

O registro paleoclimático, com foco em testemunhos de gelo

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“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



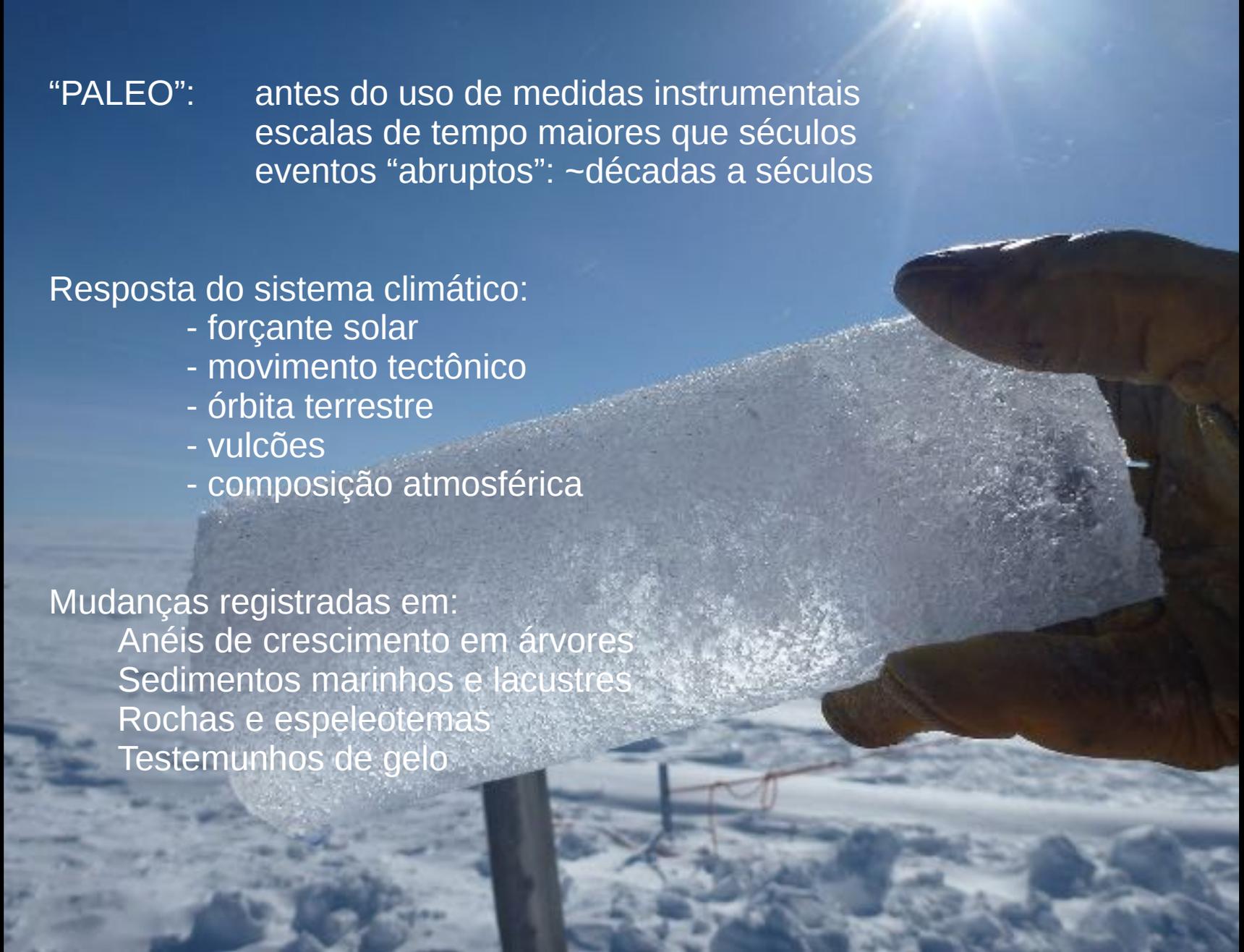
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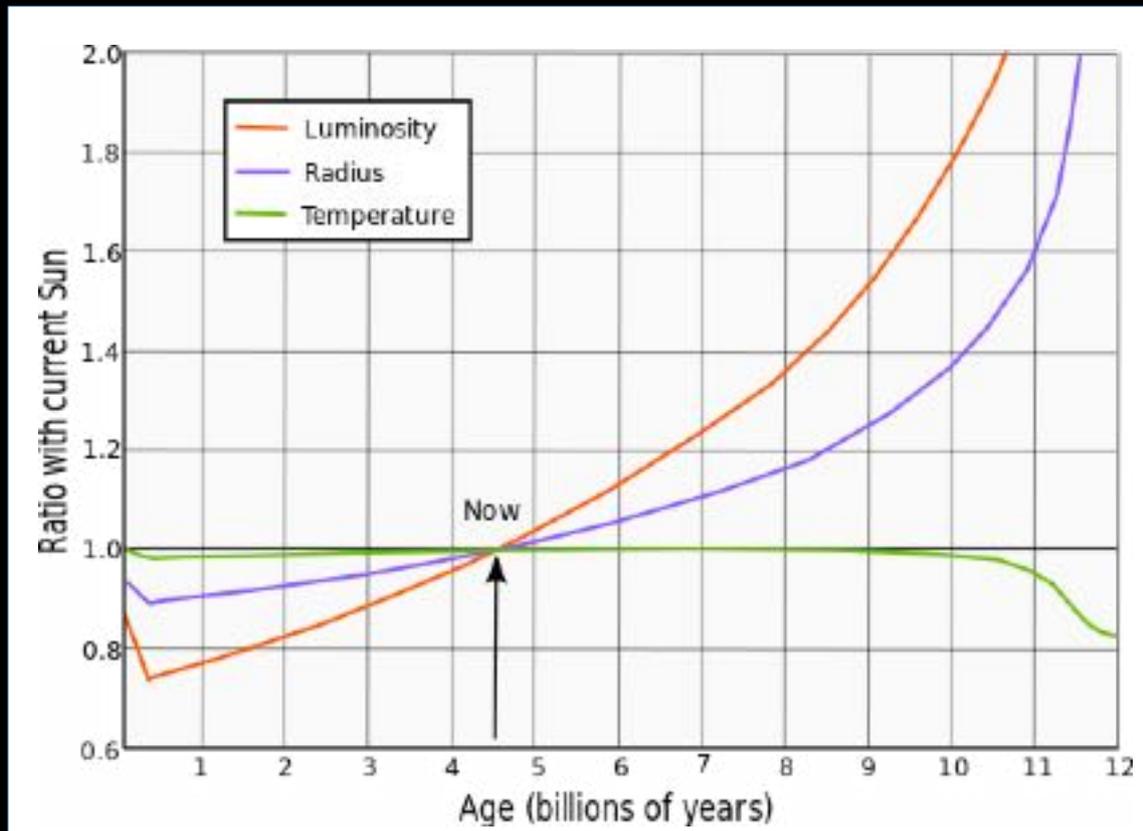
Mudanças registradas em:

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

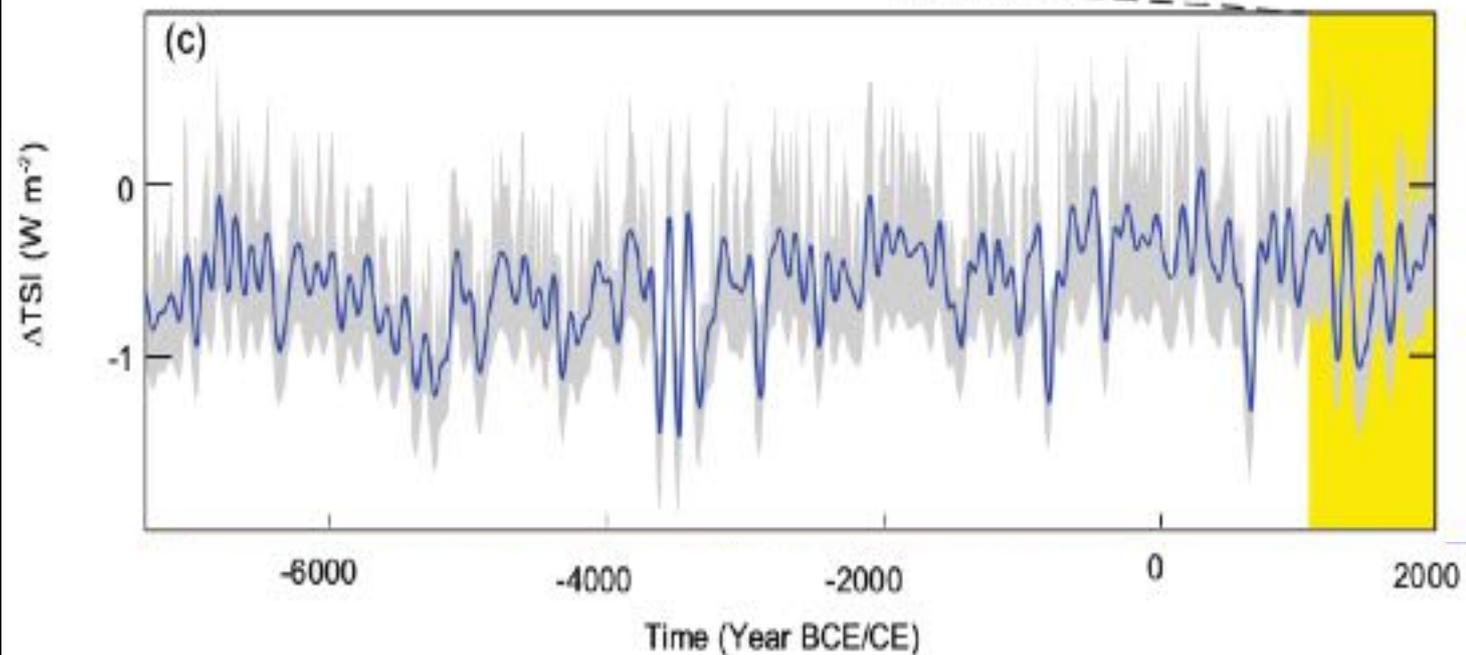
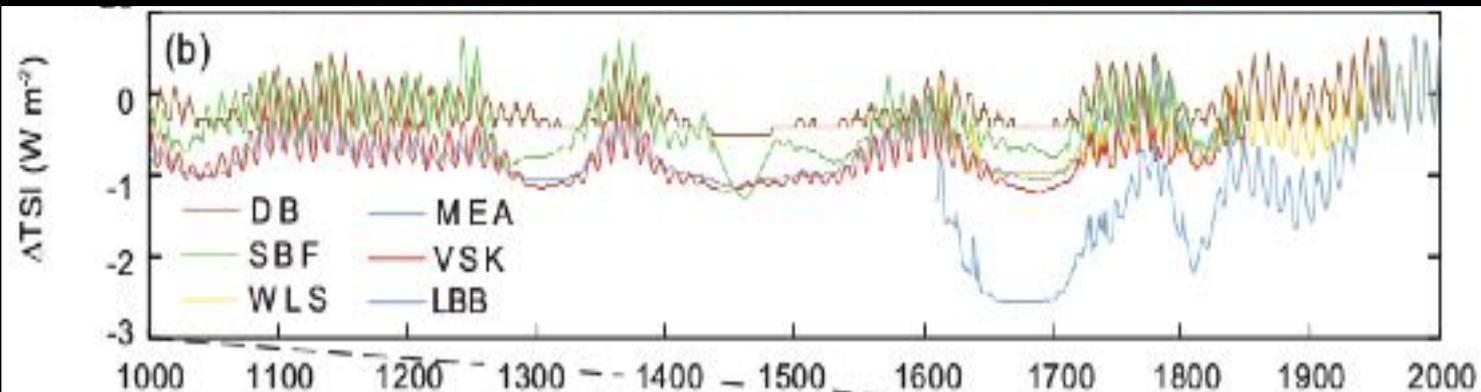


Forçante solar

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

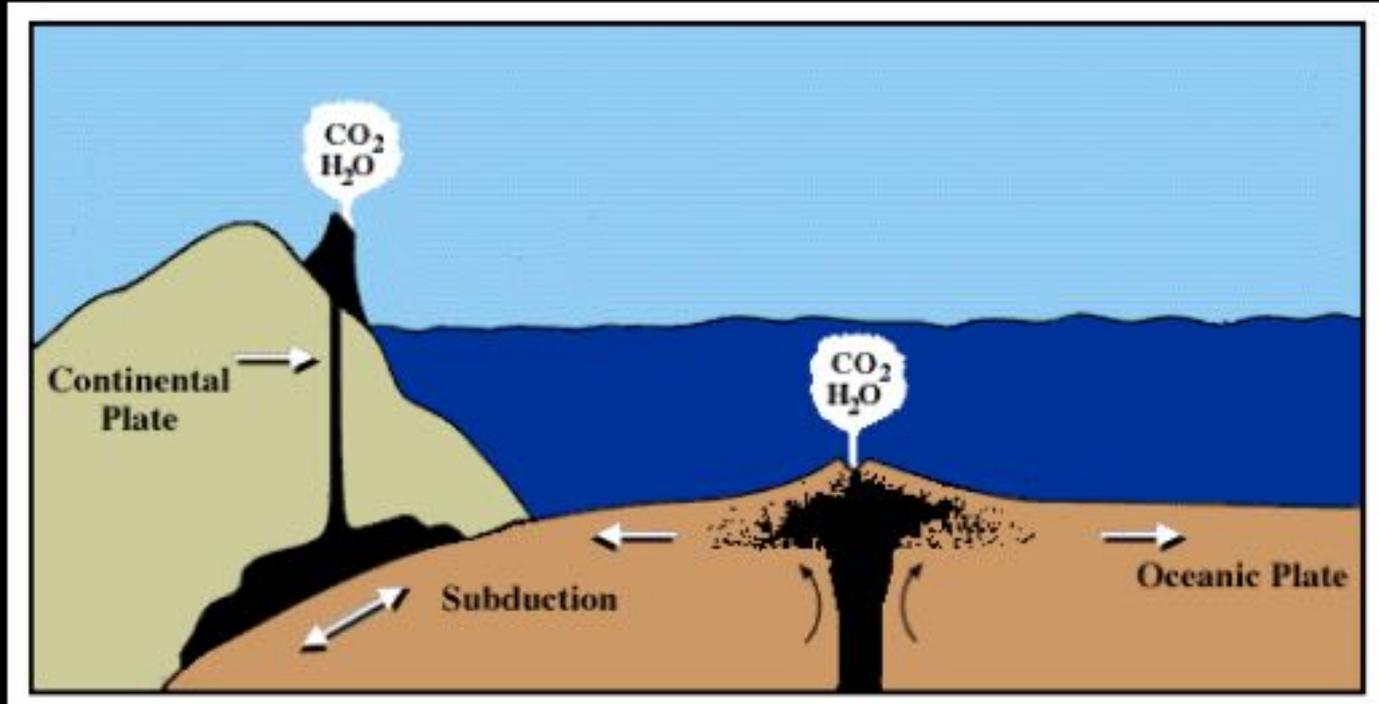


Forçante solar reconstruída



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

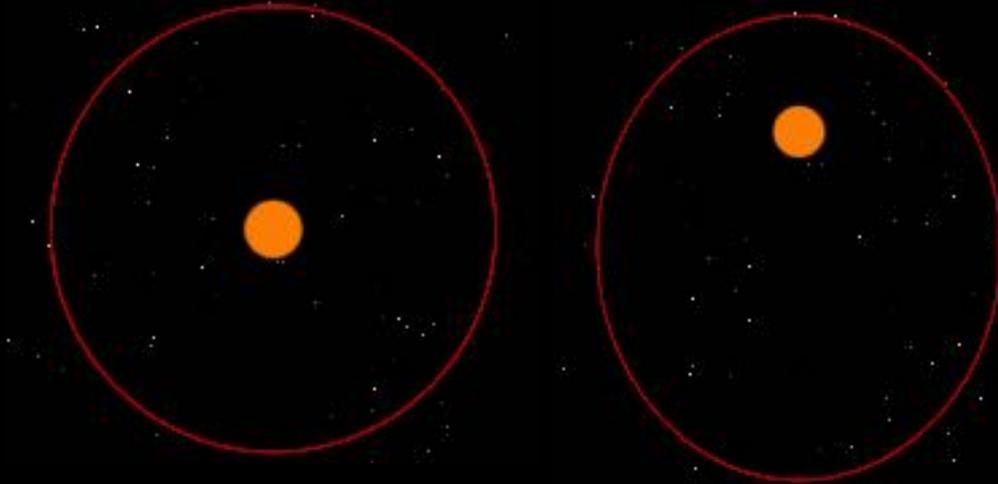
As the continents shift there is increased subduction and volcanic activity which increases CO_2 into the atmosphere



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



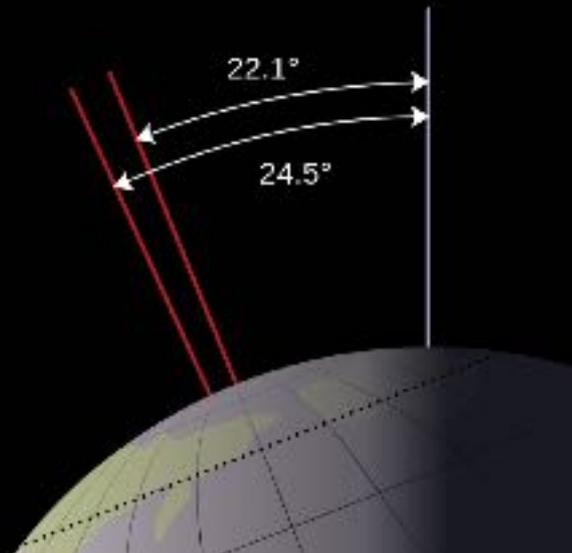
Eccentricidade

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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 - precessão do eixo de rotação da Terra
 - precessão da órbita
 - inclinação da órbita

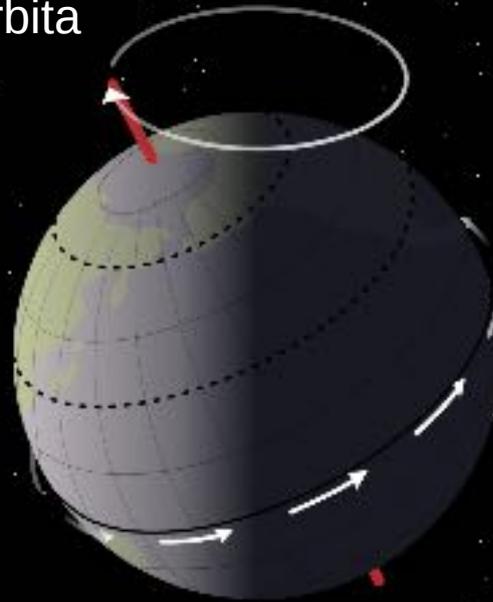


Inclinação do eixo

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
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 - precessão da órbita
 - inclinação da órbita

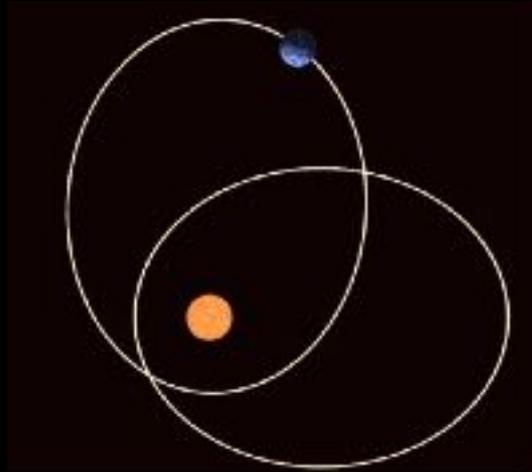


Precessão do eixo

Período: 25,8 ka

Forçante orbital

- Mudanças do fluxo de radiação solar → eras glaciais/interglaciais
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 - eccentricidade da órbita
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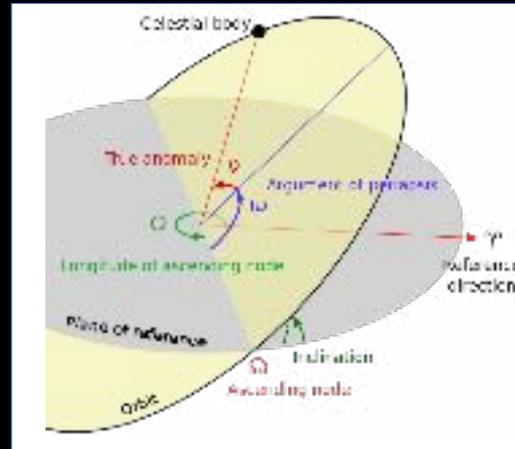


Precessão da órbita

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
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 - inclinação da órbita

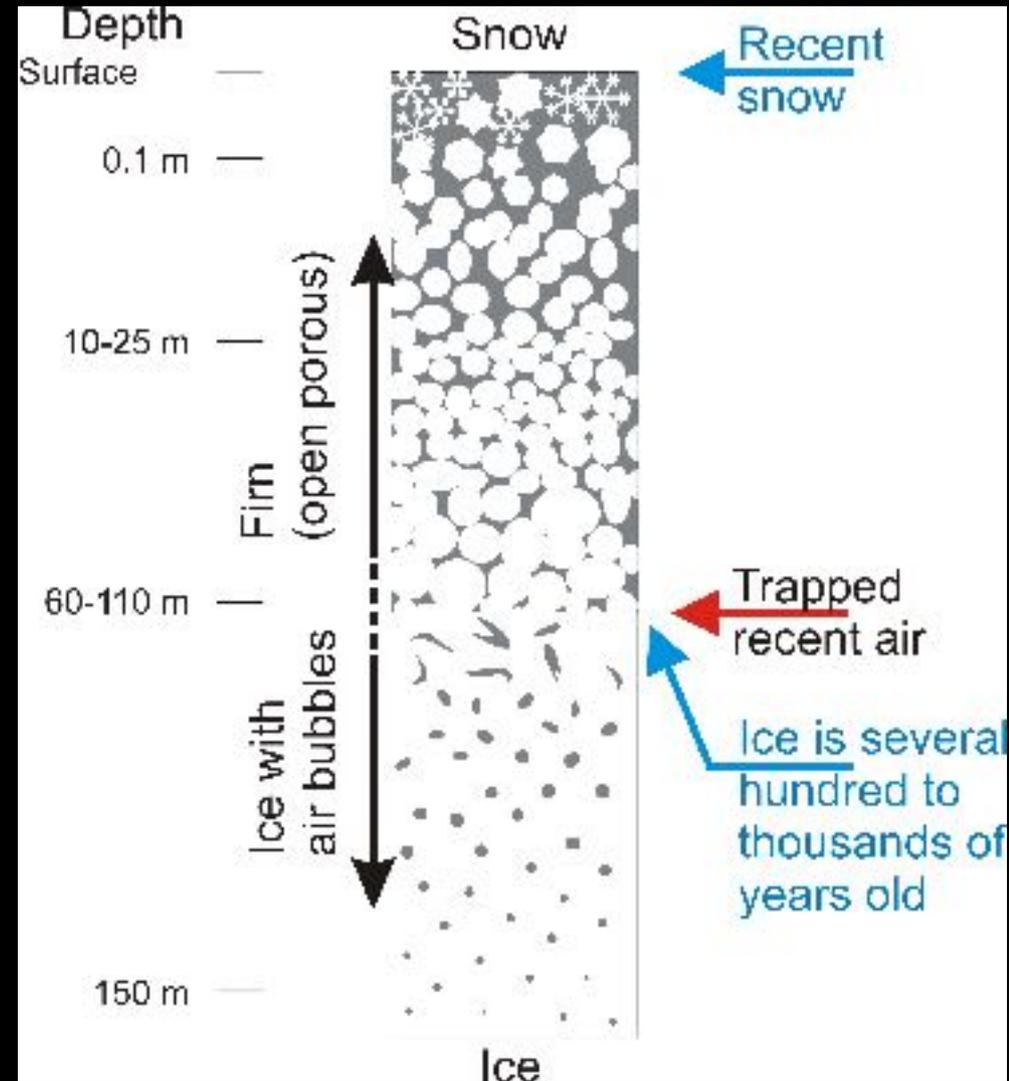


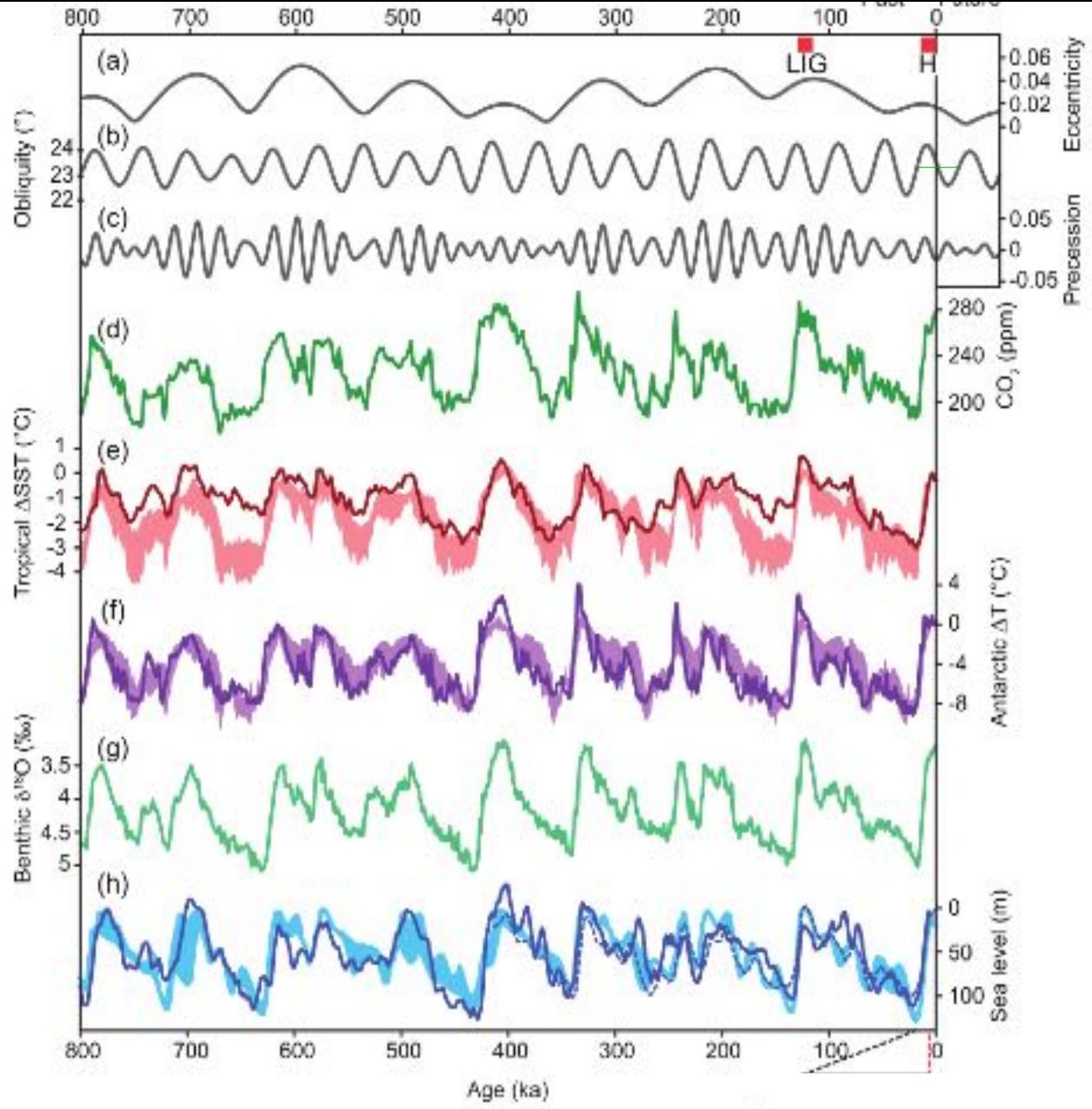
Inclinação da órbita

Período: 100 ka

O registro paleoclimático em testemunhos de gelo

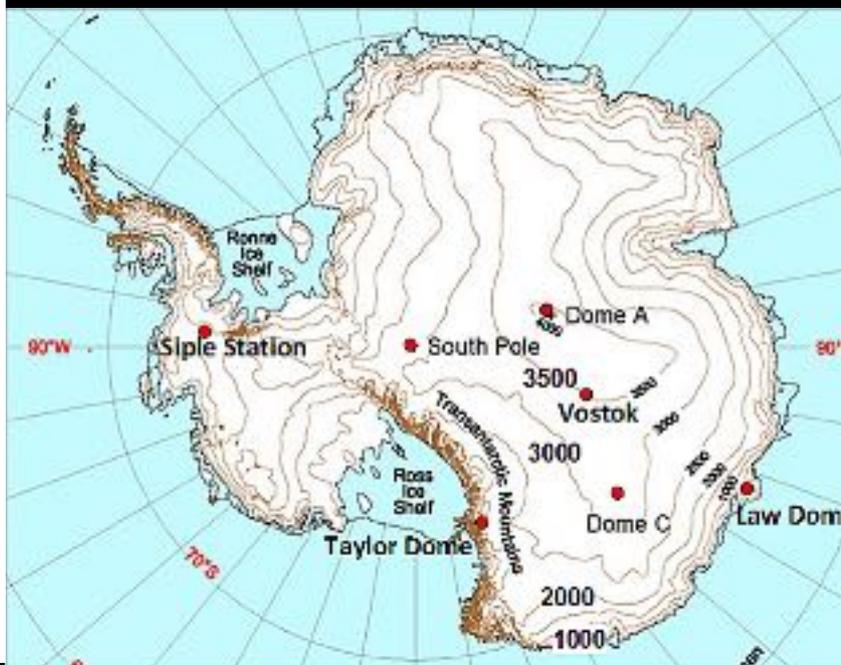
- Bolhas de ar aprisionadas em geleiras
- Química atmosférica da neve
- Sujeito a difusão gasosa entre poros
- Taxas de acumulação definem a resolução temporal: Antártica x Andes
- Escala de 800 ka em Dome C, Antártica

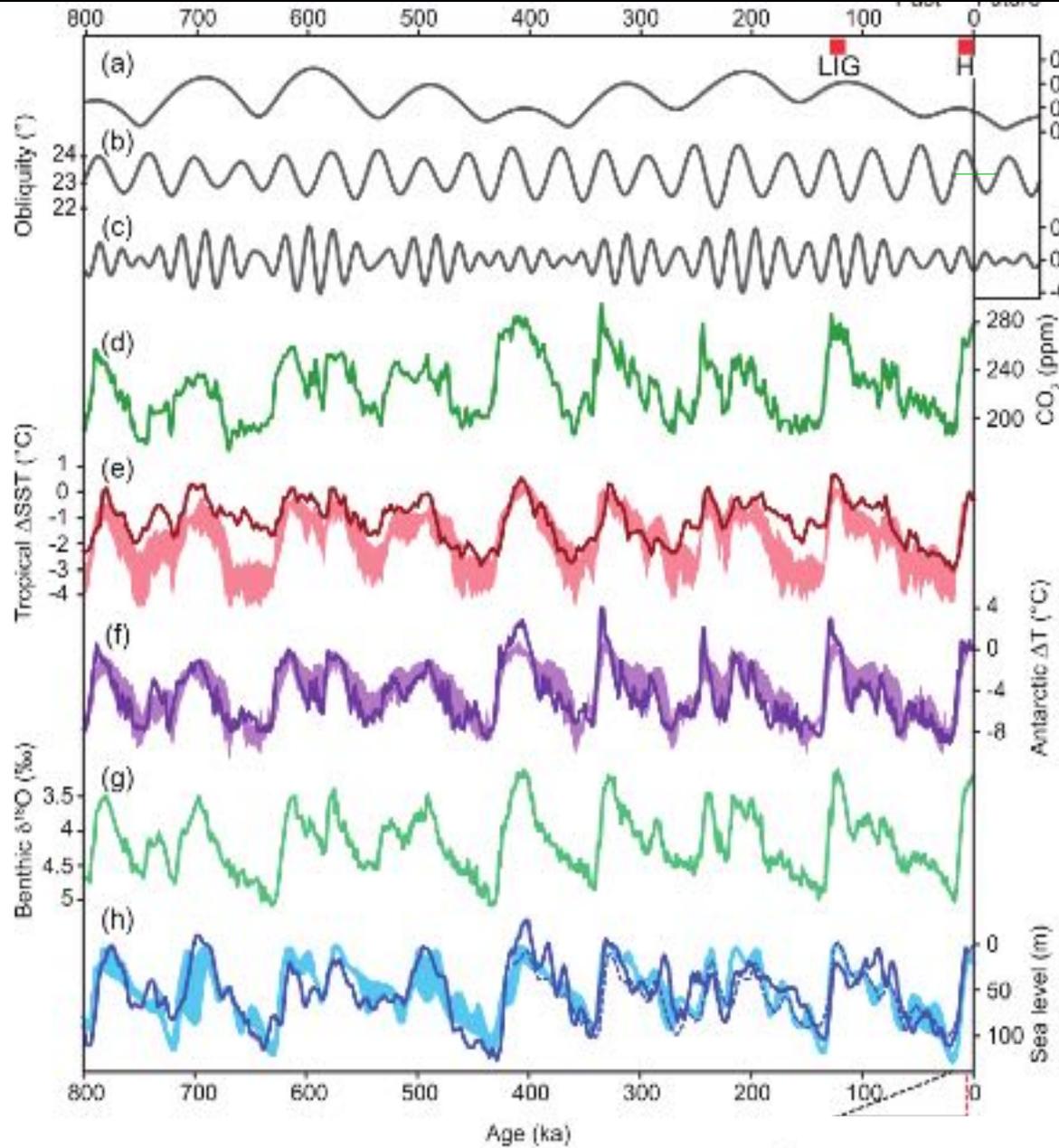




Variações orbitais (Milankovitch)

← CO2 no testemunho de Dome C

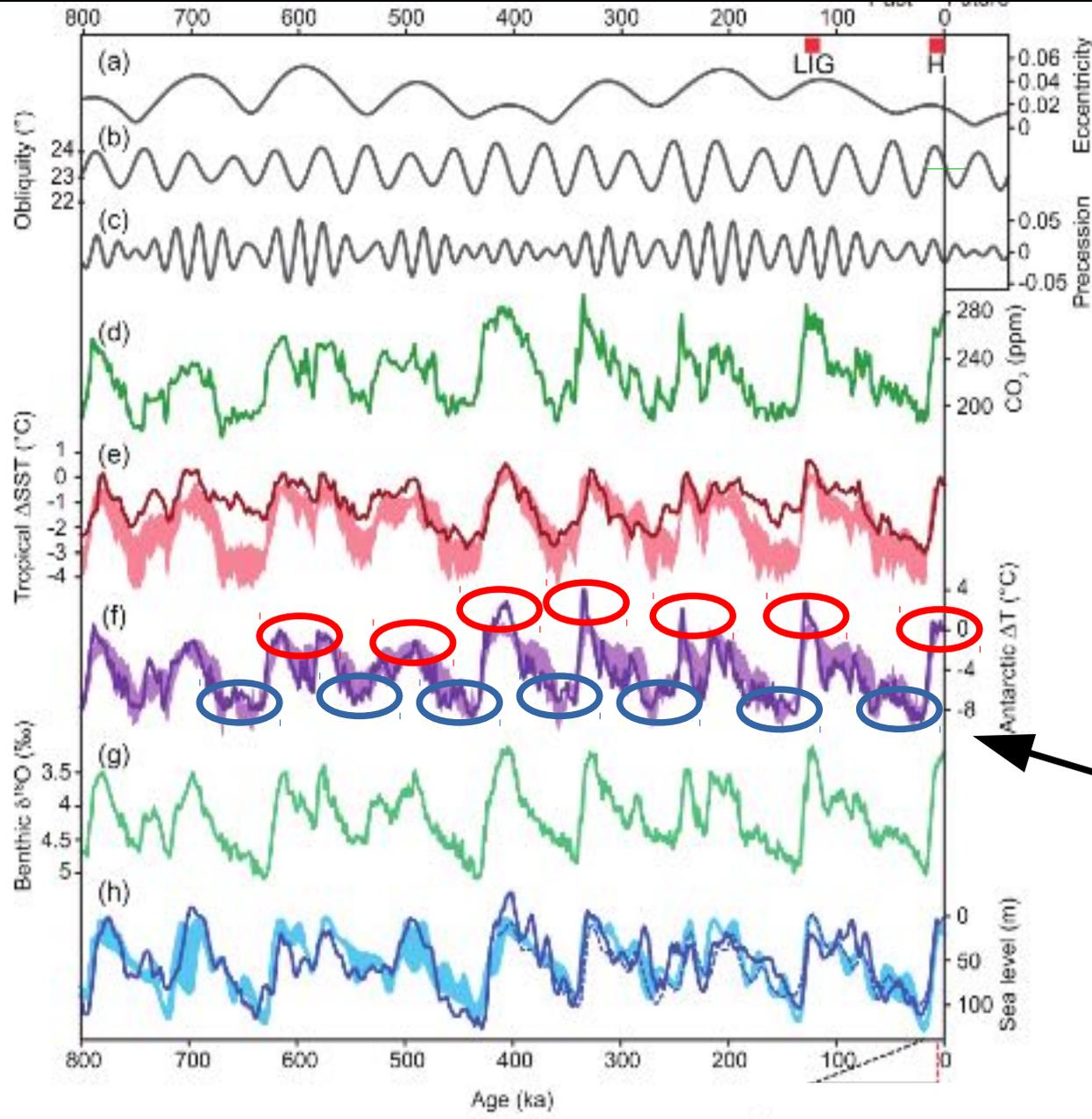




Variações orbitais (Milankovitch)

← CO2 no testemunho de Dome C

← Temperatura definida a partir de isótopos da água

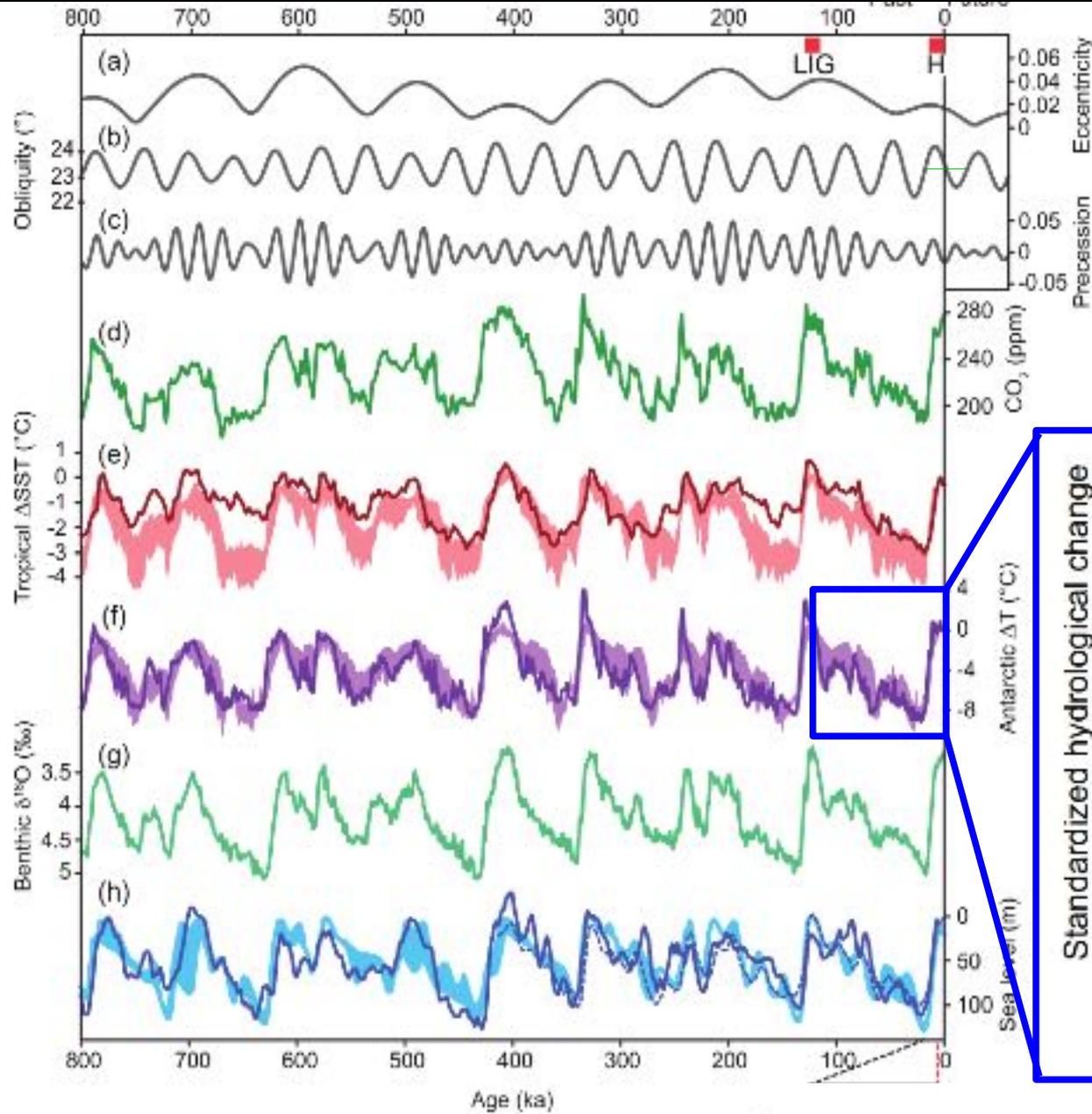


Variações orbitais (Milankovitch)

← CO2 no testemunho de Dome C

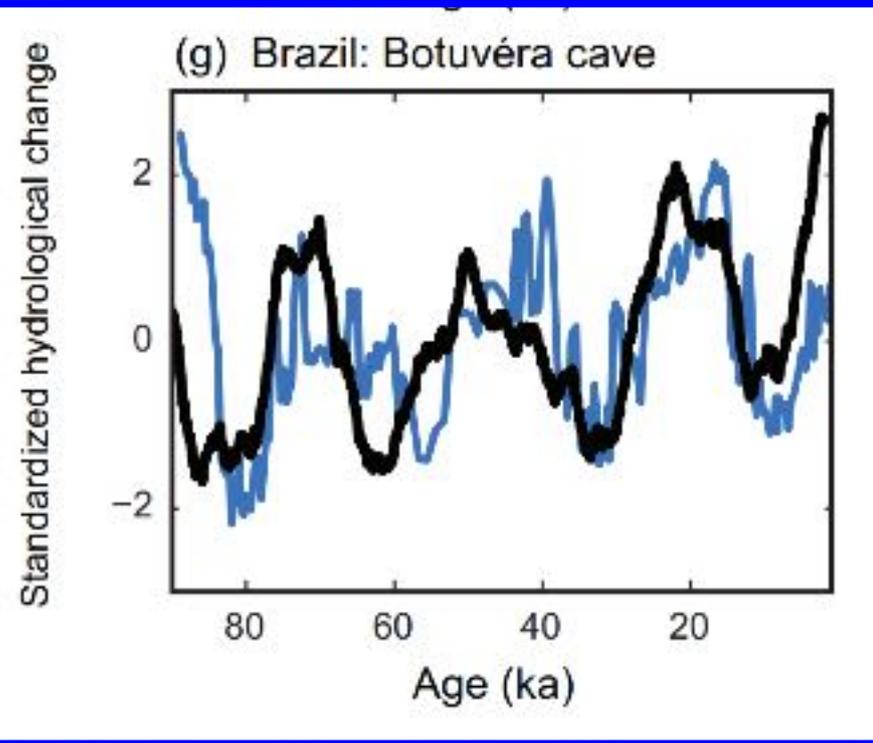
← Temperatura definida a partir de isótopos da água

← “Eras glaciais” / interglaciais

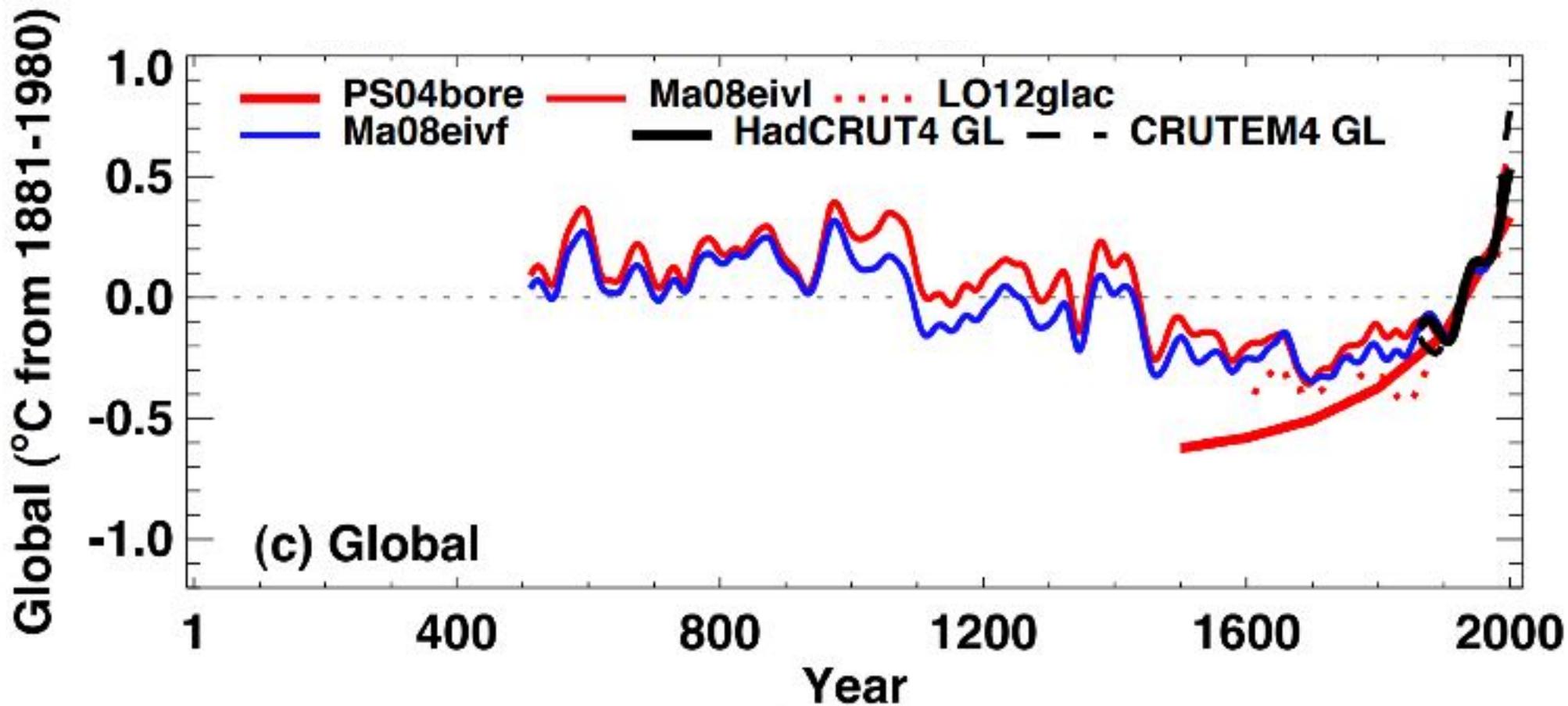


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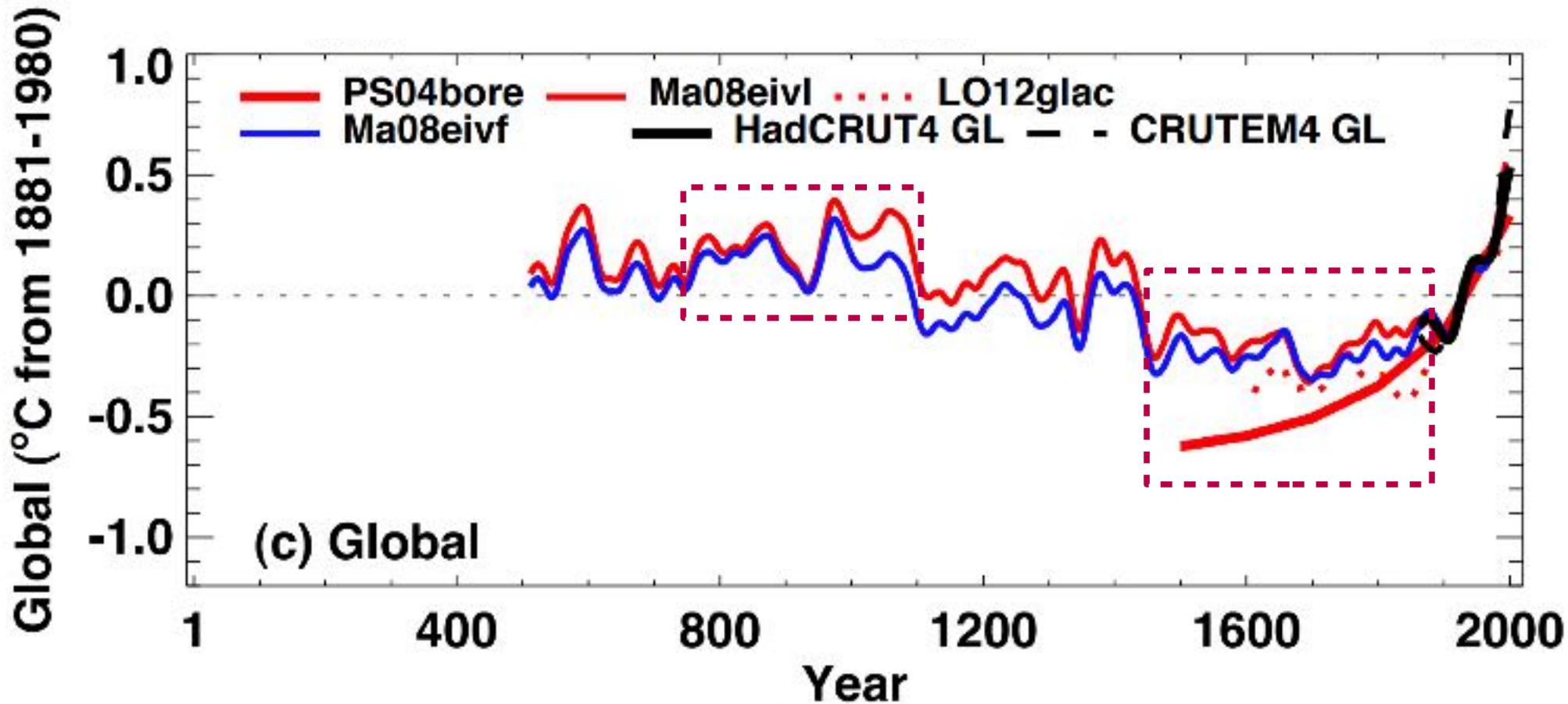
← CO₂ no testemunho de Dome C



Registros dos últimos 2000 anos

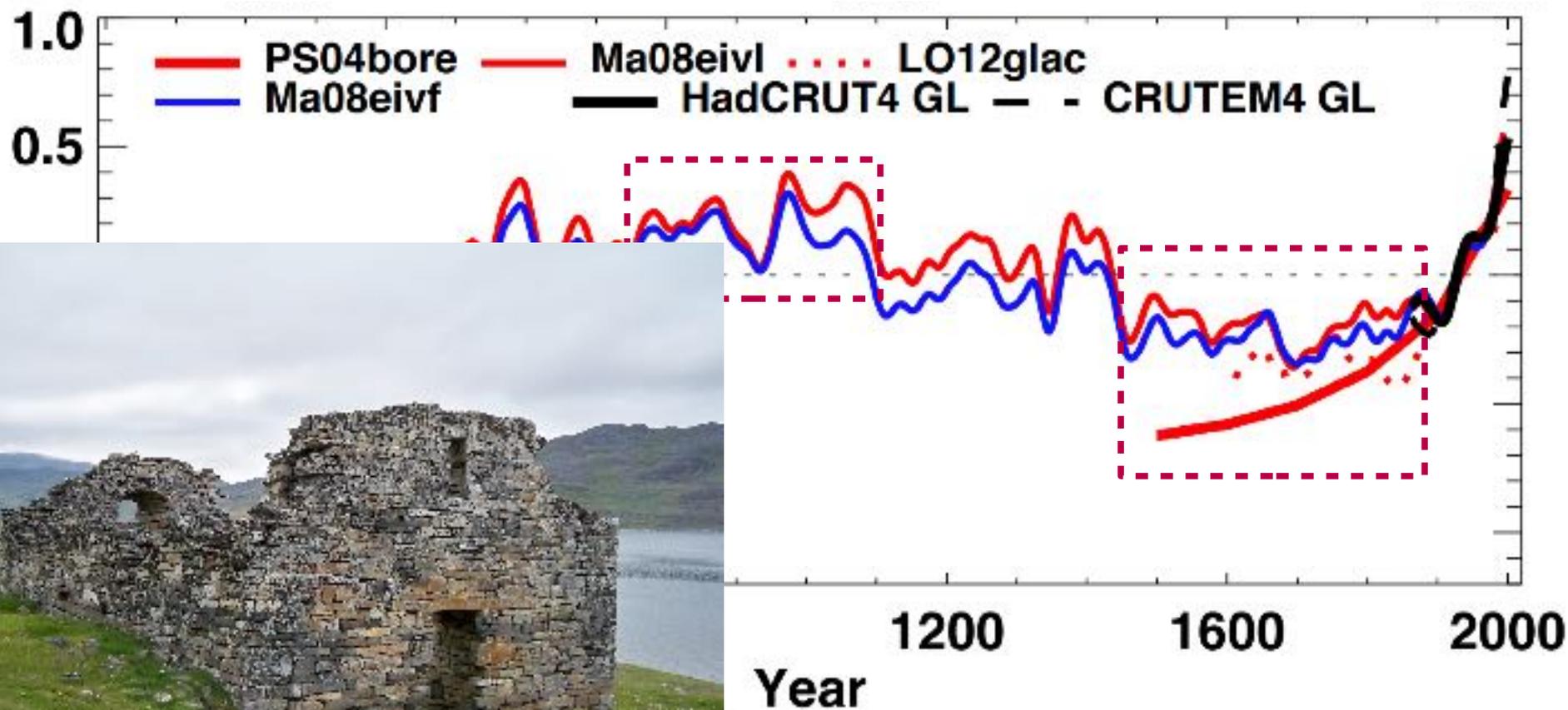


Registros dos últimos 2000 anos



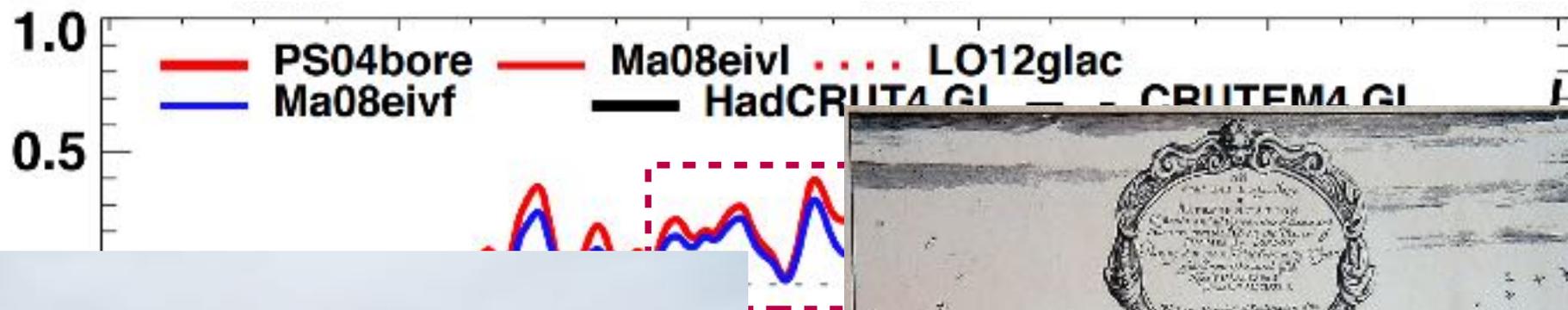
Registros dos últimos 2000 anos

1881-1980)



Registros dos últimos 2000 anos

1881-1980)



Ye



Registros dos últ

1881-1980)

1.0
0.5

PS04bore Ma08eivf
Ma08eivf Ha



Ye

Registros dos

1881-1980)

1.0
0.5

PS04bore Ma0
Ma08eivf

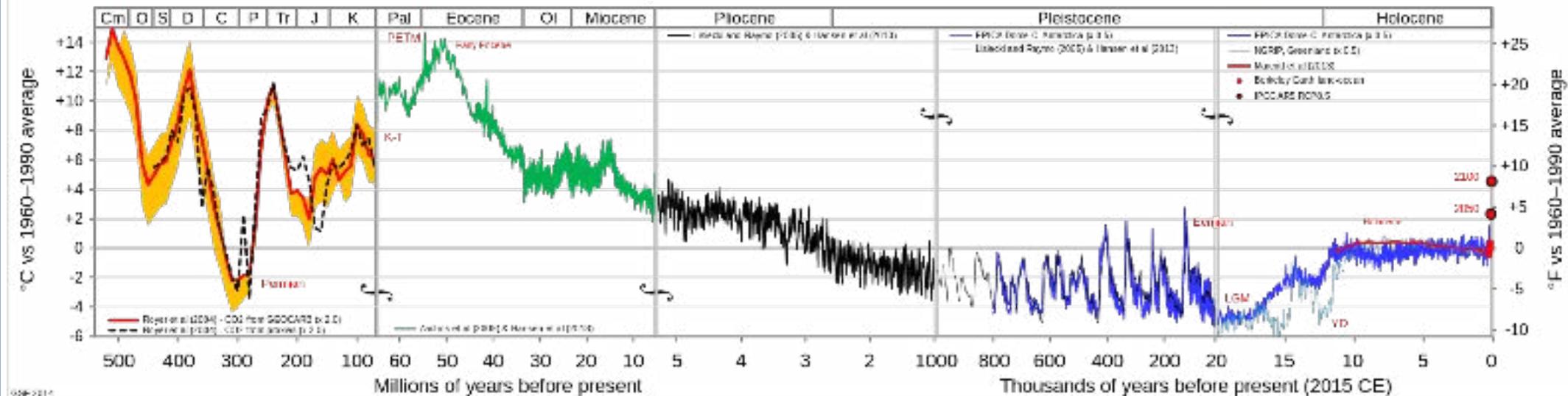


Ye



Várias escalas de tempo no registro paleoclimático

Temperature of Planet Earth



Escola tectônica

Escola orbital

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

Plantas terrestres

Dinossauros

Lago Vostok

Homo sapiens

Indo

Primatas

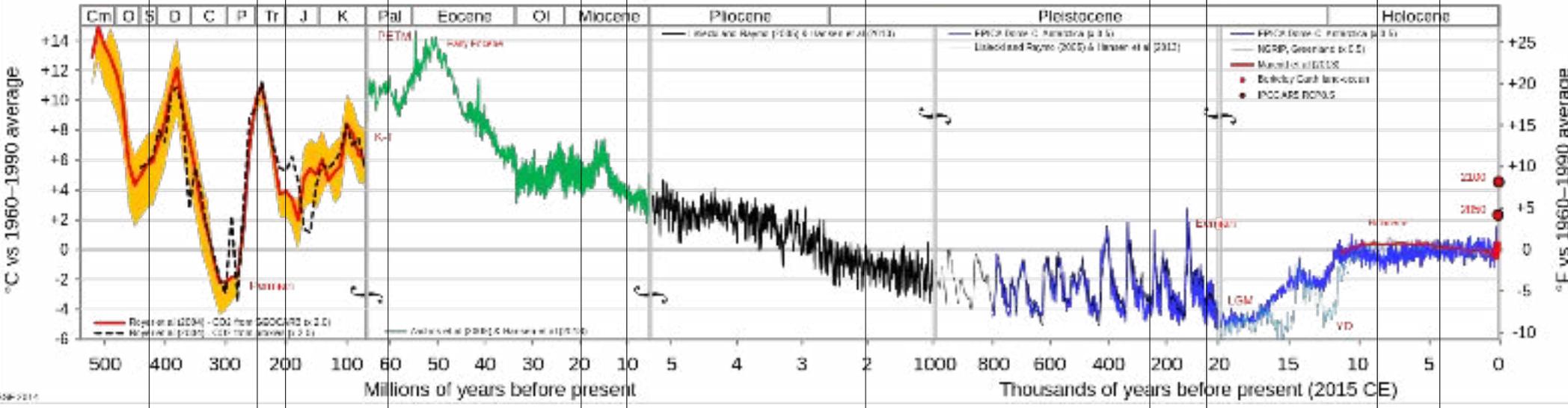
Savanas

Homo habilis

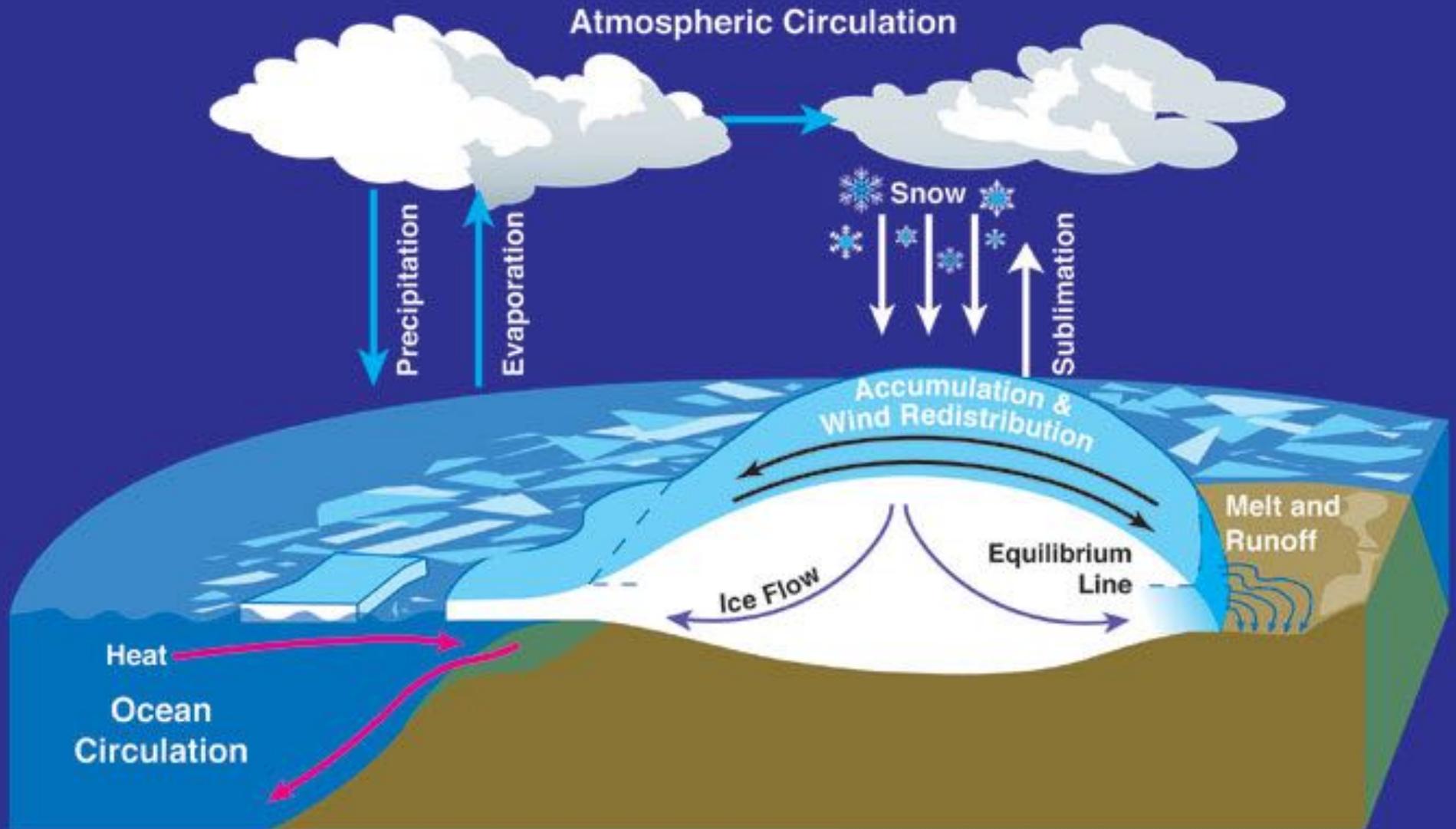
Aborígenes

Egito, Mesopotâmia

Temperature of Planet Earth

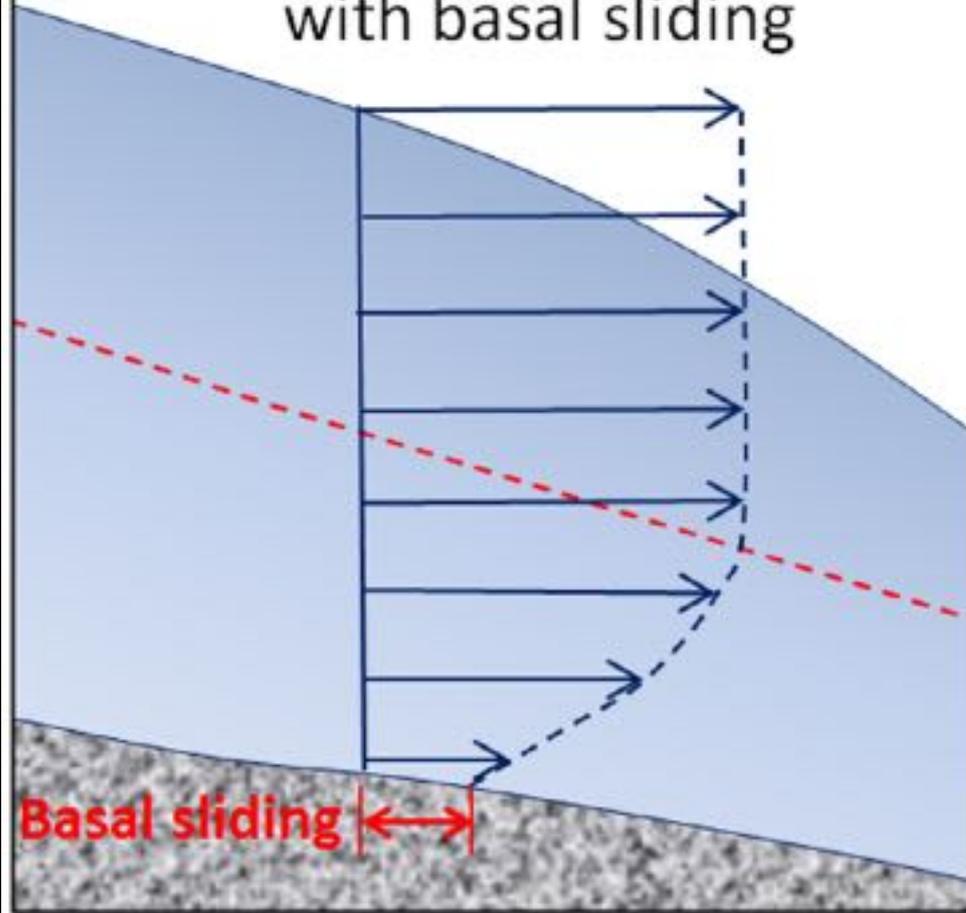


O registro paleoclimático em geleiras e mantos de gelo

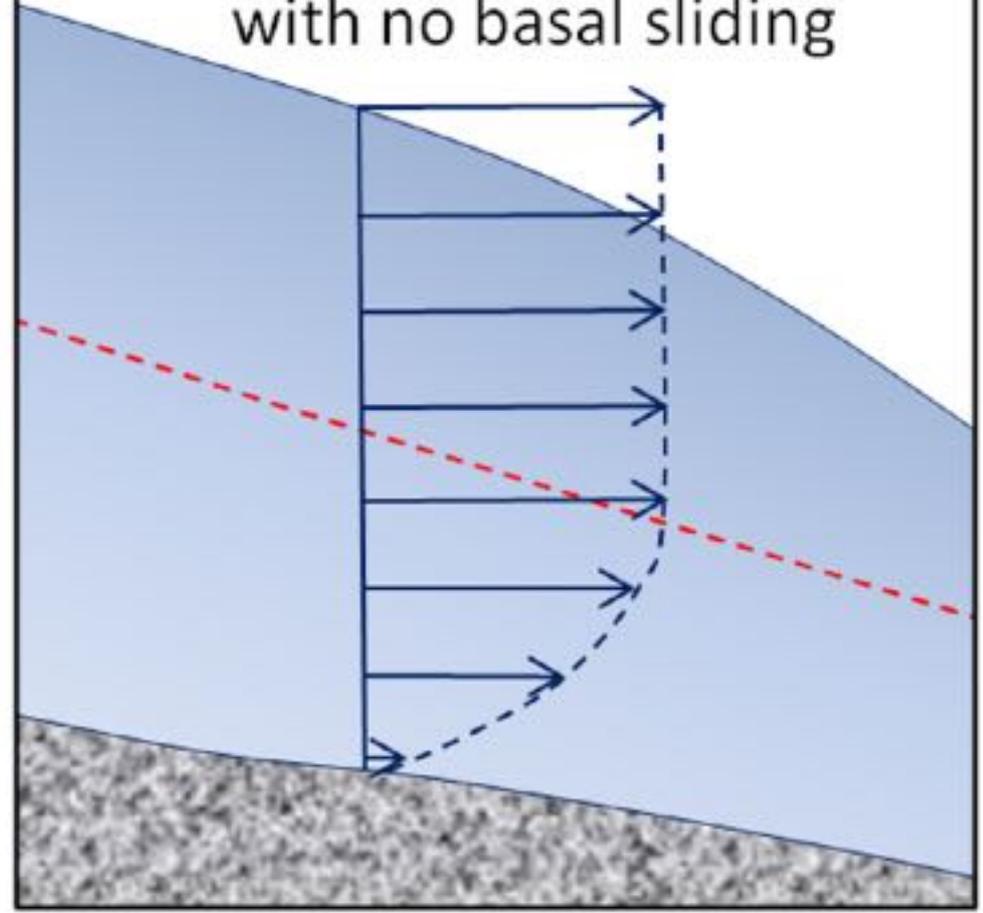


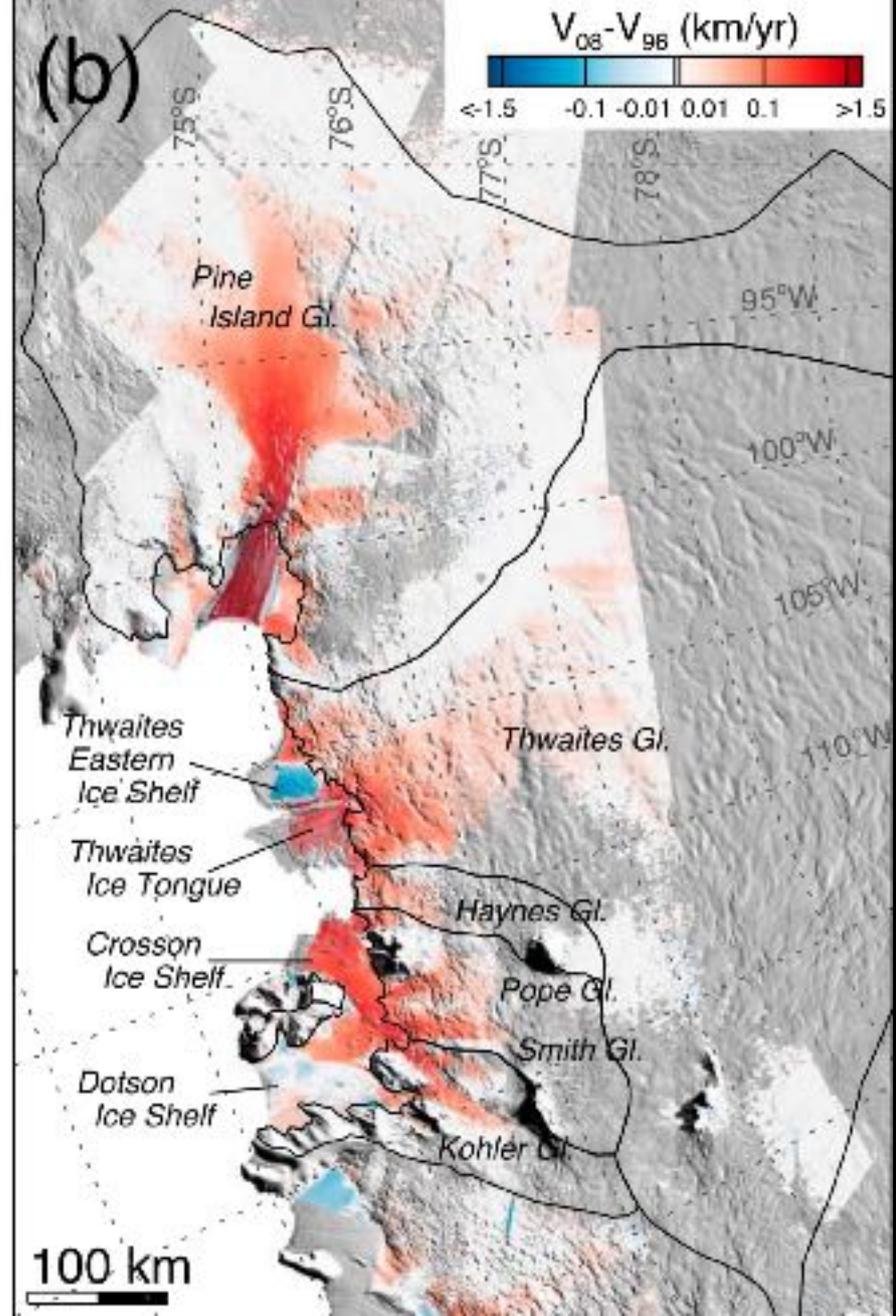
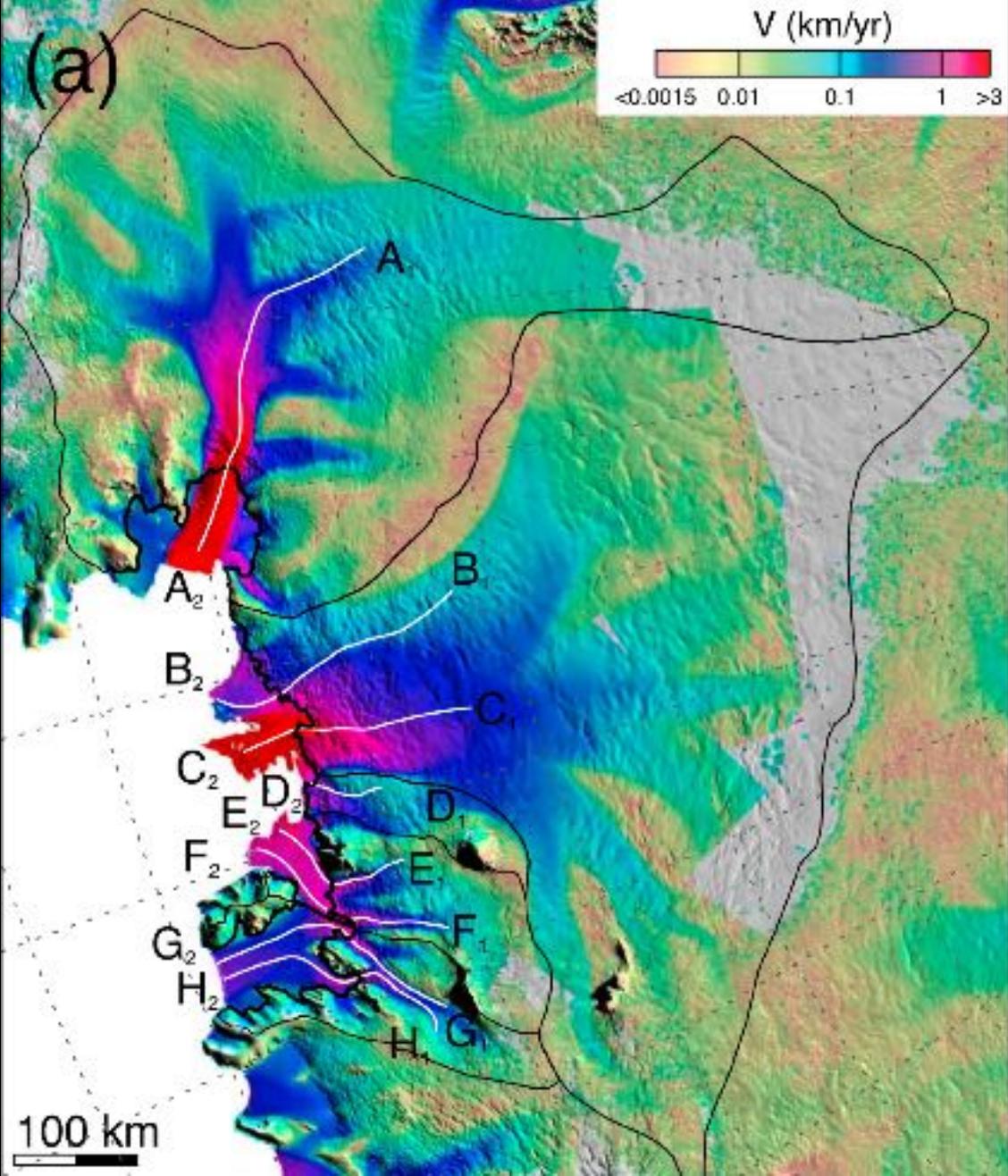
Escoamento de geleiras

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>

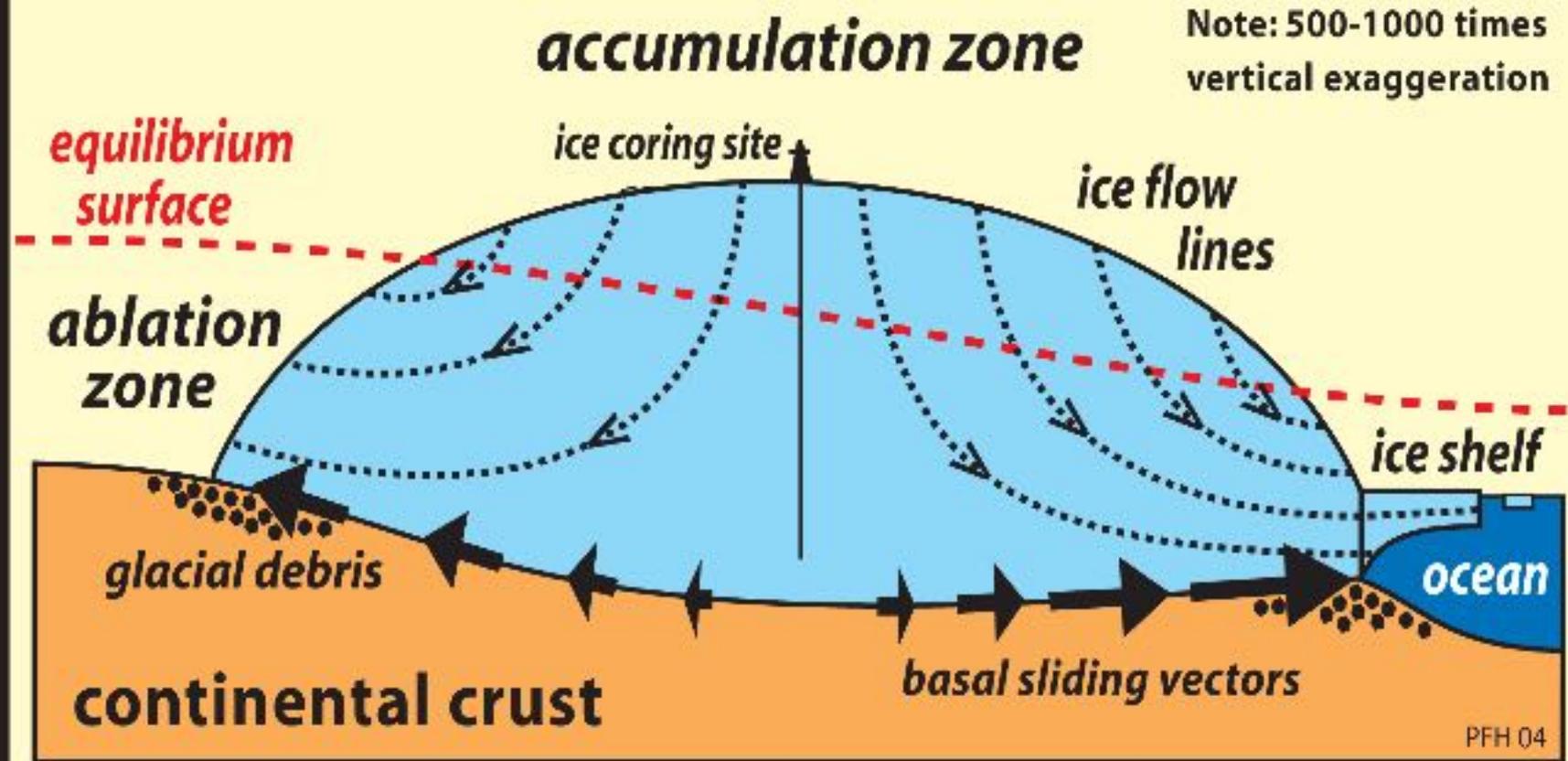


Extração e análise de testemunhos de gelo

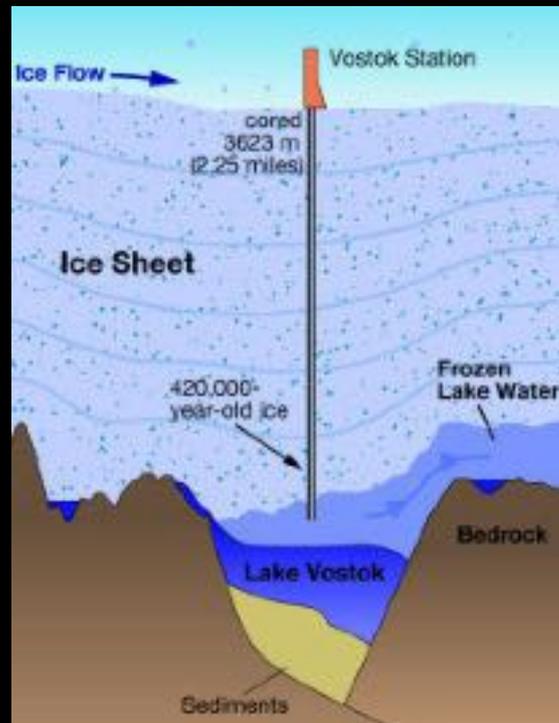
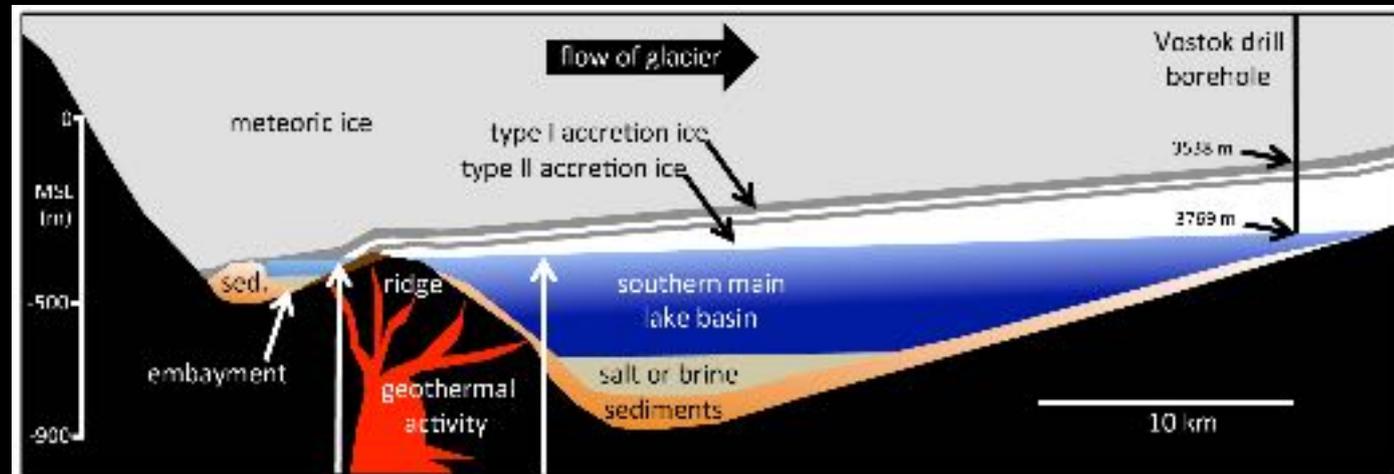
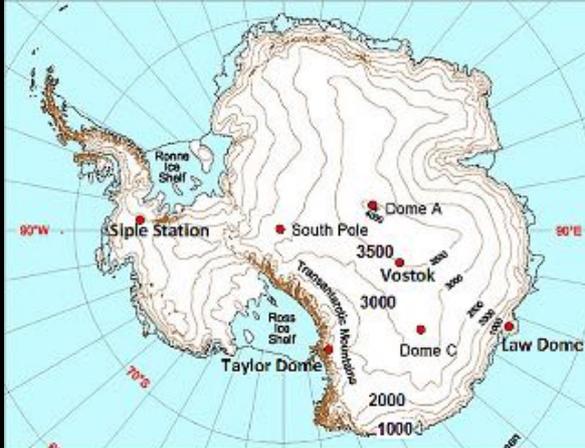


Drilling site: location, location, location...

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)

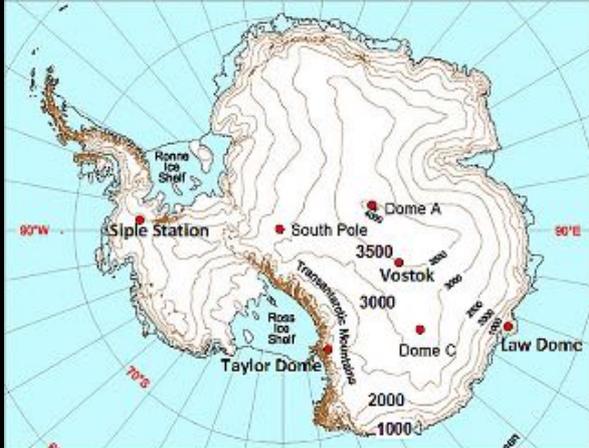
Eukarya (4%; the majority are Fungi)
 Amoebozoa
 Archaeplastida (mainly green algae, pollen?)
 Animalia (e.g., rotifers, mollusk, arthropods, *Daphnia*, brachiopod, tardigrade, sea anemone, bilaterian)
 Fungi (Ascomycota, Basidiomycota, Zygomycota)
 Chromalveolata (e.g., diatoms, dinoflagellates, yellow-green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

V6 [138 unique sequences, 80 classified taxonomically]

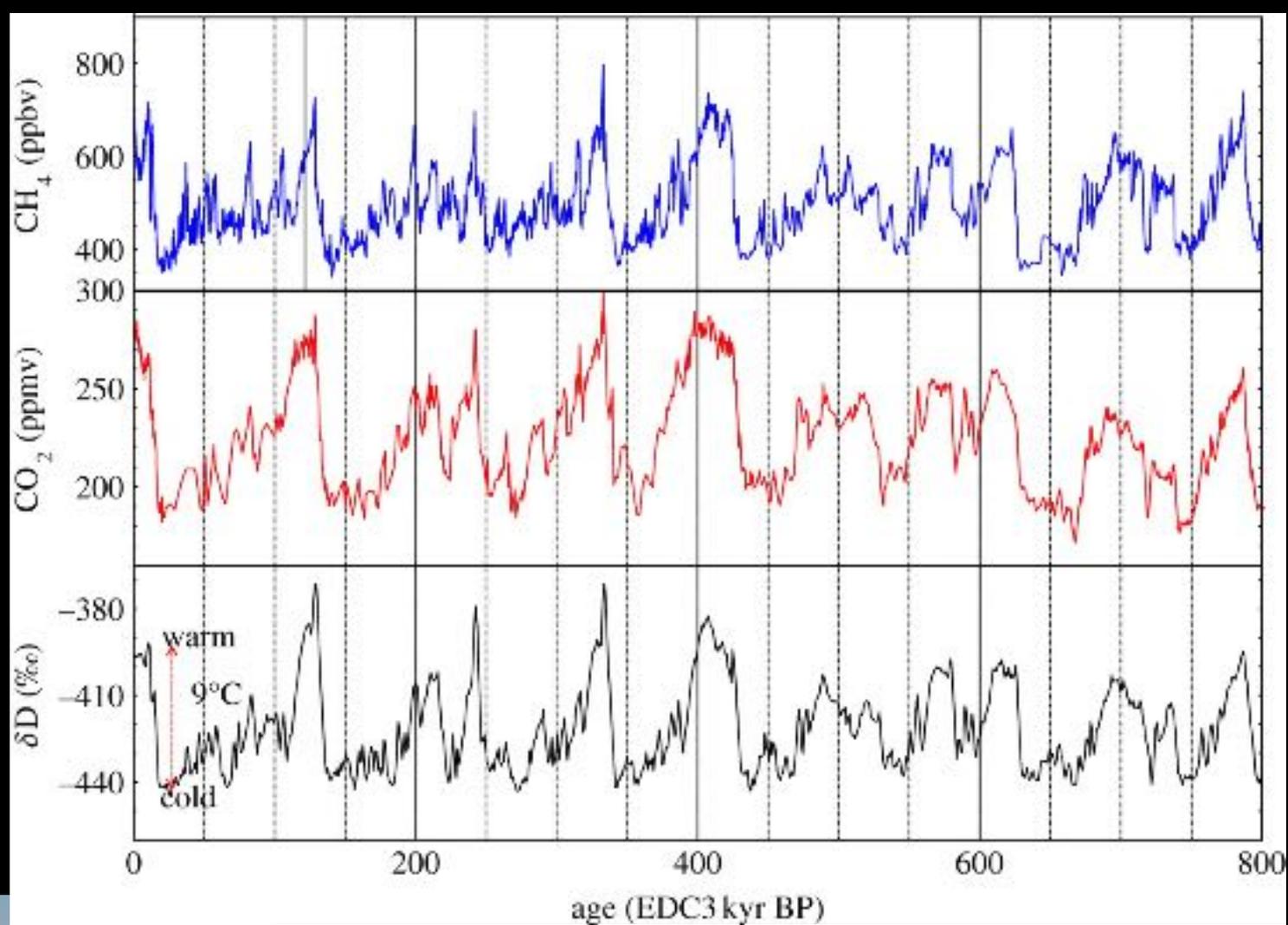
psychrophiles, mesophiles, thermophiles
 autotrophs, heterotrophs
 aerobes, anaerobes
 central metabolism, N-fixation, nitrification, denitrification, C-fixation

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)



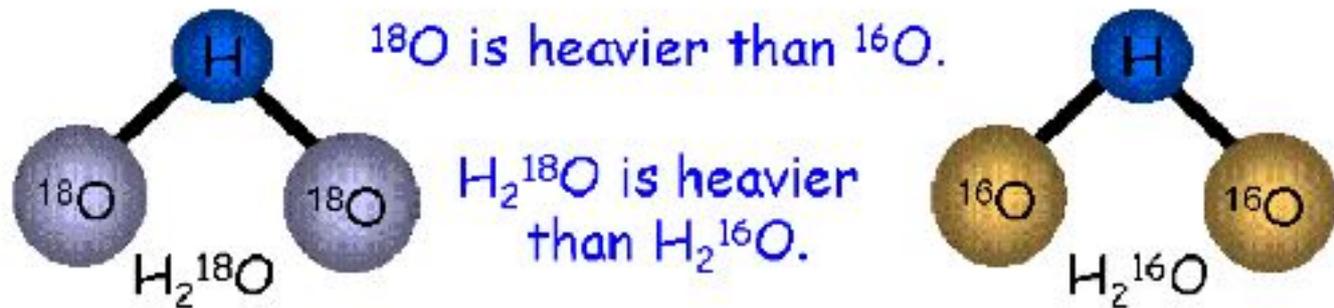
Dome C



Fracionamento isotópico

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

- 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 $H_2^{16}O$

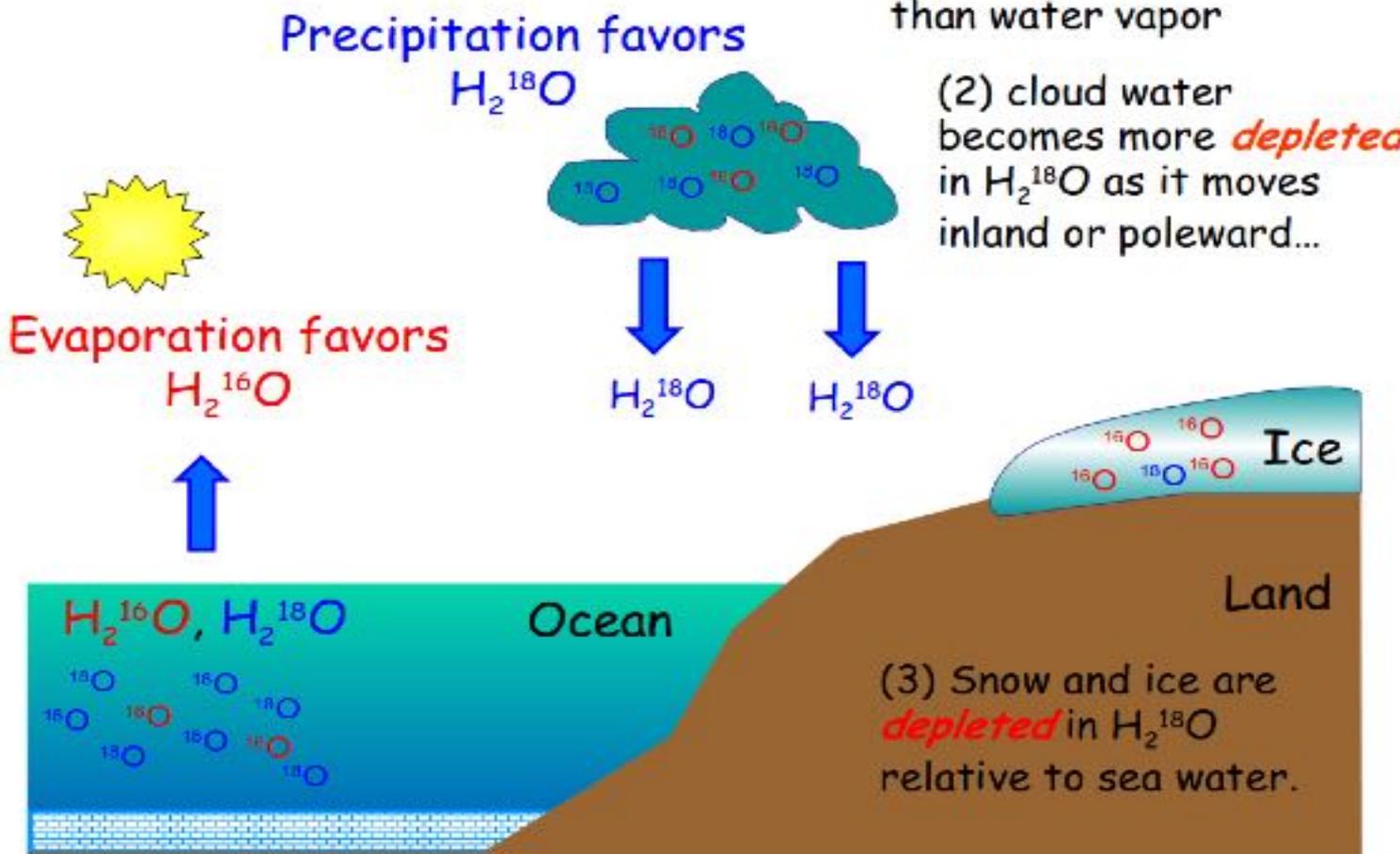


- Oxygen isotopes are also **fractionated** by marine organisms that secrete $CaCO_3$ shells. The organisms preferentially take up more ^{16}O as temperature increases.

Fracionamento isotópico

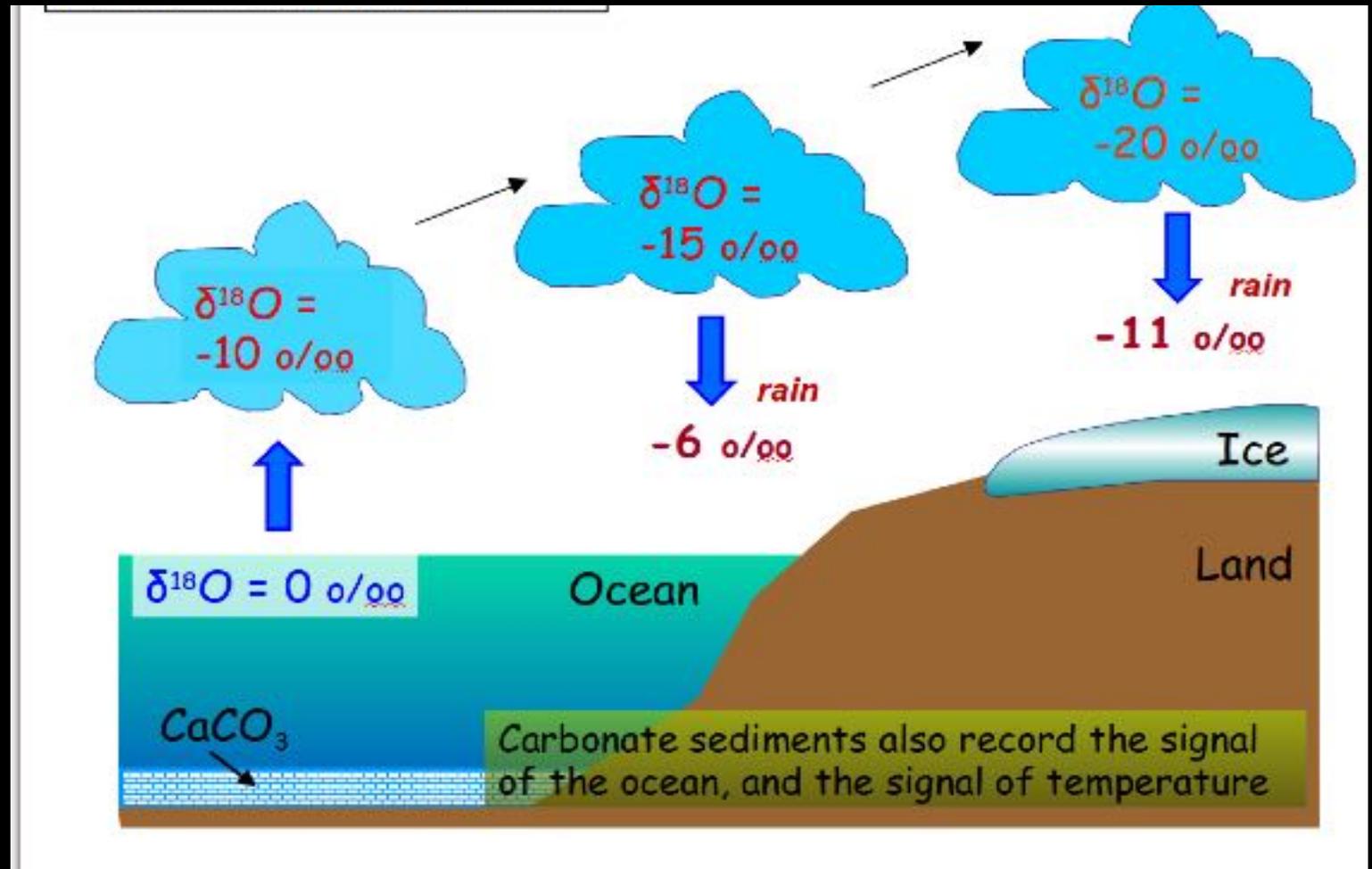
$$\delta^{18}O = \frac{(^{18}O/^{16}O)_{amostra} - (^{18}O/^{16}O)_{referencia}}{(^{18}O/^{16}O)_{referencia}}$$

Fractionation effects



Fracionamento isotópico

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



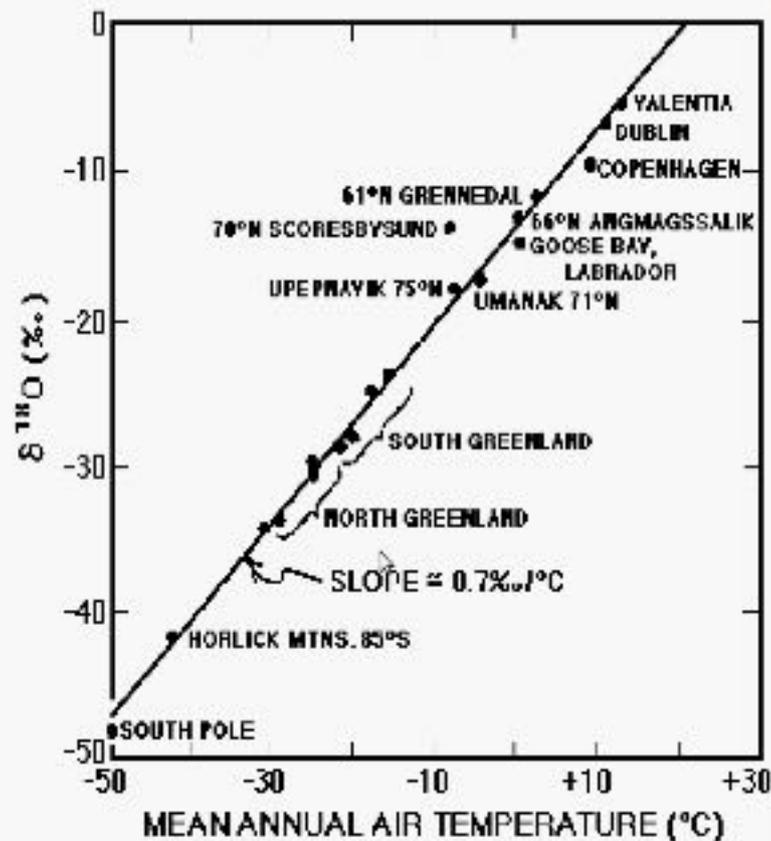
Fracionamento isotópico

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

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)

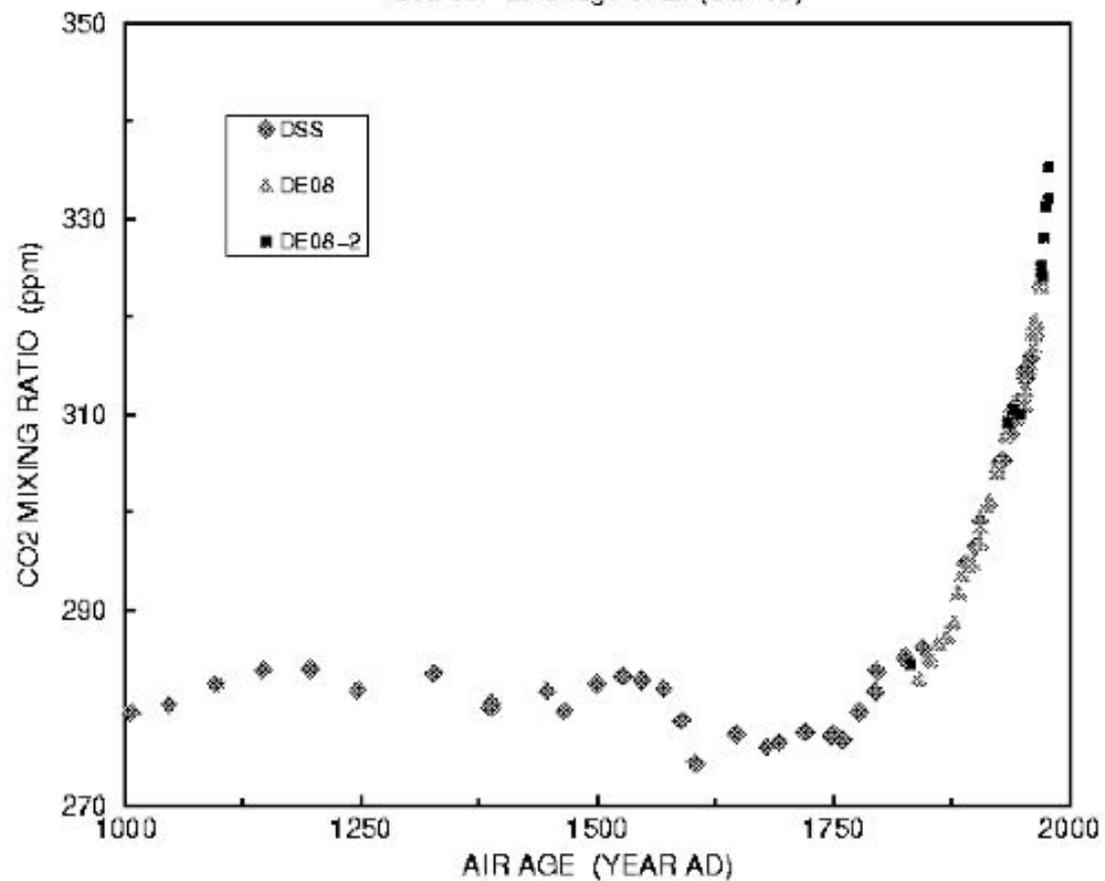


Observed $\delta^{18}\text{O}$ in average annual precipitation as a function of mean annual air temperature (Dansgaard, 1964). Note that all the points on this graph are for high latitudes ($>45^\circ$).

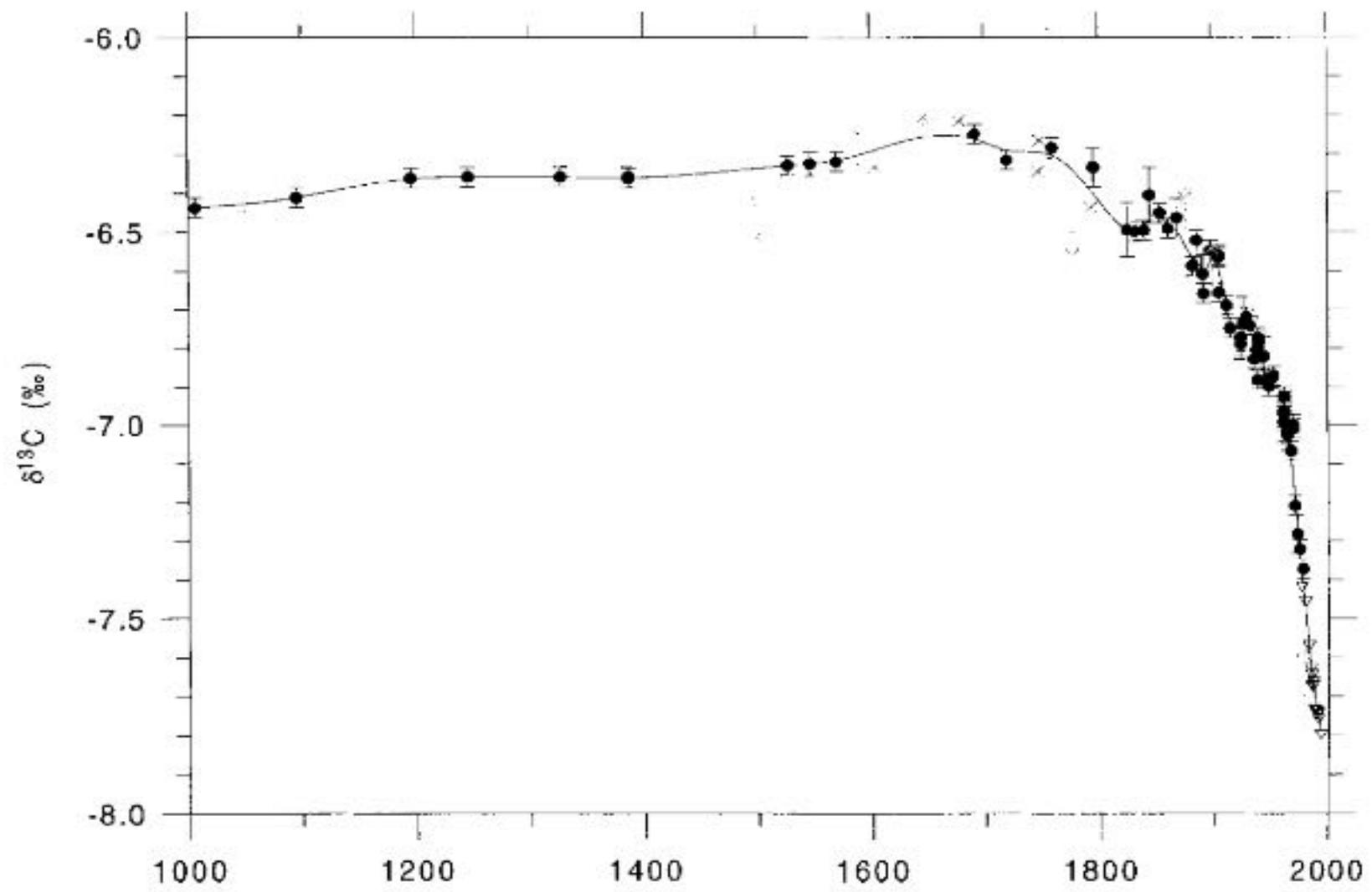
Concentração de CO₂

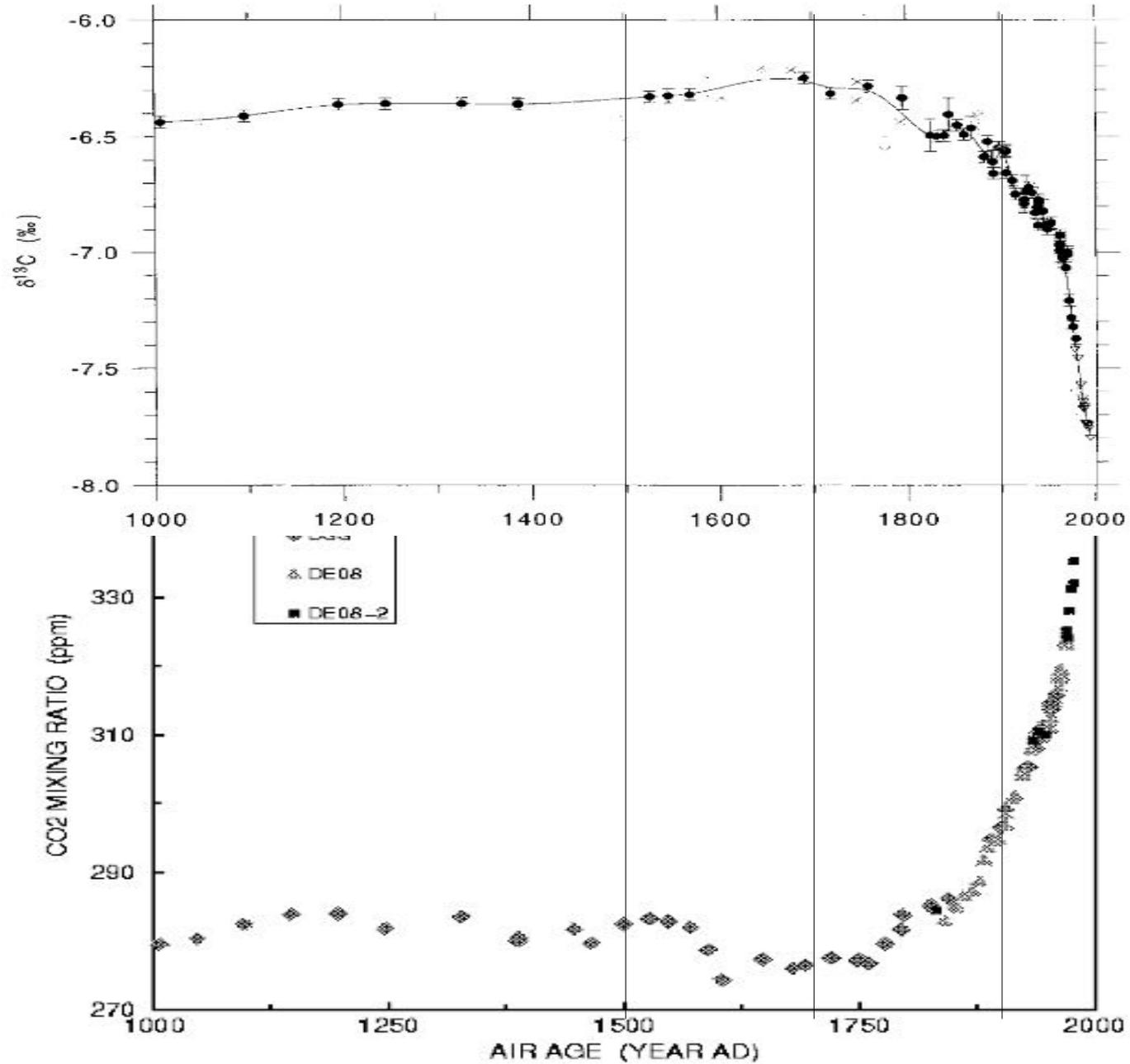
LAW DOME, ANTARCTICA ICE CORES

Source: Etheridge et al. (CSIRO)

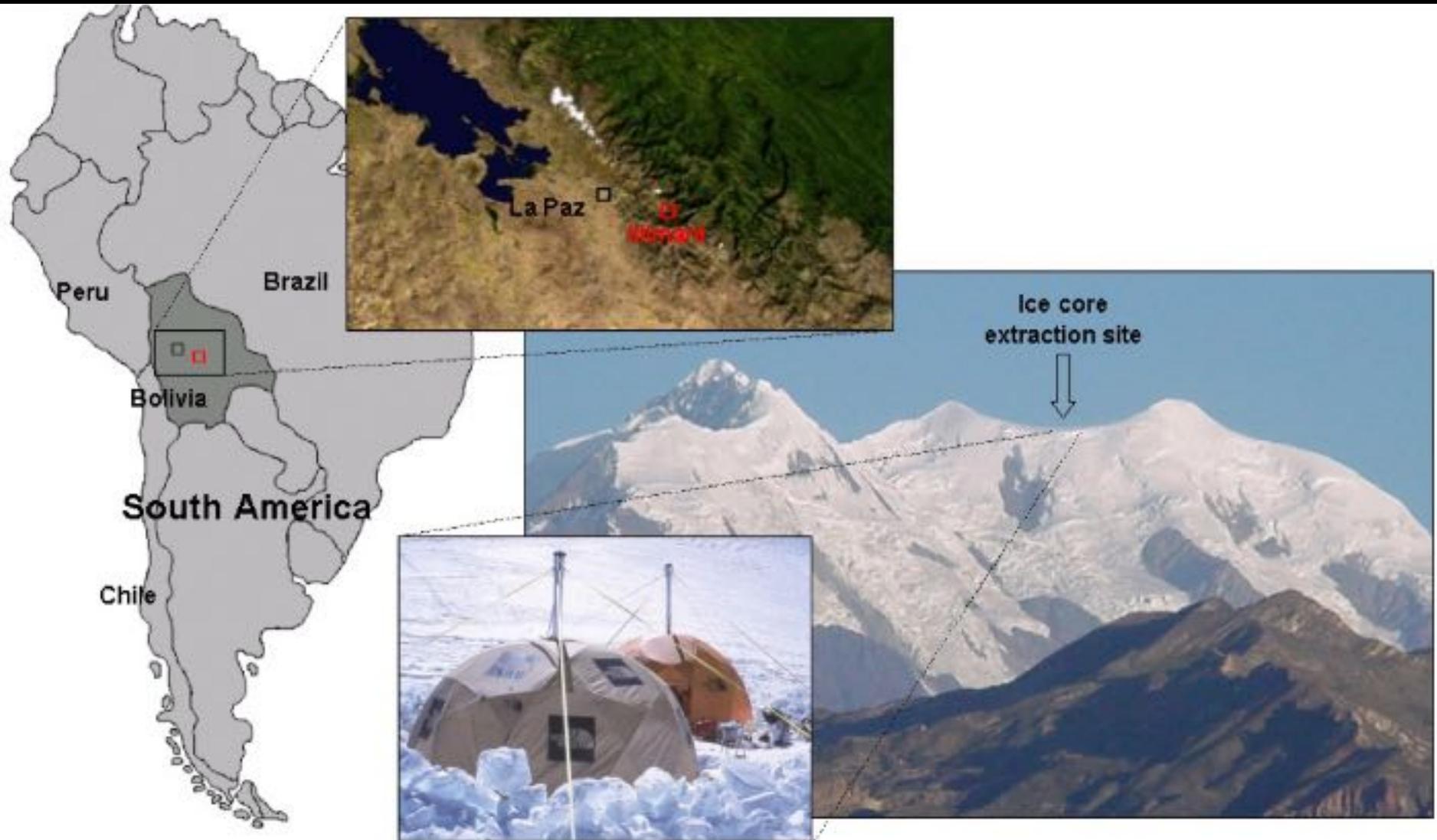


Fracionamento de ^{13}C





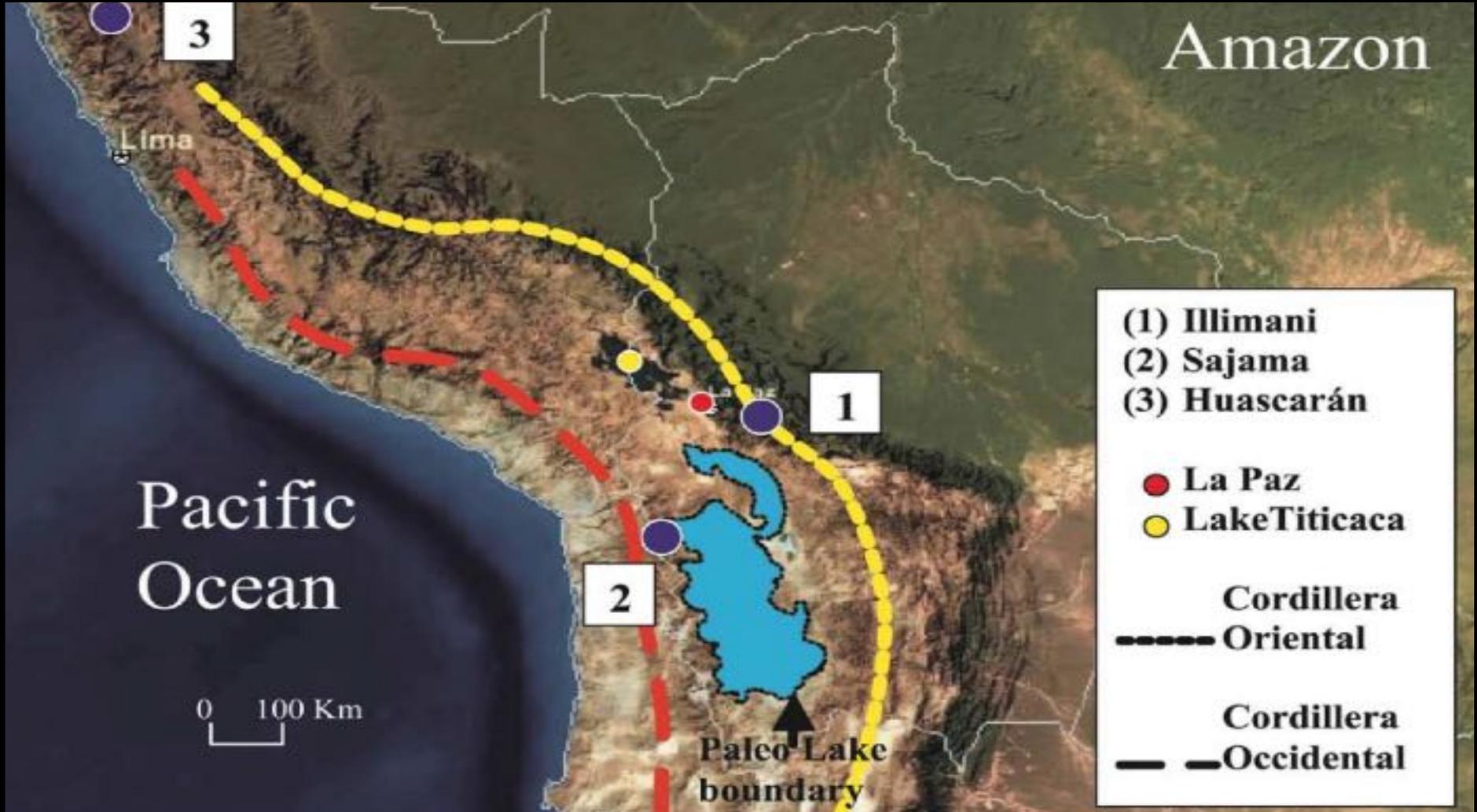
O testemunho de gelo de Illimani, Bolívia



O testemunho de gelo de Illimani, Bolívia



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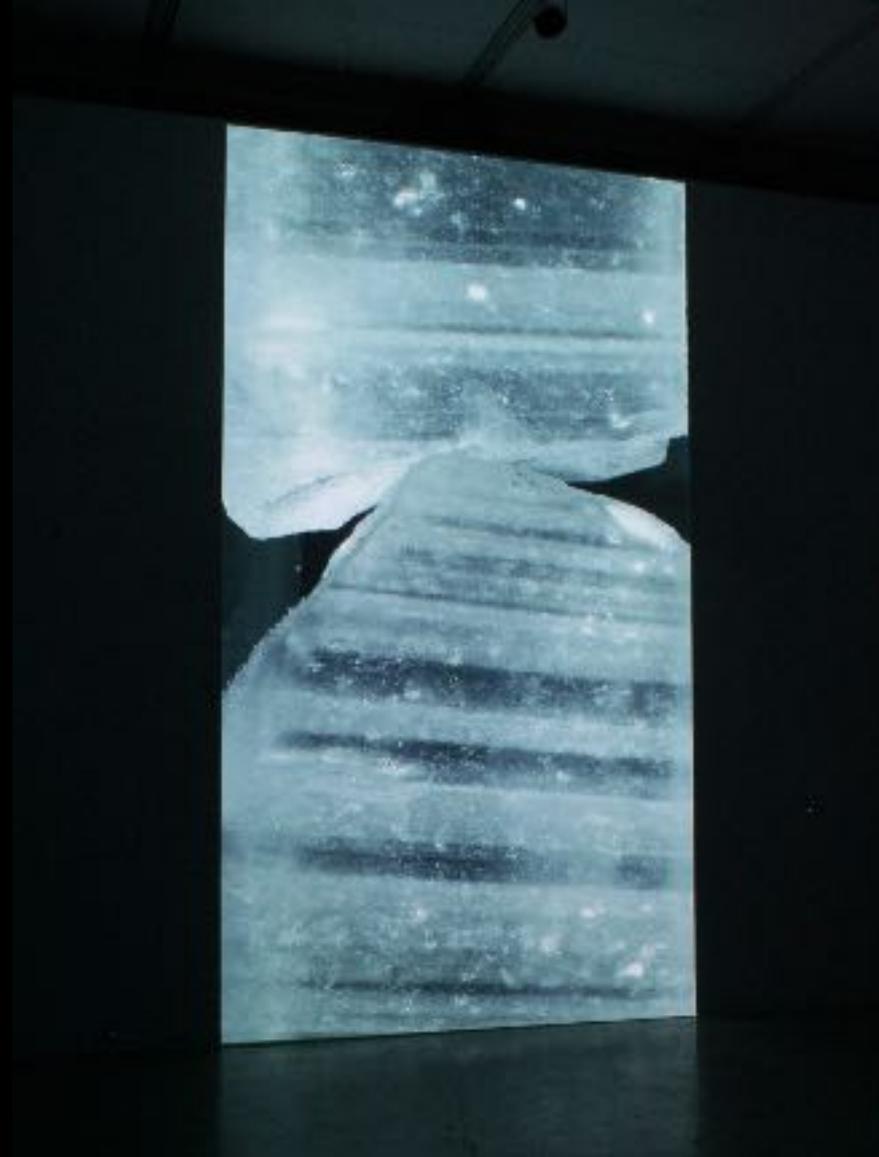
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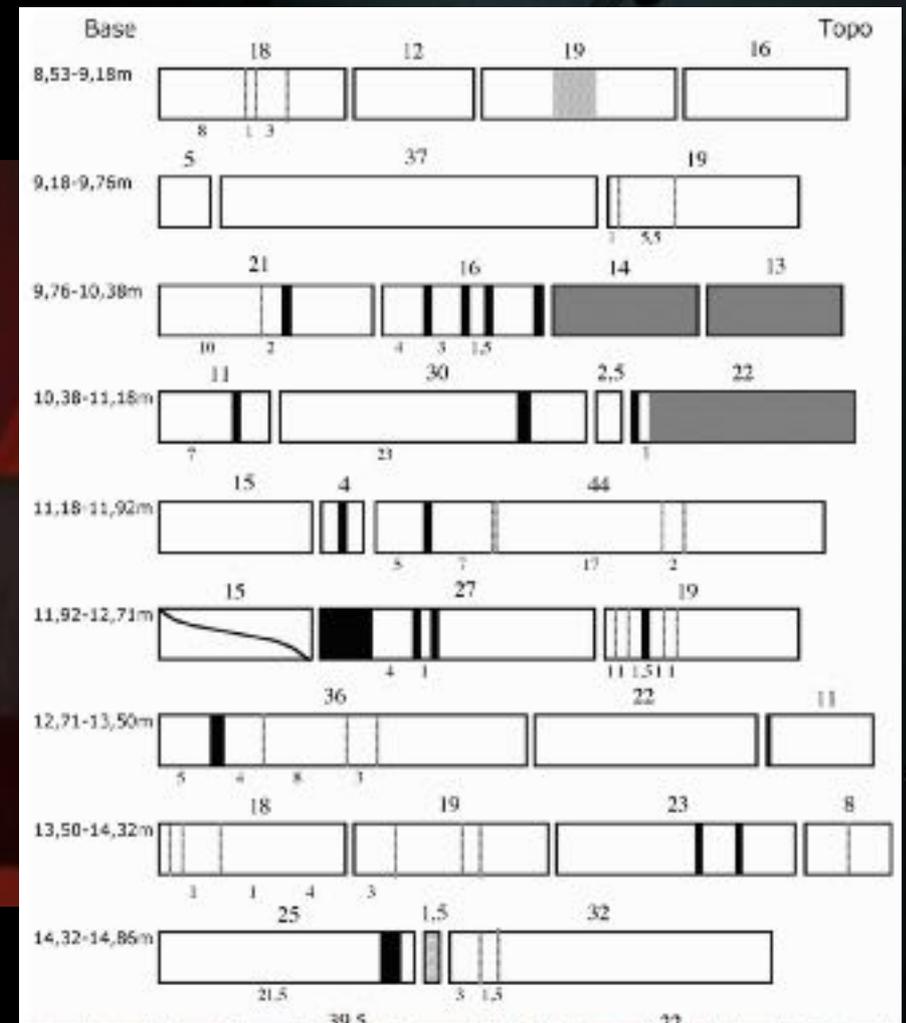
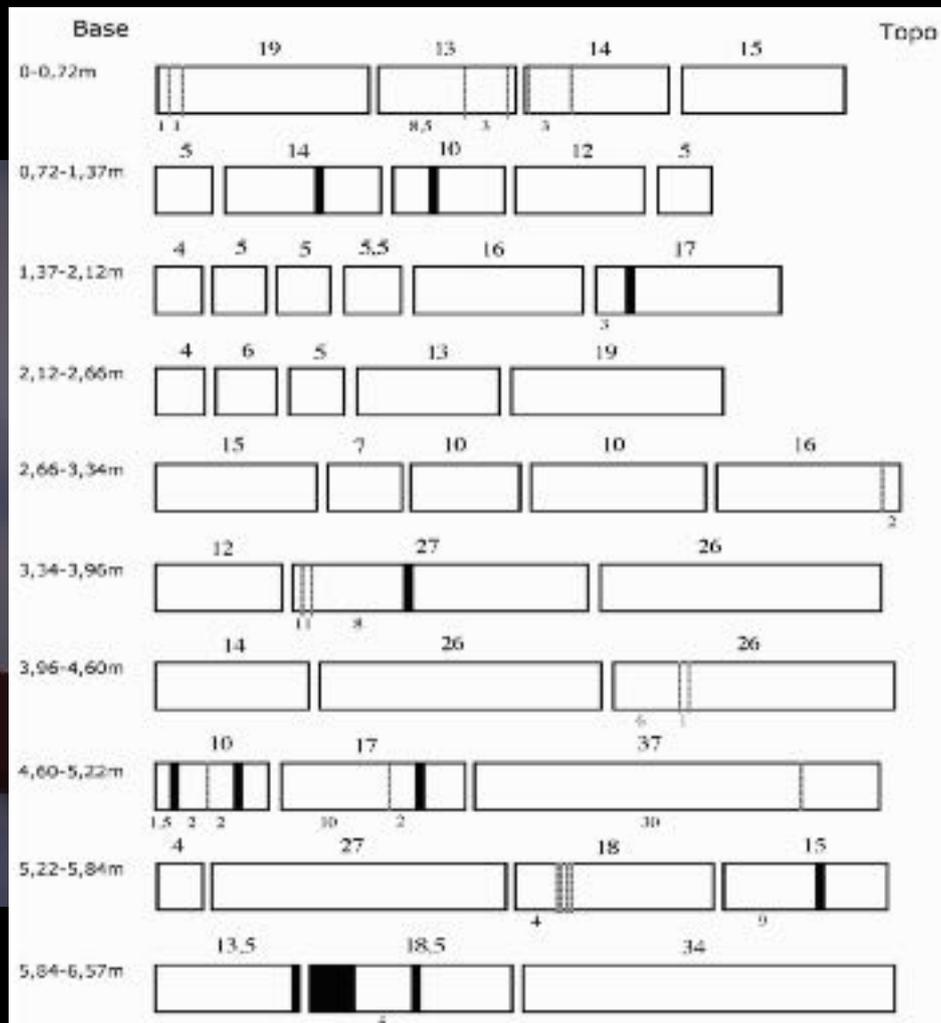
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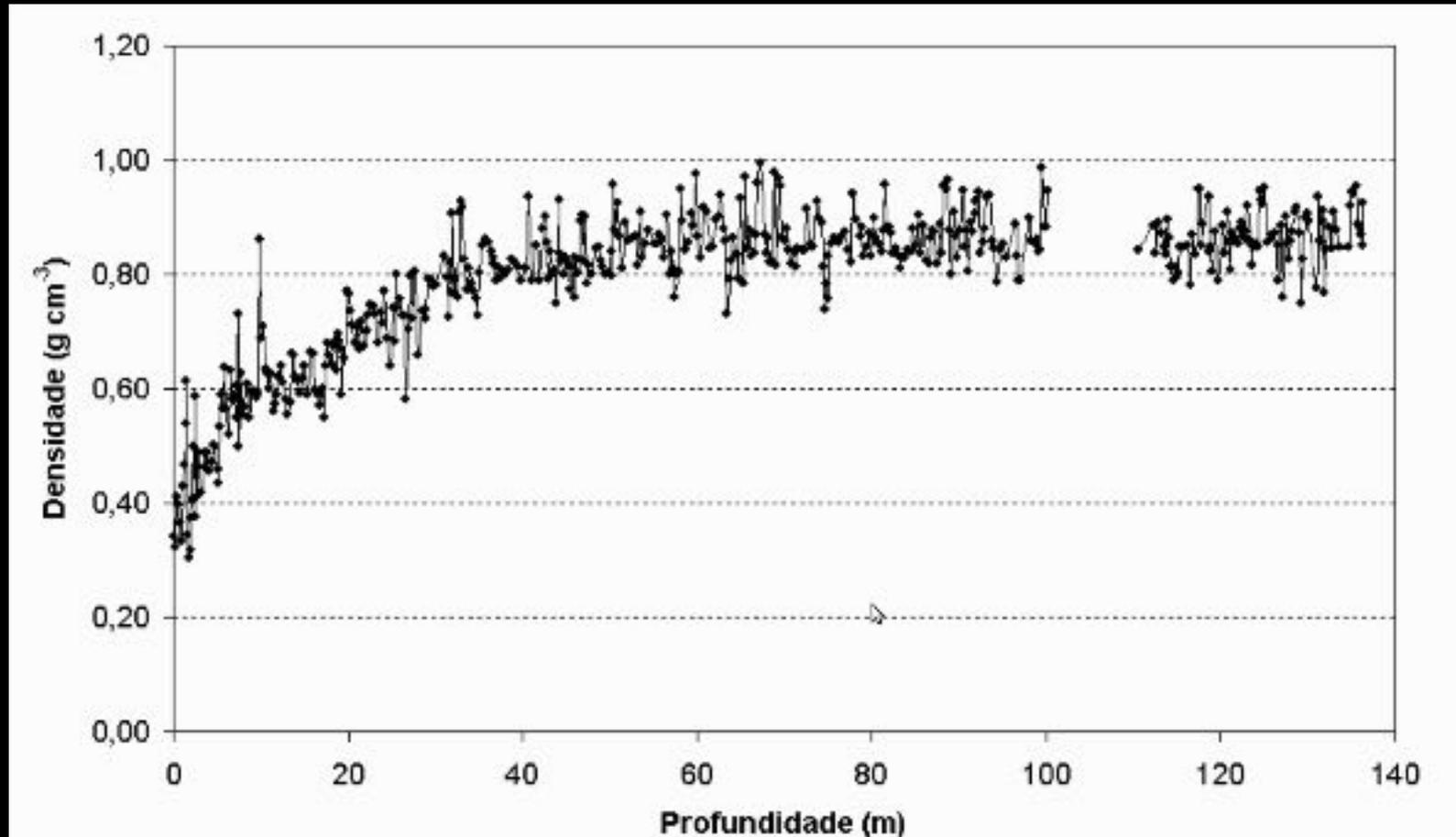
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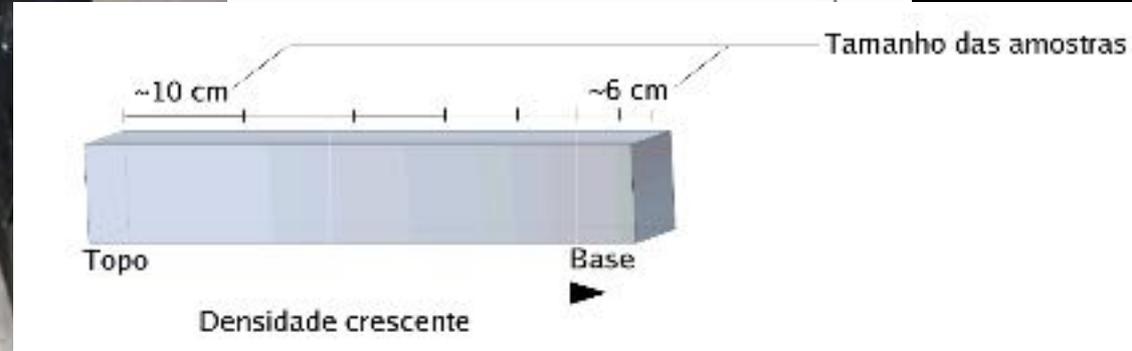
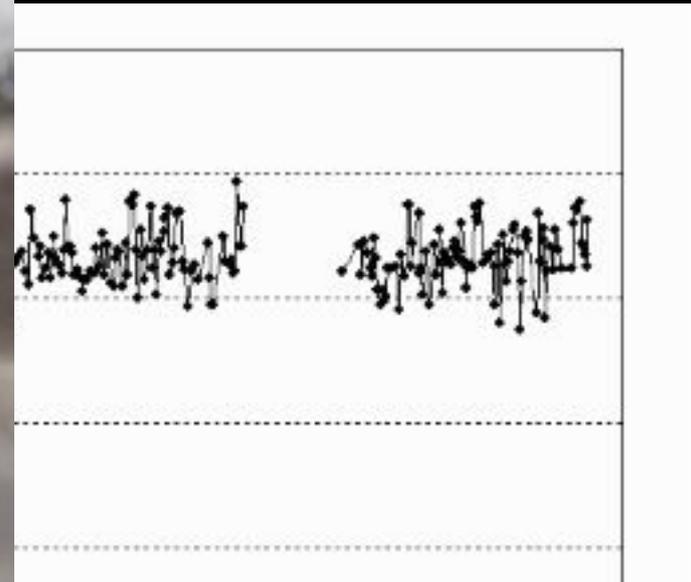
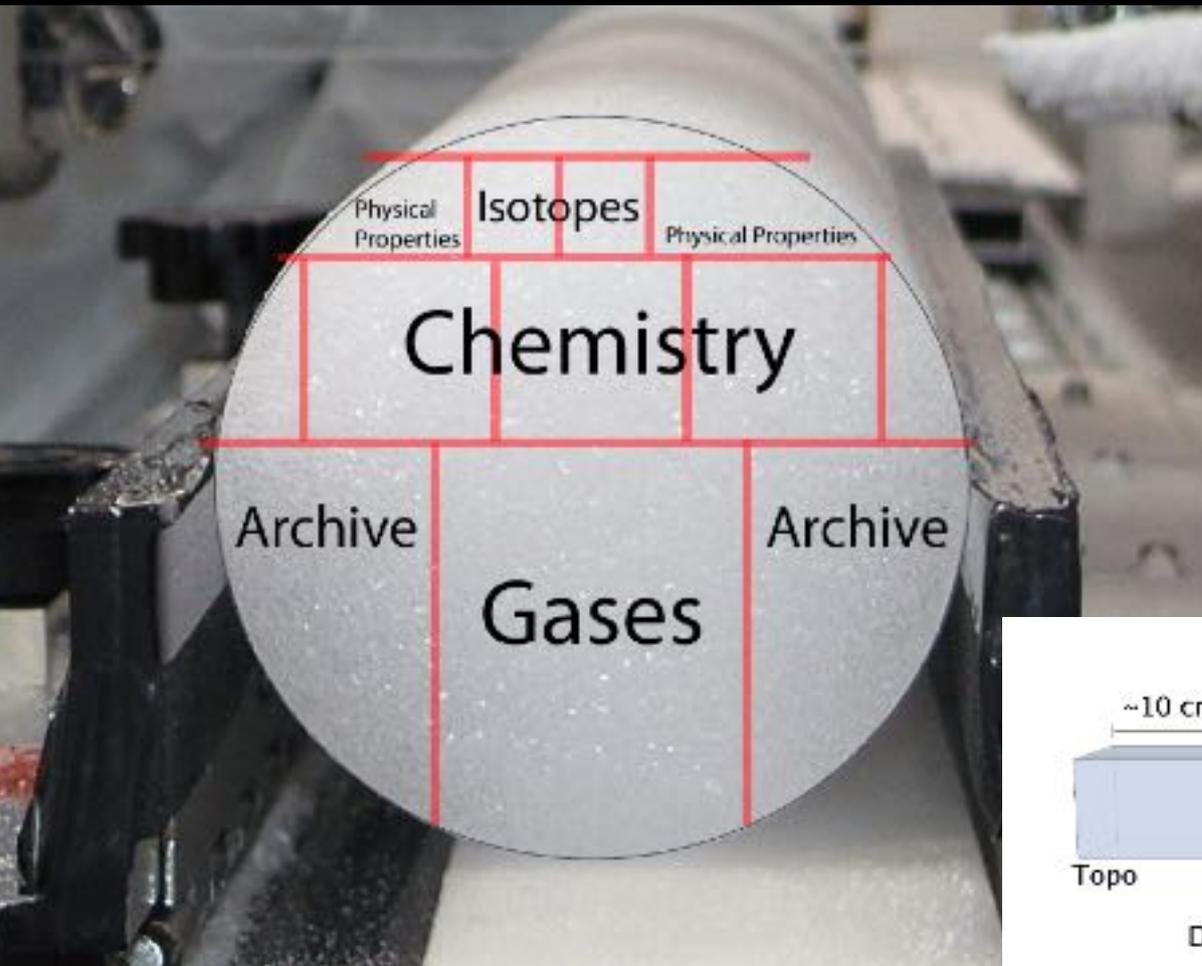
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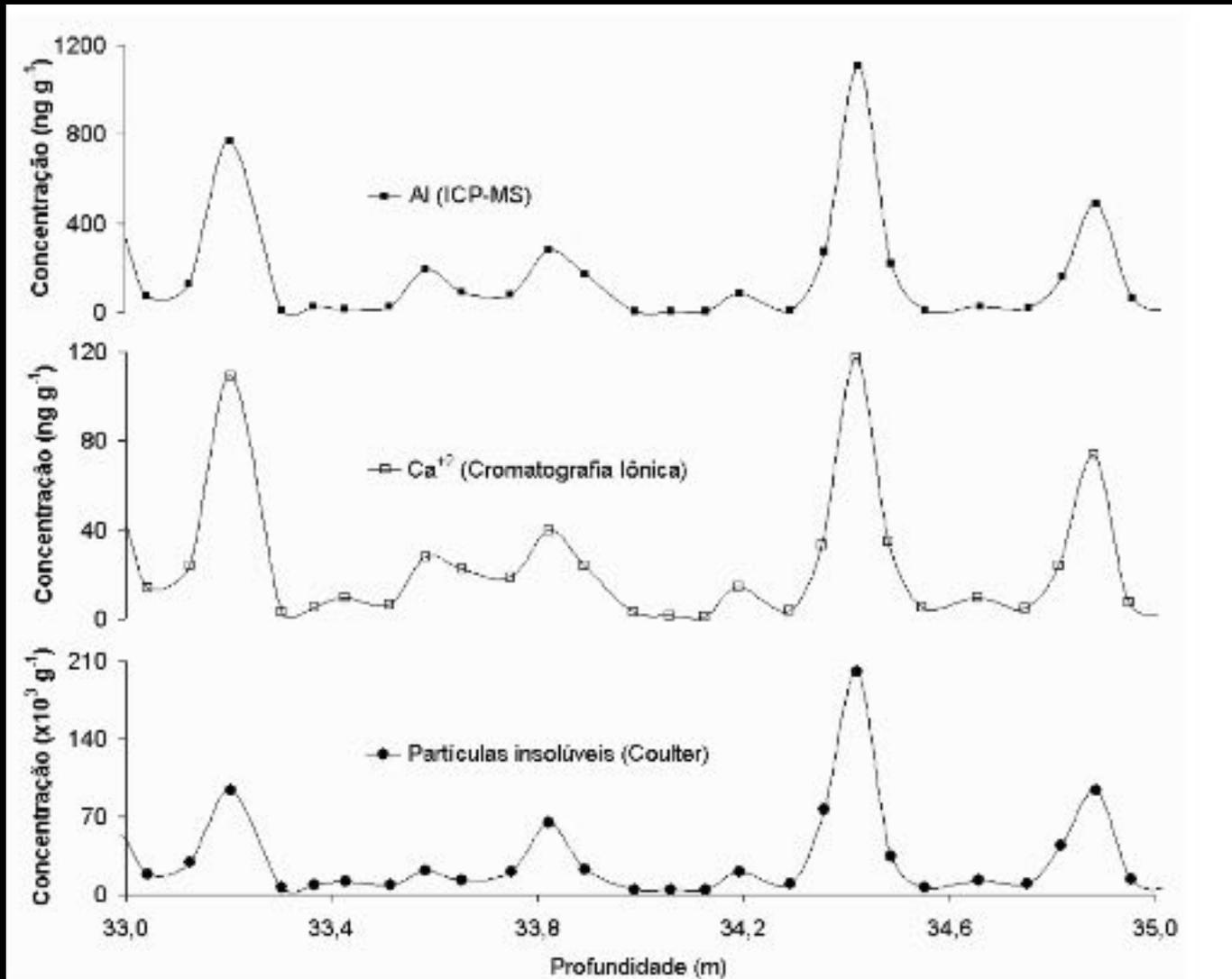
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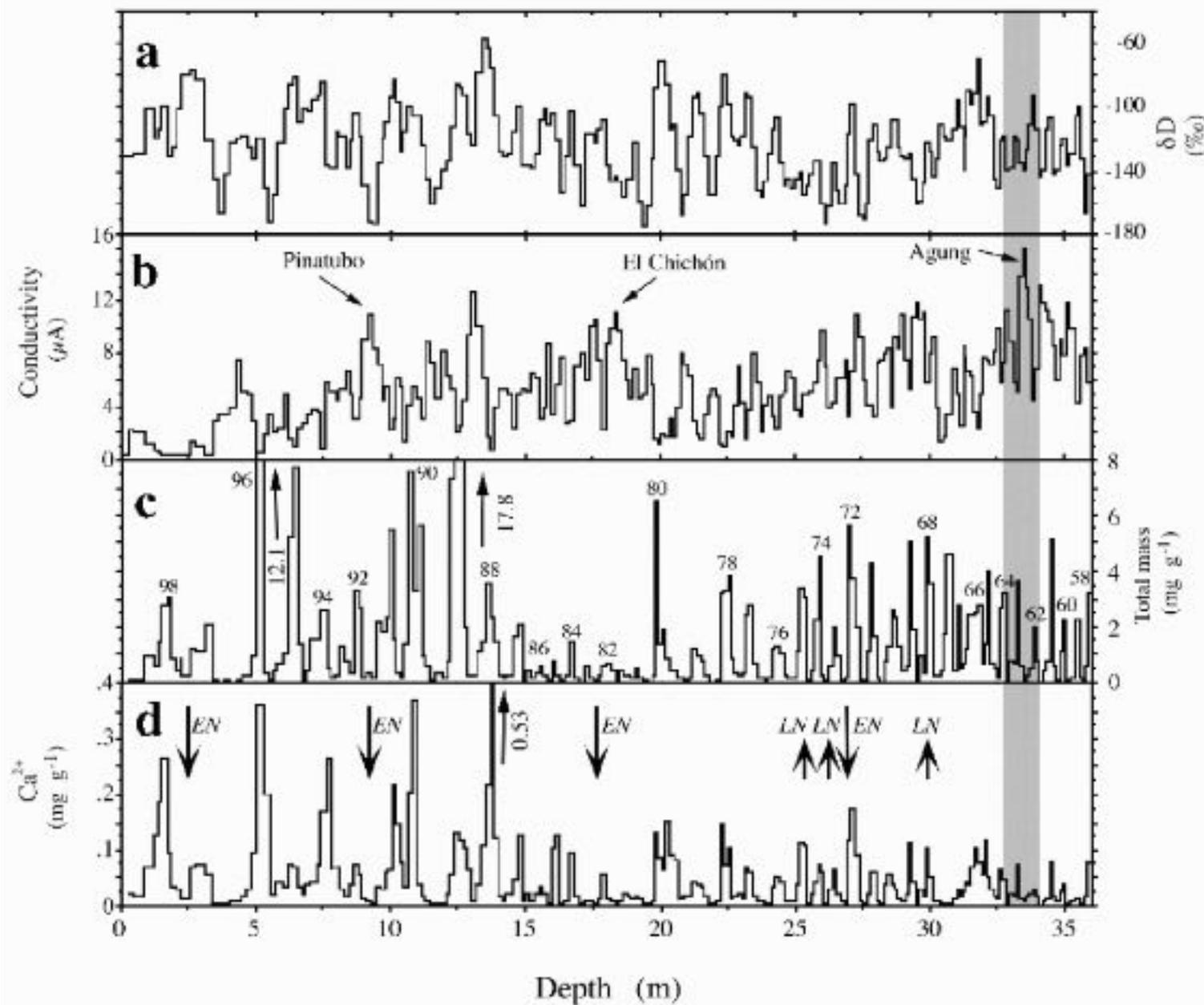


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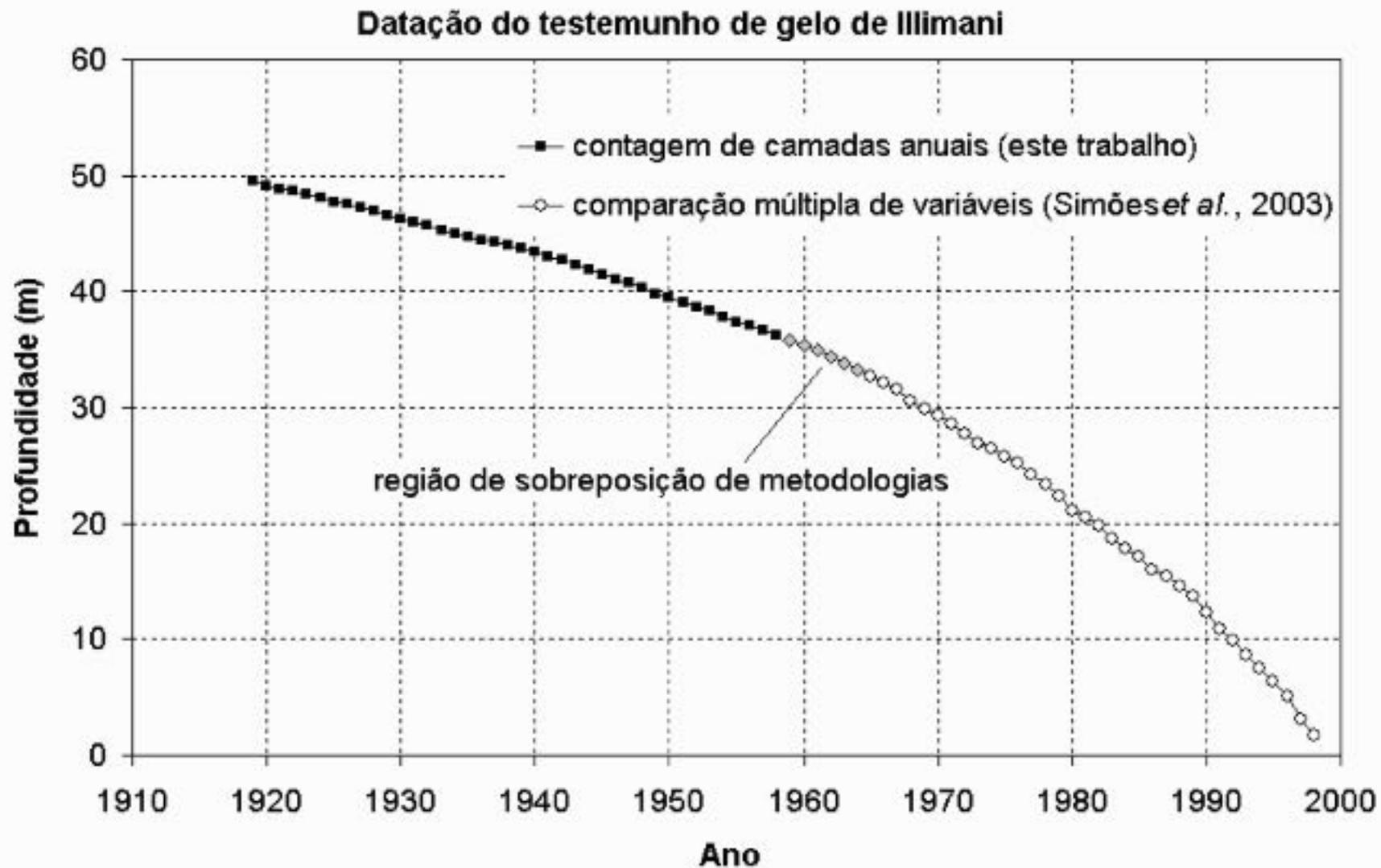


O testemunho de gelo de Illimani, Bolívia





O testemunho de gelo de Illimani, Bolívia



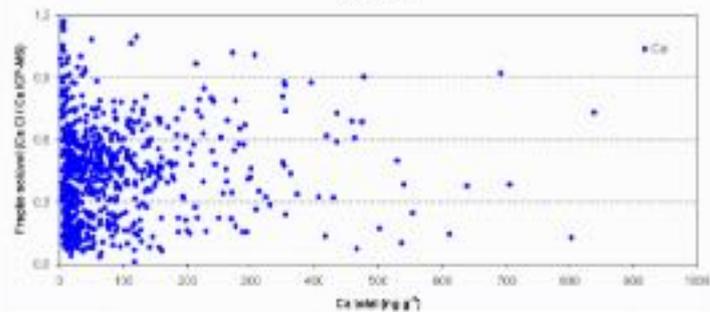
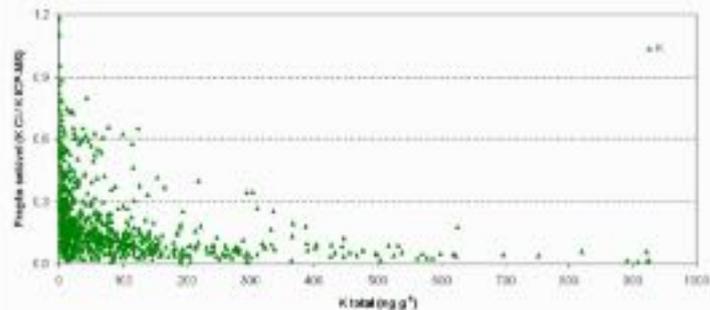
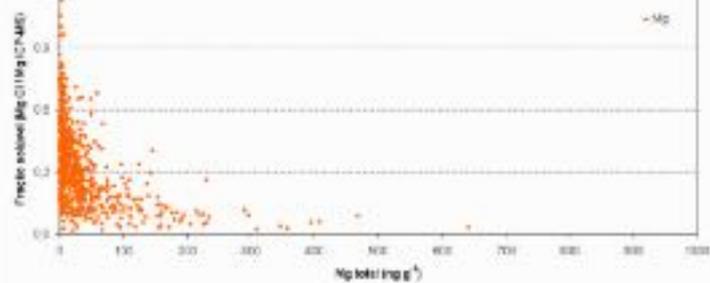
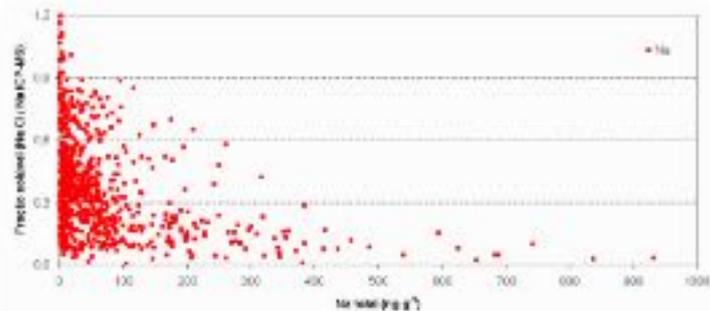
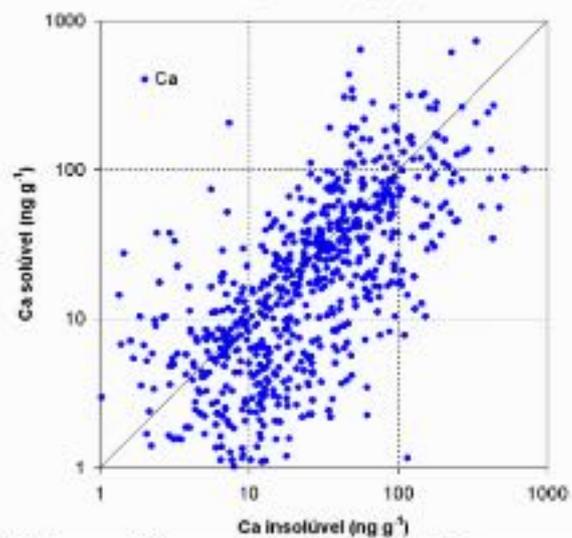
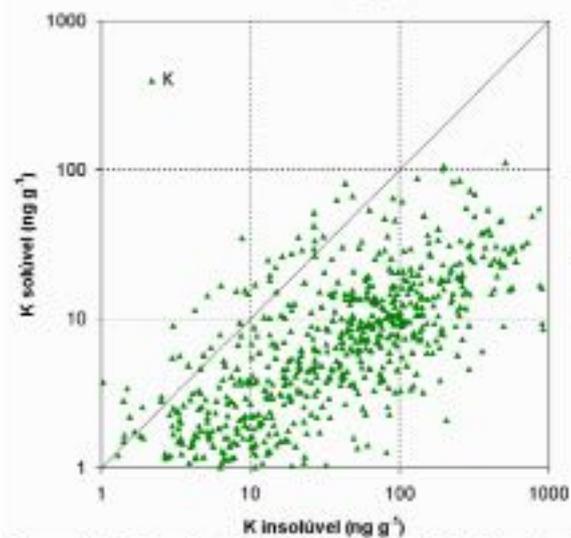
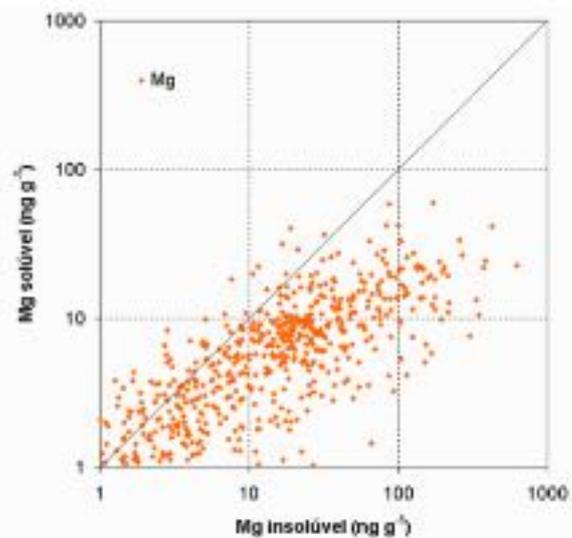
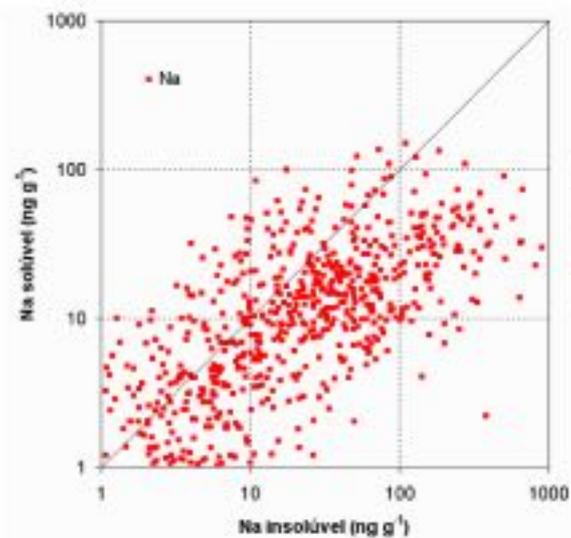
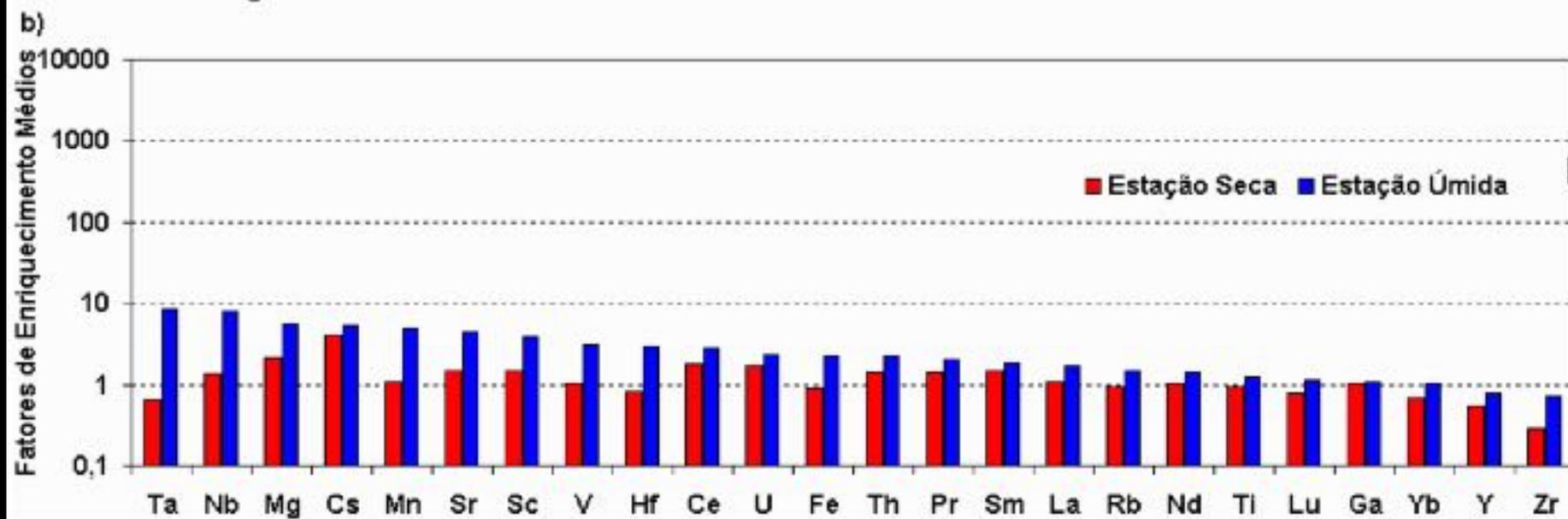
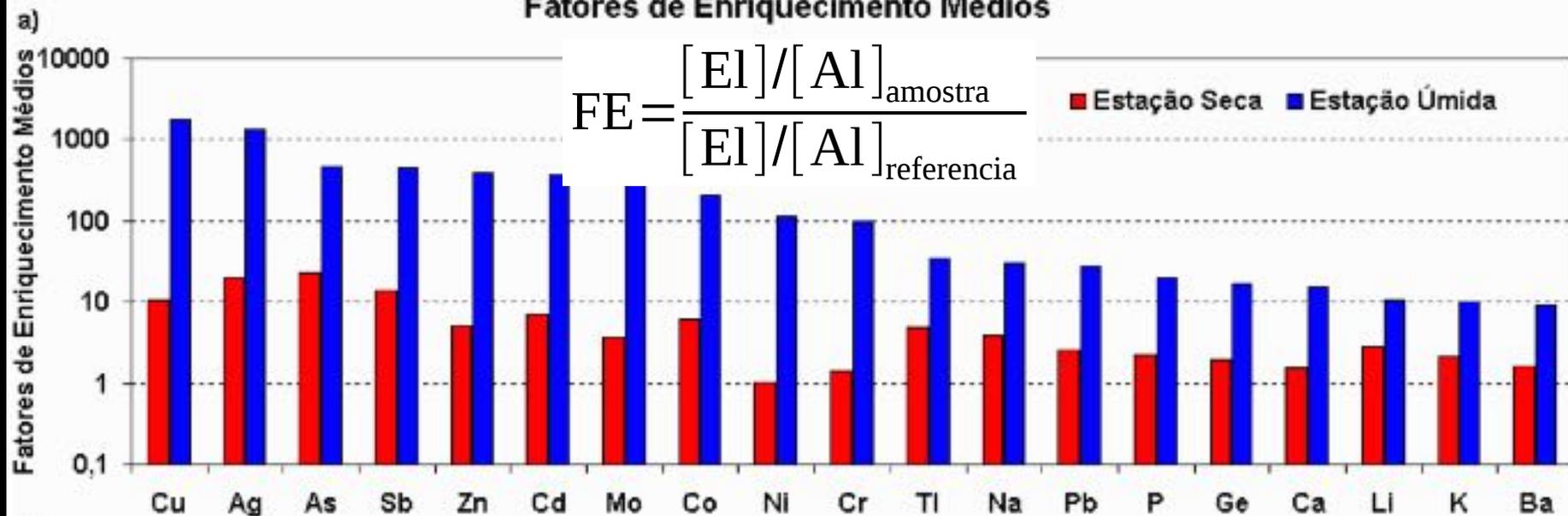
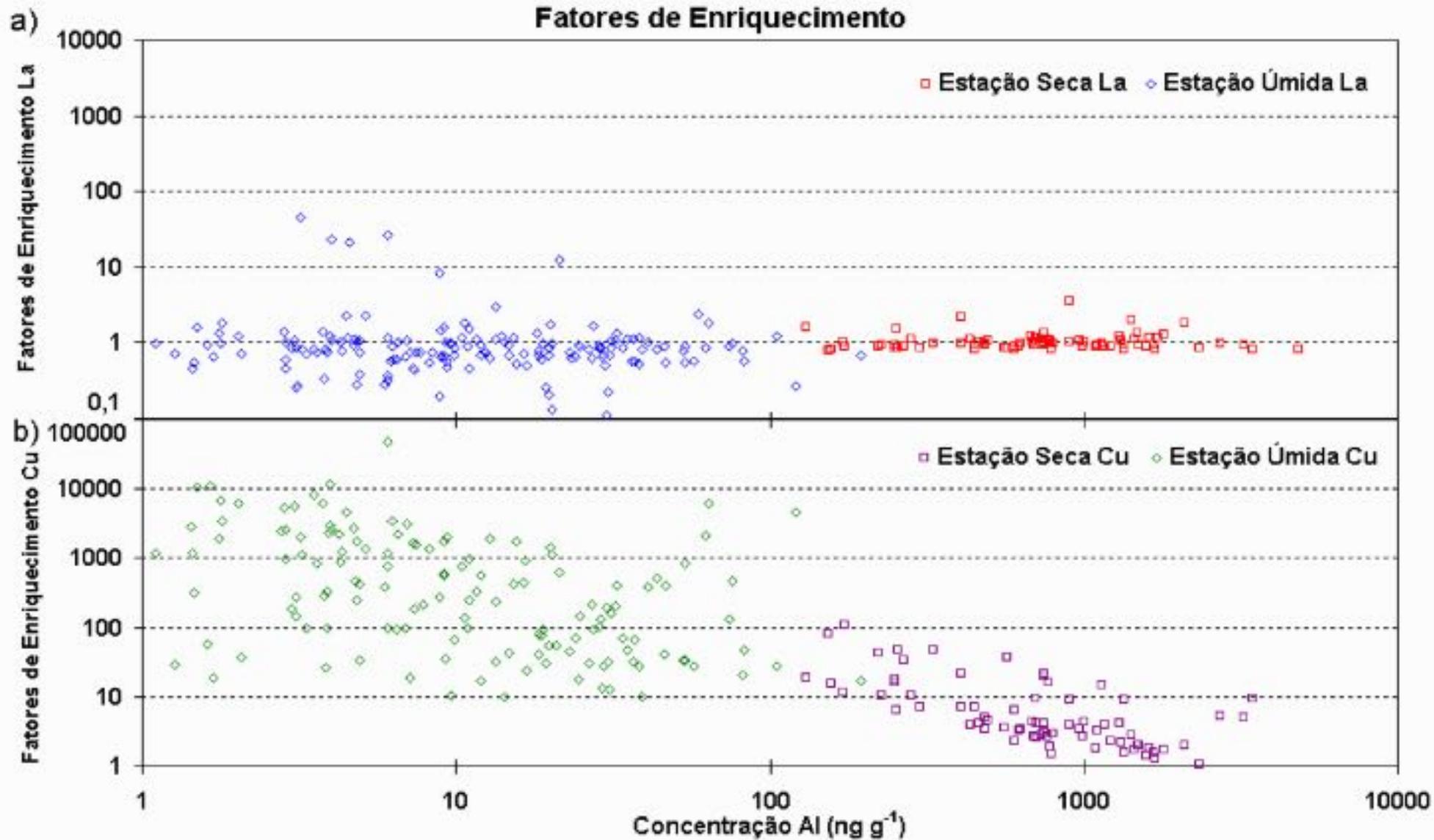


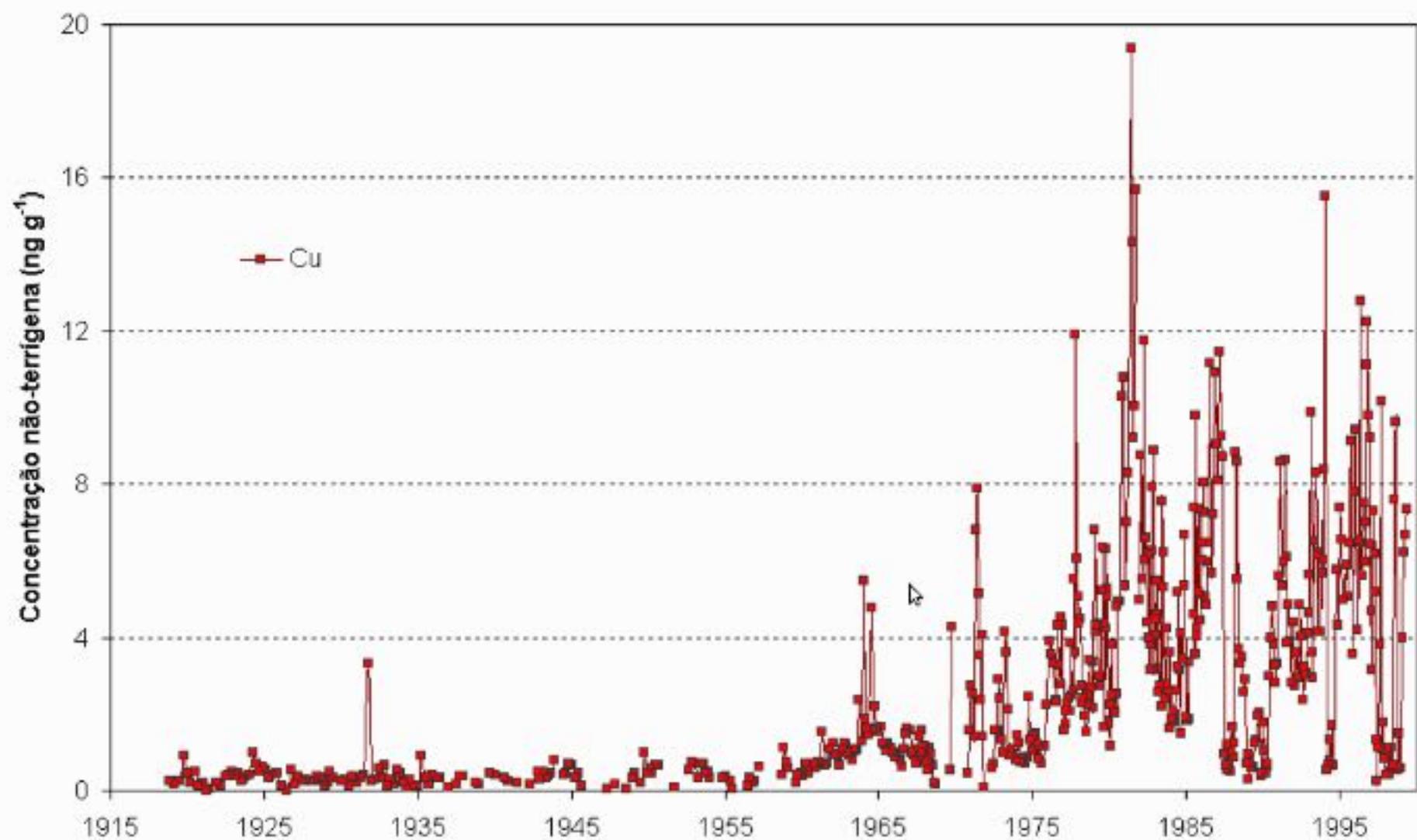
Figure 4.0. Comparison between fraction of soluble and insoluble elements (divided by total fraction) of Na, Mg, K and Ca.

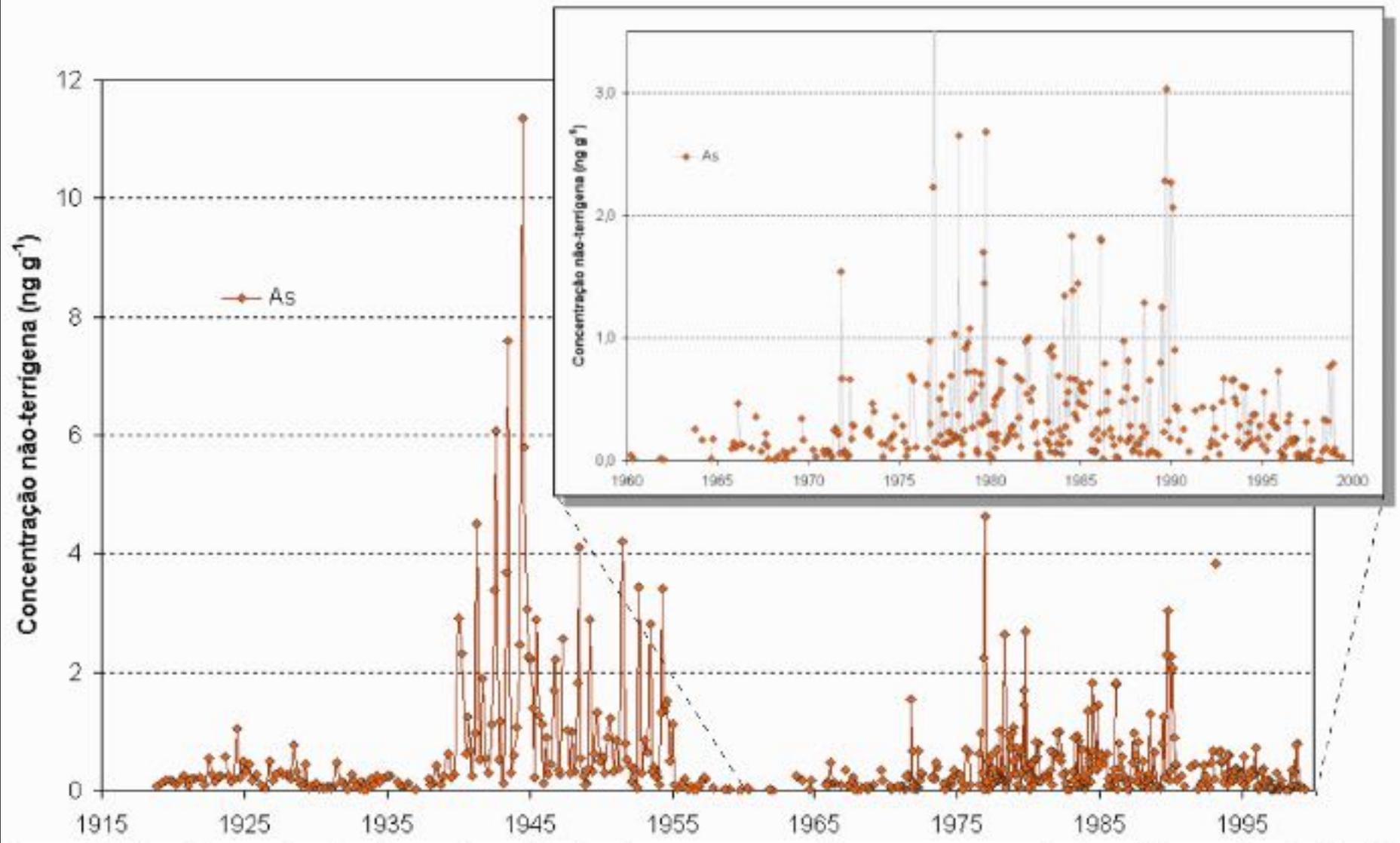
Fatores de Enriquecimento Médios

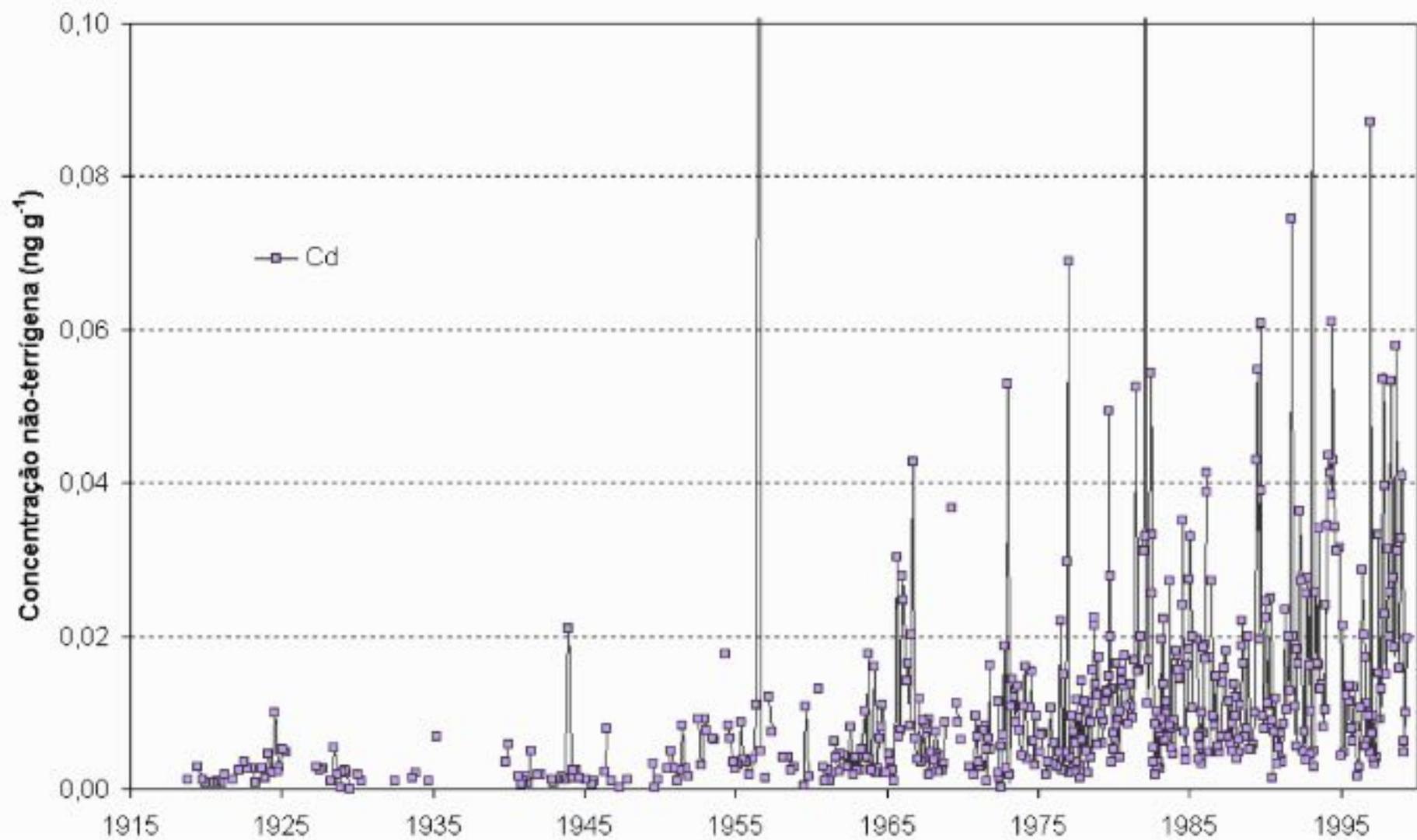


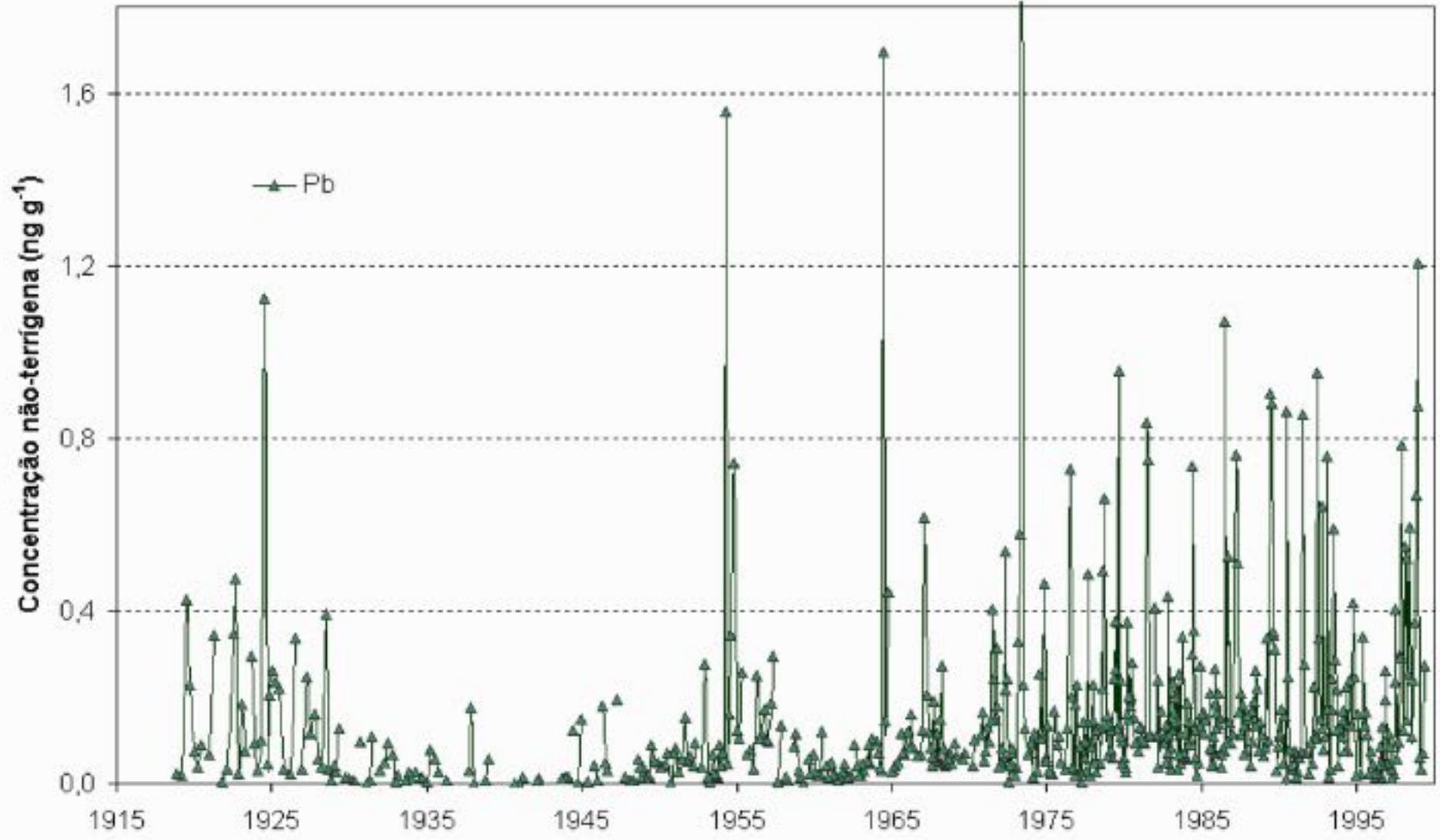
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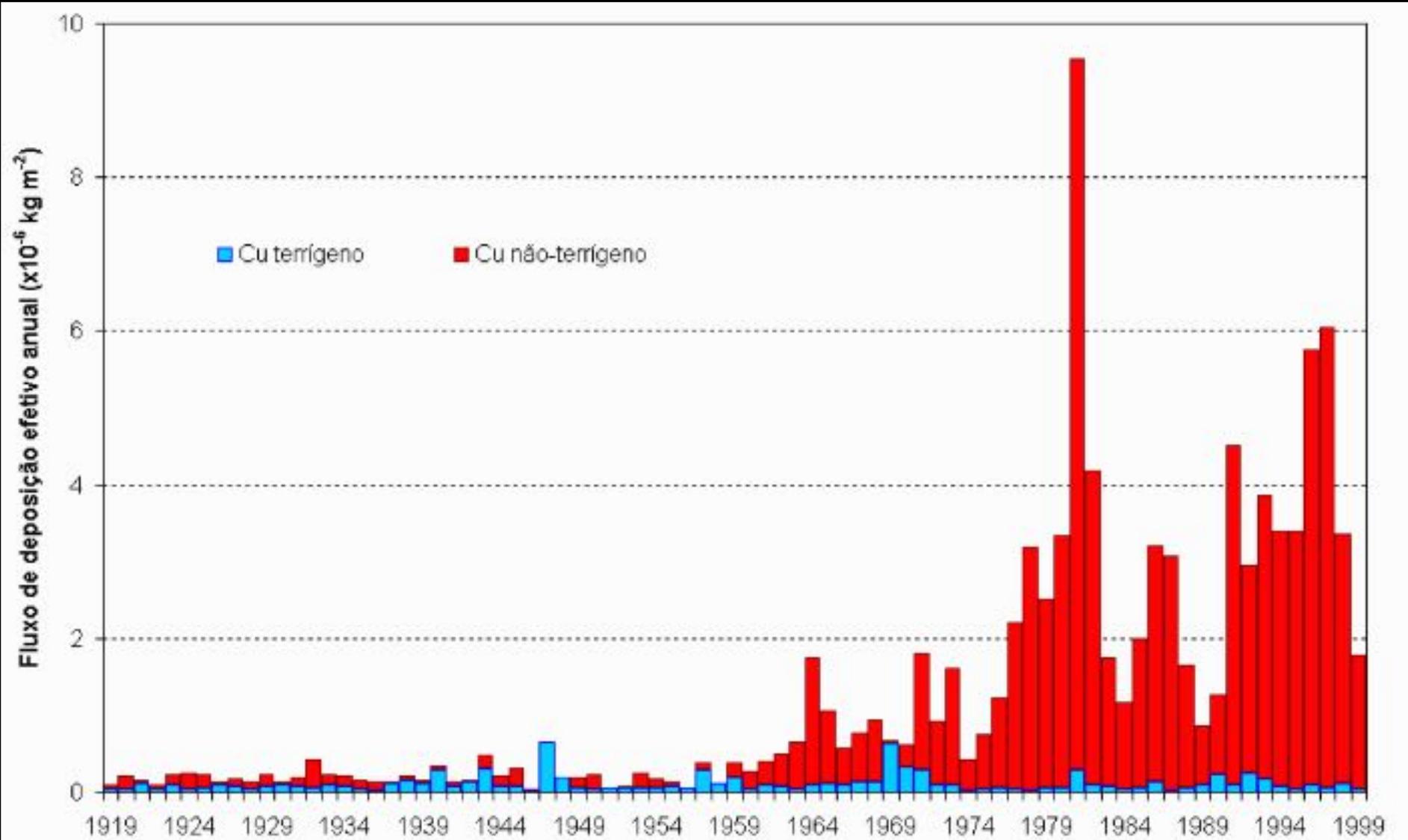


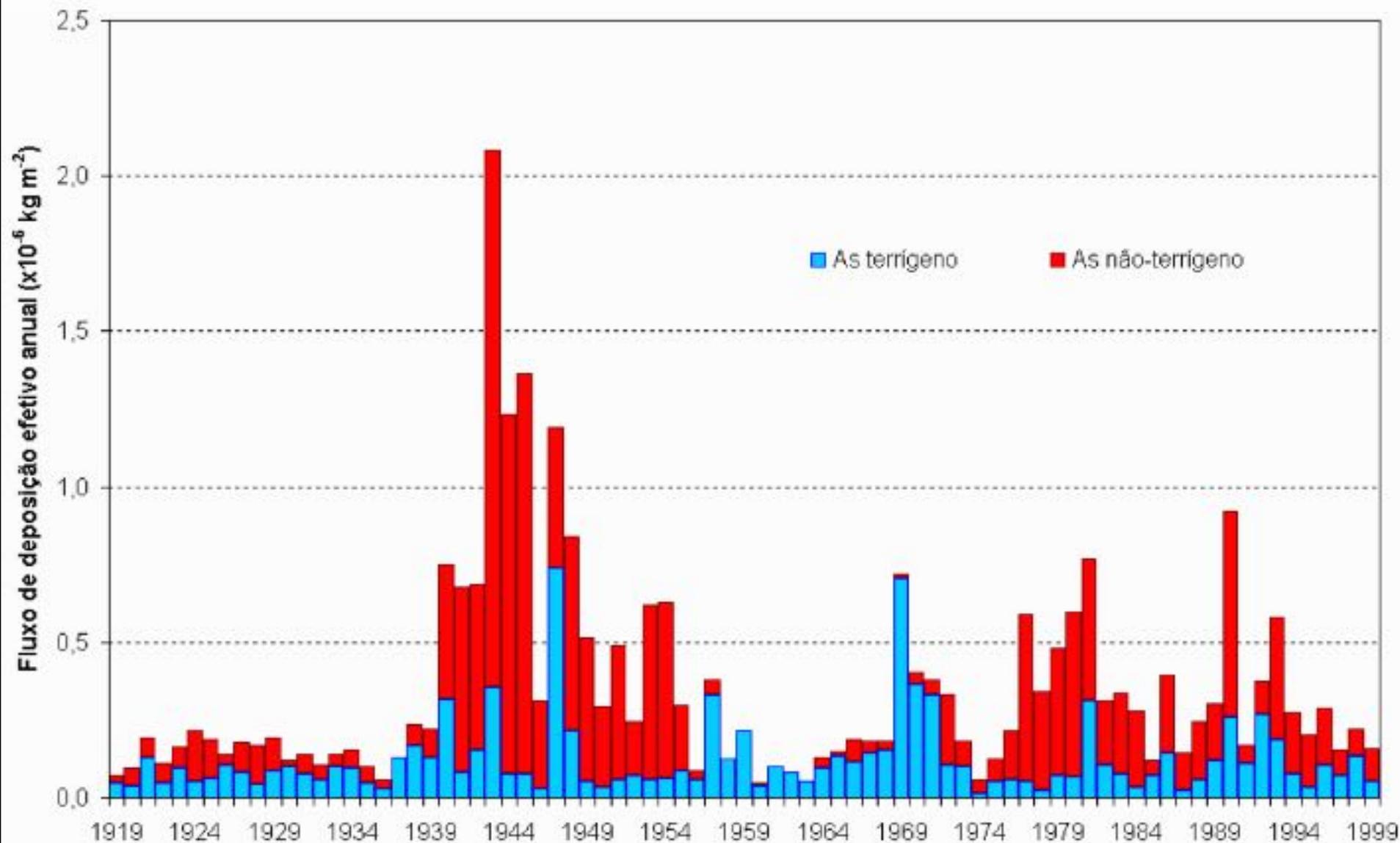


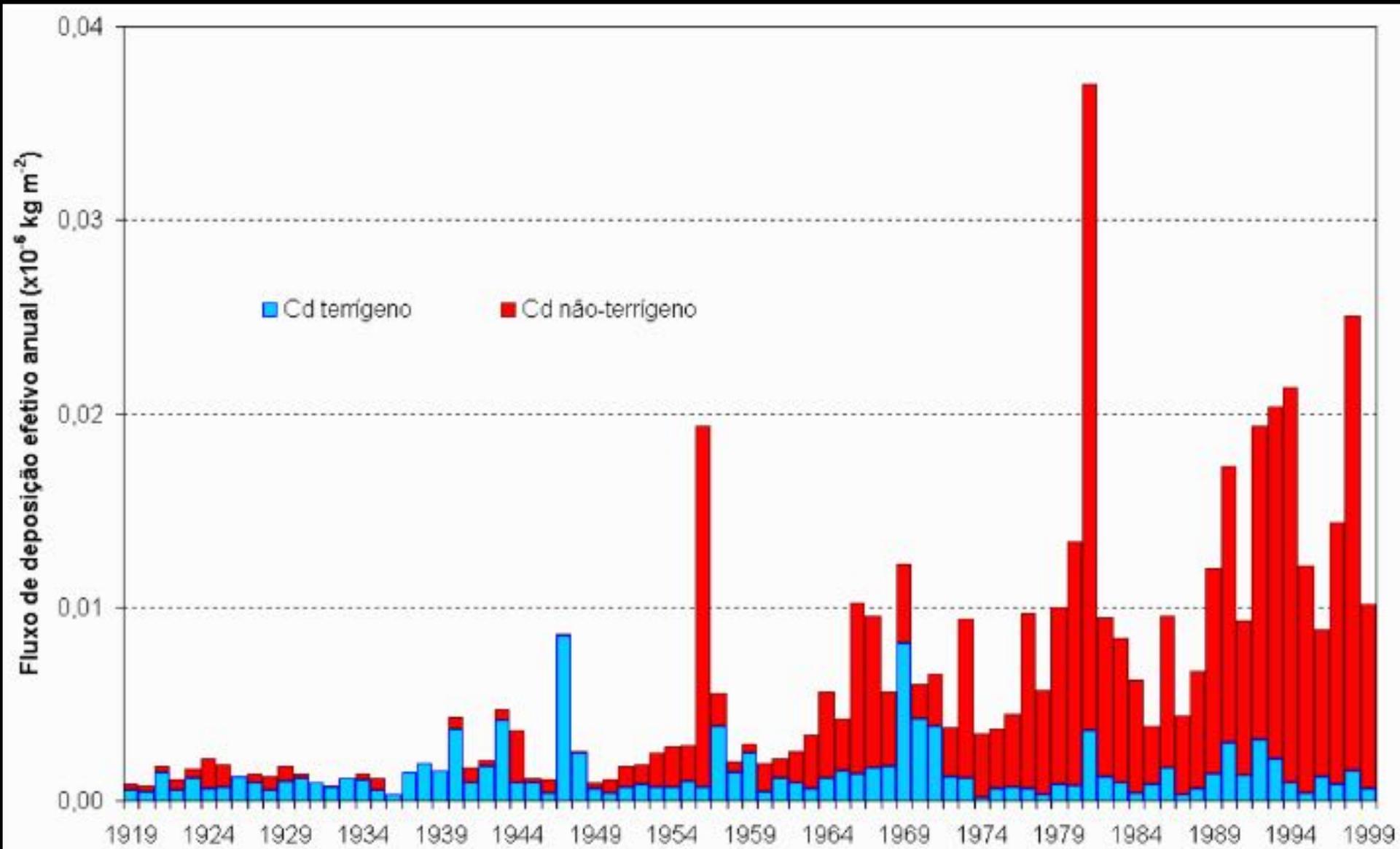


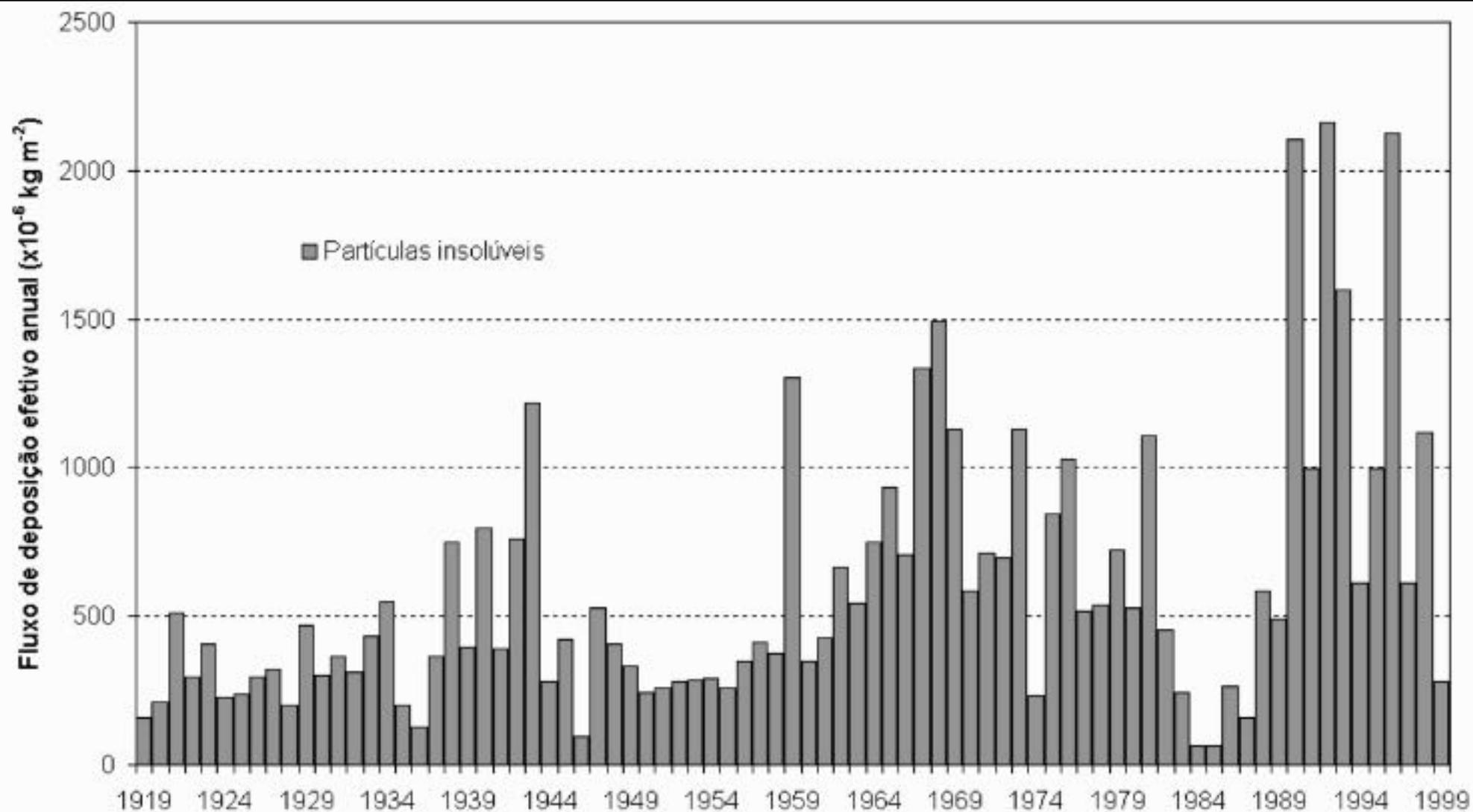


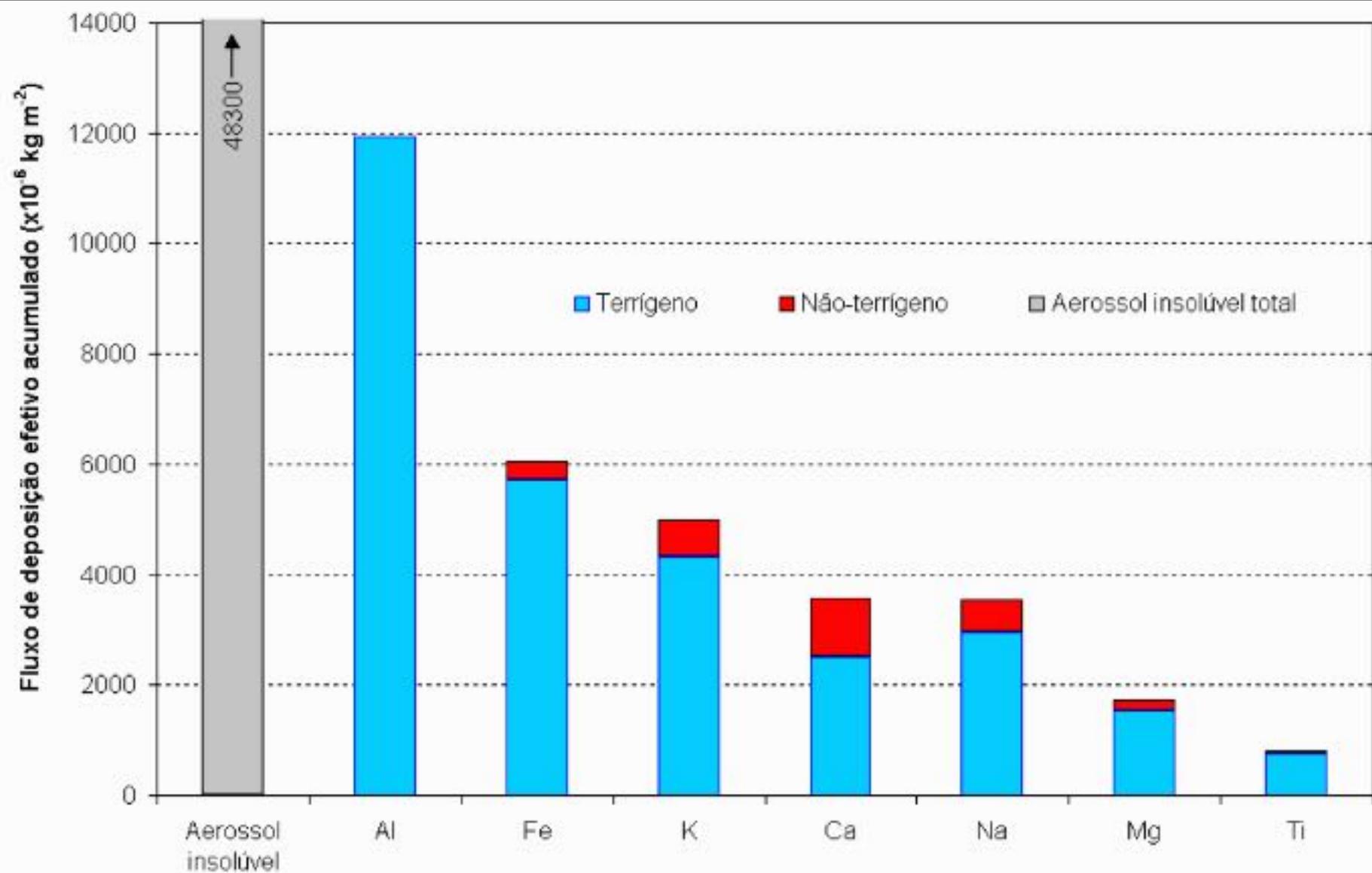


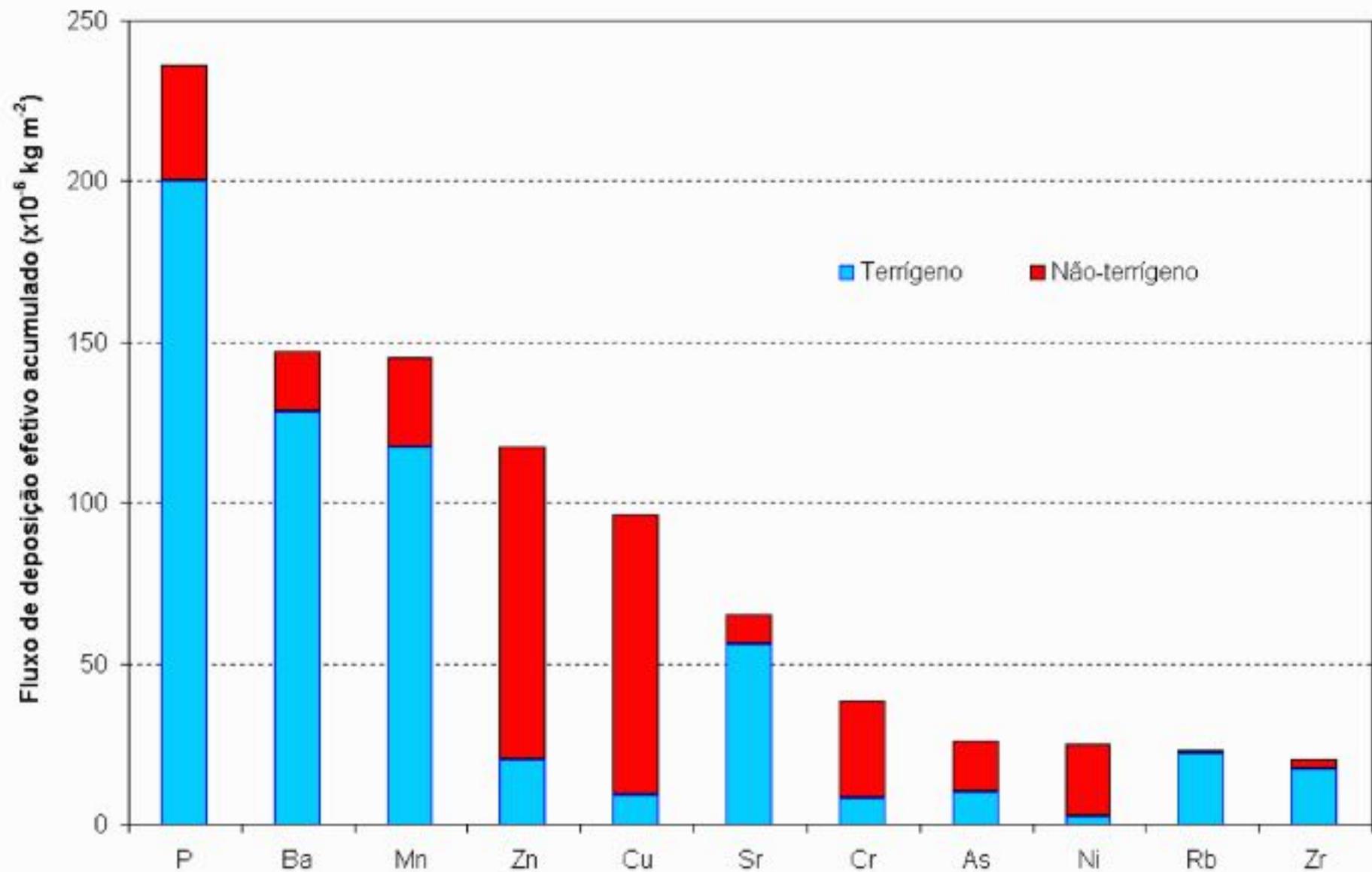


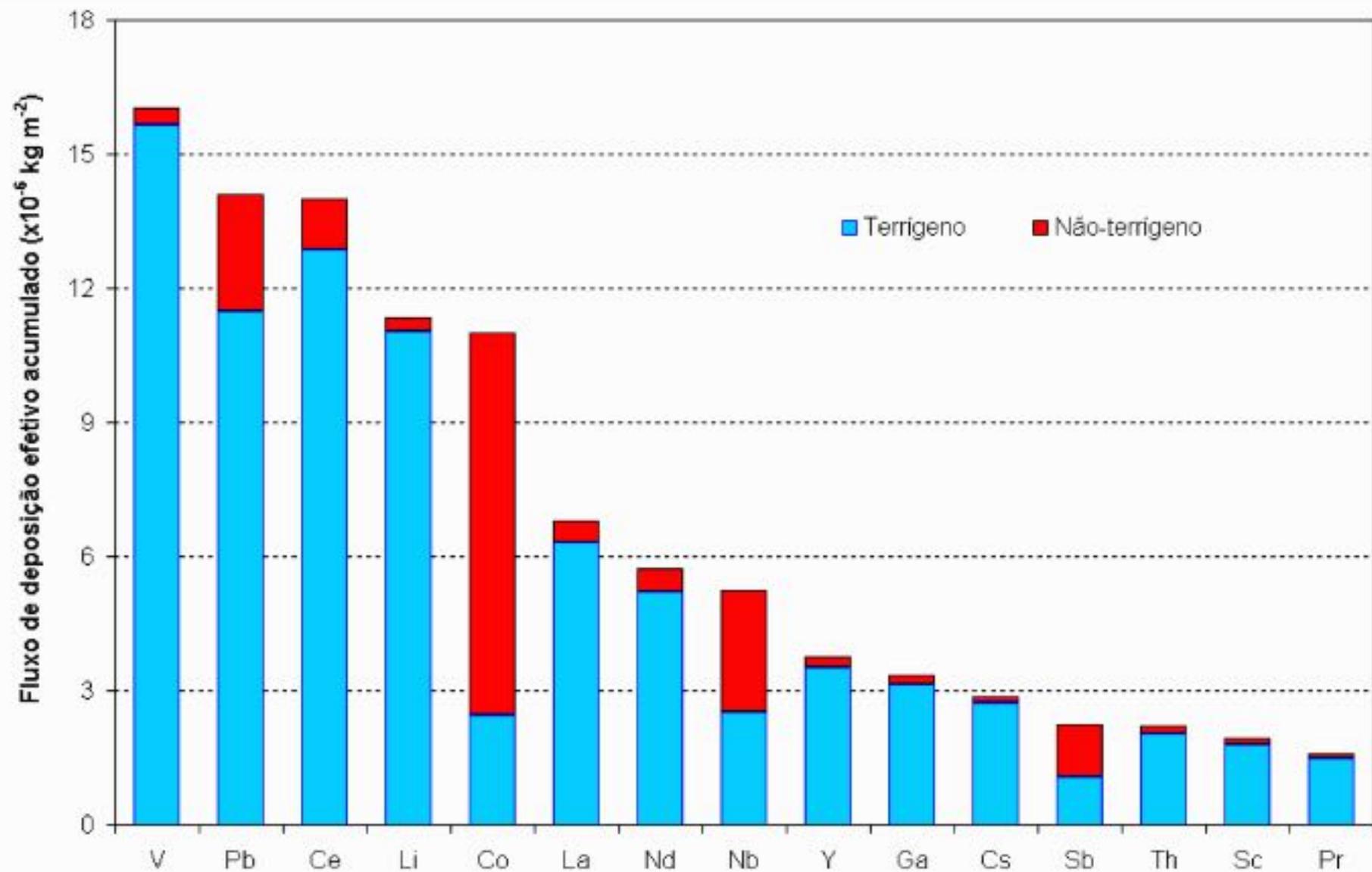












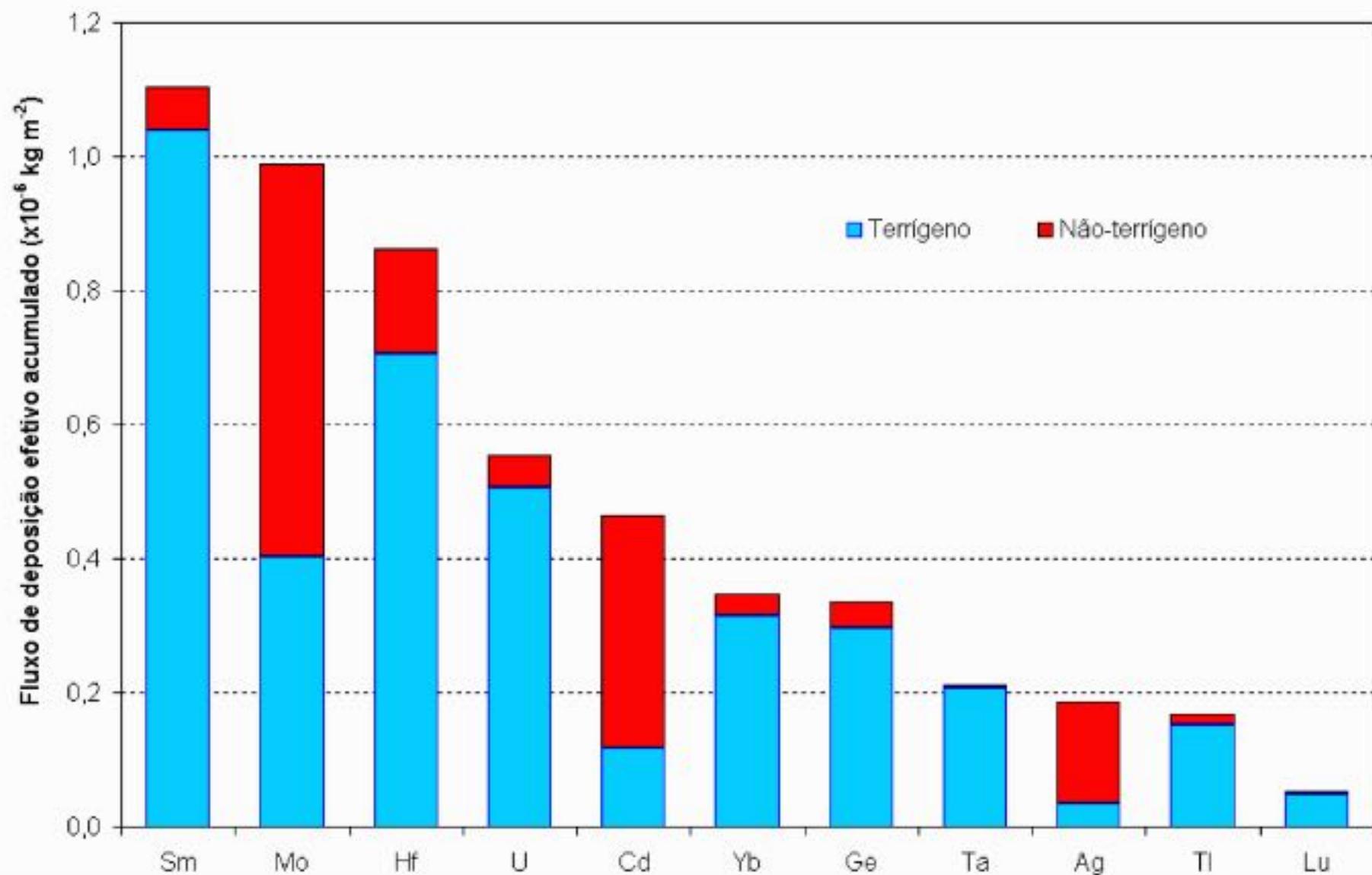
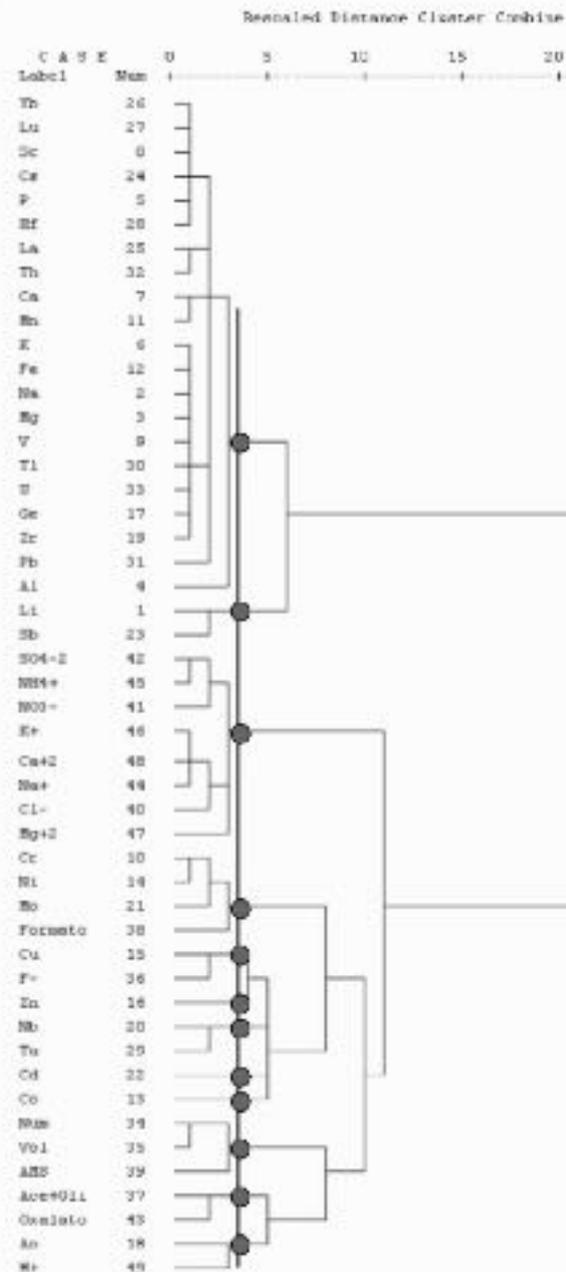
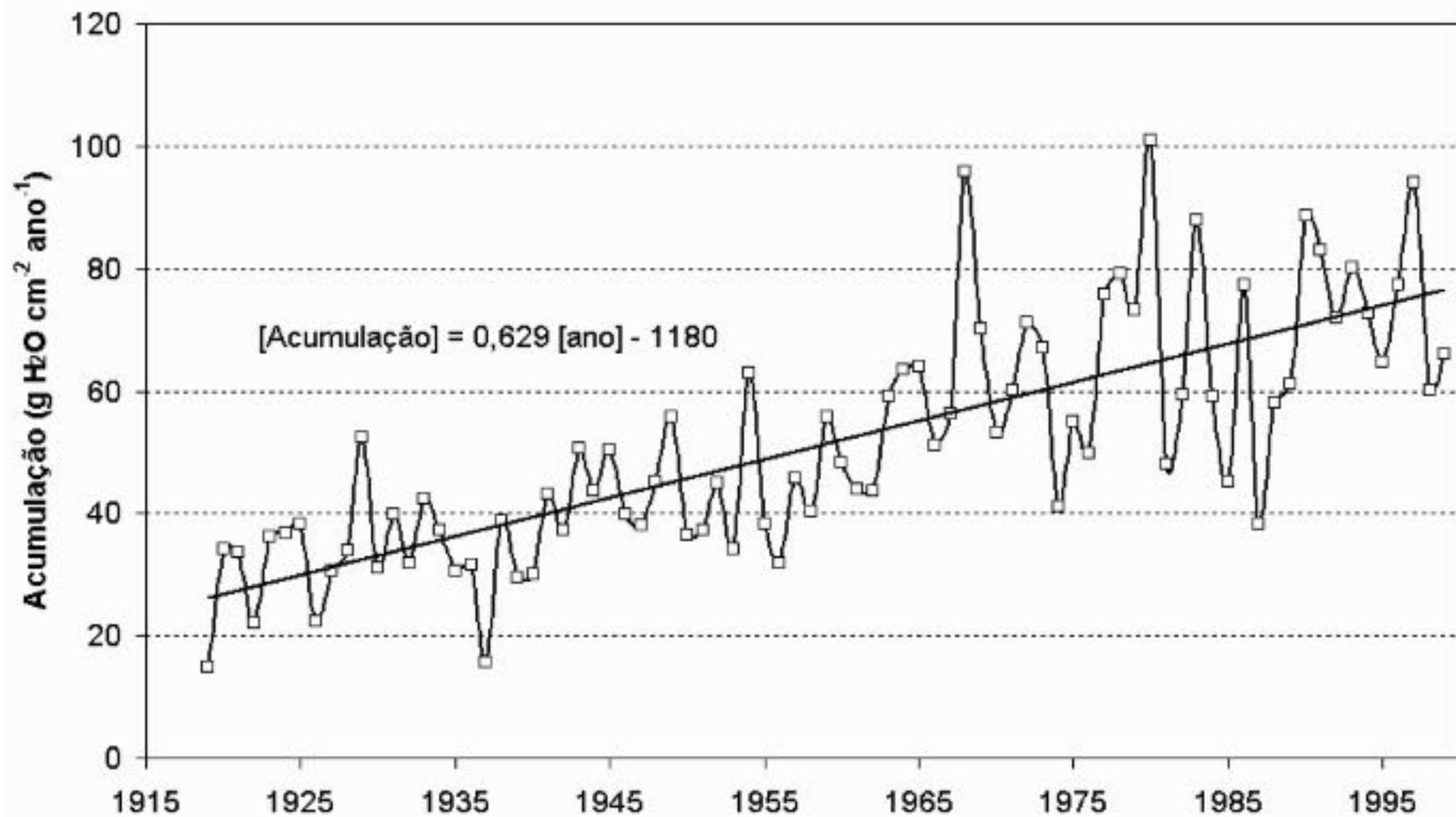


Tabela 4.11 - Assinatura elementar de fontes durante a estação seca (pg g⁻¹).

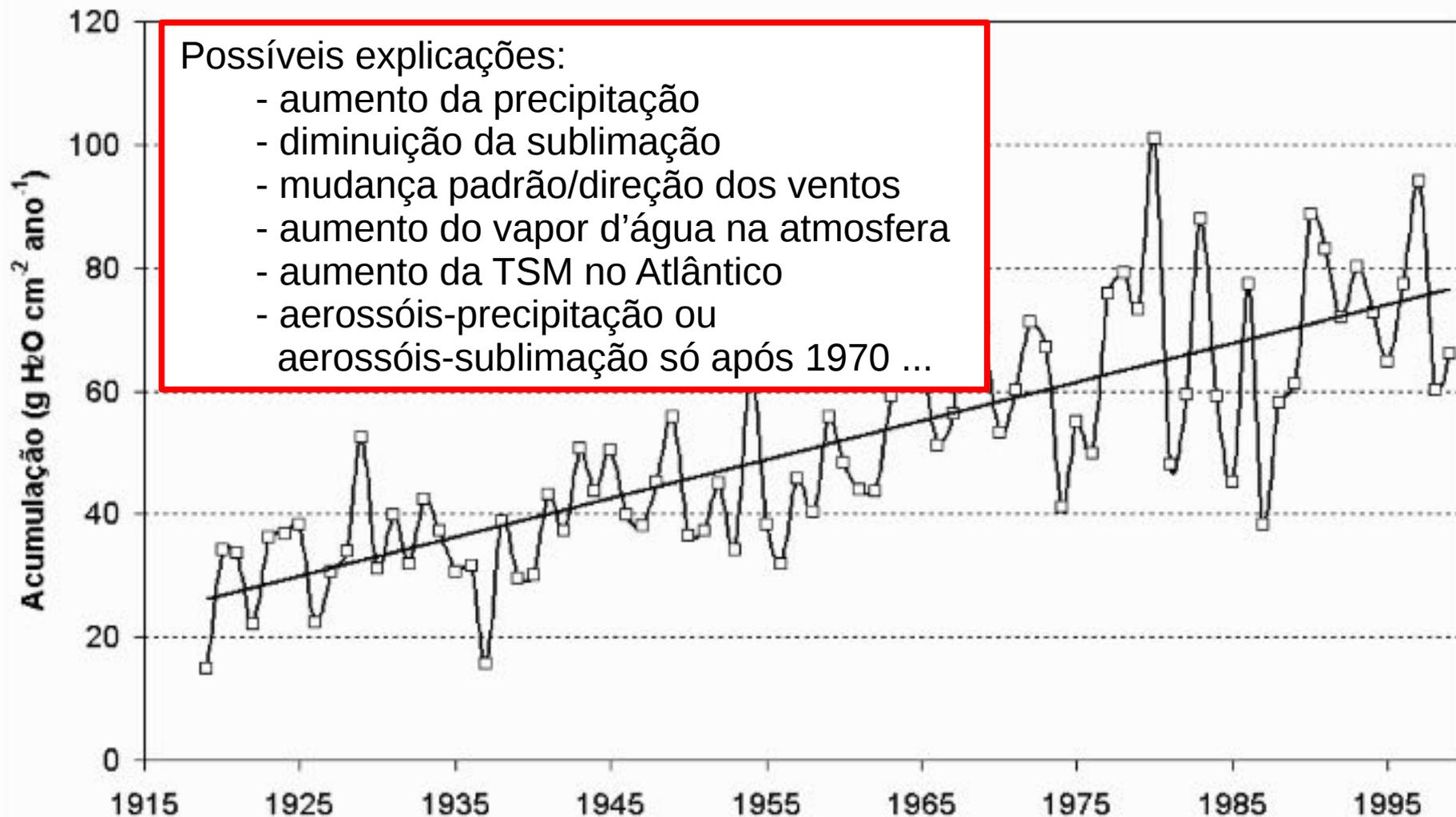
Espécie	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12
Li	439		14,3	13,1					952		14,0	21,5
Na	157000	44300	23600	1630	6750			10600	12000	344		1690
Mg	81600	23900	13100	808	5910			2420	5200	903		2460
Al	889000		310000	2500	132000	5840	57700	222000		85300	54700	
P	10900	5130	278	285	4500			207	386	16,8	205	
K	244000	73100	37000	2910	13200			834	21600	2380		3890
Ca	101000	131000	28200	29,3	4150			6240	1630	1600	893	2560
Sc	98,6	24,1		0,513	21,7			5,39	6,98		0,689	0,372
V	810	182	133	4,73	64,3			27,0	59,0	7,94		
Cr	675	716		263				247	12,3		2,01	
Mn	4660	4610	2000	45,6	1120				134	57,5		
Fe	318000	78000	46500	4230	27100				22500	2030		251
Co	31,3	4,1		2,44				17,2	9,51	243		1,82
Ni	324	272		96,3				104		15,5	8,28	40,4
Cu	381	1230	180	48,4	316			78,2	61,8	161	77,0	
Zn	3290	434		87,8		32,4			395	122	2,55	892
Ge	18,9	5,14	1,92	0,0725	1,10				1,66	0,0431	0,249	0,108
As	398		765					1100	198			0,302
Zr	1110	143	61,8		44,0			14,9	102	6,86	70,5	31,1
Nb	515	75,4		63,4	160				14,6	8,18	21,5	
Mo	26,6	13,8	2,14	2,21		0,558			0,374	2,41		1,21
Cd	3,40	8,86	0,795	0,0224							10,6	0,0577
Sb	48,4	36,8			18,7	1,13		2,14	41,0	6,37		
Cs	145	29,3	7,71	2,22	11,5		2,54	9,64	8,80			3,94
La	382	114	26,4	4,00	48,7		2,84		9,64	4,13		
Yb	17,1	3,86	1,95	0,171	1,27		0,263	1,16	0,982		0,403	0,216

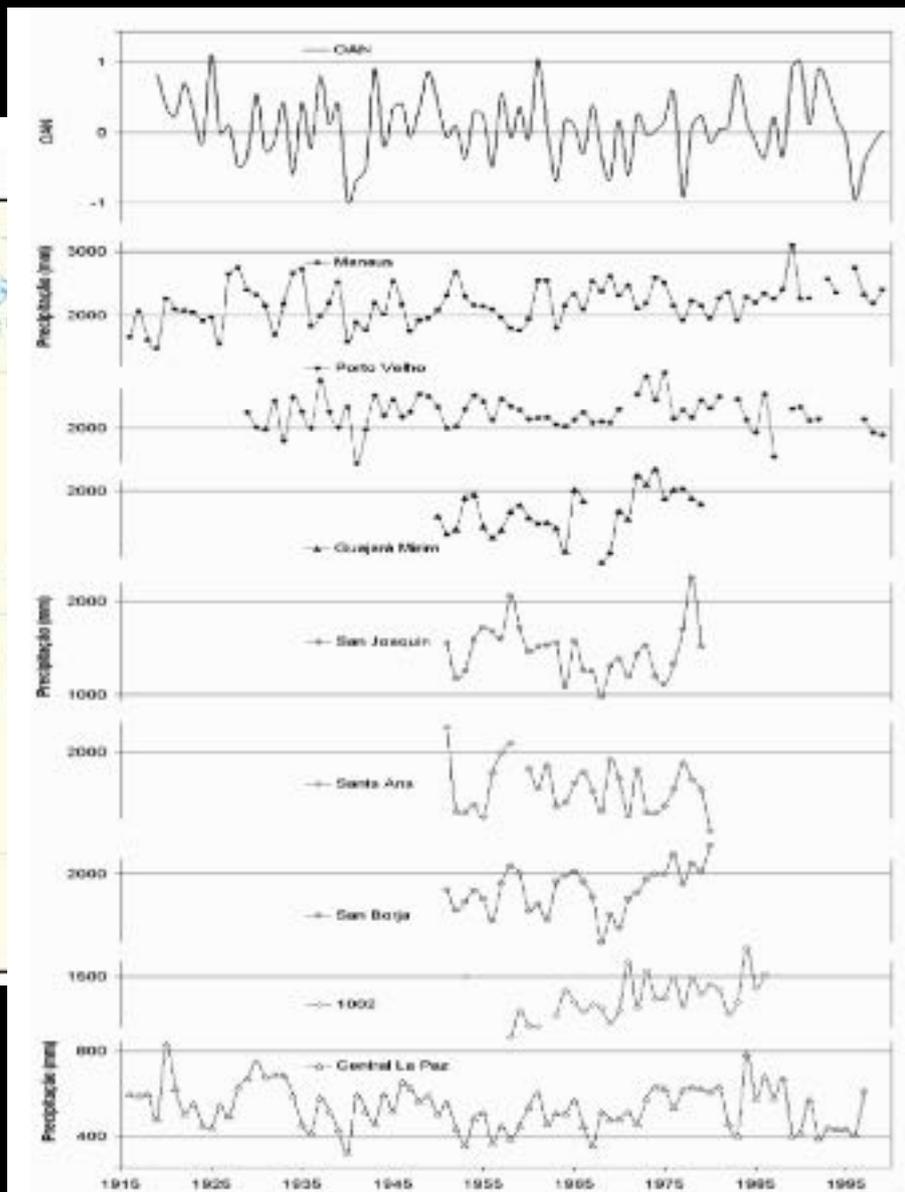


Acumulação anual - Illimani



Acumulação anual - Illimani



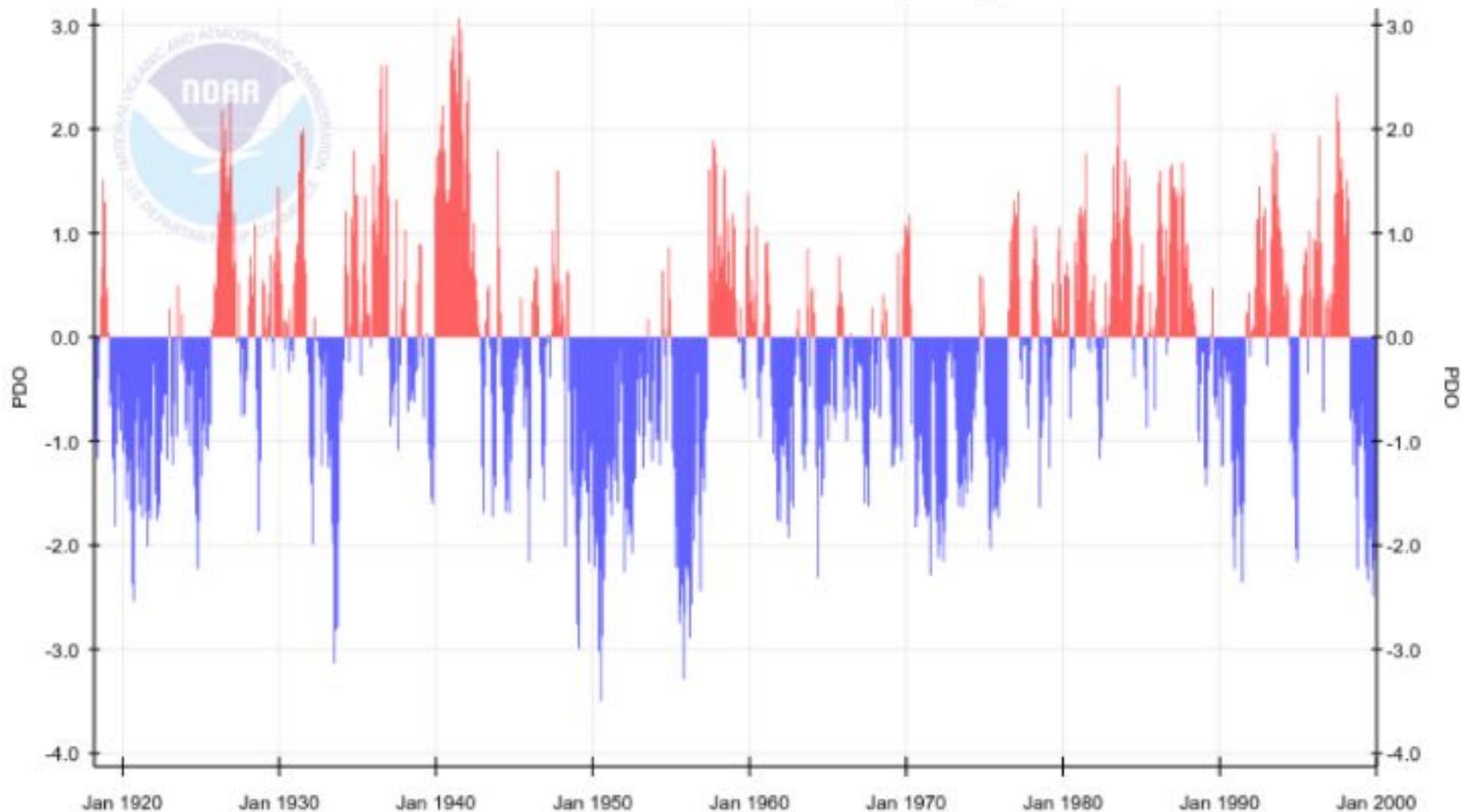


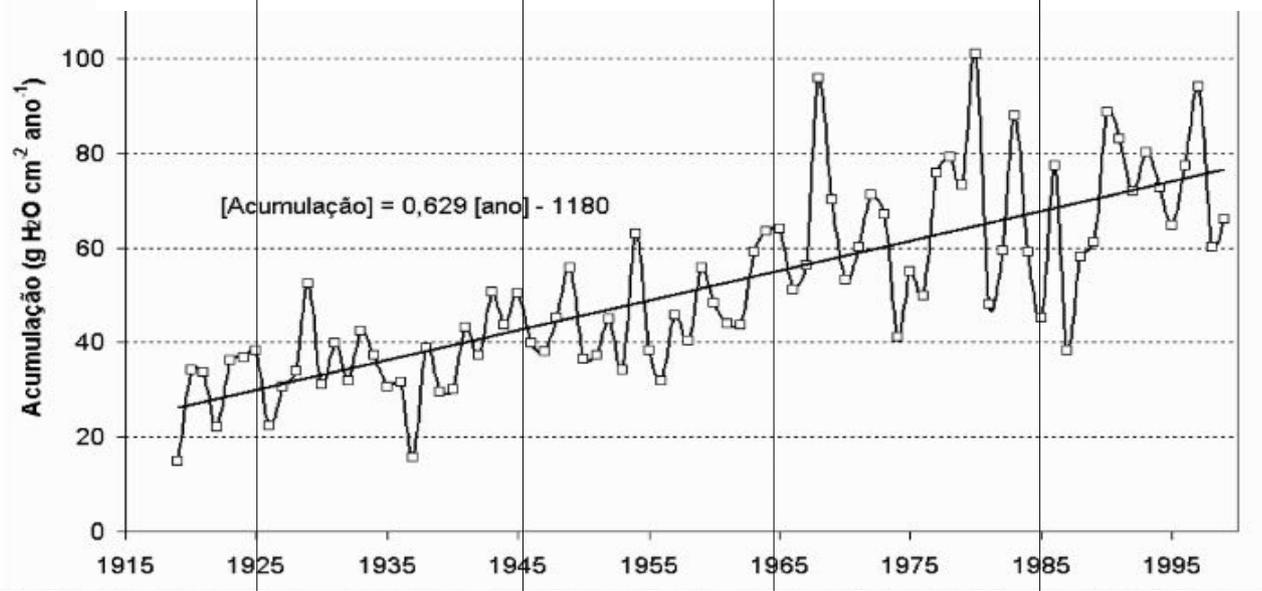
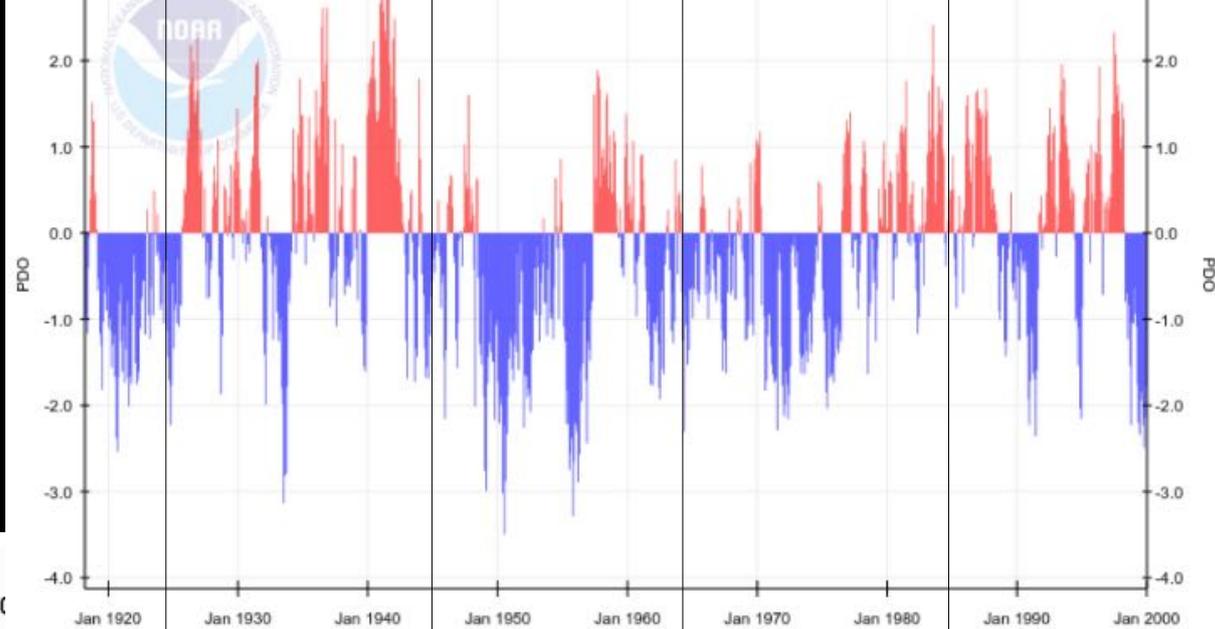
Cane et al. 1997:
Durante o século XX: Atlântico Equatorial +0.3C } Mais umidade disponível
 Atlântico Sul +1.0C }

EOF TSM do Atlântico (Sutton et al. 2000) } Tendências de longo prazo para alguns
EOF TSM do Pacífico (Cardoso, 2001) } modos de oscilação

Oscilação Decadal do Pacífico ???

Pacific Decadal Oscillation (PDO)





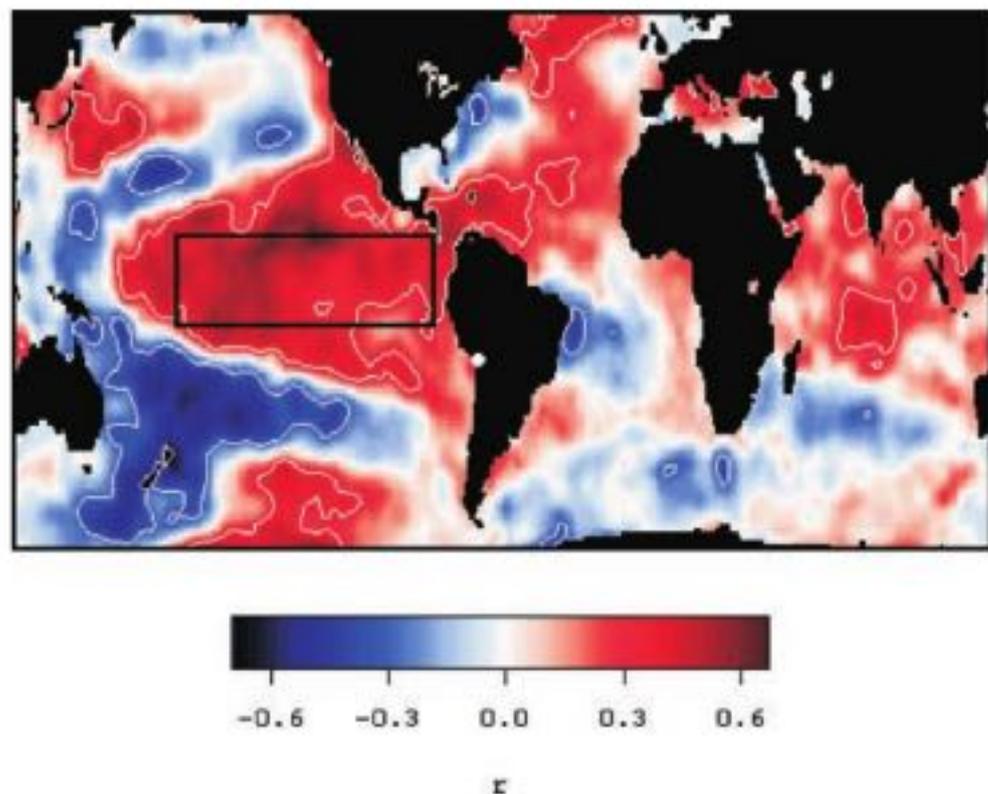


Figure 1. Correlation of global NO_x -February SSTs with net accumulation-weighted $\delta^{18}\text{O}$ at Sajama, Bolivia (white dot), 1961–1997. Regions delimited by white line are correlated at the 95% significance level. The area used in

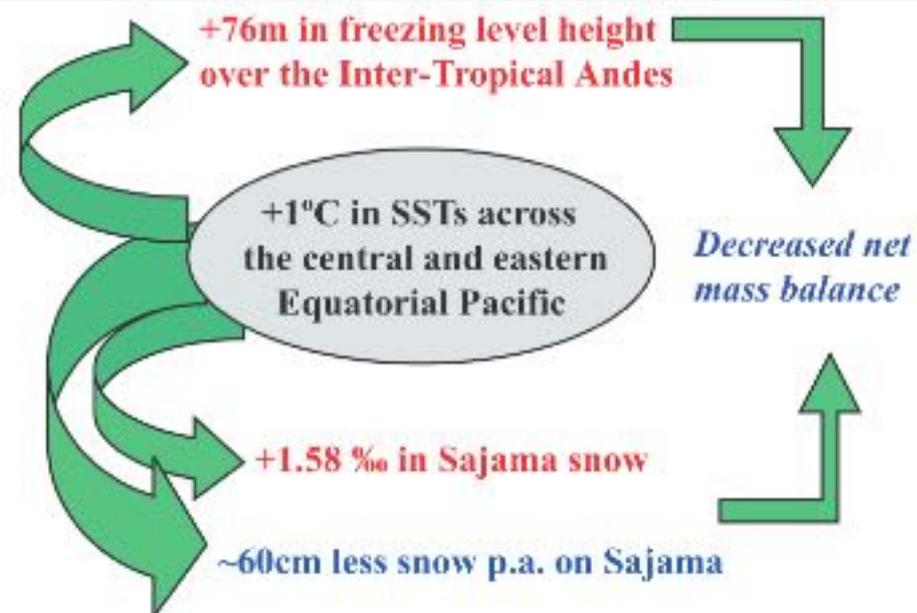
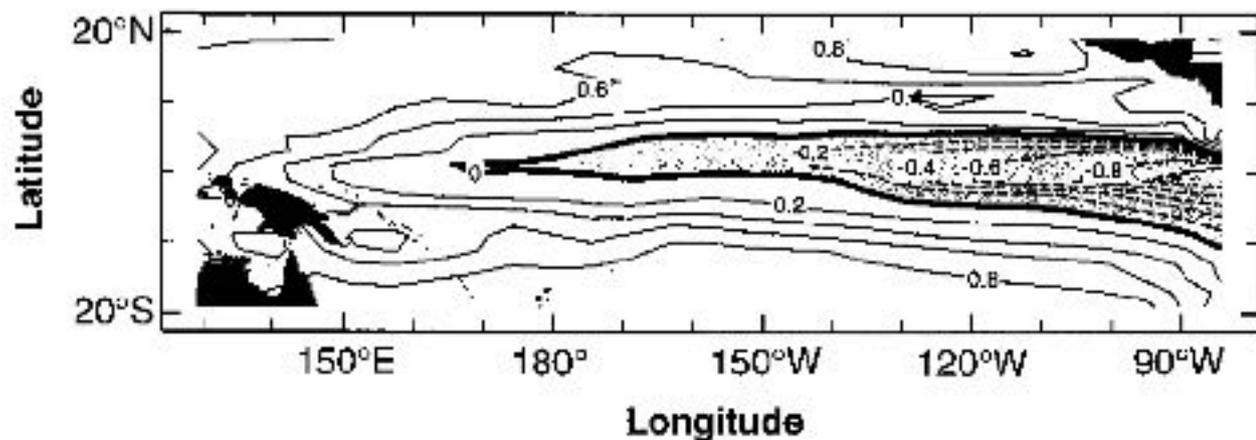


Figure 4. Schematic diagram summarizing links between central and eastern Equatorial Pacific SSTs, isotopic records at Sajama, and mass balance changes.

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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