

O registro paleoclimático, com foco em testemunhos de gelo

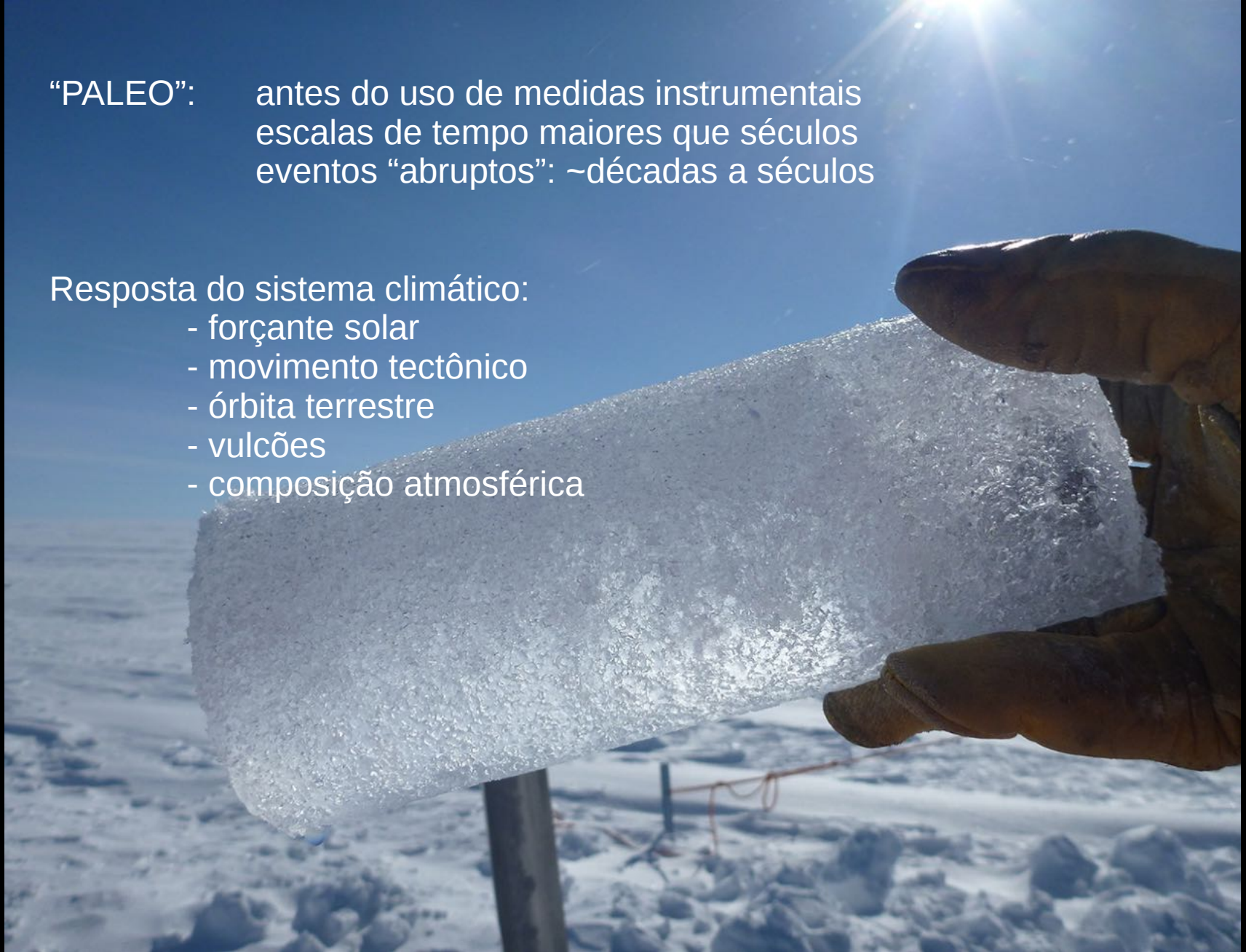
Alexandre Correia

Outubro/ 2019

“PALEO”:
antes do uso de medidas instrumentais
escalas de tempo maiores que séculos
eventos “abruptos”: ~décadas a séculos

Resposta do sistema climático:

- forçante solar
- movimento tectônico
- órbita terrestre
- vulcões
- composição atmosférica



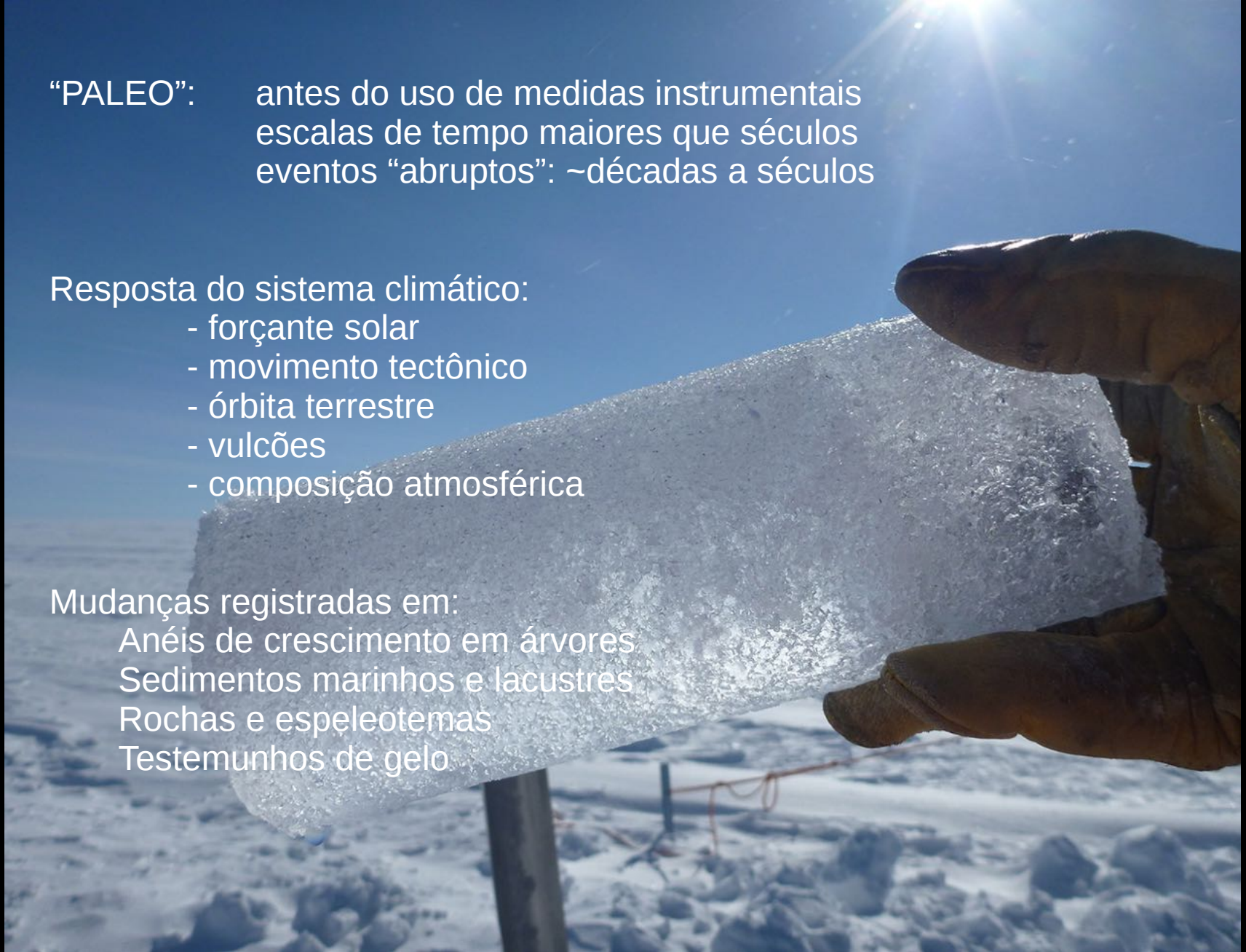
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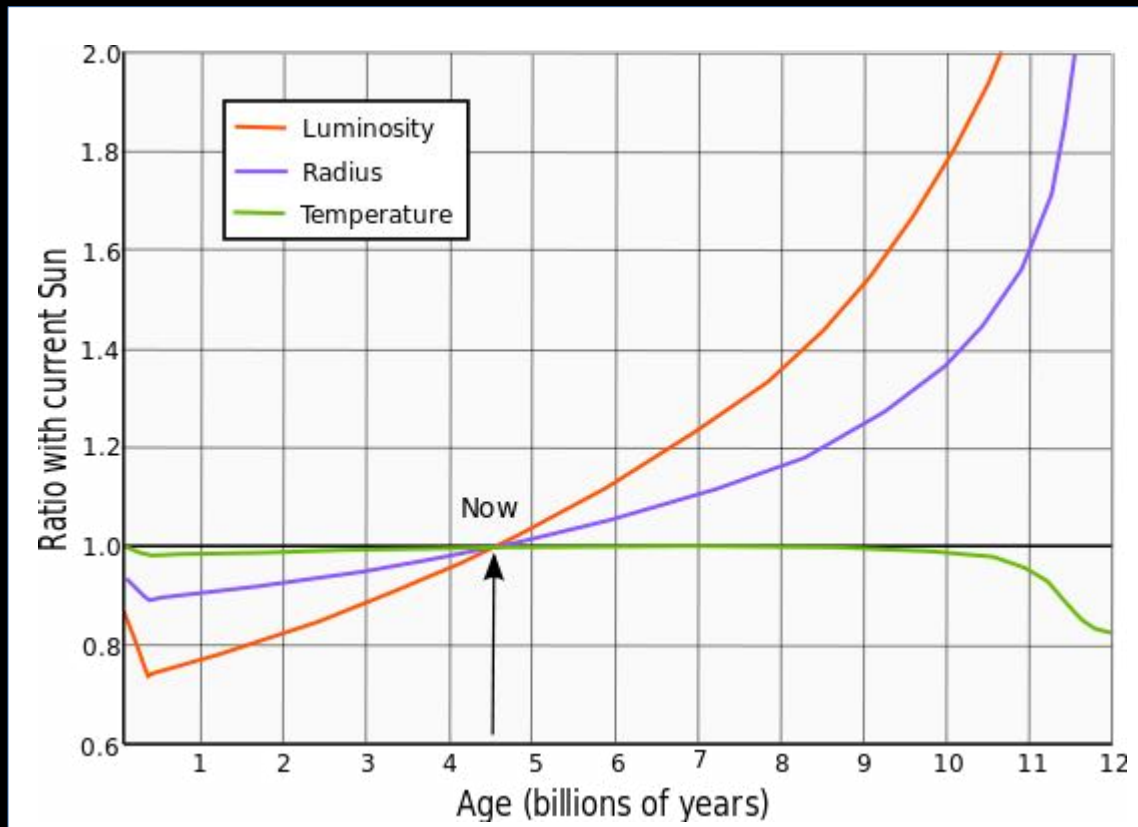
Mudanças registradas em:

Anéis de crescimento em árvores
Sedimentos marinhos e lacustres
Rochas e espeleotemas
Testemunhos de gelo

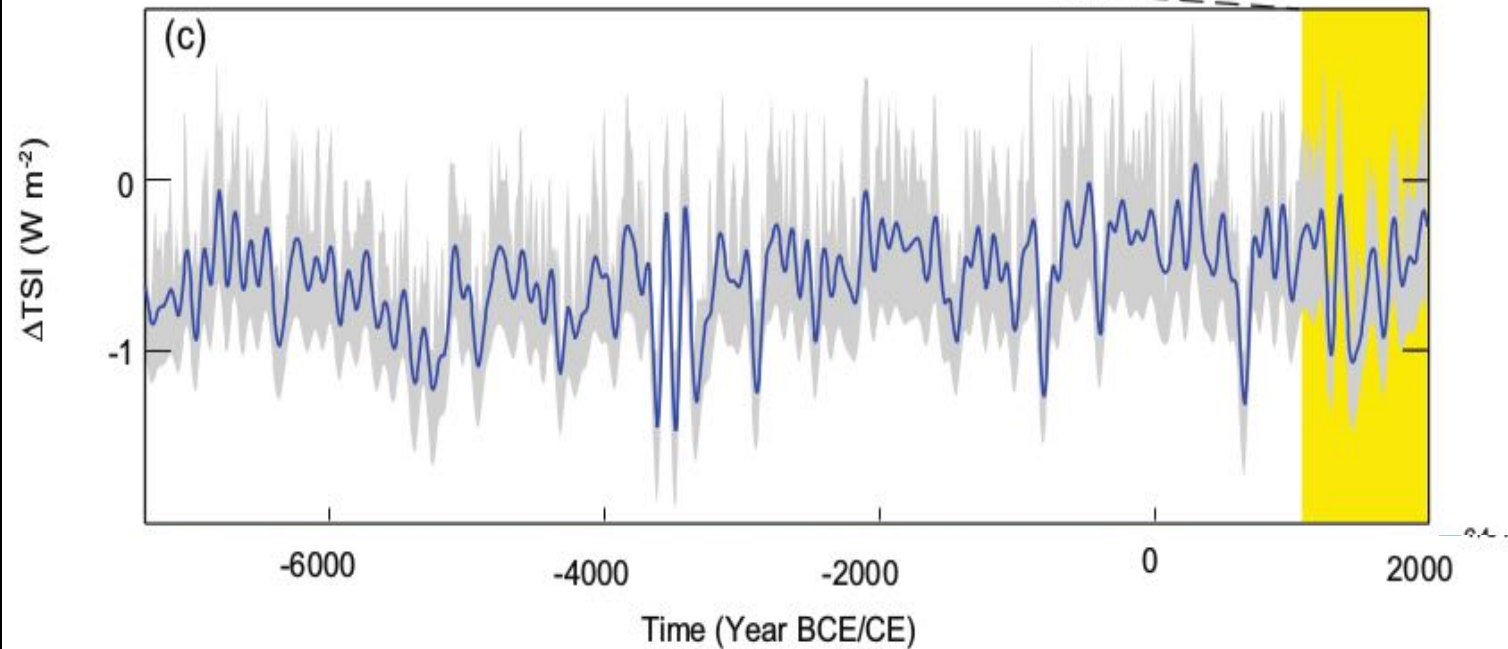
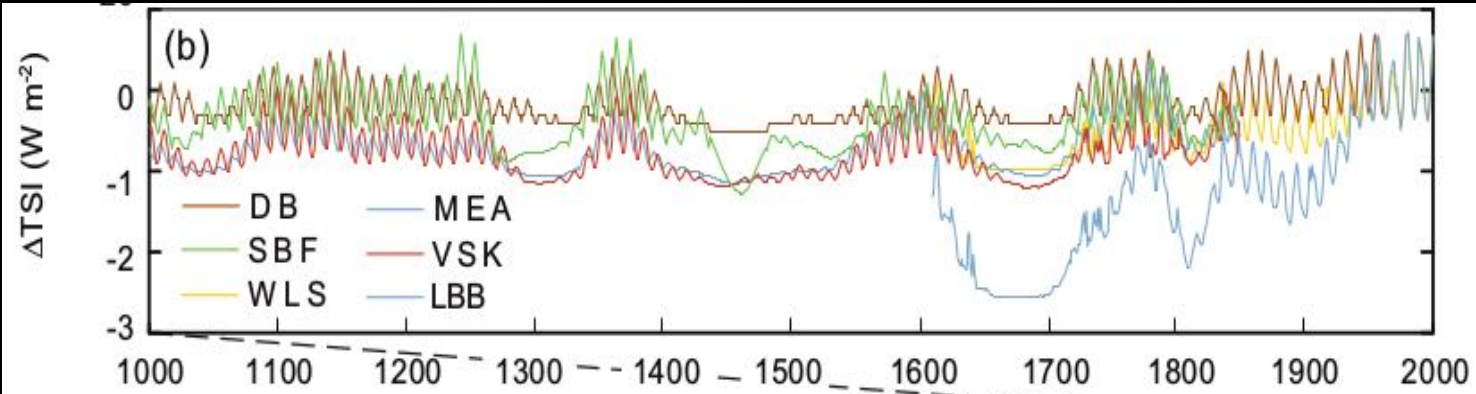


Forçante solar

- Variações do fluxo de radiação solar que atinge a Terra
- Difícil extrapolar para o passado, fora do período instrumental

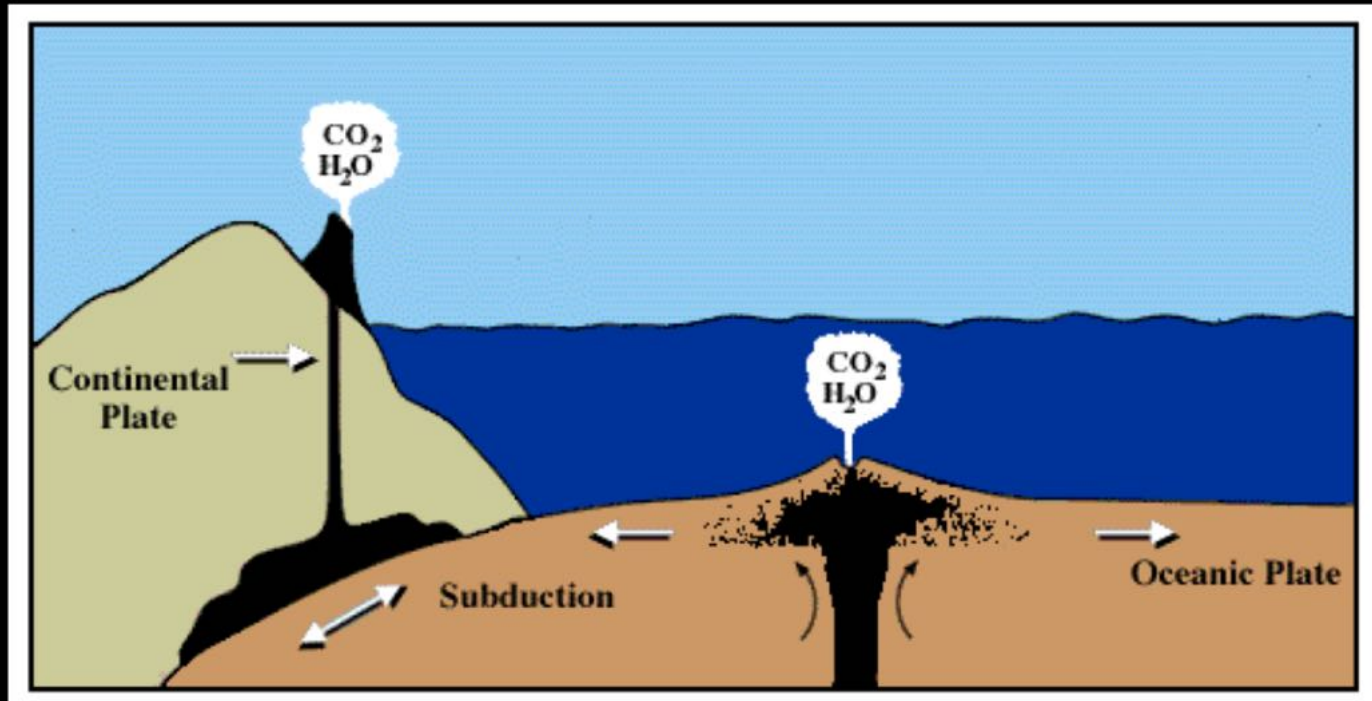


Forçante solar reconstruída



Movimento tectônico + efeito estufa (escala de milhões a bilhões de anos)

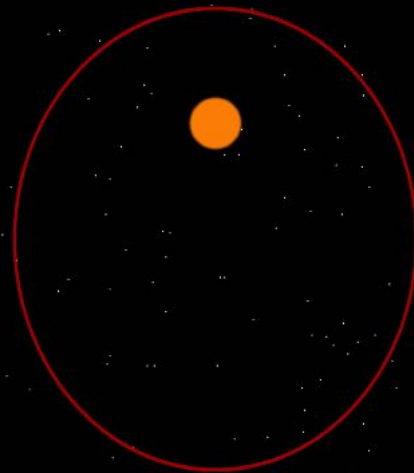
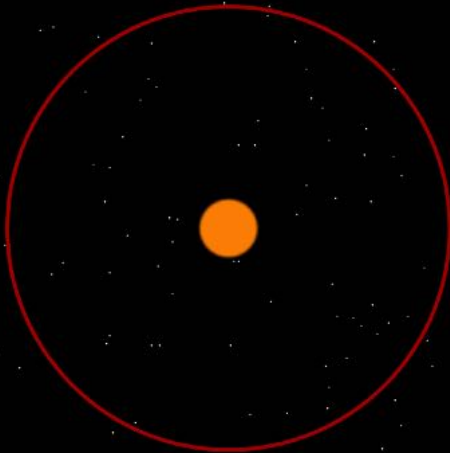
As the continents shift there is increased subduction and volcanic activity which increases CO_2 into the atmosphere



That atmospheric CO_2 is then consumed in weathering reactions on continents, and eventually returned to the ocean. This is the long-term "weathering" control of climate.

Forçante orbital

- Mudanças do fluxo de radiação solar → eras glaciais/interglaciais
- Previsível a partir de cálculos astronômicos (passado e futuro)
- Mudanças de:
 - eccentricidade da órbita
 - inclinação do eixo de rotação da Terra
 - precessão do eixo de rotação da Terra
 - precessão da órbita
 - inclinação da órbita



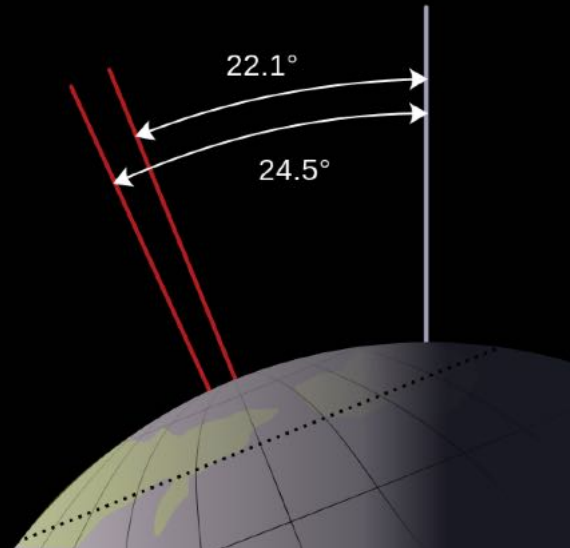
Eccentricidade

Período principal: 413 ka

Outros períodos: 95 ka, 125 ka

Forçante orbital

- Mudanças do fluxo de radiação solar → eras glaciais/interglaciais
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- Mudanças de:
 - acentricidade da órbita
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 - precessão do eixo de rotação da Terra
 - precessão da órbita
 - inclinação da órbita

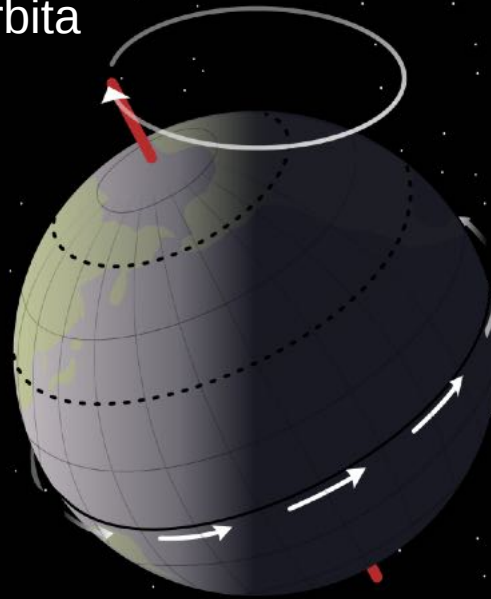


Inclinação do eixo

Período: 41 ka

Forçante orbital

- Mudanças do fluxo de radiação solar → eras glaciais/interglaciais
- Previsível a partir de cálculos astronômicos (passado e futuro)
- Mudanças de: ecentricidade da órbita
inclinação do eixo de rotação da Terra
precessão do eixo de rotação da Terra
precessão da órbita
inclinação da órbita

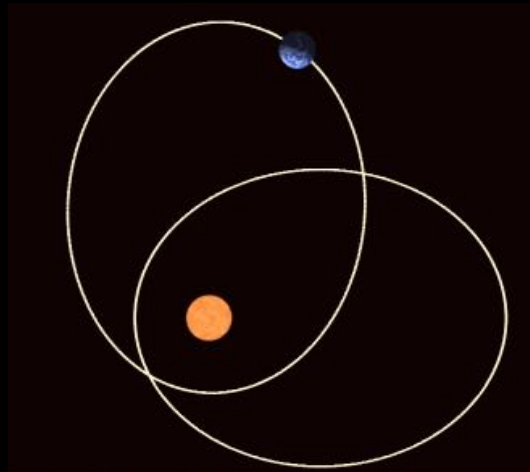


Precessão do eixo

Período: 25,8 ka

Forçante orbital

- Mudanças do fluxo de radiação solar → eras glaciais/interglaciais
- Previsível a partir de cálculos astronômicos (passado e futuro)
- Mudanças de:
 - eccentricidade da órbita
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 - precessão da órbita
 - inclinação da órbita

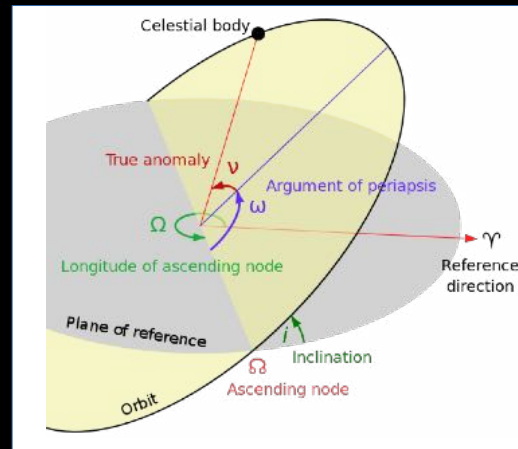


Precessão da órbita

Período: 112 ka

Forçante orbital

- Mudanças do fluxo de radiação solar → eras glaciais/interglaciais
- Previsível a partir de cálculos astronômicos (passado e futuro)
- Mudanças de:
 - eccentricidade da órbita
 - inclinação do eixo de rotação da Terra
 - precessão do eixo de rotação da Terra
 - precessão da órbita
 - inclinação da órbita

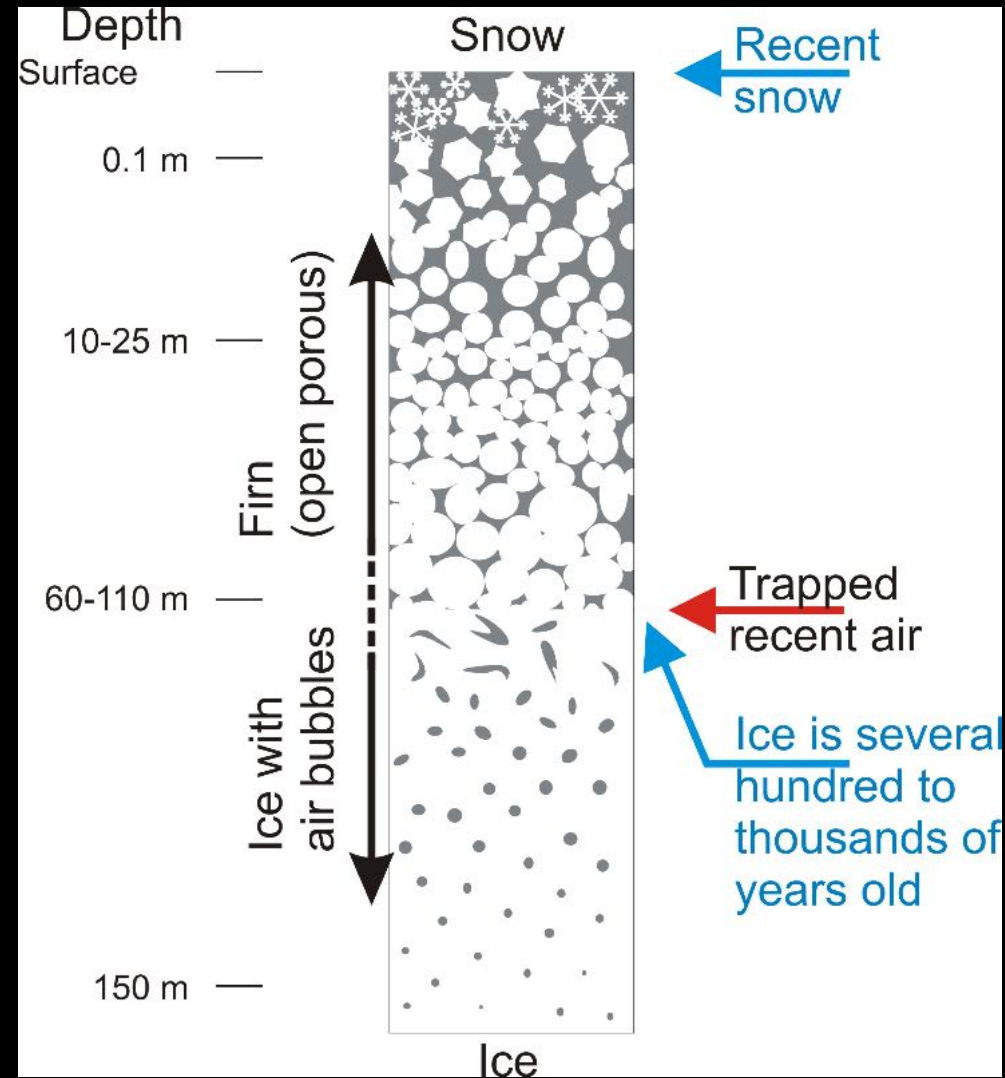


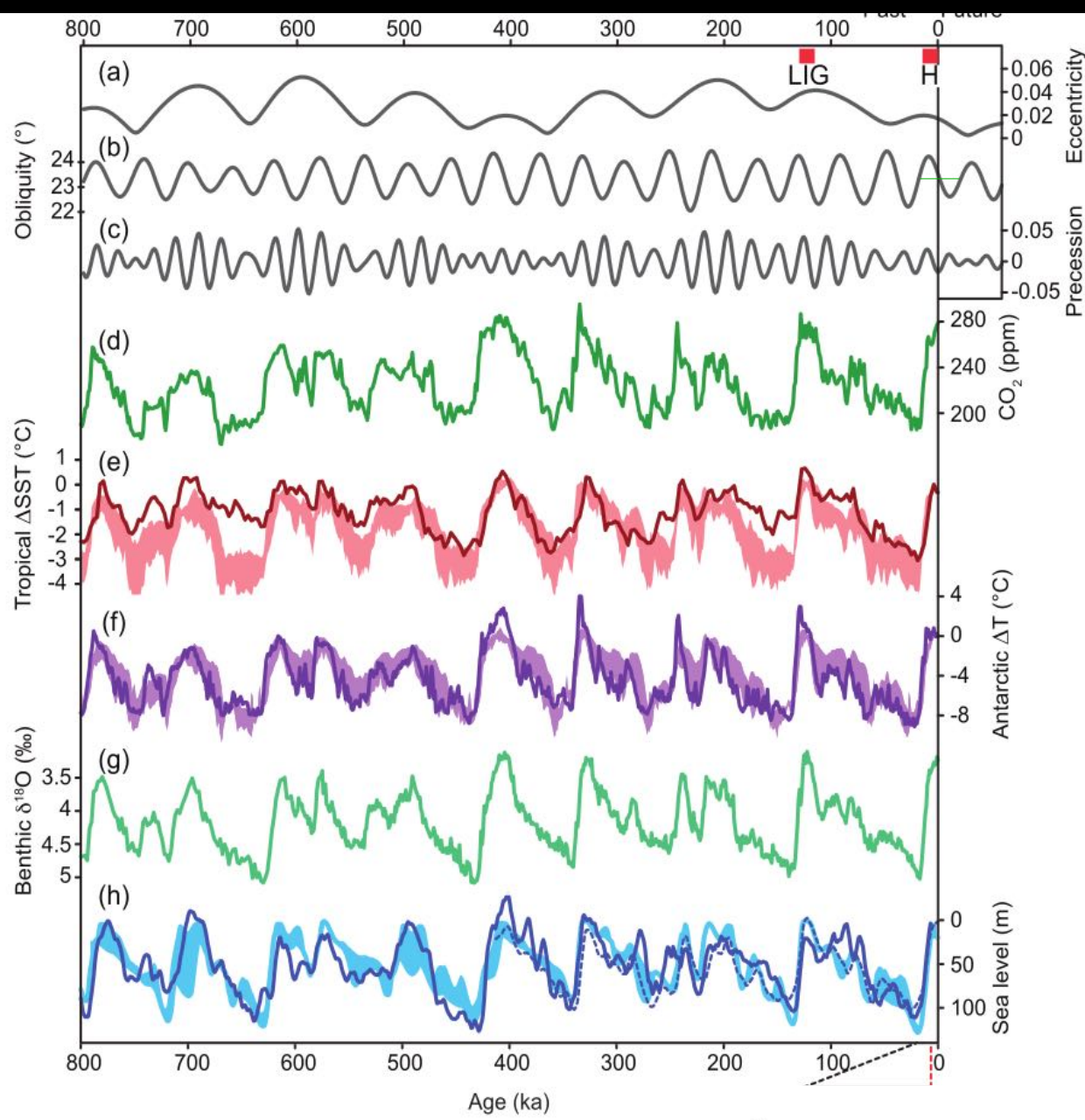
Inclinação da órbita

Período: 100 ka

O registro paleoclimático em testemunhos de gelo

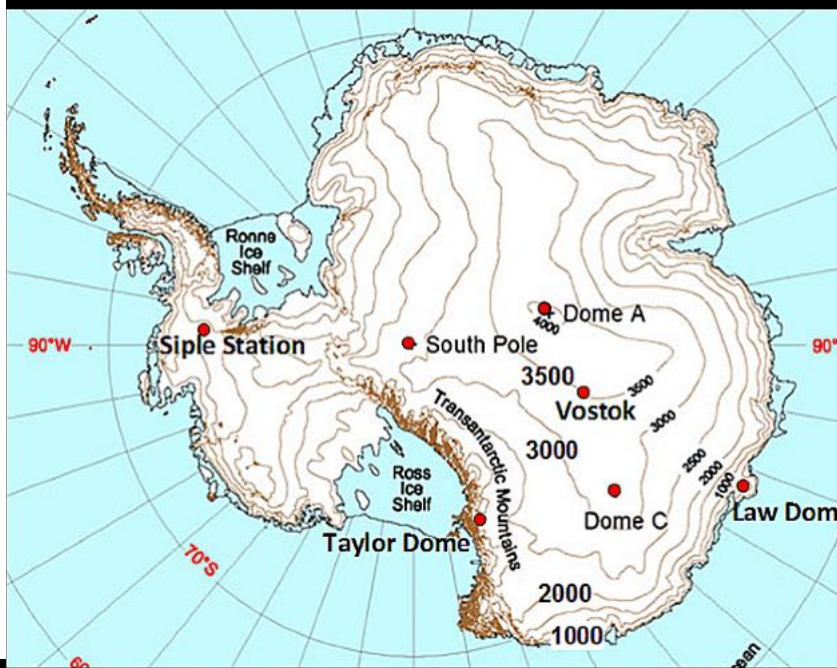
- Bolhas de ar aprisionadas em geleiras
- Química atmosférica da neve
- Sujeito a difusão gasosa entre poros
- Taxas de acumulação definem a resolução temporal: Antártica x Andes
- Escala de 800 ka em Dome C, Antártica

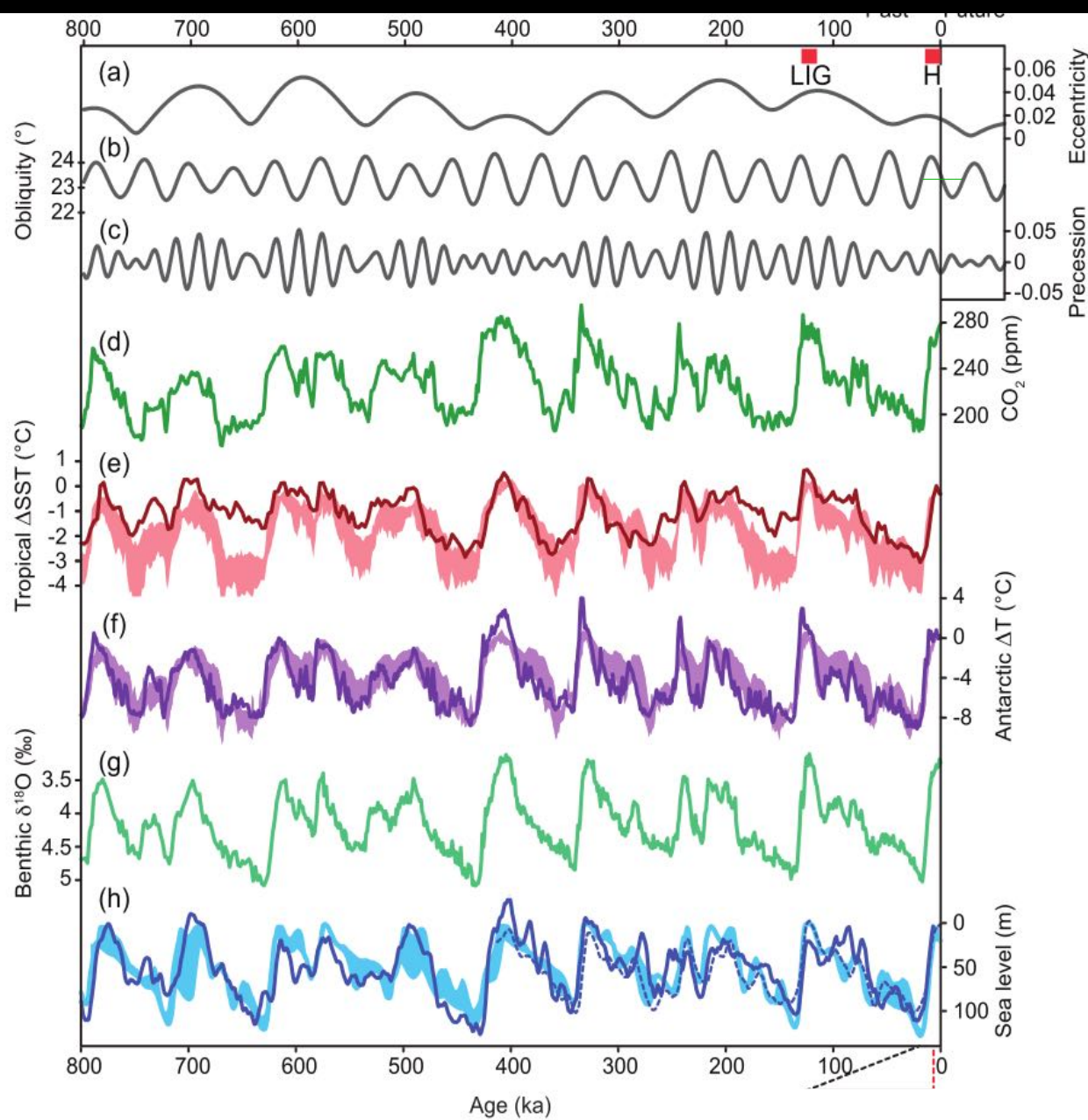




Variações orbitais (Milankovitch)

← CO_2 no testemunho de Dome C

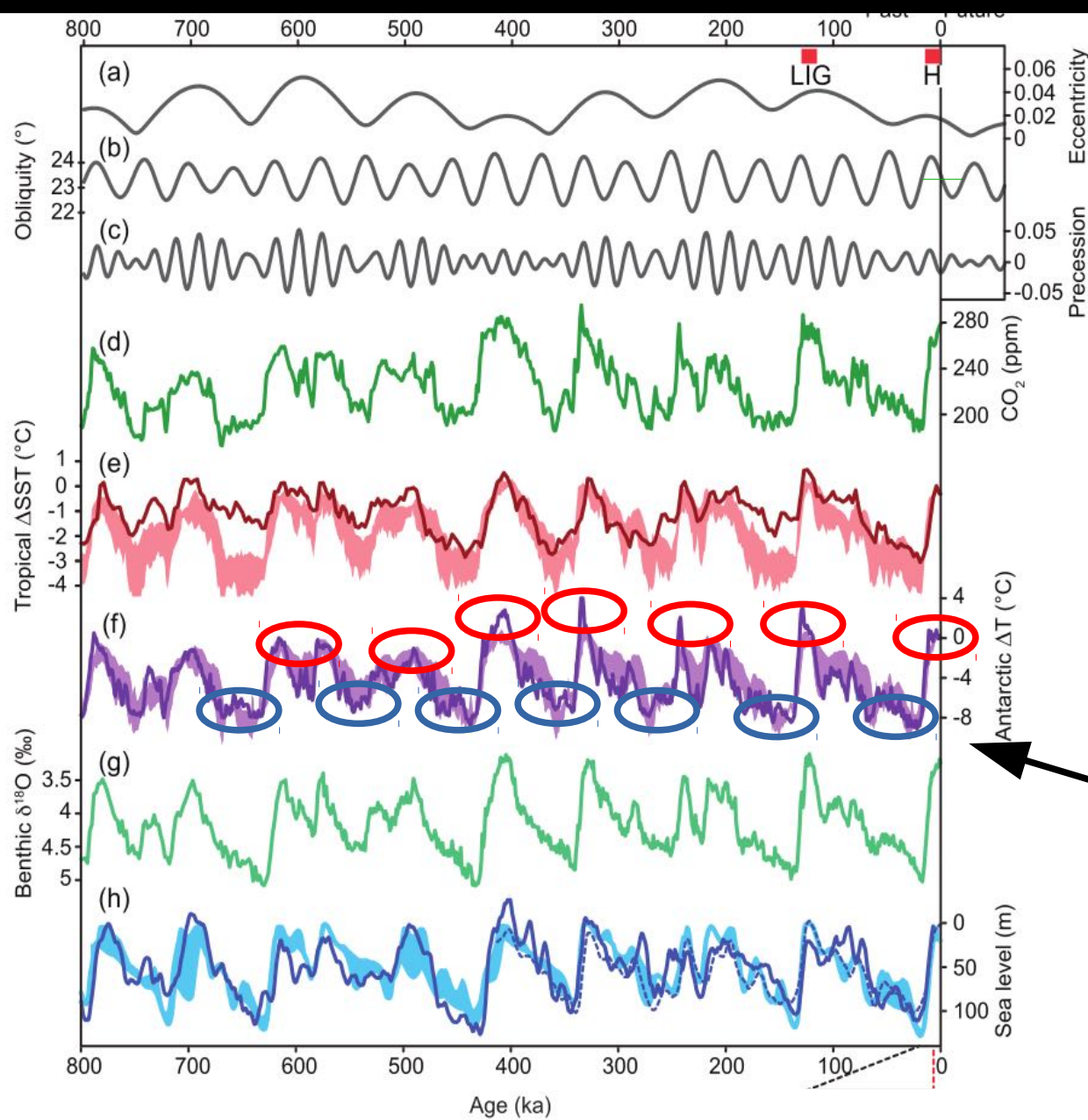




Variações orbitais (Milankovitch)

← CO₂ no testemunho de Dome C

← Temperatura definida a partir de isótopos da água

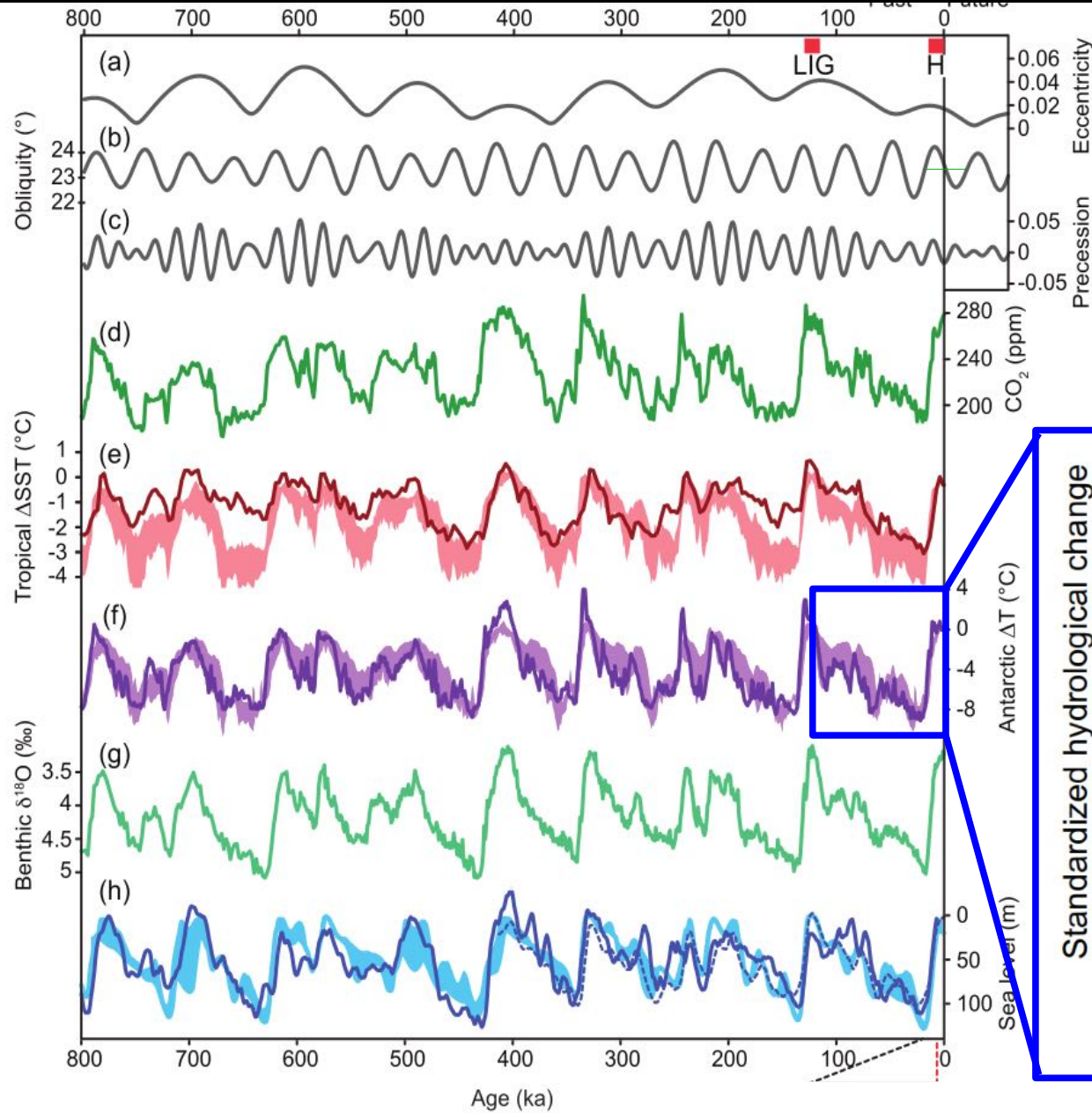


Variações orbitais (Milankovitch)

← CO2 no testemunho de Dome C

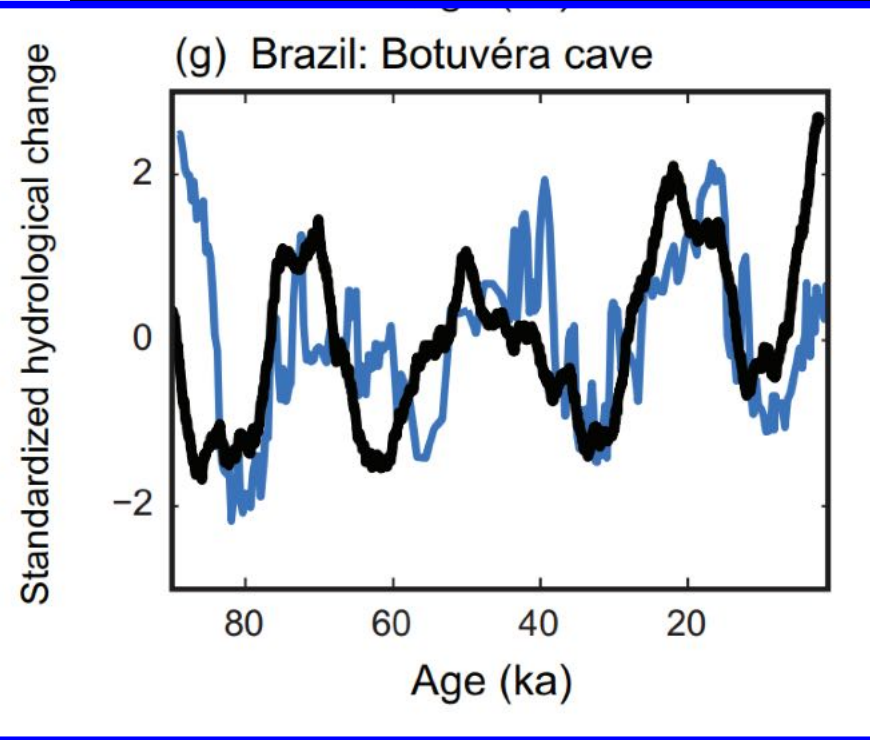
← Temperatura definida a partir de isótopos da água

← “Eras glaciais” / interglaciais



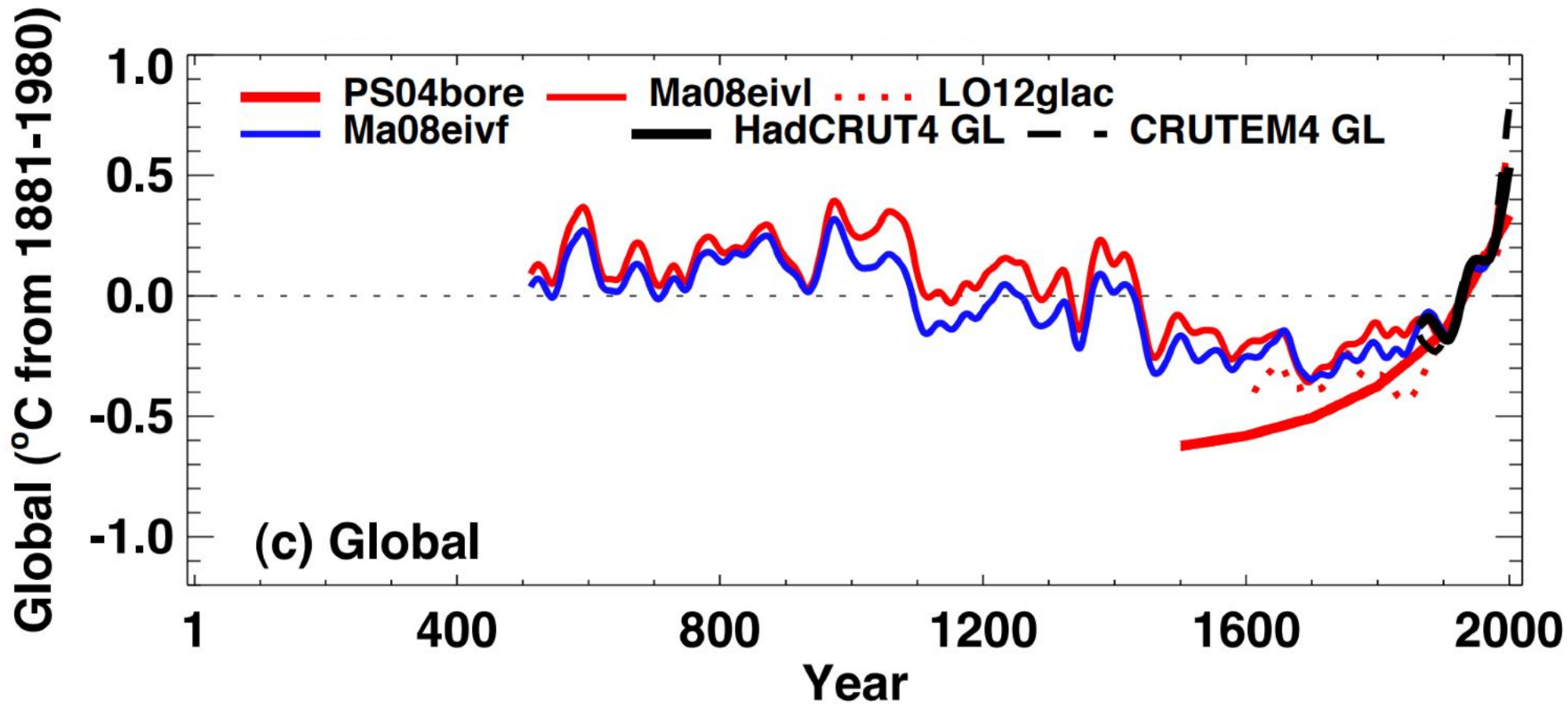
Variações orbitais (Milankovitch)

← CO2 no testemunho de Dome C

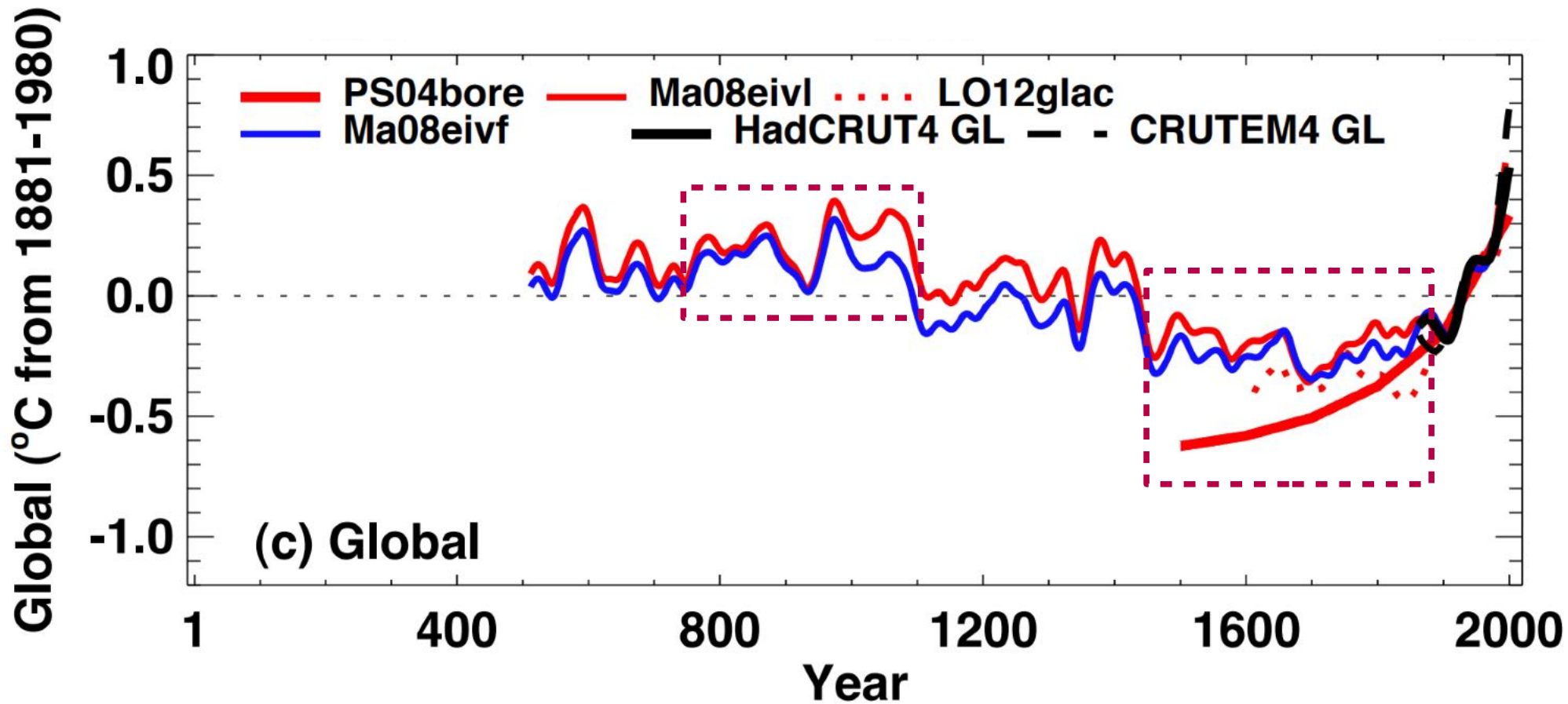


Standardized hydrological change

Registros dos últimos 2000 anos

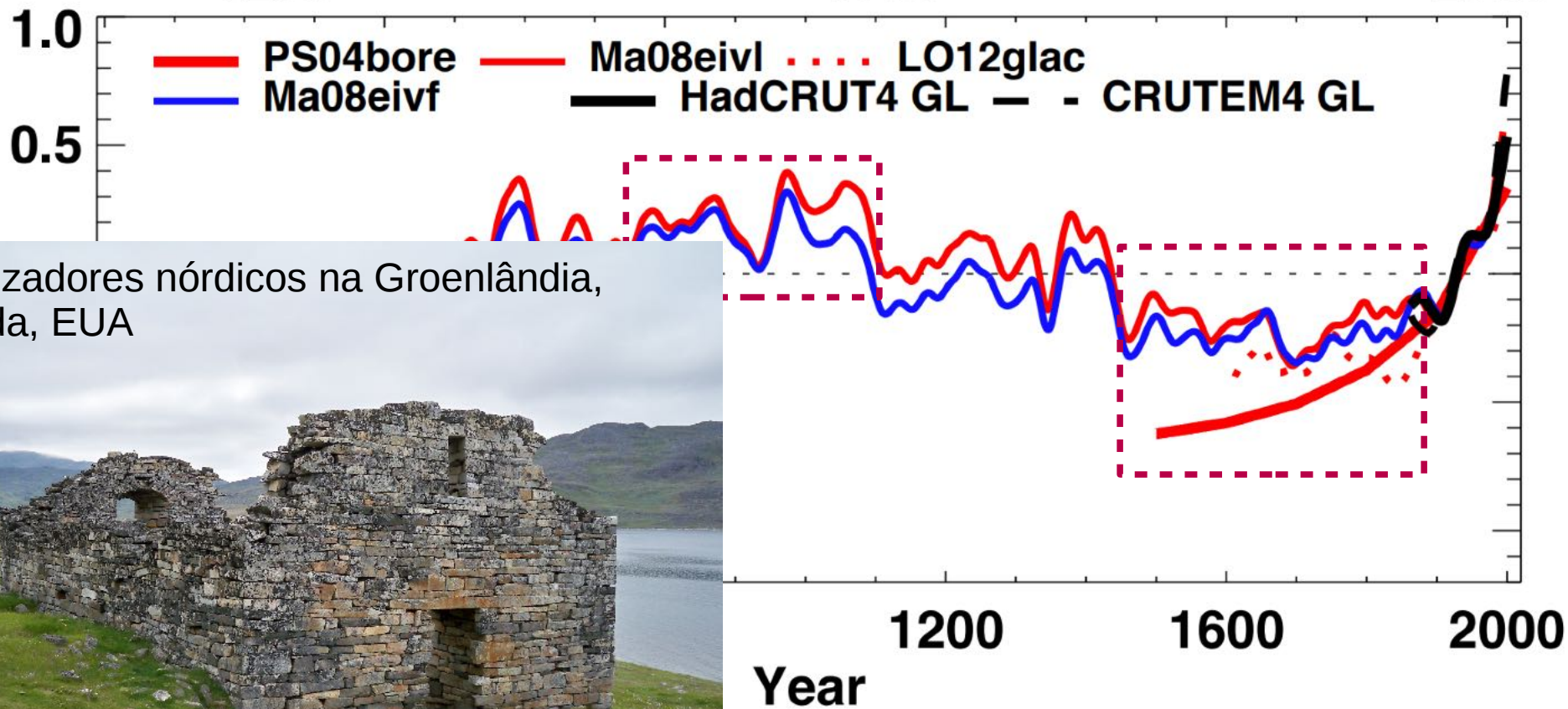


Registros dos últimos 2000 anos



Registros dos últimos 2000 anos

1881-1980)



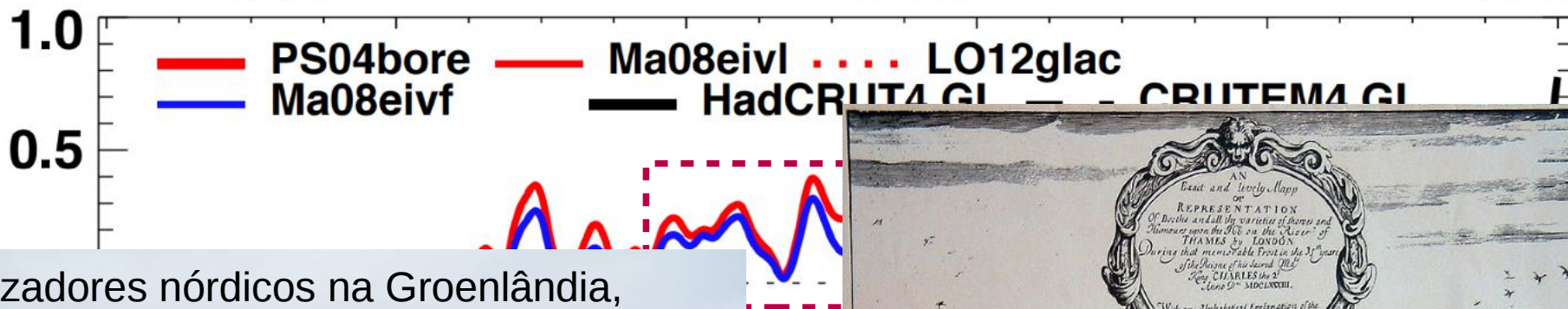
Colonizadores nórdicos na Groenlândia,
Canada, EUA



Ruínas de igreja nórdica na Groenlândia

Registros dos últimos 2000 anos

1881-1980)



Colonizadores nórdicos na Groenlândia, Canada, EUA



Ruínas de igreja nórdica na Groenlândia



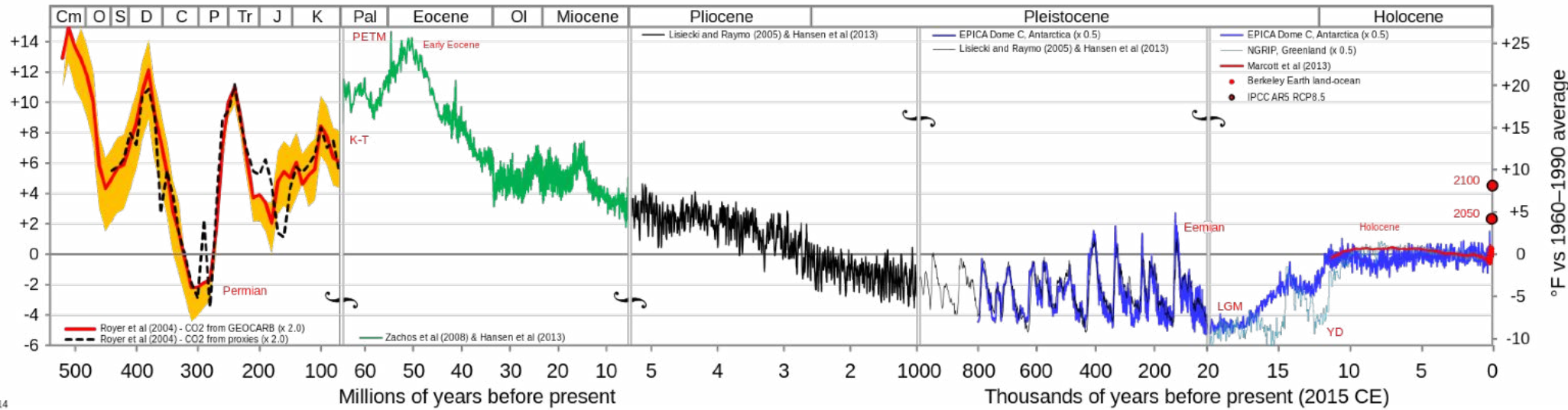
Ye

Ferros no gelo, sobris o Rio Tâmisia em

The Temple... The Phoenix... The Peacock... The Swan... The Unicorn... The Dragon... The Centaur... The Gnome... The Dwarf... The Elf... The Fairy... The Sprite... The Gnome... The Dwarf... The Elf... The Fairy... The Sprite... The Gnome... The Dwarf... The Elf... The Fairy... The Sprite...

Várias escalas de tempo no registro paleoclimático

Temperature of Planet Earth



Escala tectônica

Escala orbital

Extinção P-Tr: 95% esp. marinhas,
70% verteb terrestres

Plantas terrestres

Dinossauros

Lago Vostok

Homo sapiens

Indo

Primatas

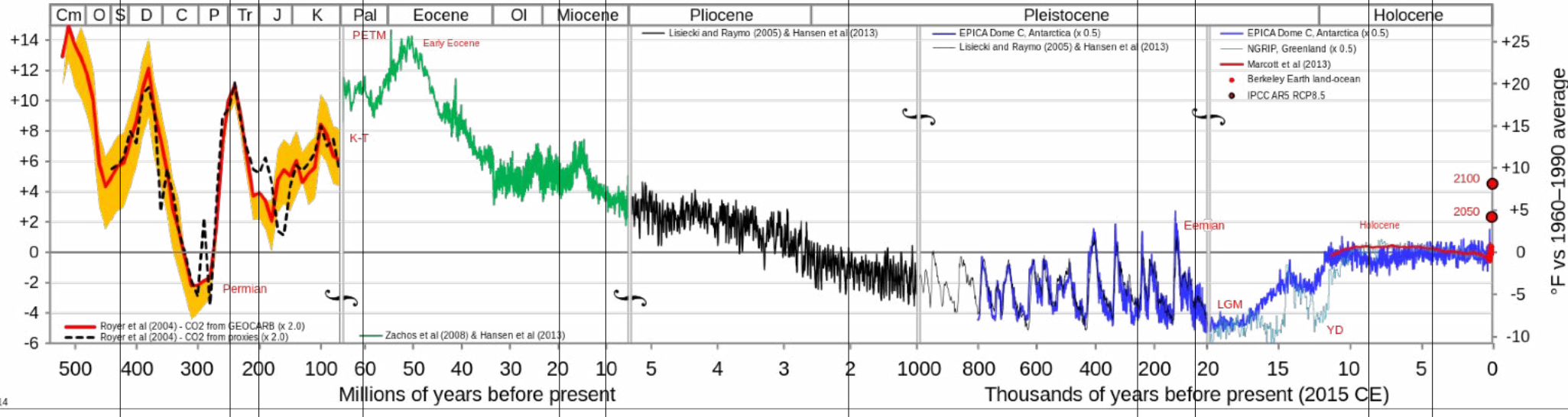
Savanas

Homo habilis

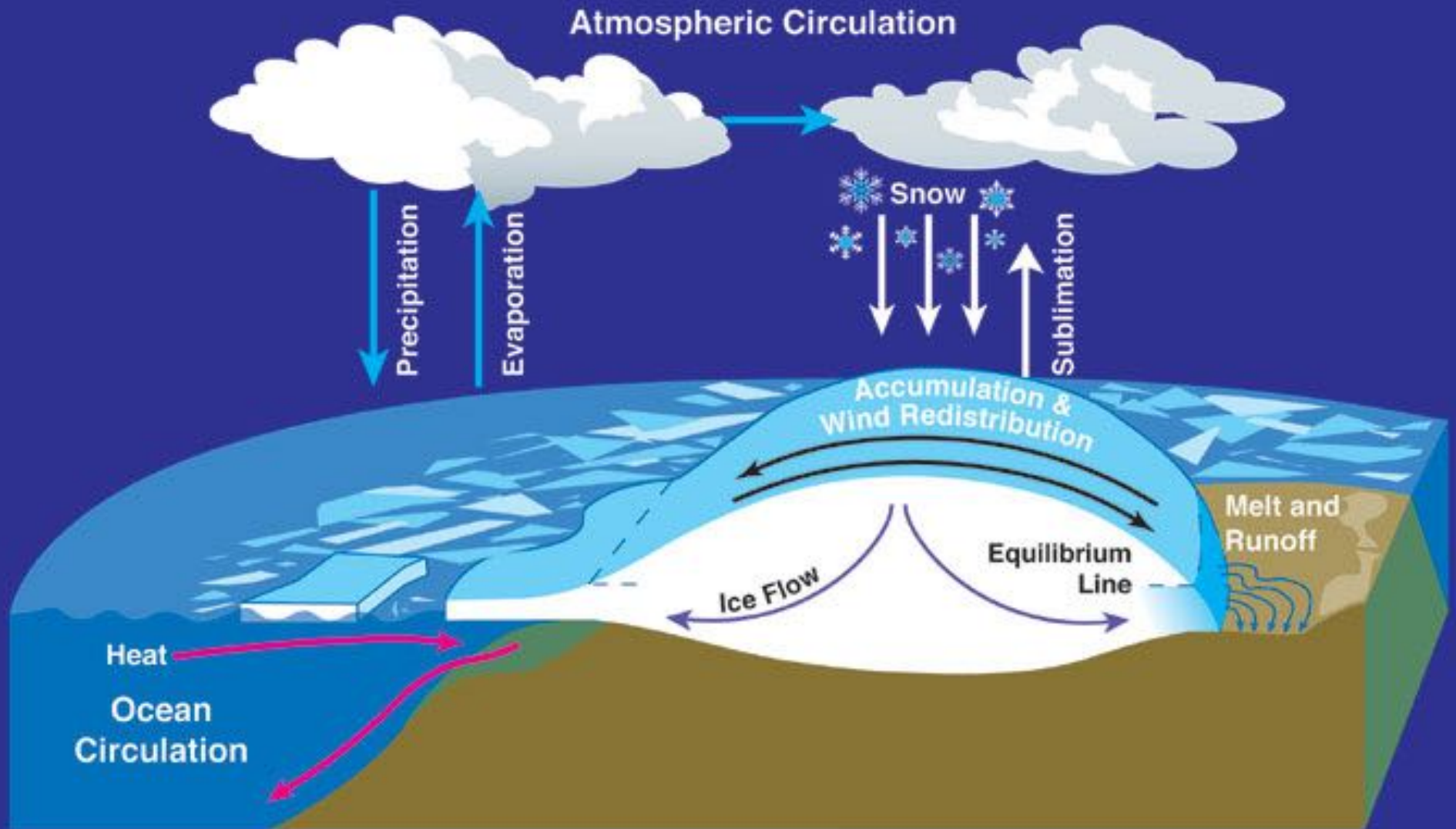
Aborígenes

Egito, Mesopotâmia

Temperature of Planet Earth

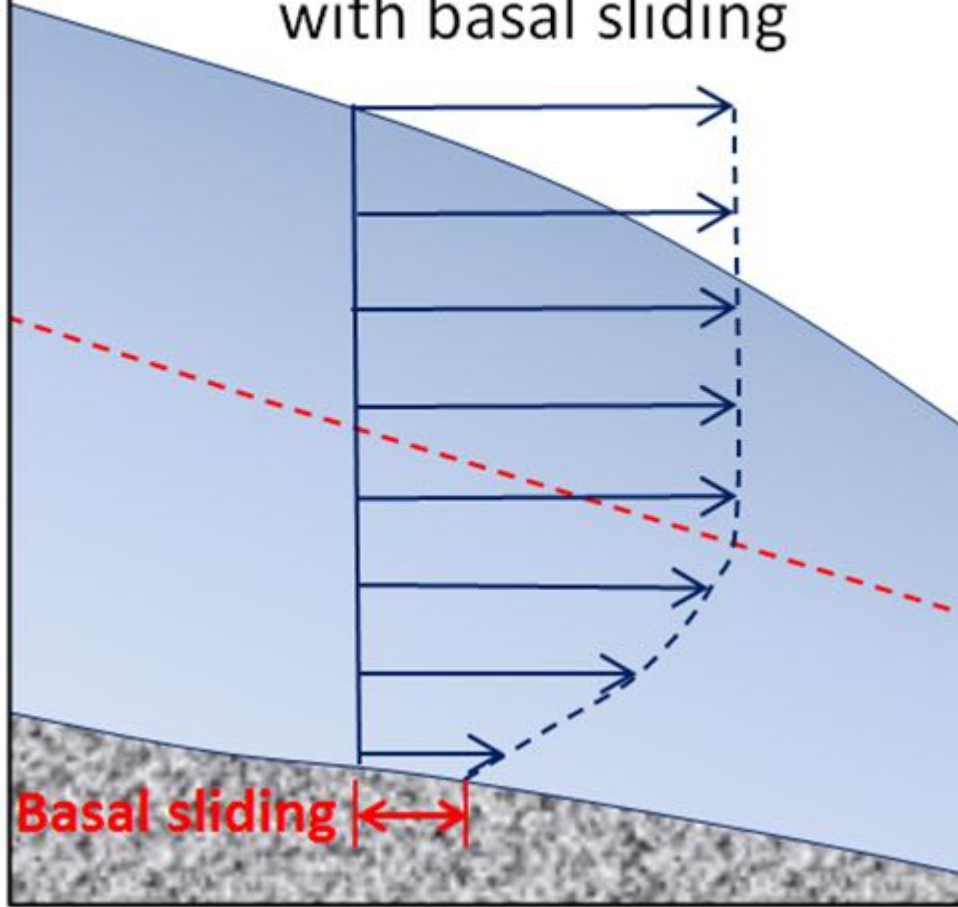


O registro paleoclimático em geleiras e mantos de gelo

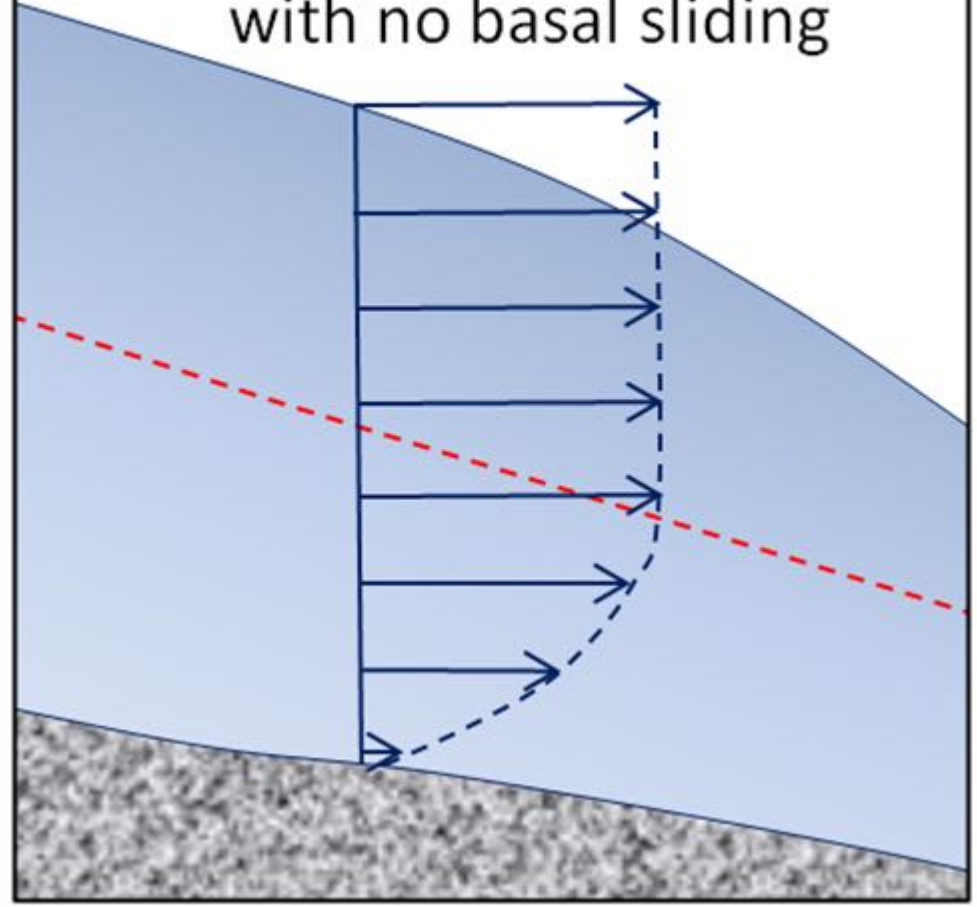


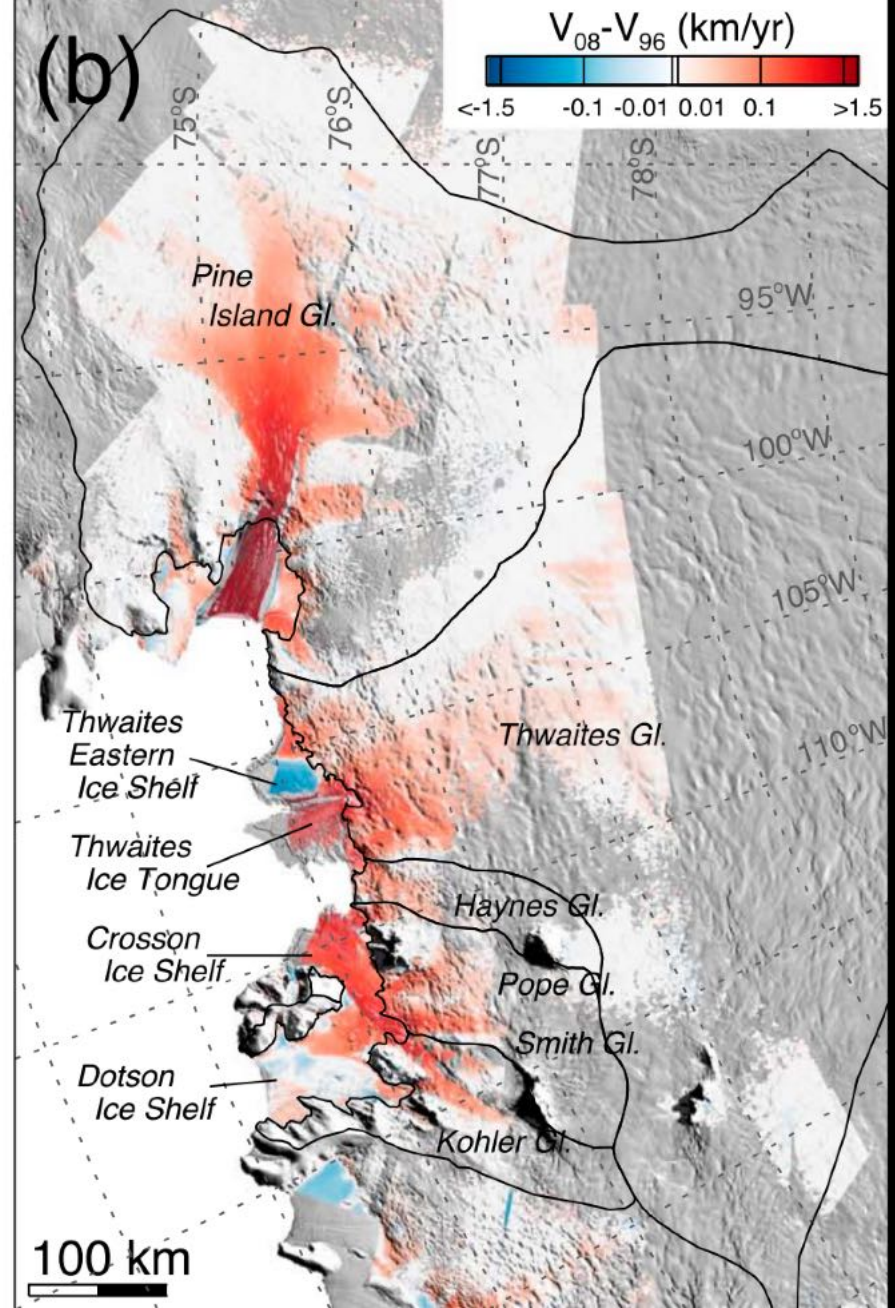
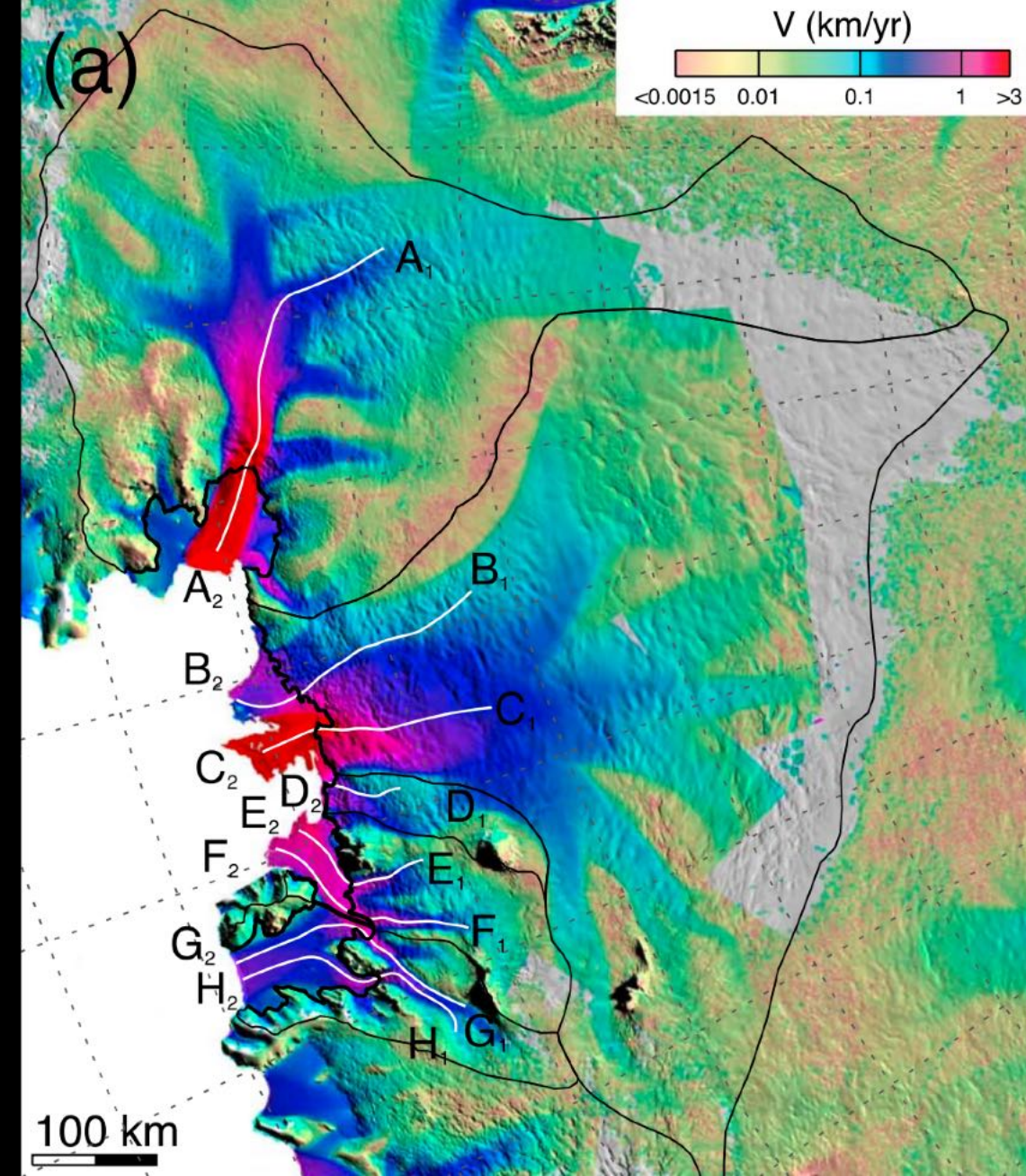
Escoamento de geleiras

Rate of ice motion with basal sliding



Rate of ice motion with no basal sliding





Escoamento de geleiras

<https://youtu.be/lxfORXWph2Q>

<https://youtu.be/njTjfJcAsBg>

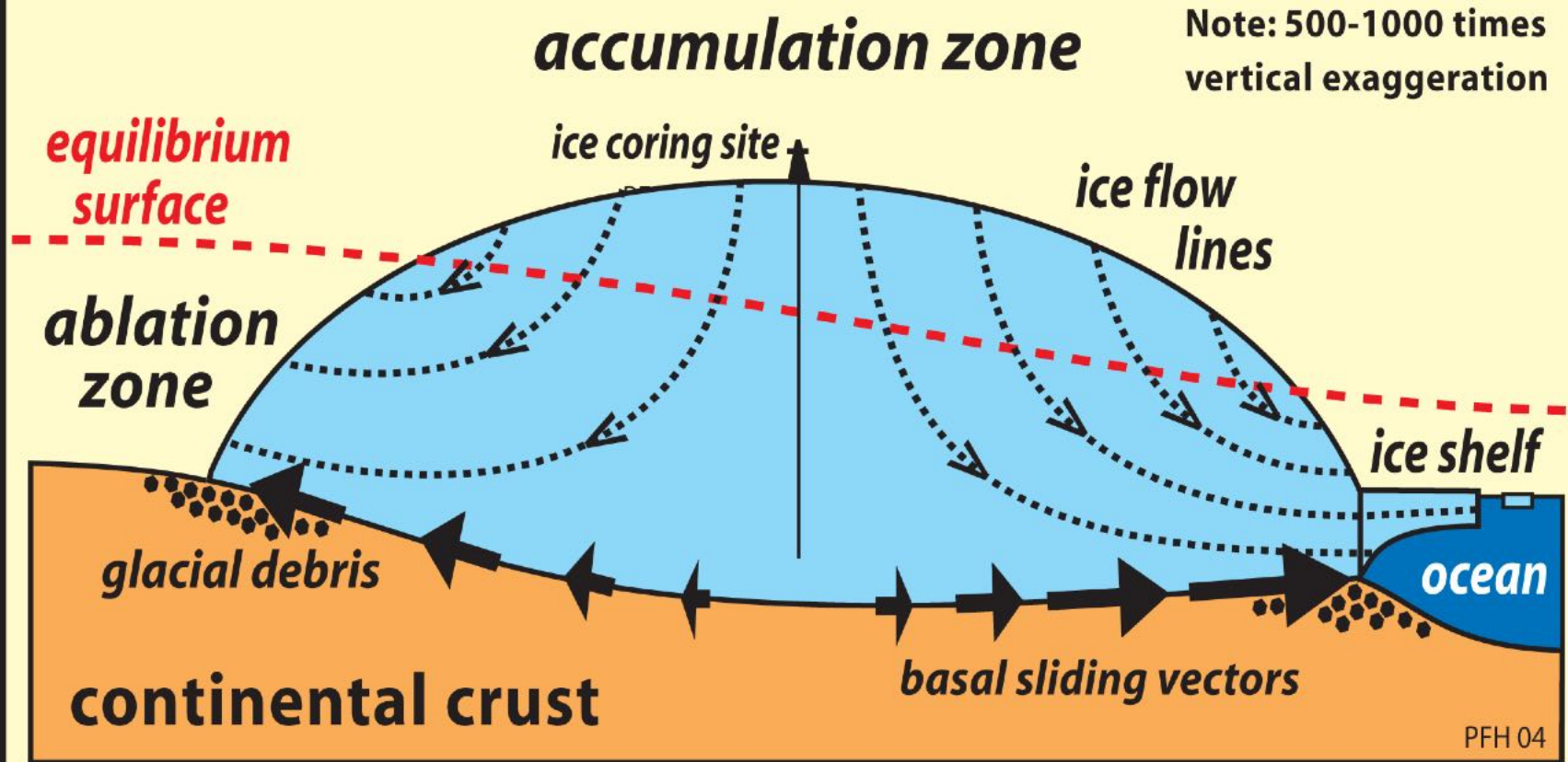


Extração e análise de testemunhos de gelo

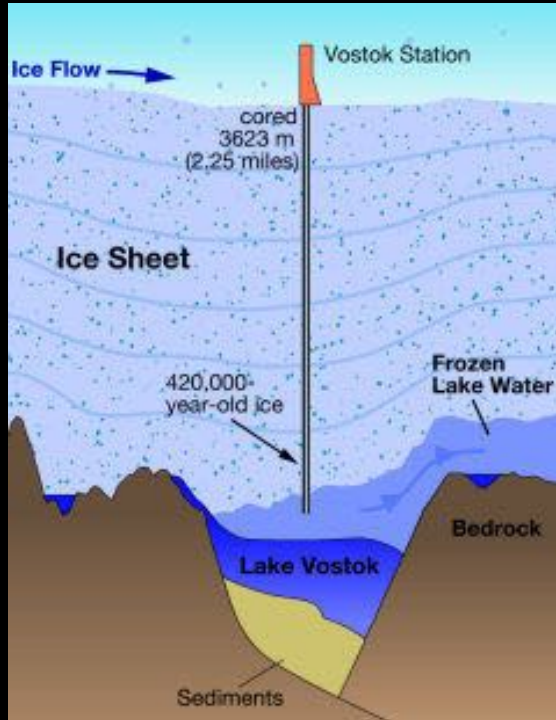
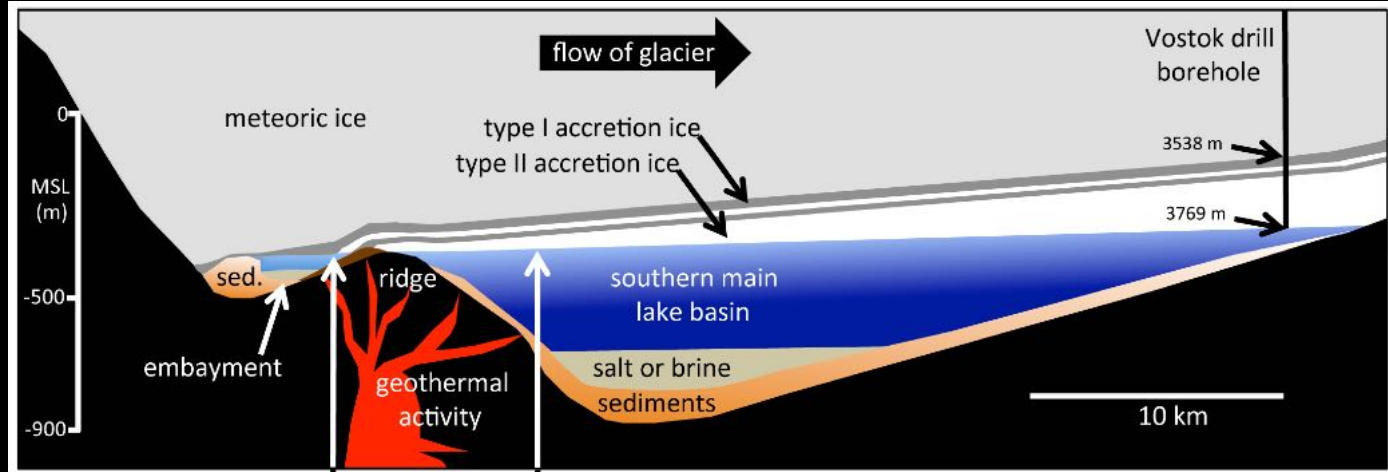
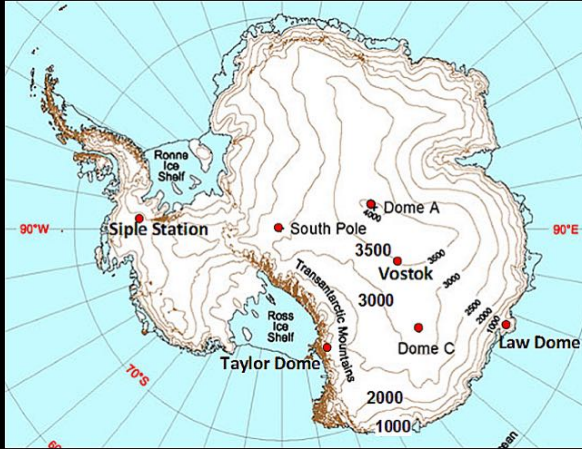


Drilling site: location, location, location...

IDEALIZED ICE-SHEET DYNAMICS



Lago Vostok



V5 (3,369 unique gene sequences, 1,543 classified taxonomically)

psychrophiles, mesophiles, thermophiles
 autotrophs, heterotrophs
 aerobes, anaerobes
 central metabolism, N-fixation, nitrification, denitrification, C-fixation

Bacteria (96%)
 Firmicutes
 Cyanobacteria
 Actinobacteria
 Gammaproteobacteria
 Alphaproteobacteria
 Betaproteobacteria
 other bacteria

Archaea (<1%) (deep sediment and methanotroph species)

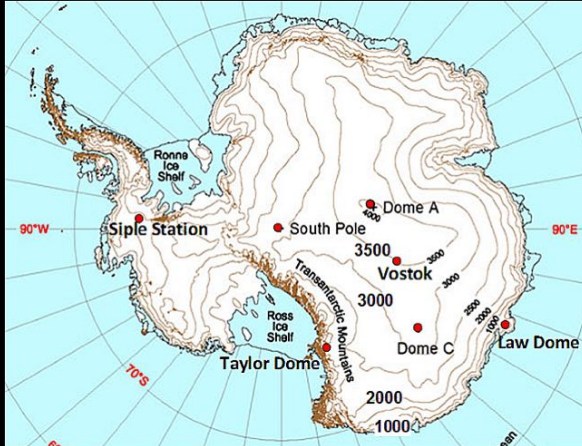
Eukarya (4%; the majority are Fungi)
Amoebozoa
 Archaeplastida (mainly green algae, pollen?)
 Animalia (e.g., rotifers, mollusk, arthropods, *Daphnia*, **brachiopod**, **tardigrade**, **sea anemone**, **bilaterian**)
 Fungi (Ascomycota, Basidiomycota, **Zygomycota**)
 Chromalveolata (e.g., diatoms, dinoflagellates, yellow-green algae, ciliates)
 Excavata
Rhizaria (*Paulinella* sp.)

V6 (138 unique sequences, 80 classified taxonomically)

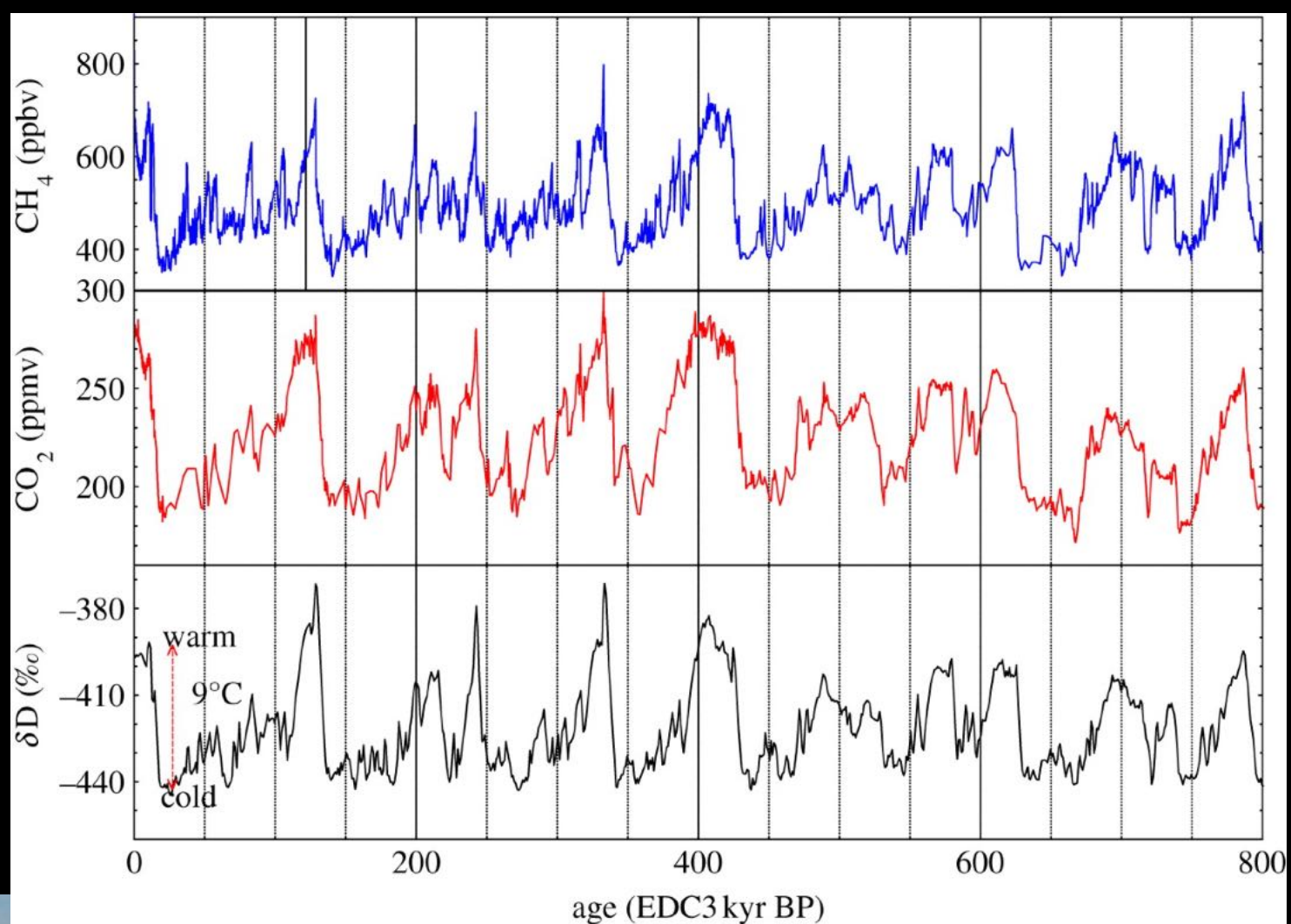
psychrophiles, mesophiles, thermophiles
 autotrophs, heterotrophs
 aerobes, anaerobes
 central metabolism, N-fixation, nitrification, denitrification, C-fixation

Bacteria (77%)
 Gammaproteobacteria
 Betaproteobacteria
 Firmicutes
 Actinobacteria
 other bacteria

Eukarya (23%; the majority are Fungi)
 Fungi (e.g. thermal vent fungus, Antarctic)
 Archaeplastida (pollen?)
 Animalia (arthropods, **fish**, **annelid**)



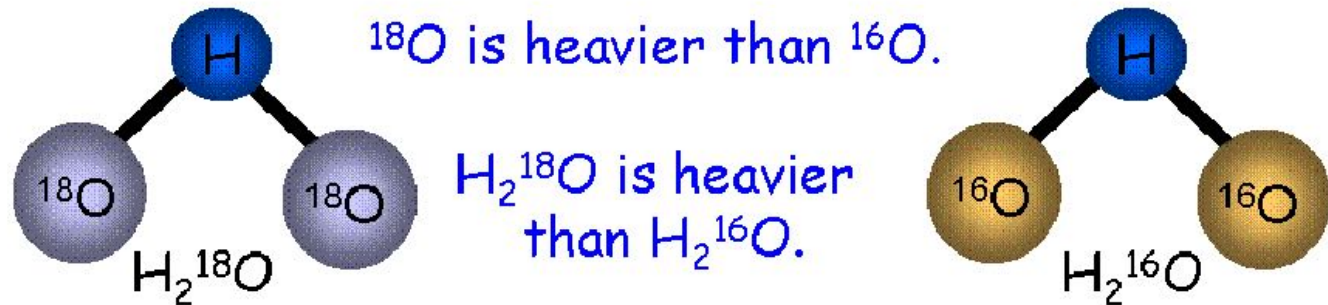
Dome C



Fracionamento isotópico

$$\delta^{18}\text{O} = \frac{(^{18}\text{O}/^{16}\text{O})_{\text{amostra}} - (^{18}\text{O}/^{16}\text{O})_{\text{referência}}}{(^{18}\text{O}/^{16}\text{O})_{\text{referência}}}$$

- Oxygen isotopes are **fractionated** during evaporation and precipitation of H_2O
 - H_2^{16}O evaporates more readily than H_2^{18}O
 - H_2^{18}O precipitates more readily than H_2^{16}O

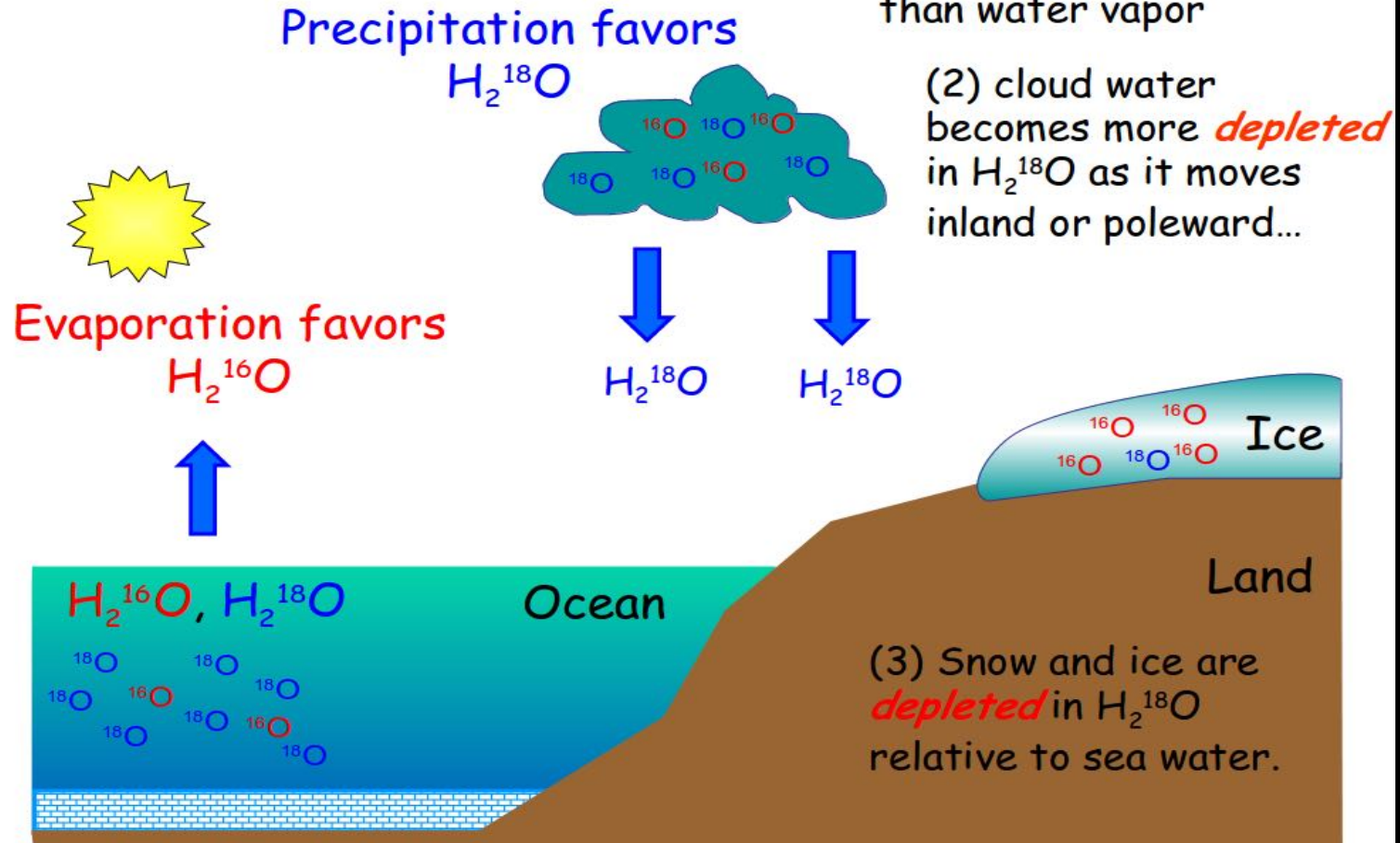


- Oxygen isotopes are also **fractionated** by marine organisms that secrete CaCO_3 shells. The organisms preferentially take up more ^{16}O as temperature increases.

Fracionamento isotópico

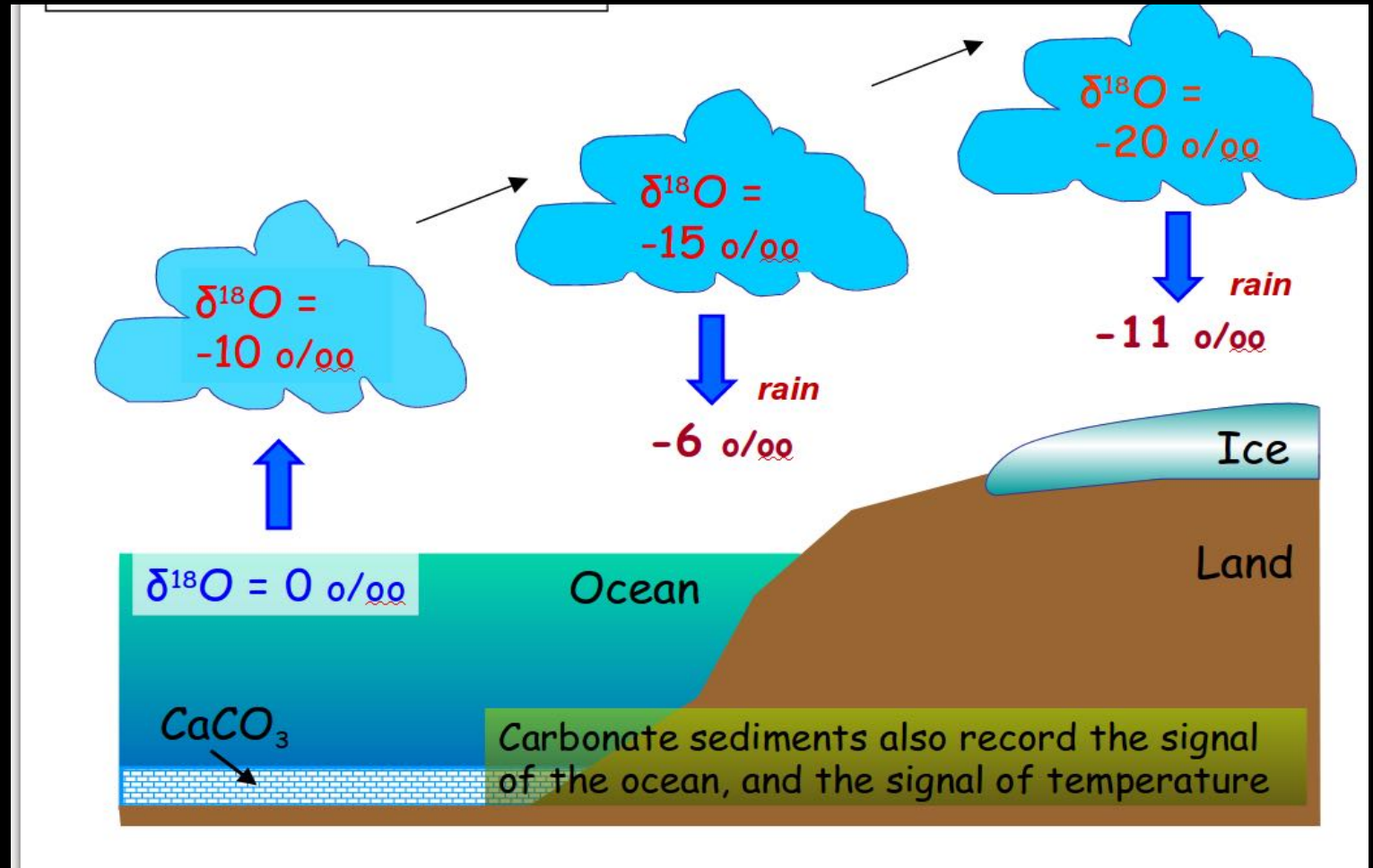
$$\delta^{18}O = \frac{(^{18}O/^{16}O)_{amostra} - (^{18}O/^{16}O)_{referência}}{(^{18}O/^{16}O)_{referência}}$$

Fractionation effects



Fracionamento isotópico

$$\delta^{18}\text{O} = \frac{(^{18}\text{O}/^{16}\text{O})_{\text{amostra}} - (^{18}\text{O}/^{16}\text{O})_{\text{referência}}}{(^{18}\text{O}/^{16}\text{O})_{\text{referência}}}$$



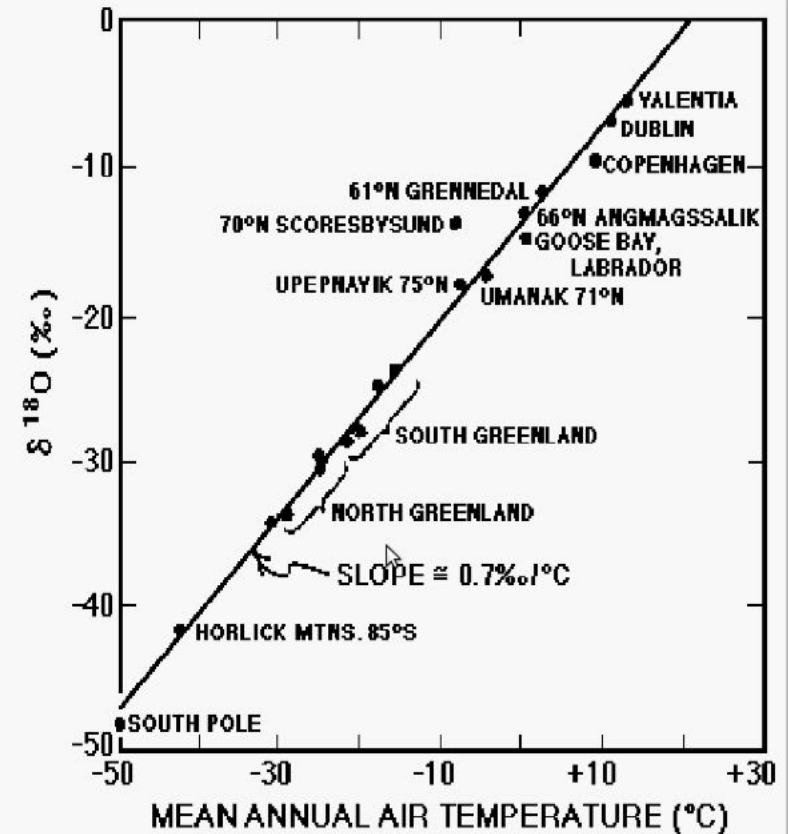
Fracionamento isotópico

$$\delta^{18}\text{O} = \frac{(^{18}\text{O}/^{16}\text{O})_{\text{amostra}} - (^{18}\text{O}/^{16}\text{O})_{\text{referência}}}{(^{18}\text{O}/^{16}\text{O})_{\text{referência}}}$$

We can also show that the $\delta^{18}\text{O}$ of precipitation is well correlated with temperature!

So, if we know the $\delta^{18}\text{O}$ of water or ice, we know what the air temperature was at that time.

(Note that hydrogen isotopes work the same way)

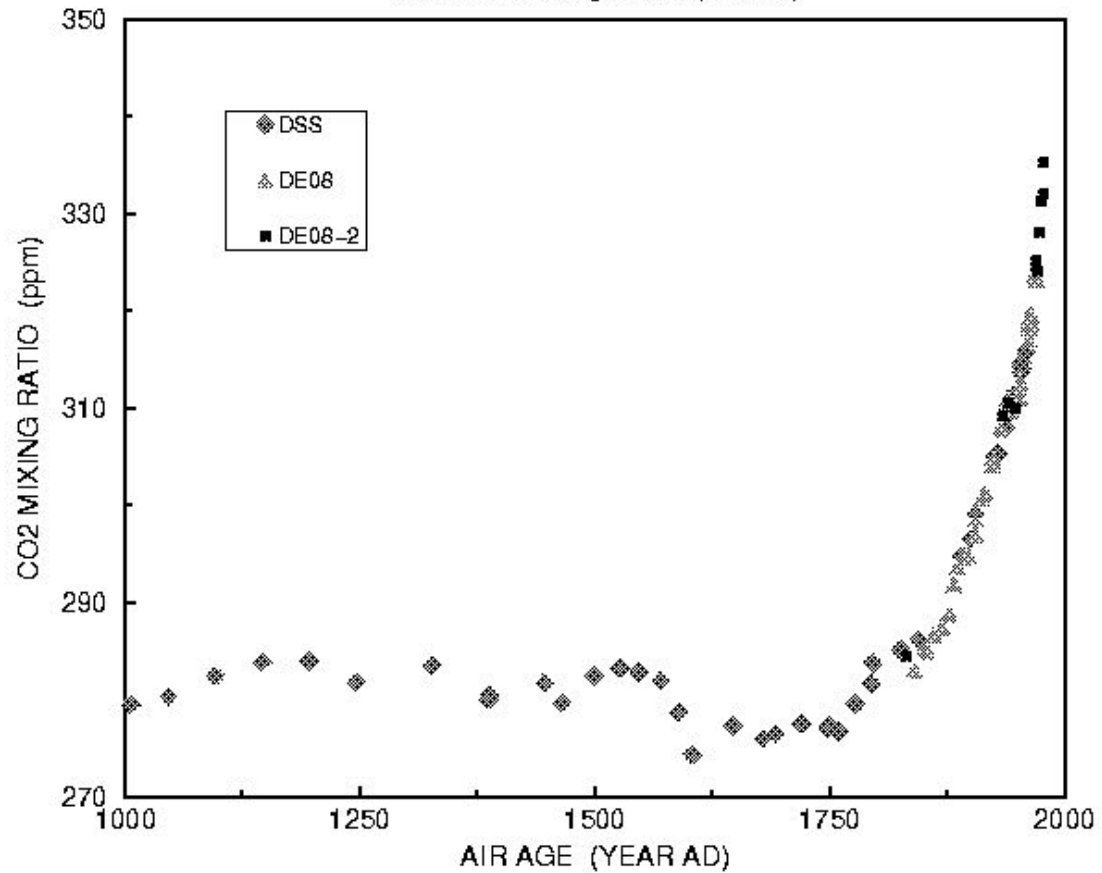


Observed $\delta^{18}\text{O}$ in average annual precipitation as a function of mean annual air temperature (Dansgaard, 1964). Note that all the points on this graph are for high latitudes ($>45^\circ$).

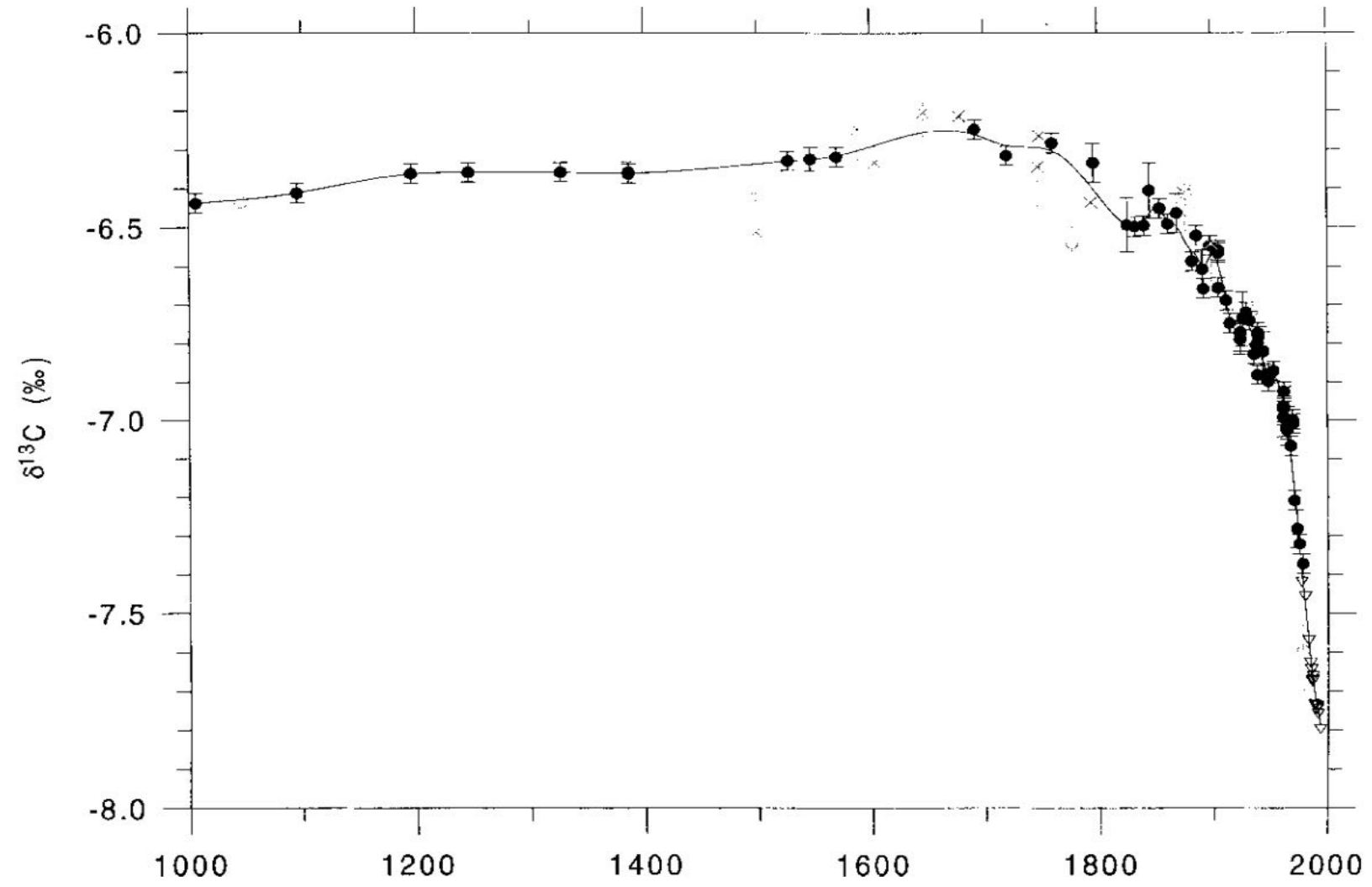
Concentração de CO₂

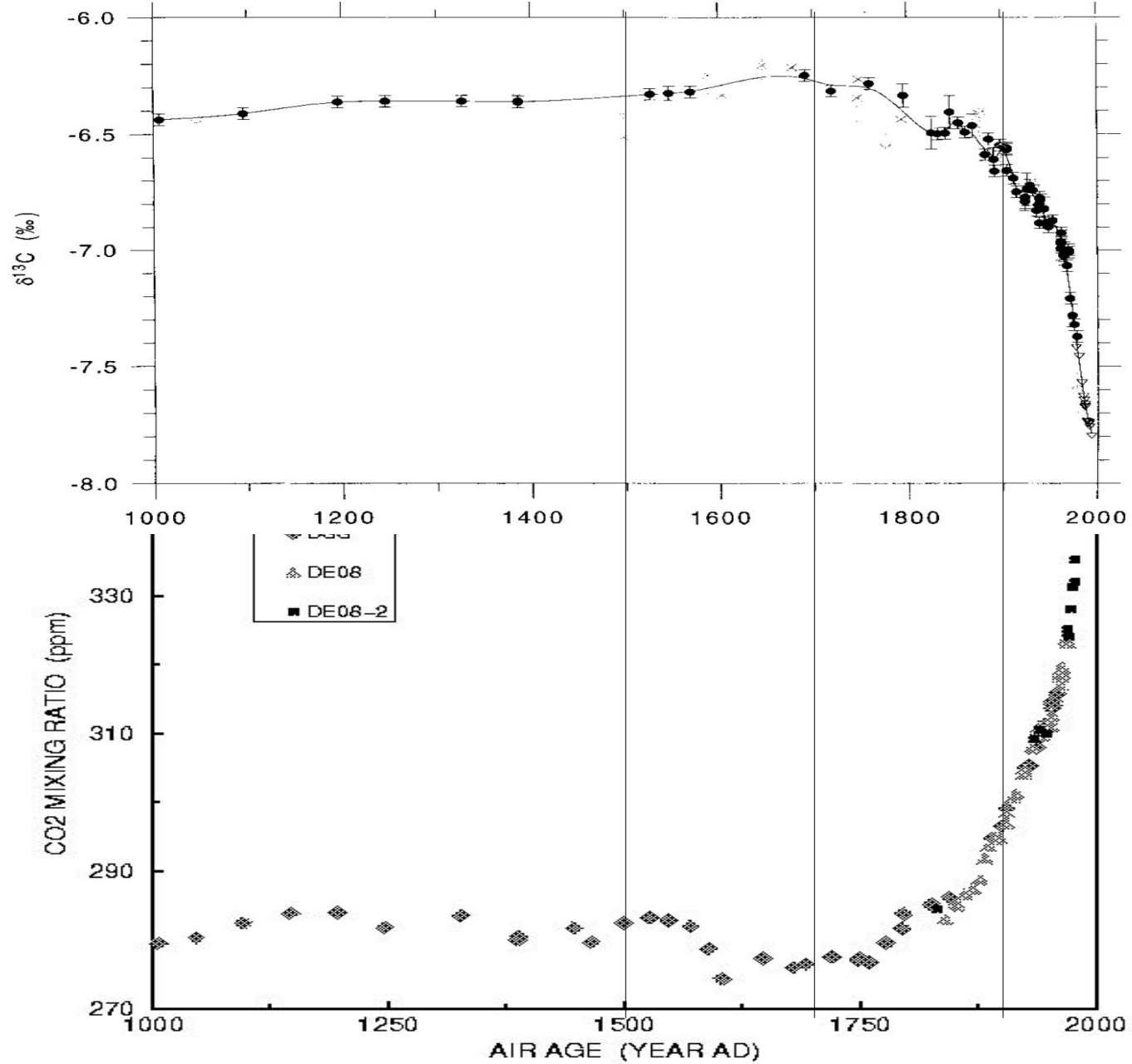
LAW DOME, ANTARCTICA ICE CORES

Source: Etheridge et al. (CSIRO)

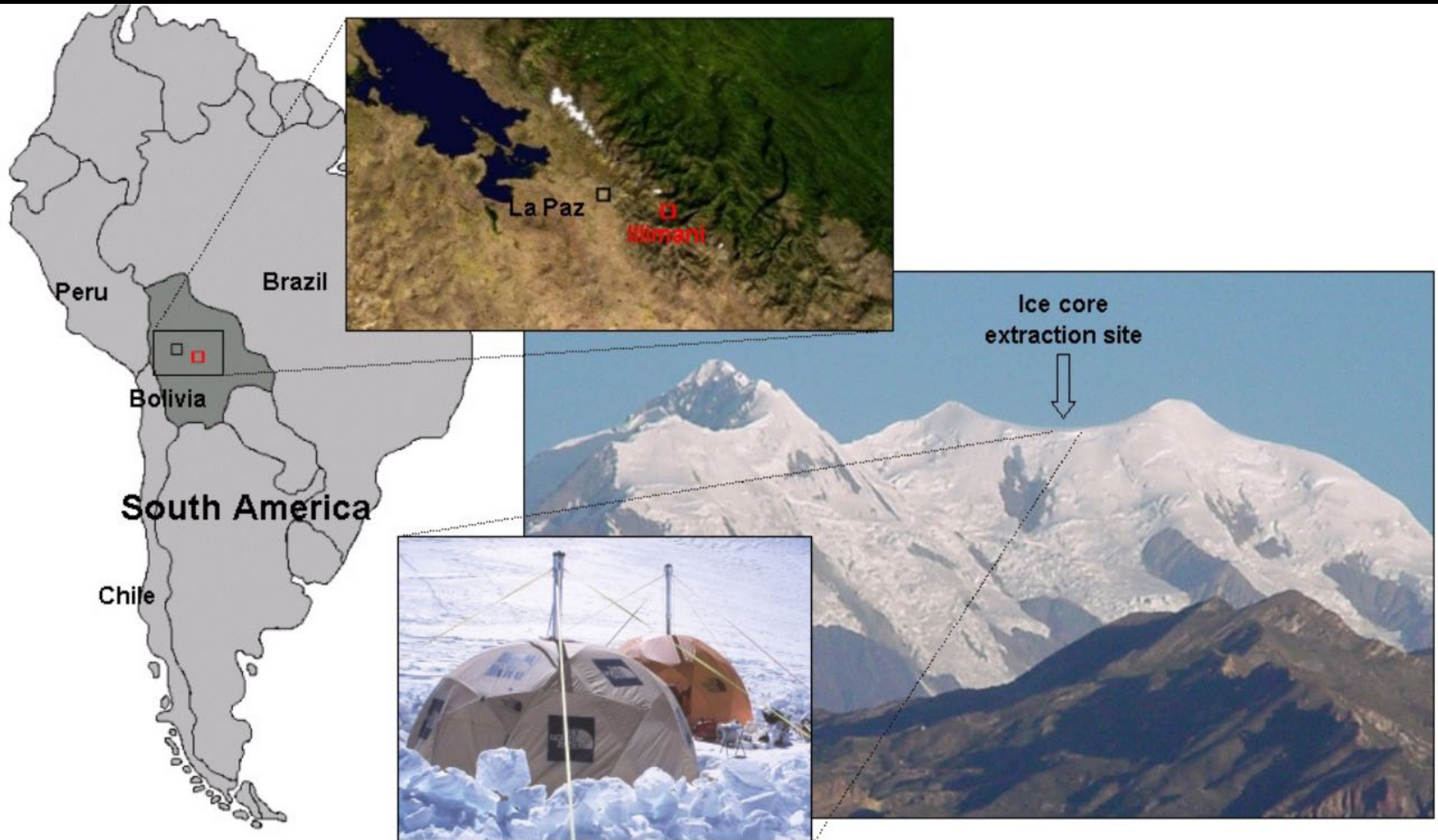


Fracionamento de ^{13}C





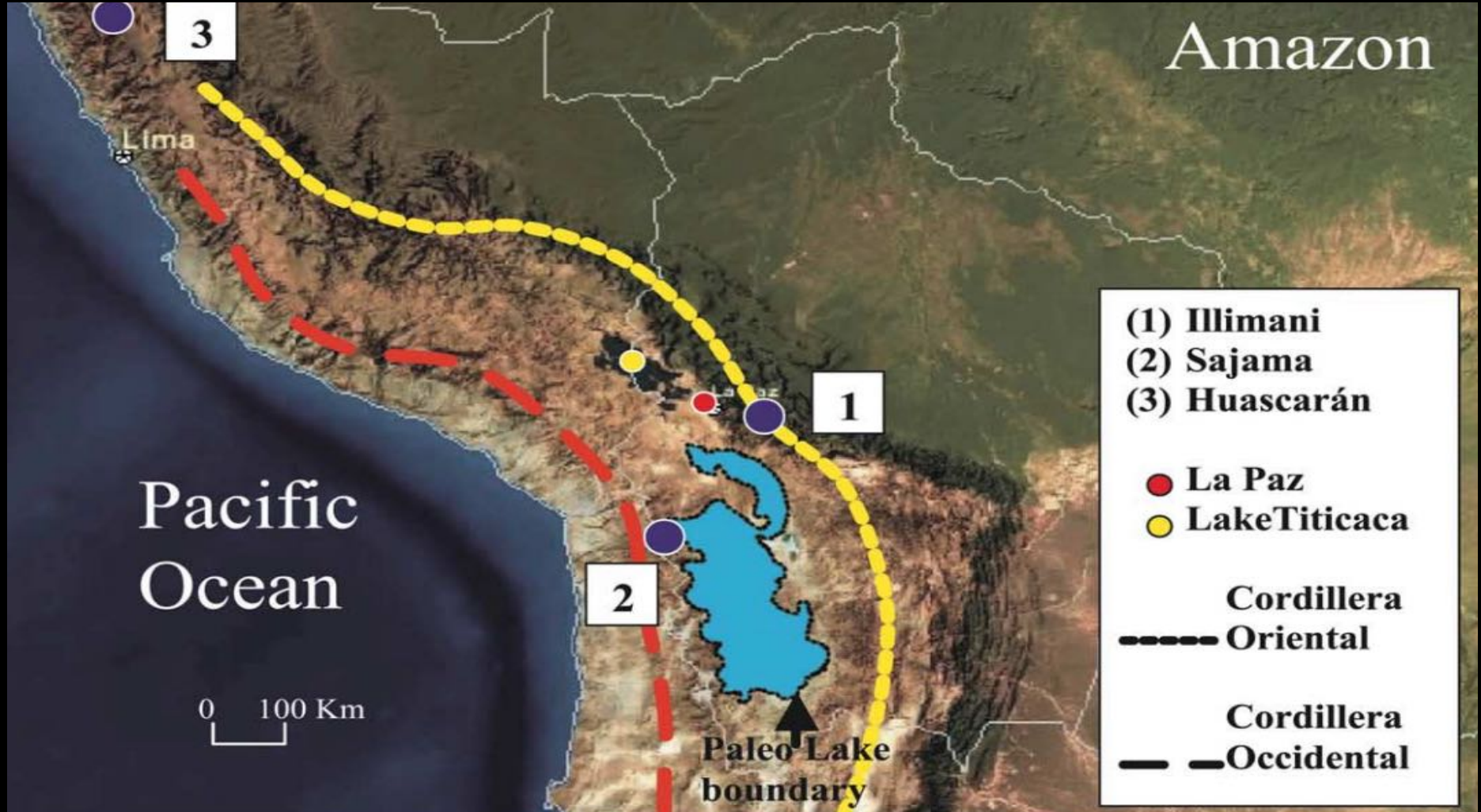
O testemunho de gelo de Illimani, Bolívia



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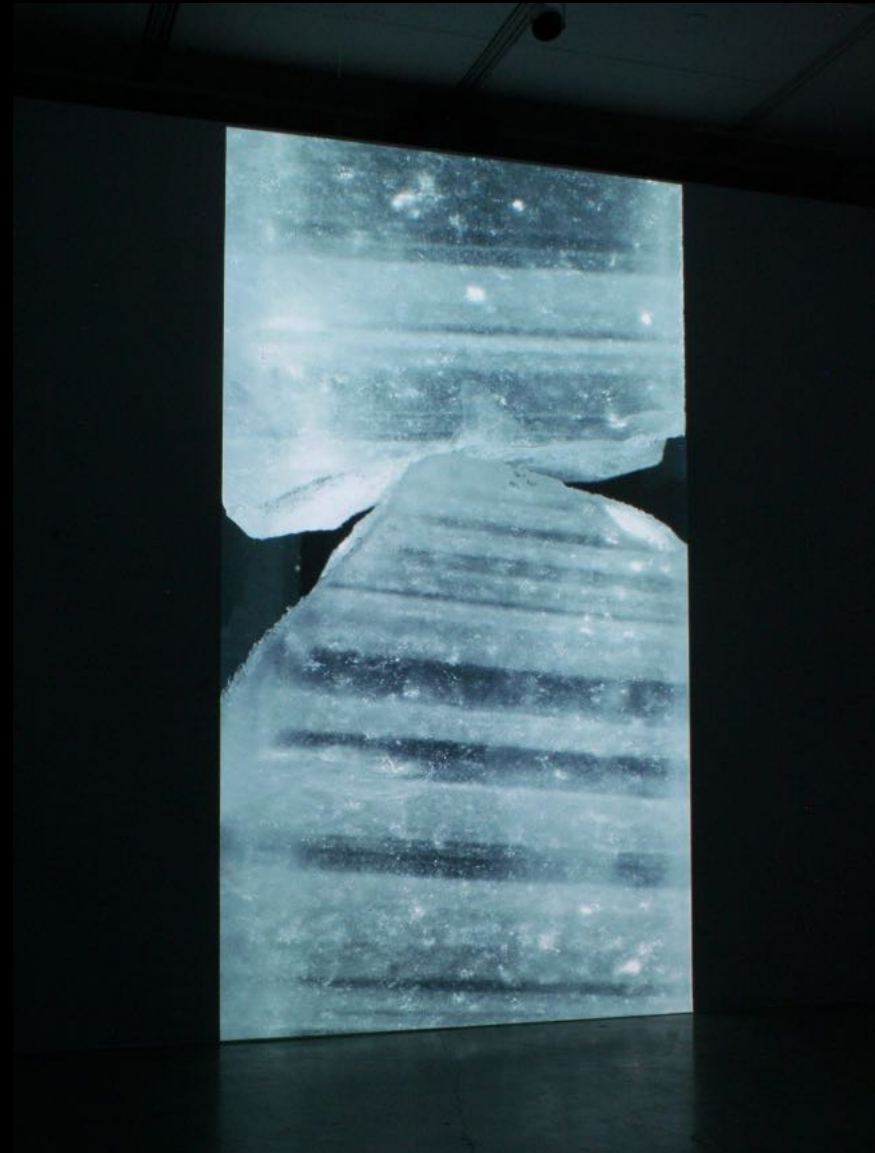
O testemunho de gelo de Illimani, Bolívia



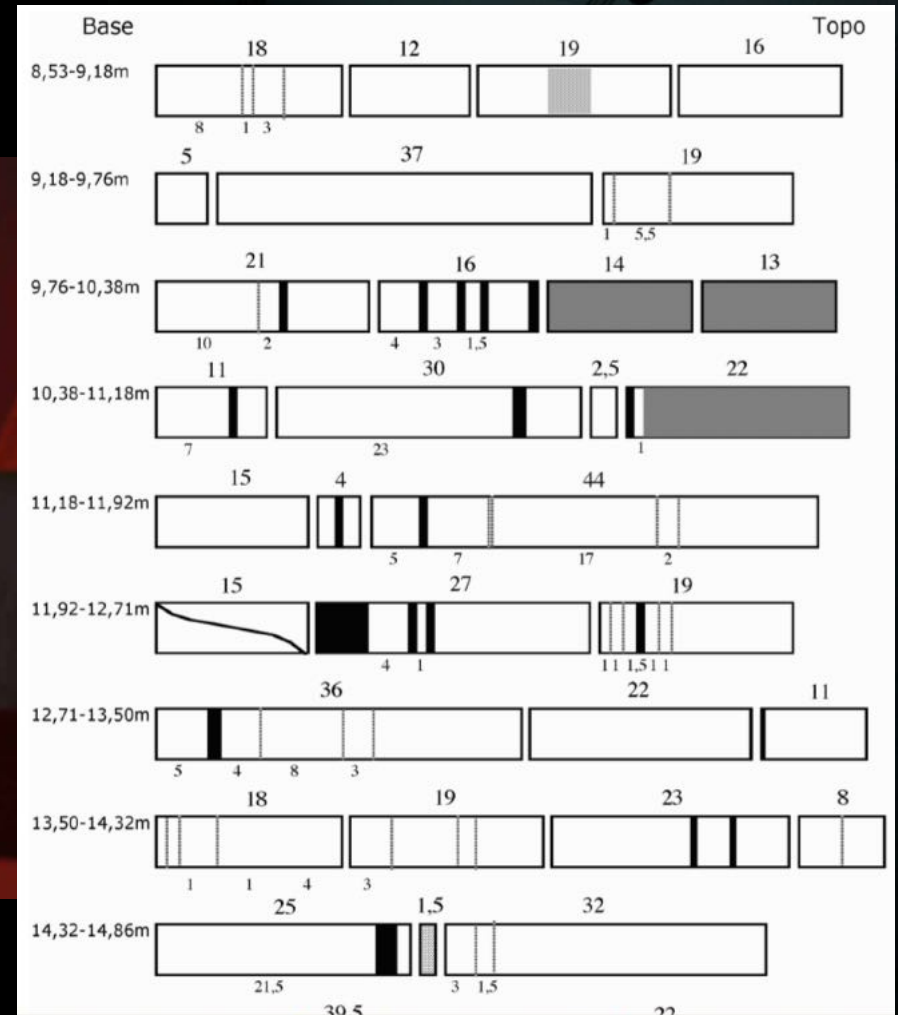
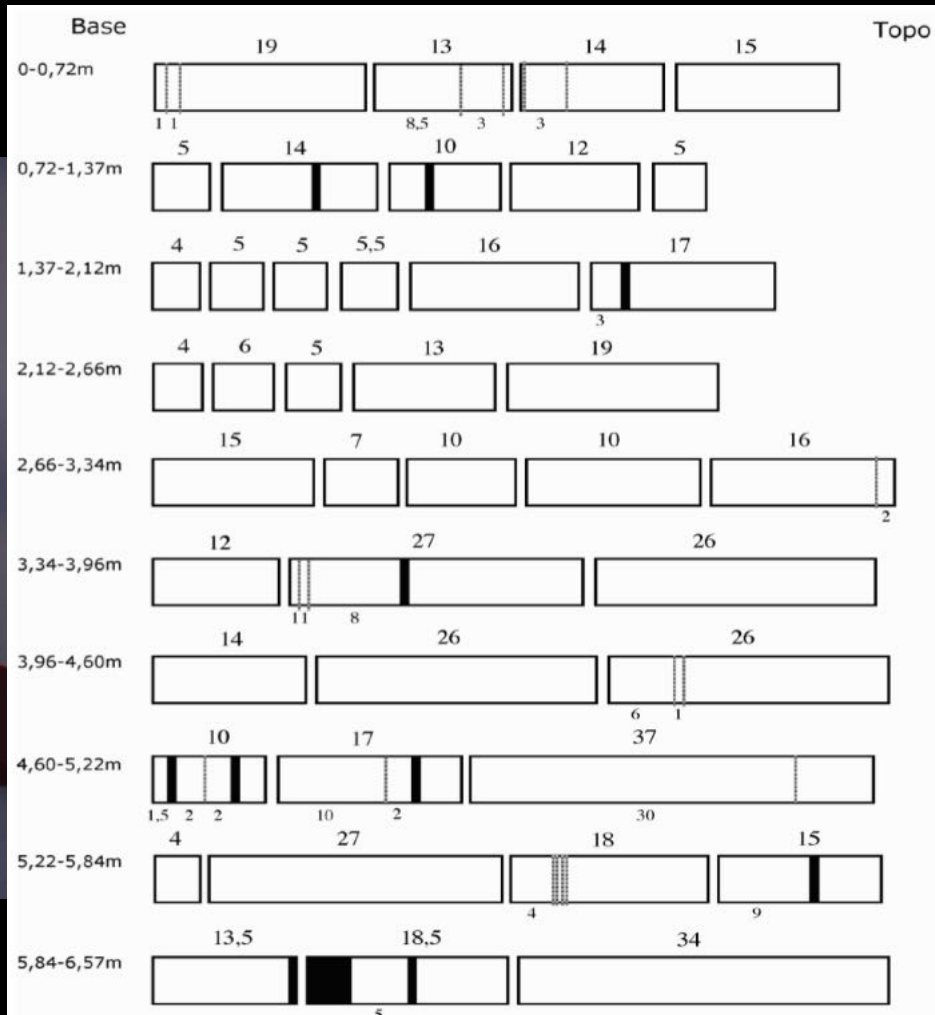
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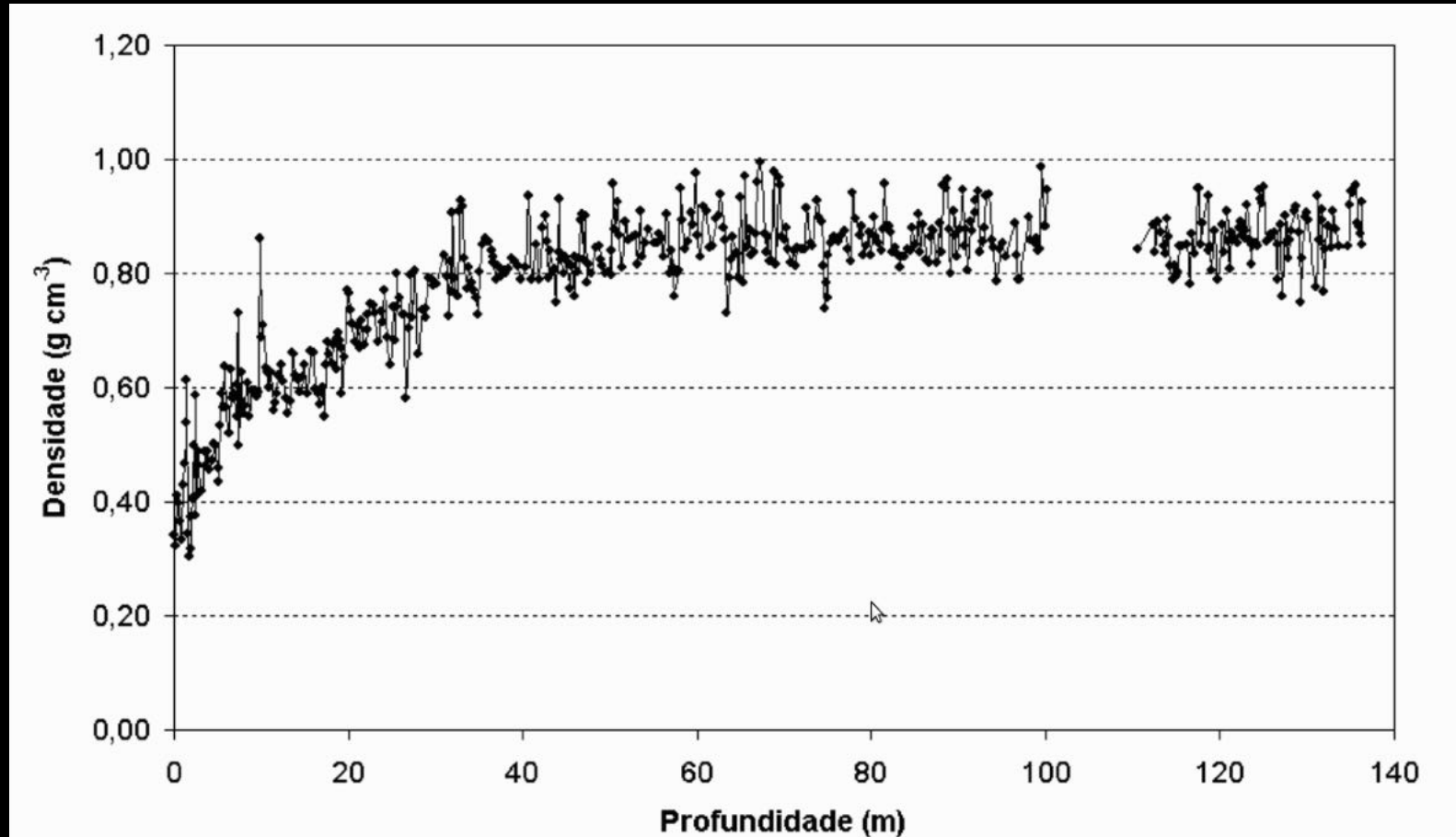
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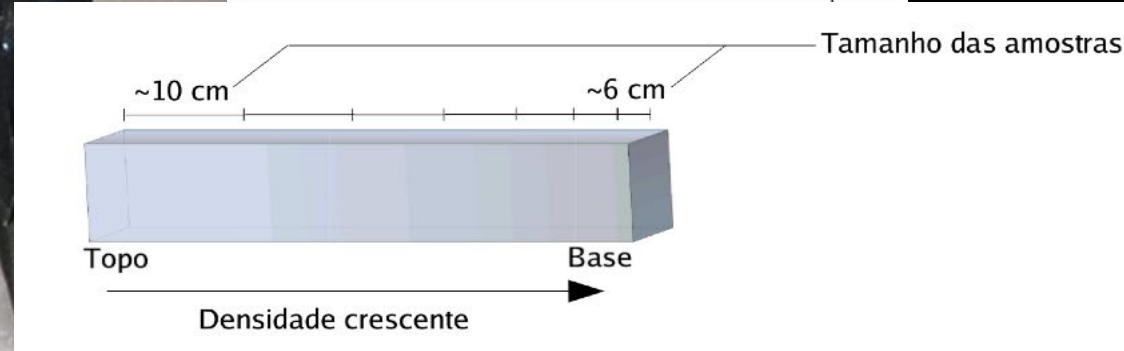
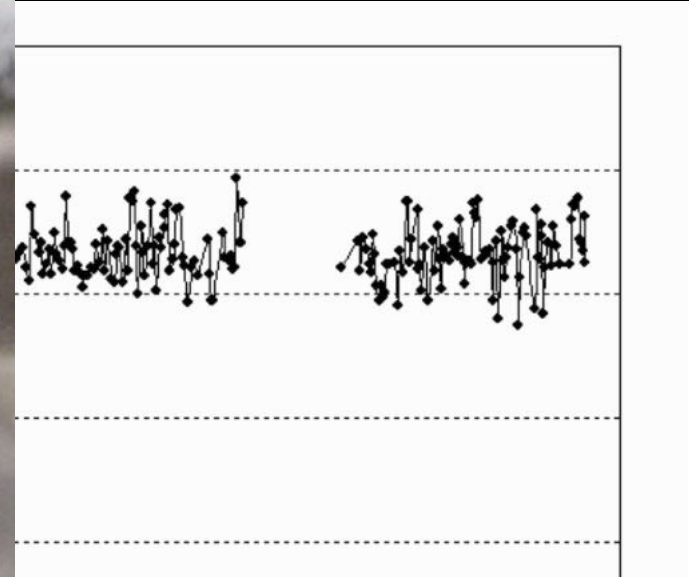
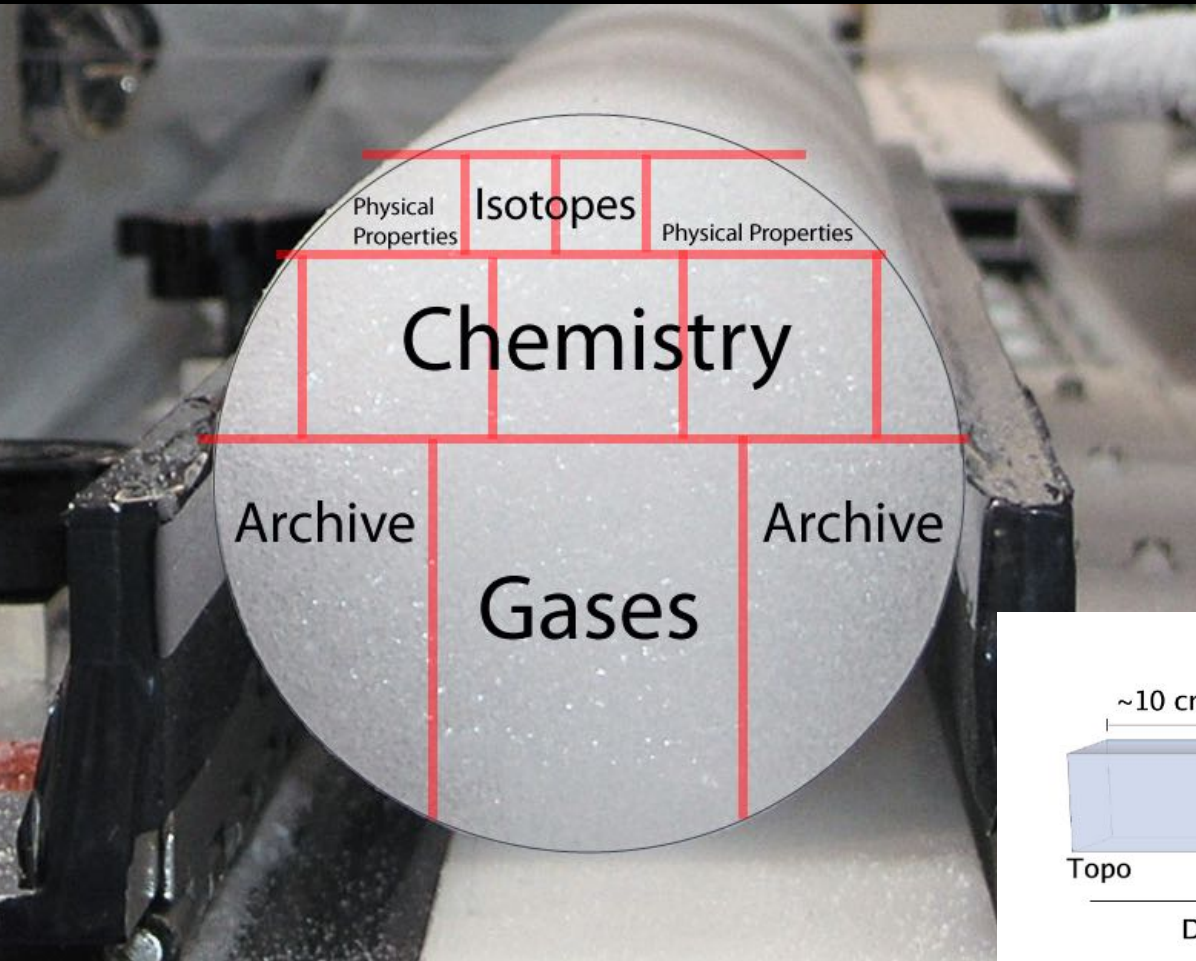
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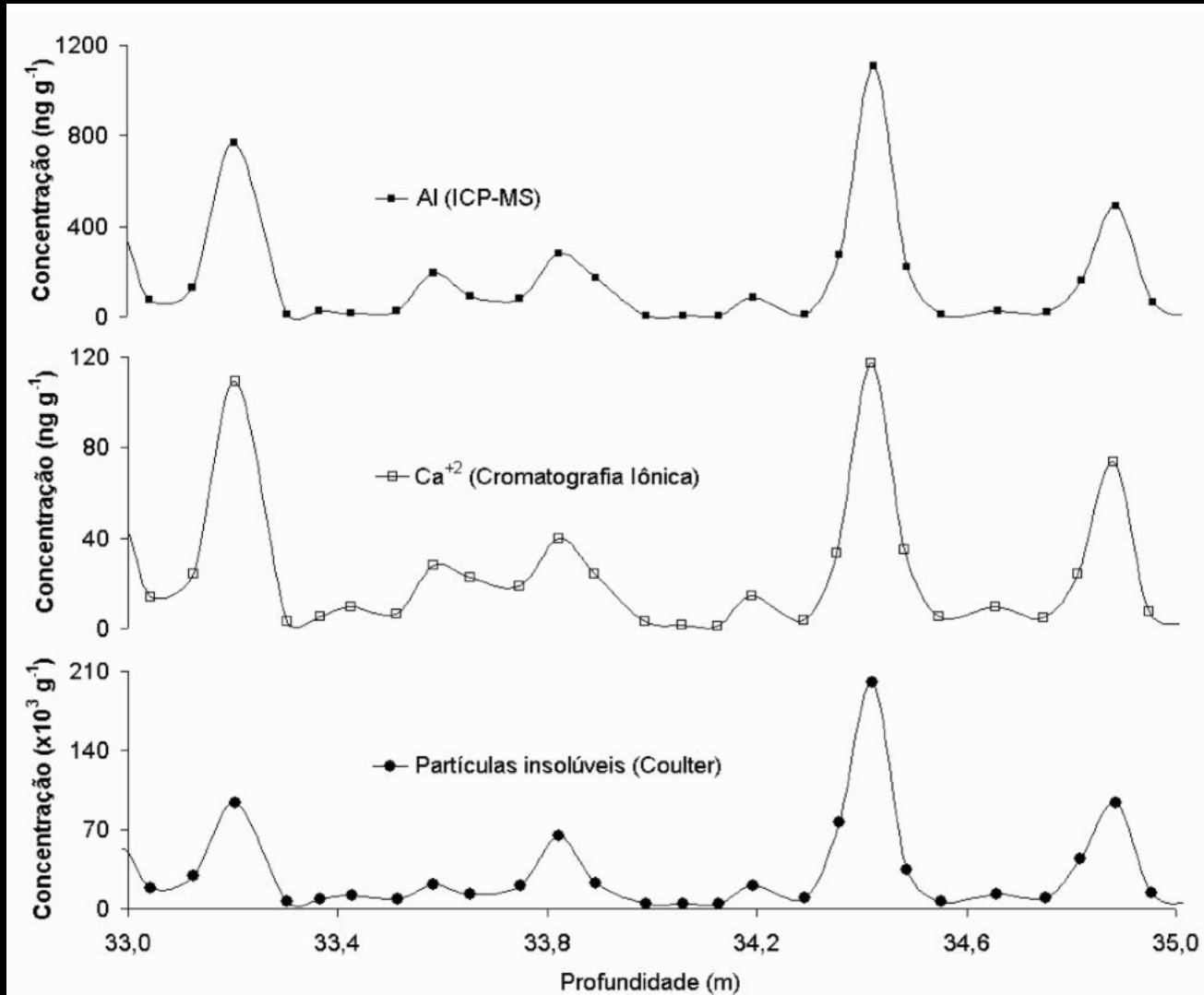
O testemunho de gelo de Illimani, Bolívia

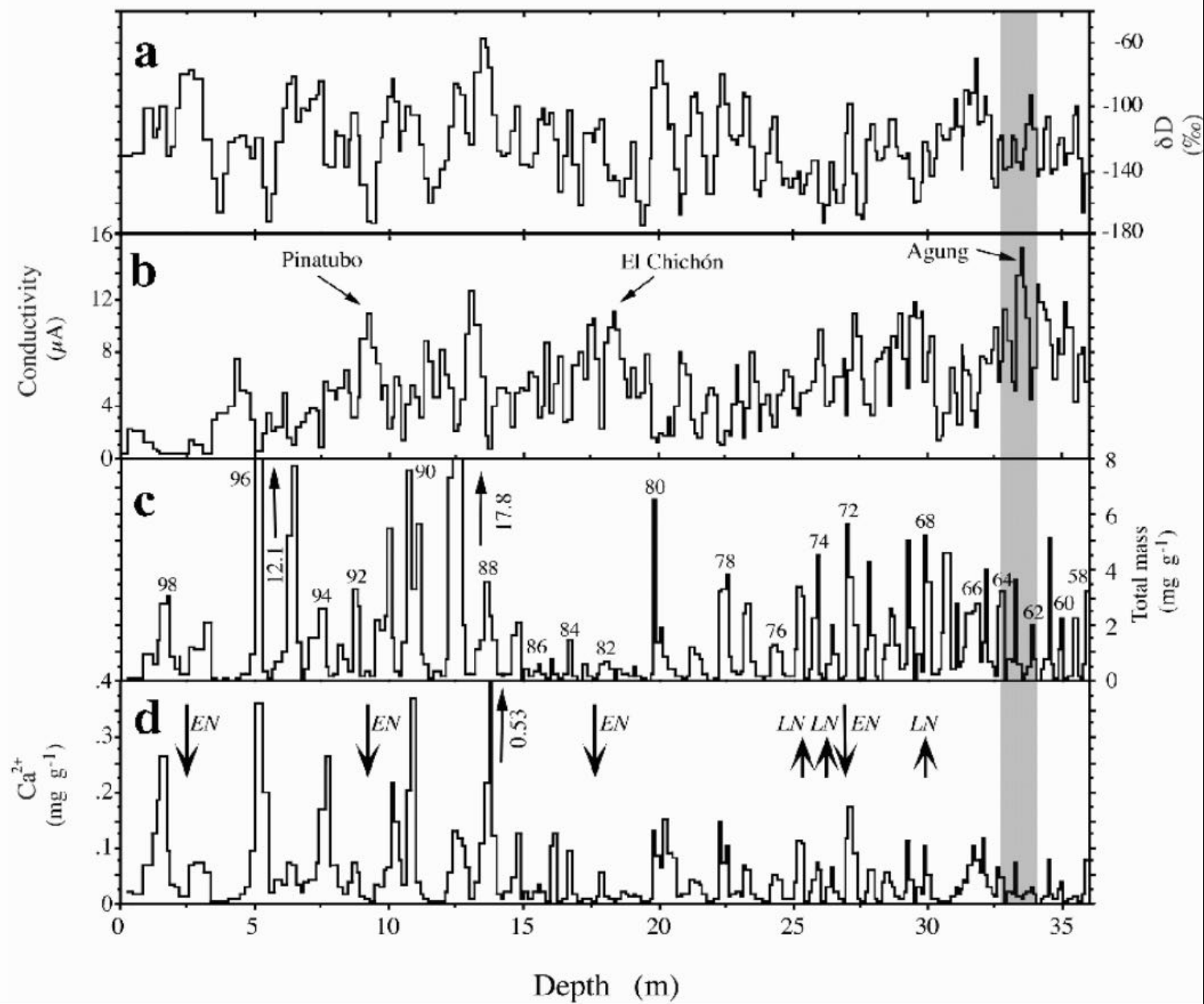


O testemunho de gelo de Illimani, Bolívia



O testemunho de gelo de Illimani, Bolívia





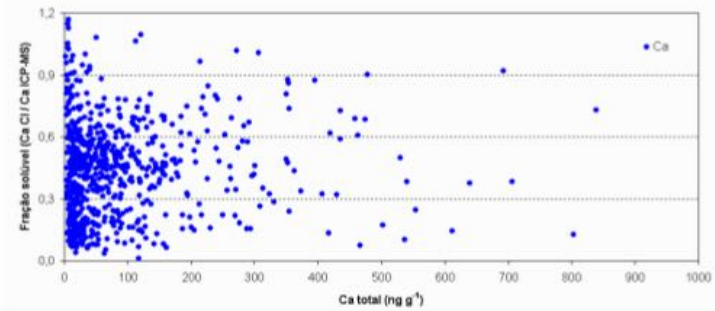
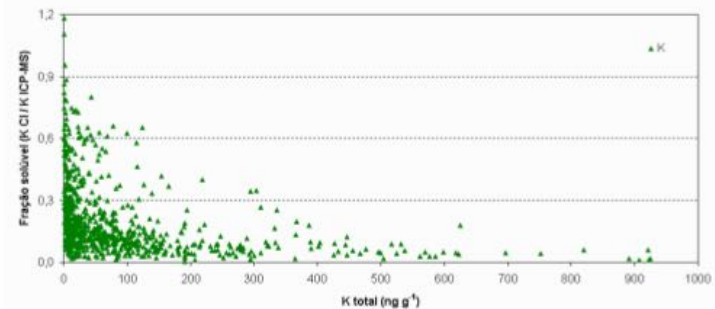
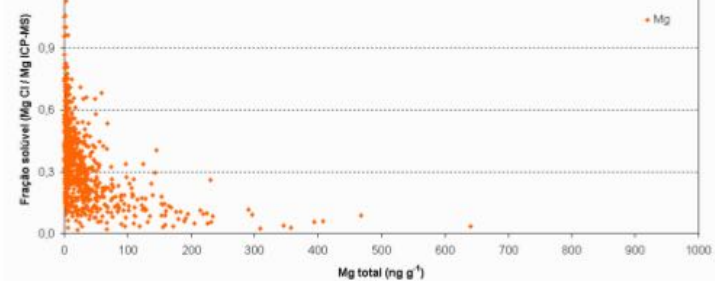
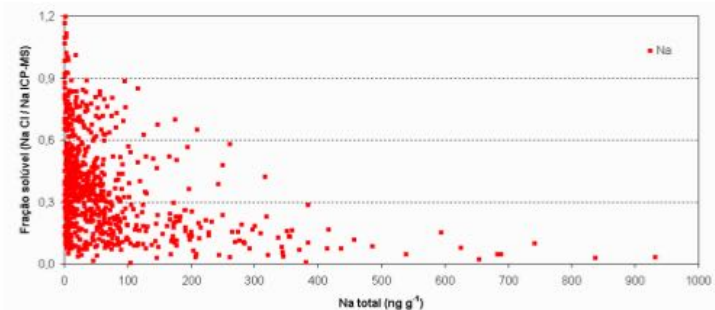
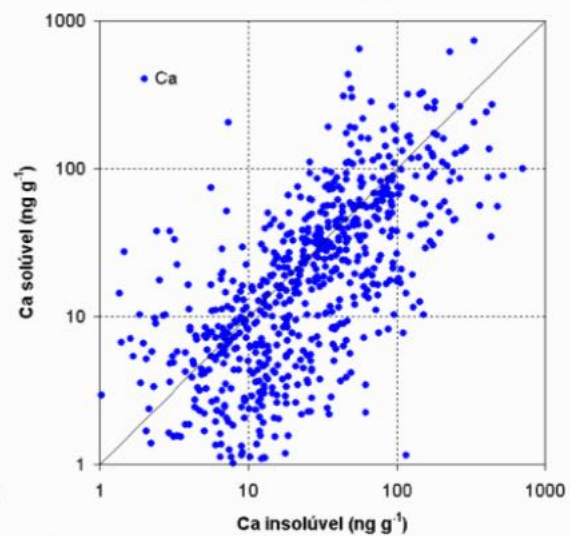
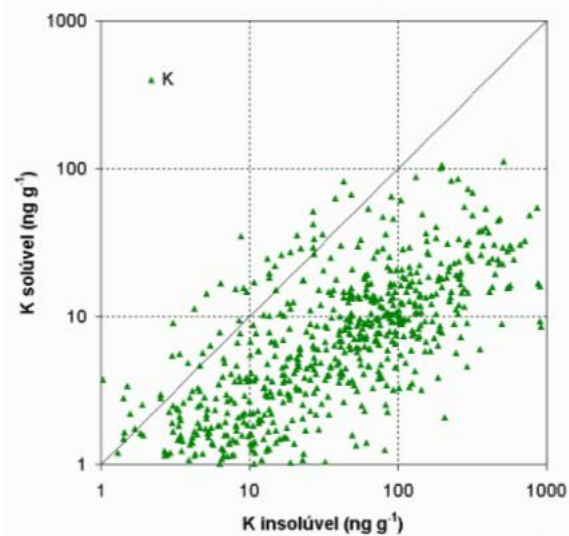
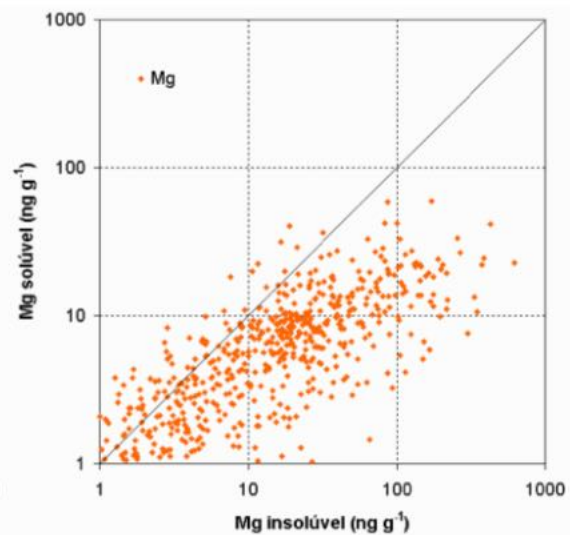
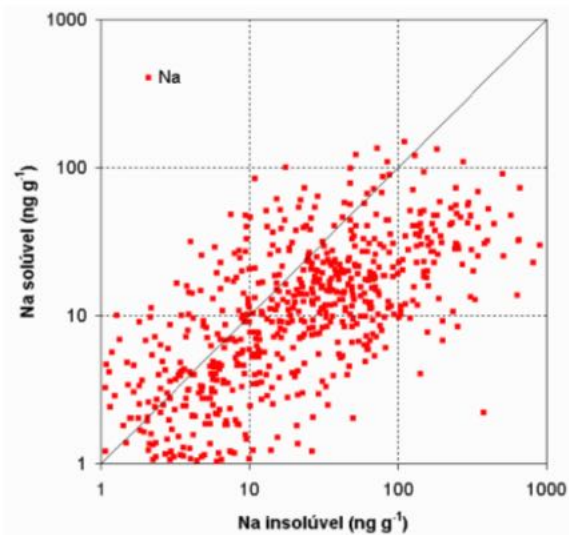
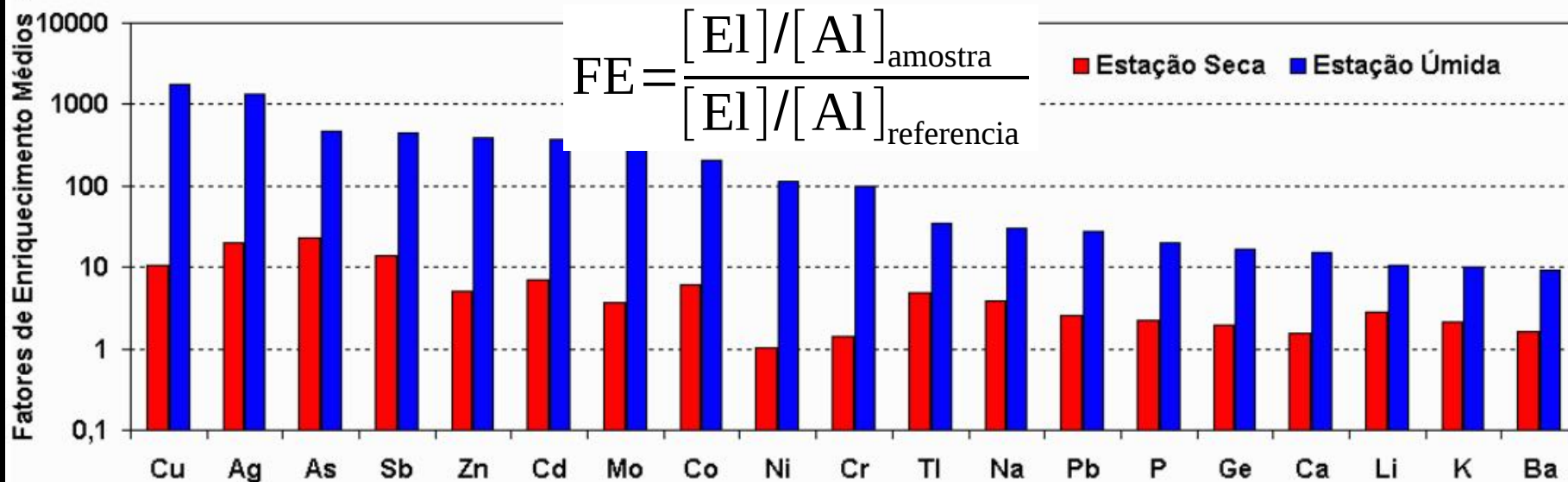


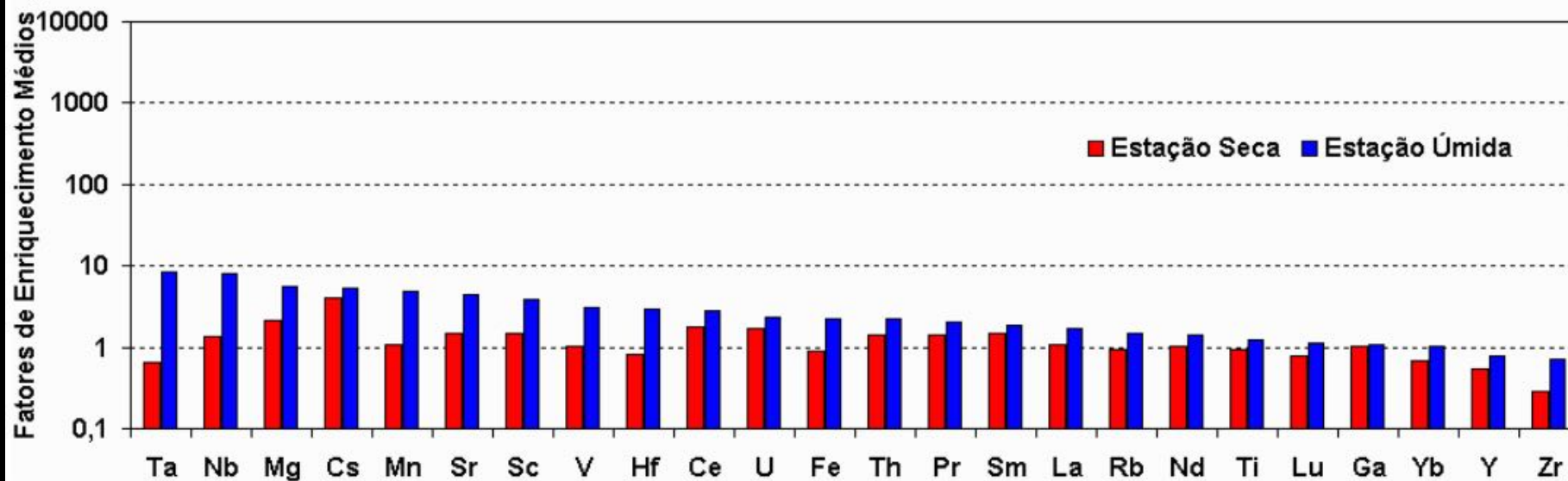
Figure 4.9. Comparison between the soluble and insoluble fractions of Na, Mg, K, and Ca in the soil samples.

Fatores de Enriquecimento Médios

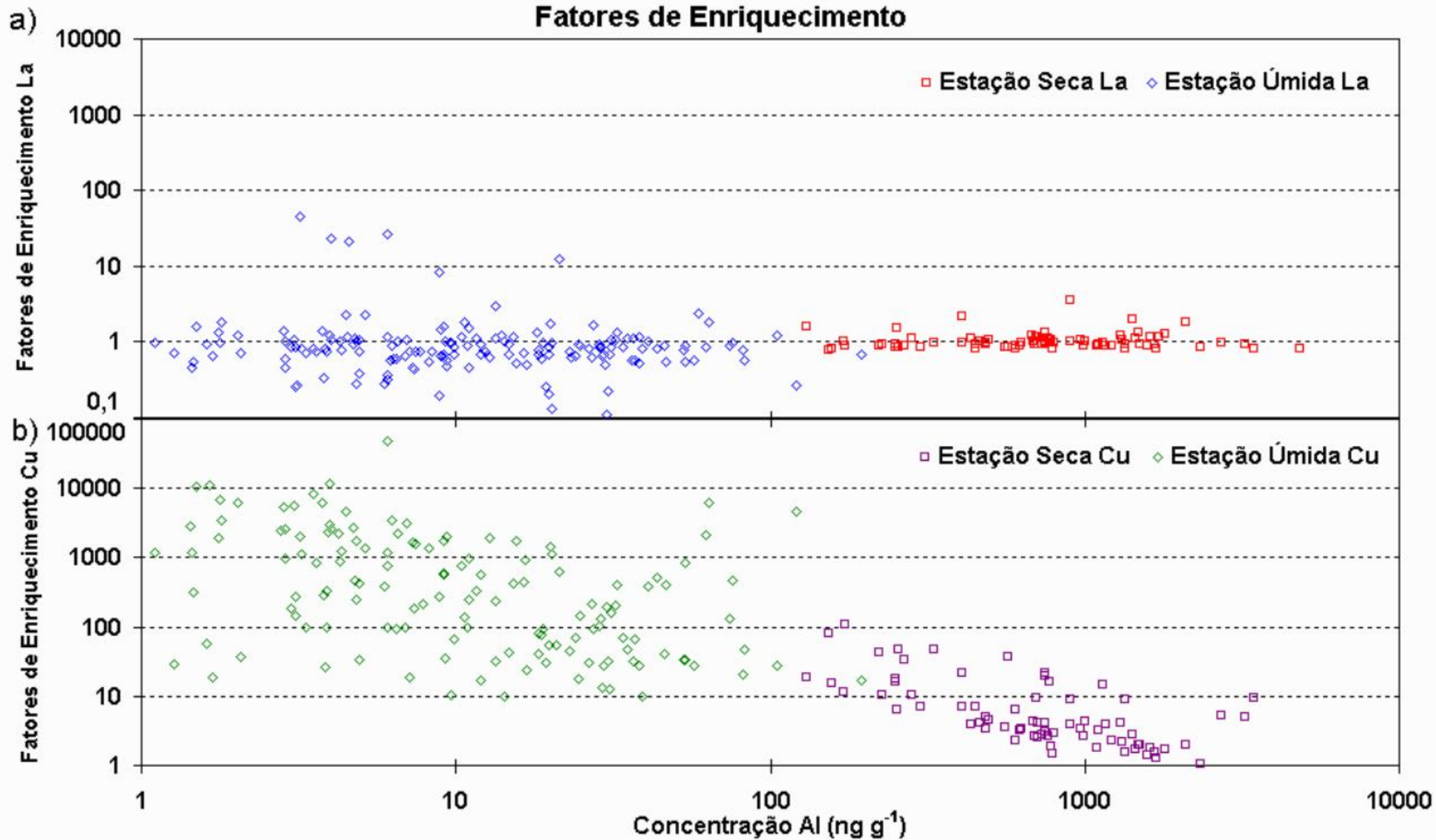
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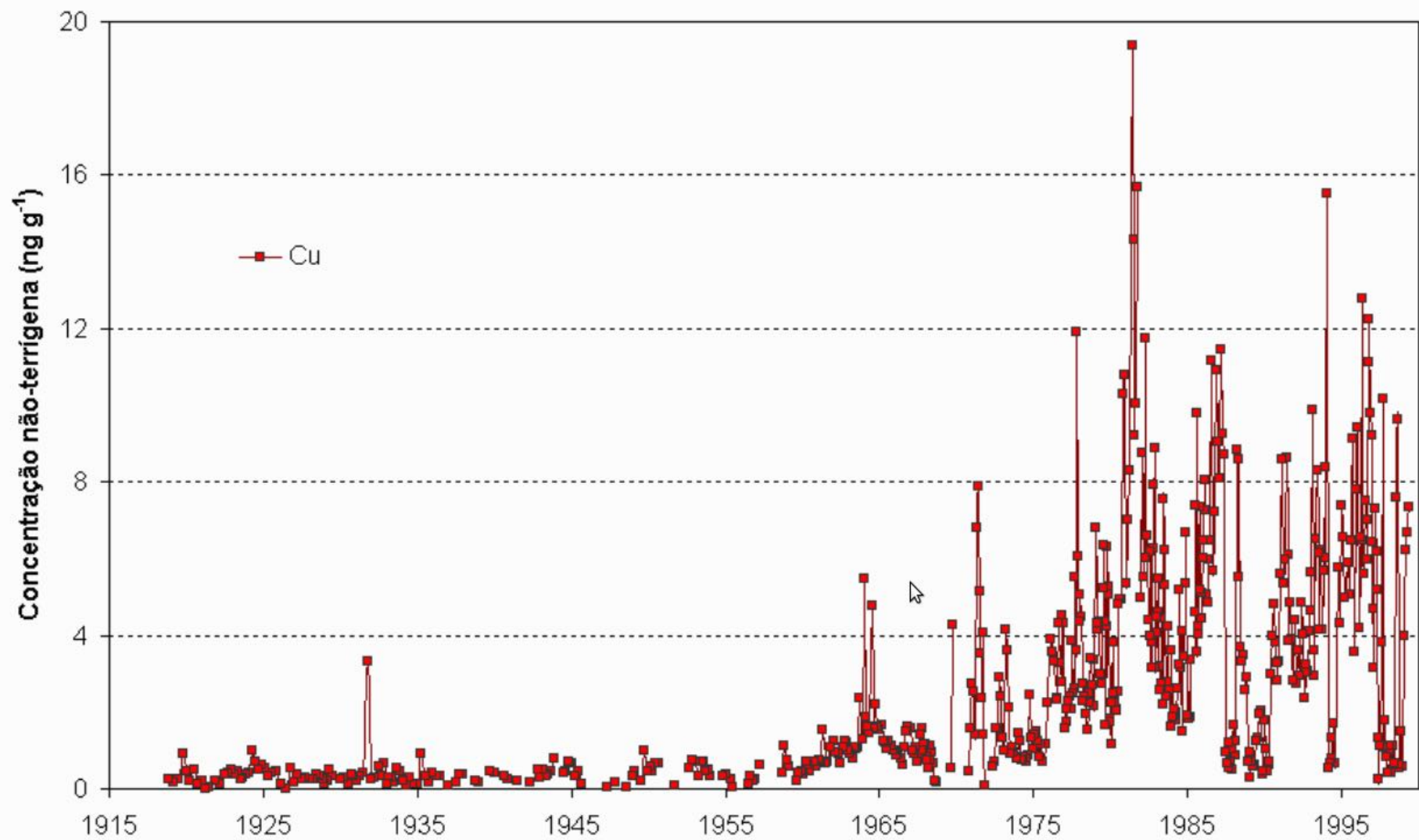


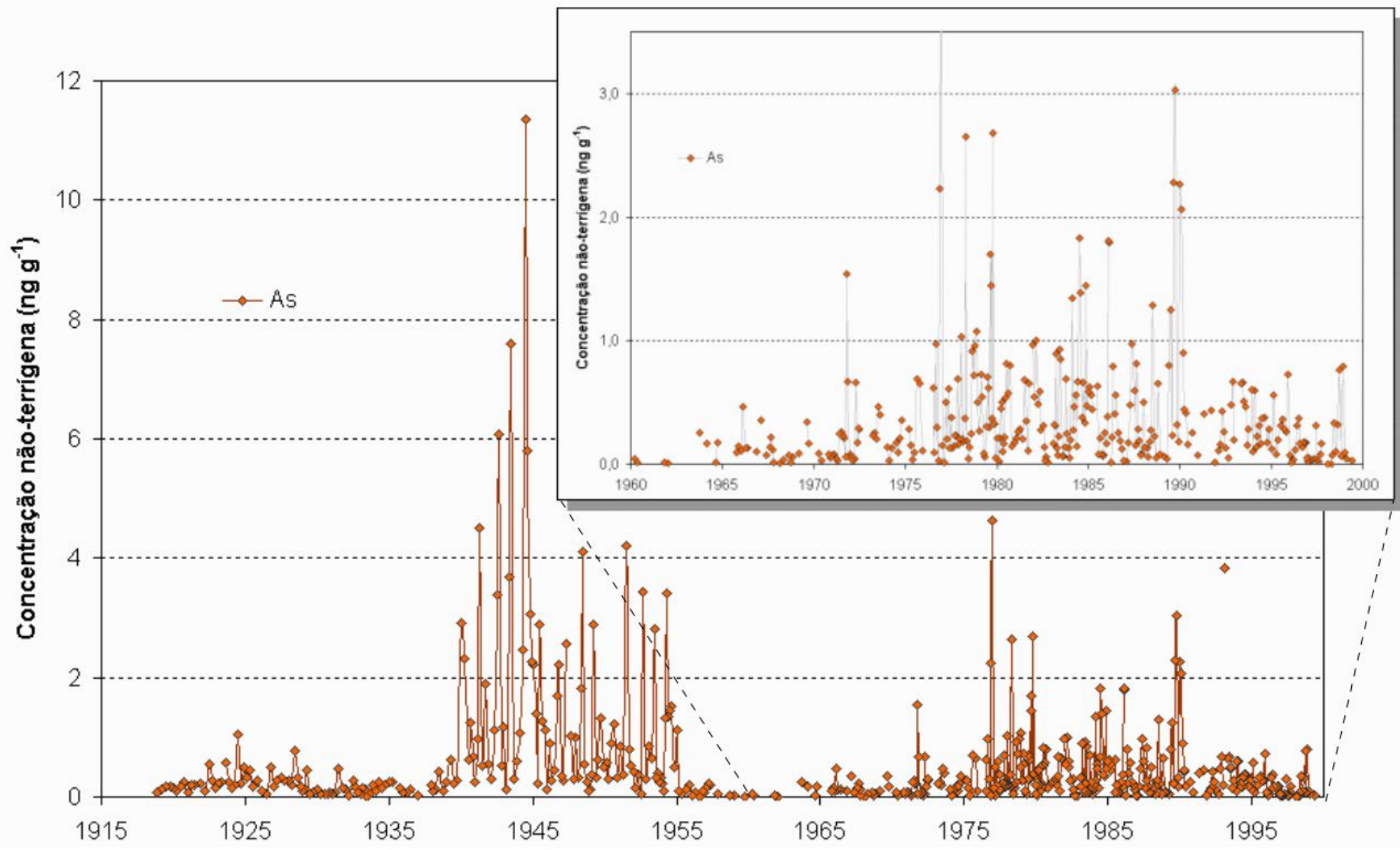
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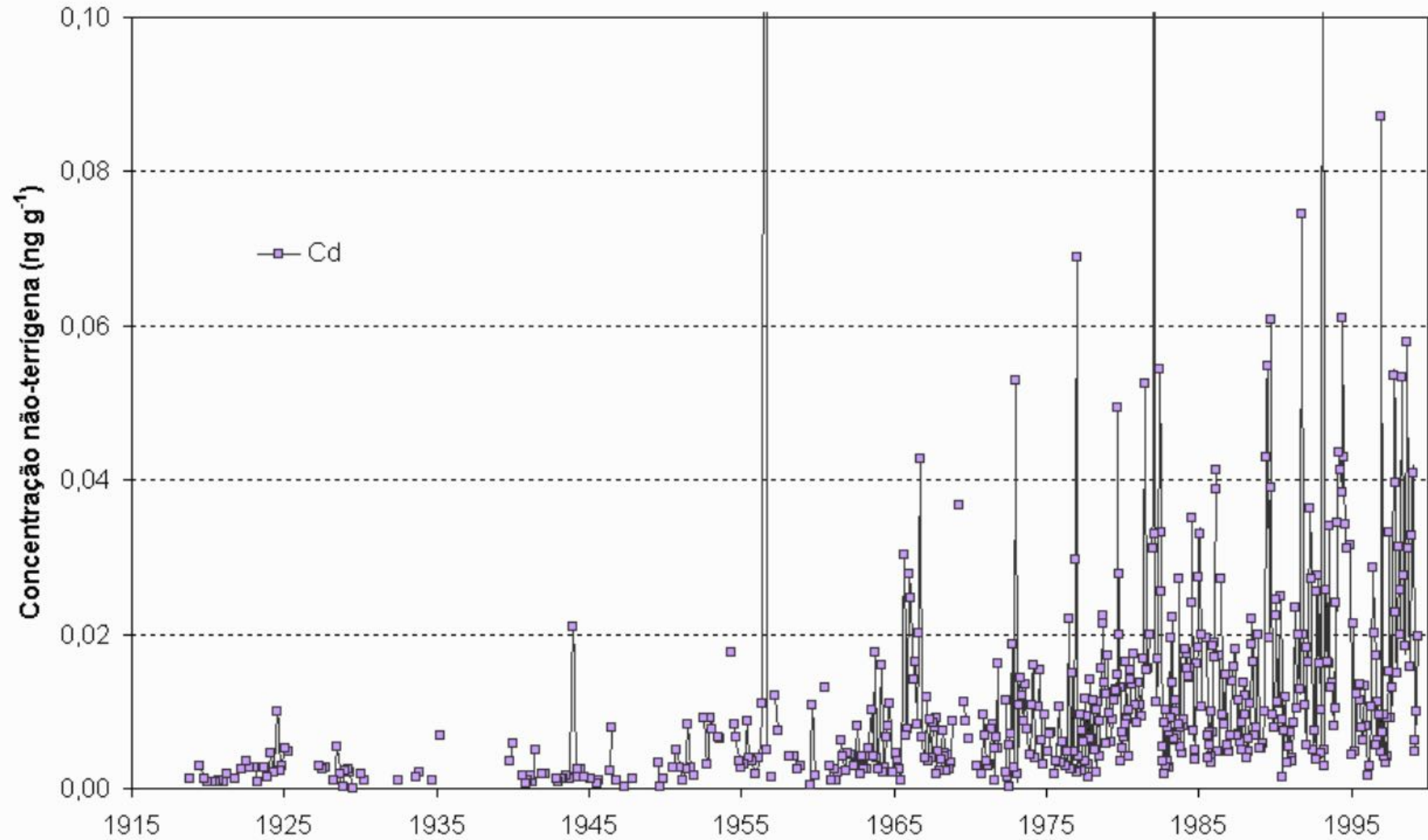


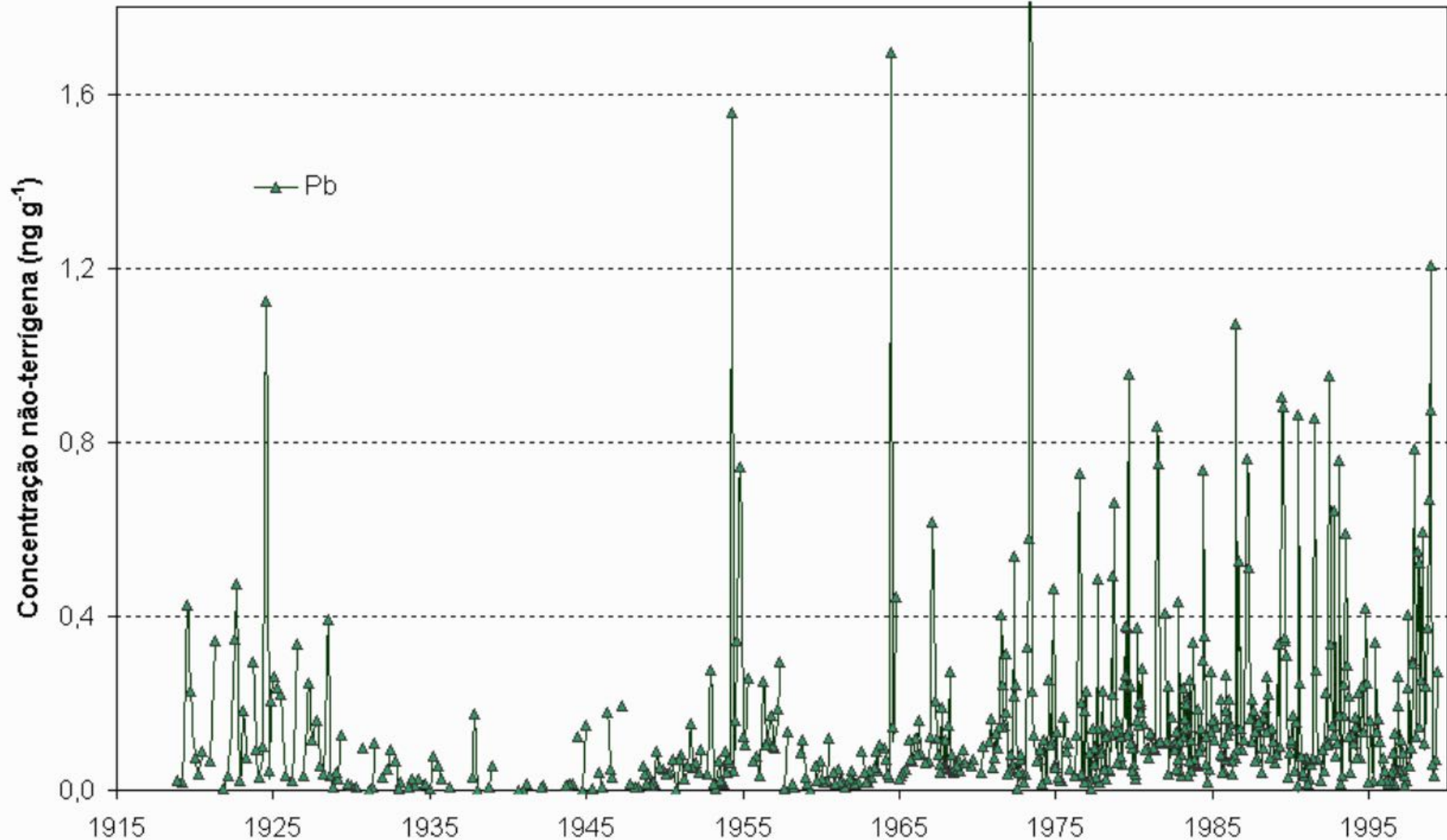
Fatores de Enriquecimento

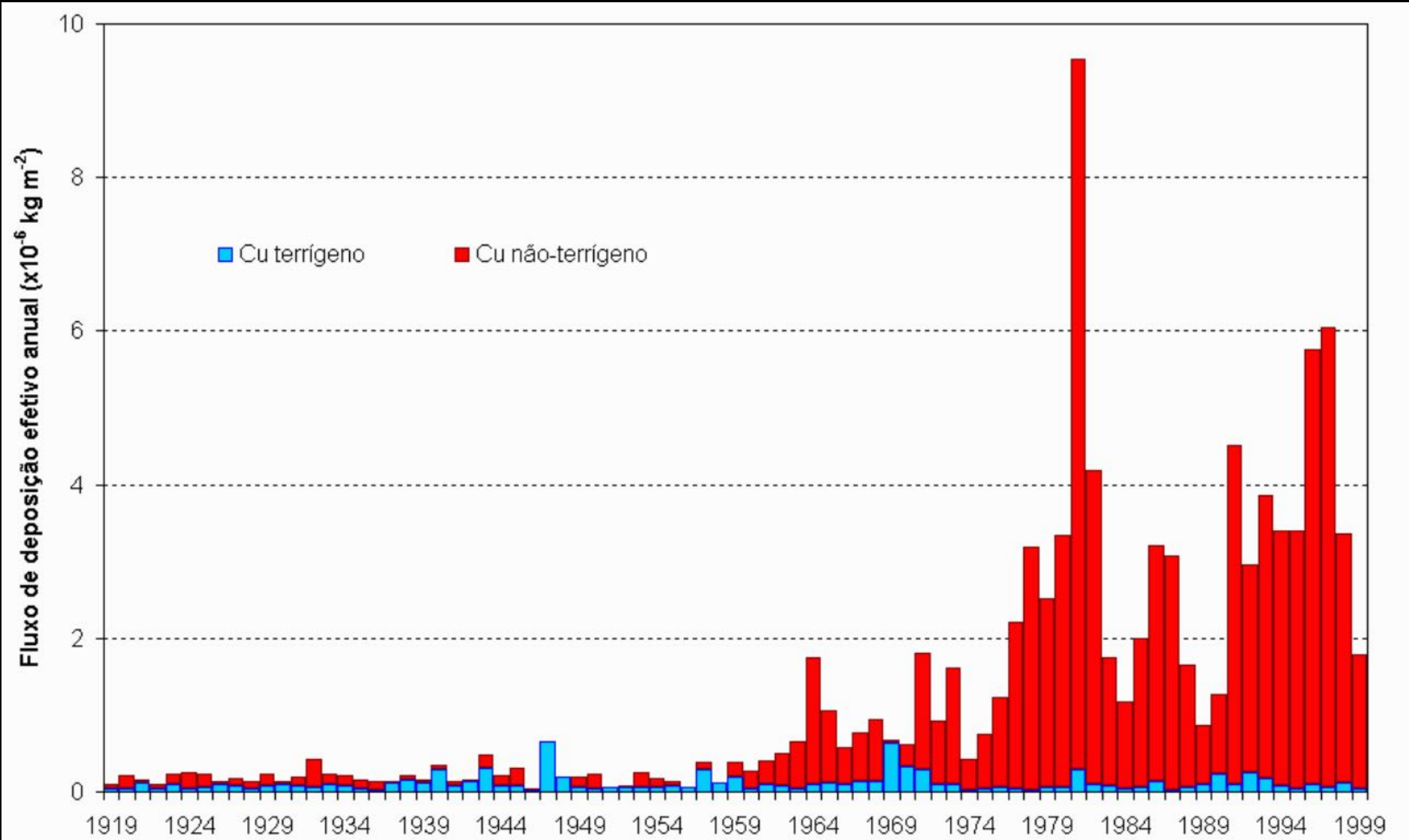


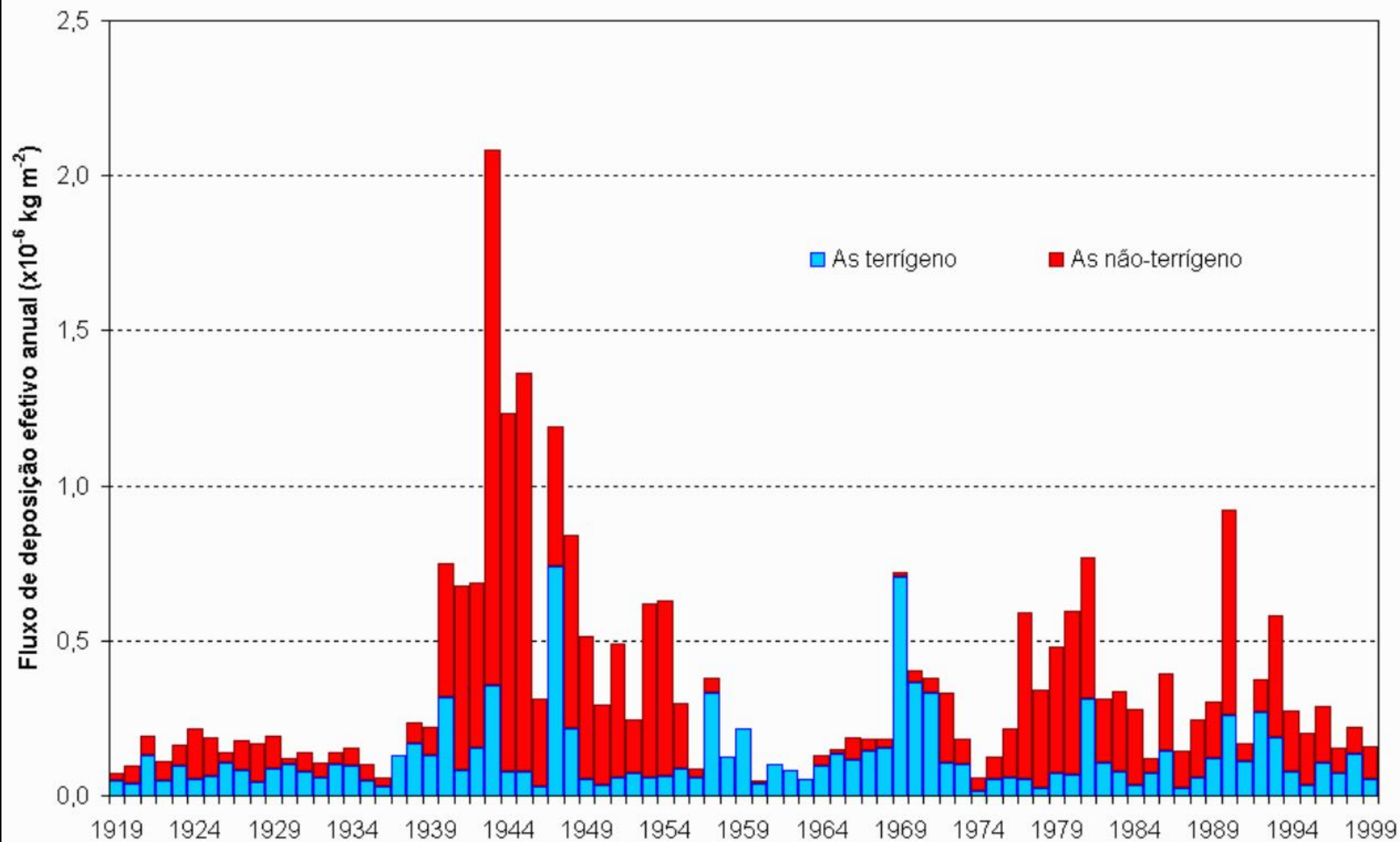


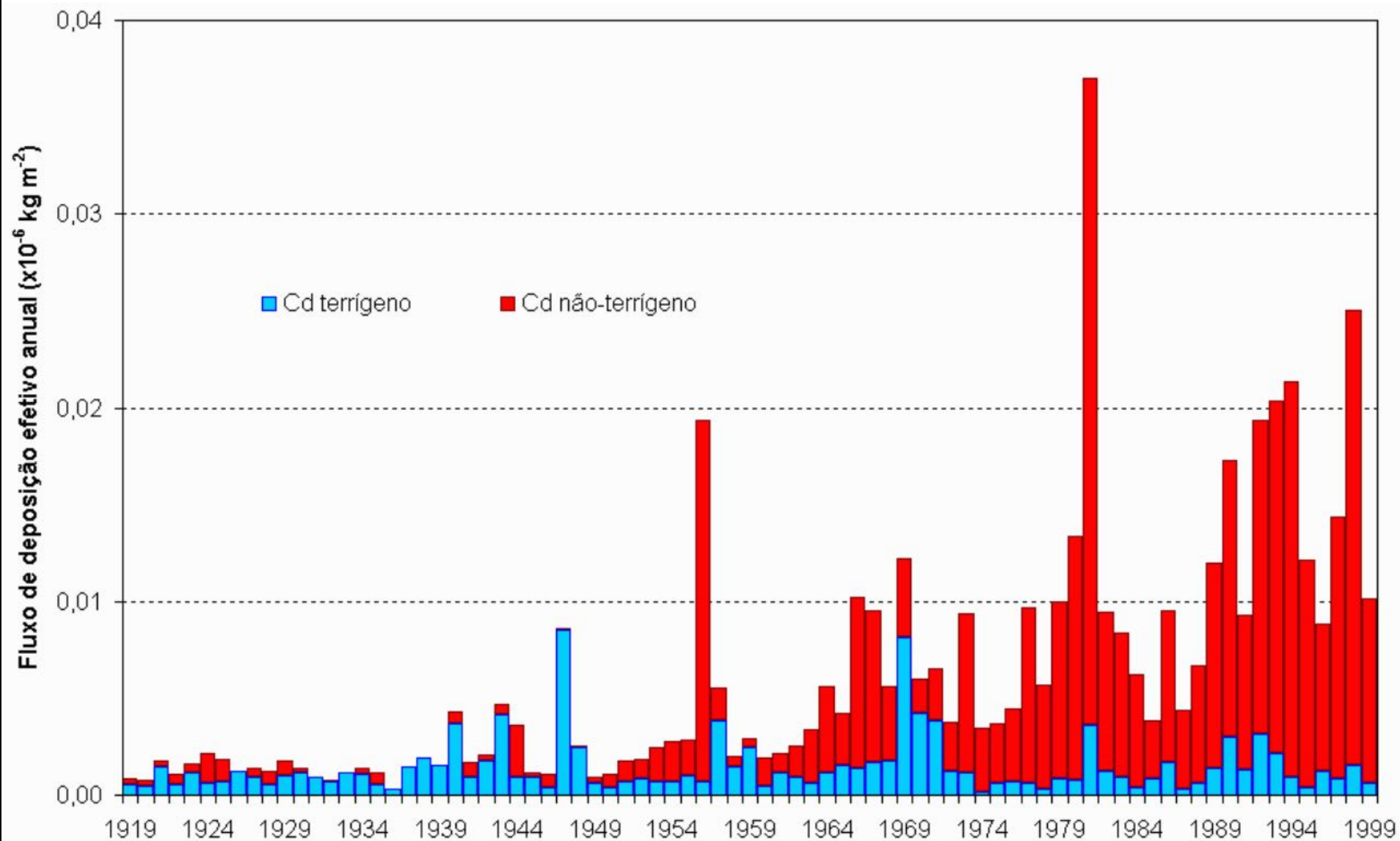


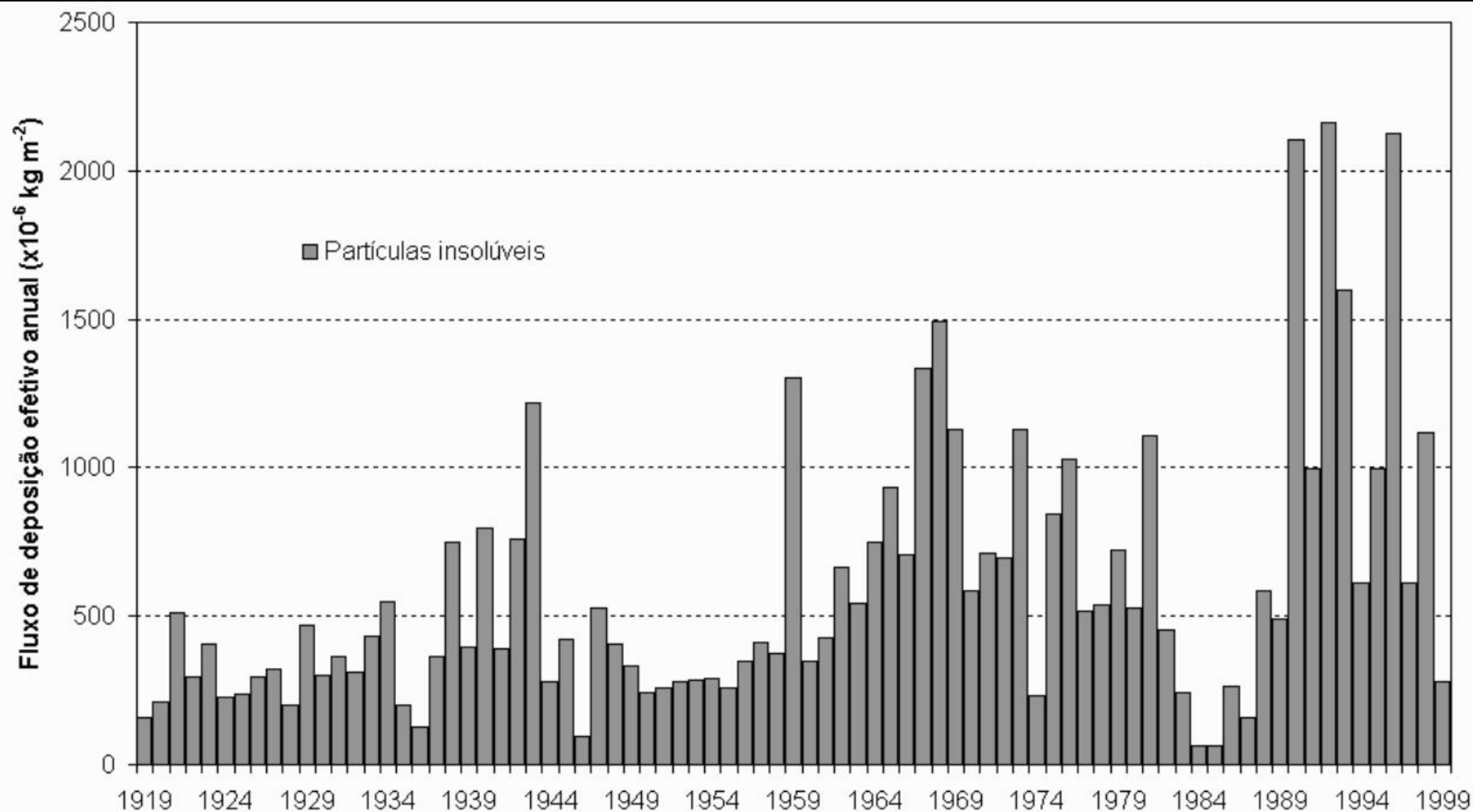




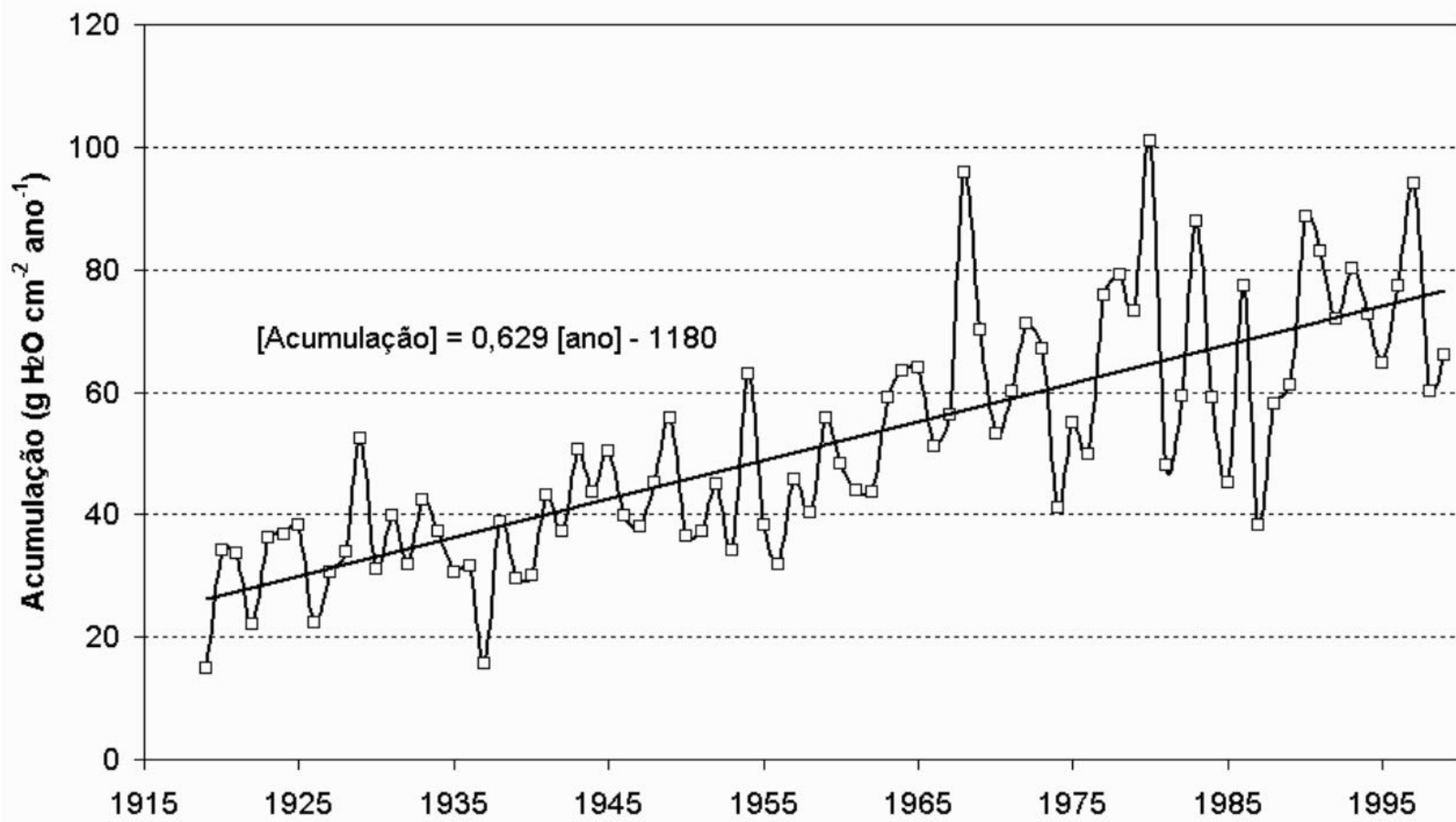




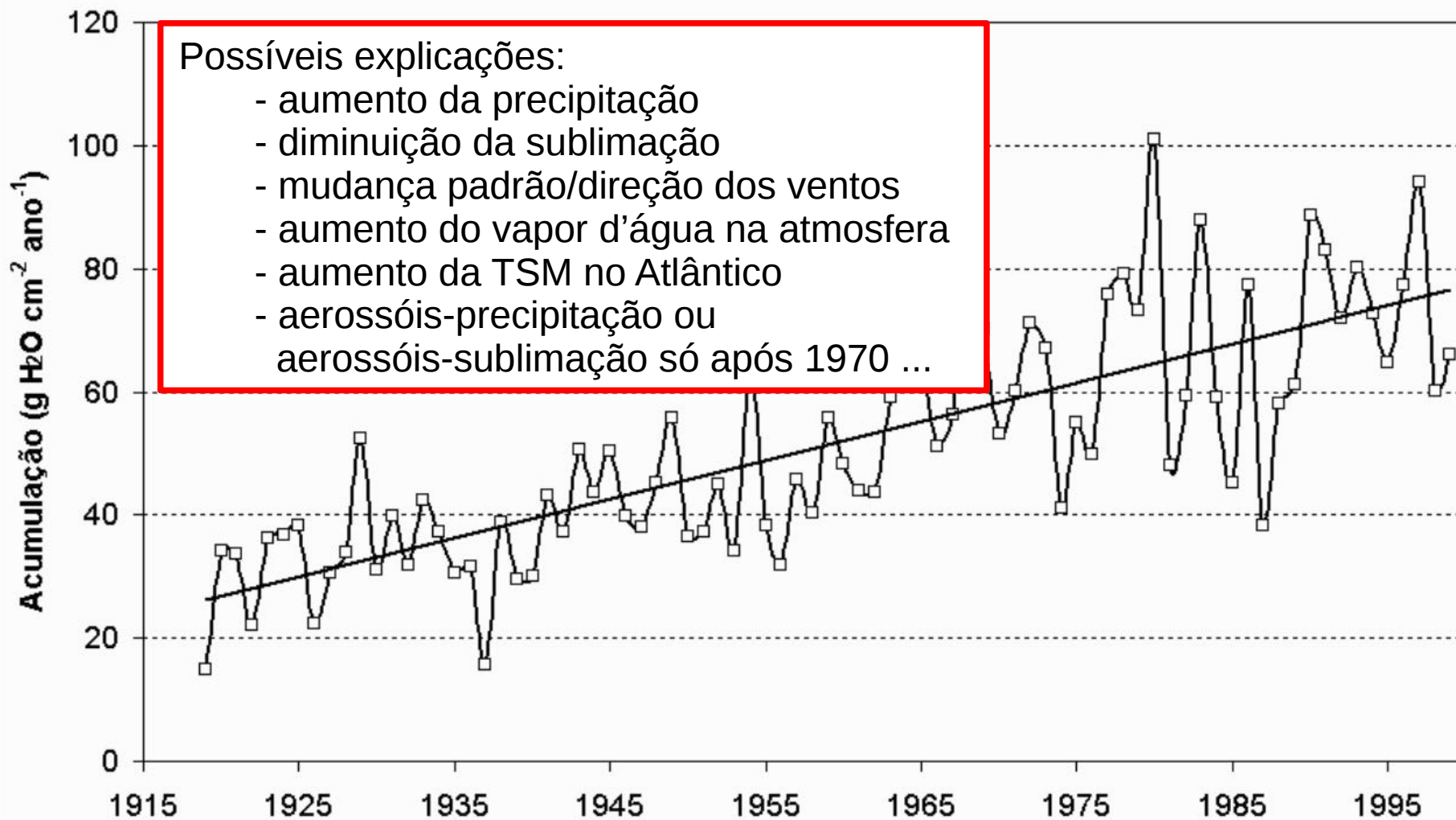


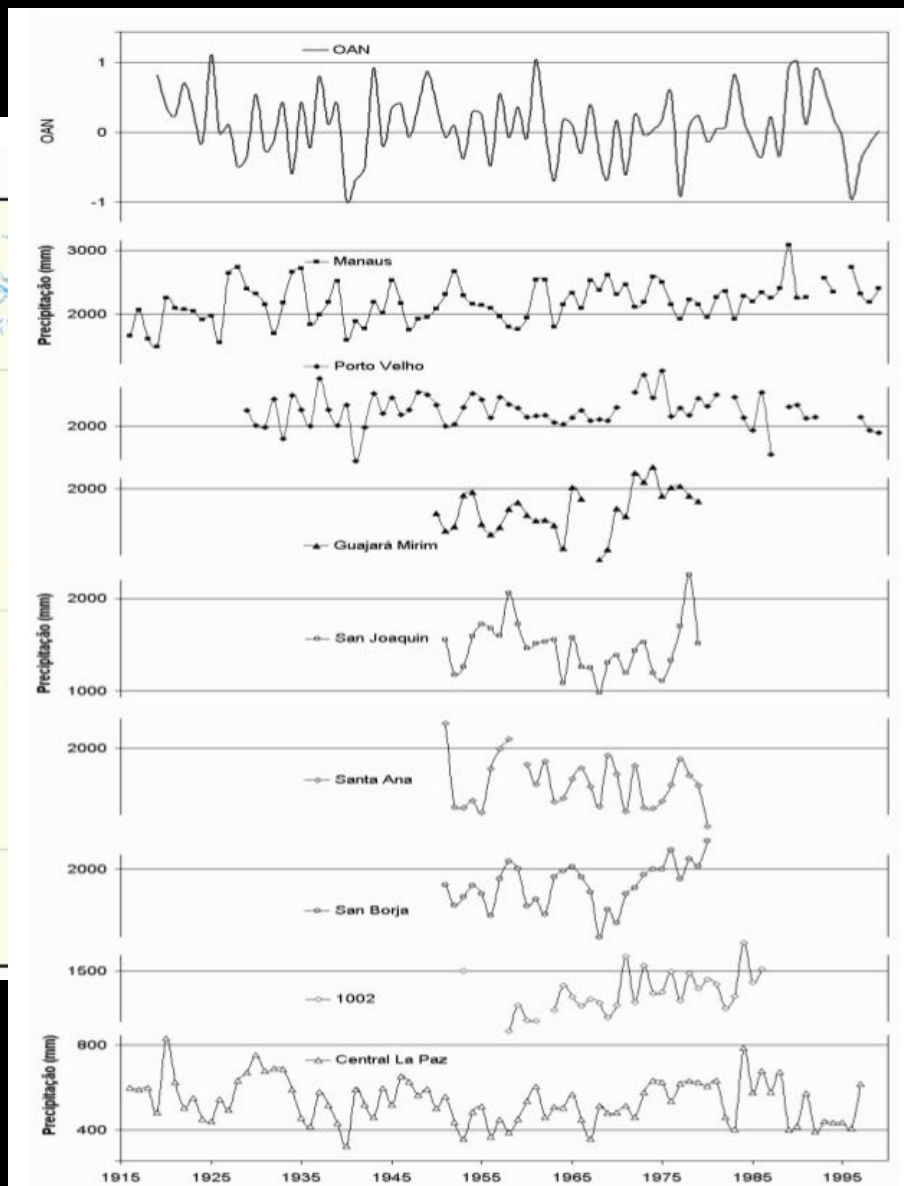


Acumulação anual - Illimani



Acumulação anual - Illimani





Cane et al. 1997:

Durante o século XX:

Atlântico Equatorial +0.3C

Atlântico Sul +1.0C



Mais umidade disponível

EOF TSM do Atlântico (Sutton et al. 2000)

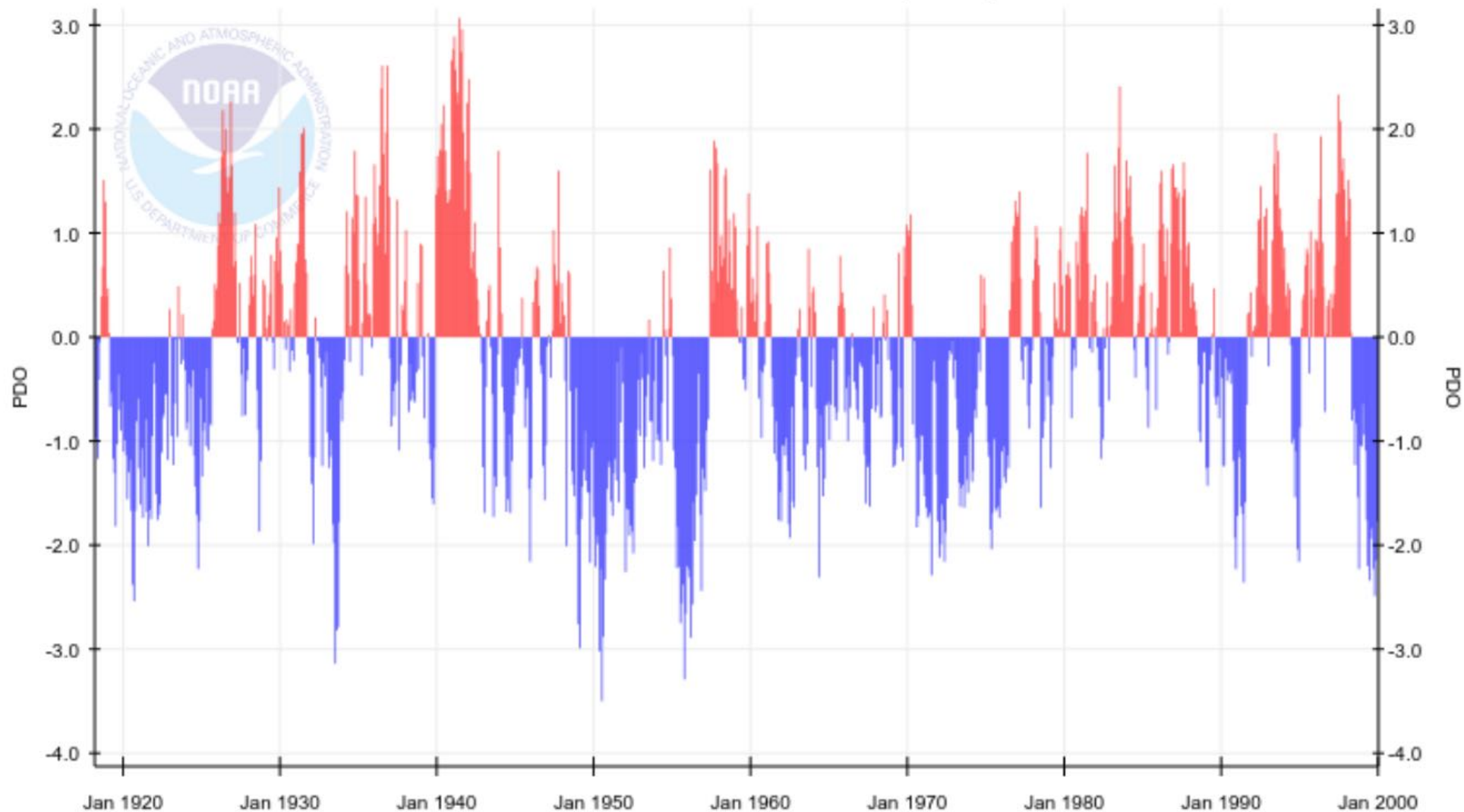
EOF TSM do Pacífico (Cardoso, 2001)

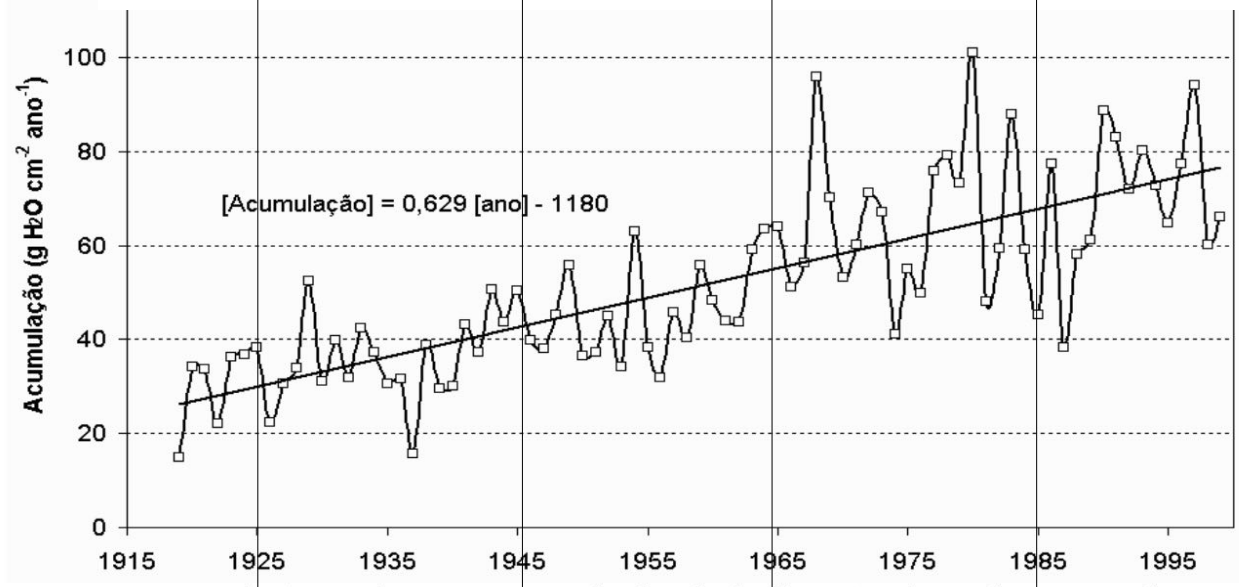
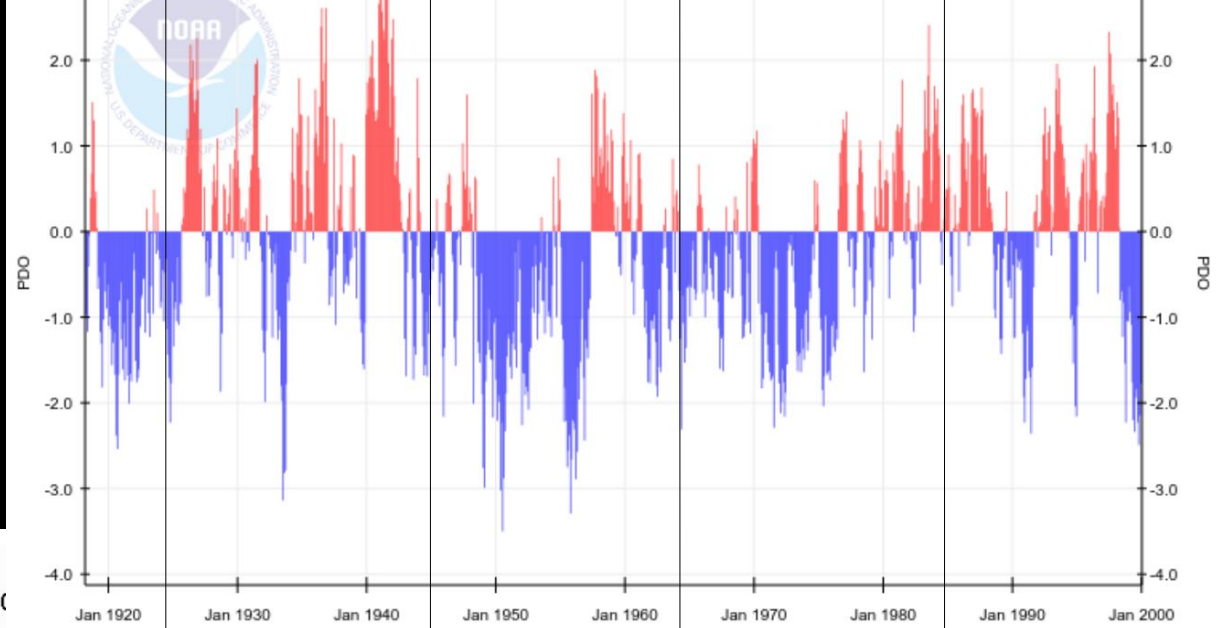


Tendências de longo prazo para alguns
modos de oscilação

Oscilação Decadal do Pacífico ???

Pacific Decadal Oscillation (PDO)





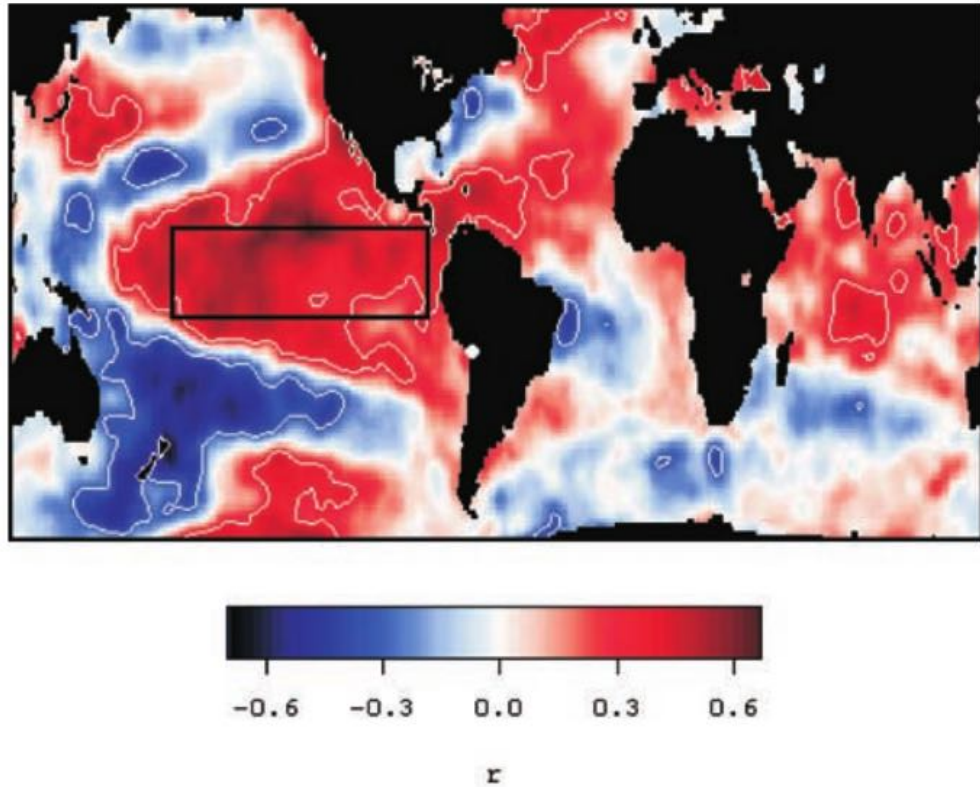


Figure 1. Correlation of global No_x-February SSTs with net accumulation-weighted $\delta^{18}\text{O}$ at Sajama, Bolivia (white dot), 1961–1997. Regions delimited by white line are correlated at the 95% significance level. The area used in

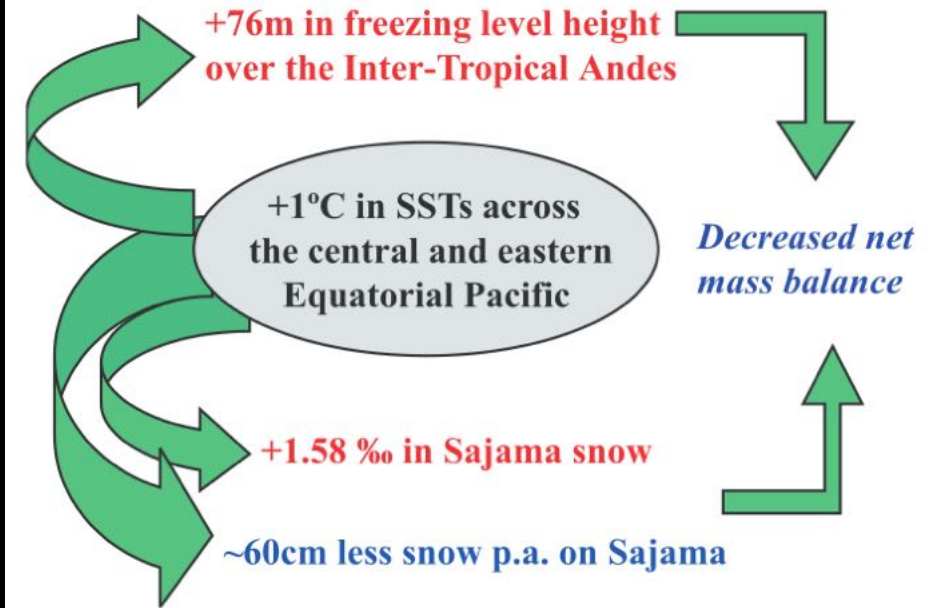
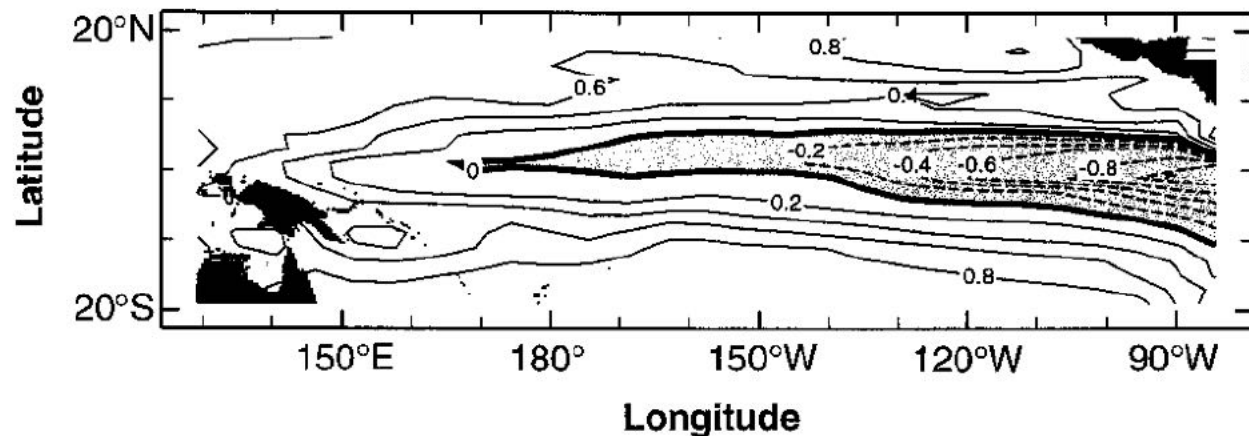


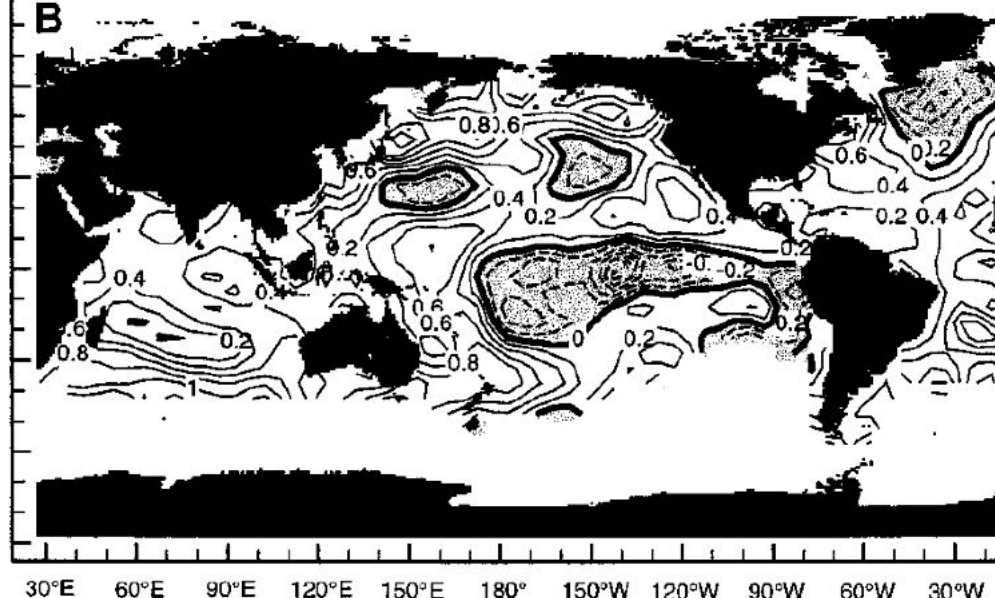
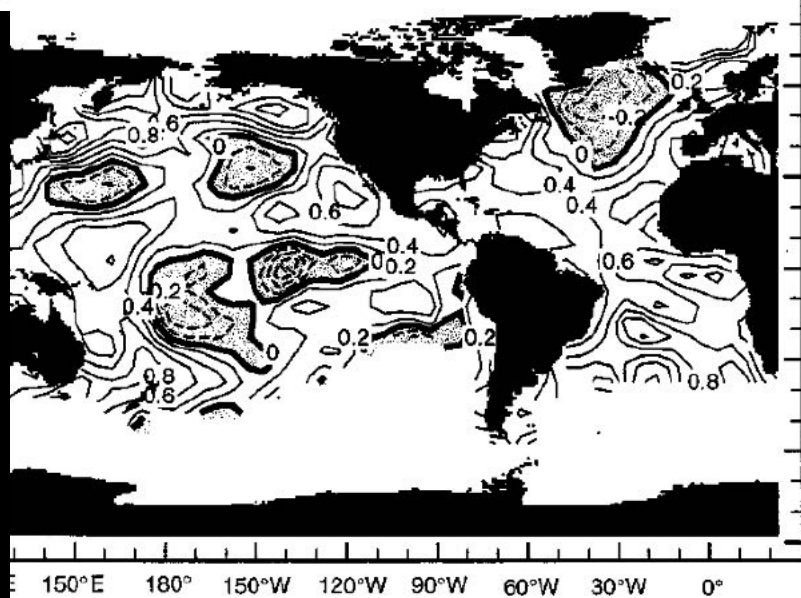
Figure 4. Schematic diagram summarizing links between central and eastern Equatorial Pacific SSTs, isotopic records at Sajama, and mass balance changes.

Fig. 1. Annual mean SST anomaly (in degrees Celsius) generated by the Lamont intermediate coupled ocean-atmosphere model (12) when forced by an imposed uniform heating. [Adapted from (7)]



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A scenic sunset over a lake. The sky is filled with dark, textured clouds, with a bright orange and yellow glow from the setting sun breaking through near the horizon. The water in the foreground is calm, reflecting the colors of the sky. In the distance, a dark silhouette of a forest line is visible. On the right side of the image, a small boat with several people on board is visible on the water.

Obrigado!

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