Climate Change
The Rule in the Geological Record

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Earth's climate has undergone dramatic changes since early in the history of the planet

Why?

- Solar system's gravitational effects on the Earth's orbit;
- Extraterrestrial dust;
- Meteor impacts;
- Solar irradiance changes;
- ….
- Orogenesis (mountain building);
- Plate tectonics (sea-floor spreading, mid-ocean ridge basalt formation and outgassing);
- Volcanism (outgassing, aerosols, dusts...);
- Long-term biological changes (i.e. evolution of land plants);
- ....
- *These processes have major impacts on earth's global-scale weathering and erosion, on ocean and atmospheric circulation, sea level, biogeochemical cycling of carbon, nutrients and other key elements throughout parts of the climate system;*
- …
- *Most of the reconstructed climate changes from the paleoclimate records are the <u>cumulative product of one of several feedback mechanisms</u> as well as of external forcing and internal variability. <u>Feedbacks operate over all timescales at different speed.</u>*

Cronin 2010 Paleoclimates 441p. Columbia Univ Press

TABLE 1.1 Causes of Climate Change*

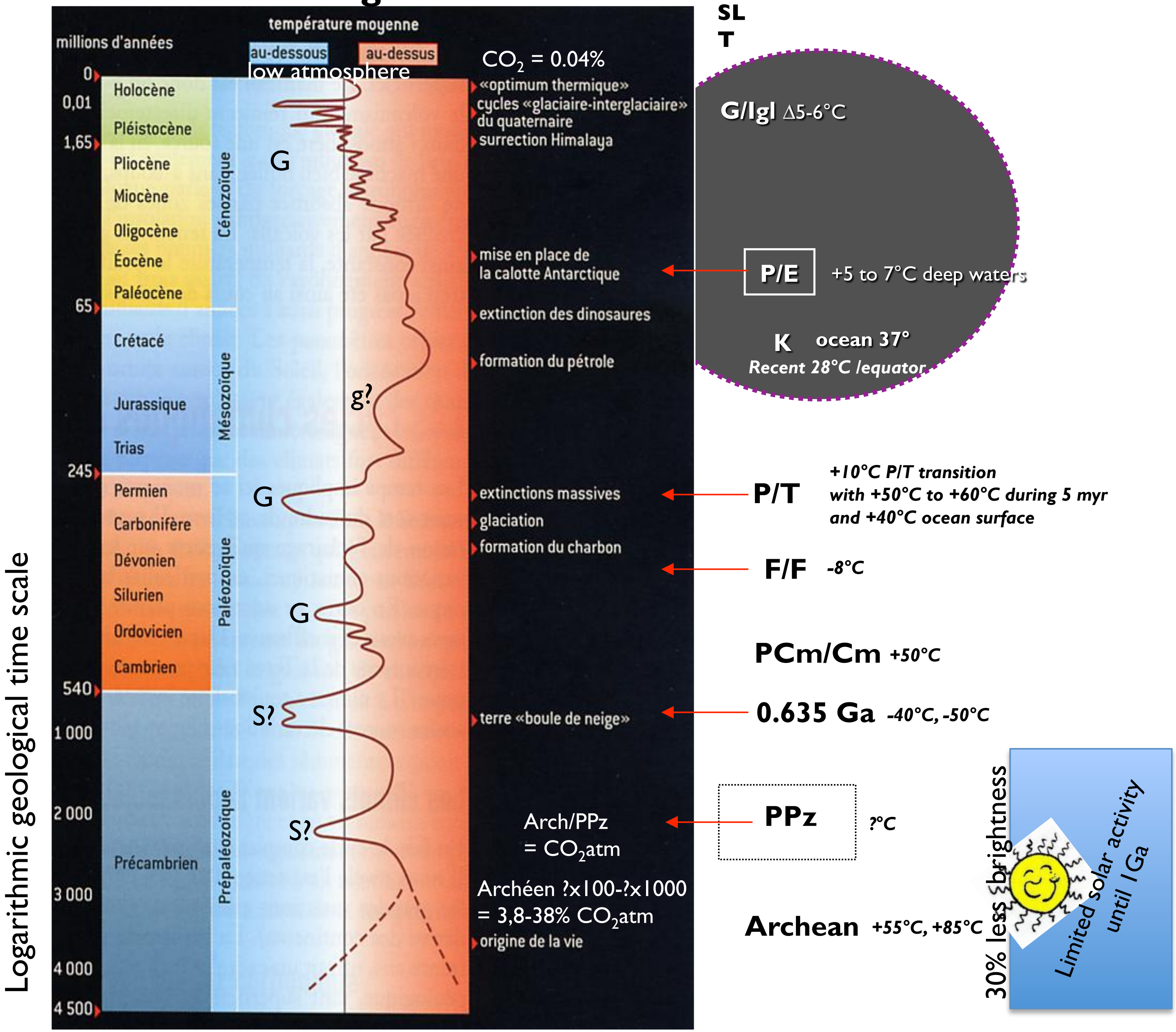
Time scales 10^{-1} - 10^{8} a

Climatology Emphasis	Paleoclimatology Emphasis
External	**External**
Solar radiation	Eccentricity
Sunspot variation and irradiance changes	Obliquity (tilt)
Solar diameter	Precession of equinoxes
Solar ultraviolet wavelength variability	Axial precession, asteroid impacts, internal plate tectonics
Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), halocarbons, tropospheric nitrogen oxides, carbon monoxide (CO), sulfate aerosols	Galactic dust
Aerosols	Solar irradiance
Explosive volcanism	Meteor impacts
Internal	**Internal**
Internal modes of variability, "unforced" variability; see Chapter 10 = ocean-atmosphere dynamic + anthropgenic action?	Orogenesis, mountain building, weathering, biogeochemical changes
	Ocean-volume changes, sea level
= **according to many experts**: ***stochastic and unpredictable****	Ice-sheet and glacial lake meltwater influx
…. *and forecasting climate change due to external forcing*	Explosive volcanism
EVEN more difficult **	Dimethylsulfide (cloud condensation nuclei)
	Mid-ocean ridge outgassing

- *PhD Harvard University, now Georgetown U., ~160 peer-reviewed publications in ~55 journals…*
  Expertise: climate changes of the past, sea level, coastal ecocystems, biodiversity, stratigraphy, sedimentology, quaternary geology, Arctic ocean climate history

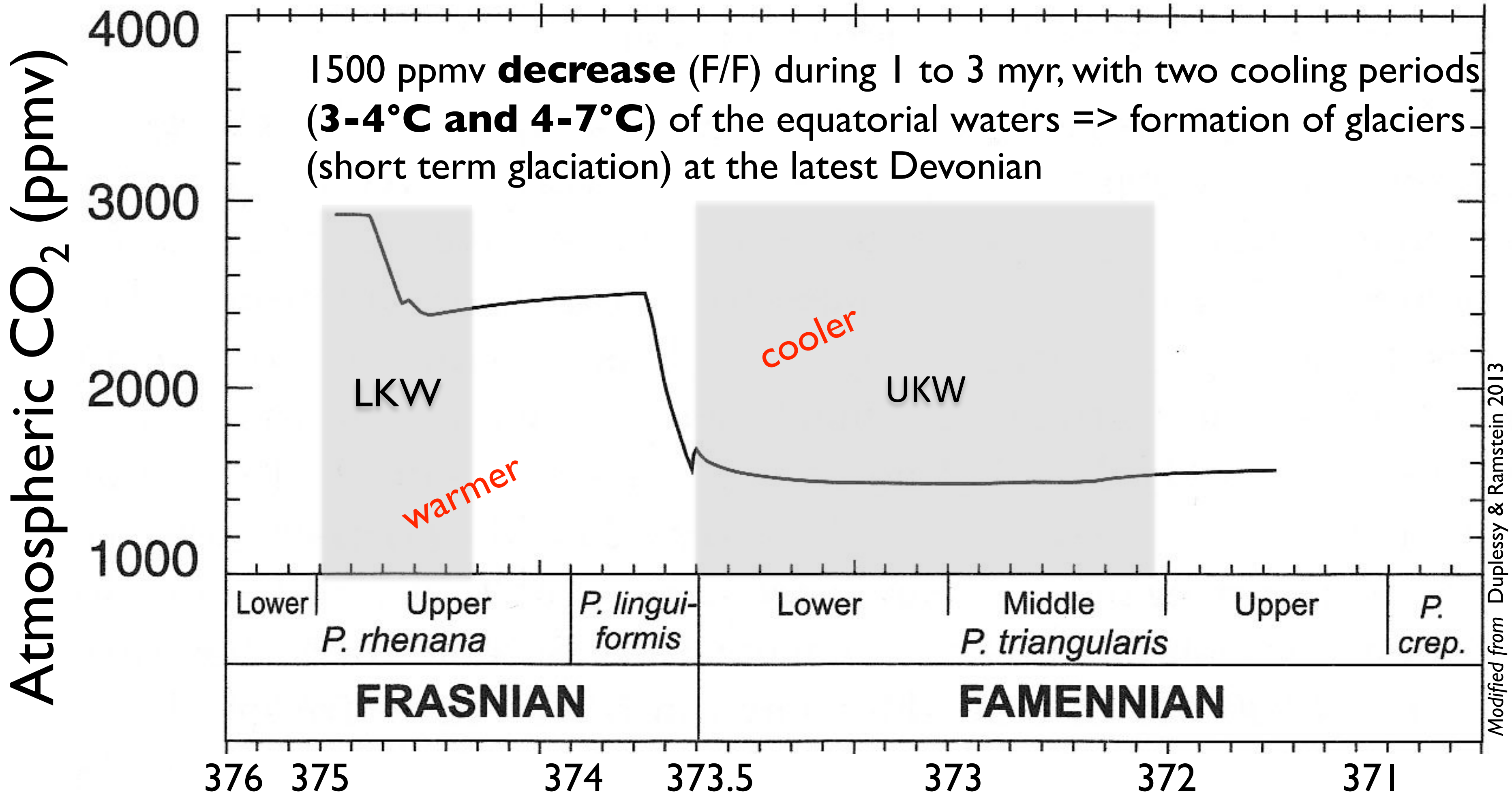
Variations of the average Earth Temperature
Climate Changes in the Past

GHG
SL
T

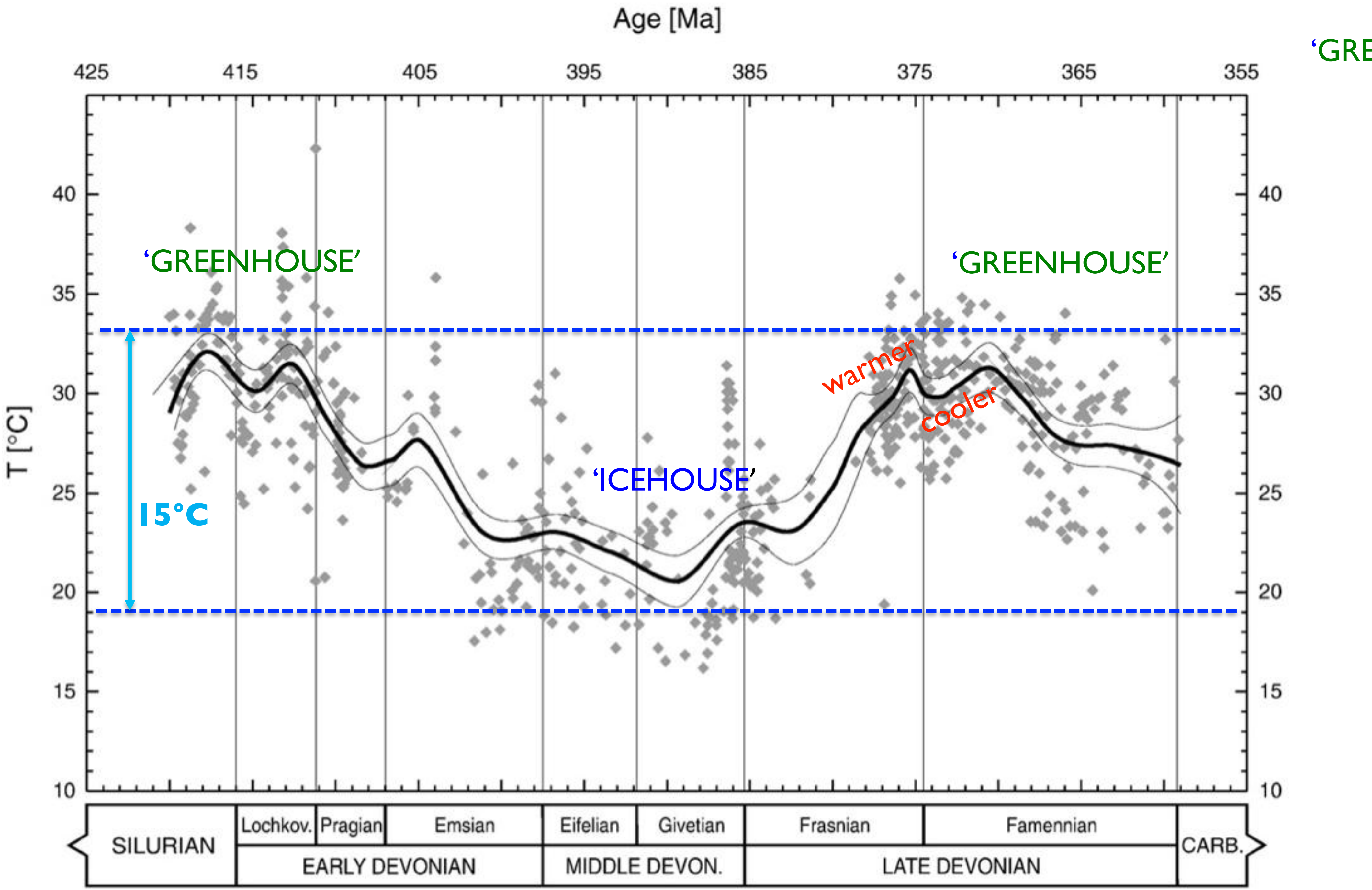


TWO ANOXIC EVENTS IN THE LATE FRASNIAN

Major Late Devonian Extinction (one of the big five mass extinctions)



F/F tropical ocean temperature was 30°C ($\delta^{18}O$ from apatite conodonts) before the coolings. The late Devonian glacial event reflected regional conditions to high latitude position for a short time => importance of the distribution of (paleo)continents.



Devonian (sub)tropical sea surface palaeotemperatures calculated from $\delta^{18}O$ conodont apatite.

(Joachimski et al 2009 EPSL)

Climate change : the Rule in the Geological Record

'**ICEHOUSE**' et '**GREENHOUSE**' succession since the Earth's formation (Frakes et al. 1992)
These periods have been questionned by the GEOCARB modeling, mainly for the Mesozoic.

BROAD SCALE	Mode	Approximate age range (Ma)
Early Eocene to present	cool	55–0
Early Cretaceous to early Eocene	warm	105–55
Late Jurassic to early Cretaceous	cool	183–105
Latest Permian to middle Jurassic	warm	253–183
Early Carboniferous to late Permian	cool	333–253
Early Silurian to early Carboniferous F/F	warm	421–333
Late Ordovician to early Silurian	cool	458–421
Earliest Cambrian to late Ordovician	warm	560–458
Latest Precambrian to earliest Cambrian	cool	615–560

Note: Time scale from Palmer, 1983; Fig. 1.2.

This succession of climatic modes takes into account a large number of 'galactic' and planetary factors, including the paleocontinents, the oceanic paleocirculation, the paleoatmospheric composition…..
….. the combination of all these factors and others…

COOL MODE => cool climate (PPz, NPz …. Late Cenozoic, glaciation)

- considerable extent of high-latitude land;
- long intervals of cooling leading to high latitude glaciation;
- marked increase in $\delta^{13}C^*$ rising to a peak during extreme glaciation;
- marked decrease in abundance of evaporites, (of volcanism)…
- …

(*) e.g. marked decrease in $CO_{2\ atm}$ through the sequestration of large C_{org} quantities on land, on continental shelves and ?deep ocean and/or surface ocean bioproductivity
=> increase in $\delta^{13}C$ and development of glaciers with a 'time lag ' between10 à 30 myr…

WARM MODE => warm climate (Cm-Ord_m, Sil_m-$Cferous_l$, Pm-J_l, K_l-Paleogene)

- in contrast to Cool Modes, the onset of warm intervals was sudden, whereas the terminations were more gradual, geographically variable (i.e. 'diachronous');'
- abrupt decrease in $\delta^{13}C$ shortly before the onset (e.g. 2‰ decrease in late Aptian…);
- increase output of CO_2 from tectonic activity (volcanism, metamorphism …);
- …

- the icehouse/greenhouse transitions were synchronous with some biotic crises or mass extinction events.

Is there a climate cyclicity? … PROBABLY

The average length of a full Cool-Warm supercycle is ~300 myr = **? Galactic Year Cycle….** with long 30-36 myr cycles toggling between '**dominant**' greenhouse and icehouse states ...

EXAMPLE
End Cool M/Onset Warm M

decrease in $\delta^{13}C$ ●

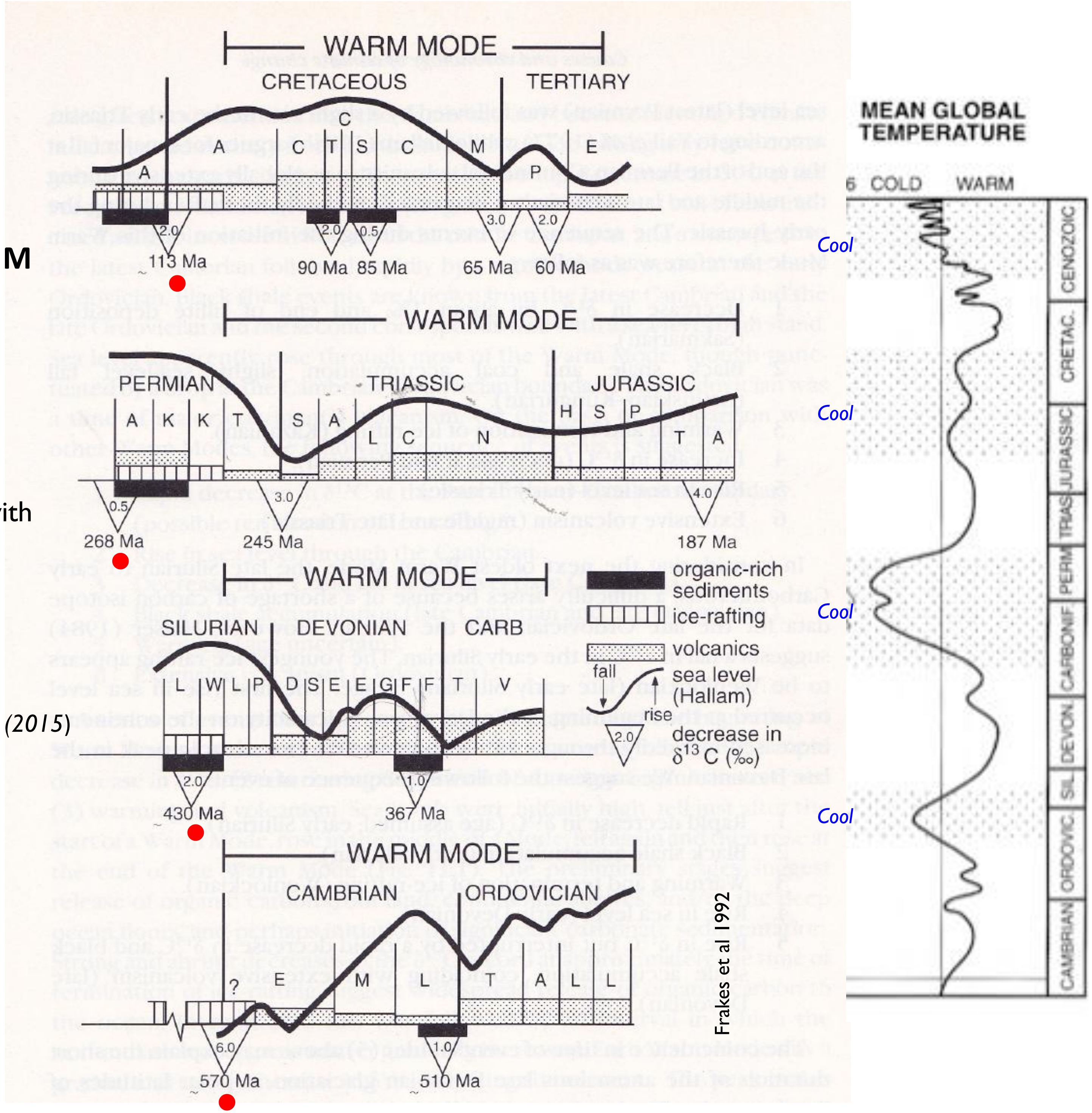
- sea level variations
- volcanism (increase of CO_2)
- ice-rafting (cessation)
- black shales (organic-rich) with decline in accumulation rate of C_{org}

….

….

⚠

Numerical Time (Ma) : not updated (2015)



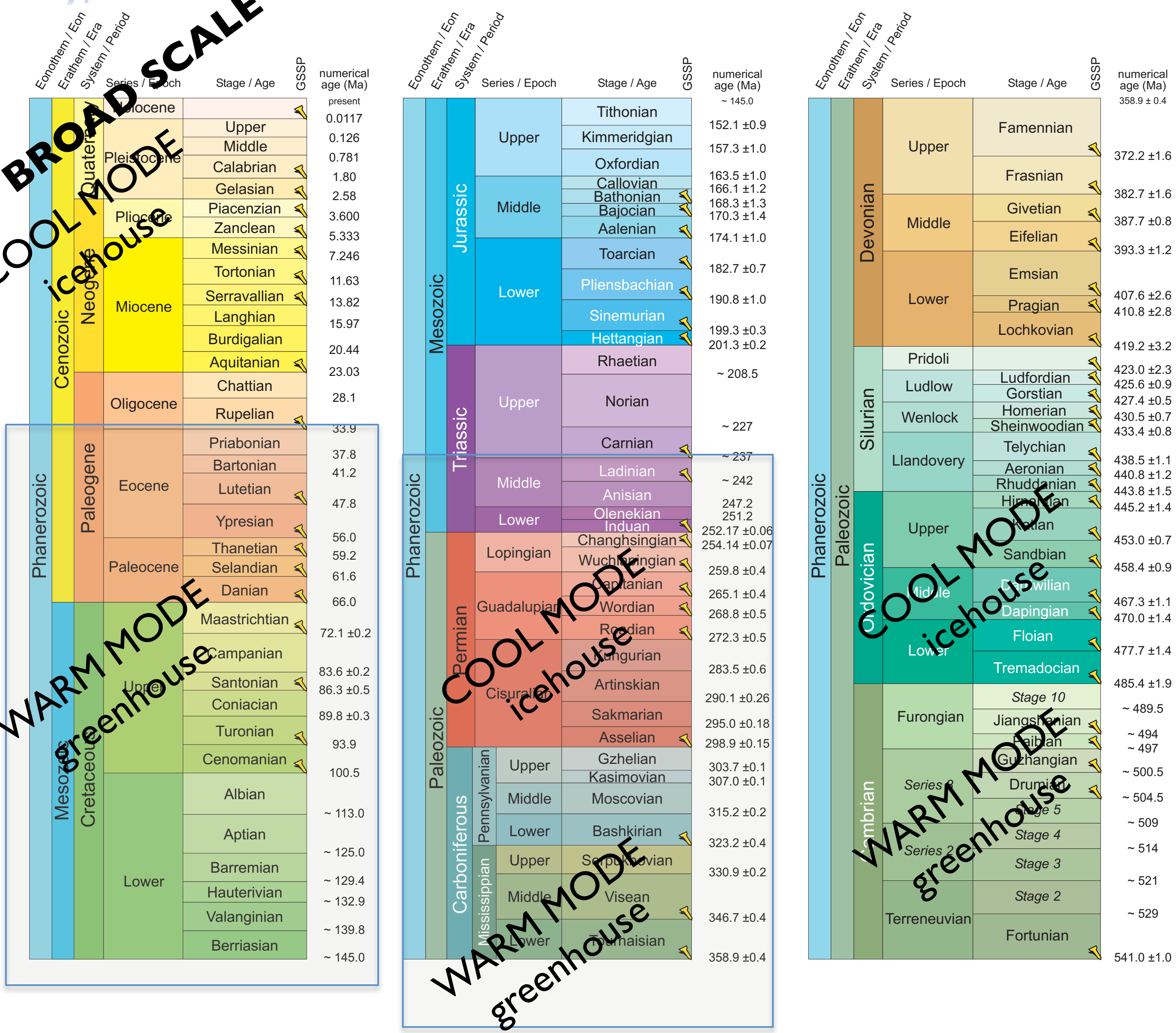
INTERNATIONAL CHRONOSTRATIGRAPHIC CHART

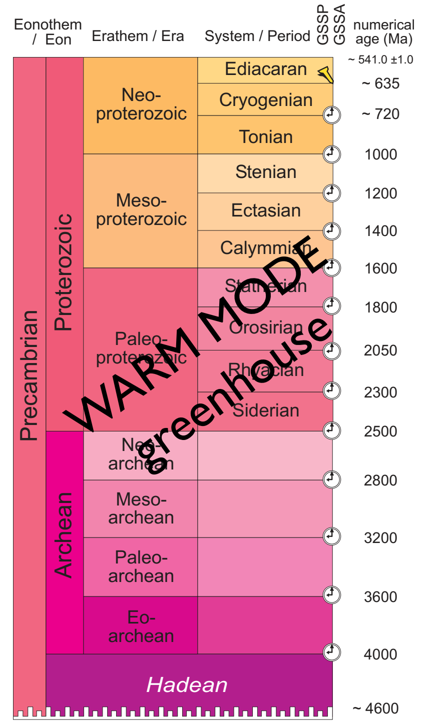
IUGS

www.stratigraphy.org

International Commission on Stratigraphy

v 2015/01





Units of all ranks are in the process of being defined by Global Boundary Stratotype Section and Points (GSSP) for their lower boundaries, including those of the Archean and Proterozoic, long defined by Global Standard Stratigraphic Ages (GSSA). Charts and detailed information on ratified GSSPs are available at the website http://www.stratigraphy.org. The URL to this chart is found below.

Numerical ages are subject to revision and do not define units in the Phanerozoic and the Ediacaran; only GSSPs do. For boundaries in the Phanerozoic without ratified GSSPs or without constrained numerical ages, an approximate numerical age (~) is provided.

Numerical ages for all systems except Lower Pleistocene, Permian, Triassic, Cretaceous and Precambrian are taken from 'A Geologic Time Scale 2012' by Gradstein et al. (2012); those for the Lower Pleistocene, Permian, Triassic and Cretaceous were provided by the relevant ICS subcommissions.

Coloring follows the Commission for the Geological Map of the World (http://www.ccgm.org)

CCGM CGMW

Chart drafted by K.M. Cohen, S.C. Finney, P.L. Gibbard

To cite: Cohen, K.M., Finney, S.C., Gibbard, P.L. & Fan, J.-X. (2013; updated) The ICS International Chronostratigraphic Chart. Episodes 36: 199-204.

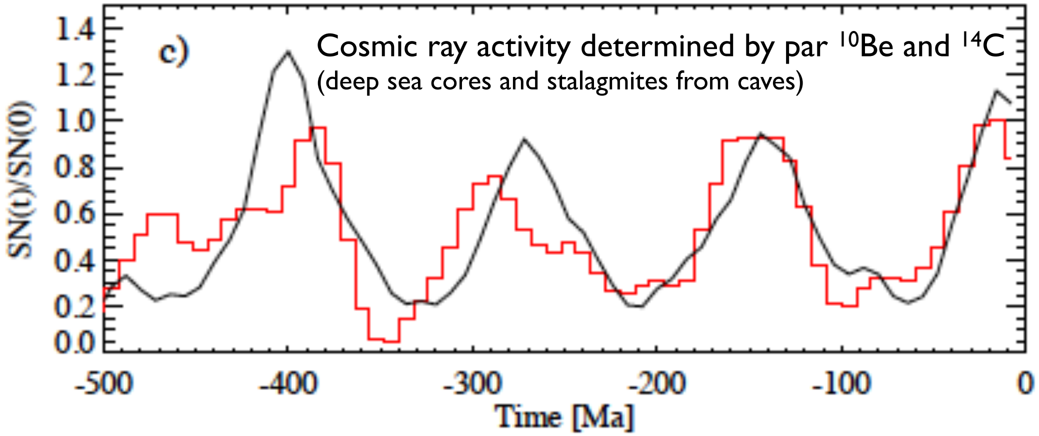
URL: http://www.stratigraphy.org/ICSchart/ChronostratChart2015-01.pdf

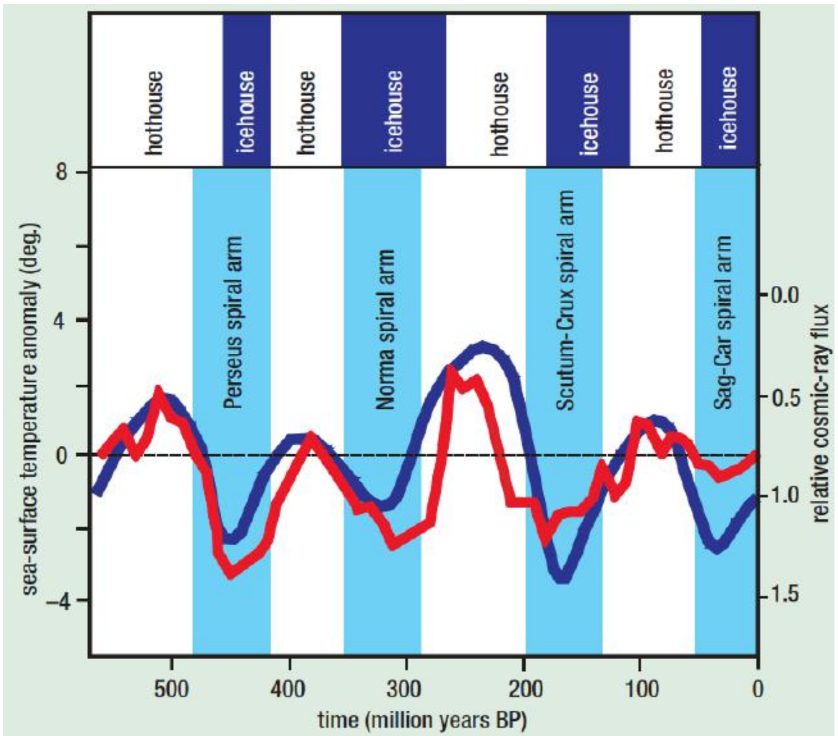
Climate change : the Rule in the Geological Record

Higher Galactic Cosmic Rays (during low solar activity)
=> cool mode (high albedo)

	Period	Myr BP	Cold intervals	Conditions	Referer
Cm	Cambrian	542	502 -492	Cold	1
O	Ordovician	488.3	455.0 -443.7	Glacial	2
			450 -445	Cold	1
			445 -442	Peak ice	3
S	Silurian	443.7	442 -415	Cold	1
D	Devonian	416	375 -361.4	Cold	1
			361.4 -360.6	Glacial	4
			360.6 -359.2	Cold	1
C	Carboniferous	359.2	375 -353	Cold	1
			353 -349	Glacial	4
			349 -345	Cold	1
			326.5 -325.5	Glacial	5
			322.5 -319.5	Glacial	5
			317.0 -315.0	Glacial	5
P	Permian	299	299 -294	Glacial	5
			294 -291	Peak ice	5
			287 -280	Glacial	5
			273 -268	Glacial	5
			267 -260	Glacial	5
			260 -251	Cold	4
Tr	Triassic	251			
J	Jurassic	199.6	184 -183	Cold	4
			167.7 -164.7	Cold	4
			162 -159	Cold	4
			150 -144	Cold	4
K	Cretaceous	145.5	140.5 -139.5	Cold	4
			137.5 -137	Cold	4
			137 -136	Peak ice	6
			125.0 -112.0	Cold	4
			97.5 -96.5	Cold	4
			91.3 -91.1	Glacial	7
			91.1 -89	Cold	4
			71.6 -69.6	Cold	4
			67.5 -66.5	Cold	4
Pg	Palaeogene	65.5	65.6 -65	Cold	4
			33 -23.03	Glacial	4
Ng	Neogene	23.03	23.03 -2.8	Glacial	4
			2.8 -0	Peak ice	8

Svensmark 2007





What Is about the Geological Record?

climate changes led many times to glaciations, extinctions, vegetation development/collapse....

- Before 1 Ga : Faint young Sun paradox;
- 2.4-2.5 Ga : Great Oxygenation Event => Huronian glaciation;
- 750-635 (…) Ma : Neoproterozoic glaciations .... with Snowball/Marinoan glaciation (Cryognenian, Ediacaran);
- 541 (...) Ma : Early Cambrian Radiation => metazoan generic diversity;
- 485.4 ± 1.9 Ma : Cambrian-Ordovician extinction event;
- 450-440 Ma : Ordovician-Silurian extinction, in two bursts, after cooling probably related to tectonic plate movements;
- 300 (...) Ma : Karoo Ice Age, cooler climate causes Carboniferous Rainforest Collapse;

....

- 252.17 ± 0.07 Ma : PERMIAN-TRIASSIC EXTINCTION EVENT;
- 199.6 Ma : Triassic-Jurassic (201.3 Ma) extinction;
- 66.0 Ma : K/T BOUNDARY => asteroid, volcanism ...;
- 55.8 Ma : PETM = Paleocene-Eocene Thermal Maximum (hyperthermal event);
- ...

- 5.3-2.2 Ma : Pliocene, climate cooler and drier, and seasonal, similar to modern climates
- 2.5 Ma to present : Quaternary glaciation with permanent ice on the poles ….

- If one thing has been constant about Earth's climate over geological time, it is its constant change. In the geological record, we can see this in the evidence of glaciations in the distant past and we can also detect periods of extreme warmth by looking for example at the isotope composition of sea-floor sediments or floral associations or…;

- Not only has the climate changed frequently, but the temperature fluctuations have been very significant : at least 15°C during the Devonian;

- During Snowball Earth times, the global mean was as cold as -50°C, while at various times during the Paleozoic and Mesozoic and during the Paleocene-Eocene thermal maximum, it was close to +30°C.

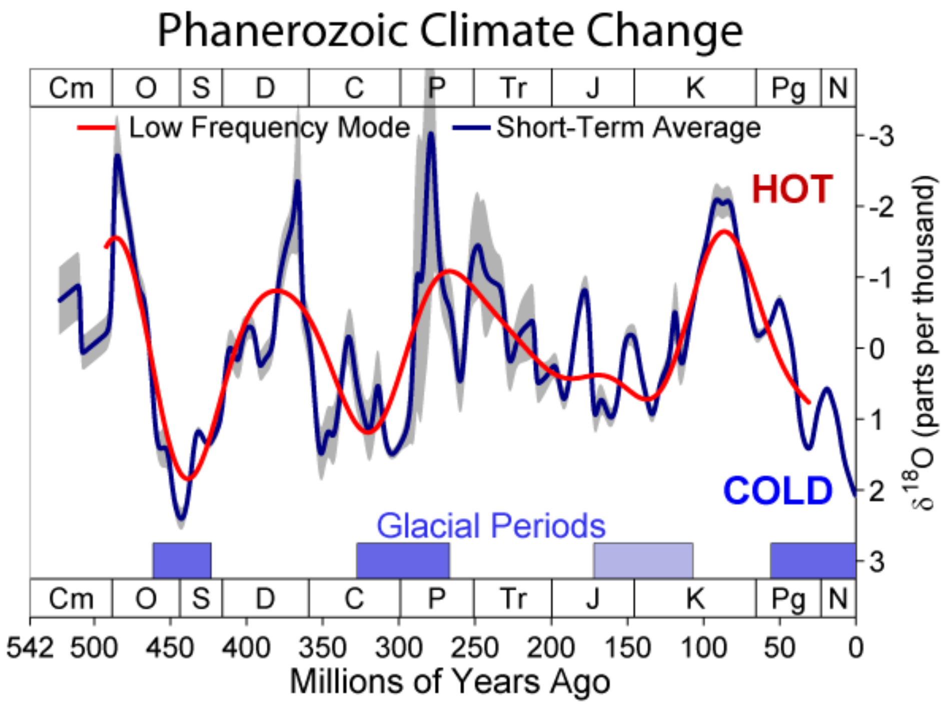
❑ **What Causes Climate Change?**

The causes of climate change are complex.
There are several major factors that can effect the climate system, including:

❑ Changes in solar output
❑ Changes in Earth's orbit
❑ Changes in the distribution of continents
❑ Changes in atmospheric content of greenhouse gases.

It is important to consider **scale** when interpreting climate change through time. Four major time scales are generally considered, which include:

- *Long term*- Hundreds of millions of years;
- *Medium term*- One to tens million years;
- *Short term*- ~160,000 years;
- *Modern period*- Hundreds of years.



http://www.globalwarmingart.com/wiki/File:Phanerozoic_Climate_Change_Rev_png

8/9th....The Precambrian : GHG very (very) high

Hadean 4.6-4.0 Ga

⇒ **1-10ppmv CH_4, x?5-x10** (abiotic, meteorite impact, serpentinization of ultramafic rocks);

Archean 4-2.5 Ga (low O_2 or even no O_2 during Hadean and early Archean[aa])

=> **CO_2?x100 à x?1000[a]**,

= = > ?degassing of the lithosphere through volcanic activity;

= = > ? Archean continents being smaller, carbon terrestrial sequestration was weak, as the alteration;

= = > ?also **methane** with **?1000ppmv ou >** de 3,8 à ~2,3 Ga related to the serpentinization and methanogens using CO_2, H_2 atm or acetates produced by OM fermentation (cf photosynthesis)[a];

= = > ?albedo (reflectivity) : very weak[d];

= = > **?C_2H_6 (ethane)**, strong IR absorber => T°>10°C[e];

= = > very low O_2 = > residence time of CH_4 ~10,000 years (and not 10 years)[e].

2.3-2.5 Ga (GOE => **O_2 x100, de 10^{-3} à 10^{-5}PAL => eucaryotes...**)

= > **O_2 ?x23**[b] between 2.5-1.8 Ga;

= = > Archean/Paleoproterozoic: O_2 increase and **collapse of CH_4**;

= = > Archean/ PPz glaciation at 2.4 Ga (tillites or glacial diamictites).

PPz-NPz (until 541Ma)

= > **CH_4 10-100ppmv** (=x60 Recent) due to recycling increase of OM through fermentation and methanogenesis[c],

[aa]Farquhar et al 2000 [a]Kasting 2005 [b]Sheldon 2006 [c]Pavlov et al 2003d [d]Rosing et al 2010 [e]Kasting 2008

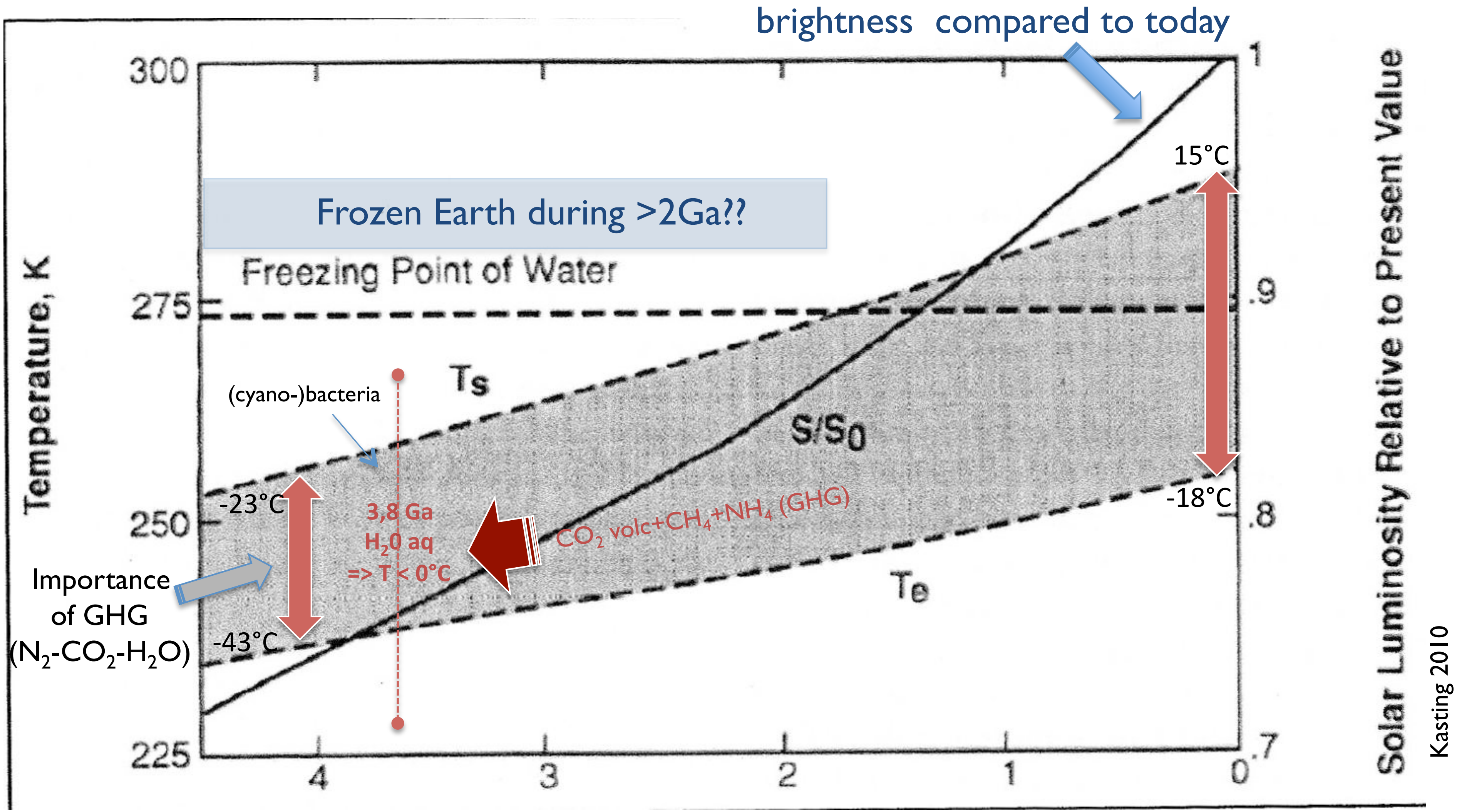
The Precambrian times

Faint young Sun paradox

- Apparent contradiction between **observations** of liquid water early in Earth's history and the astrophysical expectation that the Sun's output would be only 70% as intense during that epoch as it is during the modern epoch;
- Earth's mean surface temperature (currently 15°C) should therefore have been below the freezing point of seawater prior to about 2.0 Ga had its atmosphere remained unchanged in composition;
- Explanations of this paradox have taken into account greenhouse effects, astrophysical influences, or a combination of the two.

Faint Young Sun 'problem' or 'paradox'

Carl Sagan & George Mullen 1972



Other GHG are required for a living Earth = CH_4[a] et N_2O[b]

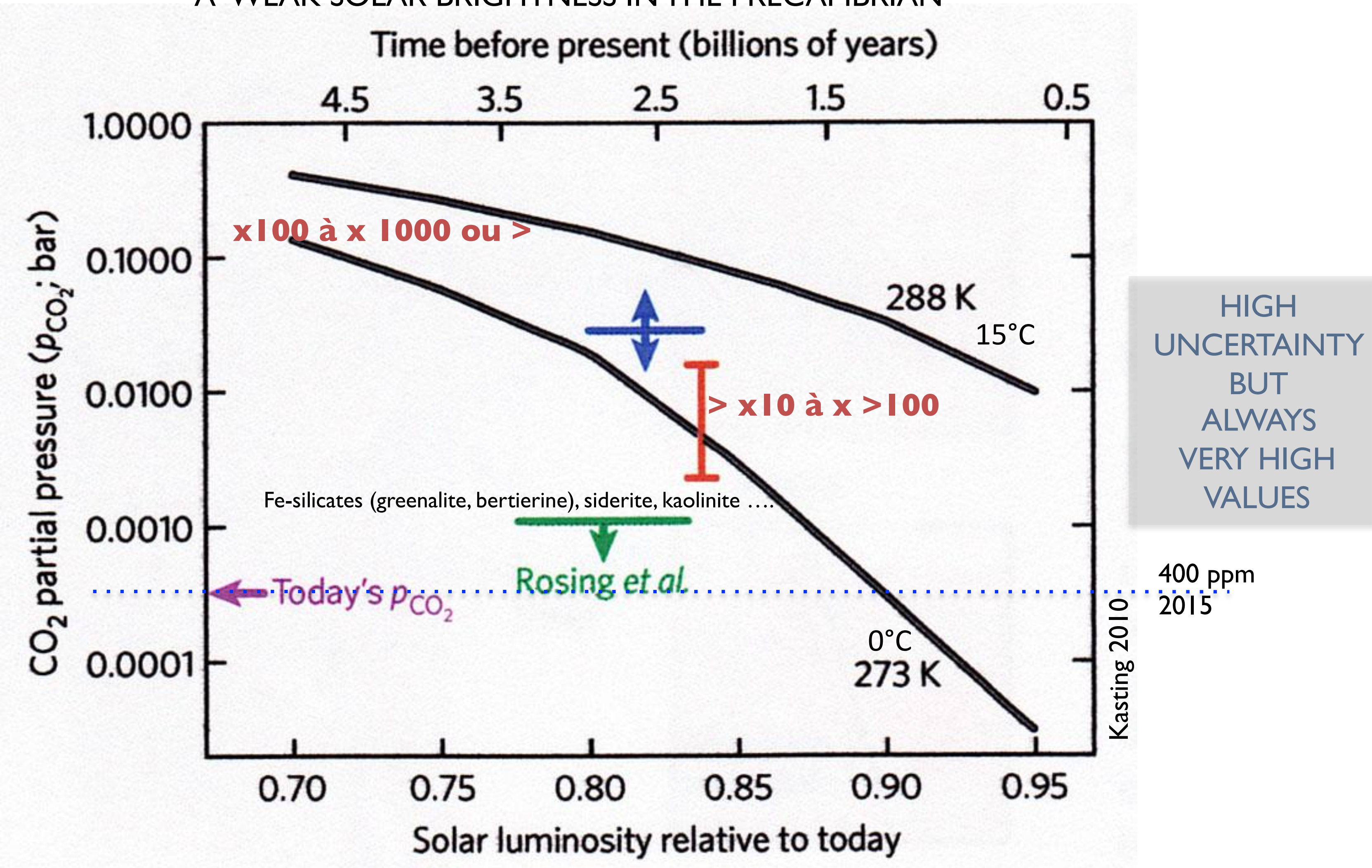
=> **CH_4 100 ppmv with flow = 10-20 times the current flow**

=> **N_2O (biological?) = flux 20 times the Recent one**

The greenhouse effect INCREASES (grey zone) because the atmosphere contained more H_2O(vap) with the T increase.

Faint Young Sun 'problem' or 'paradox'

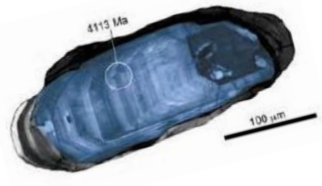
ATMOSPHERIC CO_2 CONCENTRATION TO BALANCE
A WEAK SOLAR BRIGHTNESS IN THE PRECAMBRIAN

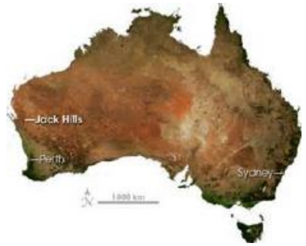


Paleosols and BIFs (Rye et al 1995) with error bar from other paleosols (Sheldon 2006)
Paleosols (Rosing et al 2010) with lower albedo? (few clouds, oc omnipresent, oc surface <> continents)
273 K freezing point
288 K to compare with modern value (with similar CO_2-H_2O and albedo)

Precambrian Greenhouse

Warmer climates than today

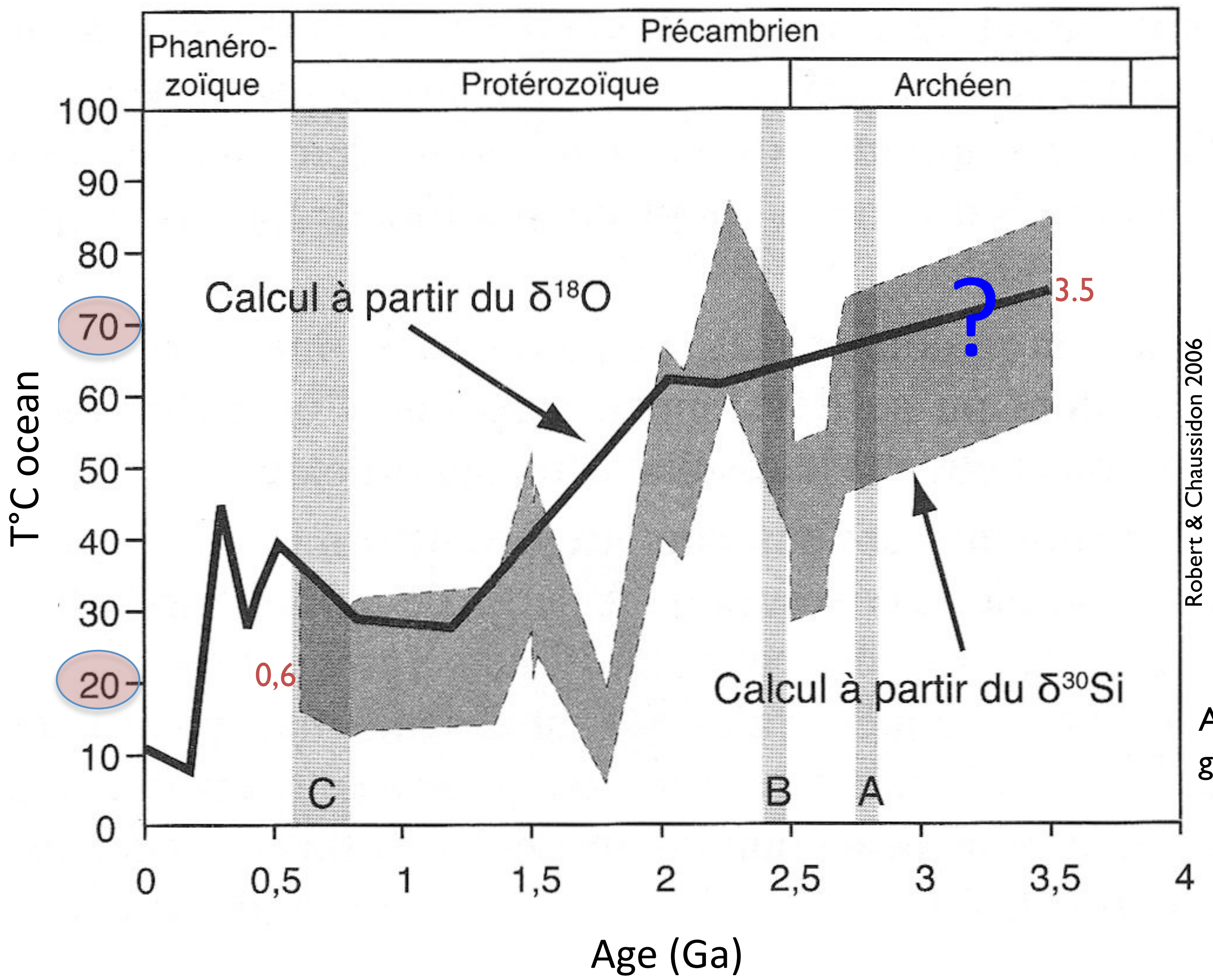




- The earliest evidence of water comes from zircons in 3.0 Ga conglomerates. These rocks contain relict zircon minerals ($ZrSiO_4$) dating back as far as 4.3 Ga implying liquid water ~<u>160 Ma after Earth formation</u>;
- By 3.8 Ga, photosynthesis left its signature in the isotopic composition of sedimentary organic carbon, again pointing to the presence of liquid water;

- The Precambrian contains abundant <u>low latitude marine carbonates</u>, it seems that ice sheets were absent during most of the time <u>except during spectacular events</u>;
- The oldest known glacial deposits date to about 2.9 Ga (Pongola SG, South Africa). Four different 'snowball' episodes are dated to 2.4 Ga, 1.9 Ga, 0.7 Ga and 0.63 Ga at low latitudes (magnetic data of associated sedimentary and volcanic rocks).

VARIATIONS OF PRECAMBRIAN SEAWATER TEMPERATURE
(from cherts, very discontinuous sampling due to the considered time lengths)



A,B,C
glaciations ....

Precambrian Greenhouse

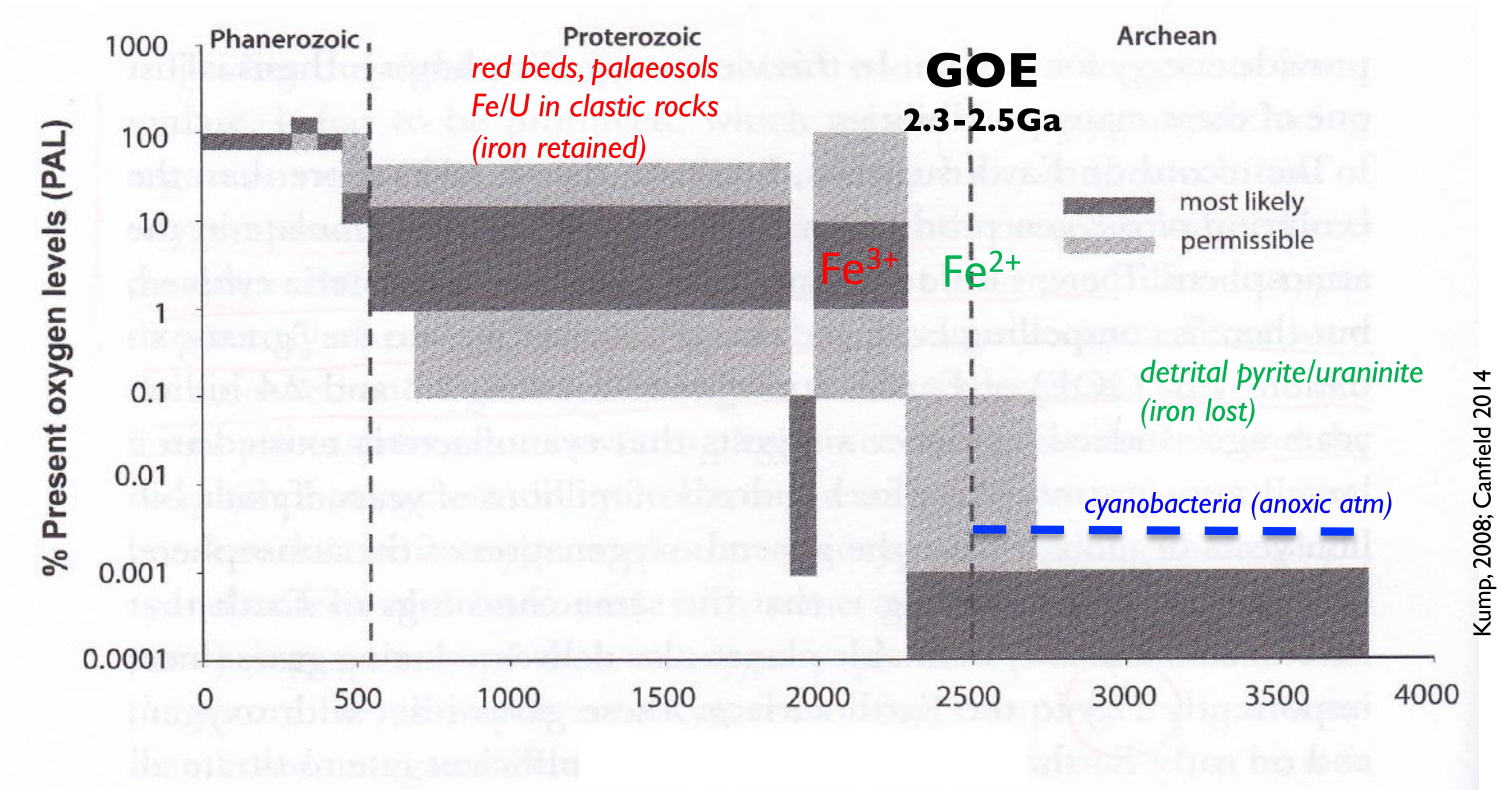
*What about the **oxygen**? Prior to 2.2 Ga, the amount of oxygen in the atmosphere and surface ocean was small*

- Iron formations (BIF) provide geological evidence for O_2 scarcity in the early Archean atmosphere and oceans until about 1.8 Ga;
- Pyrite (FeS_2), Siderite ($FeCO_3$), Uraninite (UO_2) are oxygen-sensitive minerals which faded at 2.2-1.8 Ga while red beds (oxygen-requiring rock type) rose to prominence;
- Oxygen was not higher than 1% of present-day levels, and might have been much lower;

- « Canfield Ocean » : dissolved Fe was removed from the oceans NOT by reaction of O2 (…) BUT rather by reaction with sulfide => the deep oceans remained anoxic;
- Anoxygenic photosynthesis predated oxygenic photosynthesis; Sulfide-oxidizing anoxygenic phototrophs produced sulfate, used by sulfate-reducing bacteria which oxidized the OM produced by the phototrophs
- ….The processes include methanogenesis, sulfate reduction and decomposition of dead organic biomass, aided by different fermenting bacteria.

ATMOSPHERIC OXYGEN THROUGH TIME

Mainly driven by tectonics, not only by cyanobacteria

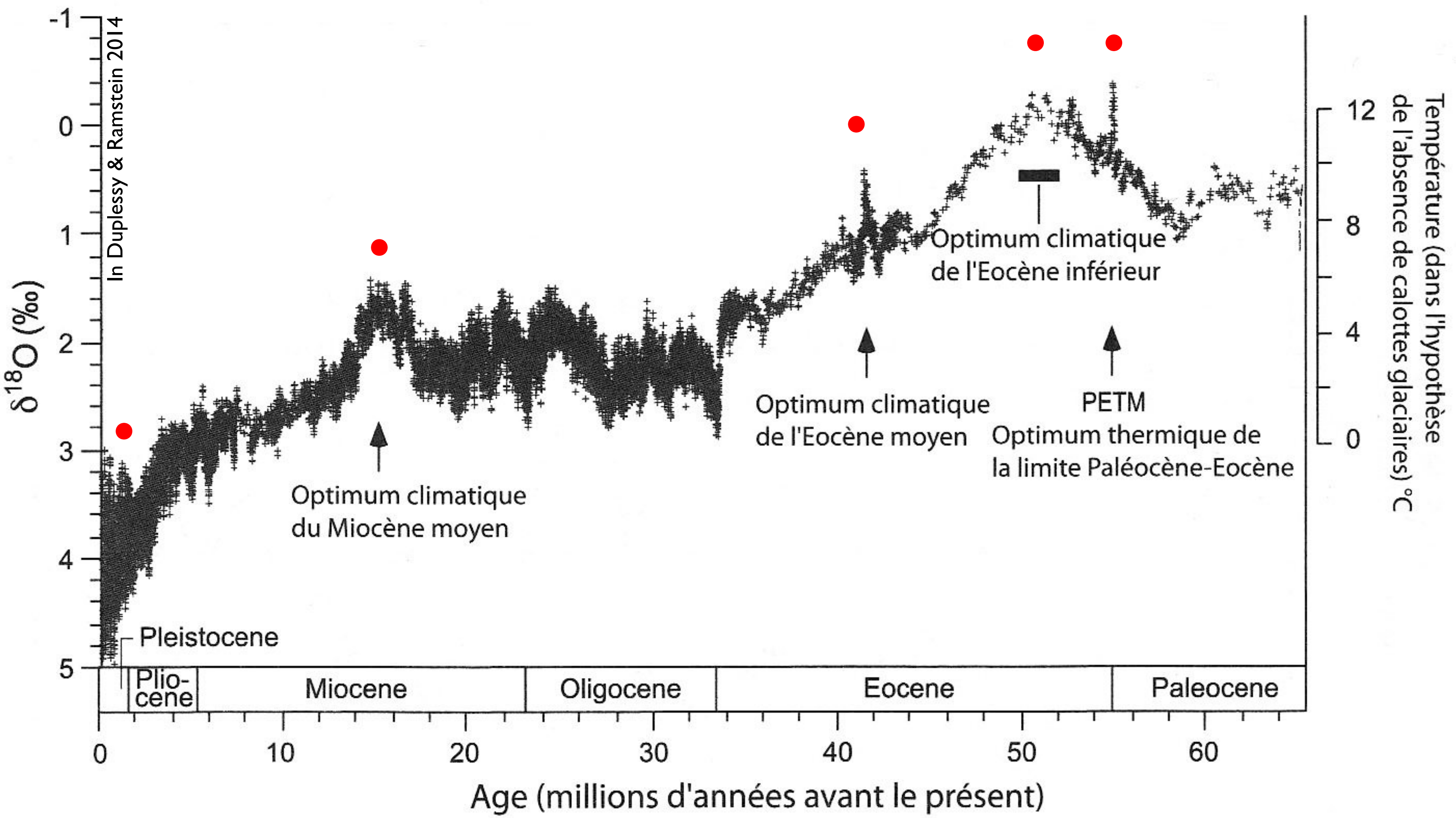


- It takes more than the evolution of O_2 production before O_2 accumulated in the atmosphere;
- Cyanobacteria existed in a largely anoxic atmosphere for 100'Ma (or Ga) before general oxydation of the atmosphere. Reducing gases (H_2…) from the mantle reacted with O_2 liberated from the burial of organic carbon and pyrite into sediment;
  => as Earth cooled, the tectonic churning slowed and reducing gases decreased;
- GOE (2.5-2.3 Ga) marks this time and oxygen accumulated;
  new nutrients (P …) were also available accelerating organic matter production ….

Long Cooling of the Cenozoic (starting ~55 Ma => ice ages) with

Cenozoic Extreme Climate (Hyperthermal) States

low pole-to-equator thermal gradient; ice-free polar region, elevated CO_2 (up to 1800 ppm)



Long Cooling of the Cenozoic (starting ~ 55 Ma => ice ages) with

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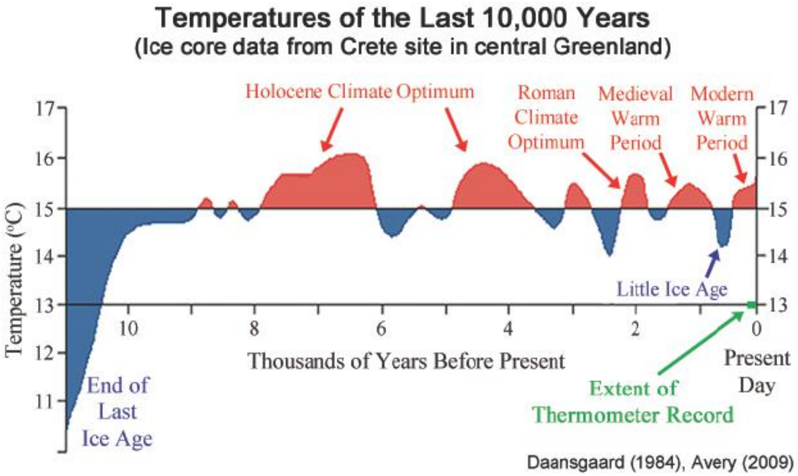
- PETM (Paleocene-Eocene Thermal Event): 55.8 Ma
  = global warmth lasted ~200,000 yr with a T increase up to 8°C)

- E-O (Eocene/Oligocene transition ~33.5-33.7 Ma)
- Mid-Miocene : 18-14 Ma ('Mid Miocene Climatic Optimum')
- Early-Middle Pliocene : 4.5-3.0 Ma

T increases up to 5°C

- … Pleistocene
- … Holocene



- Historical period
- (climatic optima)

T increases up to ?1°C

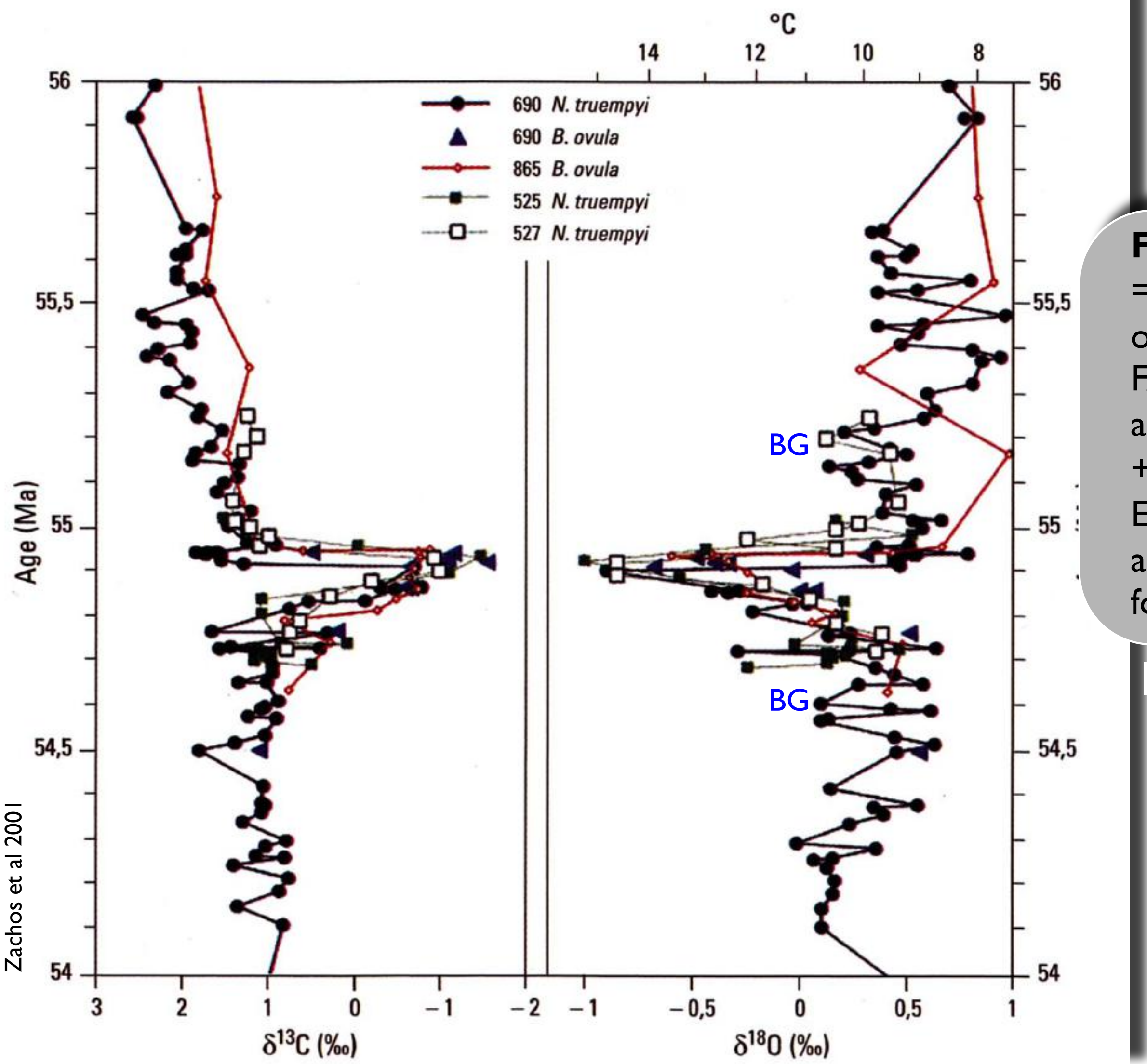
Paleocene-Eocene Thermal Maximum

The 'greenhouse' response is well documented,
the origin(s) of the greenhouse releases not

- PETM event (~200,000yr) started with a massive amount of CO_2 rapidly released (2000-6000GtC, ~< 20,000yr) to the oceans and atmosphere (or a CH_4 release rapidly oxidized to CO_2);
- Global temperature rose by about ~5°C in the tropics and ~8°C at high latitudes, ocean became acidified;
- On land warming led to changes in the distribution of precipitation, an increase in weathering areas and changes in flora and fauna;

- PETM response involved neutralization of CO_2 by $CaCO_3$ sediments, changes in the hydrological cycle and responses of land and ocean ecosystems to climate change.

PETM benthic shells with LIGHT $\delta^{13}C$ and $\delta^{18}O$ during ±10 000yrs



Zachos et al 2001

PETM

Fast degassing (^{12}C)
= clathrates ($\delta^{13}C$ = -60‰)
or OM-rich source rock
FAST i.e.
a few 1000'yr and NOT myr!
+
Extinction of benthos starting at 54.98 Ma
and crisis (biodiversity of 30-50%) among
foraminifers due to the acidification ... + ...

= WARMING
of 5 to 7°C in the deep ocean of high latitudes, SL +6m in <20,000yr

pH 7.6 and $C0_{2\ atm}$ 1800ppm (simulation)

CO_2 changes during the PHANEROZOIC

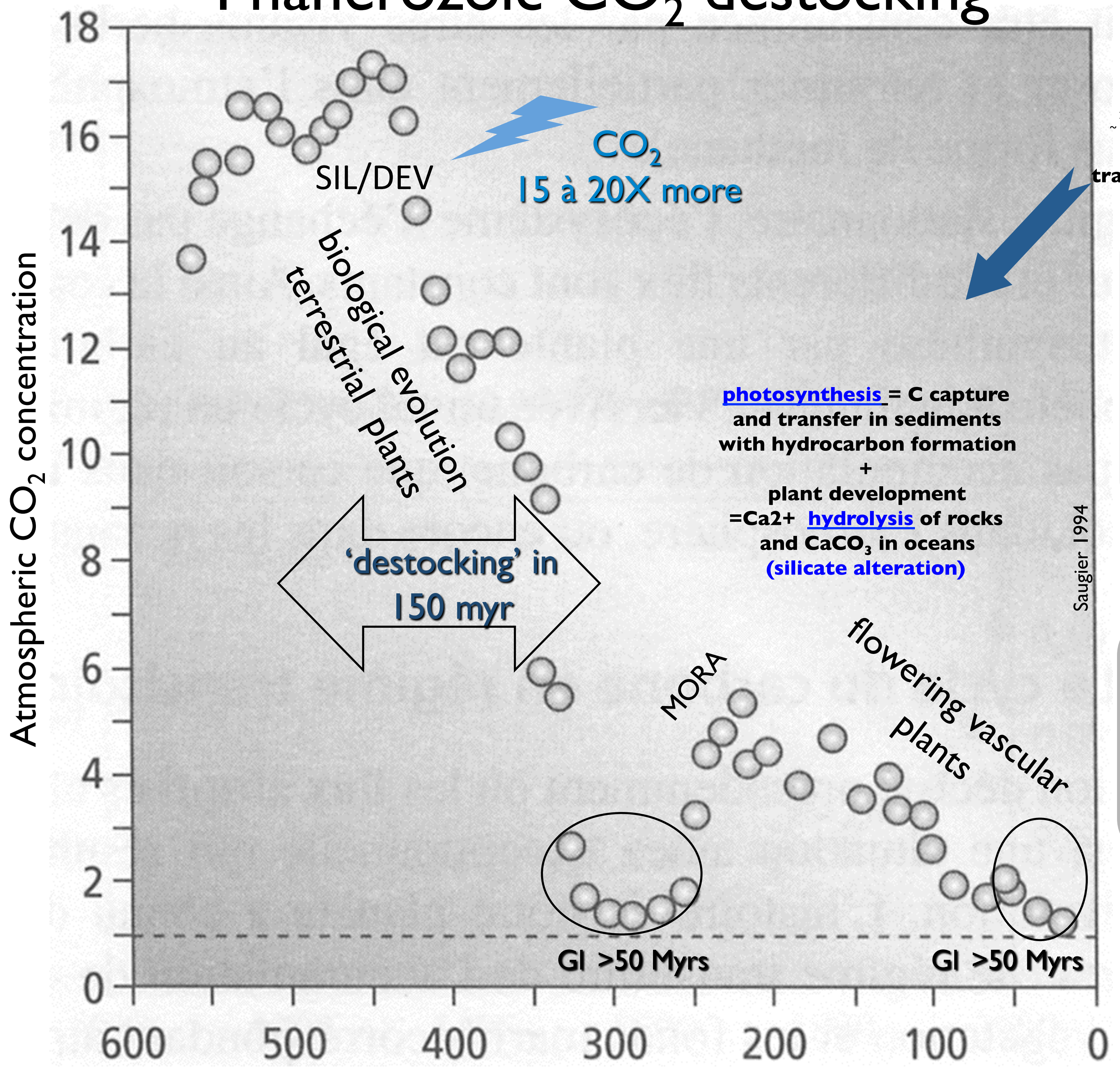
- Since land plants evolved about 400 myr ago (Silurian), CO_2 concentrations varied by perhaps a factor of 10, from (?3000)-1500 ppm (Silurian) to180 ppm (recent ice ages);

- Both past CO_2 concentrations and the climate sensivity to a doubling of CO_2 are poorly known;

- Glacial/Interglacial CO_2 changes **were modest** in magnitude, from 180 to 330 ppm.

What processes might lead to larger CO_2 changes?

Phanerozoic CO_2 destocking



= 'plant factory' extracting

~≈?60GtC/yr from atmosphere

(photosynthesis+respiration)

transformation mineral => organic

=

natural

elimination

of C

from the atm

until

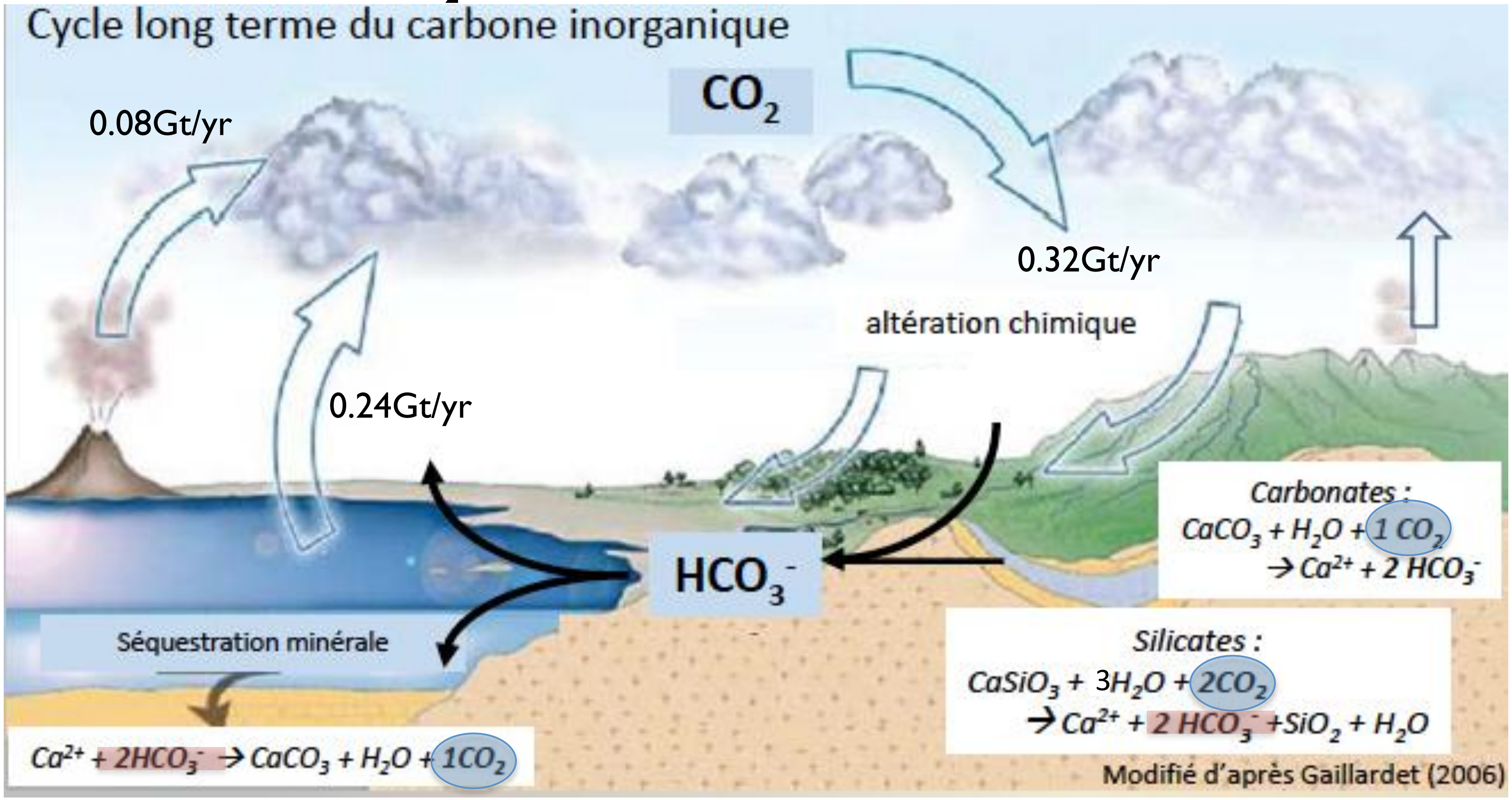
equilibrium

= pre-industrial

period

ALTERATION (HYDROLYSIS) OF SILICATES IS A CO_2 PUMP

Source and sink of CO_2



Alteration of carbonates: $1CO_2$ removed=> $1CO_2$ released=> **0 CO_2 sequestered**

Alteration of Ca and Mg silicates : $2CO_2$ removed => $1CO_2$ released **=> 1 CO_2 sequestered**

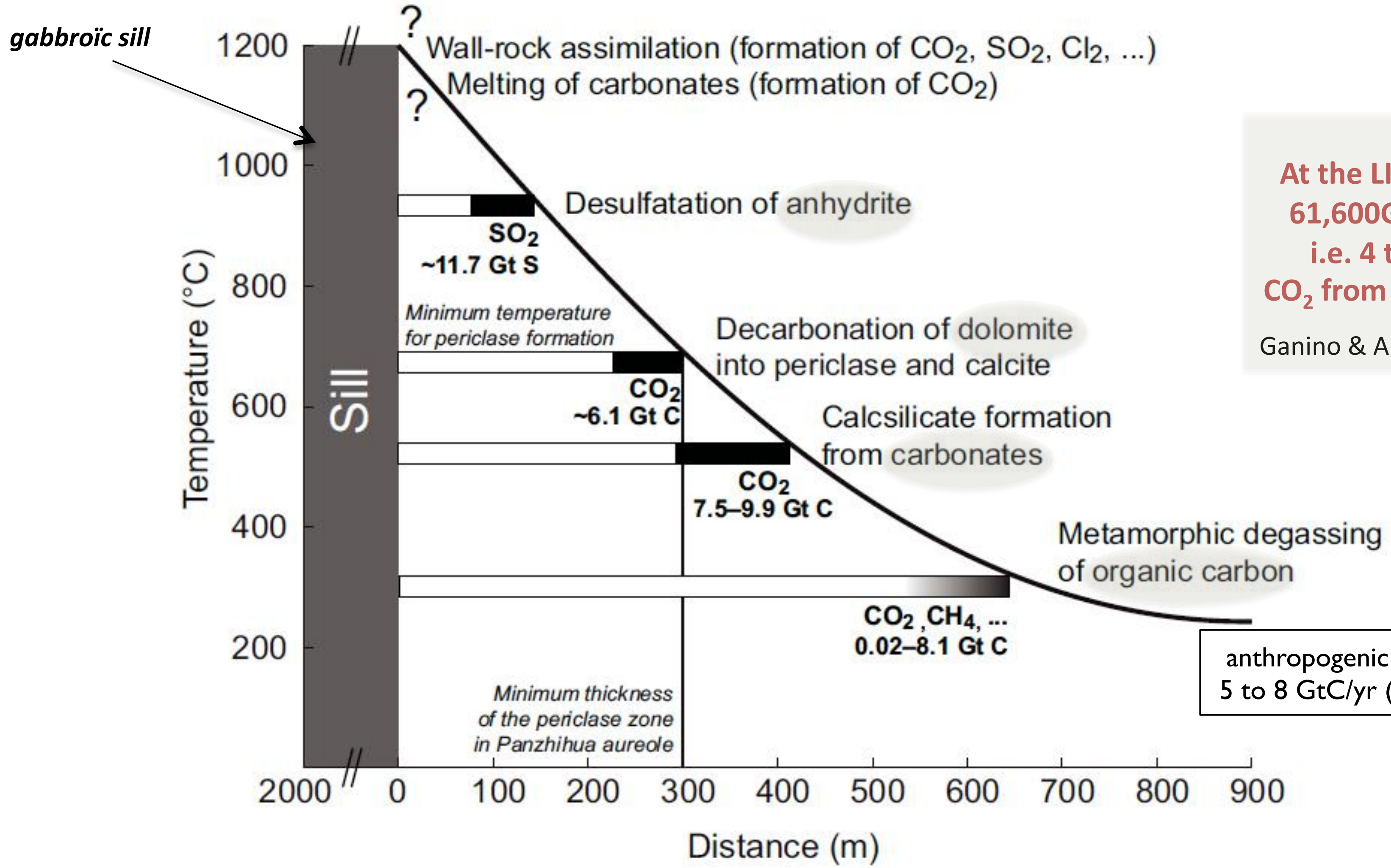
$MgSiO_3 + 2CO_2 + H_2O \Rightarrow Mg^{2+} + SiO_2 + 2HCO_3^-$

$2KAlSi_3O_8 + 2CO_2 + 3H_2O \Rightarrow K^+ + 2HCO_3^- + 4SiO_2 + Al_2Si_2O_5(OH)_4$

CO_2 consumption through the Himalaya Alteration = 34x the total CO_2 content of our current atmosphere

LIP or LARGE IGNEOUS PROVINCE : CONTACT METAMORPHISM

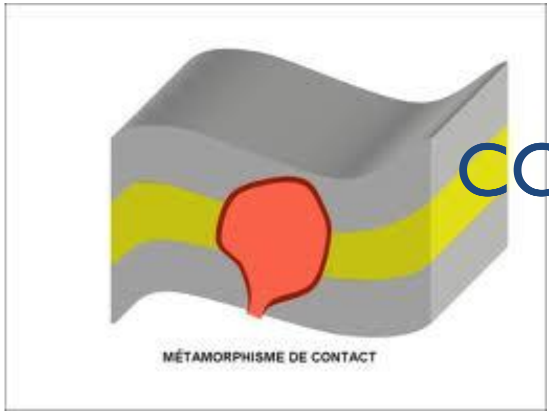
- GHG (CO_2,CH_4, SO_2…) degassing in carbonates (**decarbonatation**), coal, evaporites, organic shales
- Permian Siberian traps (here below) intruded in the Silurian series of China



At the LIP scale
61,600Gt CO_2
i.e. 4 to 9x
CO_2 from magma

Ganino & Arndt 2009

anthropogenic contribution
5 to 8 GtC/yr (atm 750GtC)

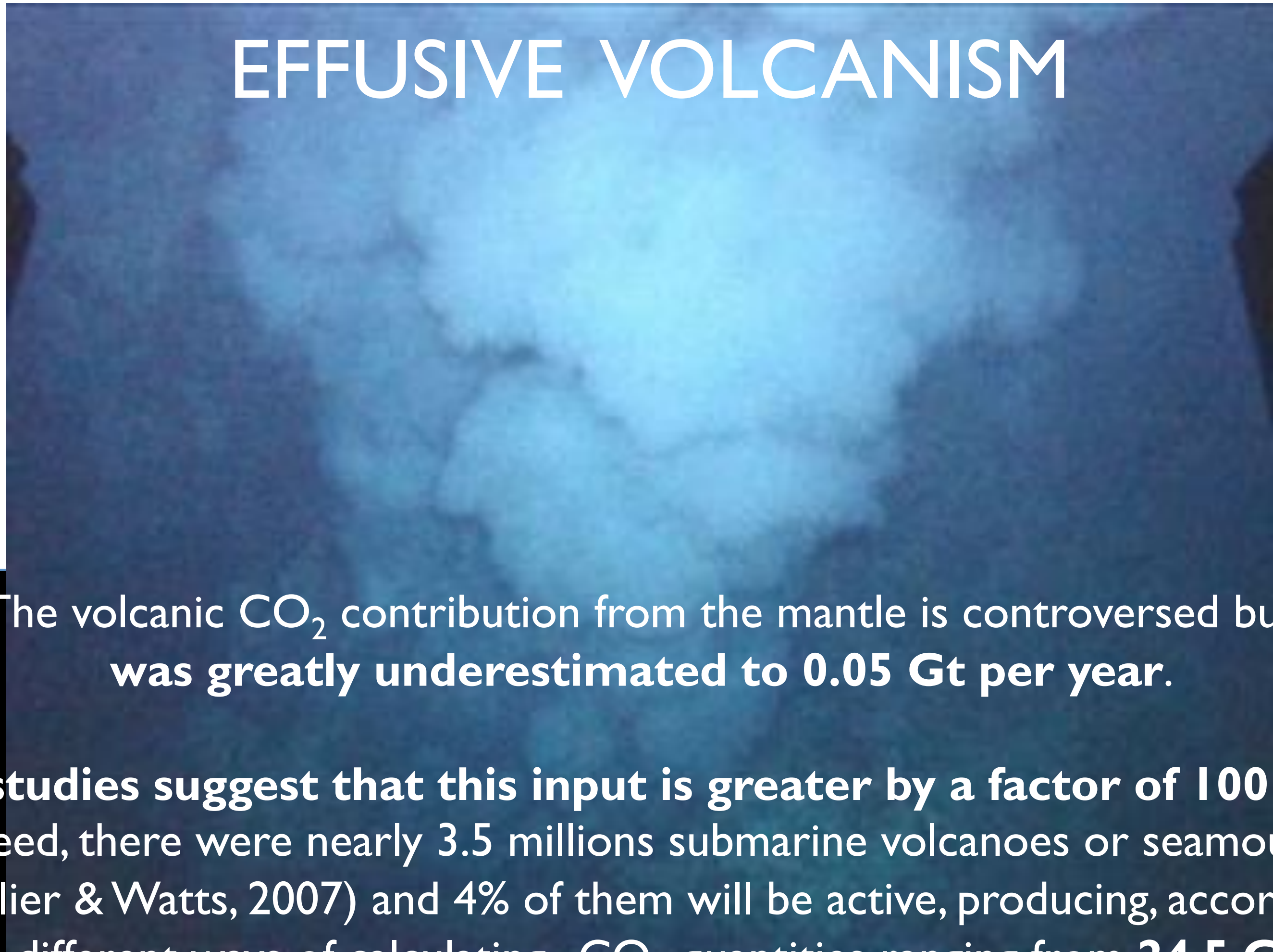


CONTACT METAMORPHISM

- Svensen and Jamveit (2010-2015) : large volumes of greenhouse gases, such as CH_4 and CO_2 are formed by contact metamorphism (400 à 500°C) of organic-rich sediments (and in volcanic basins) in aureoles around sill intrusions;
- **Only 1%** (wt%) of organic carbon in the shales and sandstones **in one** of these basins generated 230 to 920 GtC (or 310 à 1200 Gt of methane) **on the scale of a few years**;

- Studies in the Karoo Basin (S. Africa) ~600-3500 Gt CH_4, in the Voring and More basins (offshore Norway) ~2700-16,200Gt CH_4 … demonstrates that thousands of Gt of potent greenhouse gases can be generated on a time **of 10-1000 years** within an aureole of a **single** sill.

- **Contact metamorphism can trigger global climate change**



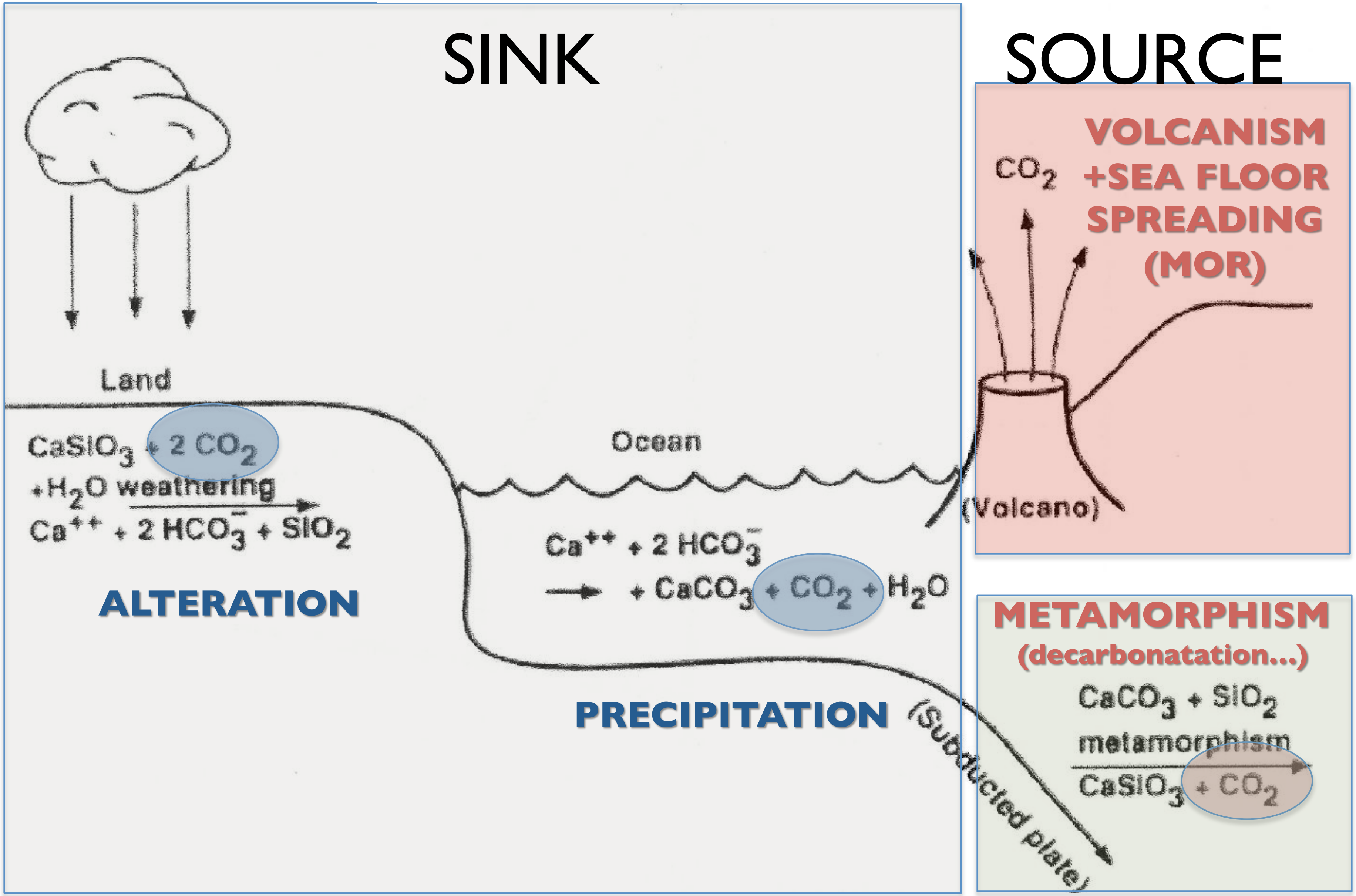
EFFUSIVE VOLCANISM

The volcanic CO_2 contribution from the mantle is controversed but **was greatly underestimated to 0.05 Gt per year**.

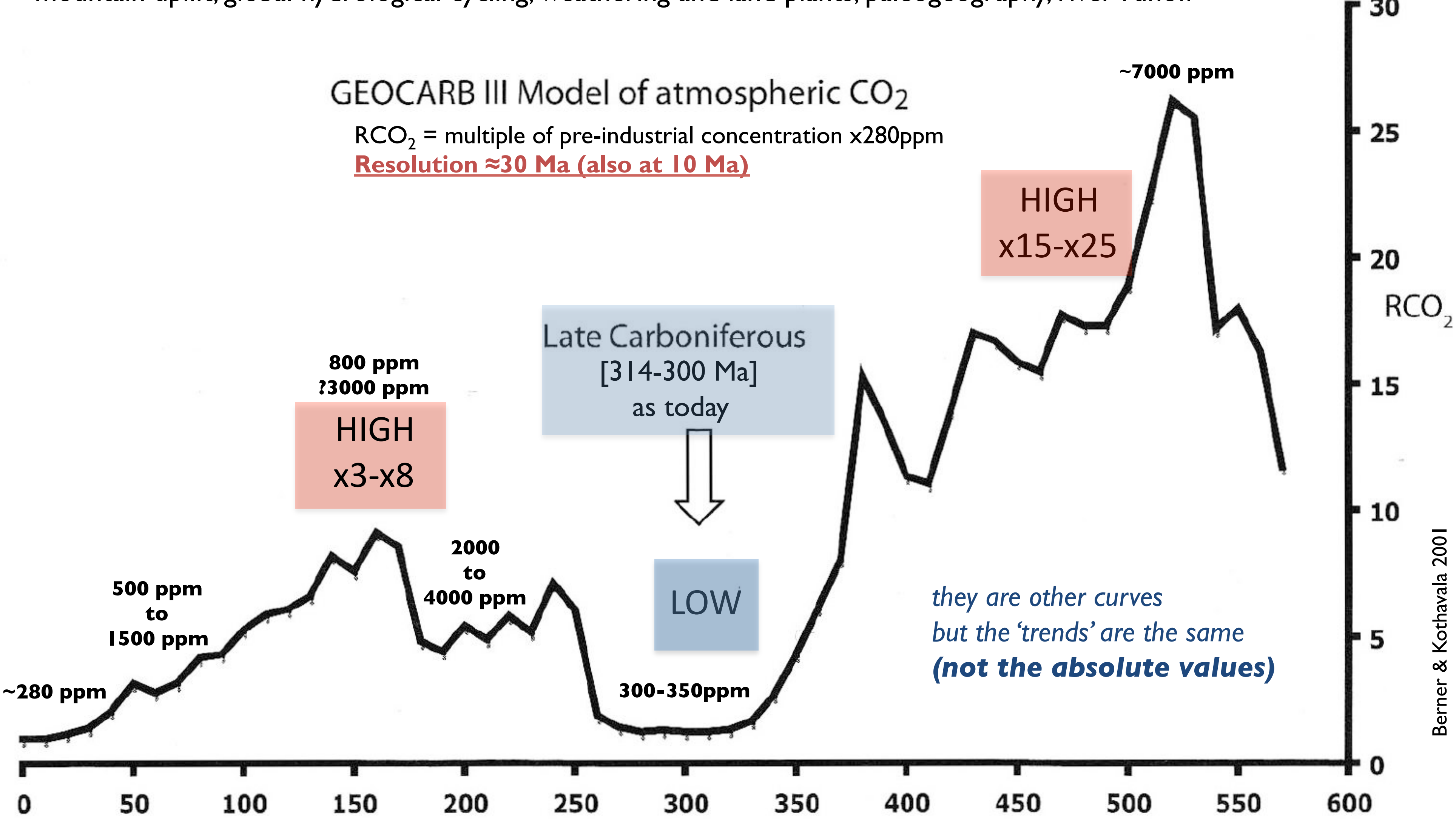
Recent studies suggest that this input is greater by a factor of 100 or more. Indeed, there were nearly 3.5 millions submarine volcanoes or seamounts (Hillier & Watts, 2007) and 4% of them will be active, producing, according to the different ways of calculating , CO_2 quantities ranging from **24.5 GtC/yr** (Kerrick & Caldeira 1998, Kerrick 2001) to **121 GtC/yr** (Casey 2010). These figures are to be compared with the recognized anthropogenic contribution **(5 to 8 GtC/yr)**.

Statistical studies of submarine volcanic provinces are needed to establish comprehensive isotopic balances.

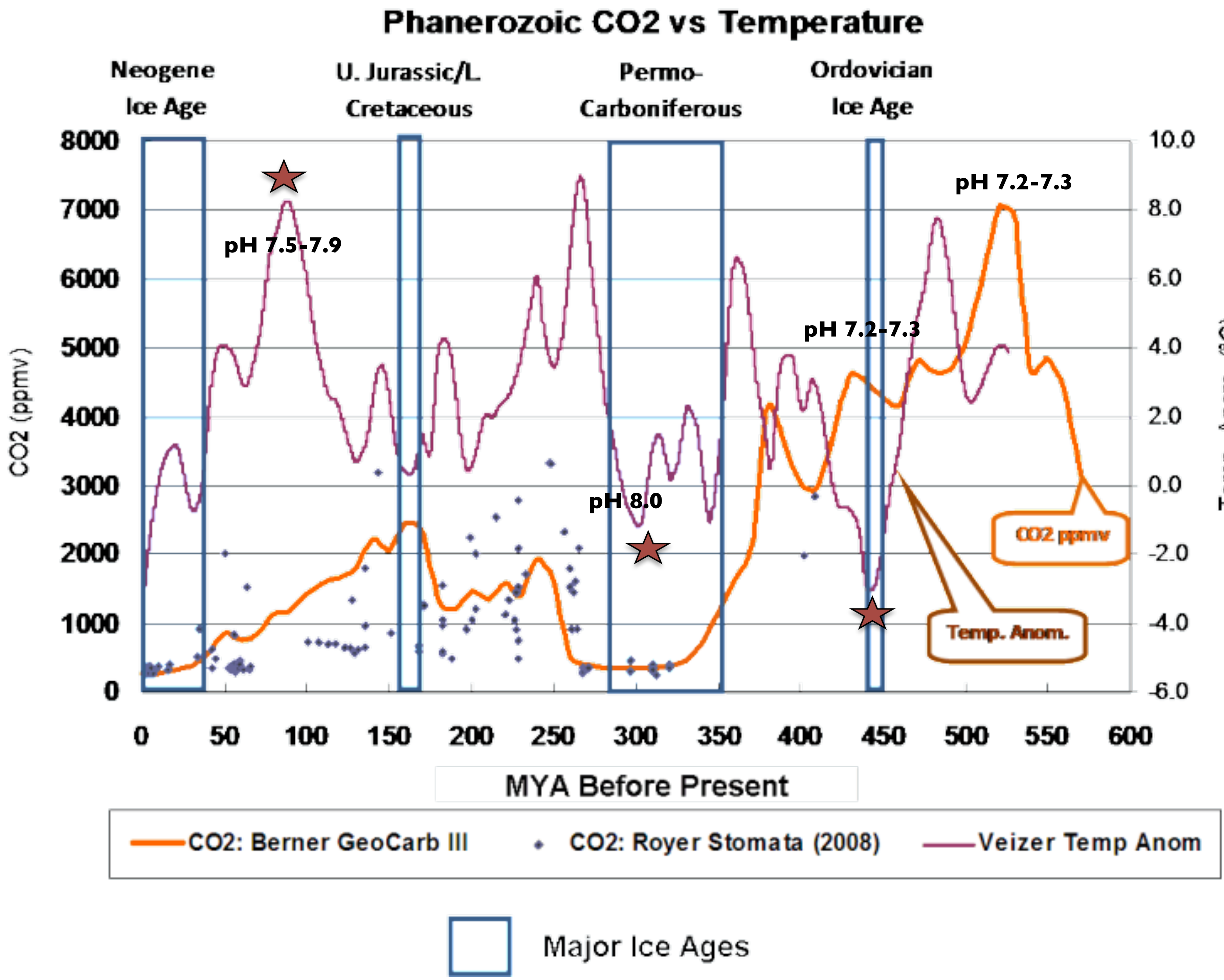
THE CARBONATE – SILICATE CYCLE *s.l.*



GEOCARB model incorporates >11 biogeochemical equations for weathering rates (continental silicate rocks), CO_2 flux from volcanic, metamorphic, and carbonate diagenetic processes, C burial and uptake in carbonates, mountain uplift, global hydrological cycling, weathering and land plants, paleogeography, river runoff



ppm from proxies. Error bars from CO_2 estimates remain large and the resolution of many data sets precludes assessment of shorter-term variability.



Phanerozoic CO2 vs Temperature
Neogene Ice Age
U. Jurassic/L. Cretaceous
Permo-Carboniferous
Ordovician Ice Age
CO2 (ppmv)
Temp. Anom. (°C)
pH 7.5-7.9
pH 8.0
pH 7.2-7.3
pH 7.2-7.3
CO2 ppmv
Temp. Anom.
MYA Before Present
CO2: Berner GeoCarb III
CO2: Royer Stomata (2008)
Veizer Temp Anom
Major Ice Ages

Comments on the PHANEROZOIC T/CO_2 curves

- Permian CO_2 concentrations dropped below 210 ppm with great plant and animal species diversification. The change of atmospheric T was around 8°C.
  By comparison the **current** global T **change** is 0.5-0.7°C while CO_2 concentration is 400 ppm. *If the global T depends of CO_2, the change of T at present would be around 8°C or higher, as it was during the Permian;*

- From Late Jurassic to Late Cretaceous, temperature **increased** (+2°C up to +8°C from current T) while CO_2 atm concentrations **decreased** from ~2300 ppm to ~1000 ppm;

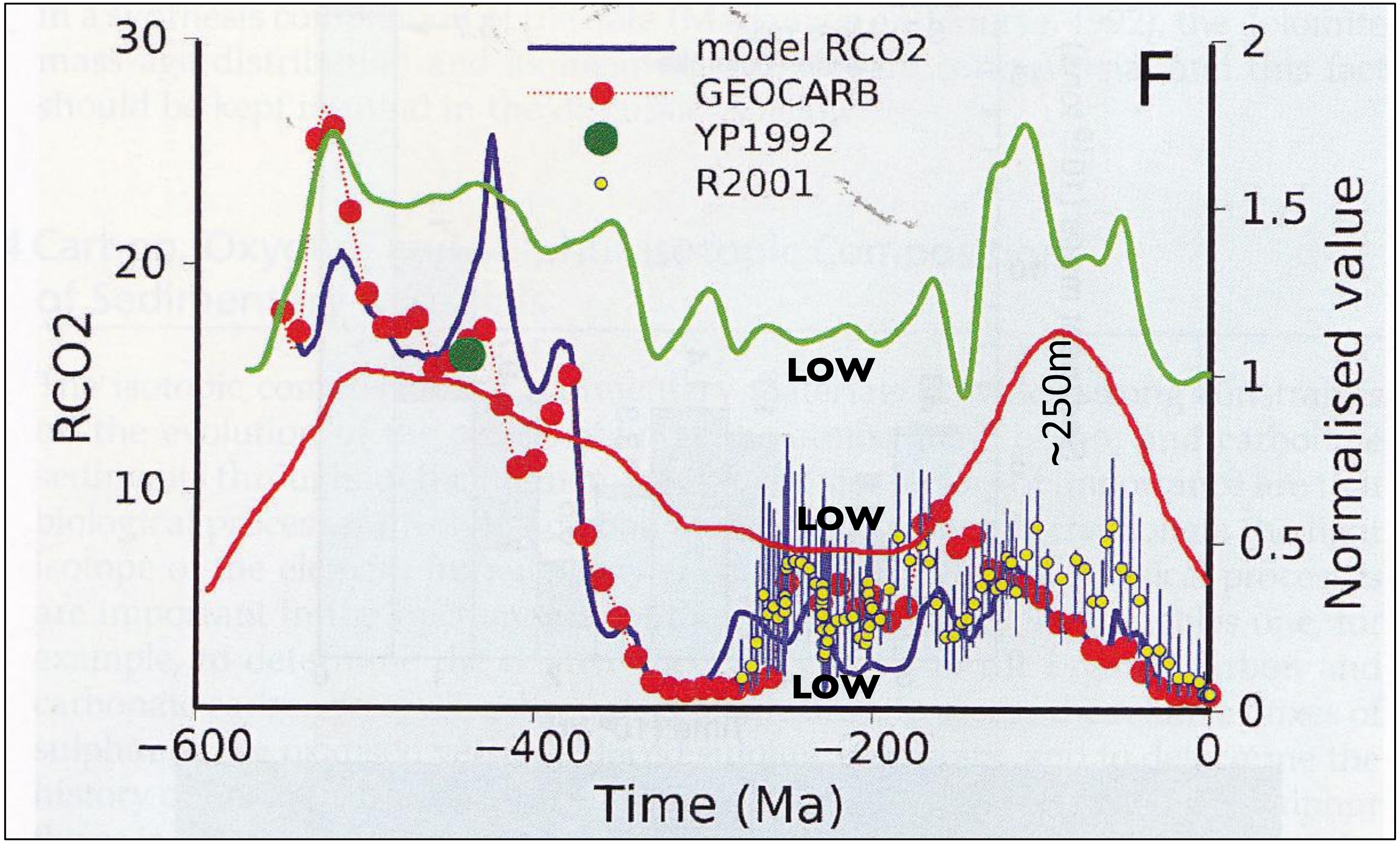
- During the Ordovician, T **decreased** (-3°C, icehouse) while CO_2 atm concentration was **elevated** (~4500 ppm);

- … most of the time, the T **was higher** that the current T by several degrees.

What processes might lead to larger CO_2 changes?

ATMOSPHERIC CO_2 DRIVEN BY GEOLOGICAL PROCESSES THROUGH THE PHANEROZOIC (LONG TERM)

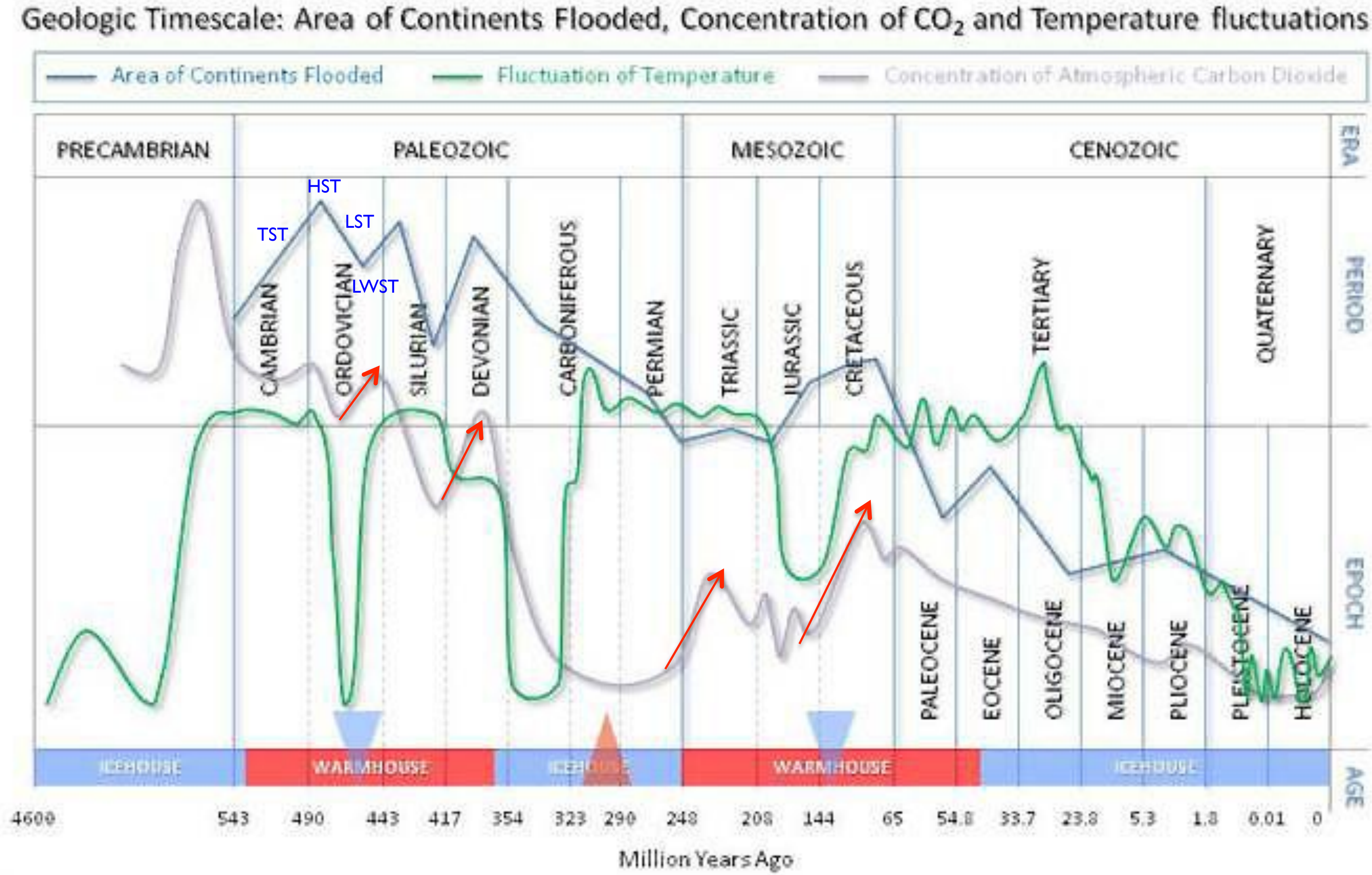
Three 'parallel' curves…



in Mackenzie & Andersson 2013

First order relative sea level changes (red curve), mid ocean ridge accretion rate (green curve) RCO_2 (blue curve) from paleosols (green dots), fossil plant stomata (yellow dots) and GEOCARB (red dots).

ATM CO_2 DRIVEN BY GEOLOGICAL PROCESSES THROUGH THE PHANEROZOIC ('MEDIUM' TERM)



1- *Analysis of the Temperature Oscillations in Geological Eras* by Dr. C. R. Scotese © *2002*. 2- Ruddiman, W. F. 2001. *Earth's Climate: past and future*. W. H. Freeman & Sons. New York, NY. 3- Mark Pagani *et all. Marked Decline in Atmospheric Carbon Dioxide Concentrations During the Paleocene*. Science; Vol. 309; No. 5734; pp. 600-603. 22 July 2005. 4- Ronov, A. B. 1994. *Phanerozoic Transgressions and Regressions on the Continents: A Quantitative Approach Based on Areas Flooded by the Sea and Areas of Marine and Continental Deposition*. American Journal of Science 294:777–801. 5- *Source for Nomenclature and Ages:* © 1999, The Geological Society of America. *Product Code CTS004*, Compilers: A. R. Palmer and John Geissman. *Conclusion and Interpretation:* Nasif Nahle ©2005, 2007, 2009. *Corrected on 07 July 2008 (CO2: Ordovician Period).*

Comments on the PHANEROZOIC SL/T/CO_2 curves

- Higher SL correspond with periods of warming while lower SL are generally associated with periods of cooling;

- **This is not systematic** : e.g.
  (i) end Silurian shows stable warming while continental flooded area (CFA) decreased;
  (ii) during the Carboniferous there was an ice age with a non linear CFA decrease;
  …

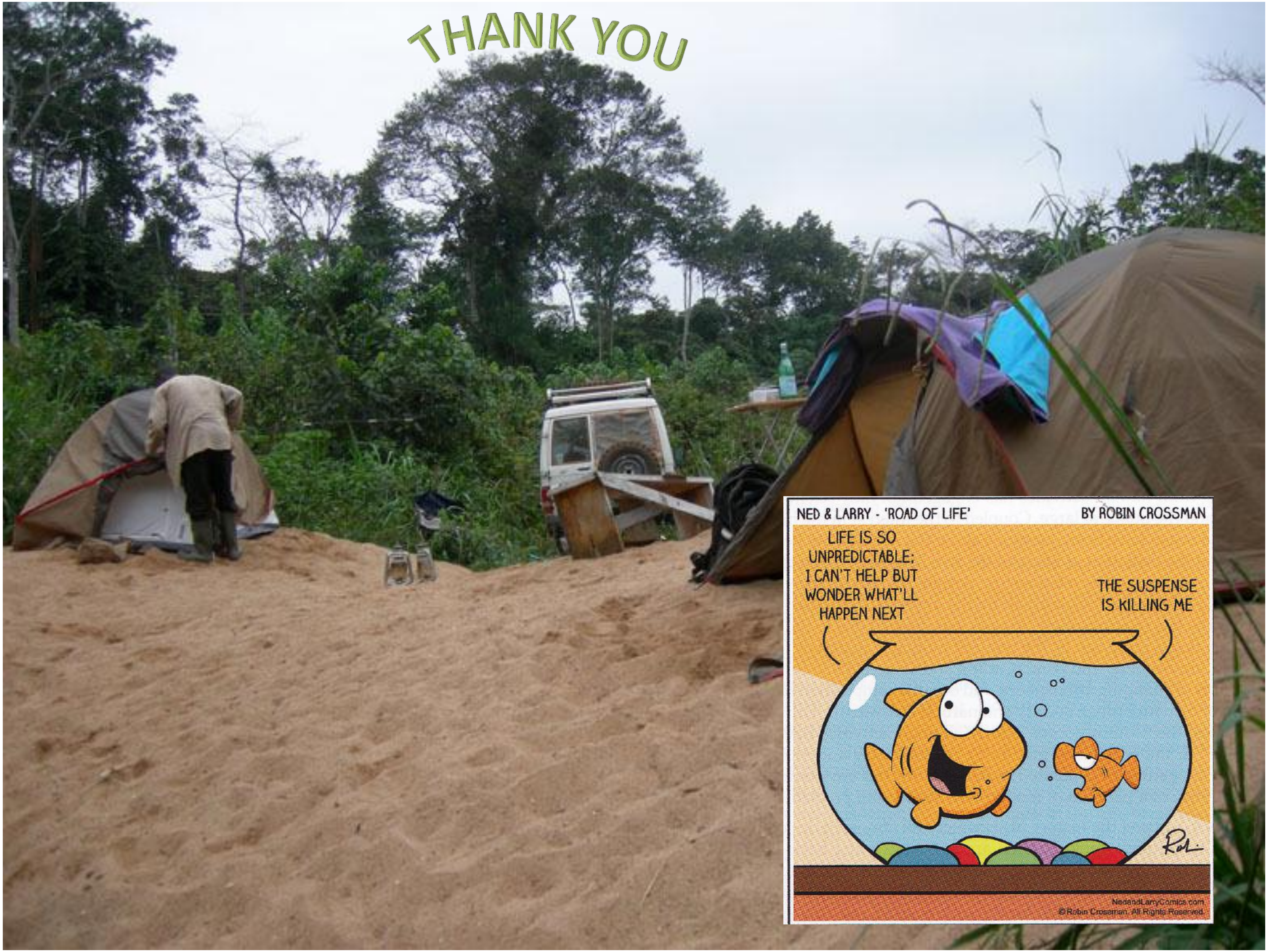
- At the geological scale, sea levels have fallen since the Oligocene until at least today ….. (transition from the **late** greenhouse period to the current icehouse);

- In the graph, **increases** of CO_2 atm concentration follow drops in SL.
  Drops of SL being caused by ocean cooling, the load of CO_2 released to the atmosphere is much smaller than the load of CO_2 released to the atmosphere when the oceans are warming => the oceans are the second driver of the Earth's climate.

CONCLUSION

- They were **large variations** in planetary surface temperature (land and ocean),
- CO_2, CH_4 (H_2Ov, N_2O, H_2S ….) levels **were very high most of the time**;
- The Earth's global climate change is determined by **internal factors** (plate tectonics, biological activity ...) and **factors originating in space** (solar activity, space dust, astronomical parameters...);
- Geology points to a current climate change which happens sequentially in two main climate periods, **greenhouse and icehouse**. It also reveals the succession of (four) natural phases : transgression, highstand, regression and lowstand. Currently, the Earth is passing trough a lowstand phase.
  The Cenozoic succession of these phases show that Earth is **GEOLOGICALLY** cooling at the present time, we live in a relatively cool climate – an icehouse Earth, an **unusual** state (at a geological scale);
- In the normal course of Milankovitch cycles, the present interglacial should give way within 2,000 yrs to a gradual, uneven decline in global T and a major ice age about 23,000 yrs from now.

THANK YOU



NED & LARRY - 'ROAD OF LIFE'
BY ROBIN CROSSMAN
LIFE IS SO UNPREDICTABLE; I CAN'T HELP BUT WONDER WHAT'LL HAPPEN NEXT
THE SUSPENSE IS KILLING ME
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