😎CLIMATE HISTORY AND PALEOCLIMATOLOGY - CATALOGUE OF QUESTIONS

Question	
1	El Niño and Pliocene warm period – hypothesis and evidence • Walker circulation weak/reversed •
2	causes and consequences of NH glaciation
3	orbital forcing at low-latitudes
4	global ice volume variability during the Pleistocene – hypotheses and link to orbital variability
5	factors influencing delta18O in benthic forams, ice cores and spelethems
6	three different proxies for SST and how variations between them derive
7	delta13C in benthic forams, oceanic distribution between glacial and interglacial state in AO
8	potential analogues for future warming: PETM and early Pliocene warm period
9	atm. CO2 during Cenozoic and during glacials/interglacials and two methods of reconstruction o
10	PETM, its hypotheses and associated carbonate chemistry change in the ocean
11	changes in biological pump, strength and efficiency, reconstruction and influence on atm. CO2
12	Heinrich events, their evidence from higher to lower latitudes, timing and underlying process
13	D/O events, features in records, causes and evidence for and against them
14	events leading to glacial termination (insolation, GHG, oc. & atm. circulation, ice sheets, sea level)
15	climate forcing factors during the Holocene
16	evidence past changes global ice volume, when and where onset, factors of growth and decay on Cenozoic, orbital and millennial time scales)
17	positive and negative feedbacks in carbon cycle
18	snowball Earth, its hypotheses and evidence in geological record
19	postulated causes of P/T mass extinction and similarities to early Cretaceous OAEs

Answers by Verena; please add/adjust to your needs (using a different color)!
Answers by Maurice; please add/adjust to your needs (using a different color)!

1 What happens during an El Niño event? Why is the ‘Pliocene warm interval’ considered to represent a ‘permanent El Niño’ state? Explain the evidence (proxy observations) that this hypothesis is based on.

During an El Niño event, the Walker circulation, i.e the zonally oriented tropical Pacific atmospheric circulation (normal conditions = air rises in convective towers in the west Pacific, flows eastward, descends in the east Pacific, and then flows westward at the surface as the trade winds) weakens or reverses. El Niño is accompanied by high air pressure in the western Pacific as well as low air pressure in the eastern Pacific. As a result the thermocline on the west coast of South America is reduced, upwelling of cold water by the trades prevented, and the ocean surface is 2 - 5°C warmer than outside an El Niño event. The temperature gradient between the east pacific and west pacific is smaller.

The Pliocene warm interval is often considered to represent a permanent El Niño like state since delta18O values of two ODP sites, laying in the west and east of the Pacific, 5-2Ma before now only show a small temperature gradient before the temperature gradient is spreading to recent values. Cold water masses were mainly absent in the eastern tropical Pacific. Furthermore, the thermocline in the eastern Pacific was deeper relative to today.

The proxy used for this observation is a paired measurement of the Mg/Ca ratio and delta18O on foraminiferal shells (a surface-dwelling species) in sediment cores taken from the seafloor at both ODP sites. Using the calibration of Dekens et al (see paper below), where in the shells isotopic composition of the seawater is recorded as well as the Mg/Ca ratio, the delta18O at the time of shell precipitation can be infered with the following equation:
T = 16.5 - 4.80 * (delta18Ocalc - (delta18Oseaw - 0.27)

- Inferring past SST values from two foram species:
  - one living at the surface (delta18O shows SST)
  - one living at the base of the photic zone (delta18O shows T at 100 m depth)
- the records show a low gradient between surface and 100 m temperature which indicates warm waters at surface as well as in 100 m depth -> low thermocline

Critics to this paper is the use of only two data points.

see literature: M. W. Wara, A. C. Ravelo, M. L. Delaney (2005): Permanent El Niño–Like Conditions During the Pliocene Warm Period, Science, Vol 309

2 What were the likely causes and the climatic consequences of Northern Hemisphere glaciation?

two requirements need to be fulfilled:
- cold enough temperatures in NH so that precipitation falls as snow and ice does not melt away in summer
- sufficient moisture supply for snow accumulation
- increase in obliquity amplitude 3.2M years ago means there were periods when summer insolation was extraordinary low

moisture supply comes from two sources:
- The closure of the Isthmus of Panama (Closure of the american seaway, CAS; final 2.8Ma, but before several re-openings). This restricted water exchange from the Pacific to the Atlantic at low latitudes and therefore induced an increased polward transport of warm and salty water (increase in Gulf Stream intensity). This strengthening of the thermohaline circulation supplied higher salinity waters and more moisture to the high latitudes where ice sheets could build up until an albedo-feedback was reached for the climate to slip into the first ice age. But timing does not fit perfectly for this hypothesis.

- increase in North Pacific stratification
  - caused by a reduction in surface salinity (freshwater cap; halocline)
  - could have been initiated by closure of Panama (more saline waters in Atlantic and less saline Pacific)
  - reduced surface salinity = stronger density gradient which amplifies seasonality of SST in

Commented [1]: Correct me but INCREASE in obliquity means higher seasonal variation -> warmer summers. A DECREASE in obliquity would mean less seasonal variations and colder summers.

Commented [2]: yep true but is it then wrong in the slides? slide 11: https://moodle-app2.let.ethz.ch/pluginfile.php/337811/mod_resource/content/0/2016_ClimHist_%20Pliocene_warmth_additionalnotes.pdf

Commented [3]: no, on the slides the oscillation increases which means we have higher AND lower obliquity alternating, the ice sheets then formed during an low obliquity of about 22°. Further so much ice needs to have cumulated that it could not completely melt during the next maxima of obliquity (24.5°)

	North Pacific ○ halocline would have reduced nutrient supply to the surface which leads to decrease in biological production but increase in nutrient stocks utilized ▪ less evasion of CO2, potentially reducing pCO2 ○ leading to: **higher evaporation rates in late summer/autumn and could thus supply moisture for ice sheet creation in North America** • The reduction of the CO2 levels below 280ppm which could be a threshold for glacial-interglacial cycles to occur. • The Uplift of the Tibetian-Himalayian Plateau, the Rocky Mountains along with an intensified monsoon caused increased weathering of silicate rocks and therefore CO2 removal from the atmosphere • positive Ice albedo feedback sets in once ice formation is initiated • The climatic consequences of the Northern Hemisphere glaciation are an irreversible ‘climate crash’ at the end of the Pliocene (2.75 Ma) and the slipping of the earth into a glacial-interglacial cycle at the beginning of the Pleistocene.
3	Which orbital forcing mechanism is primarily affecting low-latitude climate patterns such as monsoons? • At low and middle latitudes, changes in the amount of incoming solar insolation follow the 23’000 year rhythm of orbital precession (wobbling) which weakens or strengthens monsoons • largest changes in insolation in those latitudes caused by precession of equinoxes (23 ka cycles) • Earth closer to sun = higher insolation rate in the tropics • effect of precession & eccentricity largest in low latitudes while at high latitudes obliquity signal is dominant • more intense summer insolation maxima and deeper winter insolation minima always co-occur Briefly outline how this mechanisms influences the distribution of incoming solar radiation in different seasons. How does this orbital forcing affect low latitude precipitation, and which mechanism is likely responsible for the observed pattern? • When summer insolation was higher in the past than today (for the NH, where most continents are, that means June solstice in the perihelion), the summer monsoon circulation should have been stronger, with greater heating of the land, stronger rising motion, more inflow of moist ocean air, and more rainfall. Same reasoning for the winter monsoon: If winter insolation weaker than today, then that would have enhanced the cooling of the land surface, which should have driven a stronger down-and-out flow of dry air from land to sea. • More intense summer insolation maxima and deeper winter insolation minima occur together at any one location. Stronger in-and-up monsoonal flows in summer should occur a • at the same times in the past as stronger down-and-out monsoonal flows in the winter
4	How did global ice volume vary through the Pleistocene? reconstruction of ice volume: • ice-rafted debris • delta18O record from forams records show that • no IRD present earlier than 2.7 Ma • between 2.7 and 09 ice sheets were growing and shrinking on 43ka cycle • transition interval between 0.9 and 0.6 Ma

- after 0.6 Ma 100ka cycle becomes dominant
- gradual shift to more positive delta18O foram values which indicates more ice on land and/or cooling of deep ocean

Pleistocene: 2.58 Ma yrs ago until 11.700 yrs ago (last glacial period)
global ice volume variation:
from seawater delta18O as an ice volume proxy derived
the late quarternary period (past 1Ma) is punctuated by a series of large glacial(big global ice volume)-interglacial(small ‘) changes within cycles that last about 100,000yr.

What are the main hypotheses linking the observed changes in the geologic record to orbital variations?

Milankovich theory to explain ice-sheet volume changes with orbital variations:

- insolation on Earth is strictly related to orbital variations
- summer insolation has most important control factor over ice sheet growth
- ice sheets lag behind summer insolation

much of the variability occurs with periodicities corresponding to that of the precession, obliquity and eccentricity of the earth’s orbit.
atmospheric and climate properties seem to have been oscillating between stable bounds.

- precession = wobbling, 26,000yrs
- obliquity = axial tilt (24.5 to 22.1 degree) 41,000yrs
- eccentricity = orbital shape around sun (nearly circular - mildly elliptical) ~ 400,000yrs

Milankovich theory cannot explain:

- why most dominant cycle changed from 43ka to 100ka during 0.9-0.6 Ma
- why eccentricity signal is strongest between 0.6 Ma and the present, given that its influence on insolation is minimal
- why precession is always secondary cycle, even before 0.9 M, given that it has strongest impact on insolation

other hypotheses linking observed changes to orbital variations:

Huybers: lack of precession, 23ka cycle, due to cancelling out

- higher than normal insolation when Earth is closer to the Sun
- is cancelled by shorter-than-normal length of summer
- summer ‘hotter but shorter’ which cancels out

Rayno: precession changes cancel out across Hemispheres

- insolation minimum during NH summer cancelled by insolation maximum during SH winter
- delta18O changes in NH are cancelled by delta18O changes in SH ice sheets

the 100ka mystery:

- long term cooling during the Cenozoic allowed ice sheets to survive some 41 ka cycles (in this case the 100ka cycles are simply multiple of 41 ka and/or 23ka cycles when the ice couldn’t ‘survive’

main hypothesis:

- providing warm summers in NH to melt glaciers away for termination?

- the fact that ice sheets first appeared in the NH within the last 3 Myr can be explained by very slow tectonic-scale cooling, but the evidence that ice sheets grew and melted over much shorter intervals of time requires a different explanation. The driver of these shorter-term variations in the amount of ice is orbitally driven insolation changes.

	- orbital control of ice sheets: ablation of ice sheets happens rapidly when summer temperatures above 0C >> max rates of accumulation; summer insolation control of ice sheets (most sensitive 65N); ice growth in NH when low summer insolation (orbital tilt small, aphelion, high eccentricity); climate point = equilibrium line of ice sheet meets surface, when meets land on NH ice sheet growth initiated; positive feedback: growing ice sheets reach higher altitudes with lower temperatures; maximum ice volume lags behind minimum summer isolation; underlying bedrock is depressed (elastic / viscous response: positive feedback with ice accumulation + melting); orbital control could onset since gradual cooling since last several Myr; Milankovitch explains ice volume responses at 41,000 and 23,000yr, reason for lagging 5 thousand yrs behind solar minimum; missing: dominance of 41,000yr cycle, large oscillations 100,000yrs - CO2, CH4 ~ 100,00yr cycle; 30% less during GMs; carbon stored in deep ocean, but mechanism still unclear; reduced CO2 solubility on colder waters, greater biological pumping, changes in deep-ocean circulation; CH4 ~ 23,000yr due to summer monsoon; CO2, CH4 ~ 23,000yr (precession): forcing of ice sheets, fast feedback of minimum insolation; ~ 41,000yr (eccentricity): ice-driven feedback; ~ 100,000yr: combination of both - dominance of 41,000yr cycle although smaller changes in insolation (23,000yr cancelled out by hemispheres? co2 feedback?); 100,000yr cycle unsolved (gradual cooling? internal ice sheet responses paced by summer insolation? NS teleconnections?)
5	What factors influence delta18O in benthic foraminifers? 1. Water ∂18O (influenced itself by precipitation, evaporation, runoff and global ice volume) 2. Water temperature (higher temperature = lower delta 18O values: delta18O value decreases by 1 permil for each +4.2 K) 3. Water salinity 4. The carbonate growth temperature (in fact the growth of the shell, hence the gained ∂18O depends on the water temperature). This effect is however stronger for planktonik foraminifers,while benthic live in a more or less stable temperature. 5. The vital effect of the organisms (which might cause species dependent offsets in the isotopic signals; some species travel to lower depth during reproduction which would result in a different delta18O signal during that time and will skew the record). ice cores? - **precipitation and evaporation** - air temperature over ice - delta18O composition of source (higher values at source create higher values in ice) - proximity of source region - primary season of precipitation (more snow during winter = more negative delta18O values) - elevation of ice (higher up = more negative in delta18O) - evaporation rate - precipitation rate - delta18O influenced mostly by seasonal variations in precipitation (large scale variations over ice sheet) ○ precipitation in summer heavier (more positive delta18O) than in winter due cold winter air can hold less water vapor and heavy isotope rain out fast, leaving more light isotope by the time precipitation reaches ice sheet - evaporation rate of moisture source (i.e. on fractionation that takes place during evaporation) - fractionation processes during condensation and precipitation - distance between moisture source and ice sheet (similarly to continental & altitude effect).

speleothems? (stalagmites and stalactites, the latter from above)

- form from precipitation of $CaCO_3$ through the reaction of dripping groundwater and soil CO_2
- groundwater delta18O heavily influenced by summer monsoon
  - negative values = stronger monsoon from ocean along with greater fractionation
- highly neg. delta18O in Brazilian and Chinese speleothems with 23ka cycles used to demonstrate orbital monsoon theory (i.e. positive influence of precession on strength of monsoon both in NH and SH)

Speleothems are formed from waters that are sourced from rainfall falling on the land surface and percolating through the ground into the cave system.

1. This means that the oxygen isotopic composition of any speleothem is influenced first of all by the oxygen isotopic controls over the rainwater

2. Depending upon the location of the cave, the oxygen isotopes in rainwater may be controlled by the source of rainfall, by temperature, or by the amount of rainfall.

3. Moreover, speleothem deposition is controlled the release of carbon dioxide (CO_2) from the drip water and the deposition of calcium carbonate to form the speleothem ($CaCO_3$). During both of these reactions oxygen isotopes can fractionate and this process leaves speleothem carbonate with higher δ18O values than the water from which the speleothem is formed.

4. Also, in areas where there is a lot of limestone between the surface (where the rainwater infiltrates the ground) and the cave (the point of speleothem growth), large aquifers of water can build up. These aquifers can allow water to be stored for years allowing old and new waters to mix and exchange their isotopic value before forming the speleothem.

6 Explain at least three different proxies for sea surface temperature (SST). Describe the advantages and disadvantages of the use of each of them and explain the factors that could lead to slight differences between the SST estimations derived from each of these proxies.

- U_k^{37} proxy: analysis of alkenone chains in organic matter (chain of 5 to 41 carbon atoms). At lower temperatures, species create higher amount of unsaturated carbon with double bonds, i.e. 37:4 (-> chain of 37 carbons with 4 double bonds). Application restricted as it is insensitive to T > 29℃
  - ↓T ≙ ↑# double bonds
- TEX_{86}^H proxy: another biomarker proxy similar to the U_k^{37} one, this time using an index of carbon tetraethers. advantage is that there is no warm temperature limit and does not suffer from changes in ocean chemistry or preservation, i.e. salinity, $[CO_3^{2-}]$, partial dissolution and/or diagenesis. Analysed are the membrane species from some random archaean species; the more C5 rings there are, the more fluid the membrane which is needed in colder temperatures. Has age restriction.
  - ↓T ≙ ↑# C5 rings
- □^{18}O proxy: using the empirical relation between oxygen isotopes in foram shells and temperature conditions in the sea water. One of the most used ones. Values depend on temperature, salinity and volume of water locked up in ice sheets. Not as high age restriction as the other two proxies since forams did not get extinct.
  - ↑+1‰ □^{18}O in forams ≙ ~ -4℃

- Mg/Ca ratio: increases with increasing temperature and decreases with increasing pH; problem due to species migration vertically (e.g. during reproduction period) and add calcite layers at depths significantly deeper than their principal habitat; this proxy is sensitive to salinity
- Microfossil transfer functions: infer how species living today changed due to changing climate using a regression model; commonly used microfossils are planktonic forams, radiolaria, etc. but must be living today and during the times which are investigated

Commented [4]: Just for understanding: this is similar to the difference between butter & margarine. Margarine has more unsaturated C bonds and is thus less hard at lower T.

- Clumped isotopes in carbonates or organics: random distribution of heavy rare isotopes (13C & 18 O). At low temperatures heavy isotopes clump together in the same molecule. If we measure a high amount of heavy isotopes sticking together, than it was cold.
    - Advantage: only temperature dependent, also applicable for extraterrestrial climate
    - Disadvantage: independent of d18O of water and independent of d13C of DIC, difficult to measure, Signal not always preserved)
-

7 How can the delta13C in benthic foraminifers be interpreted?

- cold/glacial conditions: delta13C of benthic forams is low due to input from land

Figure 1 shows the modern (a) and glacial (b) distribution of delta13C in the West Atlantic. Describe the present-day pattern observed in delta13C in the Atlantic Ocean, and the reasons for this distribution. How was the delta13C signal different in the Last Glacial Maximum, and what can we learn about glacial-interglacial changes in the ocean circulation?

delta13C can trace:

biological pump:

- photosynthesis preferentially incorporates 12C thus surface waters enriched in 13C (how much indicates degree of nutrient consumption)
- export of low delta13C into the deep ocean and subsequent respiration lead to low delta13C in the deep

water masses/mixing:

- different water masses which form at surface and sink into lower ocean with different delta13C signatures (NADW signal > AABW signal)

age of water masses:

- low delta13C signal is advected along the conveyor belt and continuous input of low delta13C due bioproductivity from above thus the older the water mass the lower the delta13C signal

state of climate:

- during glacials, 12C from storage on land transported to ocean again and thus ocean has lower delta13C signal
- volcanic input of 12C enriched carbon leads to low delta13C signal in the ocean (high volcanic 12C input together with nutrient input from ashes/organic matter increases oceanic bioproductivity which leads to increased export of organic matter into the lower ocean (black shales)

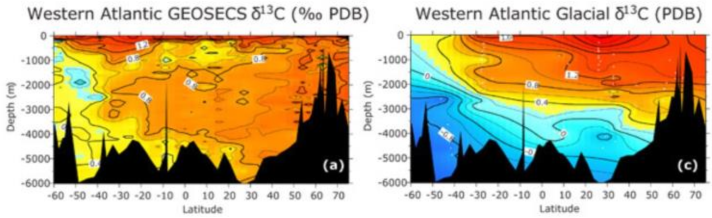


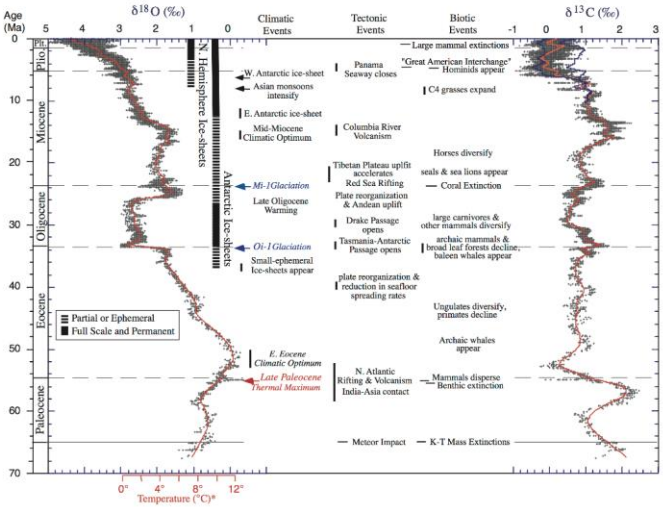
Figure 1: (a) Modern δ^{13}C and (c) LGM δ^{13}C transects for the western Atlantic (Oppo and Curry, Nature Education, 2012)

- modern delta13C distribution:
    - in general: ocean has a higher signal in delta13C due to transfer of 12C onto land (plants preferentially take up 12C and since we are in an ‘interglacial’ state with high land cover by plants currently, the ocean has an increased 13C signal
    - upper ocean in euphotic zone high delta13C concentration due bioproductivity

	• lower AO basin filled up by NADW (strong AMOC) which has lower delta13C signal than upper ocean due to bioproductivity input of low delta13C from the surface along its way into the deep ocean • AABW to the south (left side of figure) which is the densest deep water has the lowest delta13C signal in the modern ocean ○ outgassing in SO leads to less DIC in AABW water mass • glacial delta13C distribution: • GNAIW instead of NADW (less active AMOC) leads to stronger stratification of water masses in the Atlantic • delta13C signal is mainly restricted to the GNAIW region • AABW water mass fills out the lower ocean (> 2 km) • Southern Ocean leak closed, no outgassing occurring and instead bio pump removes CO2 from the atm. and thus accumulation of 12C in deeper ocean i. high accumulation of 12C in deep ocean = low delta13C signal
8	Which two time periods in the Cenozoic record have been discussed as potential analogues for future warming, and why? • The PETM (see also question 10: 55 Ma, SST +9 K at higher and +5 K at lower latitudes, BWT increase of 4-5 K, recovery after 100 ka, negative delta13C excursion,) due to its massive and rapid release of ^{12}C inorganic carbon from (most likely) methane clathrates resembles to some degree the human influence since the industrial times. restrictions when comparing PETM to today's Climate Change: • PETM over much longer time period • vastly different initial conditions (pCO2 as well as tectonics and ocean circulation) • emission rate was different than today: ○ PETM: over 170'000 years with < 1.1 Gt C / year emission ○ Today: over 150 years with ~ 10 Gt C / year emission • Early Pliocene Warm Period (3.3-3.0 Ma) -> see El Nino question (#1) • Temperatures 3 K higher than pre-industrial • similar CO2 concentrations in the atm. than today (~360-440 ppm) • sea level +6 m higher and ice was absent in Greenland • Pacific Ocean was in permanent El Niño state (reduced eastern eq. upwelling, deep thermocline, reduced temperature gradient in western and eastern eq. Pacific which possibly had global impacts) ○ zonal SST gradient much lower than today • this could be used as analogue to equilibrium state of a globally warmer world that is, according to model estimates, similar to the climate in the late 21st century • warming occurred over decades to centuries • similar conditions than today ○ tectonic setting ○ ocean circulation ○ plant and animal life • scientific understanding of Pliocene warm incomplete factors that have contributed are • reduced albedo • higher pCO2 • enhanced subtropical oceanic mixing • and a combination of those three is needed to explain the Early Pliocene warmth restrictions when comparing the early Pliocene: • there was a general cooling trend instead of the warming trend we observe today -> no mechanism to limit warming ! • The Eocene Thermal Maximum 2 (ETM-2) which represents another rapid incursion of ^{12}C inorganic carbon 53Ma. The magnitude of the negative carbon incursion (low □^{13}C of benthic forams) is not as large as was during the PETM. The timing was also different; the PETM occurred during an eccentricity (tilt) low, whereas the ETM-2 during an eccentricity high. A

hypothetical trigger could have been oxidation of existing peat (Torf) during the eccentricity maximum in Northern America and Eurasia which was previously formed during the ecc. minima.

9 How has atmospheric CO2 concentration varied through the Cenozoic during glacials and interglacials?



a) and b)

Cenozoic = since 65Ma

- slow increase towards early Eocene climatic optimum (1500 ppm)
- gradual decrease or cooling since the Paleocene
- aberrations during the PETM, Early, Mid Eocene Climatic Optimums and Mid-Miocene Climatic Optimum caused by injection of low delta13C carbon excursion into the ocean-biosphere-atmosphere system
- early Cenozoic characterized by active volcanism which led to accumulation of GHG in the atmosphere
- gradual decrease in temperature after the EECO due to enhanced weathering of Ca/Mg silicate rocks

$$H_2O + CO_2 \rightarrow H_2CO_3$$

$$CaSiO_3 + H_2CO_3 \rightarrow CaCO_3 + SiO_3 + H_2O$$

carbonate then dissolved in rivers (high ALK) and transported into ocean basins

  - silicate weathering as a negative feedback: high pCO2 → warmer temperatures → more active hydrological cycle → more acid rain (rain with dissolved CO2, i.e. with 'Kohlensäure' H2CO3) → increased weathering → high rate of CO2 removal from the atm. → cooling trend

Glacial, Interglacial Scale:

- after onset of NH glaciation, pCO2 varies between ~180ppm (icehouse) and ~280ppm (greenhouse)
- when transitioning from green- to icehouse
  - transfer of 1/3 of atm. CO2 into the ocean
  - transfer of land-biomass into the ocean which leads to more negative delta13C signal in benthic foraminifera

What are the main controlling factors on these two different timescales?

Controlling factors Cenozoic are slow processes that can lead to high-amplitude changes in the CO2 concentrations

1. spreading rate hypothesis, i.e. increased volcanism leads to CO2 emissions
2. uplift weathering hypothesis, i.e. the Tibetan Plateau was built and created surface for increased weathering of Ca/Mg Silicates which removes CO2 from the atmosphere
3. ocean gateway hypotheses,
   a. opening of the Tasman and 10Ma later the Drake Passage allowed strong Antarctic

    Circumpolar Current to form and isolated the continent. No longer heat transport leads to ice sheet build up and stronger albedo accelerating further cooling
    b. closing of the Isthmus of Panama cut off return-flow of low-salinity water from the Pacific

Controlling factors Glacial/Interglacial

1. orbital parameters control insolation of ice sheets, mainly changes in obliquity (the tilt) amplify or suppress the strength of the seasons. Milankovich theory as a good starting point to explain 41ka obliquity and 23ka precession cycles but fails to explain the dominance of the 100ka oscillations since the 41 ka – 100 ka cycle boundary (see question 4)

2. **Ocean circulation!**
    a. Glacial sequence (i.e. how to move from warm to cold): Slow CO2 drop in 2 steps + long term trend:
        i. Closure of the Southern Ocean leak by strengthening of the freshwater cap in PAZ (Polar Antarctic Zone), 40 ppm.
        ii. activation of biological pump in southern ocean 40 ppm
        iii. decrease in exchange of Southern Ocean surface waters with ocean interior (‘Ocean stratification’), some continuous ppm.

    - lower ocean temperatures during glacials increase solubility of CO2
    - higher ocean salinity during glacials decrease solubility of CO2
        - however, these two mostly cancel each other out
    - iron fertilization due to arid conditions may further amplify CO2 drawdown by the biological pump

    b. Deglacial sequence: very quick CO2 transfer from deep ocean to atmosphere as deep oceans reconnect with atmosphere (outgassing). Potentially triggered by Heinrich events.

c) How can CO2 concentrations be reconstructed? Explain two methods in few sentences.

delta^{13}C proxy

- during glaciations, ^{12}C-enriched organic matter transferred from the land to the ocean (while at the same time ^{16}O-enriched water vapor is extracted from the ocean and stored in the ice sheets. During interglacial periods: vice-versa. □^{13}C can be analysed in either organic matter (benthic forams and C3/C4 plants) or in trapped air bubbles of ice cores
    - $\downarrow CO_2 \triangleq \downarrow \square^{13}C$ of benthic forams
    - $\downarrow CO_2 \triangleq \uparrow \square^{13}C$ of air bubbles
    - $\downarrow CO_2 \triangleq \uparrow \square^{13}C$ of plants

boron isotopes 10B and 11B

- stable in seawater as boric acid and borate ion B(OH)$_3$ or B(OH)$_4^-$
    - Boric acid enriched in 11B by 27 permill
    - transition from boric acid to borate in the range of seawater pH
    - ONLY borate ions incorporated into marine carbonates
        - measure B$^-$ and derive ocean pH
    - assuming ocean in equilibria with atmosphere and marine pH forced by CO2, one can calculate pCO2

- stomata
    - high CO2 → low stomata density per mm^2
    - low CO2 → high stomata

10 What is the PETM?

- first of a series of sudden and extreme global warming events (hyperthermals) during the Cenozoic
- at 55 Ma – boundary between Paleocene and Eocene
- SST +9 K at higher and +5 K at lower latitudes

- BWT increase of 4-5 K
- recovery after 100 ka
- negative delta13C excursion in ocean due to massive and rapid release of 12C inorganic carbon from (most likely) methane clathrates
- CCD shoaled rapidly by more than 2 km & recovered gradually
    - thus dissolution of carbonate sediments and instead sedimentation of clay layers
- shift in precipitation pattern
- extinction of 50% of benthic forams
- dispersion of terrestrial mammals

and what are the hypotheses to explain it?

- Methane-Clathrate dissociation:
    - methane hydrates a solid form of highly negative delta13C
    - found under certain temperature/pressure conditions at ocean floor
    - change in water temperature may have led to decrease of depth where hydrates are stable
    - to explain temperature increase one would need double the amount of hydrates available for dissolution so it’s **not the only cause** for observed change
- Silicate weathering:
    - would work, however slow process and not considered for PETM
- Terrestrial carbon chemistry:
    - sudden release of carbon from soils (peat?)
    - however, would only have been possible if 90% of present-day carbon was moved to the ocean (i.e. highly unlikely)
    - no evidence of this found in geologic record
- CO2 release from volcanism:
    - inorganic carbon typically 12C (delta13C: -7 permill)
    - however, too much carbon would have had to be release and is 200 times the estimate of volcanic activity at that time
- CH4 release from volcanism:
    - mantle-derived melts intruded carbon rich sedimentary layers off the coast of Norway (Swensen et al., 2004)
    - organic carbon converted to methane when exposed to heat by magma
    - would have been enough to explain -3 permil delta13C record
    - timing fits

How did the carbonate chemistry in the ocean change during this time interval?

- methane rapidly oxidized to CO2 which then is dissolved in ocean water
- rapid ocean acidification, pH goes down (to the left) and carbonate ion concentration goes down
- changes partially neutralized by rise of lysocline & CCD which results in dissolution of seafloor carbonate sediments
- since ocean no longer in equilibrium with atmosphere, outgassing on a large-scale

- gradual recovery over 100 ka when CO2 eventually is returned by chemical weathering of silicate rocks

What is the difference between Lysocline and CCD?

- At the lysocline the rate of calcite dissolution increases dramatically but is not yet 100%. The carbonate compensation depth, which lies deeper, is the depth where the calcite will be dissoluted and no calcite can be deposited (rate of supply of calcite equals rate of dissolution).
- at lysocline CaCO3 is not oversaturated anymore, begins to be undersaturated. But due to a kinetic lag, dissolution begins only at CCD.

11 How do changes in the biological pump affect atmospheric CO2?

If the pump becomes inefficient, CO2 which was stored in the ocean leaks to the atmosphere. This is mainly due to microbial activity differences according to season and latitude. in the southern ocean, the pump is inefficient because the organisms cannot use all of the CO2 which is freed from the ocean.

What is the difference between the strength and the efficiency of the biological pump?

strength:
- amount of CO2 which can possibly be released or bound
- more or less atm. CO2 is taken up by biological activity, leaving atmosphere with lower CO2 levels

efficiency:
- ratio of regenerated to preformed nutrients

- regenerated nutrient from organic matter produced at surface, sinking into ocean interior and then regenerated to inorganic forms of carbon and nutrients
    - thus: presence of regenerated nutrients in the deep linked to biological sequestration of CO2 there
- preformed nutrients originate as dissolved nutrients which were not used up by bioproductivity due to limiting factors (e.g. iron)
    - represents missed opportunity for ocean to remove CO2 from the atmosphere

efficiency can be varied by
- changes in exchange rate of SO surface waters with the ocean interior
- changes in the degree to which SO surface nutrient is consumed by phytoplankton
- changes in sea-ice coverage, causing a shift in the ability of CO_2 to escape from supersaturated SO surface waters

How can we reconstruct changes in the efficiency (think about associated uptake of nutrients)?
- infer changes from ice cores with delta18O
- use delta13C, carbonate ion concentration and MC/Ca ratio records from benthic forams
- infer changes in the biological pump from the abundance of planktic/benthic forams (ratio lower during cold periods)
- use a carbonate saturation index to infer changes in CCD and lysocline which can be used to reconstruct efficiency of biopump

In which region of the ocean do changes in the biological pump have the most influence on atmospheric CO2 and why?
- in regions of high nutrient and high insolation rates
- in the NA where nutrients are used up
- in the SO where
    - nutrient rich and high CO2 concentrated water masses are upwelled and returned to subsurface before N and P are fully used up
    - this incomplete use of nutrients leads to net outgassing of CO2
- in upwelling regions where deep, nutrient-rich waters reach the surface due to Ekman driven divergence of surface waters

the biological pump has the most influence on atmospheric CO2 in high latitudes. this is due to the seasonal changes of temperatures, solar radiation, ice cover and nutrient availability for the organisms. so, in cold times, the organisms cannot take up all the CO2; the pump is inefficient. in spring, there is the algal bloom, where a lot of CO2 can be taken up and the pump is considered efficient. when the biomass exceeds the available nutrients, the organisms die and the CO2 will get released again.

What effect does an increase in the efficiency of the biological pump have on the carbonate chemistry (e.g. the lysocline) in the deep ocean and how do these changes affect atmospheric CO2 (on glacial-interglacial timescales)?

- increased efficiency = more CO_2 removed from the atm. and stored in the deep ocean
- high regenerated nutrient rate in the ocean interior
- biological pump lowers pCO_2 by
    - decreasing concentration of DIC in surface waters

	• increasing whole-ocean alkalinity • efficient pump = much of DIC removed from surface and transferred as C_{org} into deep • there, regenerated DIC lowers deep ocean CO_3^{2-} • decrease in deep c(CO_3^{2-}) shoals CCD and lysocline → less burial of $CaCO_3$ • since burial of $CaCO_3$ is ocean's main way to reduce ALK • reduced burial leads to excess input of ALK from rivers (with high c(CO_3^{2-})) to the oceans alkalinity feedback starts and amplifies total CO_2 drawdown even more
12	What are Heinrich events? • during the last 60ka total of 6 (7) Heinrich Events • episodes of unusually abundant ice-rafting • higher concentration of cold water forams • occur during the coldest phases of the D-O cycles with prominent iceberg-discharges in the N. Atlantic • IRD as indicator for Events, composition varies with place of origin • after Heinrich Event there is a very warm D-O, an than the other cools slowly down Describe the evidence found in the geologic record from higher to lower latitudes (in the northern hemisphere), the timing, and the underlying process. **evidence:** delta18O and ocean sediments • ocean sediments in NA show large concentrations of IRD • high concentrations of cold-water forams • coincide with low values of Greenland ice sheet delta18O • wet events in pollen record from Lake Tulane (Florida) **timing:** • during last 640 ka (when Laurentide ice sheet existed) ◦ this time-period also marks the onset of the 100 ka cycle ◦ it appears: during 43 ka cycles Laurentide sheet not big enough for Heinrich event to occur • occurrence at major climate boundaries (e.g. H1 as onset of LGM termination • spacing ~10 ka – precession • slow drift towards colder temperatures followed by relatively abrupt shifts back to warmer D/O interstadials **underlying process:** • Binge-and-purge model: Laurentide ice sheet is located on soft, unconsolidated sediment which leads to massive discharge when ice on the bed reaches melting temperature (normally bed is frozen) • Jökulhlaups: dam formation at Hudson strait leads to water accumulation in Hudson Bay which is then later periodically broken and leads to discharge of freshwater out of the Hudson Bay lake • Ice sheets formed during extreme cold conditions are vulnerable to sudden climate change (iceberg discharge) • bedrock depression: What are the impacts of these events on a) high-latitude, and b) low-latitude climates. a) • H-events as indicator for stadial conditions with cold NH and increased ice-sheet extent • reduction or shutdown of AMOC • increased sea-ice formation • ice sheets on NH in growing conditions b) • NA water inflow into Mediterranean • SST in Alboran Sea (using UK37) correlates with NGRIP core (using delta18O)

	enrichment of certain cold-foram species during H-events • El Niño like wet conditions
13	What are the Dansgaard-Oeschger events? • most important climatic events during the last 60ka • oscillations of delta18O and dust concentrations • rapid warming followed by gradual cooling on millenial time (1500 years or a multiple of that (3000, 4500)) scales likely causes include a) bistability of AMOC, b) latitudinal shifts in convection and c) shifts in atm. circulation -> Rossby-Waves d) if warm → ice melt over greenland/canada → NADW (Nord Atlantic Deep Water) down → colder T → less ice melt → NADW up → warmer T → ... Describe the features that characterize these events in the geological record. • duration: millenial scale climate variability • Greenland ice record show low delta18O and higher dust concentrations during cold stadial conditions • abrupt jumps in temperature, dust content, ice accumulation rate, methane concentration • methane minima in greenland ice core during stadials, incl. Younger Dryas Explain the possible causes for the DO events and the evidences for and against each of them. • solar variability • ice-sheet instability ○ geothermal heat ○ big sheet depresses bedrock below sea level and ice drifts atop water which leads to increased flow speed ○ sea water warms/melts ice sheet from below and leads to iceberg discharges • GHG forcing: CO2 and methane linked to cold/warm periods of D/O cycles ○ open question: are they forcing or reaction? • changes in strength of AMOC and associated bipolar seesaw: ○ decreased NADW formation during stadial, lower ocean filled up by southern-sourced corrosive AABW (low carbonate ion concentration) ○ increased strength of AMOC during warm events of D/O cycle ○ cooling in NH = warming in SH and vice versa • changes in atm. circulation, i.e. relocation of Rossby Waves further to the south leads to colder conditions in the NH which impact Heinrich events

14

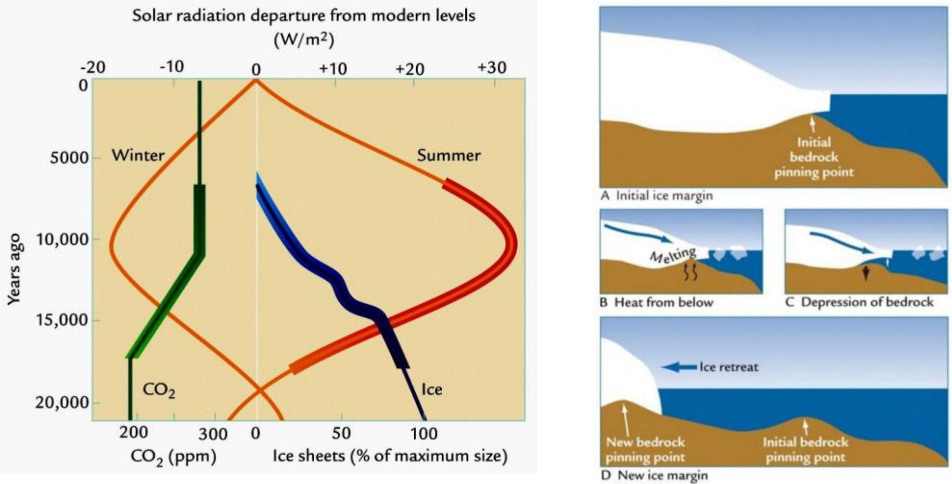


Figure 14-1 Causes of climate changes during deglaciation:
During the declacial interval between 17 ka – 6 ka, climate changes were driven by rising summer insolation and by increased concentrations of CO2 in the atm; as the ice sheets shrank, their ability to influence climate diminished.

Describe the sequence of events leading to a glacial
termination (think about changes in insolation, greenhouse gases, ocean and atmospheric circulation, ice sheets, and sea level).

Human-induced climate change through greenhouse gas emissions warms planet, raises sea levels & increases chance of extreme weather events.

- two prerequisites to pass critical threshold:
  - high obliquity + high precession effect (highest impact on tropics) → rising NH summer insolation & change in strength of monsoon
  - large NH ice-sheets prone to instabilities (bedrock depression, heat from below, melting due to sea ice)

- termination as a step-wise sequence
- global mean sea level rise by 110 – 125 m
- increase in pCO2 from 180 to 280 ppm
- ‘excess’ ice (ice sheets at their max) provide necessary volume in seaward-draining systems to produce collapse into NA that is massive and long enough to jump-start termination via oceanic/atm. teleconnections with SH

- summer melting during retreat of NH sheets injects add. freshwater; reduced AMOC initiated and maintained (decrease in sea water density in AO due to freshwater forcing)
- NH: slowdown/stop of AMOC, spread of winter sea-ice, cold ocean T, weak Asian monsoon, southward shift of ITCZ
- SH: increased upwelling, southward shift of westerlies, rise in pCO2, rapid ocean warming
- two ways to explain opposing behaviour of NH and SH:
  - oceanic bipolar seesaw (↓NADW = ↑AABW, see Gottschalk et al., 2015)
  - ITCZ pushed towards SH by spread of winter sea-ice over North Atlantic and precession effect which transfers northern stadial/interstadials rapidly to SH
  - two processes likely act synergistically
- southward displacement of westerlies around ACC has 4 effects
  - reduces sea-ice, exposing atm. to warmer ocean

- increased upwelling to bring up warmer water to melt sea-ice
- increased southward eddy transport of heat
- CO2 release/degassing by upwelling

- delivery of freshwater to NA to maintain stadial and southward displacement of SH westerlies must persist for sufficient duration to raise pCO2 above minimum level to maintain warm conditions globally

very large and isostatically depressed NH ice sheets with marine-based components
↓
rising NH summer insolation leads to ice-sheet melting and instabilities that deliver water and ice to the North Atlantic
↓
reduced AMOC and spread of winter sea ice produces particularly long NH stadials with severe winters
↓
asian monsoon weakens, ITCZ and westerlies of both hemispheres shift southwards
↓
southward shift of SH westerlies and oceanic bipolar seesaw warm Antarctica and raise pCO2
↓
prolonged effects of NH stadials raise pCO2 above threshold necessary to sustain interglacial conditions

Fig 4. from Denton et al., 2010. Essential elements of a termination. Summary of the conditions and processes described that contribute to the termination of a Late Pleistocene ice age.

15 Which climate forcing factors played a role during the Holocene?

SCALE	FORCING
millennial	• orbital forcing • humans (at start of agriculture: irrigation of rice fields, livestock, biomass burning)
century	• solar forcing (solar winds and irradiance)
decadal-to-annual	• volcanic forcing • atmosphere-ocean circulations (ENSO, NAO, PDO)
influencing all three above	• CO2 and other GHG

- strength of north tropical monsoons
- warmth of summers in north polar latitudes
- release of stored waters in the Laurentide Ice Sheet into Hudson Bay

16 What evidence do we have for past changes in global ice volume?

- delta18O in ice cores (abrupt decrease at onset of Antarctic glaciation
- CO2 reconstruction by
    - alkenones
    - UK37,H
    - TEX86,H
    - delta18O
    - Mg/Ca
    - microfossil transfer function

    - clumped isotopes ratio (lower temperature = more clumping)
- coral reefs and 14C isotope (14C via cosmic rays and decays...date coral reefs and look when sea level at certain height)
- Th/U chronology (decay of ratio with time)
- climate model studies of ice sheets (CO2 < 760 ppm)

When and where did major ice sheets emerge within the Cenozoic?

- 34 Ma onset of SH glaciation (ice sheet on Antarctica):
    - CO2 under 760 ppm (lower seafloor spreading, weathering increased due to uplift of Himalaya
    - onset of ACC creates freezer-like conditions around Antarctica
        - Drake passage opens (~34 - 48 Ma)
        - Tasmanian gateway opens (10 Ma earlier)

- 2.73 Ma onset of NH glaciation
    - closing of isthmus of Panama increases strength of Gulf Stream and brings
    - high salinity water masses into Northern Atlantic Ocean
    - increased moisture supply to the NH, westerlies bring moisture over continent which then rains out and is transported by river discharge into the Arctic Ocean
    - increased strength of Gulf Stream

Which factors determine the growth and decay of ice sheets on different timescales (Cenozoic, orbital, and millennial timescales)?

Cenozoic scale :

- CO2 and its interaction with the global biochemical cycle and weathering of silicate rocks
- plate tectonics (spreading rate, uplift of terrain, opening of ocean gateways) and associated interaction with CO2
- weathering rate of Mg/Ca silicate rocks
- albedo of the land

SCALE	WHAT DETERMINES GROWTH/DECAY OF ICE SHEETS
cenozoic scale	• plate tectonics ○ gateway openings and closures ○ BLAG spreading rate ○ uplift of terrain ○ and associated interactions with CO2 • weathering rate of Mg/Ca silicate rocks • albedo of the land and ice sheets
orbital scale	• strength of insolation by • eccentricity (i.e. non-circular path of Earth around the Sun) • obliquity (i.e. tilt) • precession (i.e. wobbling) • CO2 interactions of ocean, atmosphere and biosphere • albedo and interaction with ice sheets • strength and variability of ocean circulation (e.g. strength of AMOC) • strength and variability of atmospheric circulation (e.g. southern extent of Rossby Waves)
millennial scale	• D/O cycles • strength and variability of ocean circulation (e.g. strength of AMOC) • strength and variability of atmospheric circulation (e.g. southern extent of Rossby Waves) • strength of insolation by the sun (as above) • albedo feedback (as above)

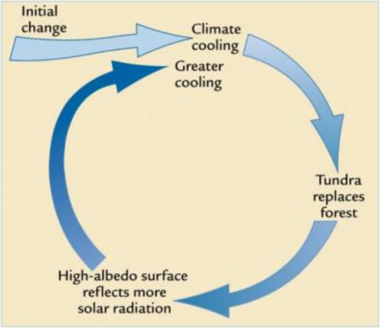
	• CO2 interactions of ocean, atmosphere and biosphere (as above)

17 What are positive and negative feedbacks in the carbon cycle? Describe briefly an example of positive and one of negative feedback.

- feedbacks alter climate changes that are already underway, either by amplifying (positive) or supressing them (negative)

<table>
<tr><th colspan="2">feedbacks</th></tr>
<tr><th>POSITIVE, e.g. albedo</th><th>NEGATIVE, e.g. chemical weathering</th></tr>
<tr>
<td>

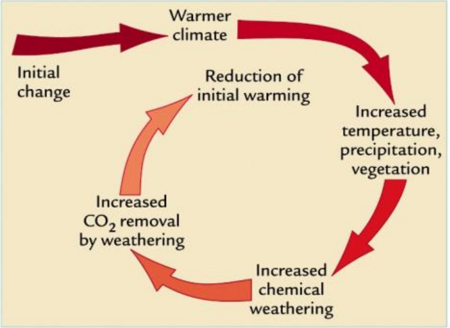
initial change = less CO2



A Vegetation-albedo feedback

</td>
<td>

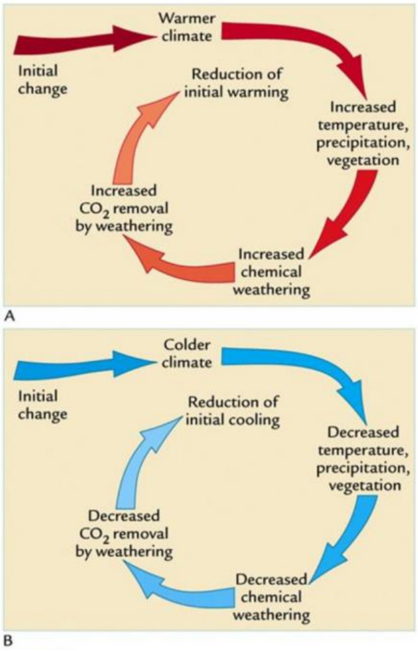
initial change = more CO2



A

</td>
</tr>
</table>

18 What is ‘Snowball Earth’?



- during neoproterozoic era, i.e. at 770 Ma weaker solar heating
- 6% lower than today's modern luminosity
- several events took place
- cooler Earth would have reduced rate of chemical weathering
    - kept CO2 values higher and moderated global temperature
- climate models suggest that CO2 levels must have been much lower to permit ice sheet growth in the tropics
- thermostat mechanism seems to have malfunctioned, at least for a while
- thermostat regulates Earth's temperature and keeps it within a certain range via a negative feedback loop
- geothermal heat keeps ocean freezing from the bottom

- reason for malfunction unknown
- one explanation: continents all at equator, where they received a lot of rainfall
- heavy tropical precipitation could have driven strong chemical weathering reducing CO2
- large amount of solar heat stored in low-latitude ocean tends to keep its surface free of ice

feedbacks having an influence:
ice-albedo:

- ice at equator reflects much more radiation since it gets hit vertically
- feedback so strong that planet froze over
- runaway freeze, extinguishing almost all life (except seafloor hot springs)

greenhouse Earth:

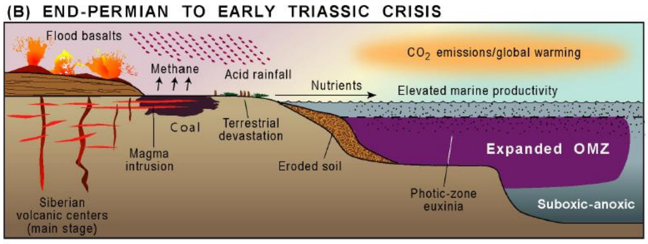
- when Earth completely frozen, induced CO2 by volcanism no longer removed from the atmosphere and it accumulates
    - no longer water in liquid form available for chemical weathering
- ca 350 times present day concentration necessary to get the climate out of snowball which translates to around 10 Ma snowball Earth time (when volcanism is the same rate as today)
- CO2 accumulation in atmosphere drives temperature up to 50 degrees
- re-activation of evapotranspriation (water vapor as GHG)
- rapid chemical weathering and transport into the ocean leads to fast accumulation of 'cap carbonates'
- carbonates have low delta13C values just before glacial deposits, gradually increasing to higher 13C values in younger cab carbonate layers

Cambrian explosion:

- succeeded by rapid diversification of multicellular life
- long periods of isolation and extreme environments spurred genetic change
- explosive radiation through environmental filter/stress
- during snowball Earth accumulation of genetic diversity in geographically separated hot springs

	When did it happen?
	750 – 640 Ma ago, end of Neoproterozoic, before Cambrian explosion (beginning of Paleozoic Era)
	
	and what is the evidence for its existence?
	
	geological record:
	• glacial debris near sea level in the tropics
	• unusual iron-rich rocks (can only form if oceans and atmosphere have little or no oxygen
	  ○ ice-covered oceans deprived of oxygen
	  ○ iron accumulates in ocean water
	  ○ precipitates when oceans free again
	• warm water carbonates (Ca/Mg CaCO3) accumulated just after ice sheets retreated
	  ○ evidence for hothouse that followed
	• neoproterozoic glacial deposits almost everywhere blanketed by carbonate rocks which represent the shortly after following hothouse conditions of around 50 degrees Celsius
	  ○ aka ‘cap carbonates’
	
	lack of early branching in eukaryotes due to mass extinct

19	What are the postulated causes of the Permian/Triassic mass extinction? 252 Ma impact event: • crater in north western continental margin of Australia • measuring of plagioclase which has an age of 250+/-4.5Ma and would perfectly fit as a trigger for P/T mass extinction • no idea if this hypothesis is still relevant today since the paper is from 2004 volcanism: • volcanic activity of the Siberian traps at 252 Ma (dating in good agreement) • flood basalts covered 2 million km^2 with lava • basaltic magma high concentration of ^{12}C into the atmosphere which lead to acid rains (devastates terrestrial ecosystems which leads to methane release of coal soils) • expanded oxygen minimum zone (OMZ) due to elevated marine productivity as nutrients from the land get transported to the ocean basins • Oceanic anoxic event = episodes of widespread marine anoxia during which large amounts of organic carbon were buried on ocean floor under oxygen-deficient bottom waters • enhanced burial due increased primary productivity or enhanced preservation methane hydrate gasification: • rapid decrease in delta13C (excursion of 12C inorganic carbon similar to PETM) • not sufficient to fully describe pattern • could be in connection with volcanism above and picture below: ○ magma intrusions into coal soils / peat soils leads to rapid outgassing and oxidation of methane ocean anoxia: • extreme high oceanic bioproductivity due to nutrient availability • oxygen in deeper layers completely used up (anoxic) by respiration • fine laminations in sediments • high Th/U ratios (Uranium decays into Thorium) • wide-spread die-off of marine life (due to volcanism, oxygen depletion, ...) • however, in some places like China and eastern Greenland, evidence for anoxia precedes extinction

- 

What are the similarities to the postulated oceanic anoxic events (OAE's) in the Cretaceous?

Cretaceous OAEs at 145 – 72 Ma, Mesozoic era (Triassic – Jurassic – Cretaceous)

- actual trigger mechanism not clearly identified -> postulated that large-scale magmatic activity initially triggered both anoxic events during P/T & during Cretaceous
- direct proxy of magmatism preserved in sedimentary record coinciding closely with onset of anoxic events not yet found
- widespread deposition of Corg rich sediments ('black shales') similar to P/T event

Weissert mentions for the early Cretaceous AOE (anoxic oceanic events):

    - four events, OAE1 is the first global black shale event → resulted in decrease of pCO2
- warming trend induced by volcanism (Java, Mariana Basin)
- widespread destabilization of clathrates (CH_4, similar to PETM)
- climate-induced ocean circulation changes result in widespread O-depletion in deep and intermediate water masses
- volcanic episodes coincide with positive C-isotope anomalies in bulk-rock samples (i.e. limestone)
- local or regional stress-amplifying factors were nutrients, suspension load or temperature changes
- pCO_2 affecting ocean chemistry was the most important factor controlling carbonate production (while the underlying trigger is volcanism)

similarities of both events:

    - volcanism as trigger
    - methane instabilization induced
    - OAE induced
    - negative delta13C structures through large-scale carbon emissions (volcanism, methane)

→ 12C inorganic carbon emissions

Climate Change in 140 characters:

Human-induced climate change through greenhouse gas emissions warms planet, raises sea levels & increases chance of extreme weather events.