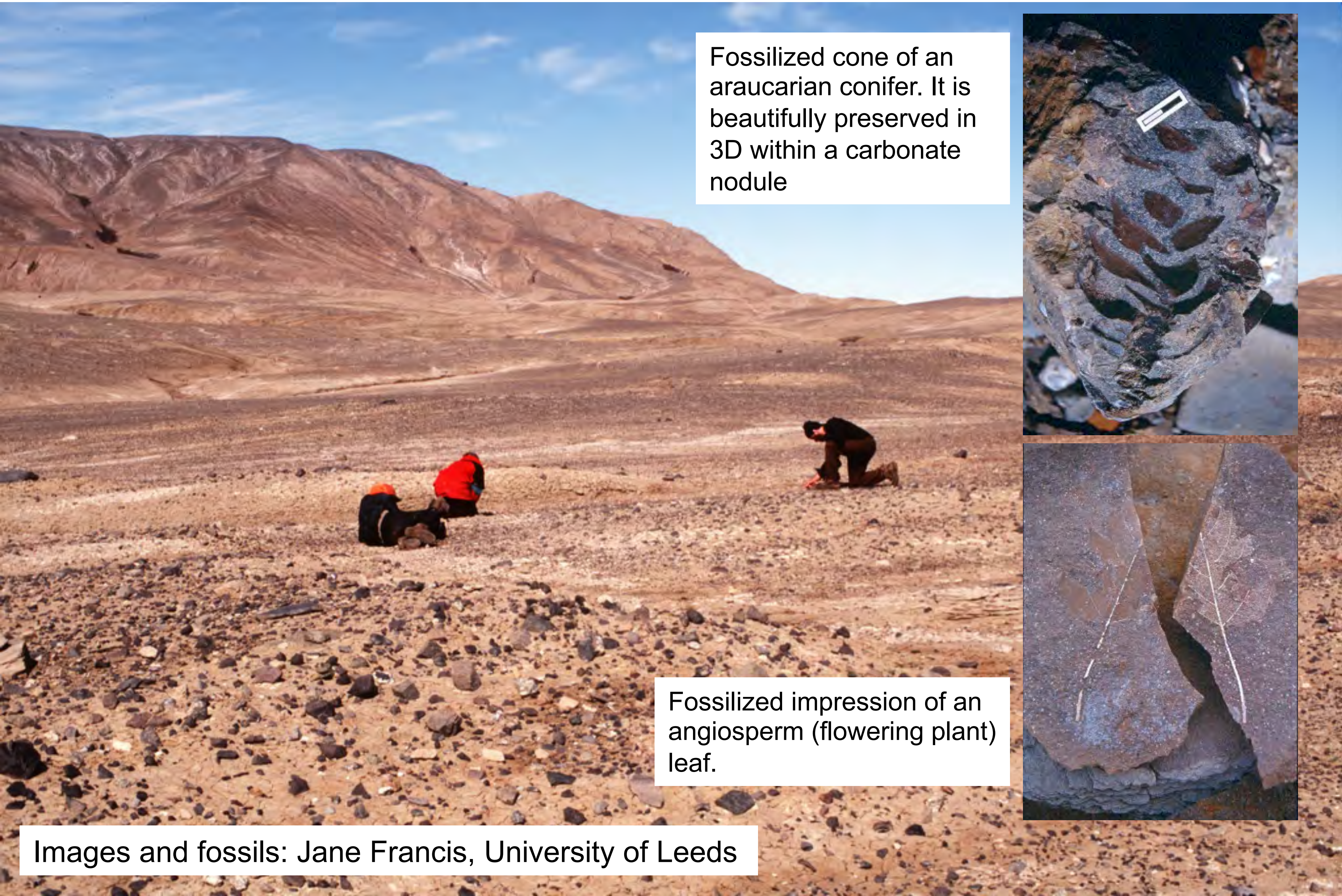
High southern latitudes: **Antarctica today**



Antarctica today:
MAT: interior : -57° C
coast: -18° C

MAT = Mean annual temperature

Eocene fossils and fossil collecting: The La Meseta Formation of Seymour Island, Antarctica

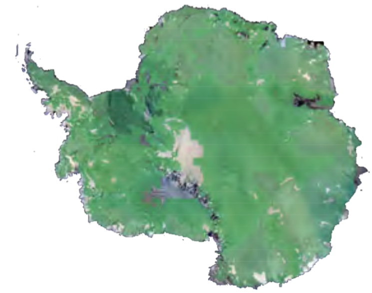


Fossilized cone of an araucarian conifer. It is beautifully preserved in 3D within a carbonate nodule

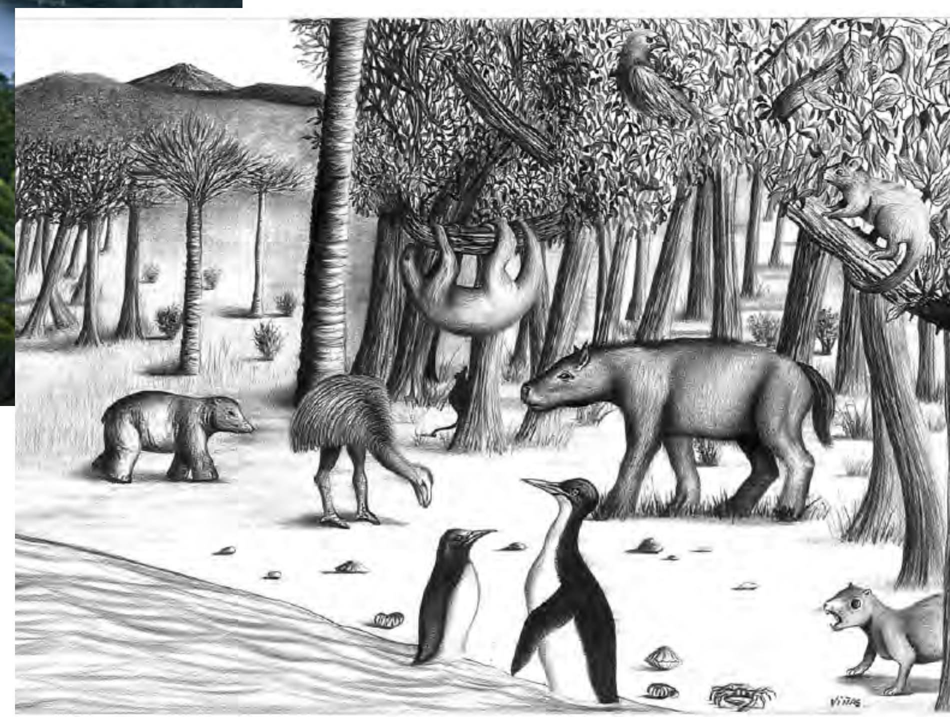
Fossilized impression of an angiosperm (flowering plant) leaf.

Images and fossils: Jane Francis, University of Leeds

Antarctica: early-middle Eocene

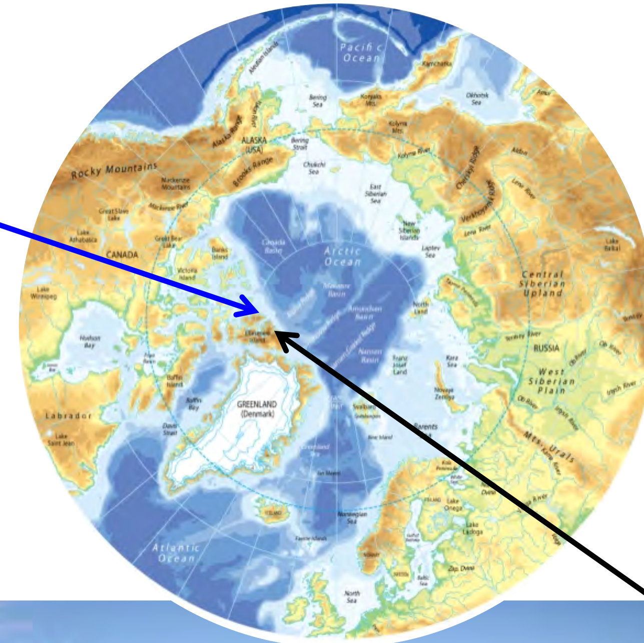


Fossil evidence suggests that during the early to middle Eocene, Antarctica was covered by *Araucaria* (monkey puzzle) and *Northofagus* (silver beech) forests found today in Chile, Tasmania and New Zealand.



Reconstructed Eocene biota of the Antarctic Peninsular, Meseta Formation (Reguero et al., 2002).

High Northern latitudes: **Arctic today**



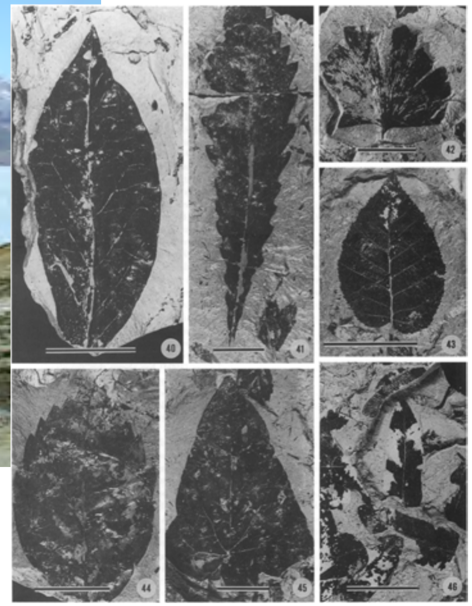
↑
Axel Heiberg Island, Nunavut, Arctic Canada

Ellesmere Island, Nunavut, Arctic Canada →

MAT TODAY -16°C

MAT = Mean annual temperature

Arctic: early Eocene Ellesmere Island

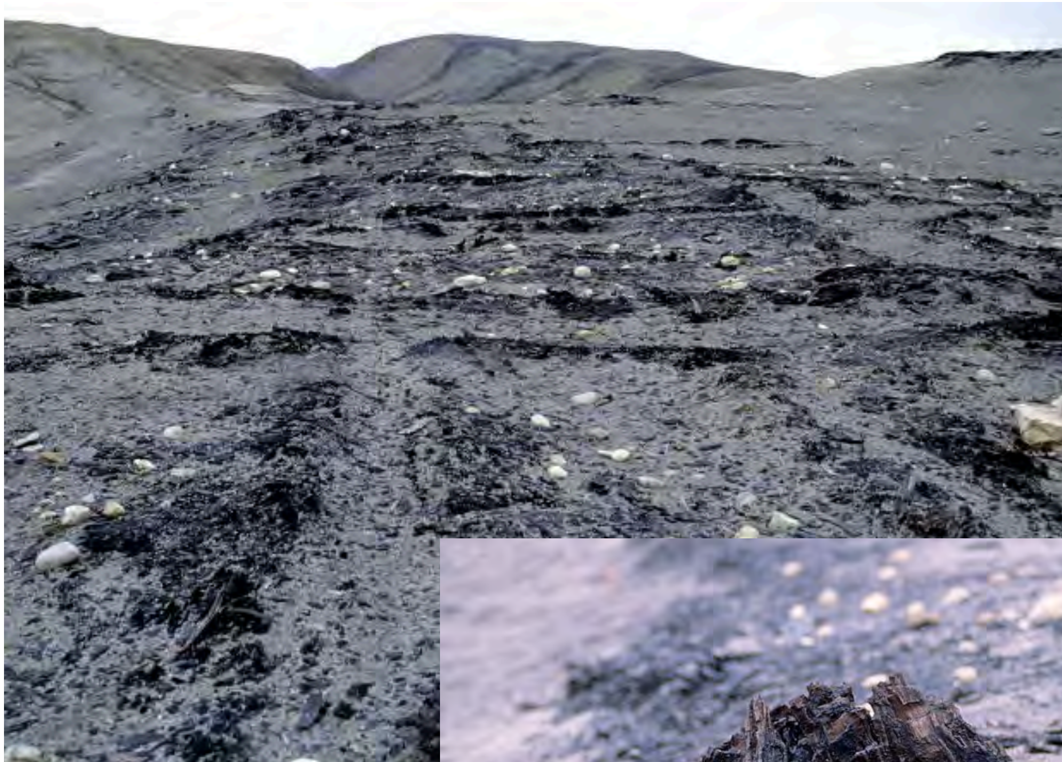


Top right: Paleontologist Malcolm McKenna collecting fossils in the Eureka Sound Group rocks on **Ellesmere Island**, summer 2001 (photo Jaelyn Eberle). Fossil finds: various species of leaves (McIver and Basinger, 1999); molar of a large brontothere (large extinct rhinoceros-like mammal, genus *Eotitanops*) and upper jaw and dentition of an Arctic tapir (*Thuliadantamolar*) and (Jaelyn J. Eberle).
http://www.thecanadianencyclopedia.ca/

Artists reconstruction (Clifford Morrows) of the Ellesmere Island environment during the early Eocene period.

Warmer, wetter early Eocene Ellesmere Island, (C. Morrow)

Arctic: early Eocene Axel Heiberg Island

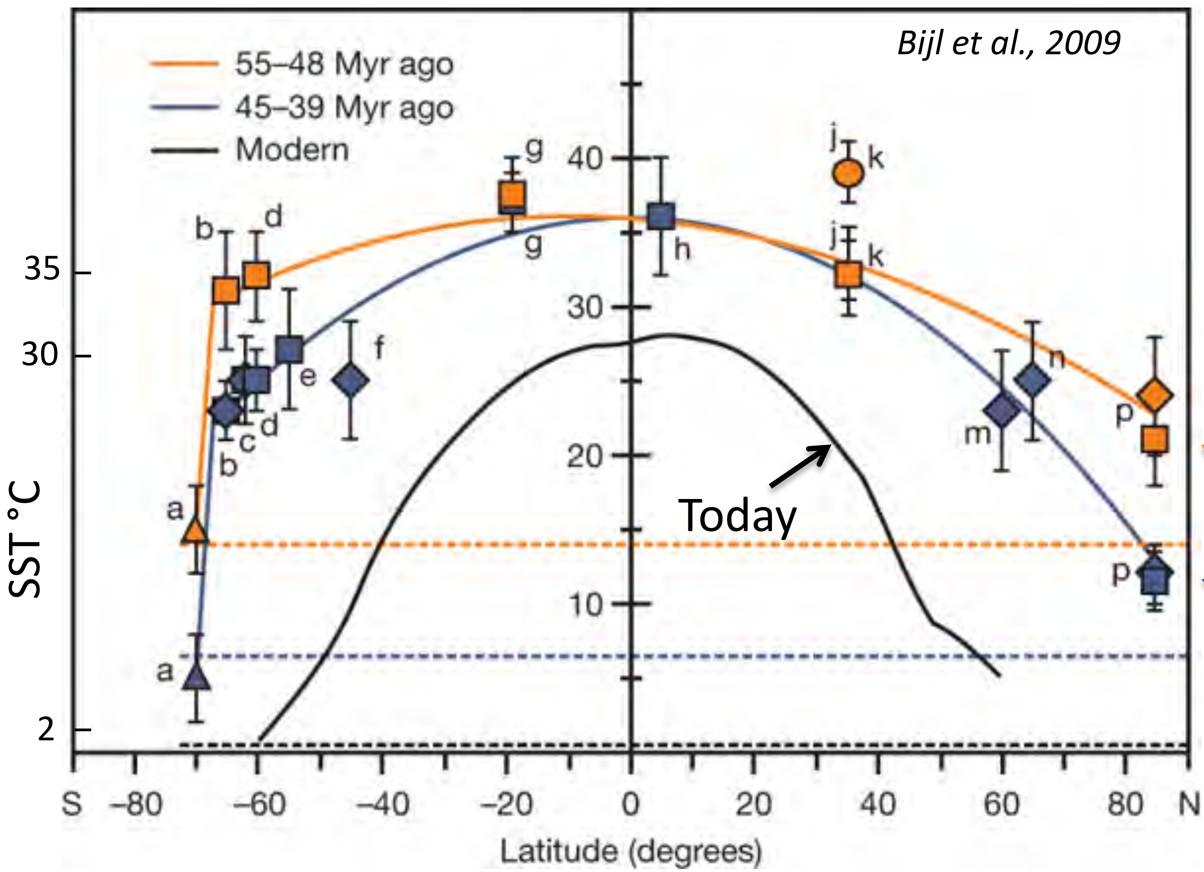


45 Ma fossilized forest remains showing the Eocene 'forest floor' and a single tree stump; **Axel Heiberg Island**, west of Greenland.

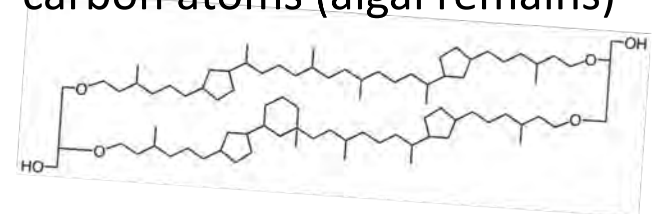
The Axel Heiberg Island fossils indicate a warm sub-tropical place similar to the 'cypress' swamplands of Florida today.

Traces of vast Eocene swamp forests. Comparable to the swamp-lands of modern Florida

Reconstructed latitudinal sea surface temperature (SST) gradients from geochemical proxies: higher global averages & warmer high latitudes



1. Tex_{86} = TetraEther indeX of tetraethers having 86 carbon atoms (algal remains)

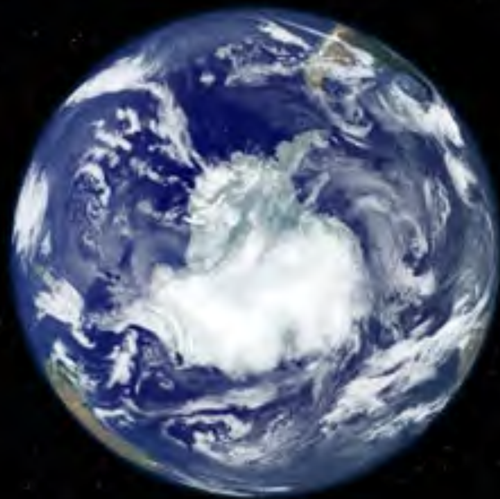


'greenhouse climate' geochemical estimates 'proxies'

2. δ^{18}O from fossil planktonic (surface floating) foraminifera

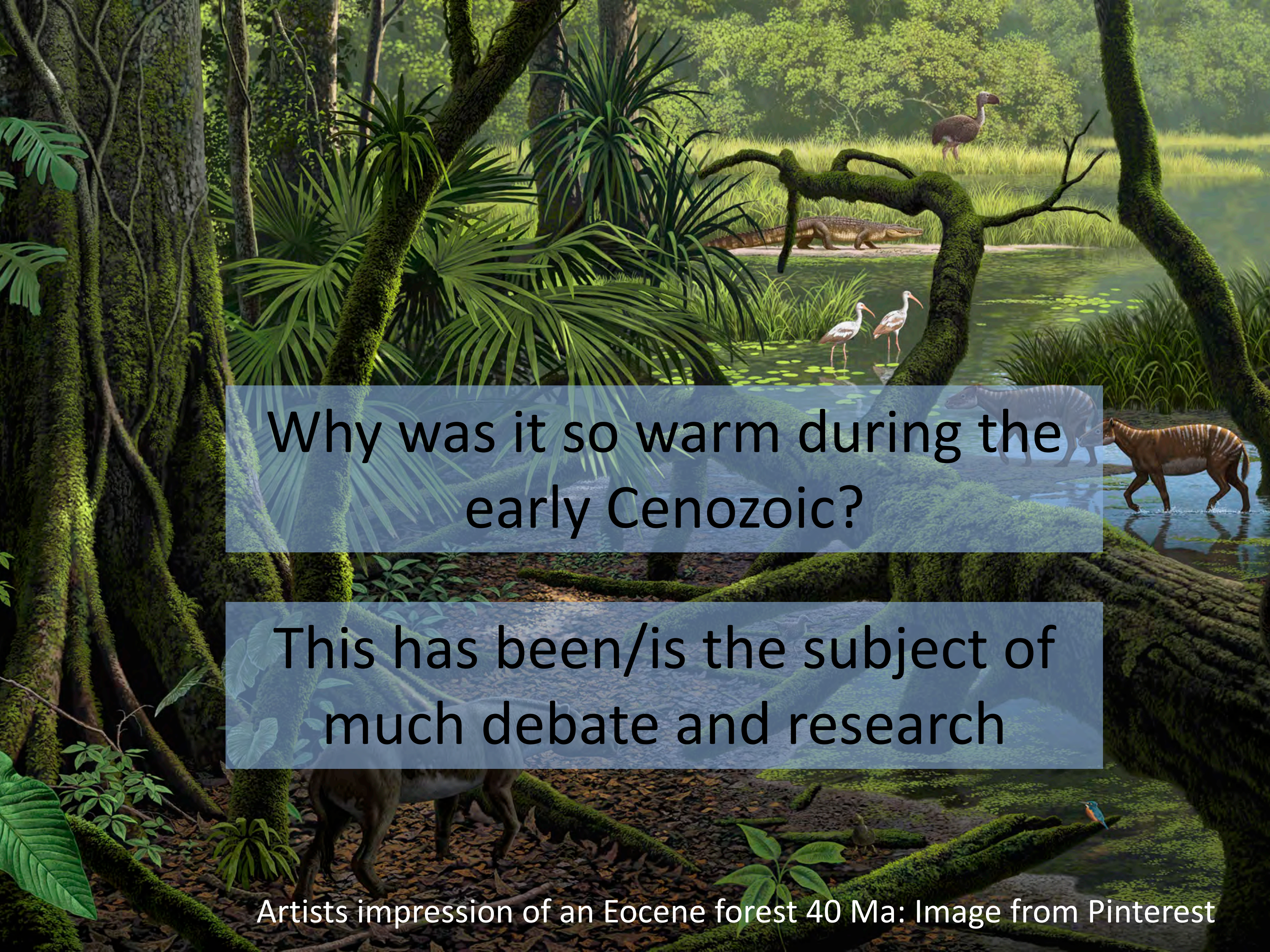
Higher seal level: Because there were no large glaciers on Antarctica or Greenland global **sea level was ca. 80 m higher than today**.

Our modern ‘icehouse Earth’



55 million years ago: Warm Earth

Henk Bruinkhuis, National Geographic



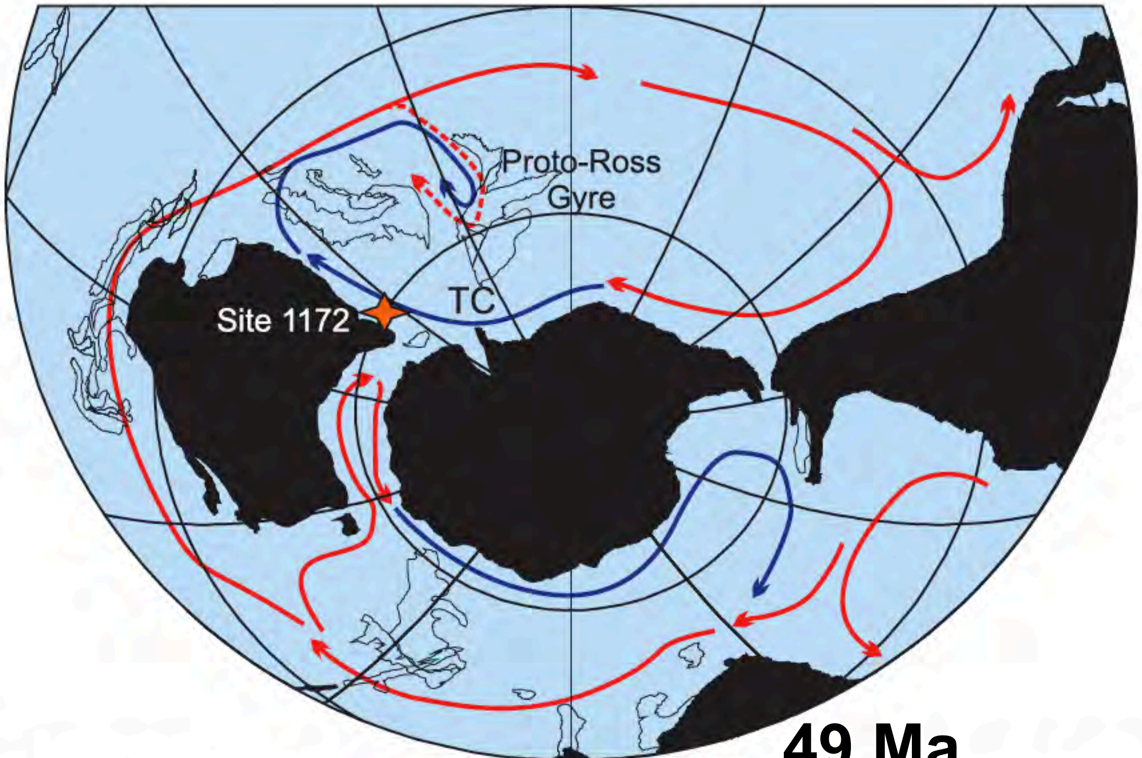
Why was it so warm during the early Cenozoic?

This has been/is the subject of much debate and research

Artists impression of an Eocene forest 40 Ma: Image from Pinterest

Hypothesis 1: Early Cenozoic warmth caused by different geography that directed ocean currents & heat south/north (H1-Tectonics)

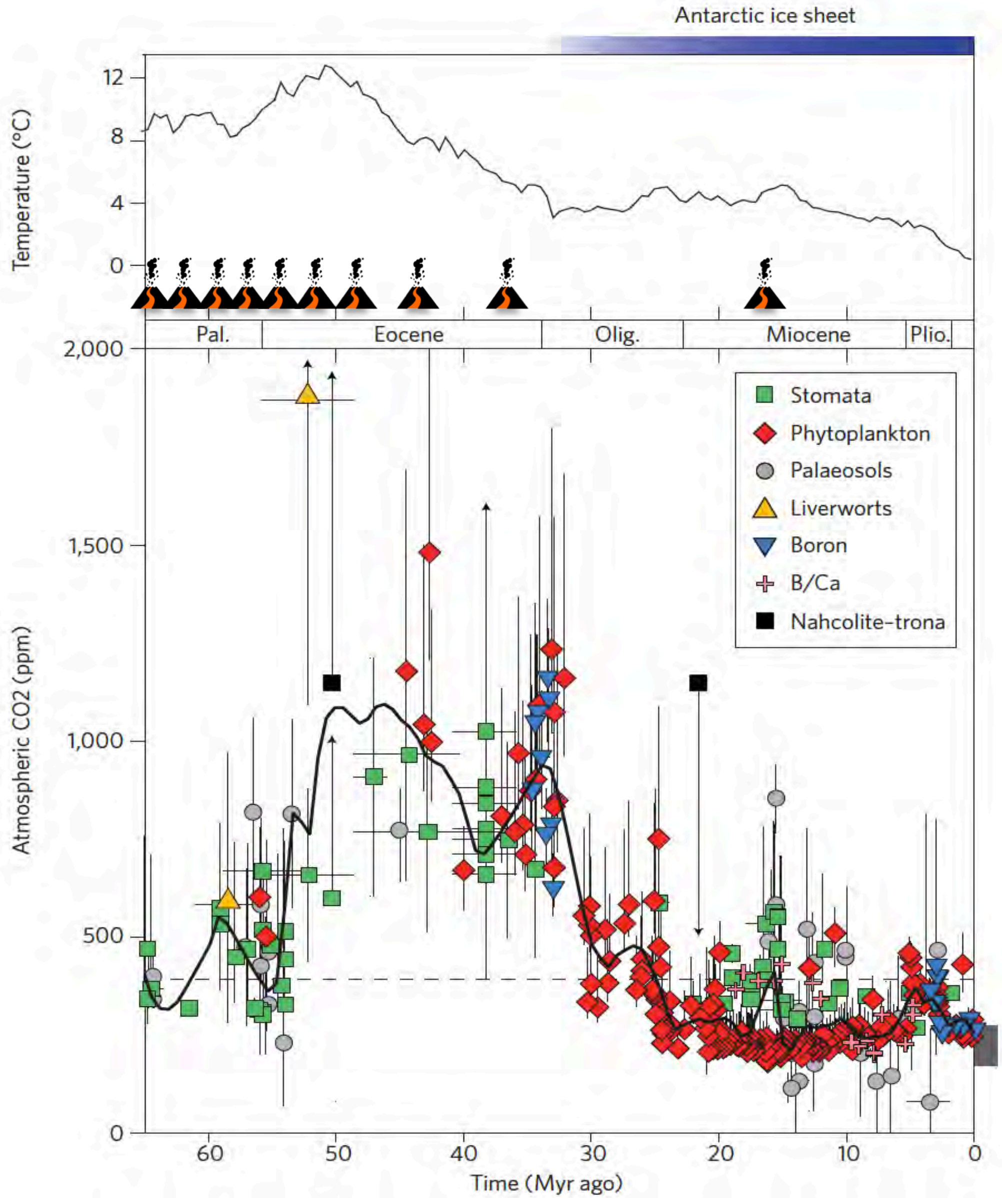
Palaeoceanographic reconstruction derived from general circulation model experiments. The orange star indicates the paleo-geographic location of ODP Site 1172 at 65°S in the southwest Pacific Ocean, under the influence of the Antarctic-derived Tasman Current (TC) (Bijl et al., 2010).



49 Ma paleogeography

- Southern land barriers blocked the cold ACC flow that today isolates Antarctica, thus warmer waters carrying heat reached Antarctica.
- Warmer world results in more water in the atmosphere (also carrying heat), therefore, stronger heat transport by the atmosphere, more hurricanes.

Hypothesis 2: Early Cenozoic warmth caused by higher than modern CO_2, i.e. a stronger greenhouse effect (H2-CO_2)



Atmospheric pCO_2 reconstructions from geological proxies show:

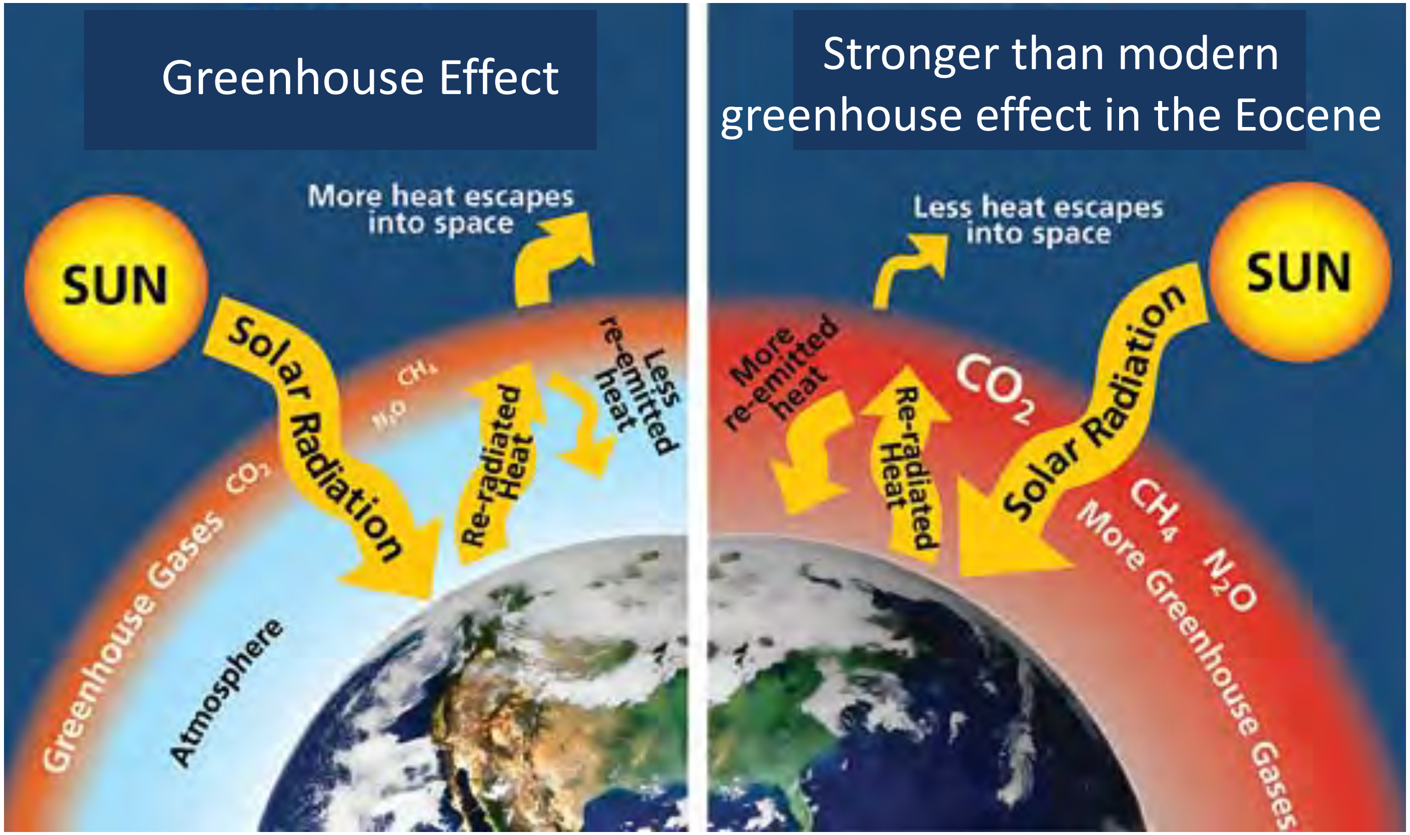
1. Up to 5 x modern CO_2 during the warm Eocene (50-35 Ma), probably due to greater tectonic activity and more volcanoes than today (e.g. Atlantic Ocean opening).

2. CO_2 dropped ca. 34 Ma and had decreased to modern levels by 25 Ma.

A summary of climate and pCO_2 indicators during the Cenozoic. Deep-sea temperatures (upper) generally track pCO_2 (lower), reconstructed from terrestrial and marine proxies. Error bars = data uncertainties. Symbols with arrows = either upper or lower limits. Vertical grey bar (right axis) = glacial–interglacial pCO_2 range from ice cores. Horizontal dashed line = present-day atmospheric CO_2 concentration (400 ppm).

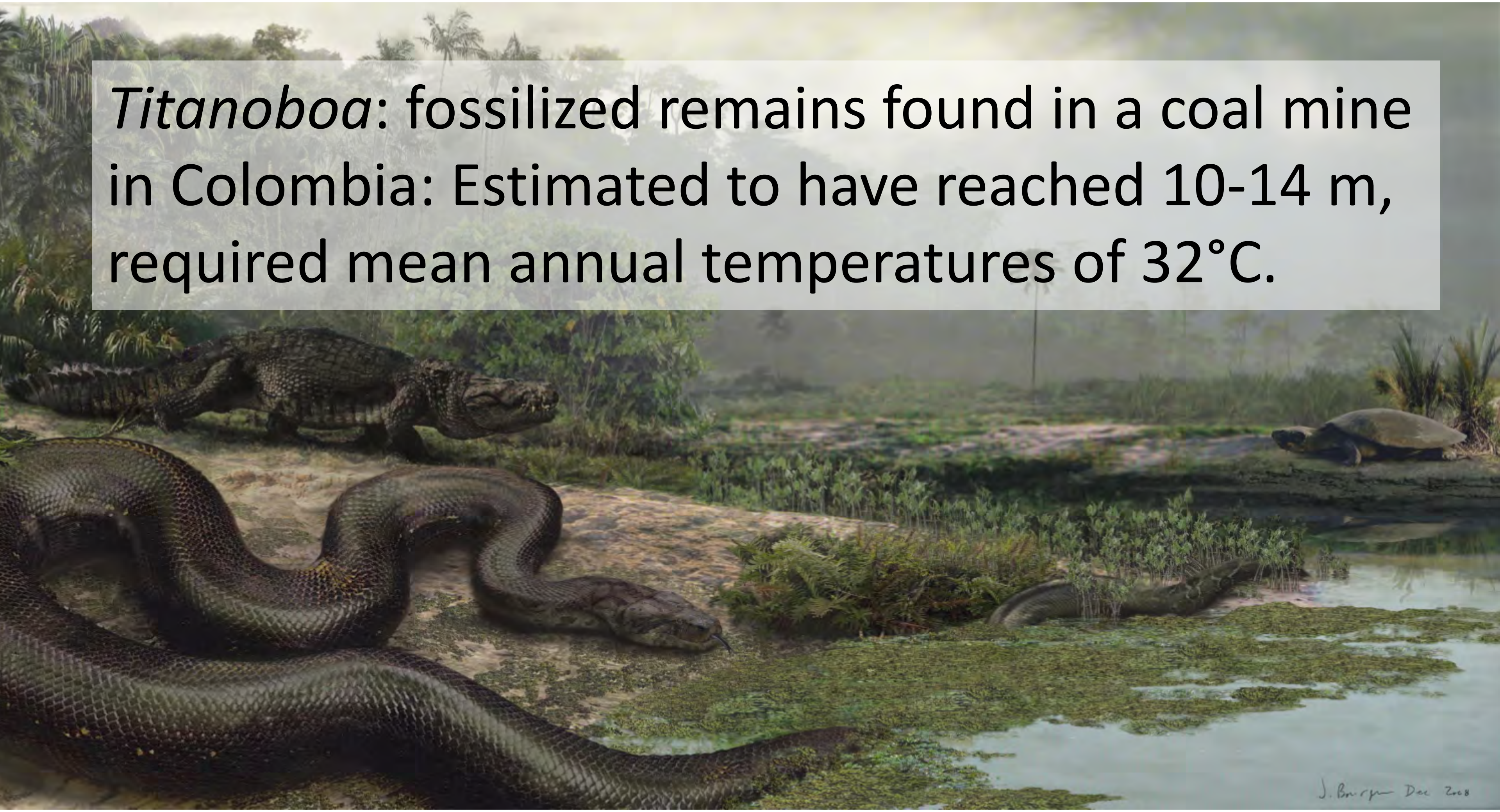
Beerling & Royer, 2010

Solenergi och växthuseffekten



An extreme climate event 56 million years ago: The Paleocene Eocene thermal maximum (PETM)

Titanoboa: fossilized remains found in a coal mine in Colombia: Estimated to have reached 10-14 m, required mean annual temperatures of 32°C.

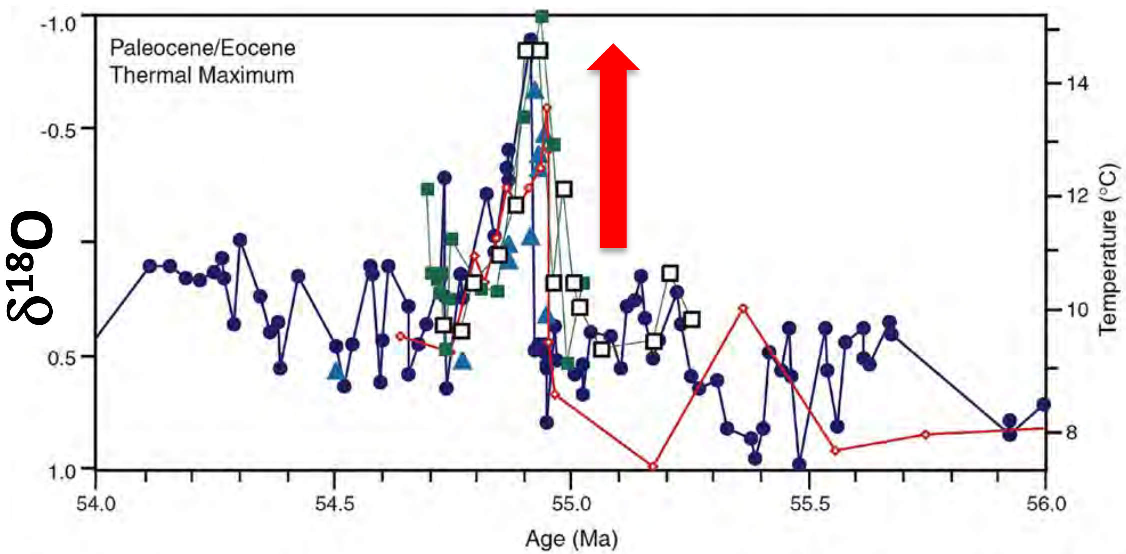


Reconstruction of a tropical humid Paleocene-Eocene environment. Illustration by Jason Bourque.

Evidence for the extreme event 56 million years ago

1. Foraminifera $\delta^{18}O$ and $\delta^{13}C$ decreases in marine sediment cores from around the world

Legend: Different deep sea core records measured on various species of benthic foraminifera

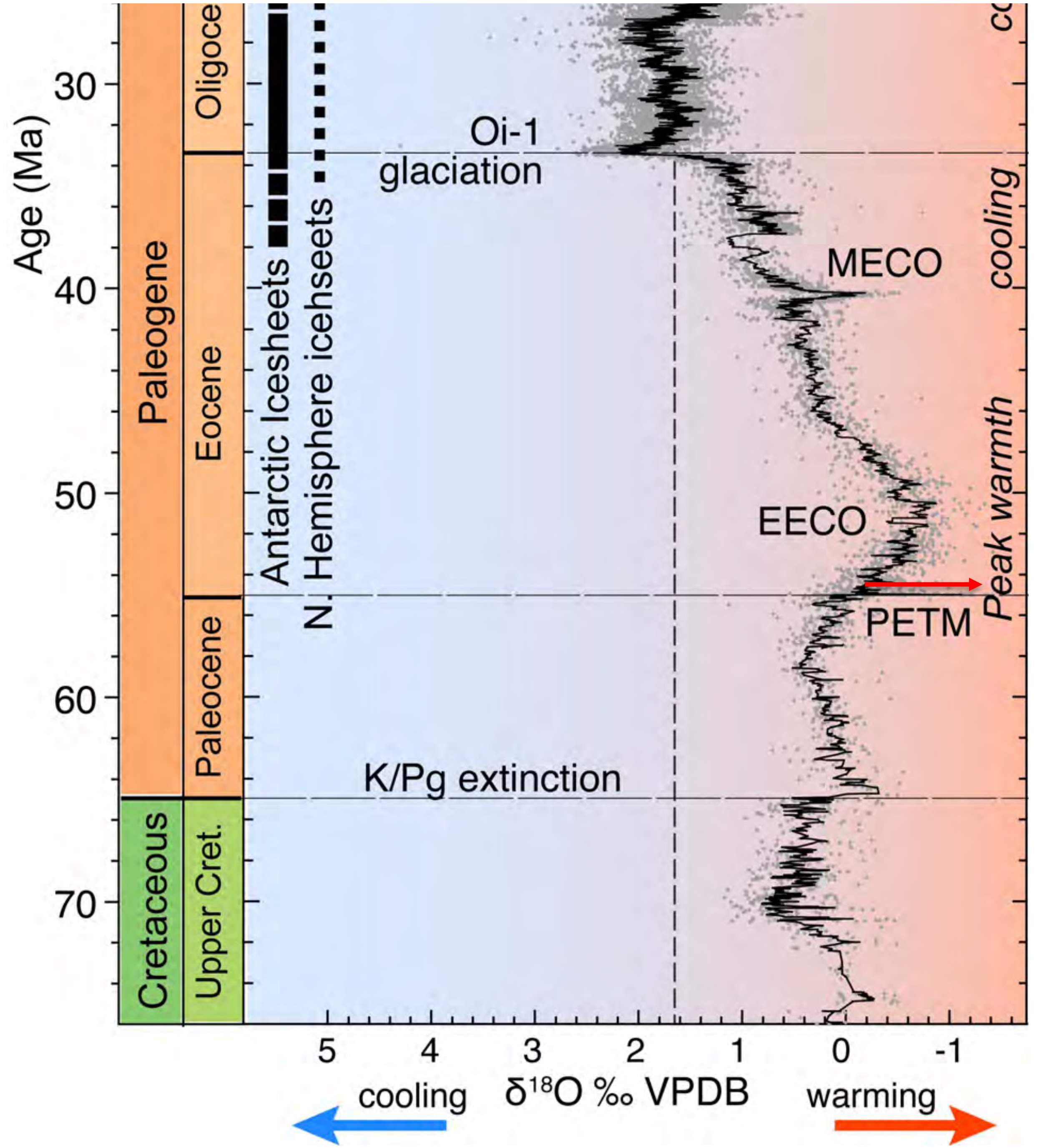


~2 ‰ VPDB $\delta^{18}O$ decrease = ~8°C (average) <u>ocean warming</u>

A ’blip’ on the curve: the PETM on the Cenozoic deep sea δ^{18}O record

Measured on thousands of samples of seafloor-living (benthic) foraminifera from all over the world’s oceans

Modified from Zachos et al., 2001, 2008; Cramer et al., 2009.



Evidence for the extreme event 56 million years ago

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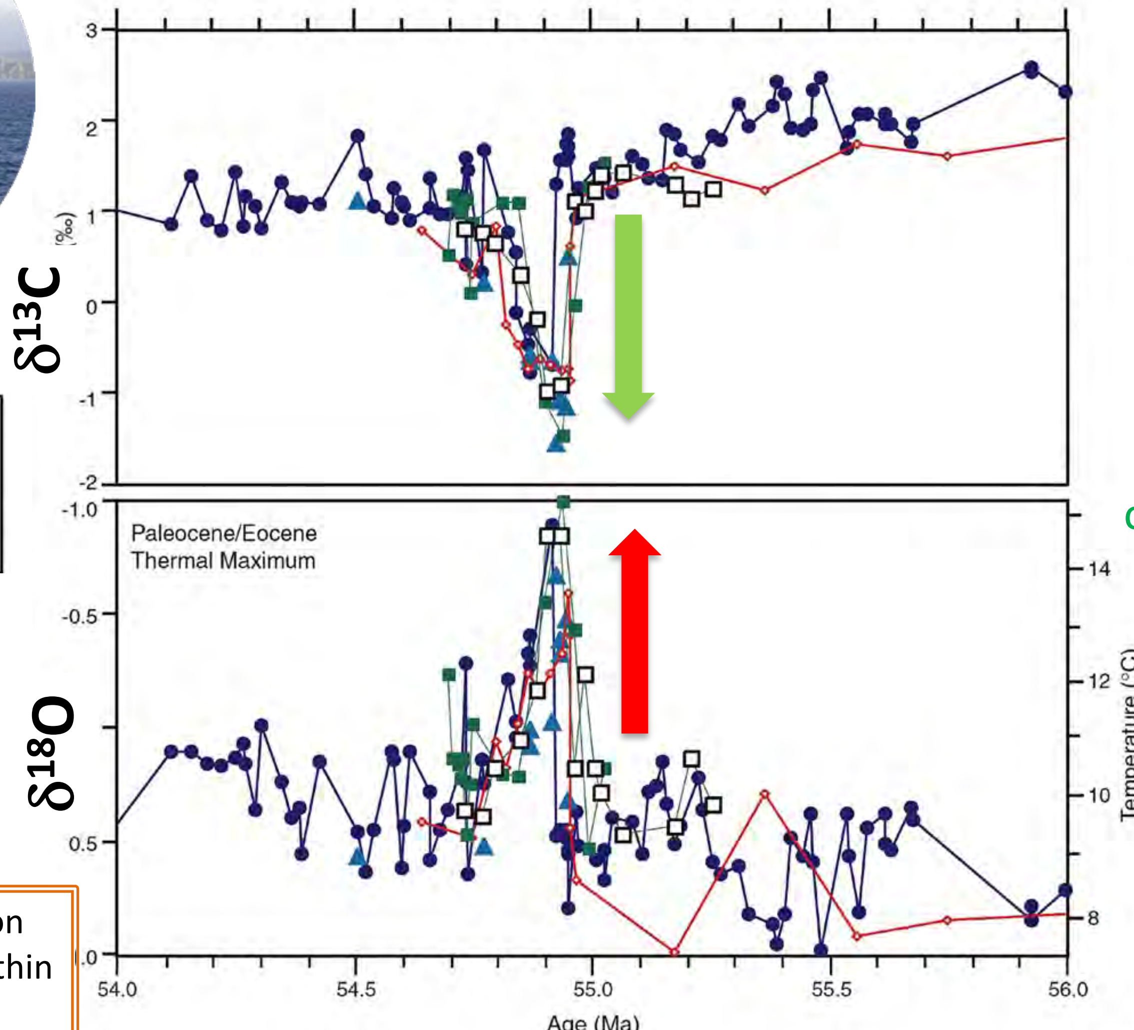


~2 ‰ VPDB
$\delta^{13}C$ decrease
= CARBON ISOTOPE EXCURSION **(CIE)**
Reflects a massive release of carbon with a low $\delta^{13}C$ signature into the ocean-atmosphere reservoir

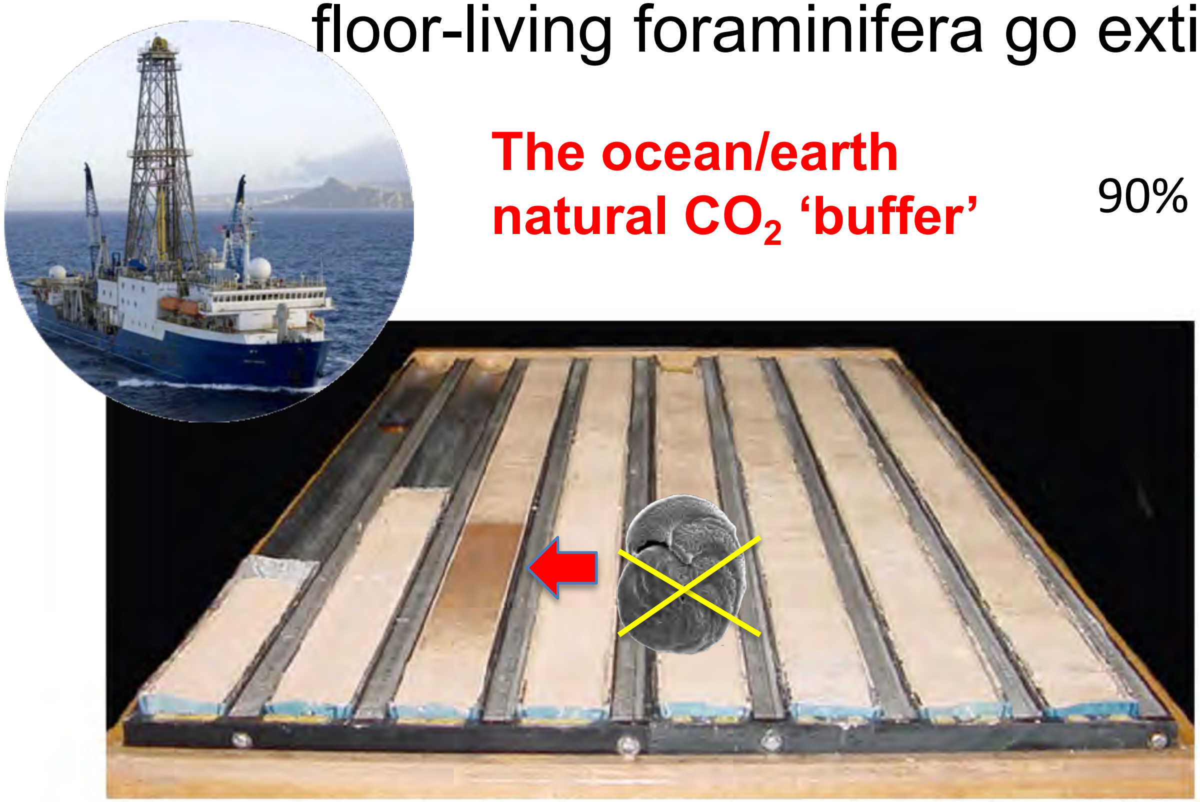
Legend: Different deep sea core records measured on various species of benthic foraminifera

~2 ‰ VPDB
$\delta^{18}O$ decrease
= ~8°C (average)
ocean warming

Warming and carbon release happened within 8 thousand years

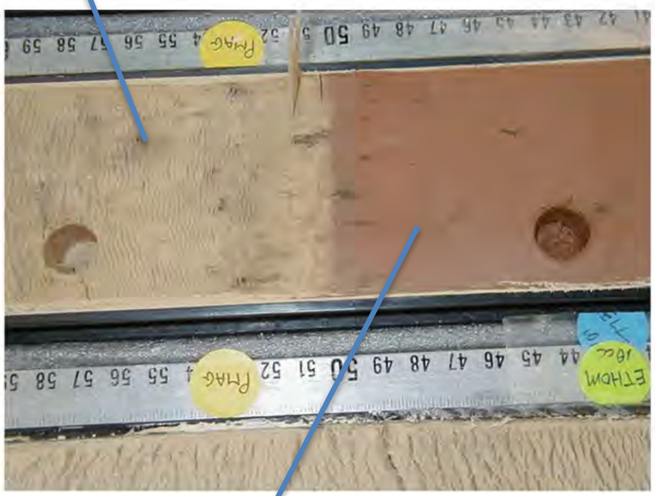
Evidence for the extreme event 56 million years ago

2. Carbonate sediments are dissolved at the seafloor, sea floor-living foraminifera go extinct: ocean acidification



The ocean/earth natural CO_2 'buffer'

90% $CaCO_3$ fossil sediments



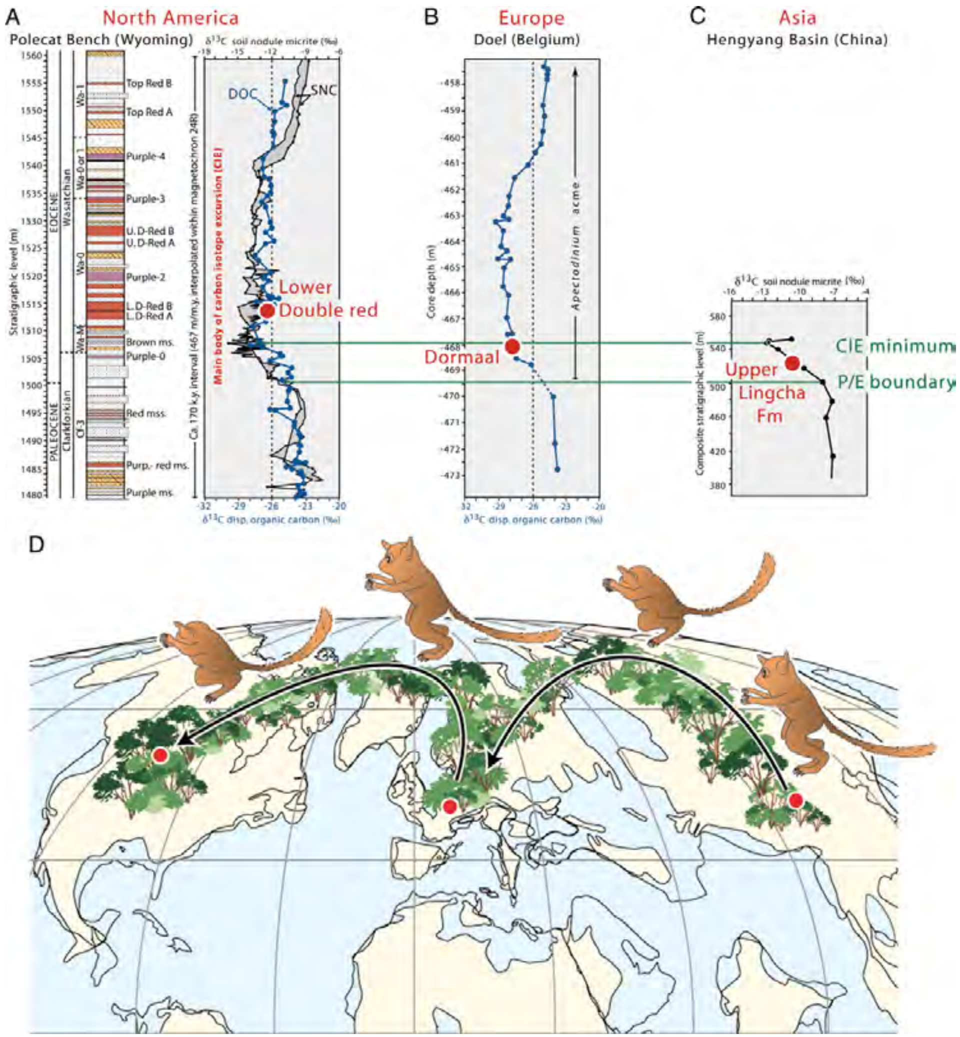
Seafloor (benthic) foraminfiera extinction

< 1% $CaCO_3$ fossil sediments

A deep sea core from the south Atlantic Ocean showing a 'brown' carbonate-free layer dated to 56 Ma (IODP Leg 208)

Evidence for the extreme event 56 million years ago

3. Land fossils show major changes among animals and plants



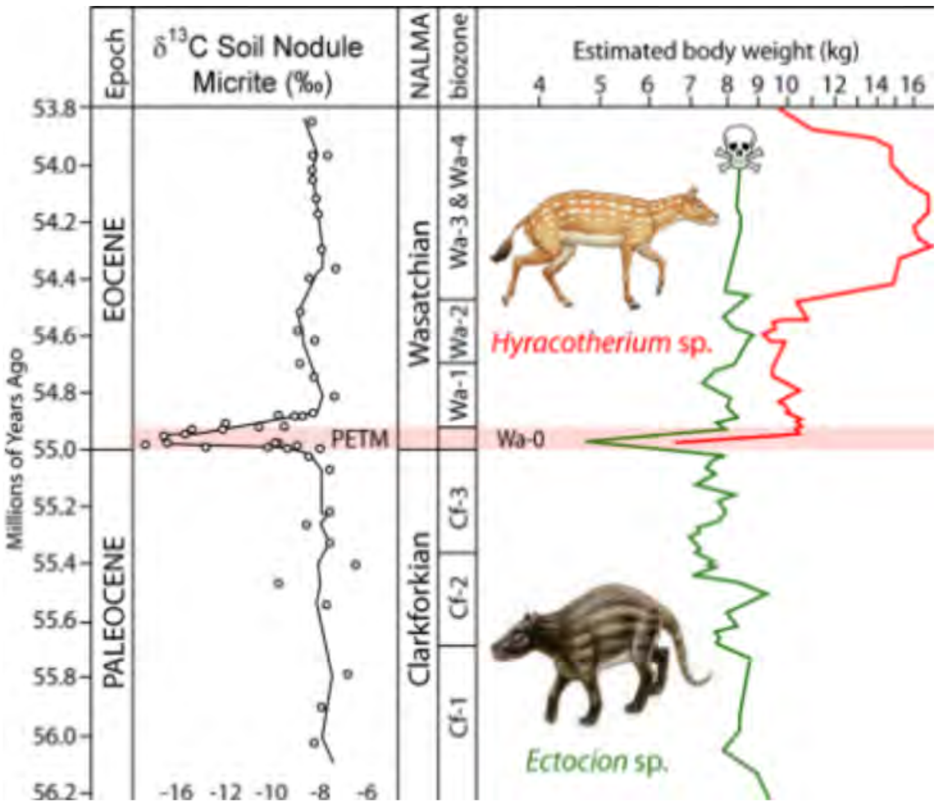
PETM migration corridor
Paleogeographic map showing hypothetical migration routes of *Teilhardina* during the earliest Eocene (Thierry Smith et al. PNAS 2006).

Timing of migration is obtained by correlations of the $\delta^{13}C$ excursion in North America (A), Europe (B), and Asia (C).

- Warmth loving animals and plants spread towards polar regions, new species suddenly appeared and major bursts of evolution occurred.

Evidence for the extreme event 56 million years ago

3. Land fossils show major changes among animals and plants



The PETM $\delta^{13}C$ excursion (CIE) is also seen in terrestrial carbonate records; proves the whole Erath C-reservoir was effected.

PETM terrestrial $\delta^{13}C$ isotope stratigraphy and land mammal response from the Big Horn Basin, Wyoming, USA.

Gingerich (2003) & Magioncalda et al. (2004).

- In low latitude regions mammals became 50% smaller as an adaptation to high temperatures, some reptiles became bigger.

PETM: The cause & significance to modern climate studies

The combination of the carbon isotope excursion (CIE) and rapid global warming at the PETM imply there was a sudden release of ^{13}C-depleted (^{12}C-enriched) carbon to the atmosphere, which resulted in increased greenhouse gases in the atmosphere, and, therefore increased climatic warming effect due to a stronger 'greenhouse effect'.

WHERE DID THE CARBON COME FROM?

This is the subject of much debate and research!

Where did the PETM carbon come from?

To answer this, we can look to the carbon cycle and think about the $\delta^{13}C$ isotopic signatures of the available carbon reservoirs:

Reservoir	Type of Carbon	$\delta^{13}C$ (‰)
Atmosphere	Inorganic CO_2	-6 to -7
C4 plants (most tropical & marsh plants)	Organic C	-23 to -25
C3 plants (most higher plants)	Organic C	-9 to -13
Surface ocean	Organic C	-22
Surface ocean	Dissolved inorganic CO_2	1
Deep ocean	Organic C	-22
Deep ocean	Dissolved inorganic CO_2	0
Methane deposits	Organic C	-60
Coal-fossil fuel	Organic C	-25
Oil-fossil fuel	Organic C	-33 to -24

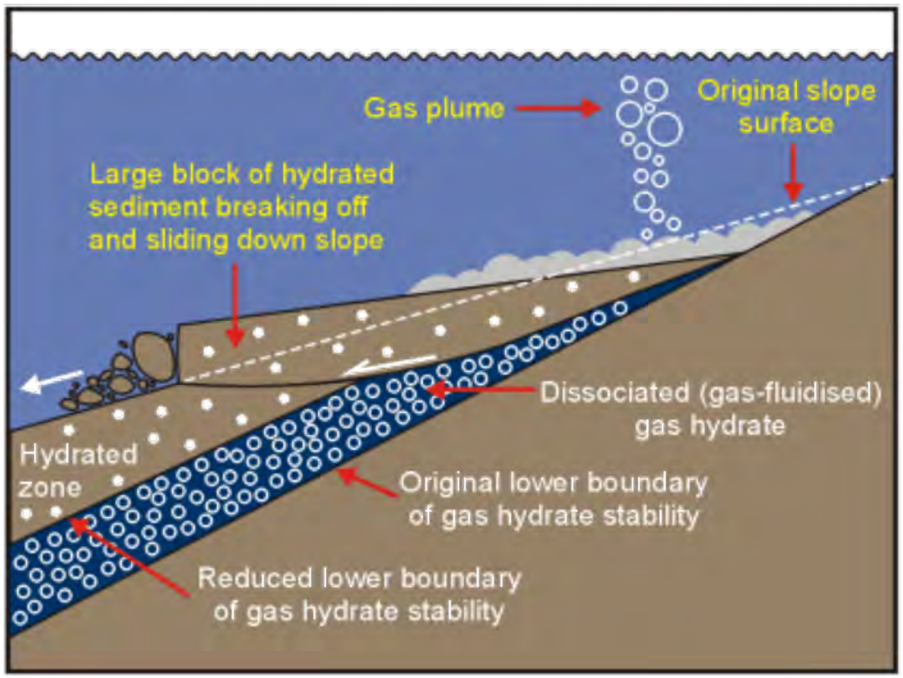
Average reservoir $\delta^{13}C$ values (after Ruddiman, 2008).

THEORIES FOR THE SOURCE OF PETM INJECTED CARBON

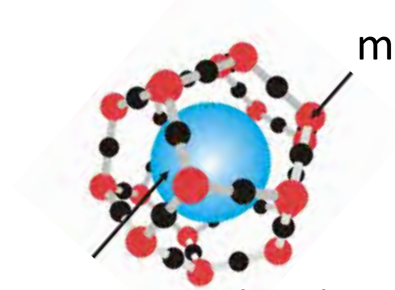
- Combustion of shallowly buried coal or peat on land (Kurtz et al., 2003)
- Increased amounts of volcanogenic methane (Storey et al., 2007; Gutjahr et al., 2017)
- Destabilized methane clathrates (frozen methane, CH_4) on ocean margins (Dickens et al., 1995), **due to a 'pre-' warming of ocean waters.**

PETM: theories on the source of carbon 1

Destabilized methane **(CH_4)** hyrdate **(**clathrates) on ocean margin by precursor ocean warming or underwater landslides (Dickens et al., 1995)



CH_4 is a strong greenhouse gas. It quickly oxidizes to CO_2.



Water molecule 'cage'

CH_4 gas molecule

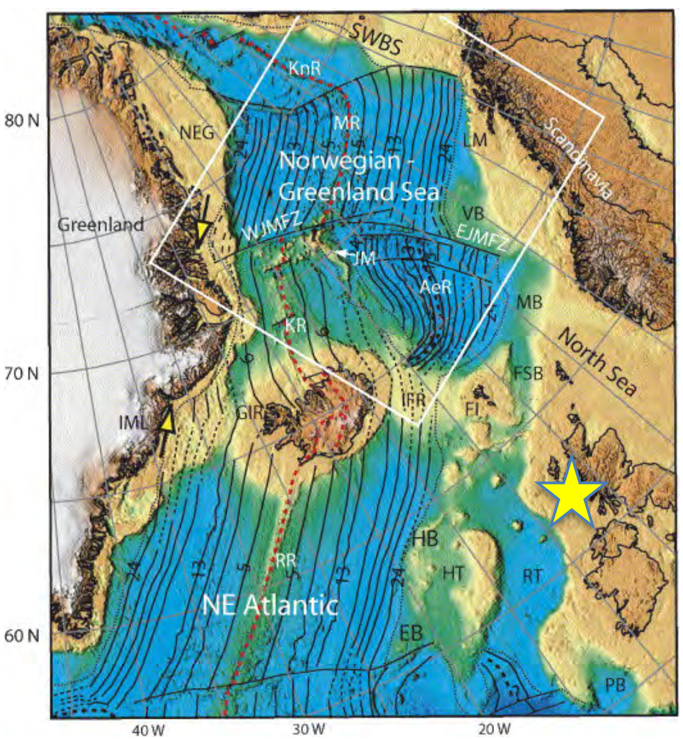
- CH_4 extreme $\delta^{13}C$ composition = -60‰ VPDB, …..compared to organic matter
- C-organic $\delta^{13}C$ (including fossil fuels, e.g. coal, gas, oil) = -13 to 25 ‰ VPDB

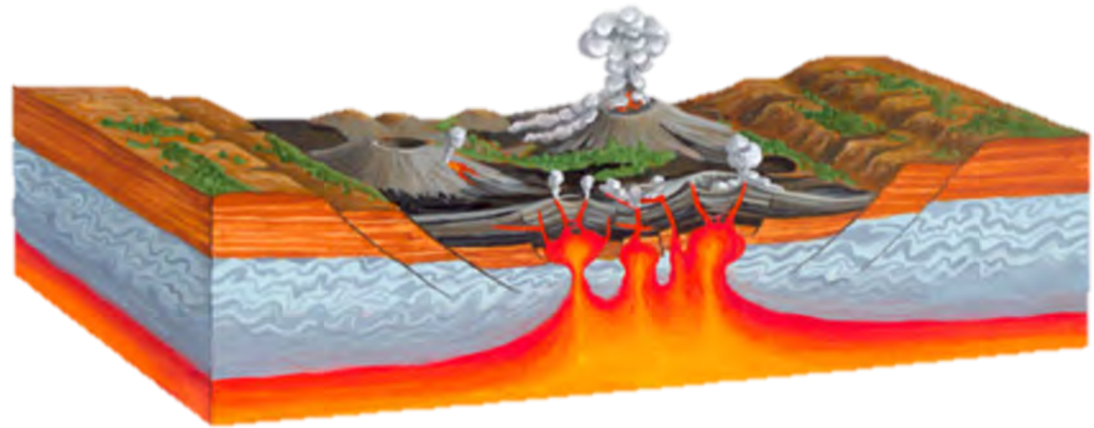
Therefore, less CH_4 is needed to produce the global $\delta^{13}C$ CIE signal than C-org: **Question: Could this happen in our future?**

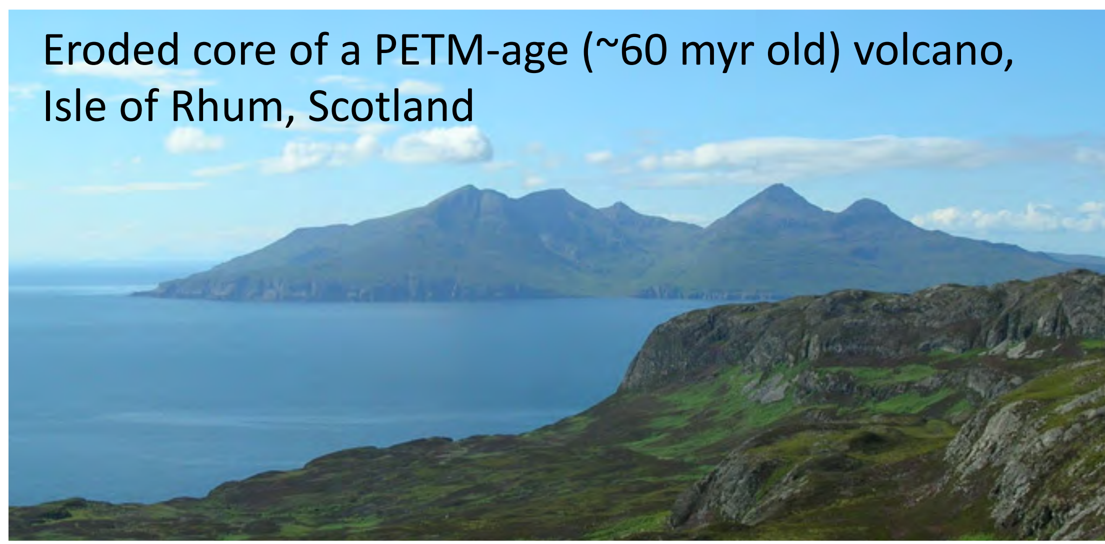
PETM: theories on the source of carbon 2

Massive release of volcanogenic carbon during North Atlantic Volcanism and opening of the northeastern Atlantic (CO_2 & thermogenic CH_4)

Storey et al., 2007;
Gutjahr et al., 2017







Eroded core of a PETM-age (~60 myr old) volcano, Isle of Rhum, Scotland

http://www.bgs.ac.uk/research/volcanoes/volcanicConnections.html

The PETM is an important **analog for current climate warming** because the rates of carbon increase in the atmosphere and temperature increase are inferred to have similar rates and magnitudes, although our modern experiment could be 10 x faster.

What stopped the PETM?
What removed the excess carbon?

Various feed backs:

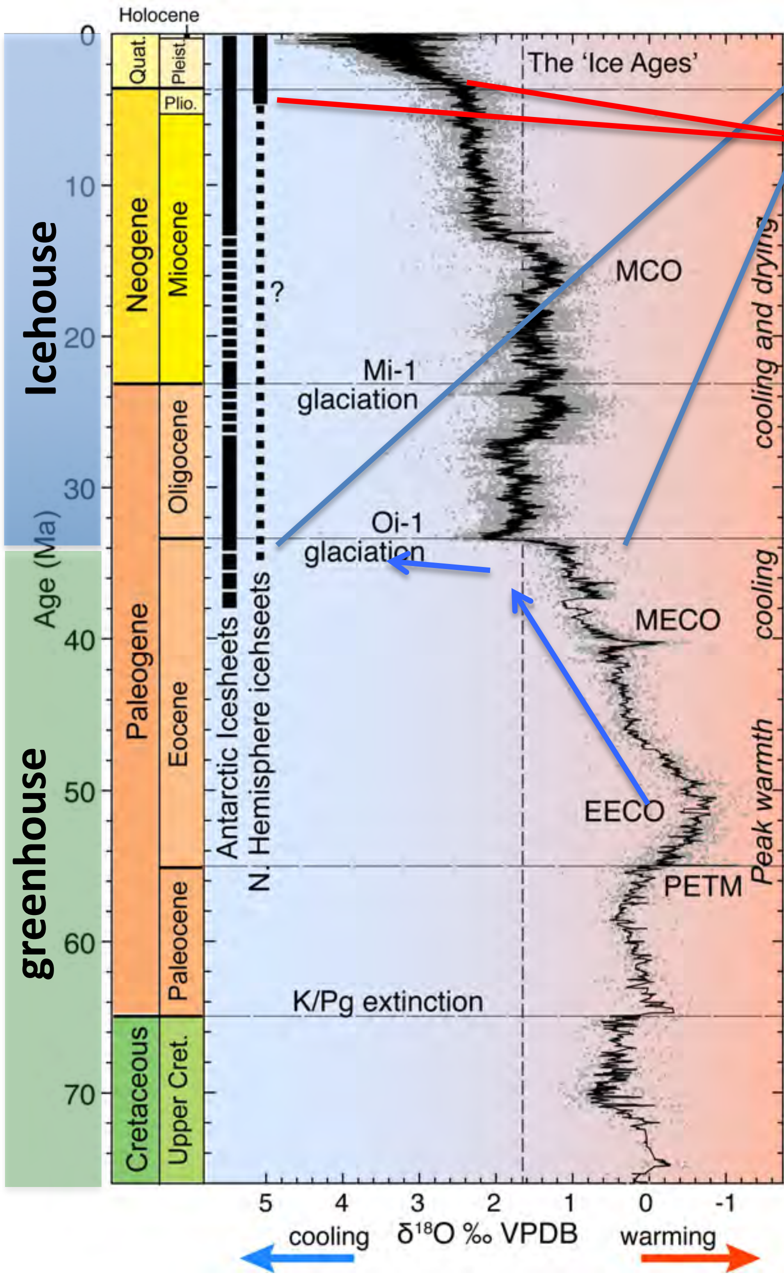
- Increased silicate **weathering** due to more active hydrological cycle and higher temperatures **(the weathering feedback).**
- Oceans took up the CO_2 – **ocean acidification**.
- Increased **biological productivity** on land and in the oceans.

The recovery took about 170 thousand years.

Summary points 2.

- The last natural **greenhouse climate** existed from the Cretaceous period to the end of the Eocene period, 80-34 million years ago.
- Fossils from Antarctica and the high Arctic provide evidence of **warmth loving animals and plants living at the poles**.
- Geochemical proxy reconstructions show **flatter equator-to-pole temperature gradients** and global averages ca. 10°C higher than modern.
- Because there were no large glaciers on Antarctica or Greenland global **sea level was ca. 80 m higher than today**.
- An even more extreme global warming event occurred ~56 Ma - the **PETM**. This is considered a near analogue for current human driven global warming.
- The general background warmth of the early Cenozoic and the PETM are associated with evidence for atmospheric **CO_2 up to 4 x modern**.

Onset of the icehouse 34 million years ago



Stage 1: cooling & **glaciation of Antarctica** 34 million years ago

Stage 2: more global cooling and drying and **glaciation of the northern hemisphere** 2-5 million years ago.

Gradual δ^{18}O increase followed by an abrupt step 34 million years ago (Zachos et al., 2001, 2008; Cramer et al., 2009).

Cenozoic climatic from deep sea δ^{18}O (Zachos et al., 2001, 2008; Cramer et al., 2009).

Stage 1: Evidence for cooling & **glaciation of Antarctica** 34 million years ago

- **Extinctions and increased evolutionary turnover** on land and in the oceans, including
  - -ocean plankton and shelled-organisms,
  - -reptiles, mammals ('Grande Coupure') plants.
  - -warmth loving plants and animals disappear from the high latitudes

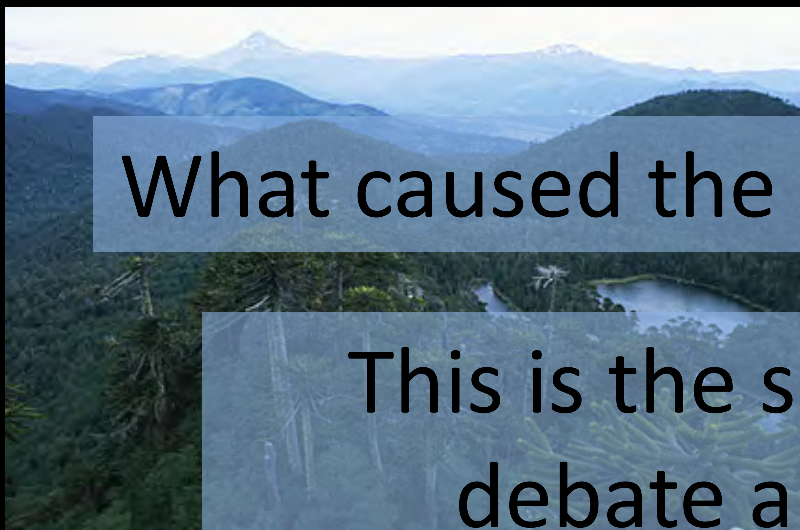
- Appearance of ice-rafted sediments (evidence for ice bergs) in sediment cores close to Antarctica

- Deep sea $\delta^{18}O$ increase of ~1.5‰ VPDB – terrestrial ice growth

- Sea level fall: 60-80 m

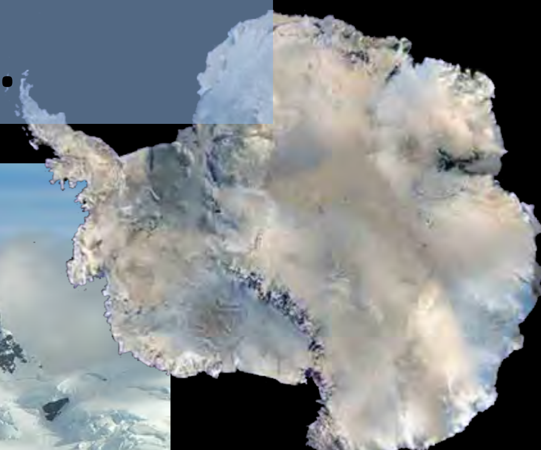
Antarctica became glaciated within 400 thousand years

Green, forested Antarctica became white ice-covered Antarctica 34-35 million years ago

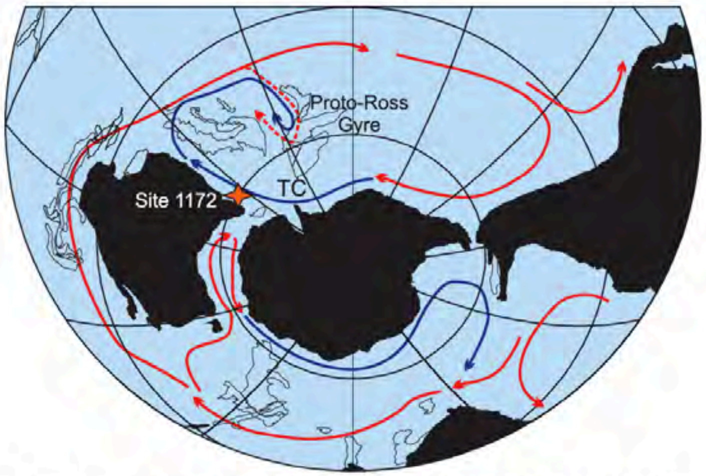


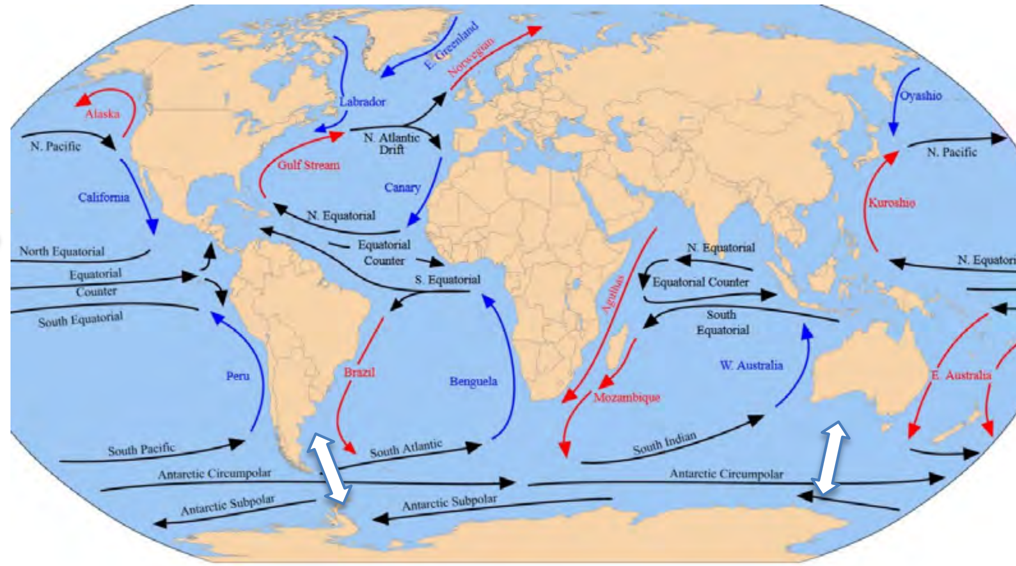
What caused the shift into the icehouse?

This is the subject of much debate and research.



Hypothesis 1: different geography isolated Antarctica; decreased ocean heat transport (H1-tectonics/ ocean gateways)





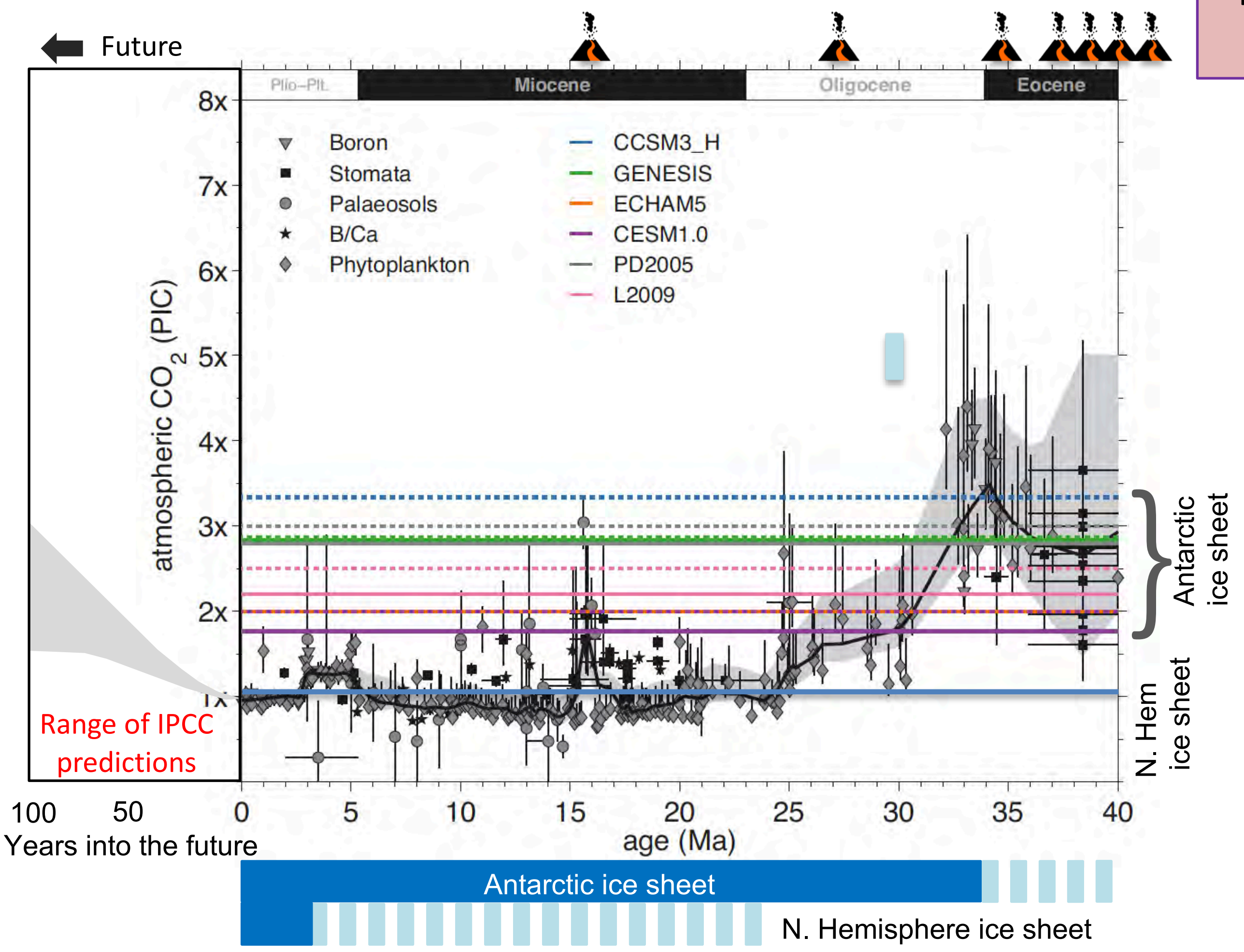
49 Ma Paleogeography,

Modern geography with a full strength Antarctic circumpolar current (ACC)

Southern land barriers opened and the cold ACC began flowing, isolating the continent from low latitude warm currents and warm air, like today.

Hypothesis 2: high CO_2 levels and strong greenhouse effect fell below a 'threshold' for Antarctic glaciation 34 million years ago ($H2-CO_2$)

Preferred hypothesis, but possibly a combination of both



A summary of CO_2 & climate indicators over last 40 myrs with Antarctic and N. hemisphere **glacial thresholds** from model inter-comparisons.

pCO_2 reconstructions and modelling show:

1. CO_2 thresholds for glaciation are higher for Antarctica than the Northern Hemisphere ice (the South Pole can be ice covered at higher CO_2).
2. Antarctic glaciation threshold depends on which model is used!
3. Eocene CO_2 is in the range of model predictions for our atmosphere within 100 years – **shows the vulnerability of glacial ice!**

Modified from Gasson et al., 2014 and DeConto et al., 2008

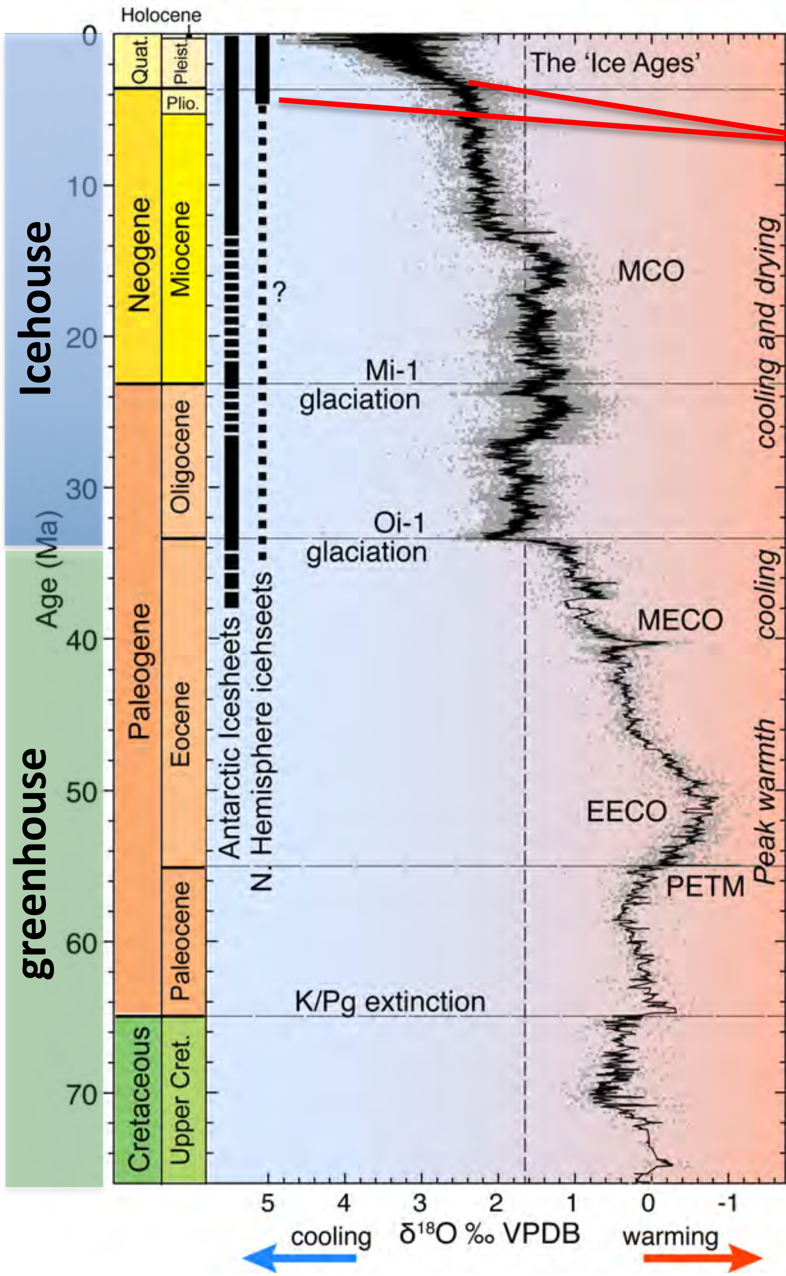
Causes of reduced CO_2?

- Decreased ocean spreading, less volcanic activity
- Increased silicate weathering due to the uplift of the Himalayas (from ~50 million years ago).

Positive feed backs once glaciation starts:

- As the oceans got colder more **CO_2** could dissolve in and be held in the oceans.
- Stronger ocean circulation in a colder world due to stronger winds and ocean mixing: more nutrients, more primary production, biology draws down more **CO_2**.

Stage 2: Intensification of the icehouse



Stage 2: more global cooling and drying and **glaciation of the northern hemisphere** 2-5 million years ago.

Further $\delta^{18}O$ increase ~3 million years ago followed the appearance of large-scale $\delta^{18}O$ swings indicating glacial cycles.

Cenozoic climatic from deep sea $\delta^{18}O$ (Zachos et al., 2001, 2008; Cramer et al., 2009).

<u>Stage 2</u>: Evidence for cooling & glaciation of the northern hemisphere 2-5 million years ago


- **Extinctions and increased evolutionary turnover on land and in the oceans**

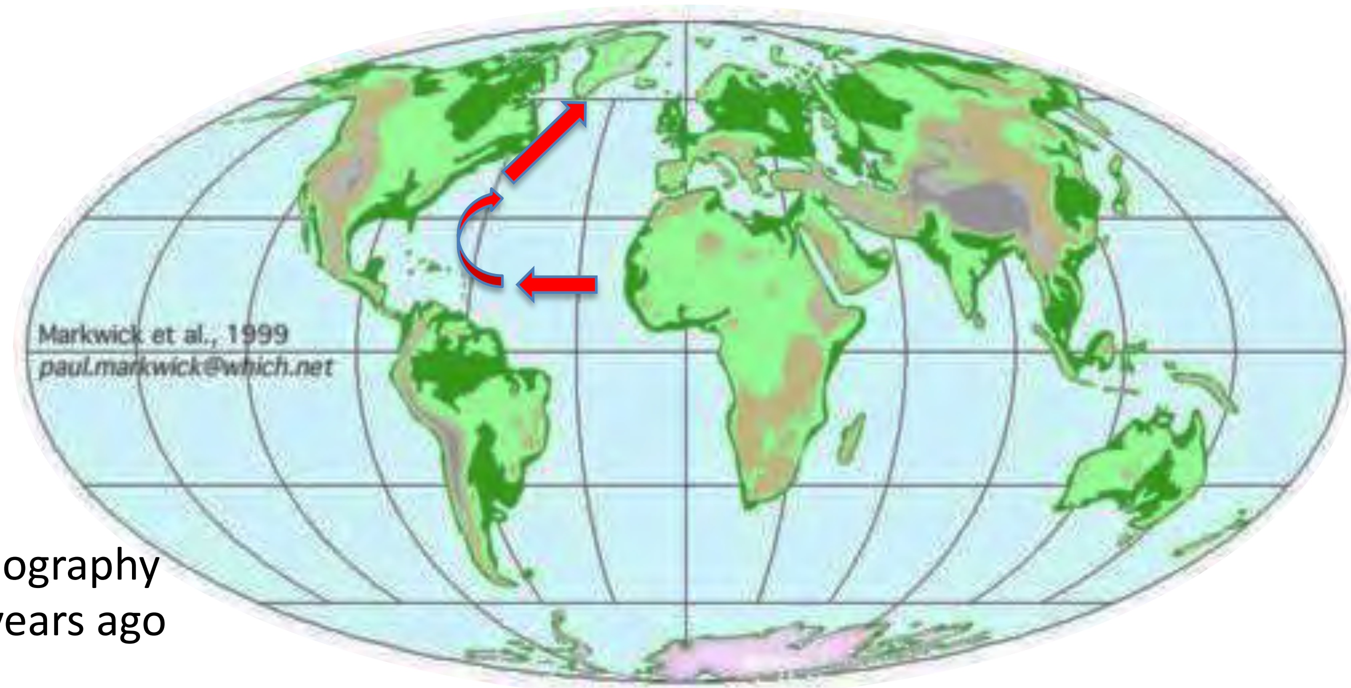
  Fossils show stronger seasons and cooling especially in the high northern latitudes. Tundra replaces boreal forests in the high Arctic.

Challenge: large scale north glaciations remove evidence of earlier ones: best evidence is found in the oceans.


- Appearance of abundant ice-rafted sediments in the North Atlantic.
- Deep sea $\delta^{18}O$ increase of– shows long term cooling trend through the Miocene to the Pliocene and sharp increases of ~1‰ ~5 million years ago.
- Beginning of sharp large $\delta^{18}O$ oscillations indicating strong glaciations: glacials and interglacials with distinct cyclicity.

The cause is more uncertain than for Antarctica!

Hypothesis 1: different geography directed ocean currents north, bringing moisture needed for snow fall and ice growth (H1- tectonics ocean gateways)

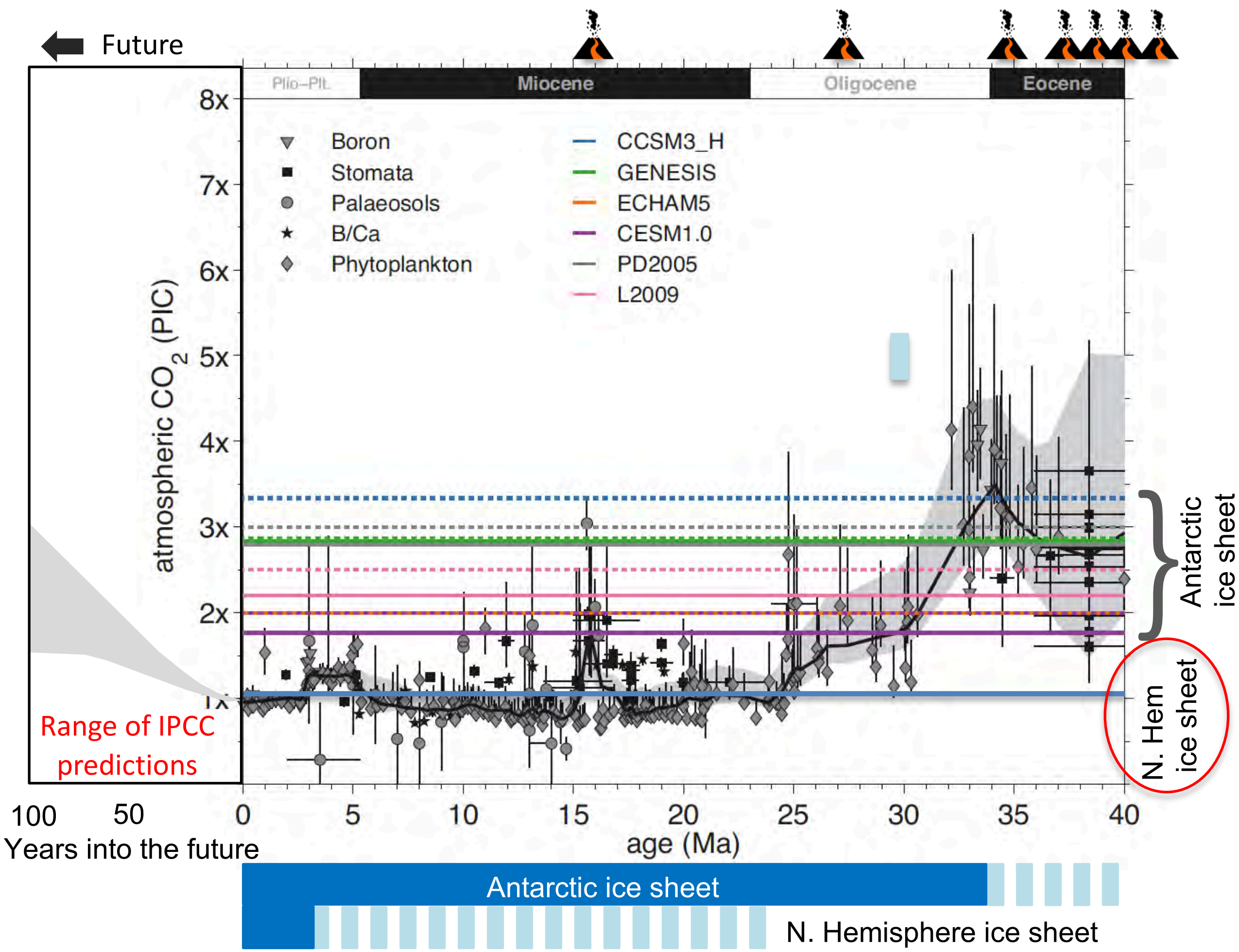


Pliocene geography
~5 million years ago

- Uplift of Panama blocks water flow to between the Atlantic and Pacific.
- Water is directed northwards on the Atlantic current bringing moisture needed for snowfall and glaciation.

Problem: this would also make the northern hemisphere warm.
-Model experiments do not support this as the only reason.

Hypothesis 2: Atmospheric CO_2 fell below a critical level allowing cooling and glaciation in the North Hemisphere (H1- CO_2)



pCO_2 reconstructions from geological proxies show:

1. CO_2 estimates indicate near modern CO_2 levels (pre-industrial) by 15 Ma.

2. Modeled northern hemisphere 'threshold' is lower than Antarctica so why didn't the large northern hemisphere glaciations start until 0-5 million years ago?

Not entirely clear!

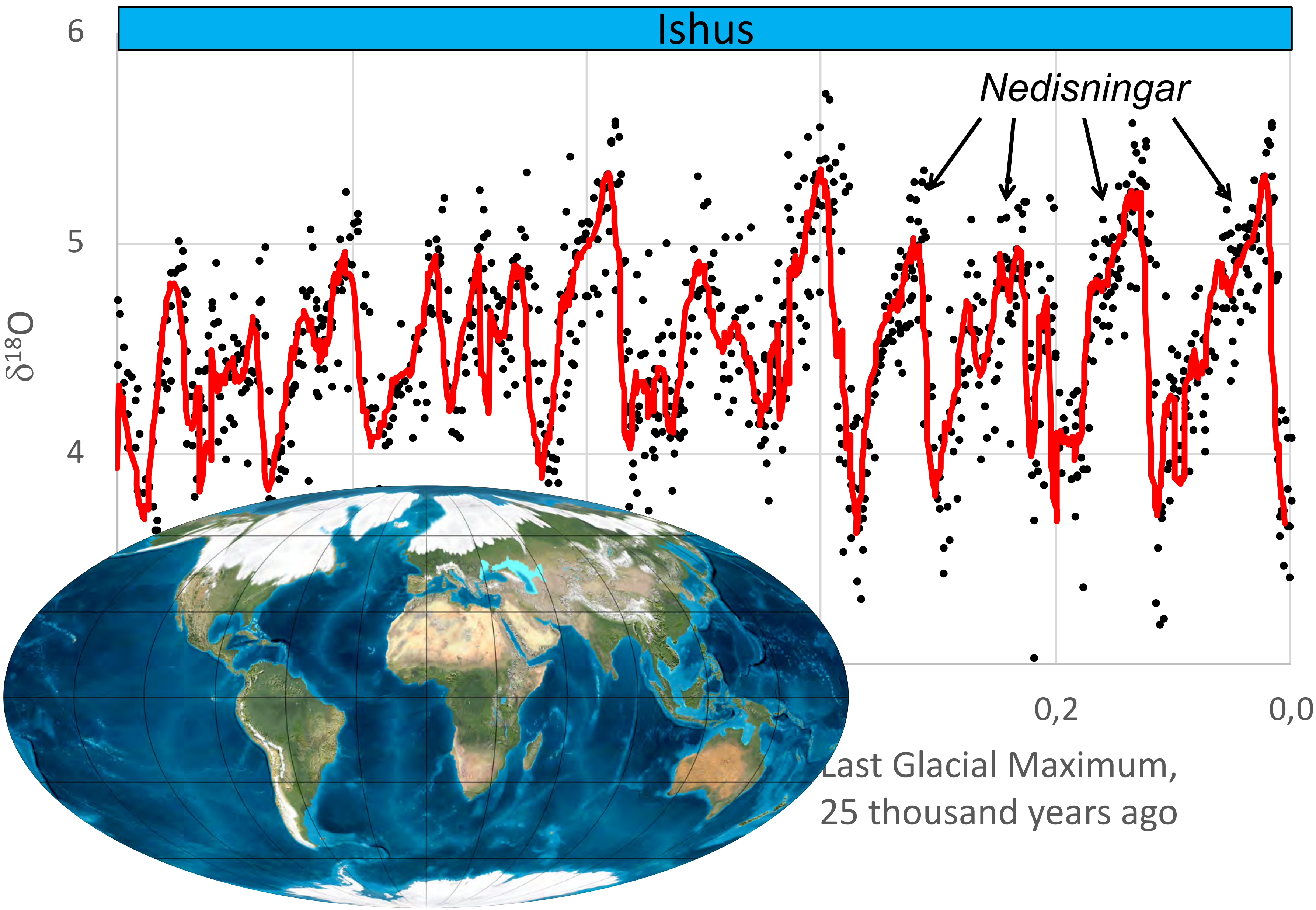
Thought to be lots of climate feed backs involved.

Subject of current research.

A summary of CO_2 & climate indicators over last 40 myrs with Antarctic and N. hemisphere glacial thresholds from GCM-ISM inter-comparisons.

Modified from Gasson et al., 2014 and DeConto et al., 2008

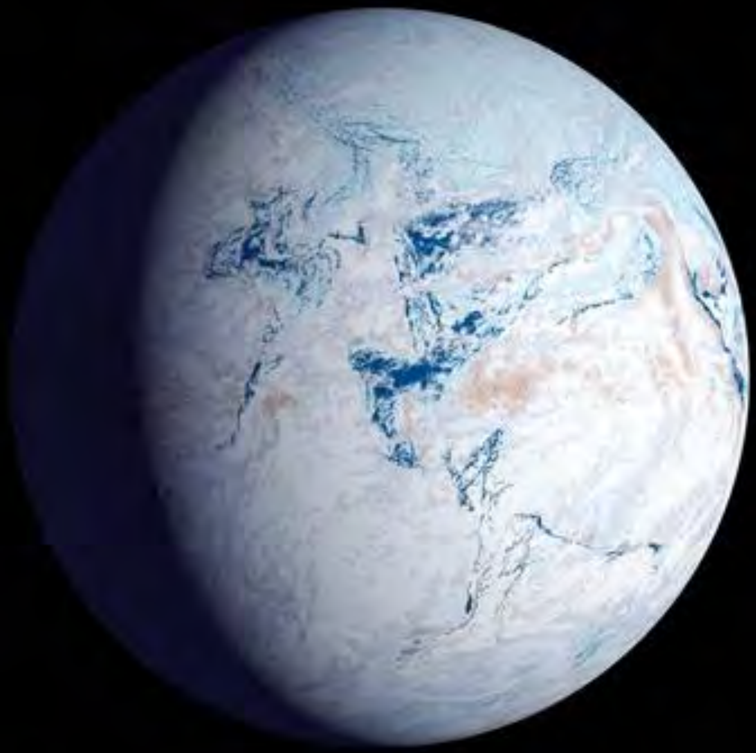
Pleistocene glacial cycles: Next week Sarah Greenwood



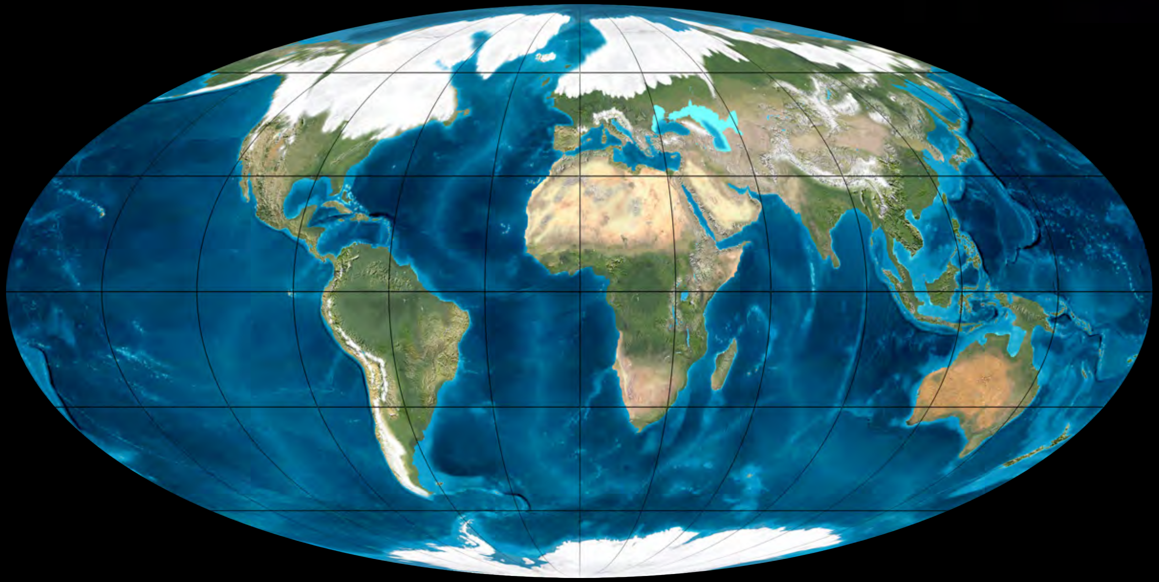
Conclusions

- ***To understand the significance of Snowball Earth we have to understand the wider range of climate variability on Earth.***
- *We can do this with **climate proxy records, and computer simulations**. The most detailed evidence comes from the past 60 million years.*
- Over its history the Earth has alternated between warm '**greenhouse**' and colder '**icehouse**' climate modes. Icehouse climates are less common.
- Shifts into and out of greenhouse and icehouse climates have been linked to to **changing palaeogeography** AND **changes in greenhouse gas concentrations**.
- Evidence suggests **changes in CO_2 were most important**. Ocean circulation pathways also seems to play a role **(the oceans transport heat to high latitudes).**
- Complex feed backs with Earth's albedo biology, clouds and carbon cycling interact and climate scientists try to unravel these complexities.
- Extreme warming at the **PETM** involved carbon release to the atmosphere. This is our closest analogue of modern human-made global warming.

Thank you for attention



Snowball Earth
~700 million years ago



Last Glacial
Maximum (LGM)
25 thousand
years ago