

# **O registro paleoclimático, com foco em testemunhos de gelo**

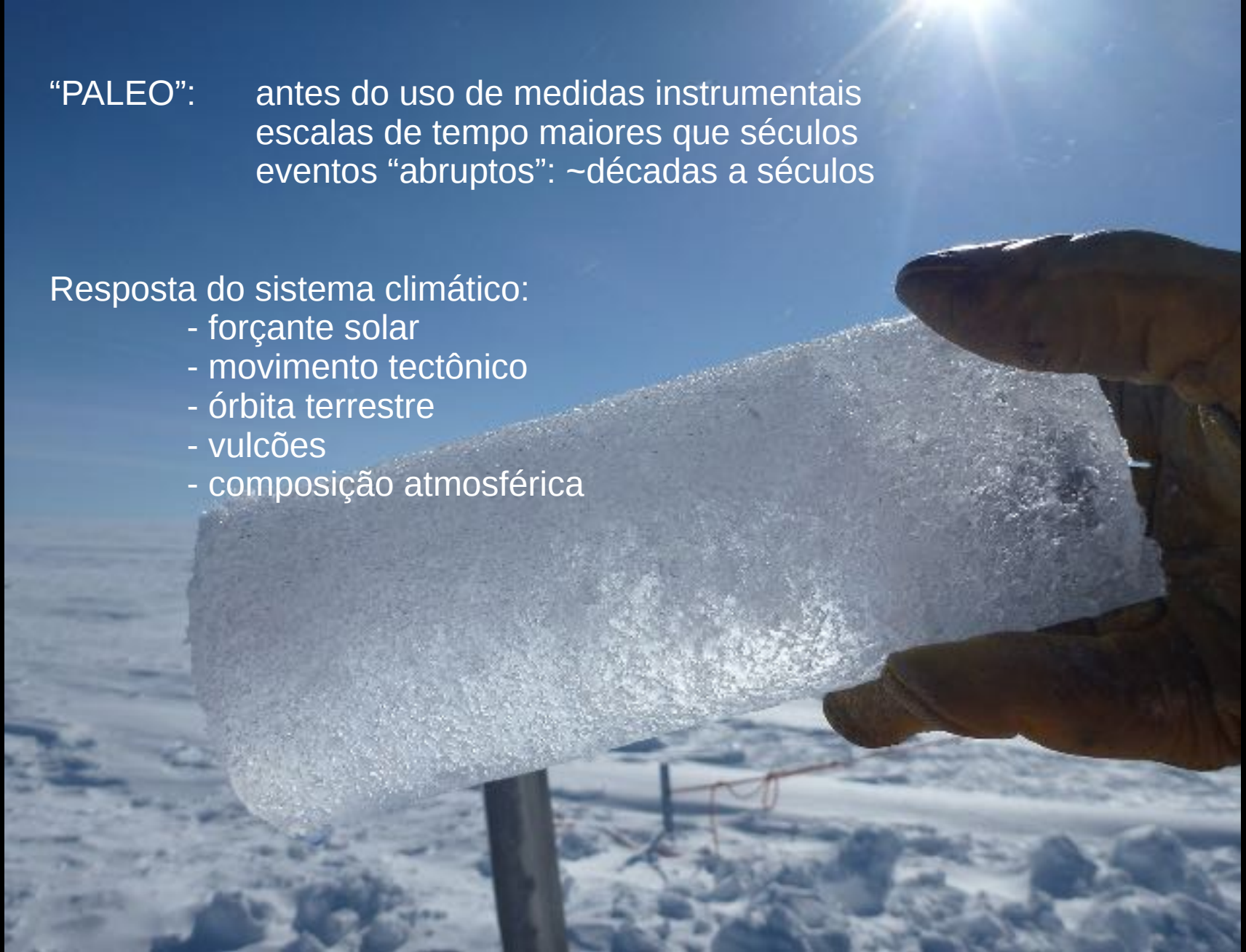
Alexandre Correia

Abril/ 2018

“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



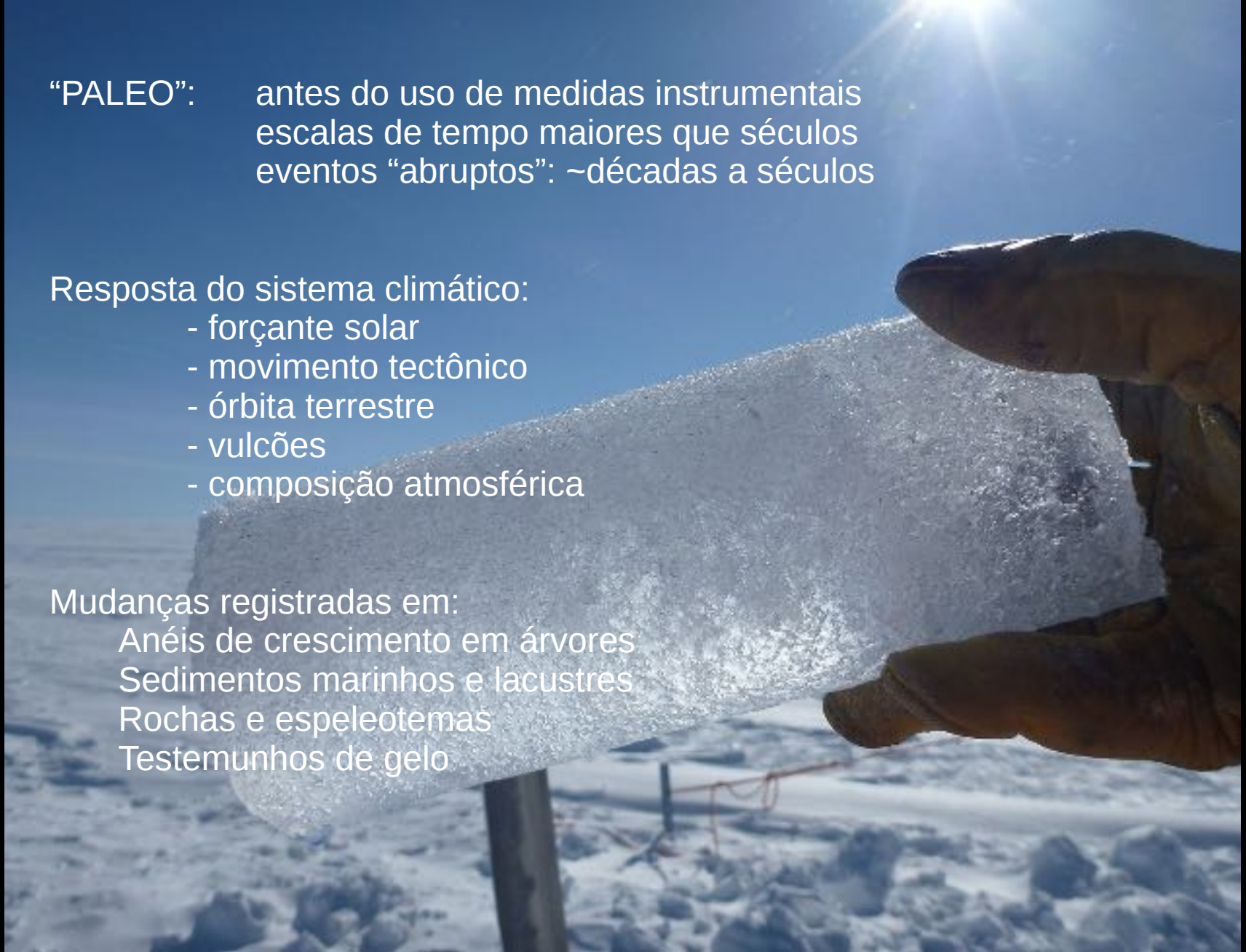
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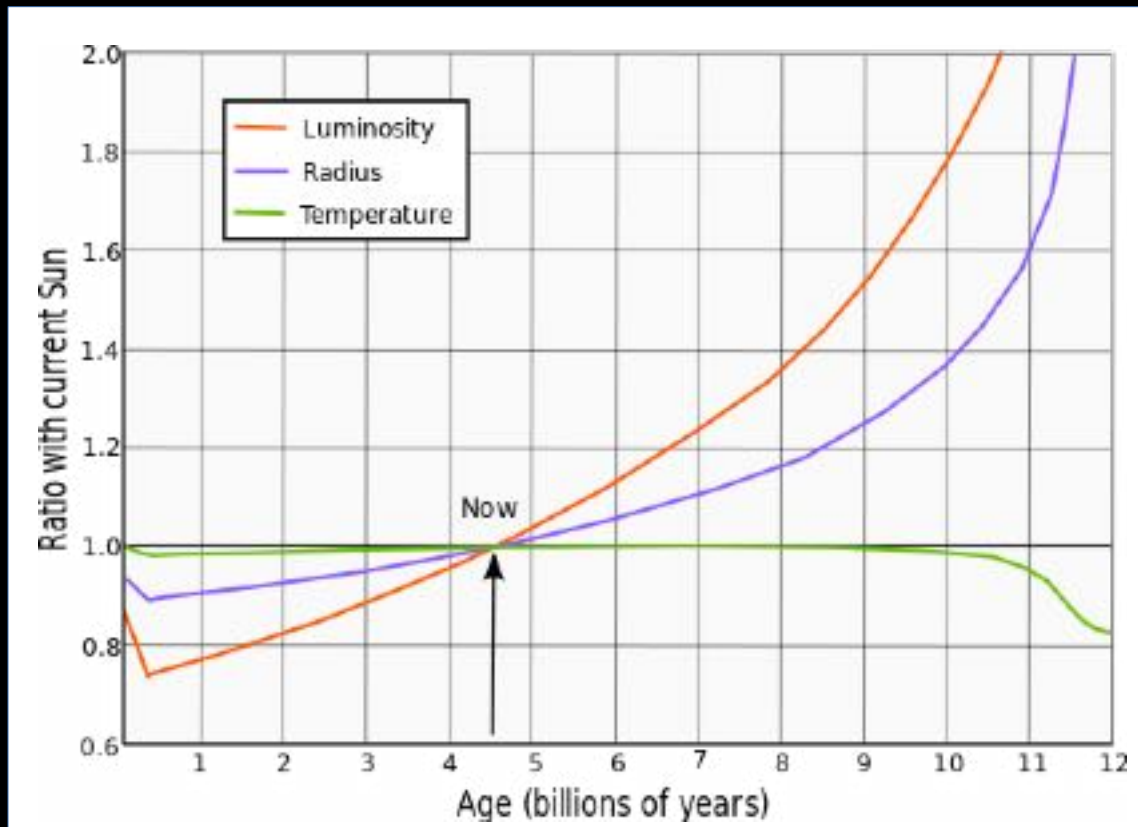
Mudanças registradas em:

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

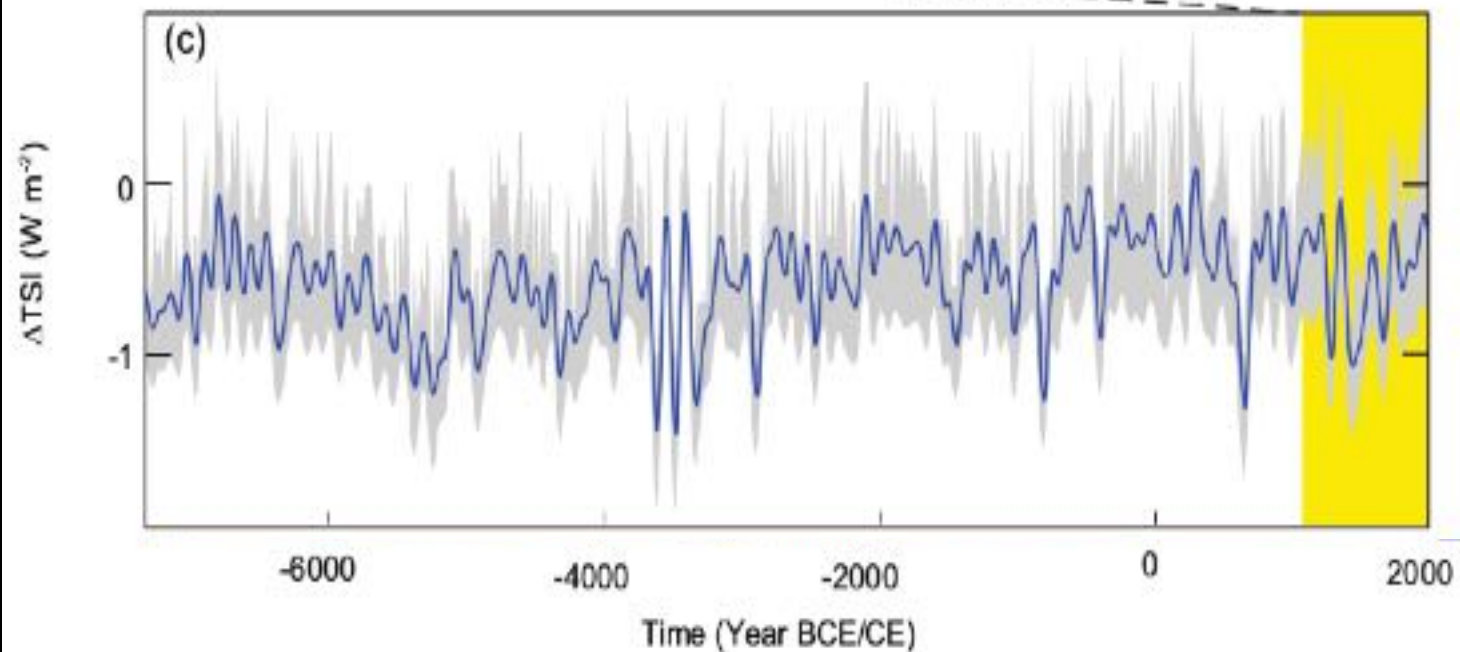
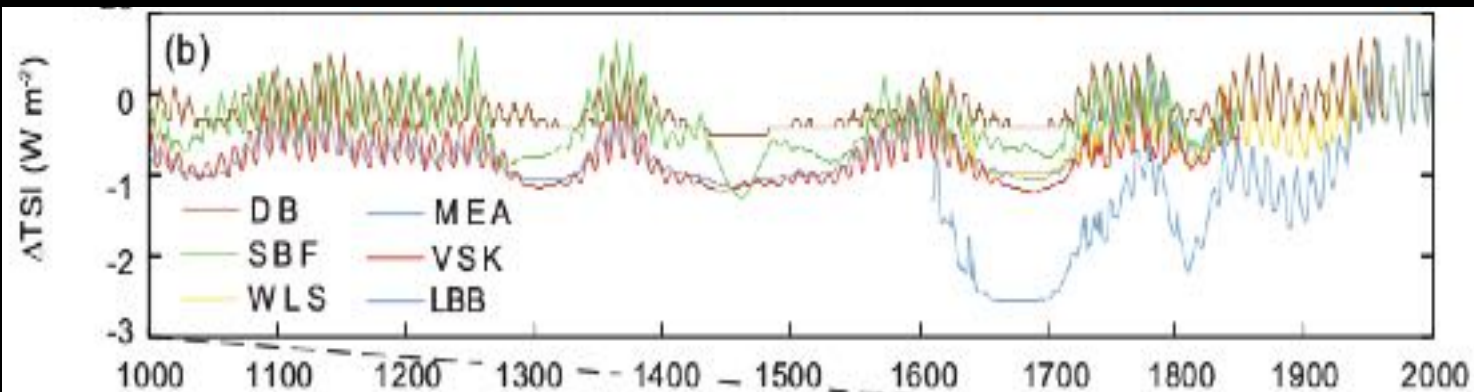


# Forçante solar

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

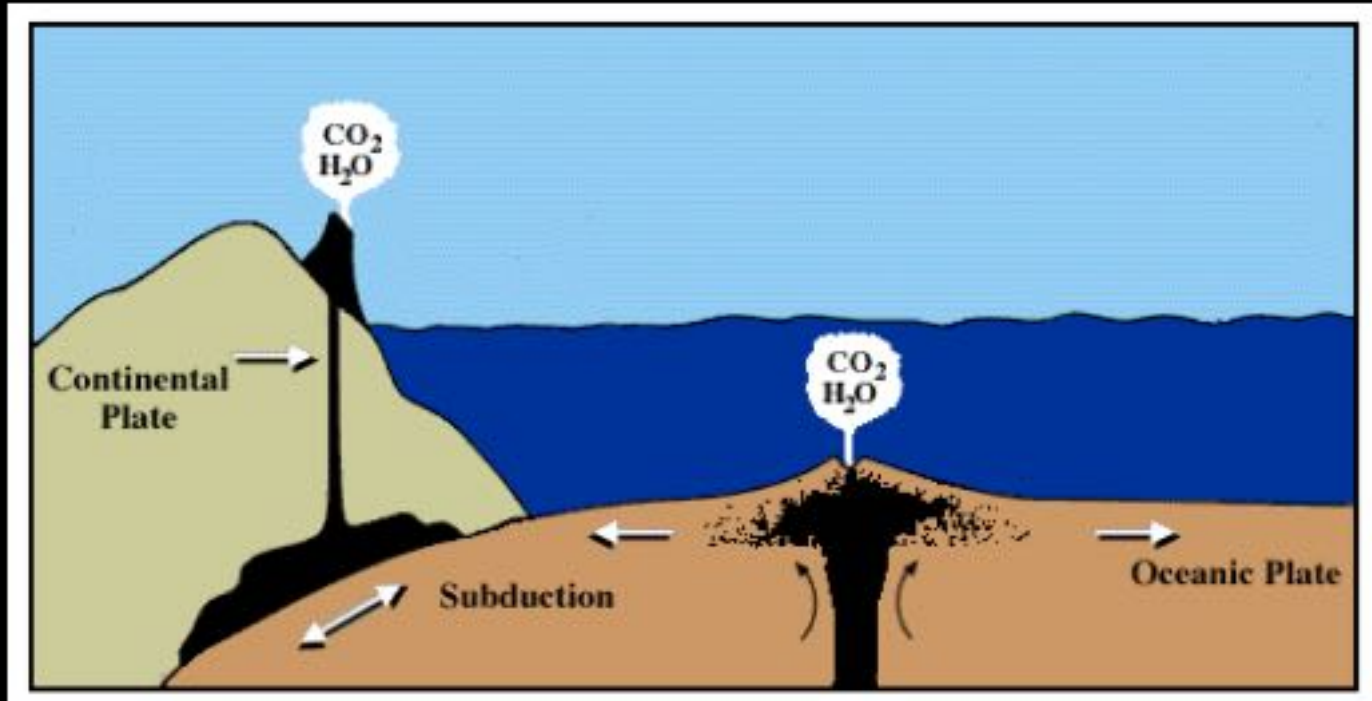


# Forçante solar reconstruída



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

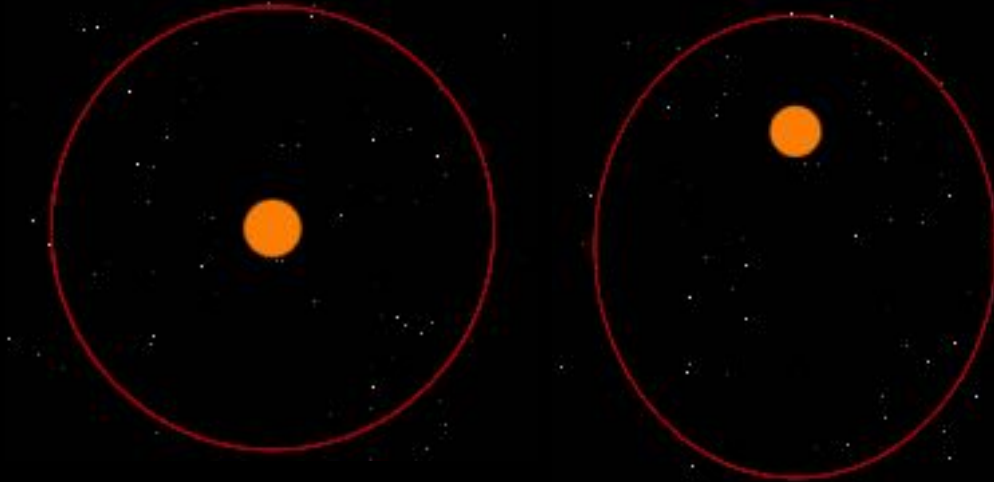
As the continents shift there is increased subduction and volcanic activity which increases  $\text{CO}_2$  into the atmosphere



That atmospheric  $\text{CO}_2$  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: ecentricidade da órbita  
inclinação do eixo de rotação da Terra  
precessão do eixo de rotação da Terra  
precessão da órbita  
inclinação da órbita



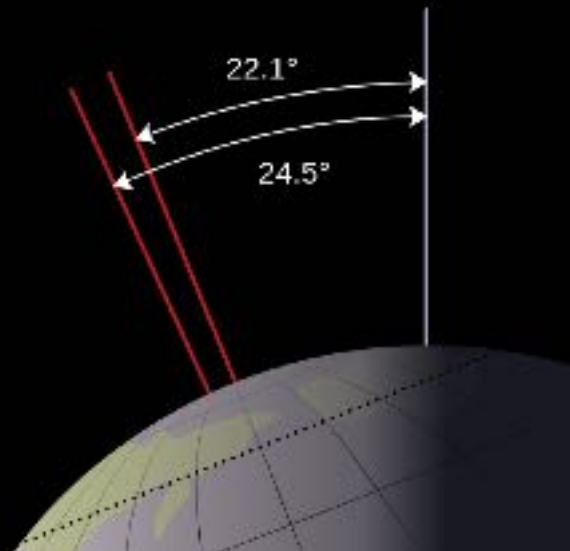
Ecentricidade

Período principal: 413 ka

Outros períodos: 95 ka, 125 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



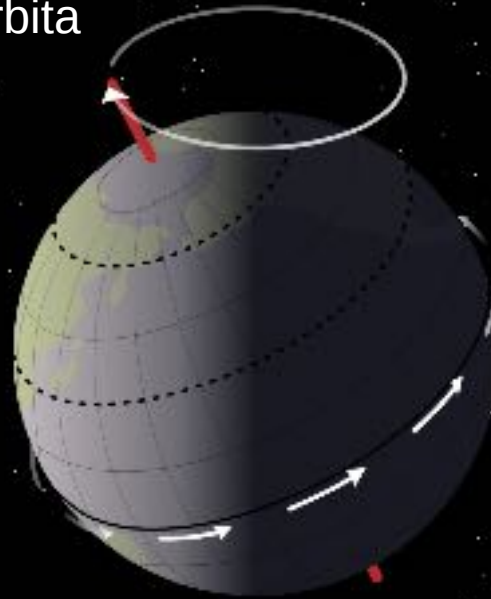
Inclinação do eixo

Período: 41 ka



# Forçante orbital

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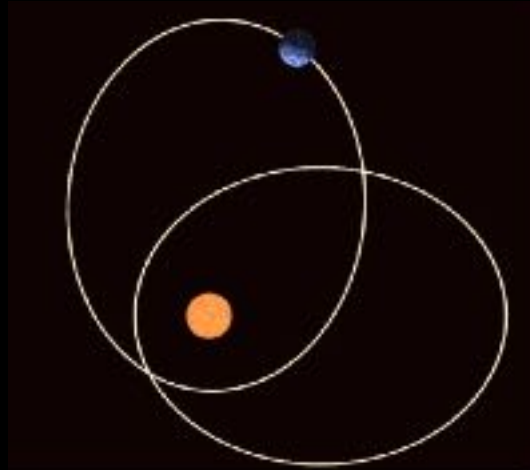


Precessão do eixo

Período: 25,8 ka

# Forçante orbital

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  - inclinação da órbita

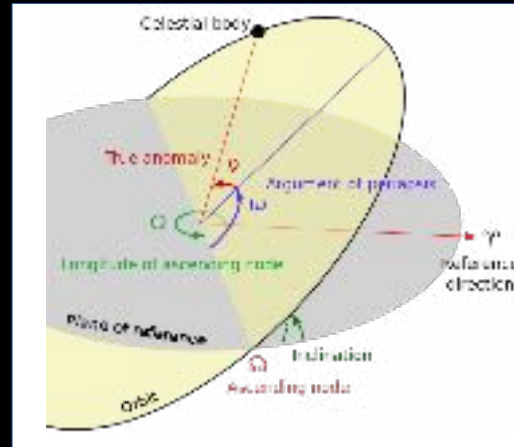


Precessão da órbita

Período: 112 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
  - inclinação da órbita

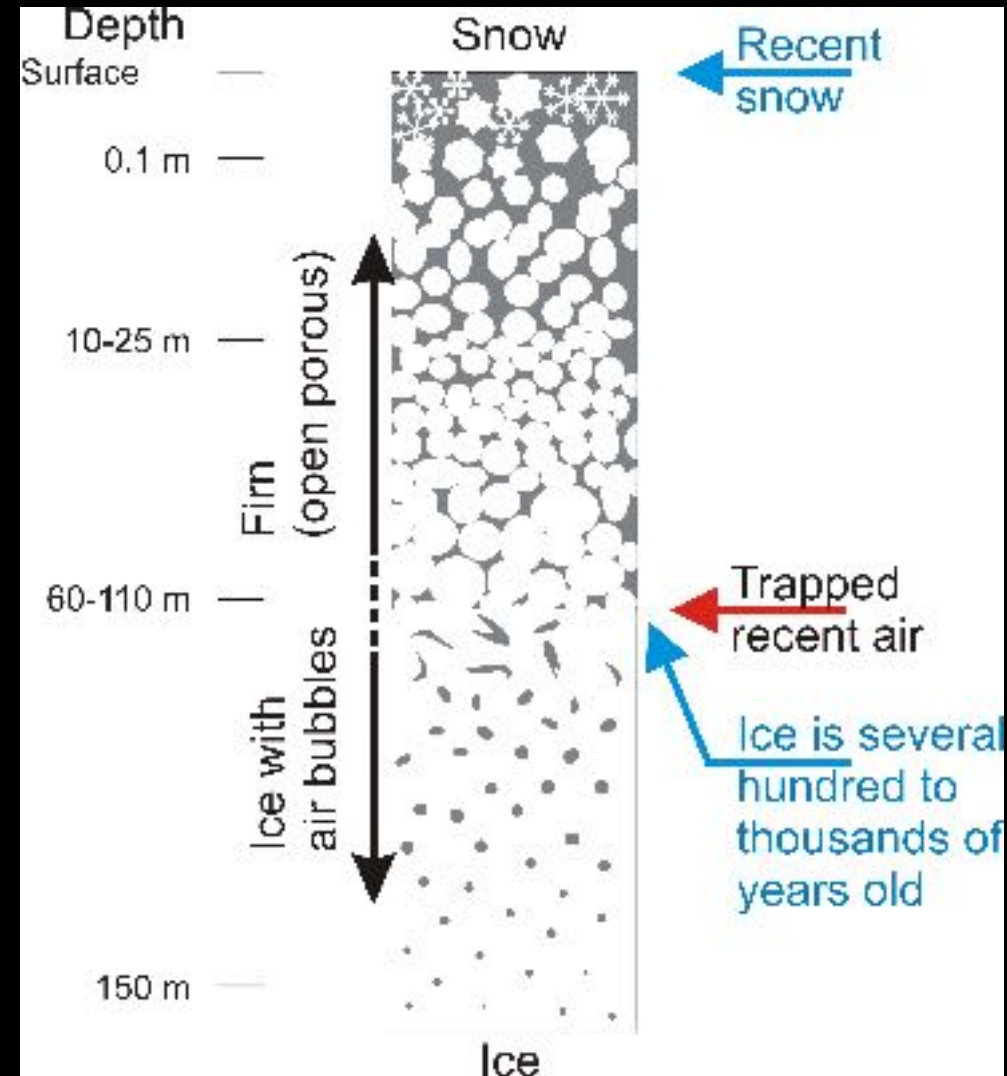


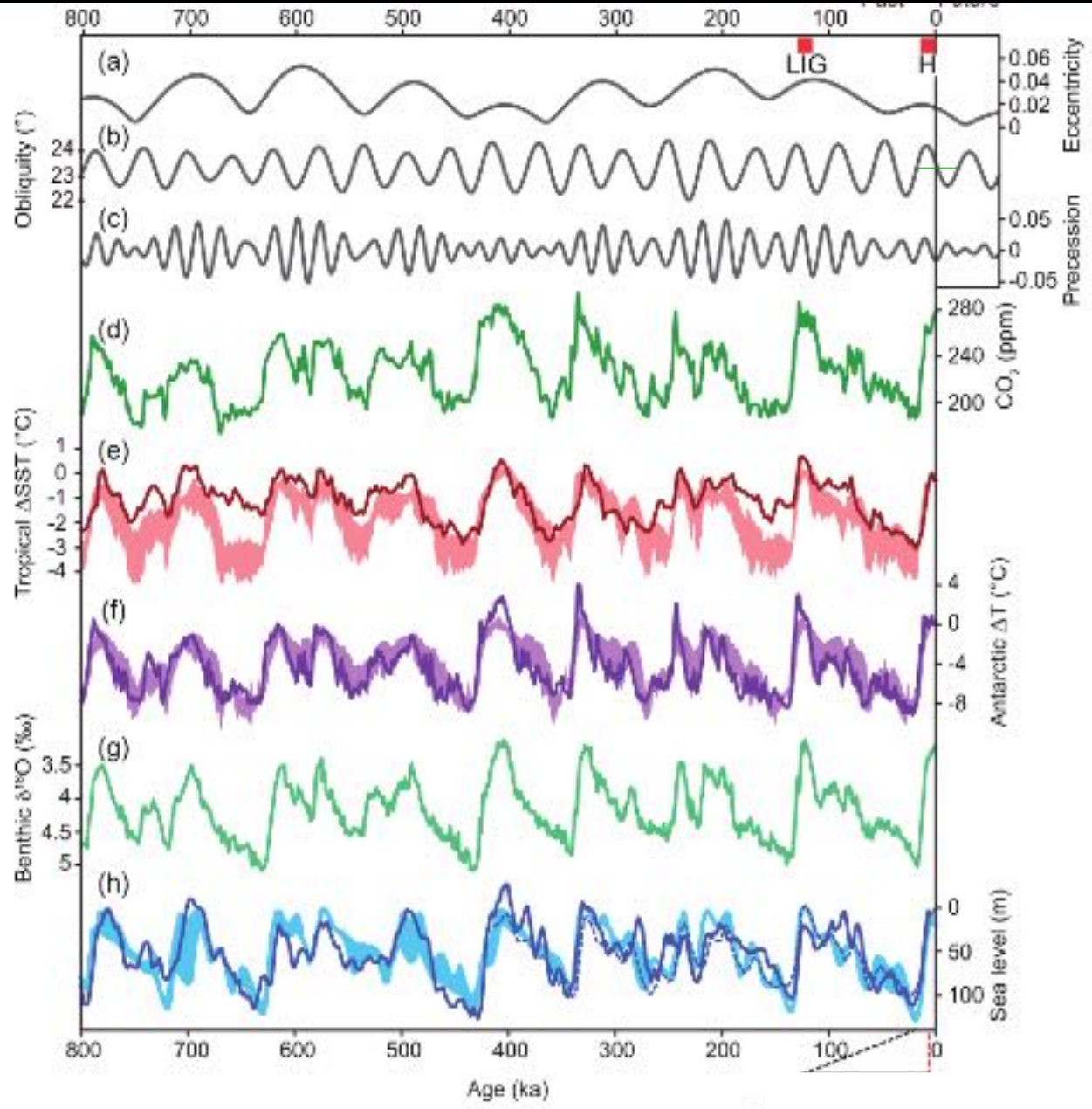
Inclinação da órbita

Período: 100 ka

# O registro paleoclimático em testemunhos de gelo

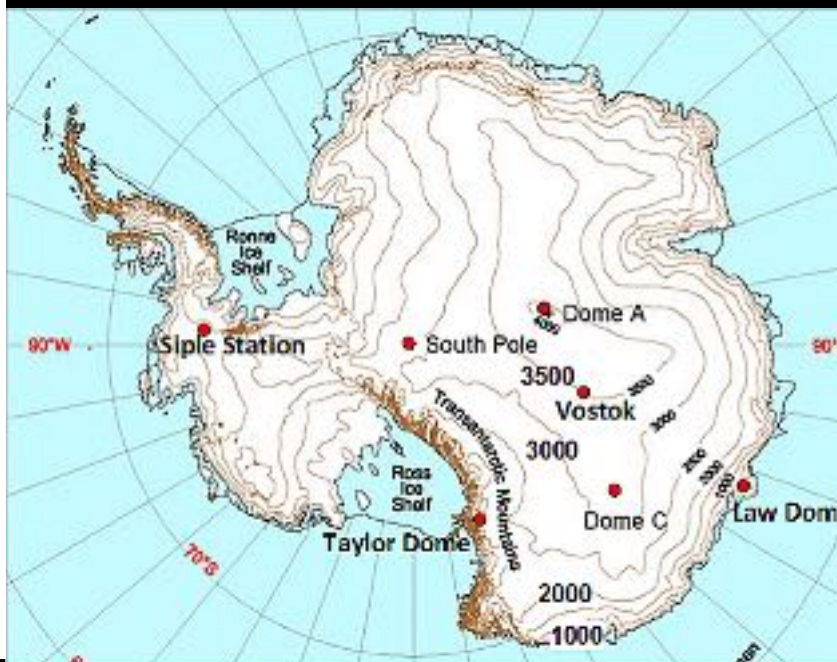
- Bolhas de ar aprisionadas em geleiras
- Química atmosférica da neve
- Sujeito a difusão gasosa entre poros
- Taxas de acumulação definem a resolução temporal: Antártica x Andes
- Escala de 800 ka em Dome C, Antártica

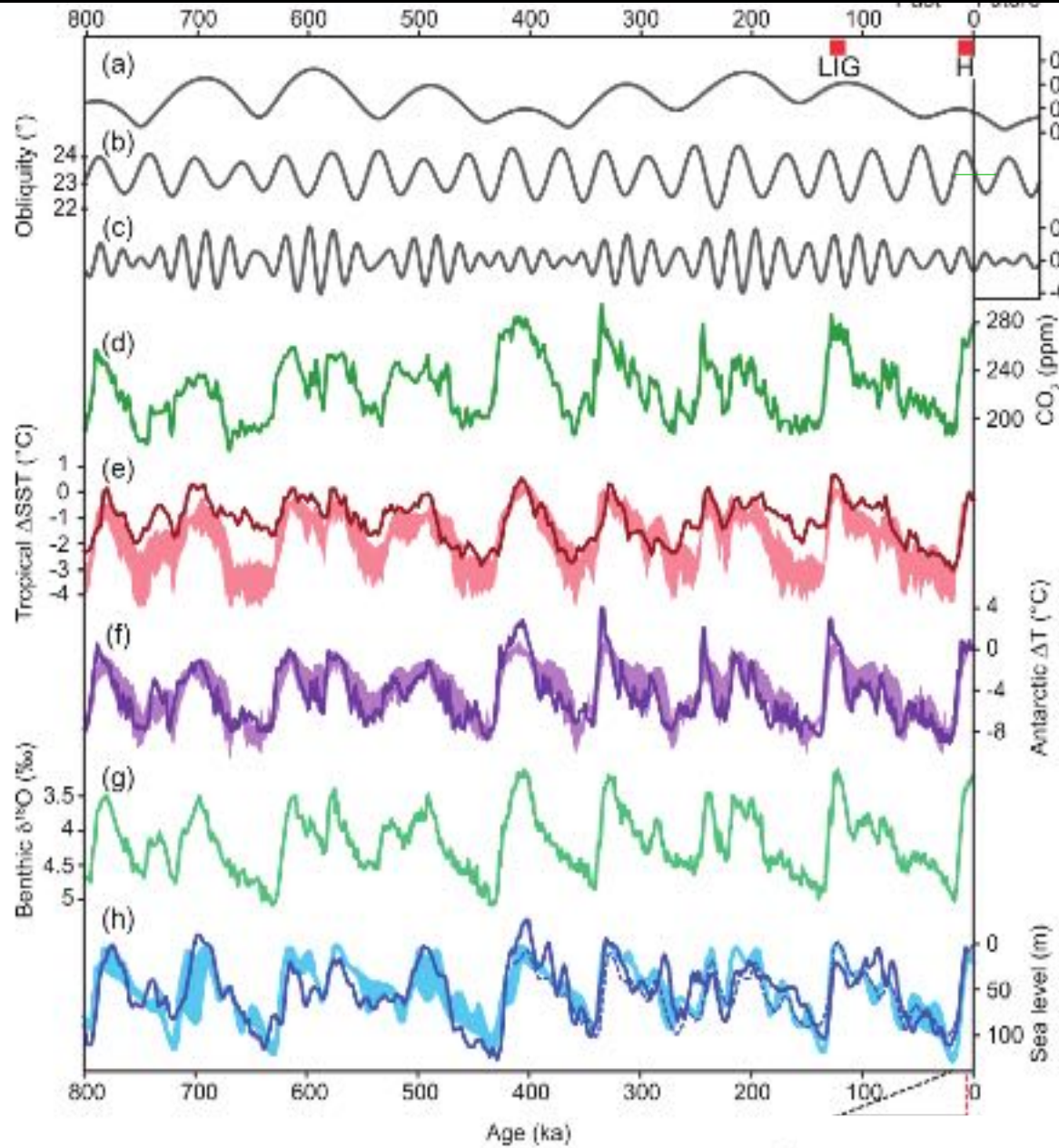




Variações orbitais (Milankovitch)

← CO2 no testemunho de Dome C

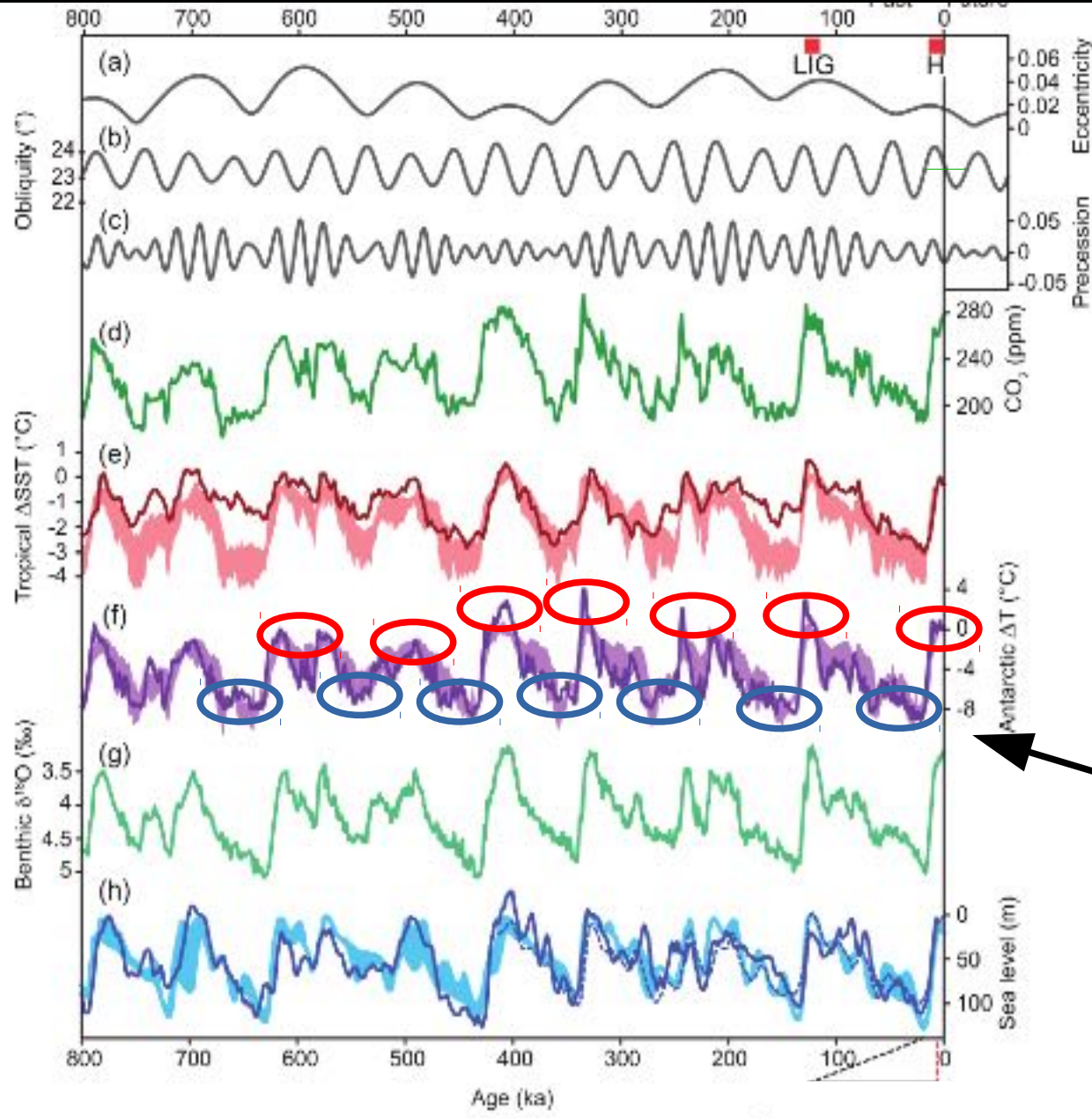




Variações orbitais (Milankovitch)

← CO2 no testemunho de Dome C

← Temperatura definida a partir de isótopos da água

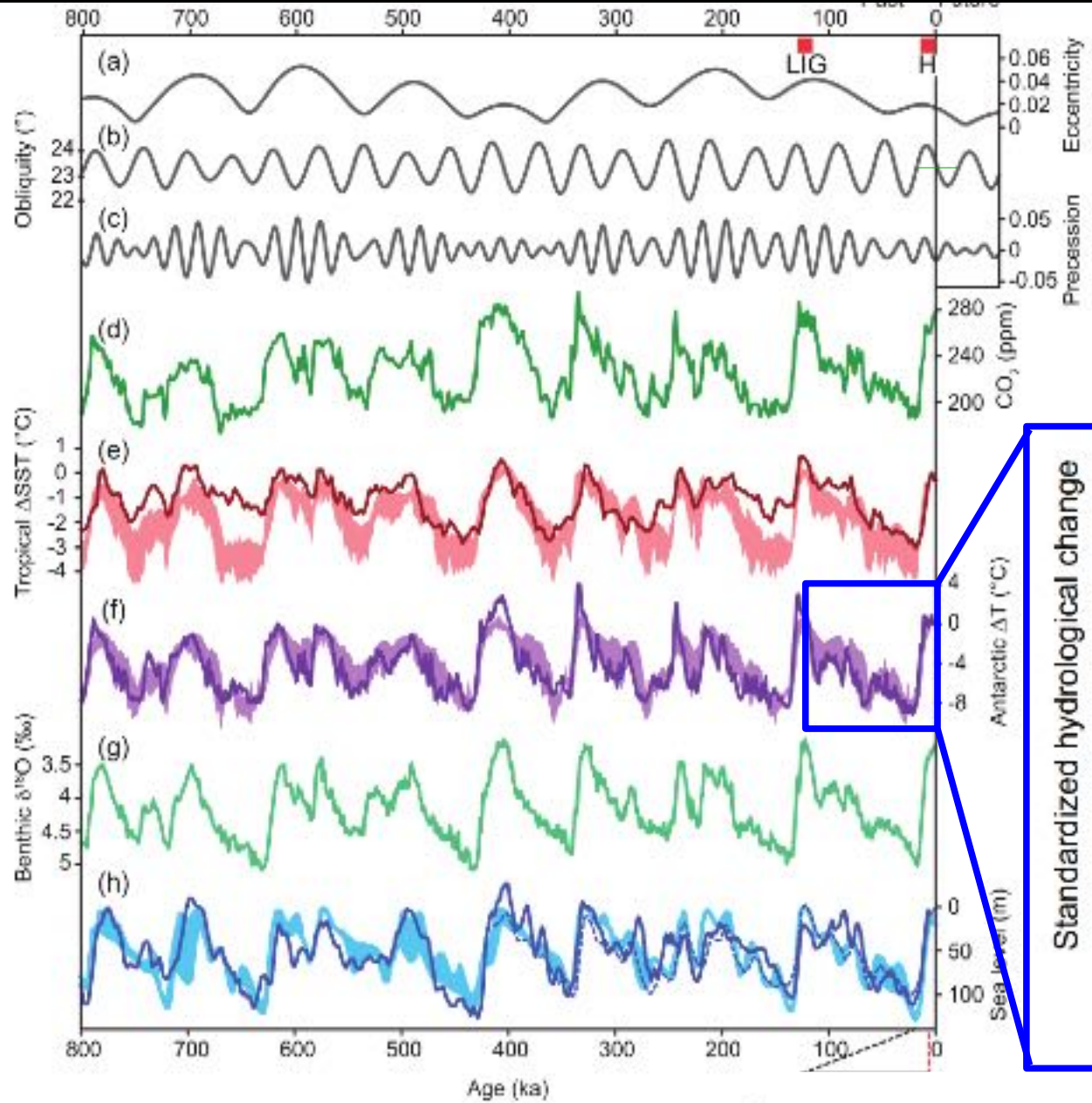


Variações orbitais (Milankovitch)

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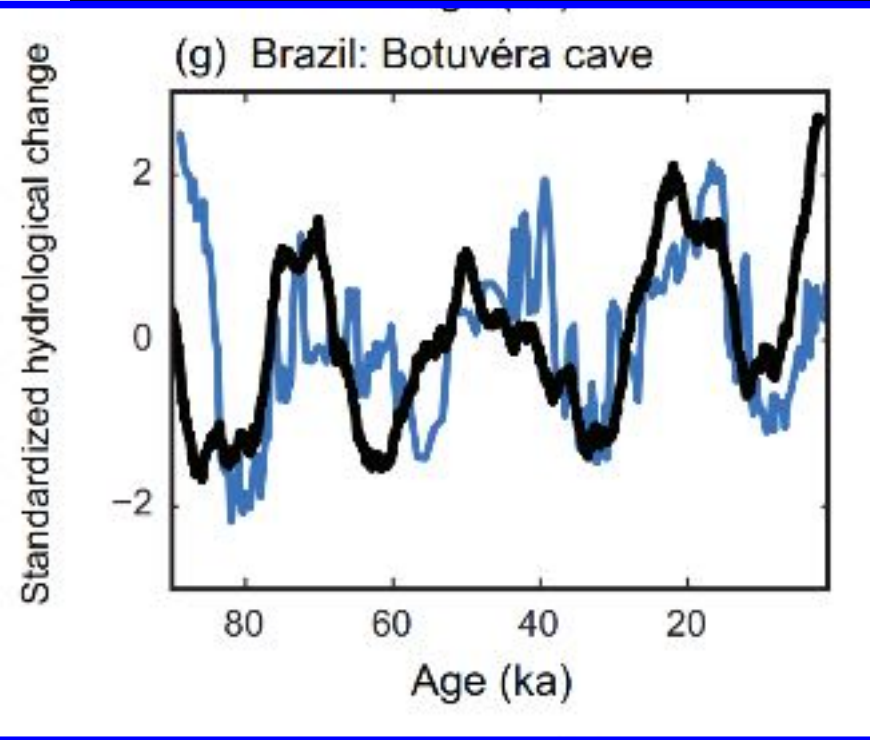
← Temperatura definida a partir de isótopos da água

← “Eras glaciais” / interglaciais



Variações orbitais (Milankovitch)

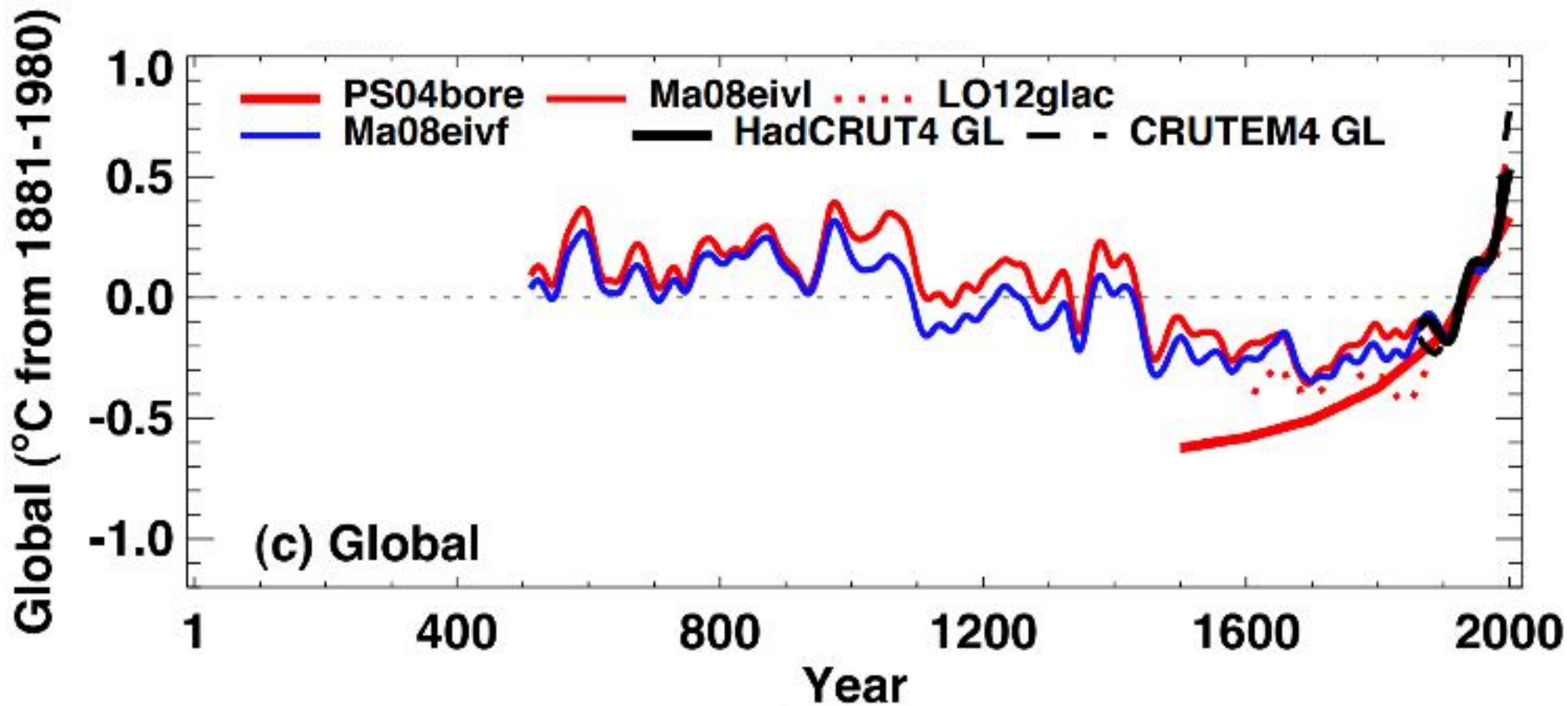
← CO2 no testemunho de Dome C



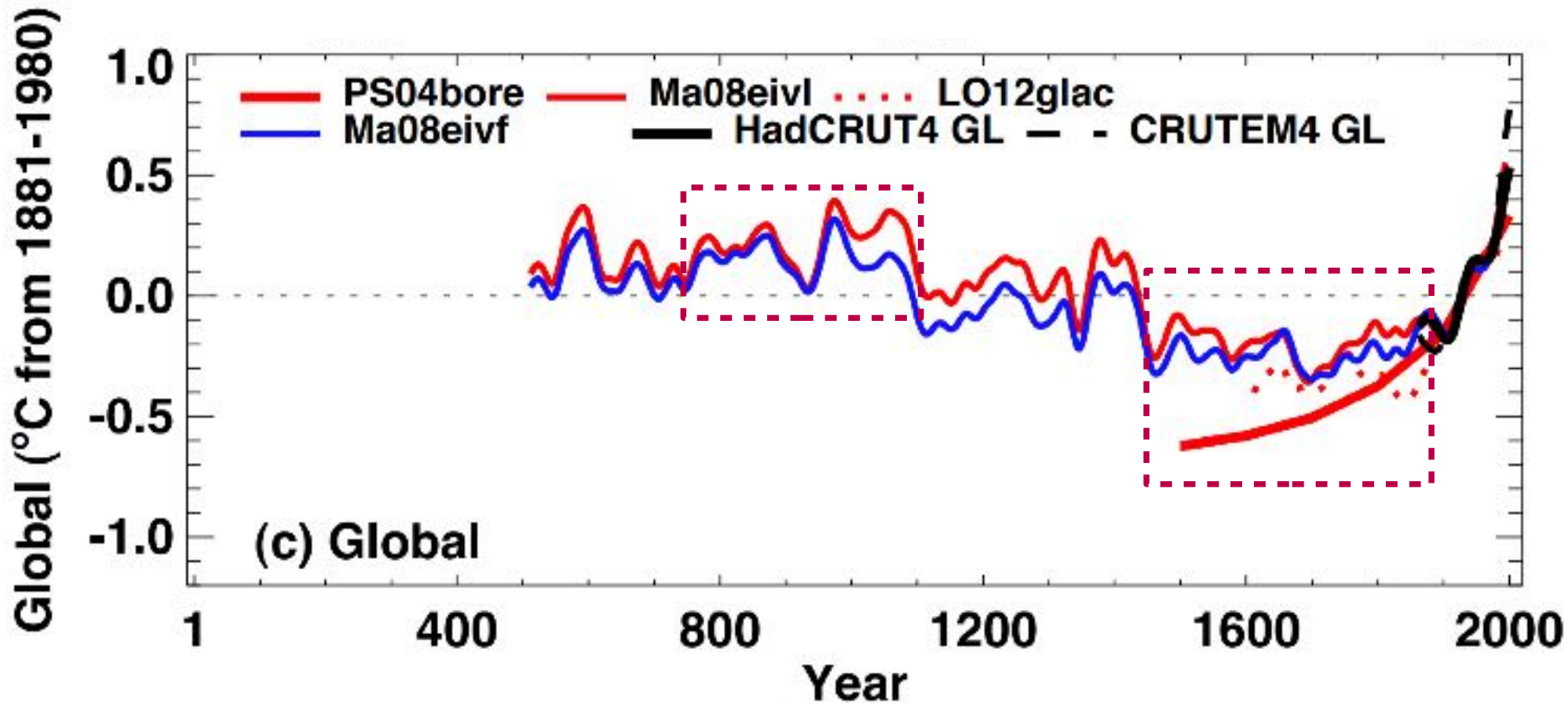
Standardized hydrological change



# Registros dos últimos 2000 anos

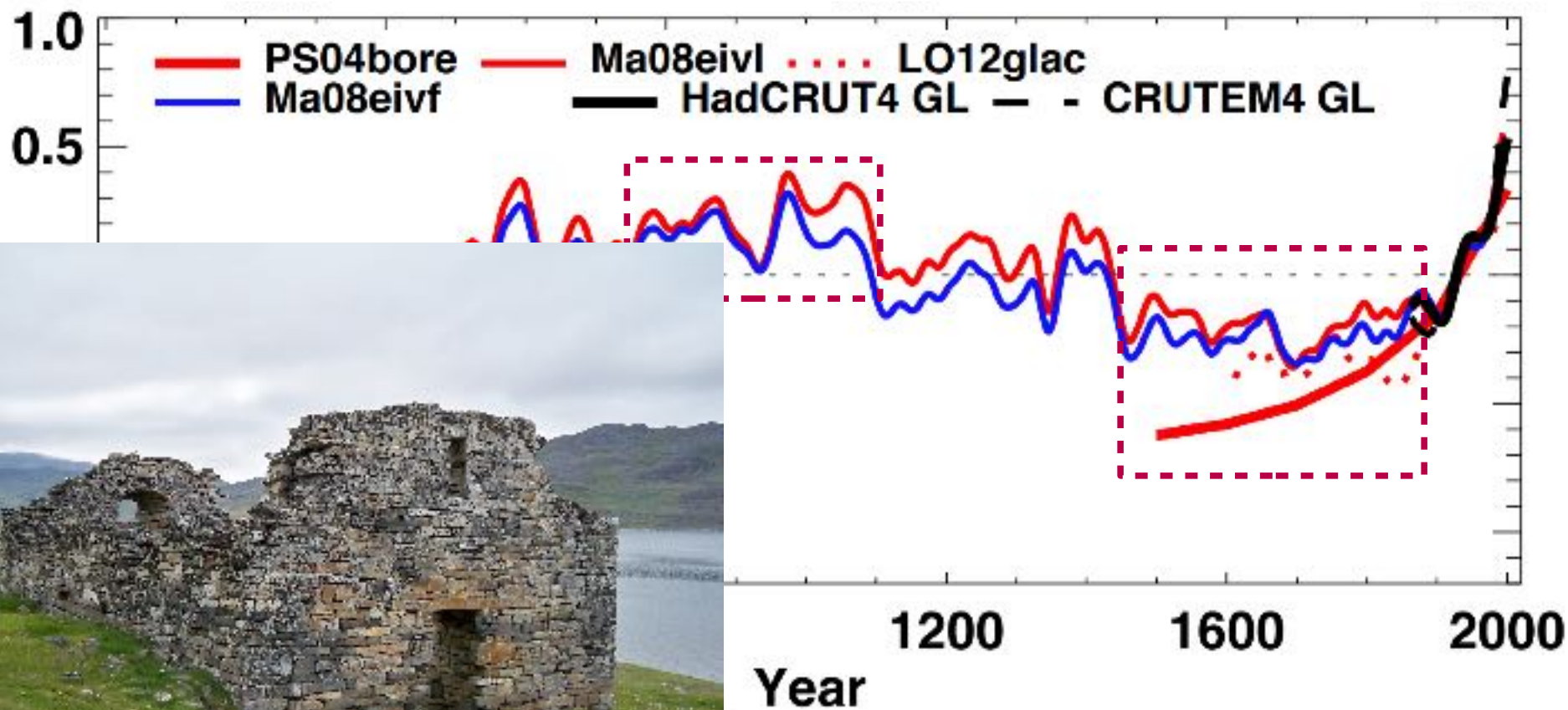


# Registros dos últimos 2000 anos



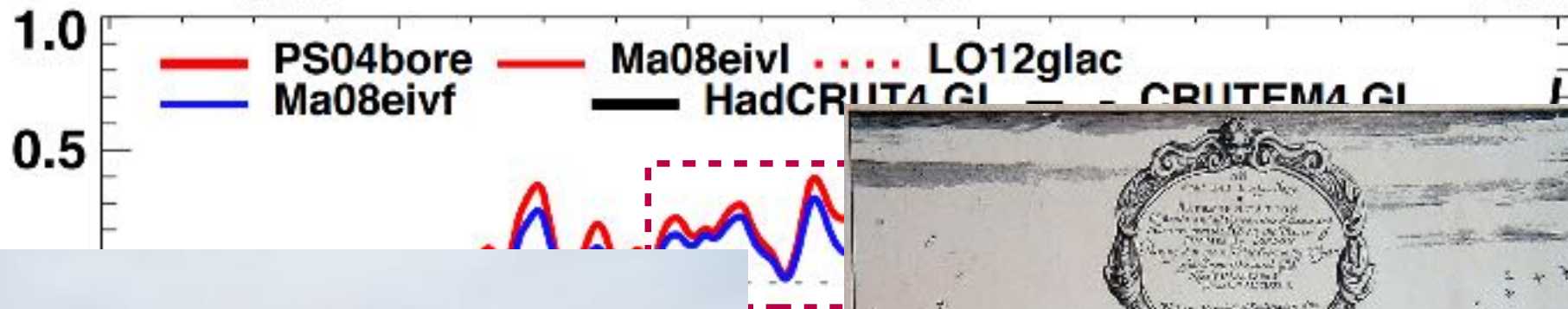
# Registros dos últimos 2000 anos

1881-1980)



# 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

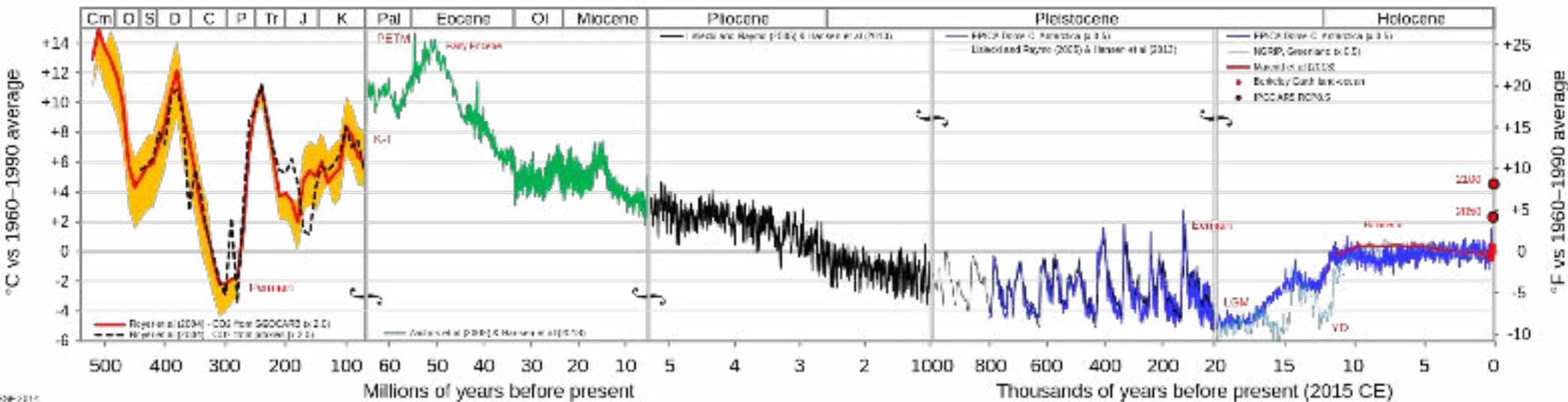


Ye



# Várias escalas de tempo no registro paleoclimático

## Temperature of Planet Earth



# Escala tectônica

# Escala orbital

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

Plantas terrestres

Dinossauros

Lago Vostok

Homo sapiens

Indo

Primatas

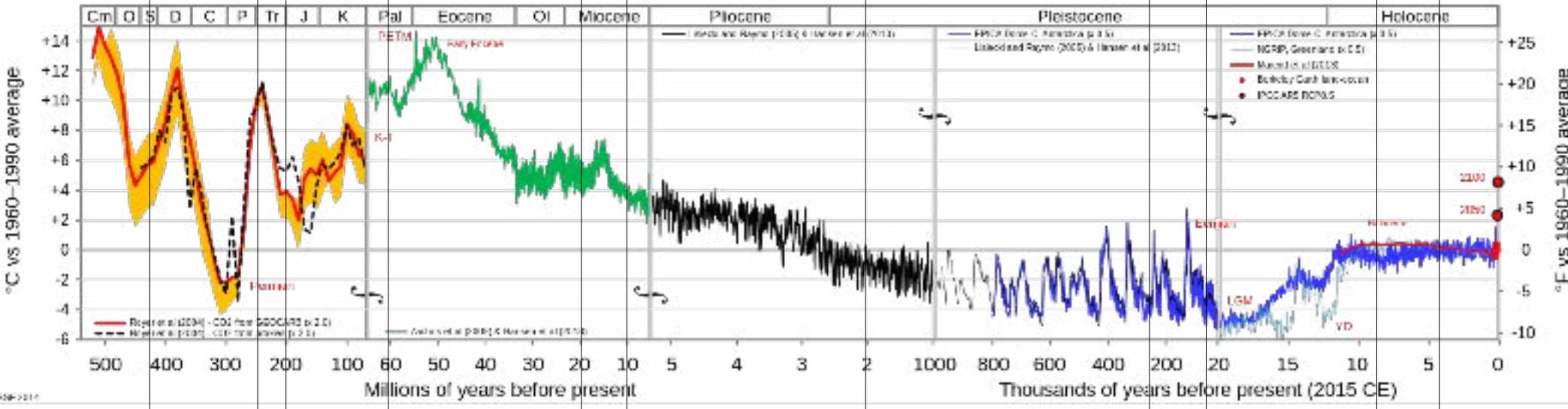
Savanas

Homo habilis

Aborígenes

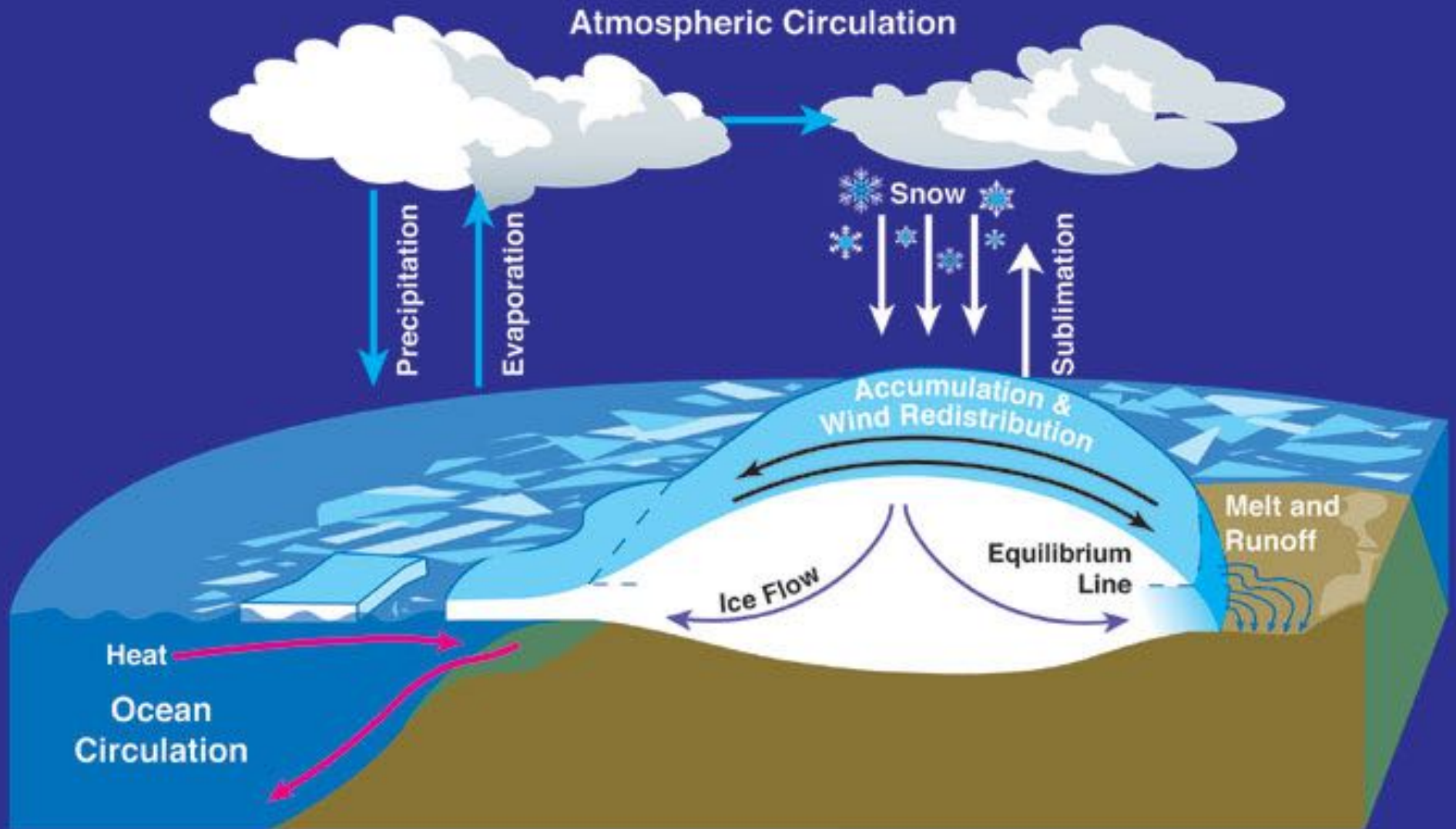
Egito, Mesopotâmia

## Temperature of Planet Earth



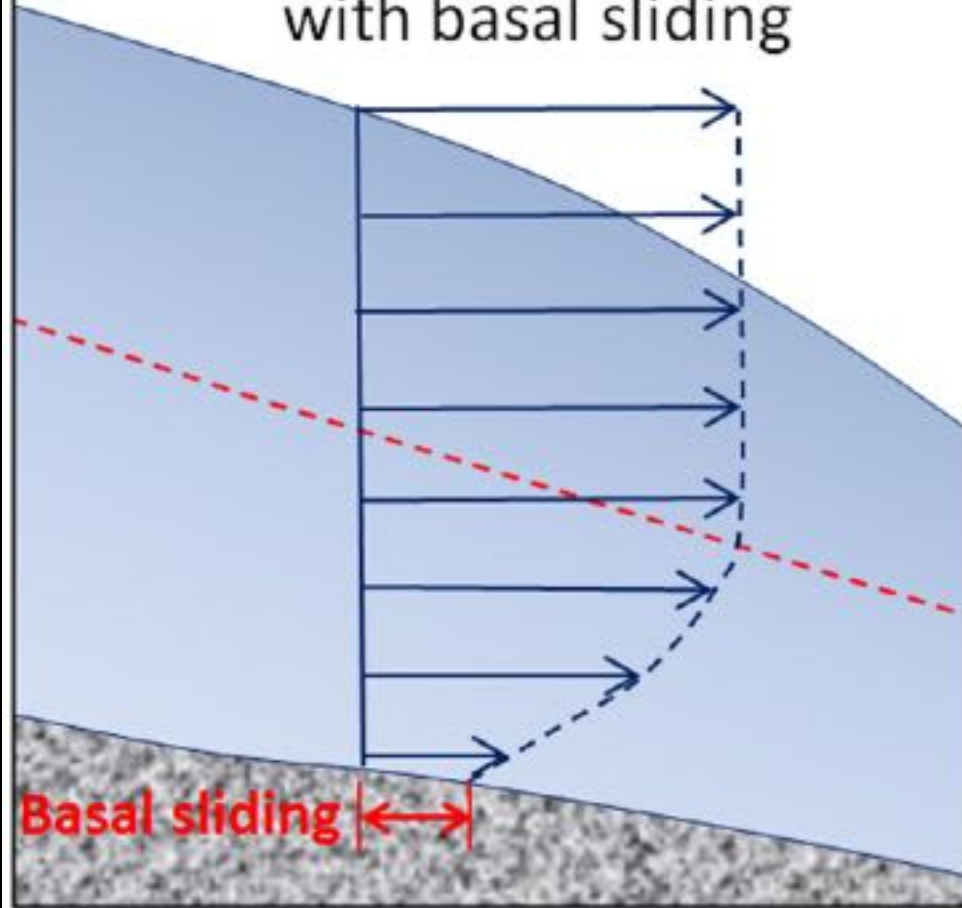


# O registro paleoclimático em geleiras e mantos de gelo

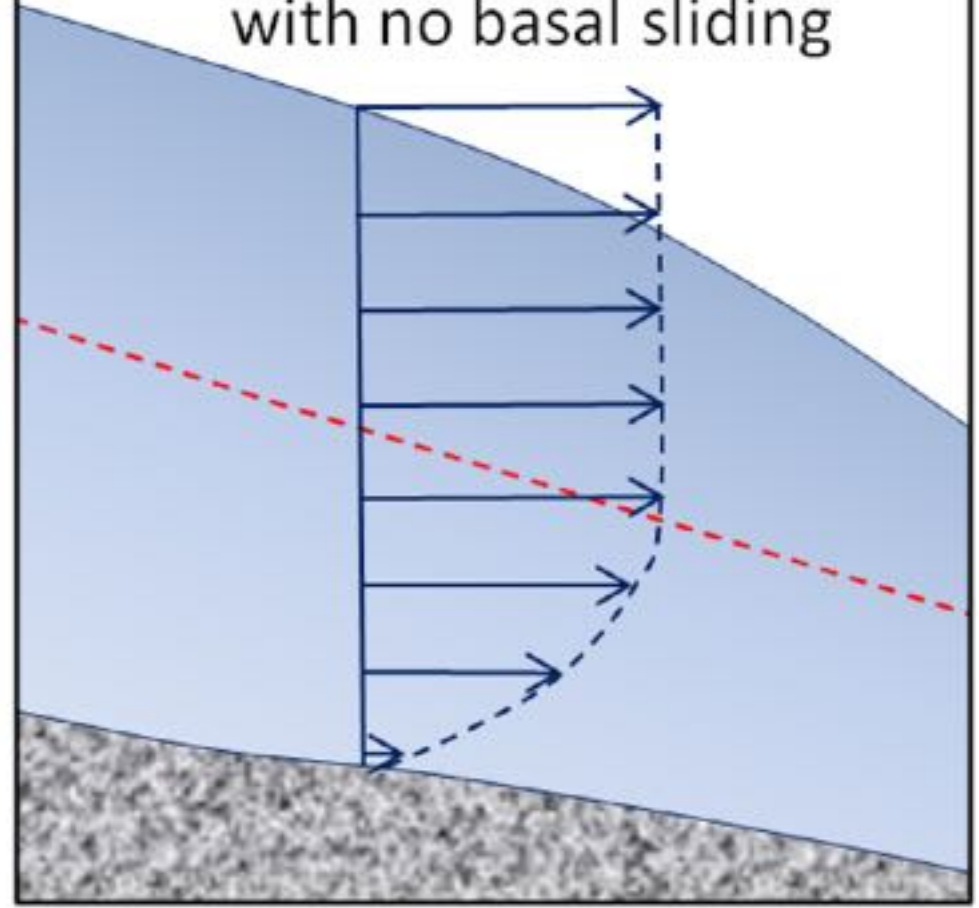


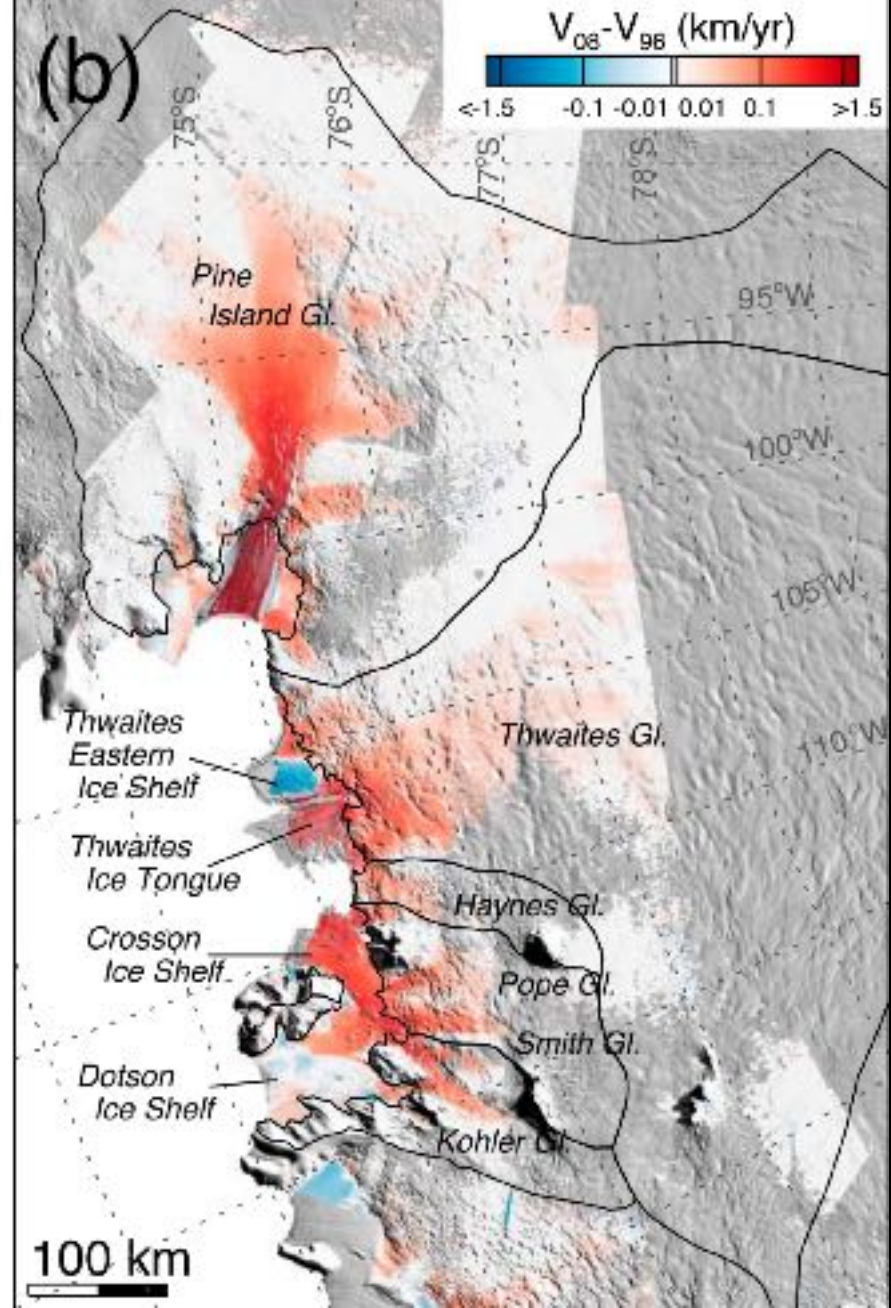
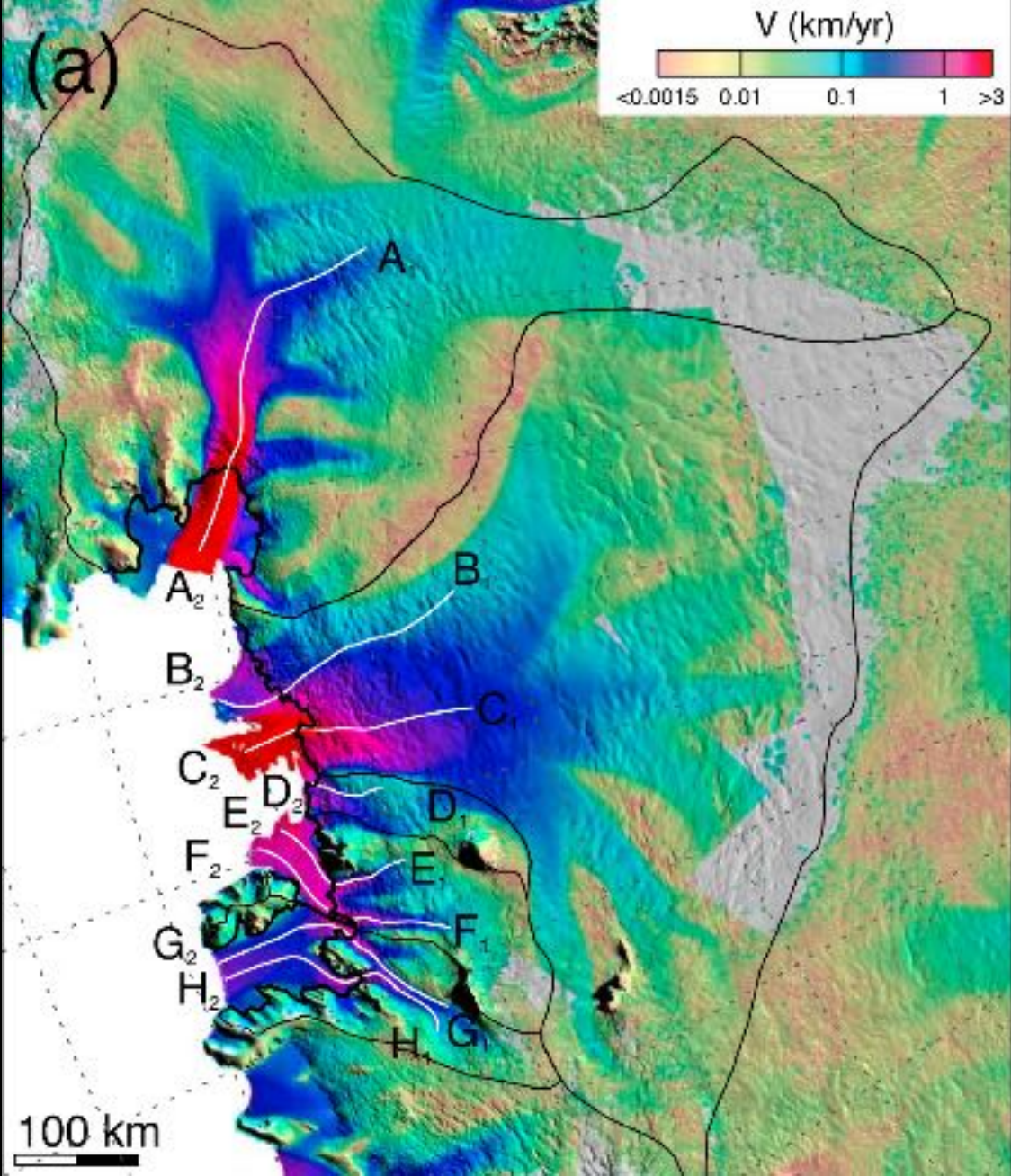
# Escoamento de geleiras

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>

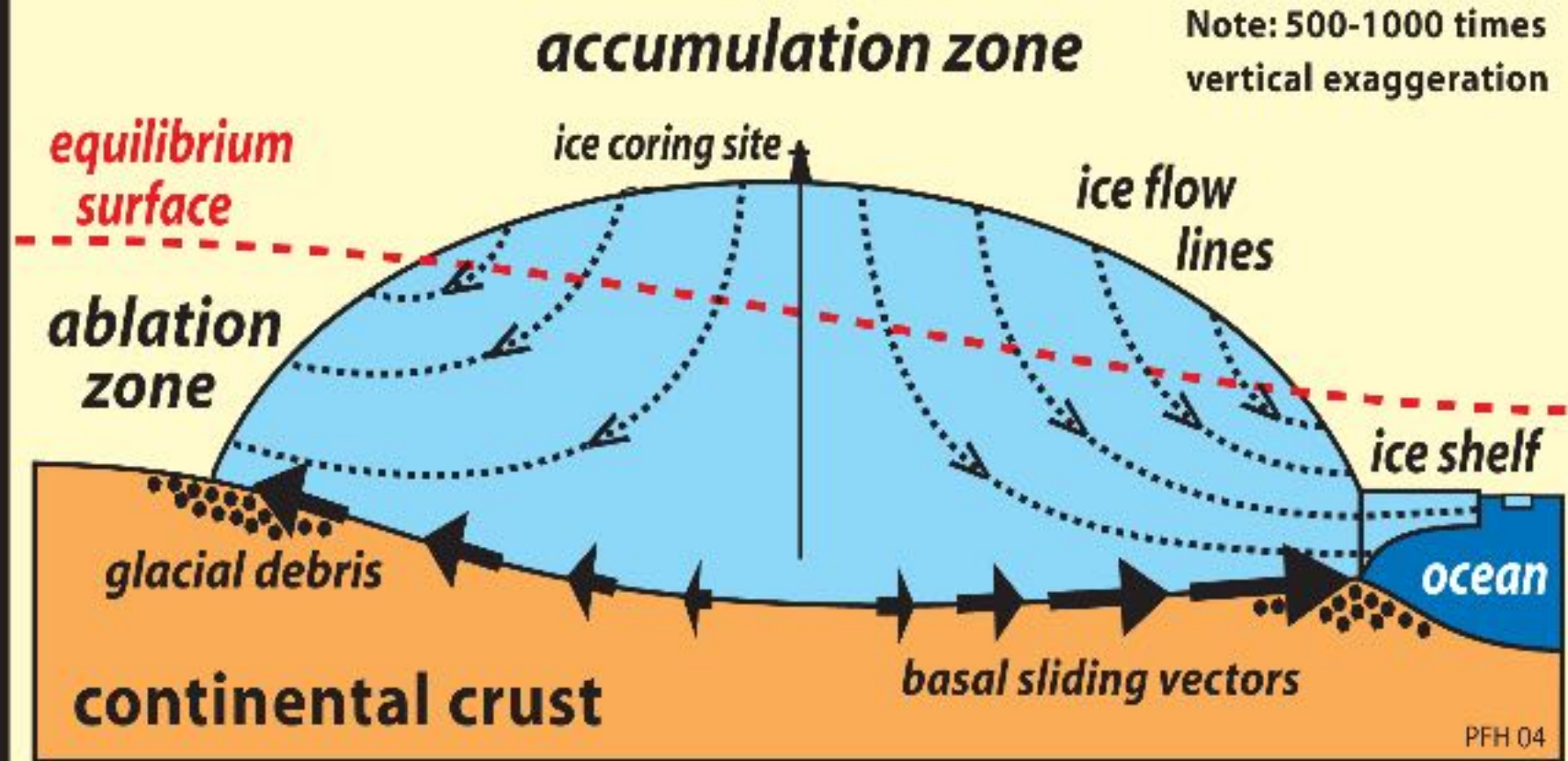


# Extração e análise de testemunhos de gelo

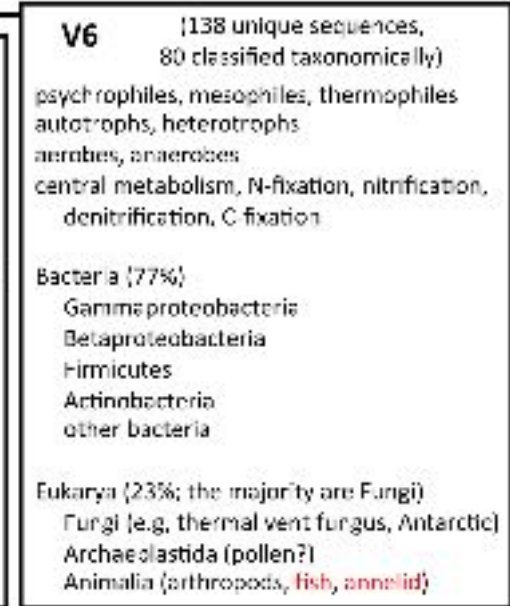
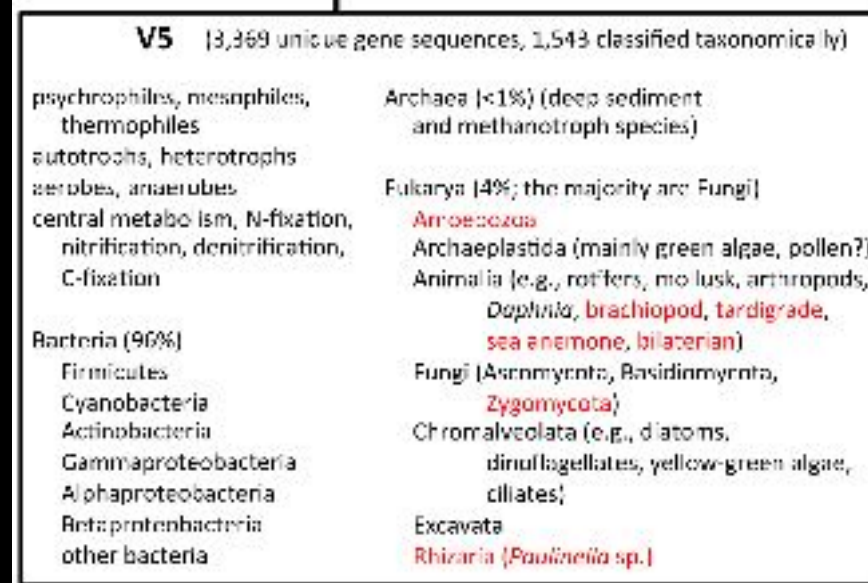
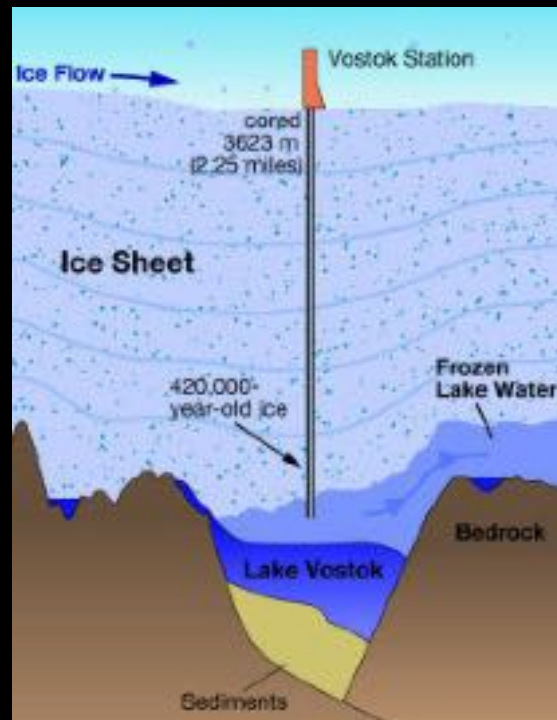
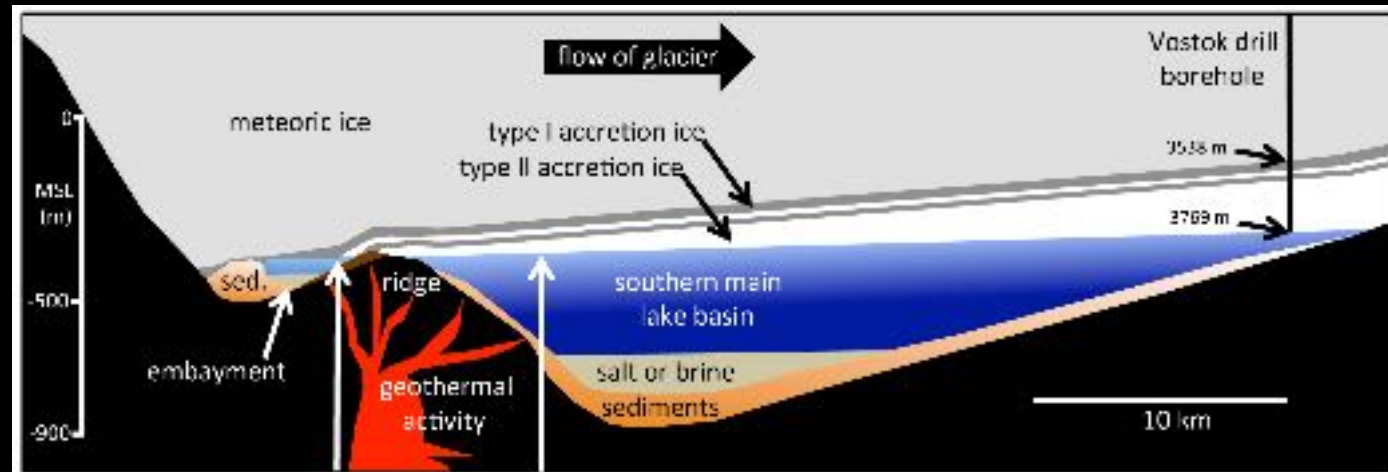
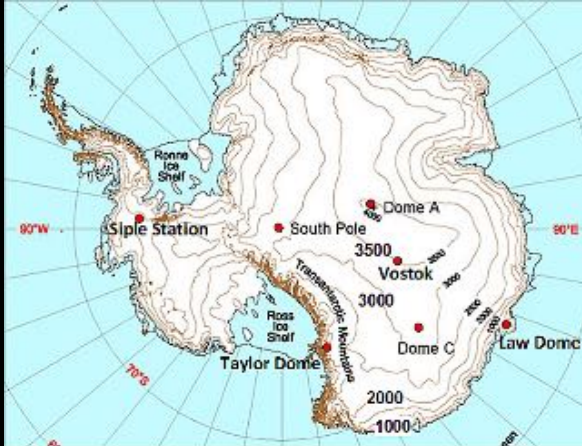


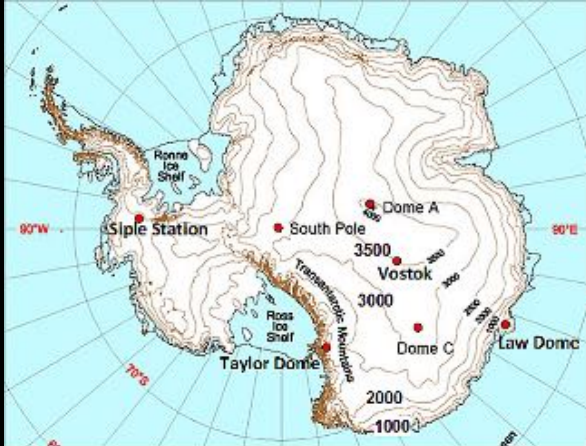
Drilling site: location, location, location...

## IDEALIZED ICE-SHEET DYNAMICS

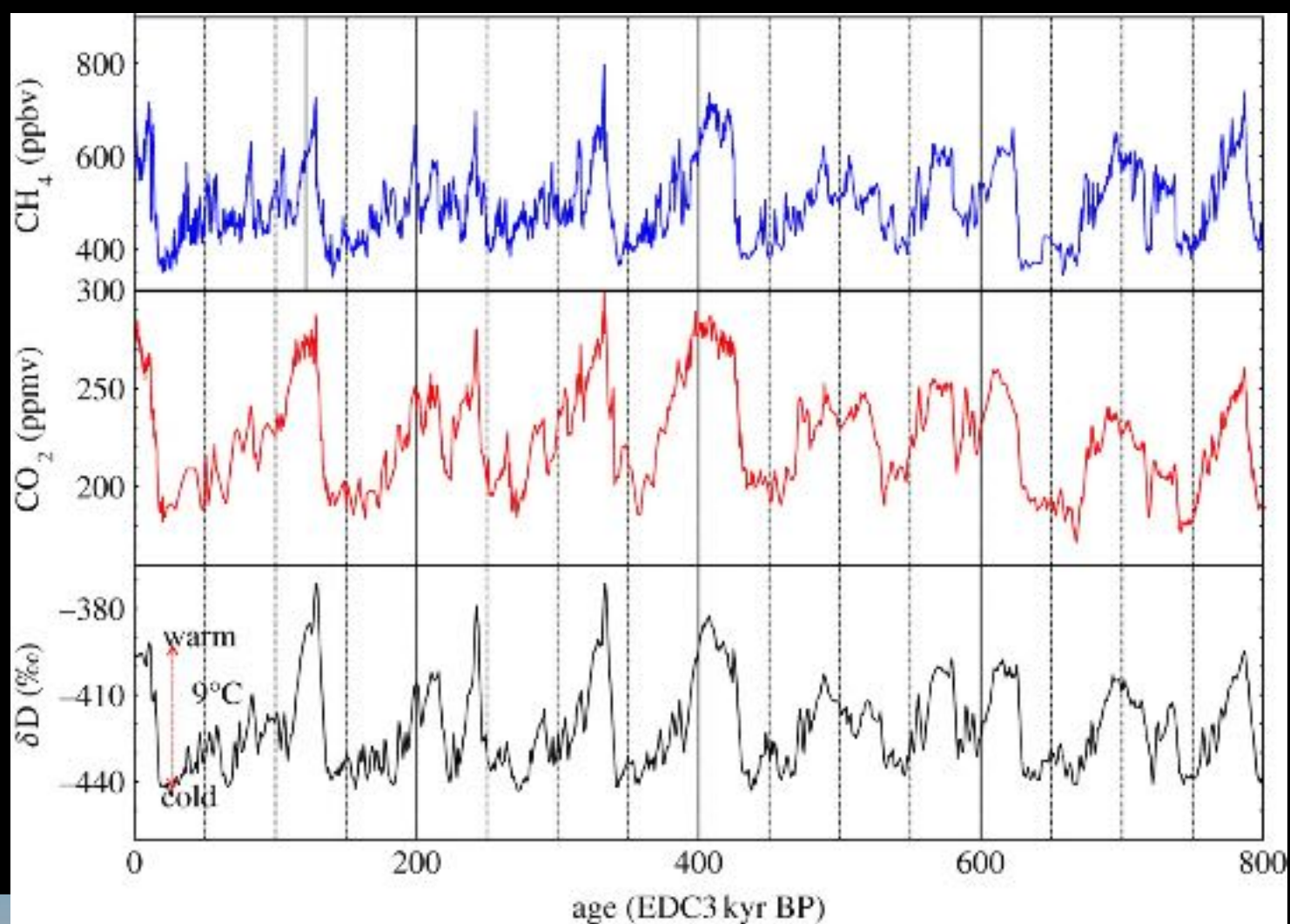


# Lago Vostok





# Dome C

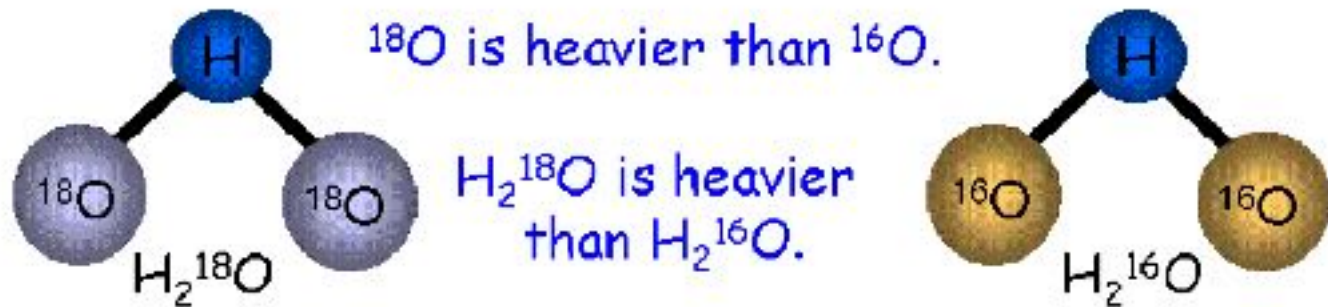




# Fracionamento isotópico

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

- Oxygen isotopes are **fractionated** during evaporation and precipitation of  $\text{H}_2\text{O}$ 
  - $\text{H}_2^{16}\text{O}$  evaporates more readily than  $\text{H}_2^{18}\text{O}$
  - $\text{H}_2^{18}\text{O}$  precipitates more readily than  $\text{H}_2^{16}\text{O}$

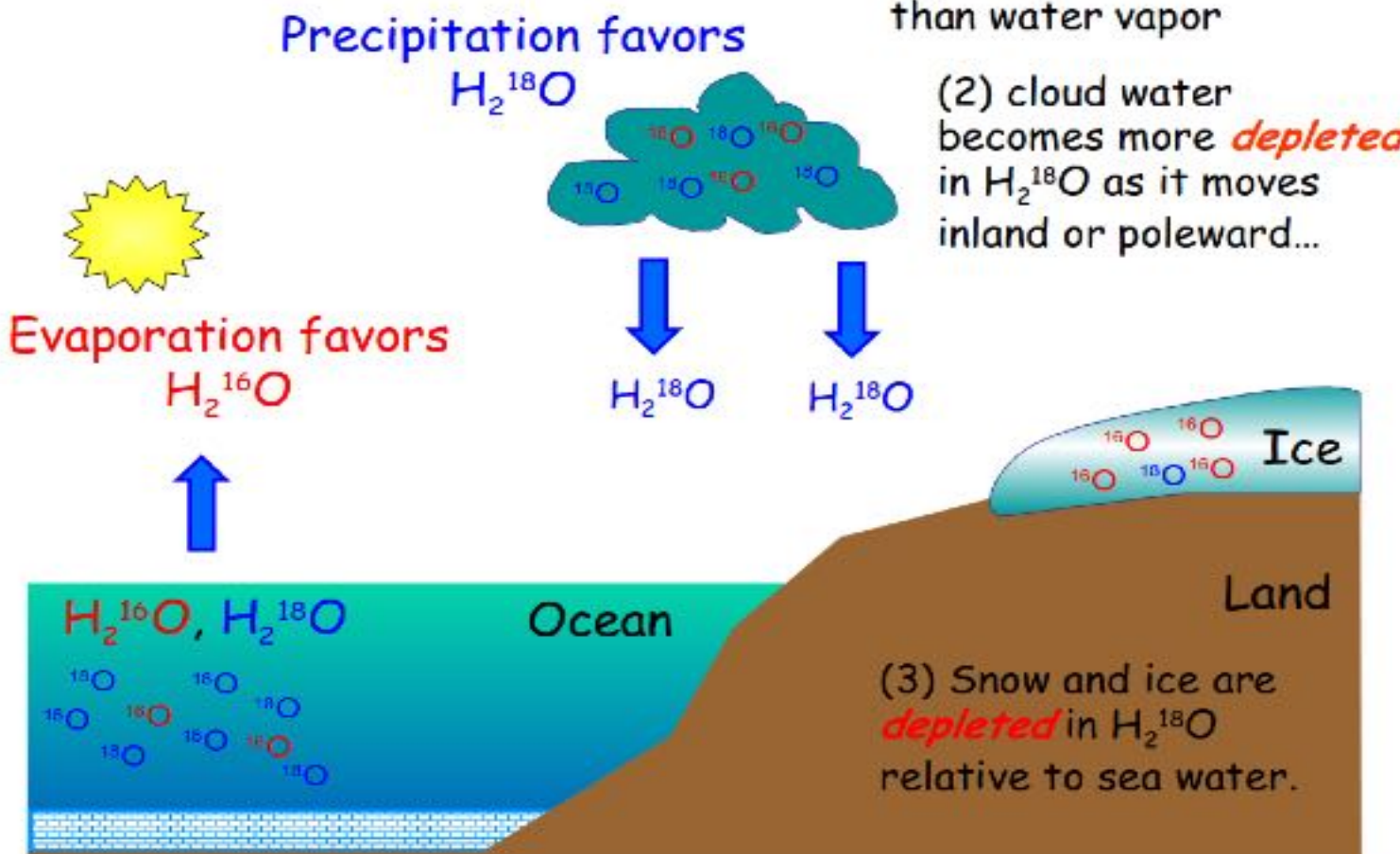


- Oxygen isotopes are also **fractionated** by marine organisms that secrete  $\text{CaCO}_3$  shells. The organisms preferentially take up more  $^{16}\text{O}$  as temperature increases.

# Fracionamento isotópico

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

## Fractionation effects



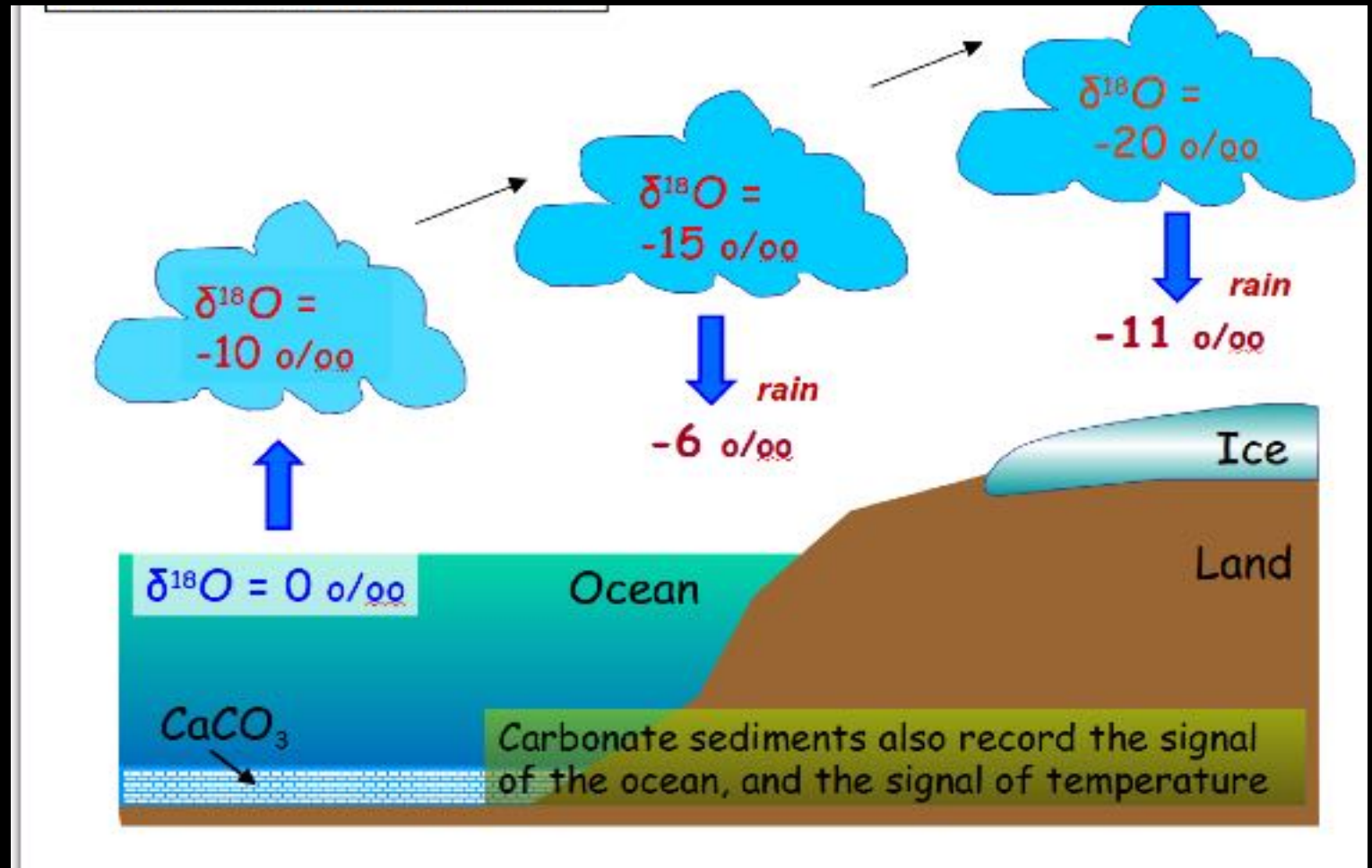
(1) Sea water is *heavier* than water vapor

(2) cloud water becomes more *depleted* in H<sub>2</sub><sup>18</sup>O as it moves inland or poleward...

(3) Snow and ice are *depleted* in H<sub>2</sub><sup>18</sup>O relative to sea water.

# Fracionamento isotópico

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



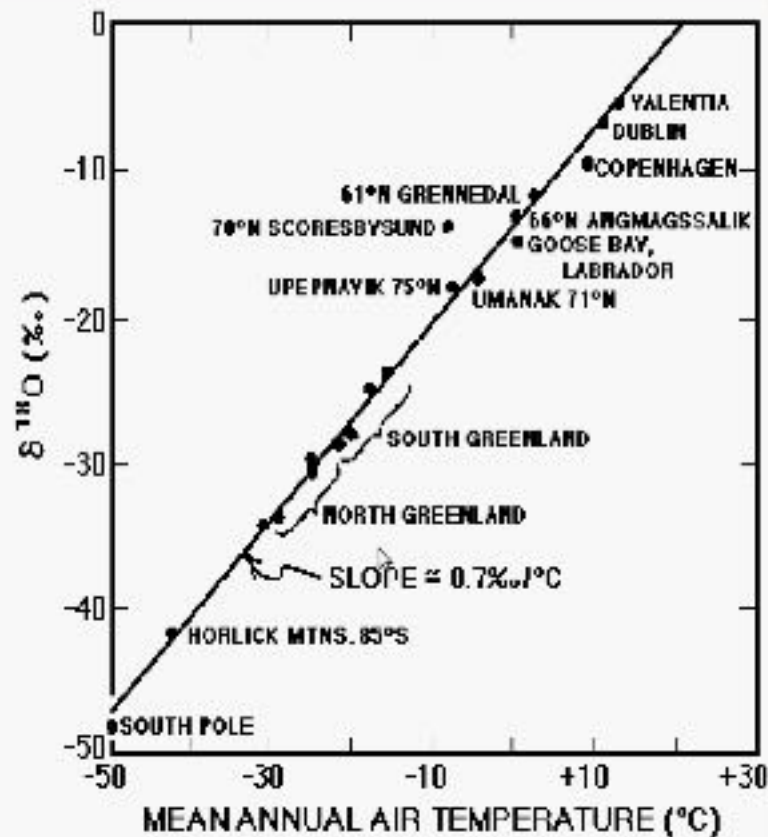
# Fracionamento isotópico

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

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)*

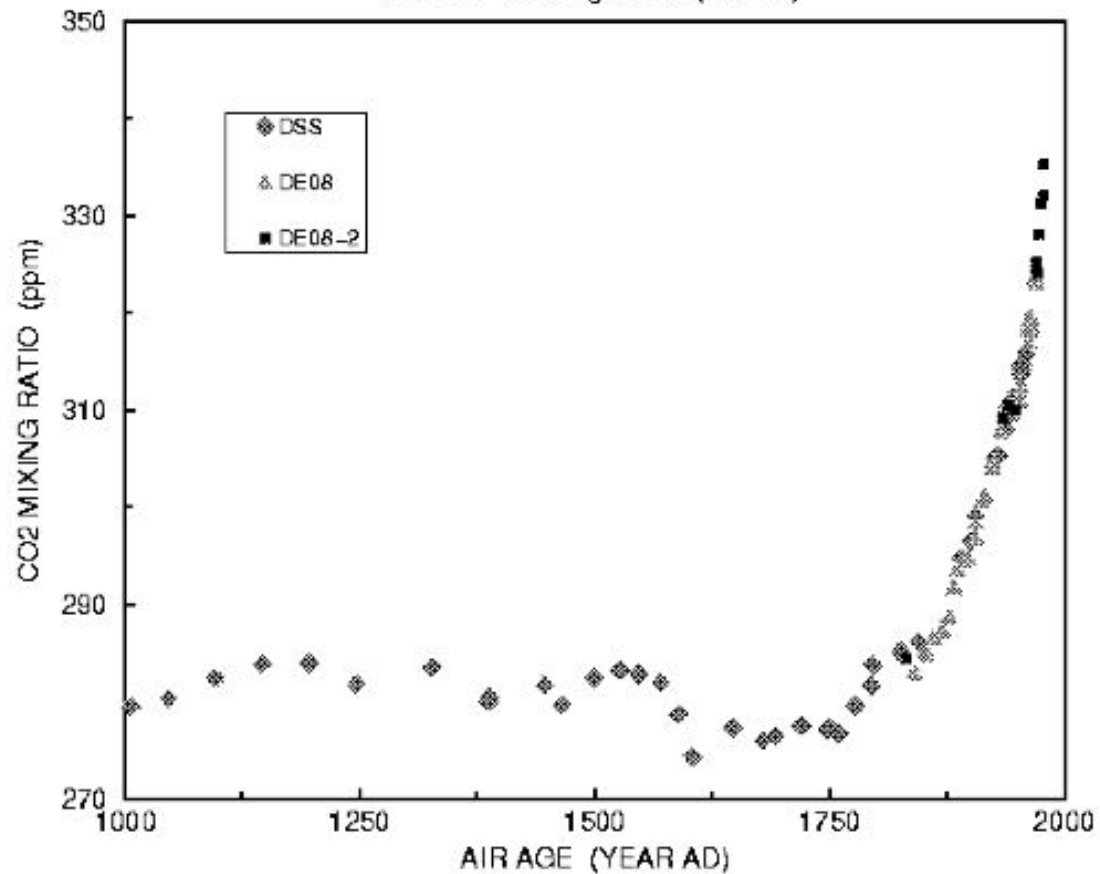


Observed  $\delta^{18}\text{O}$  in average annual precipitation as a function of mean annual air temperature (Dansgaard, 1964). Note that all the points on this graph are for high latitudes ( $>45^\circ$ ).

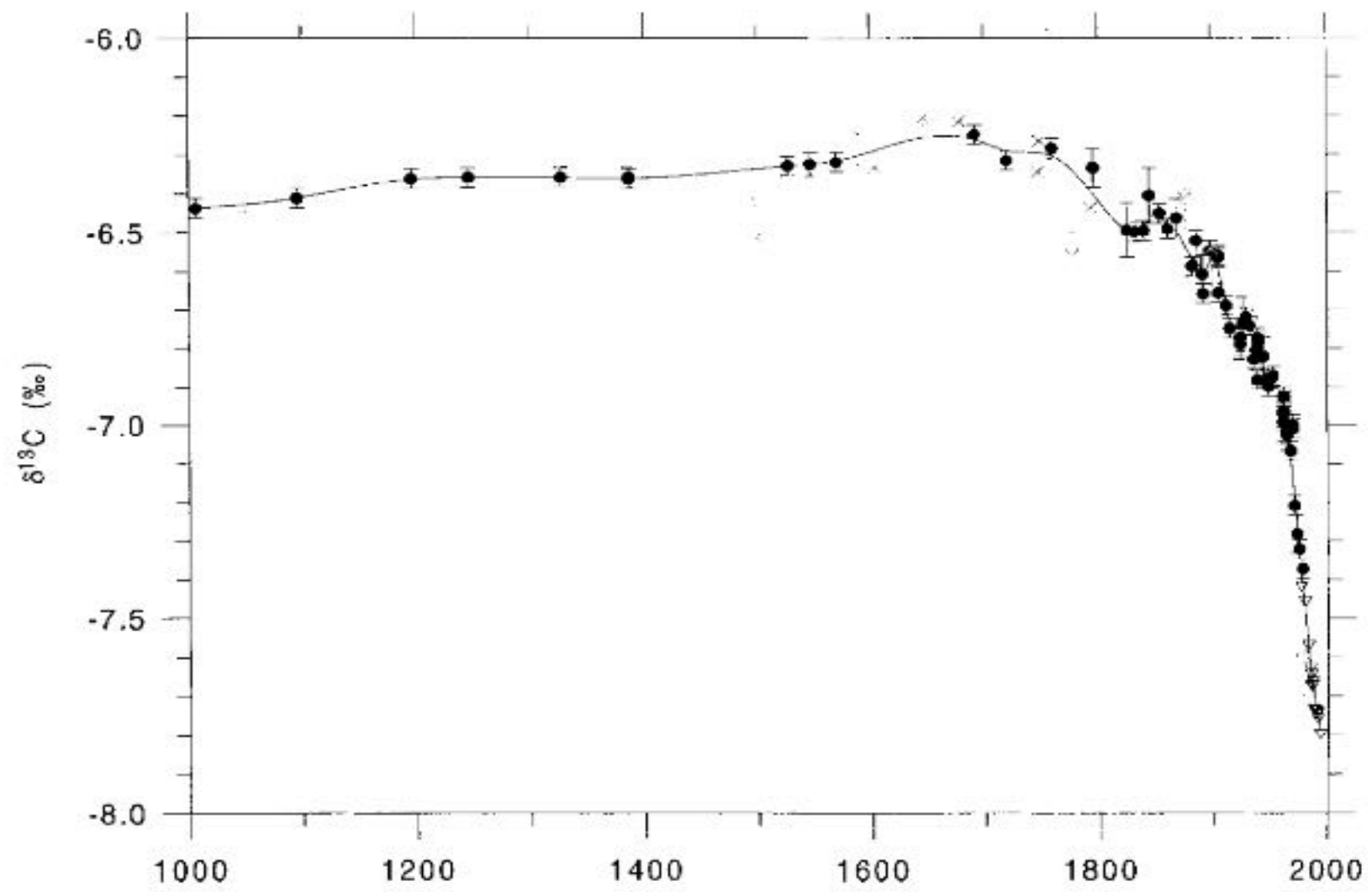
# Concentração de CO<sub>2</sub>

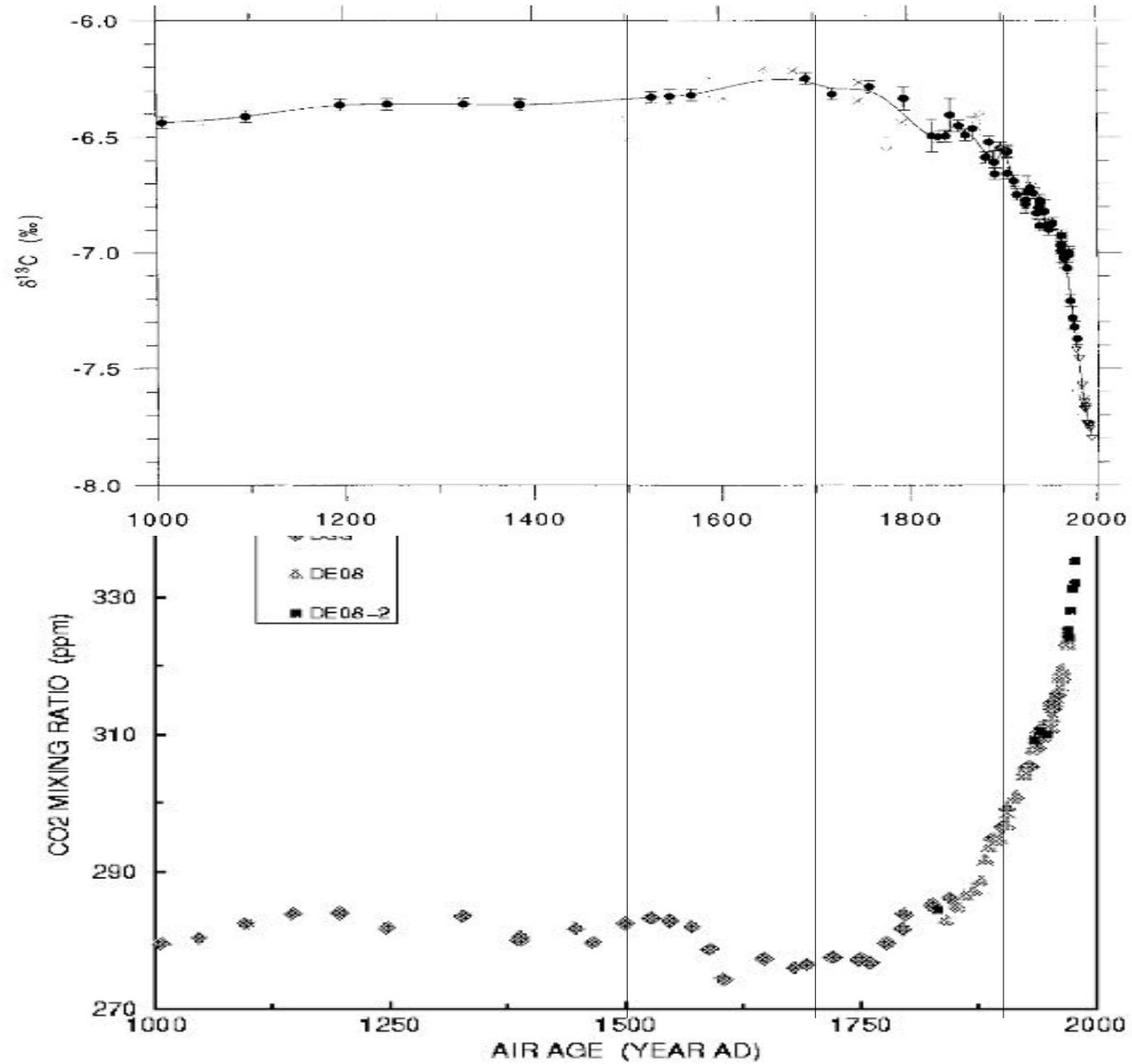
## LAW DOME, ANTARCTICA ICE CORES

Source: Etheridge et al. (CSIRO)

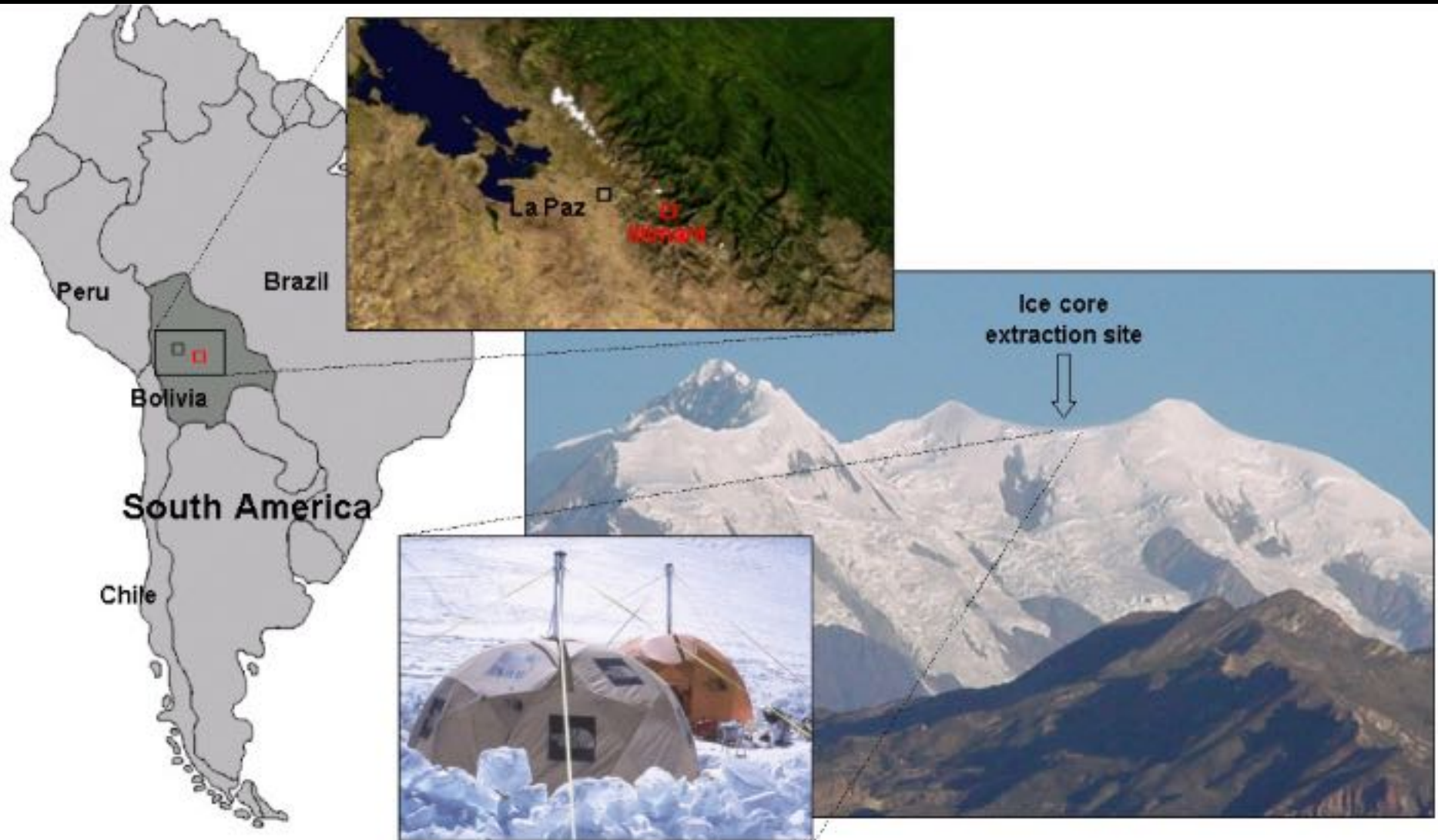


# Fracionamento de $^{13}\text{C}$





# O testemunho de gelo de Illimani, Bolívia

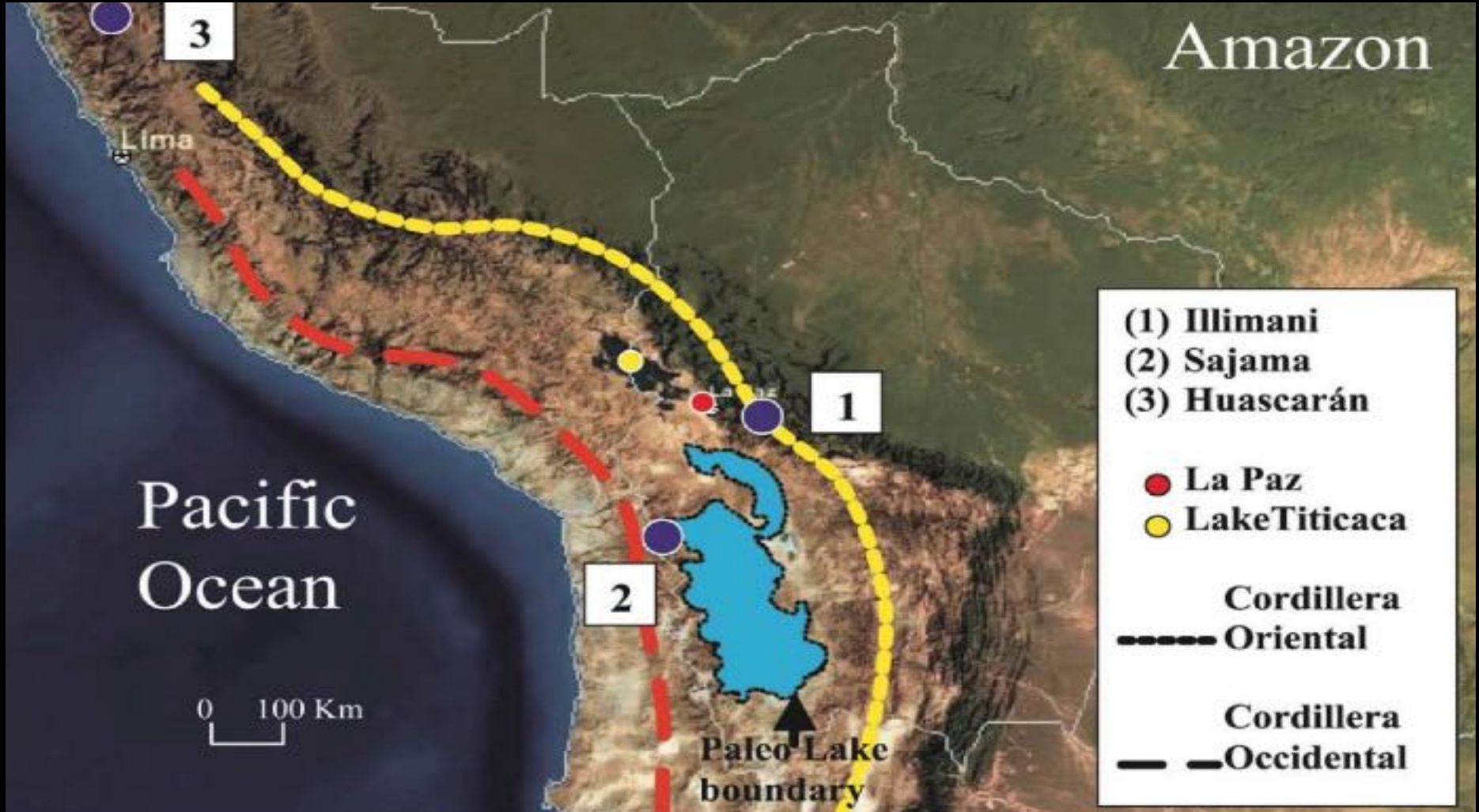




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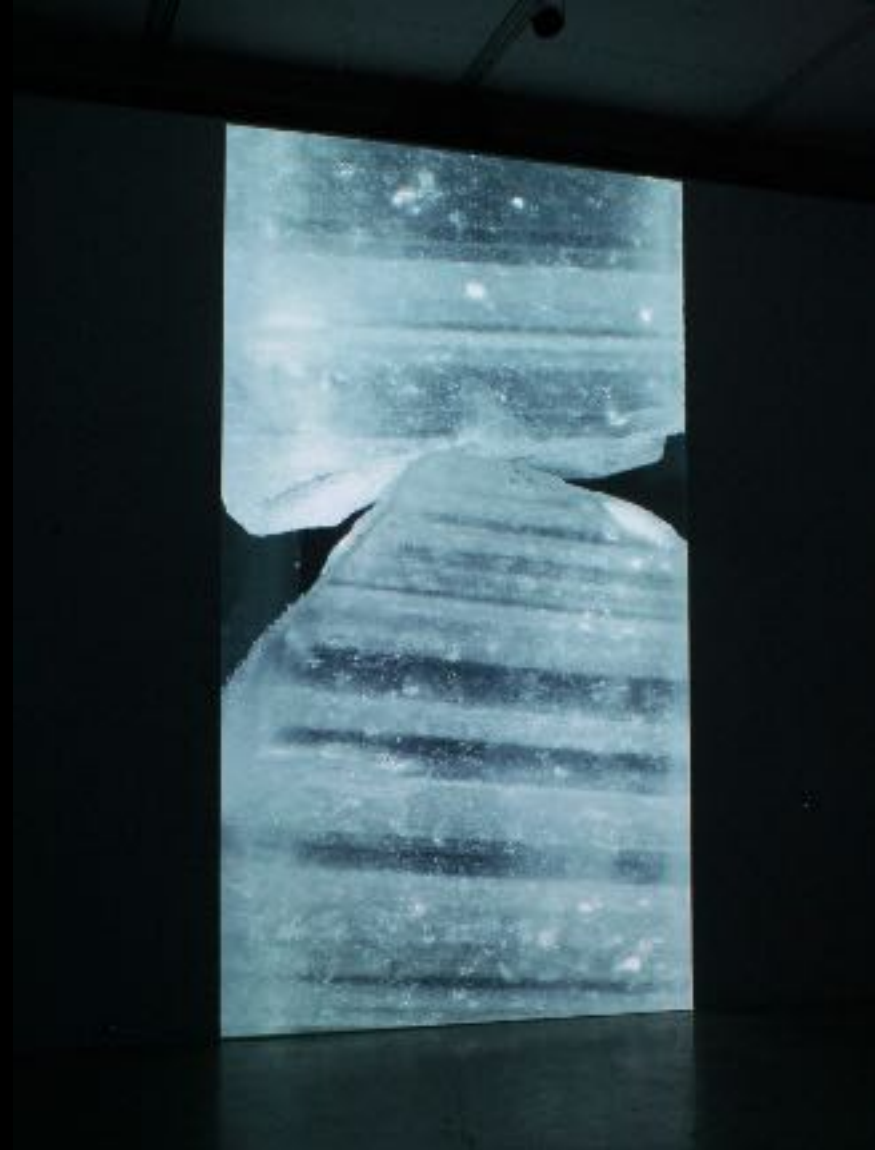
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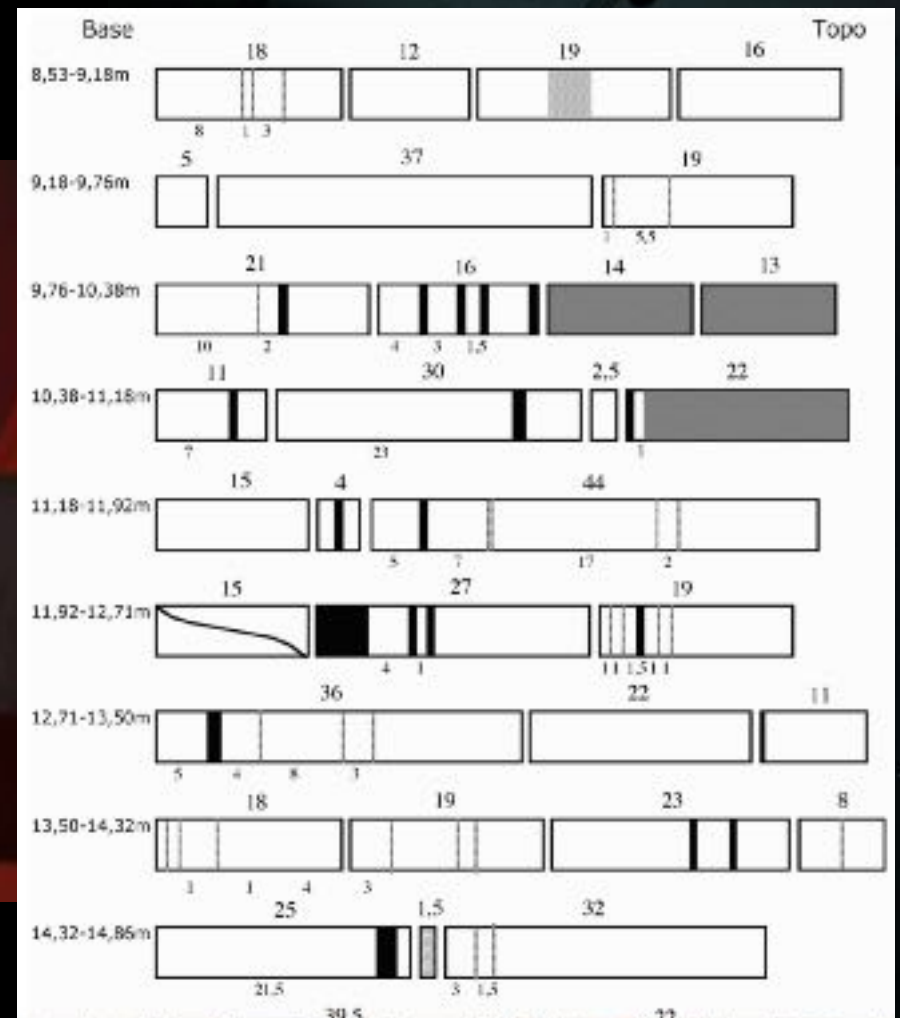
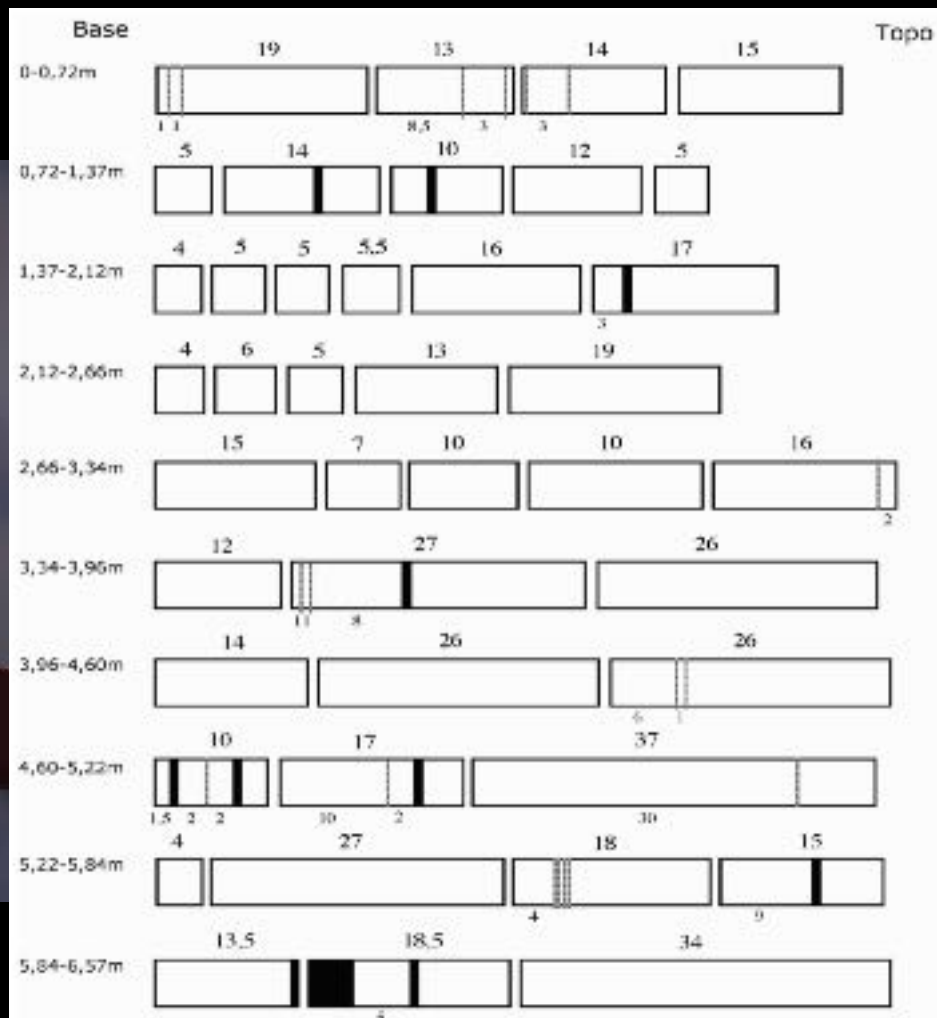
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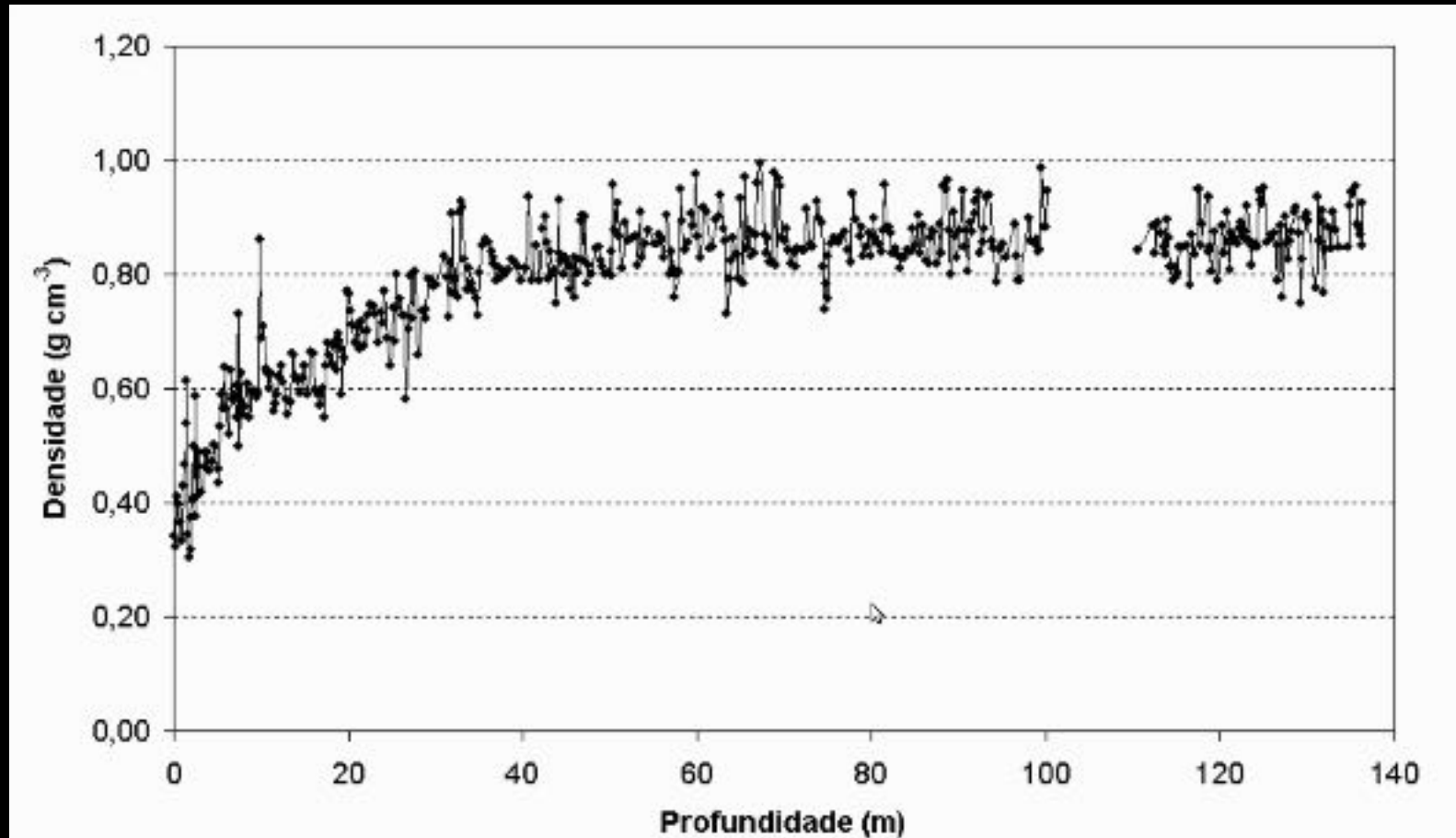
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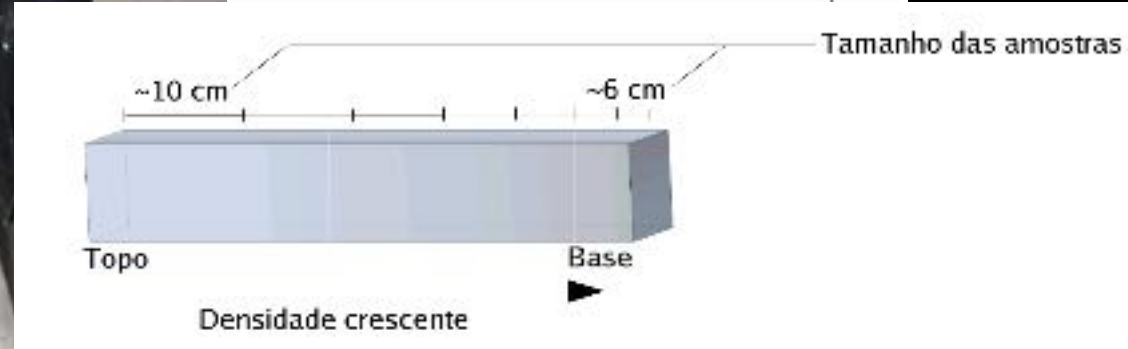
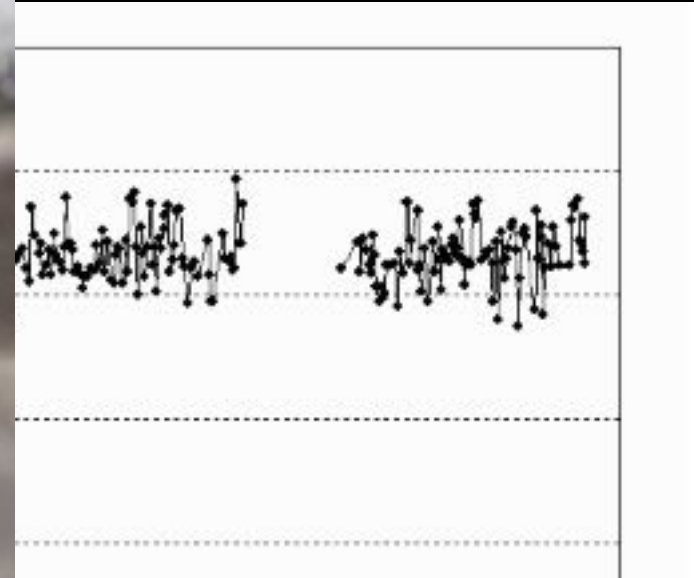
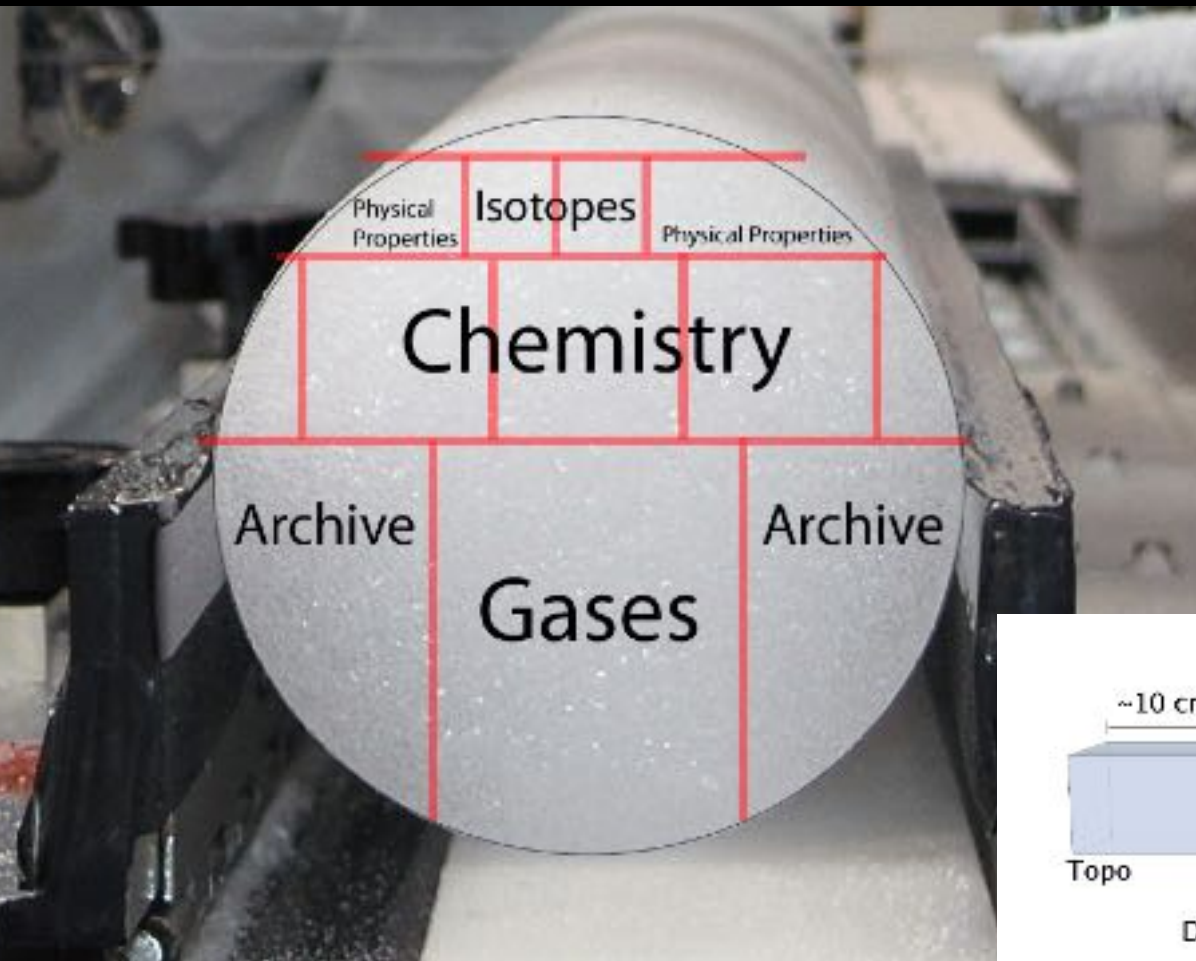
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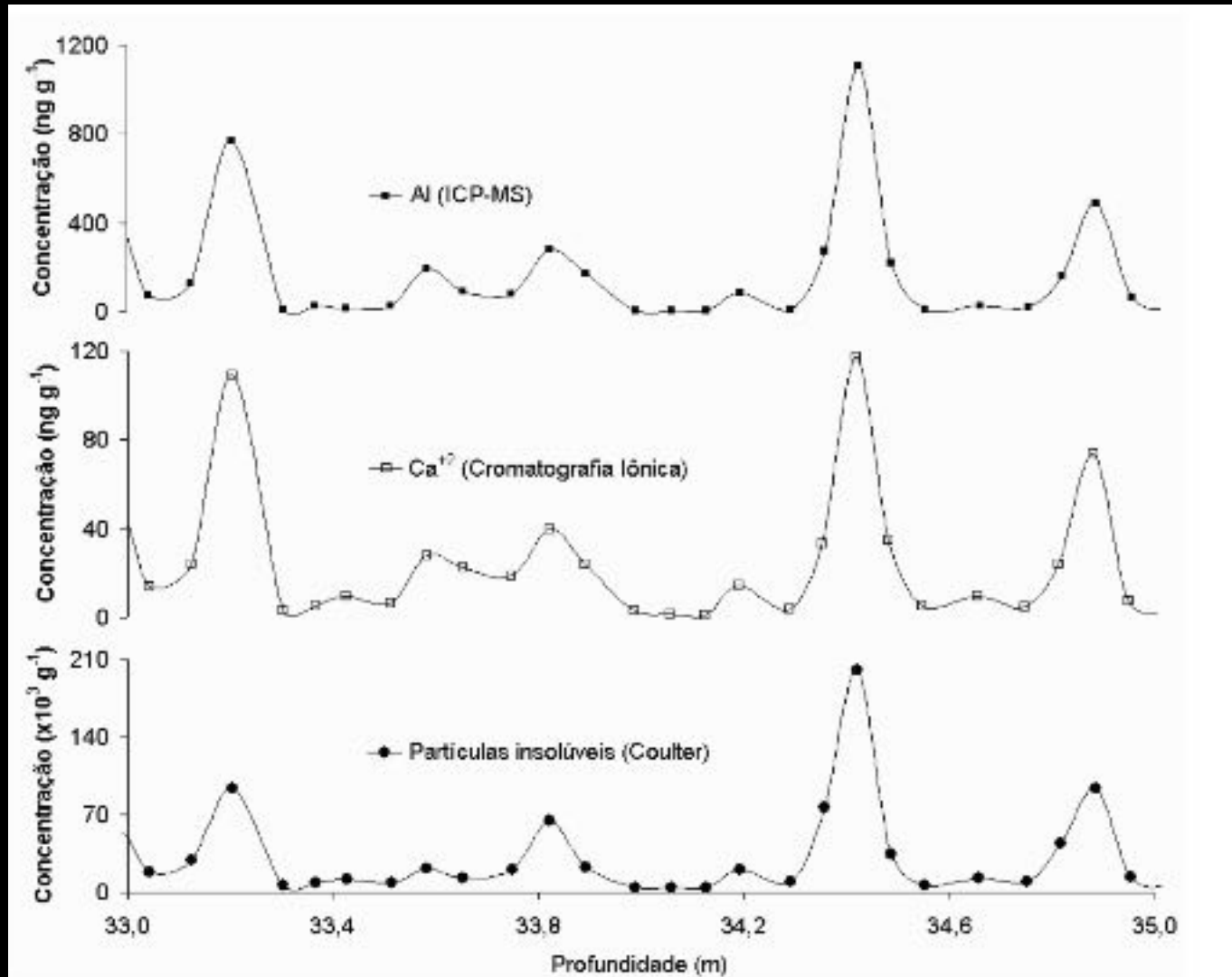


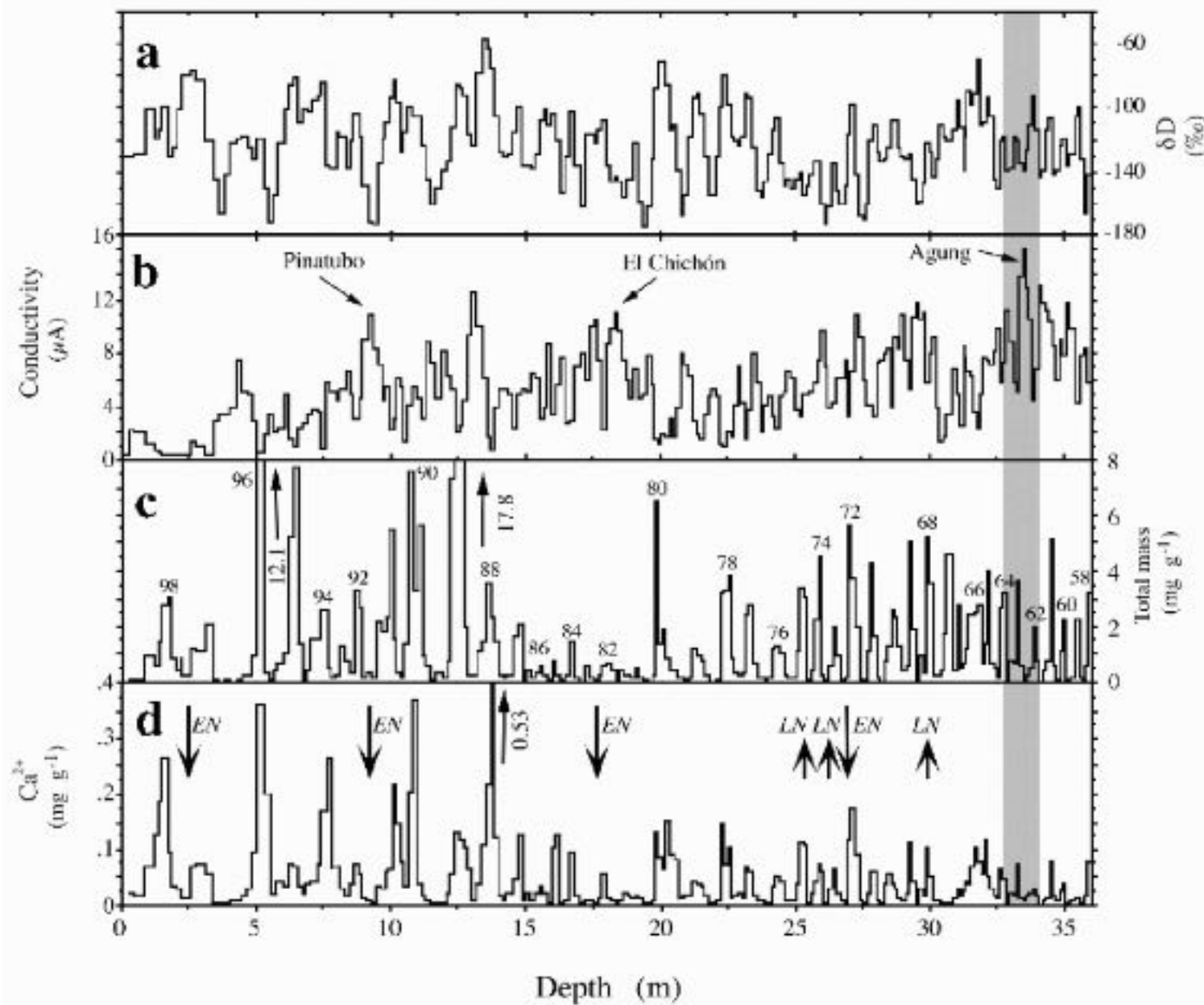
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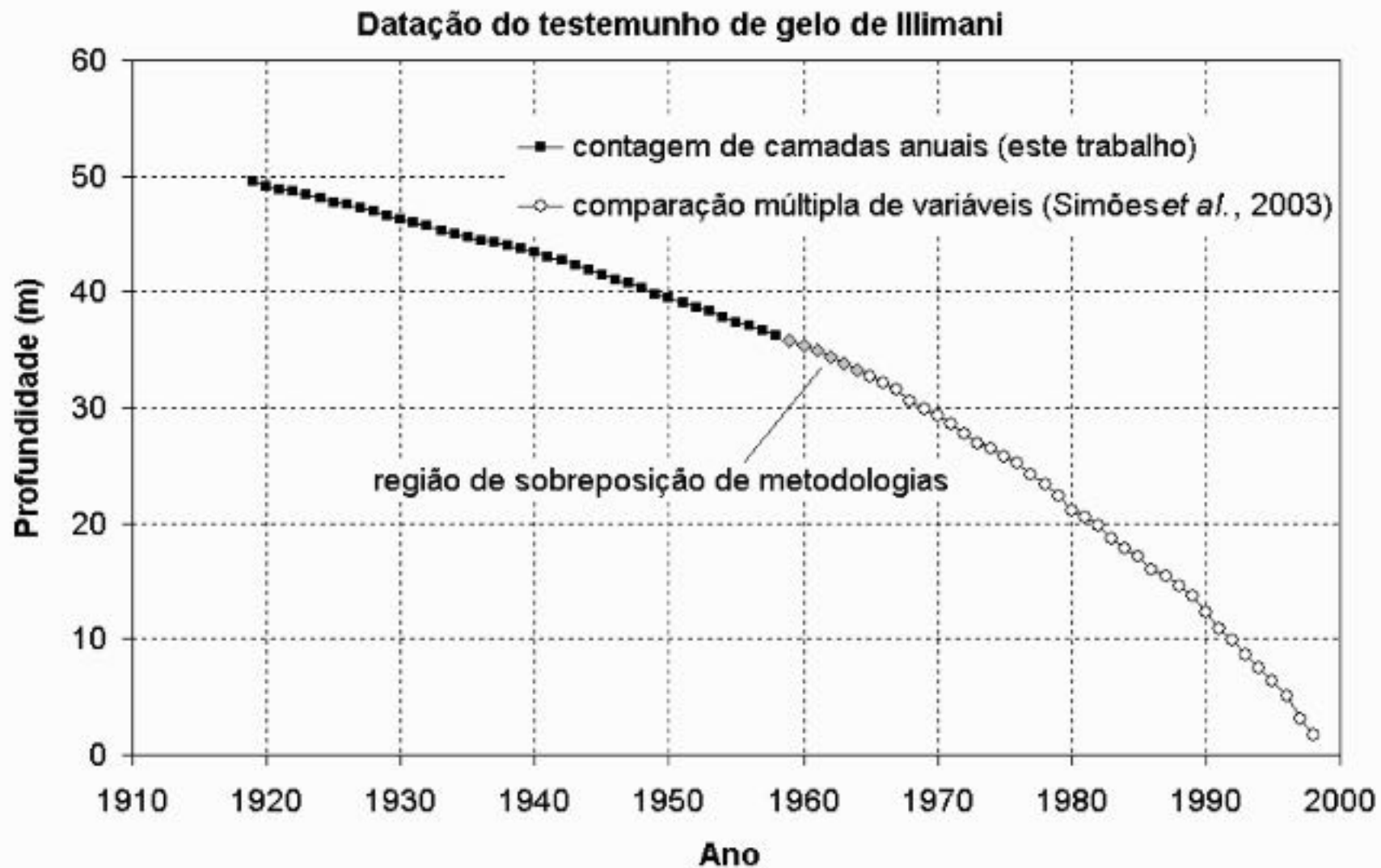


# O testemunho de gelo de Illimani, Bolívia





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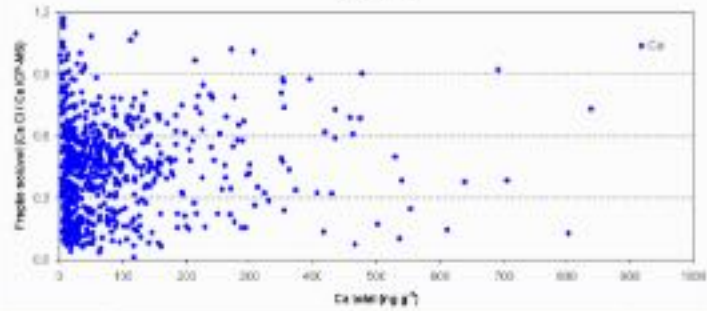
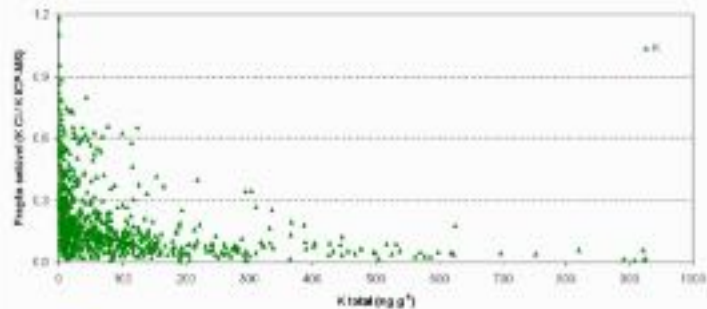
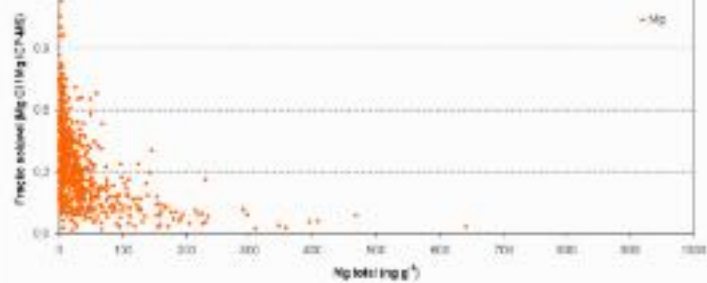
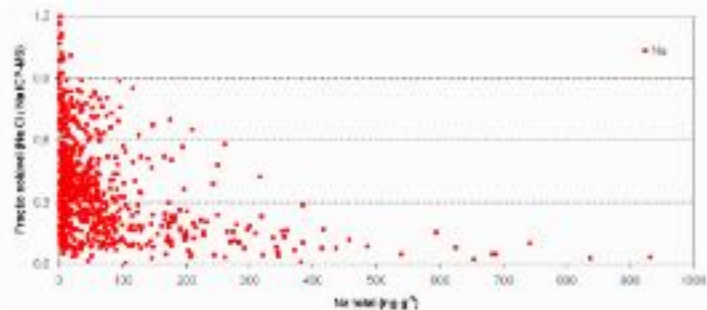
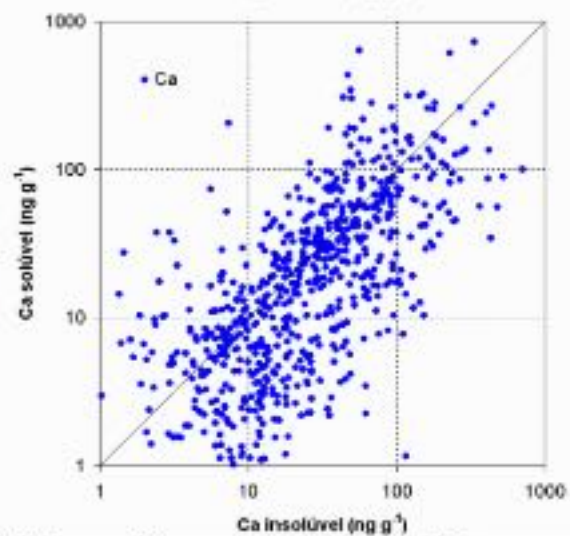
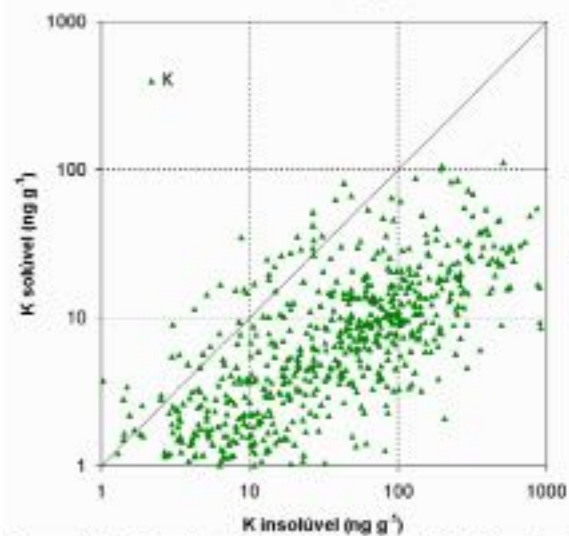
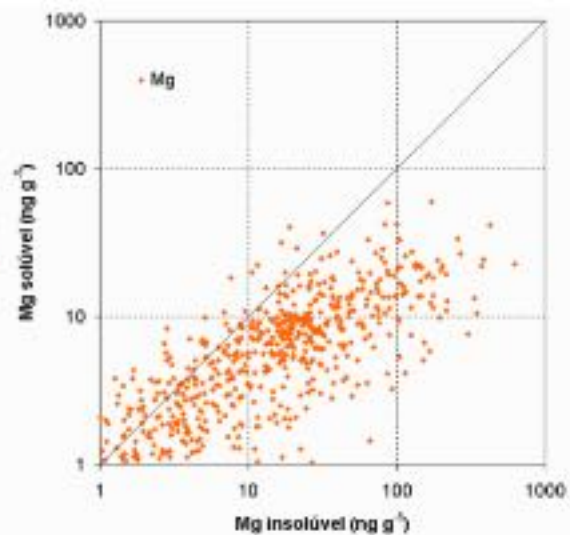
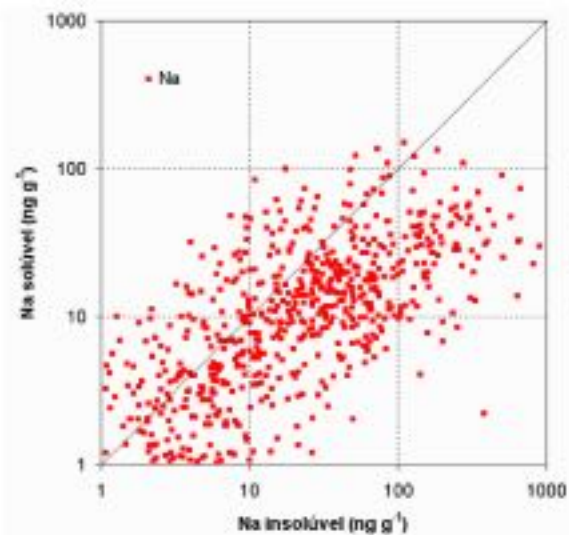
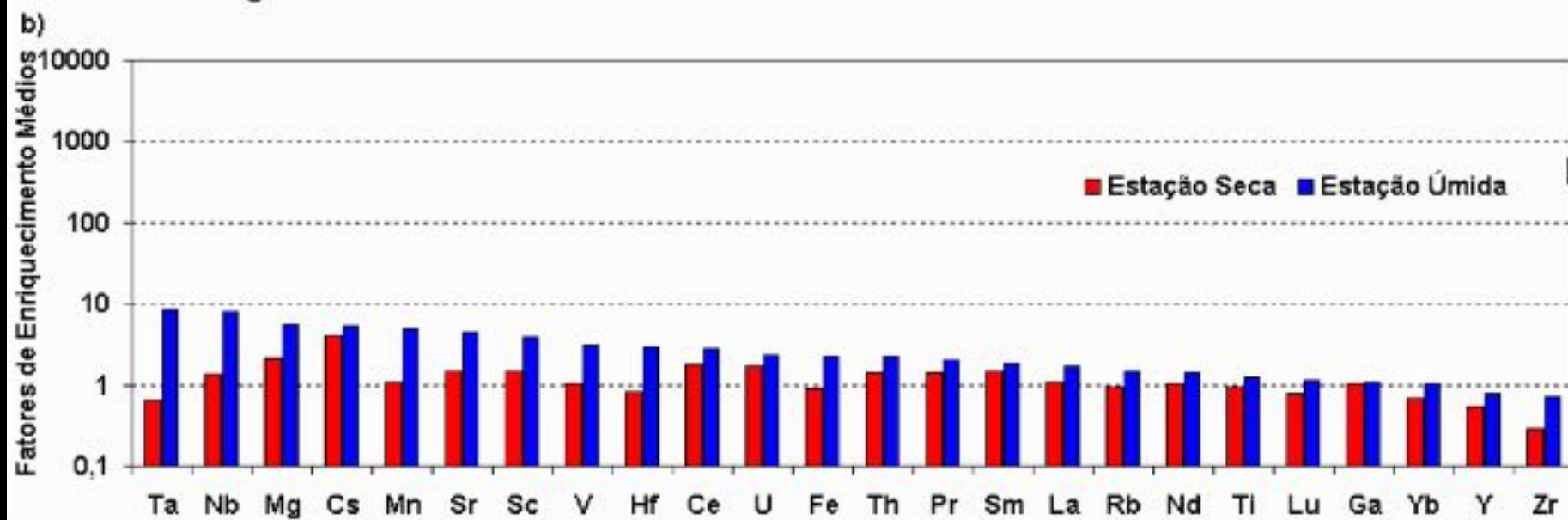
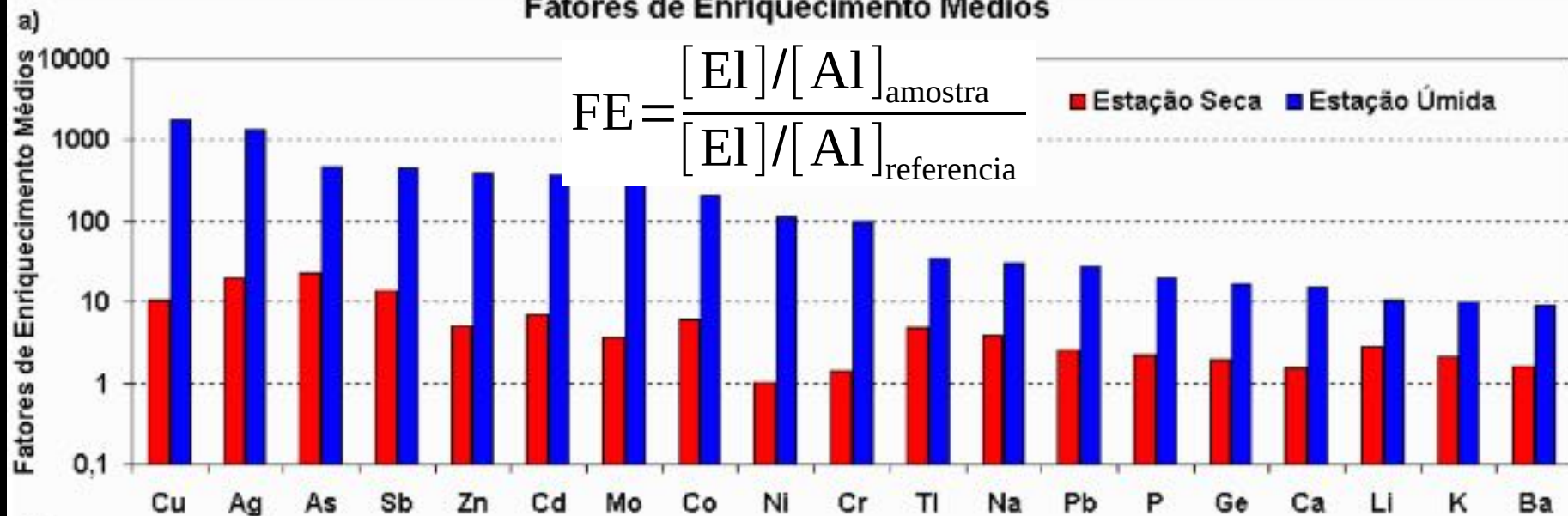
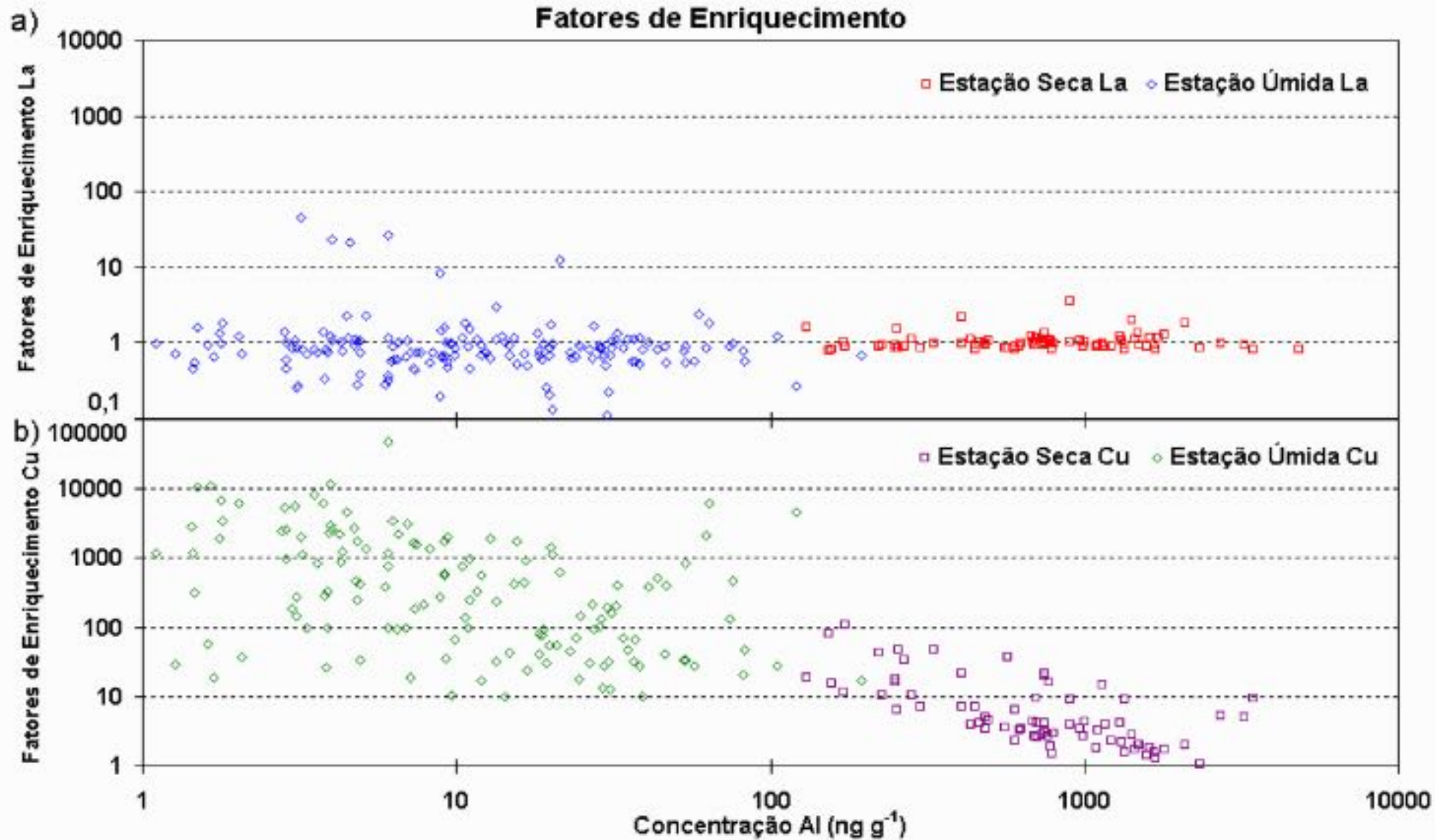


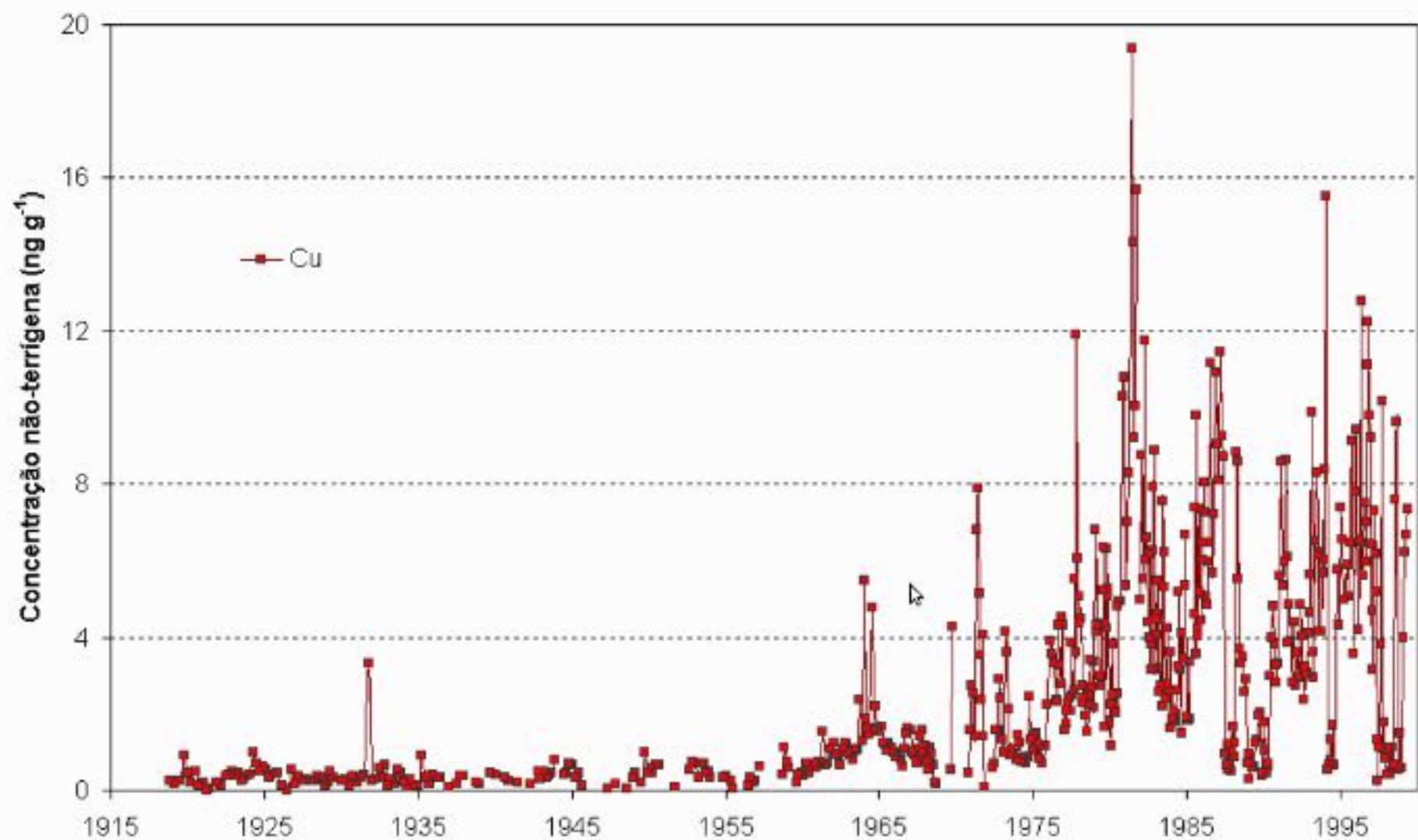
Figure 4.0. Comparison of the fraction of total Na, Mg, K, and Ca that is soluble (divided by total concentration).

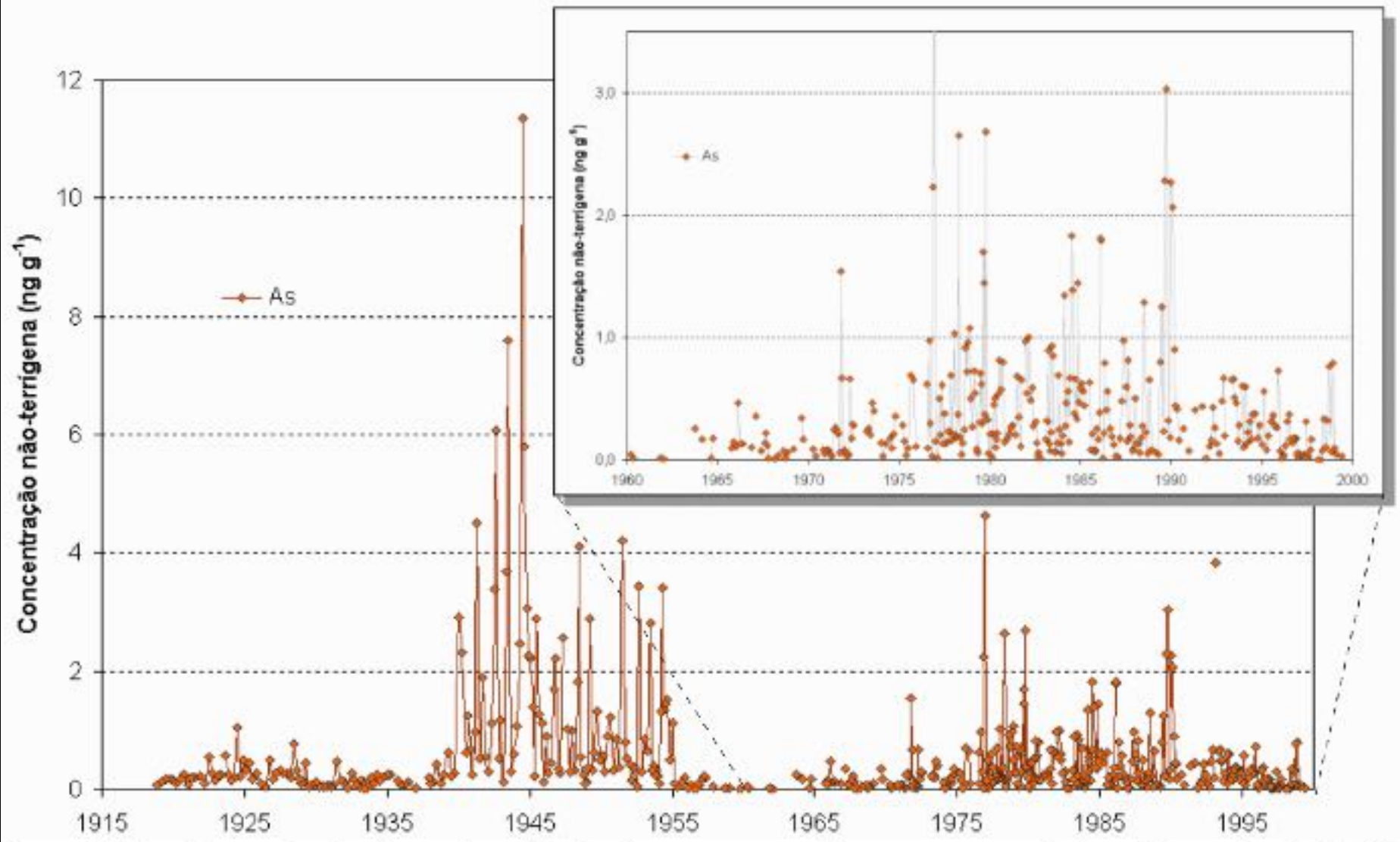
### Fatores de Enriquecimento Médios



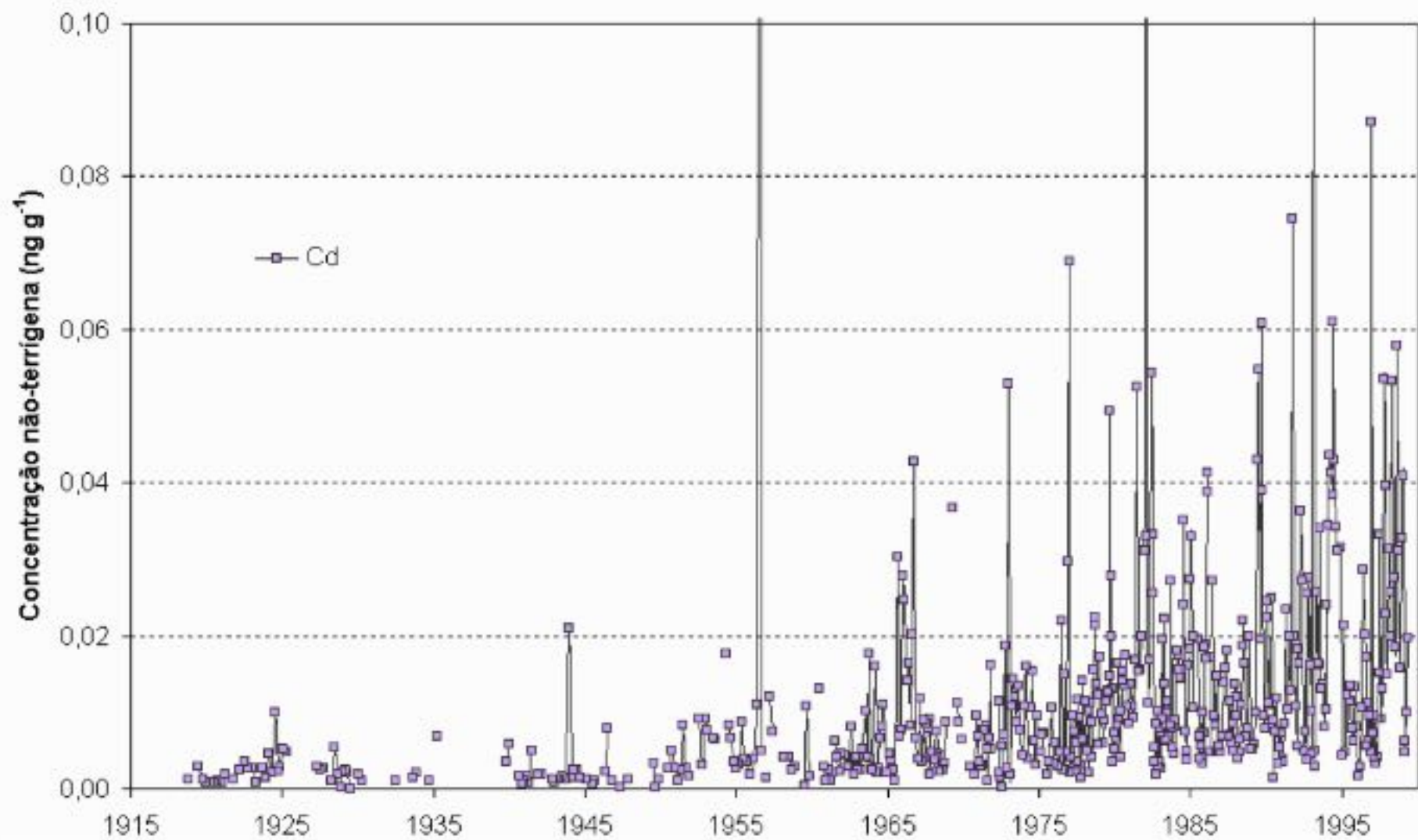
### Fatores de Enriquecimento

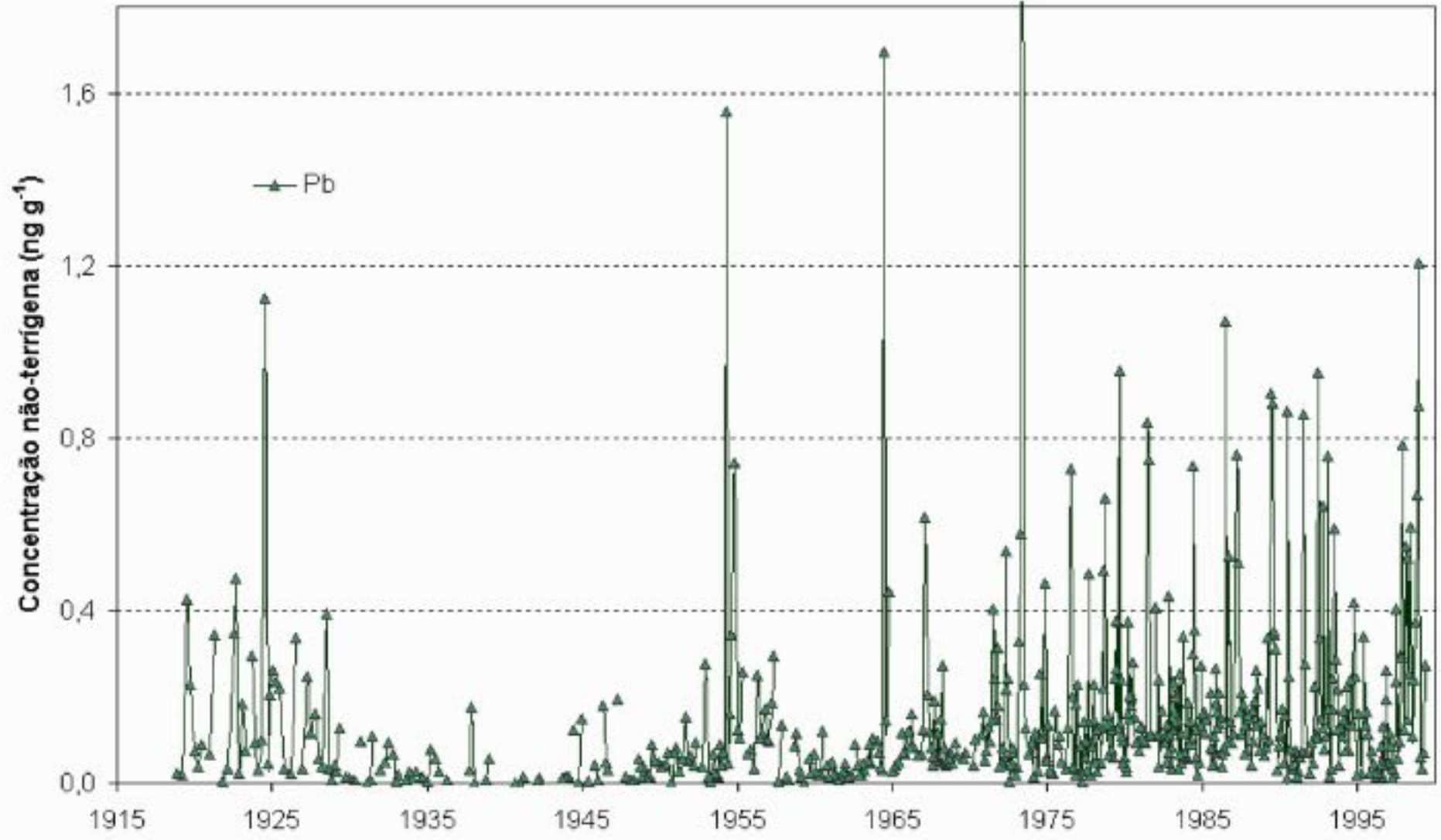


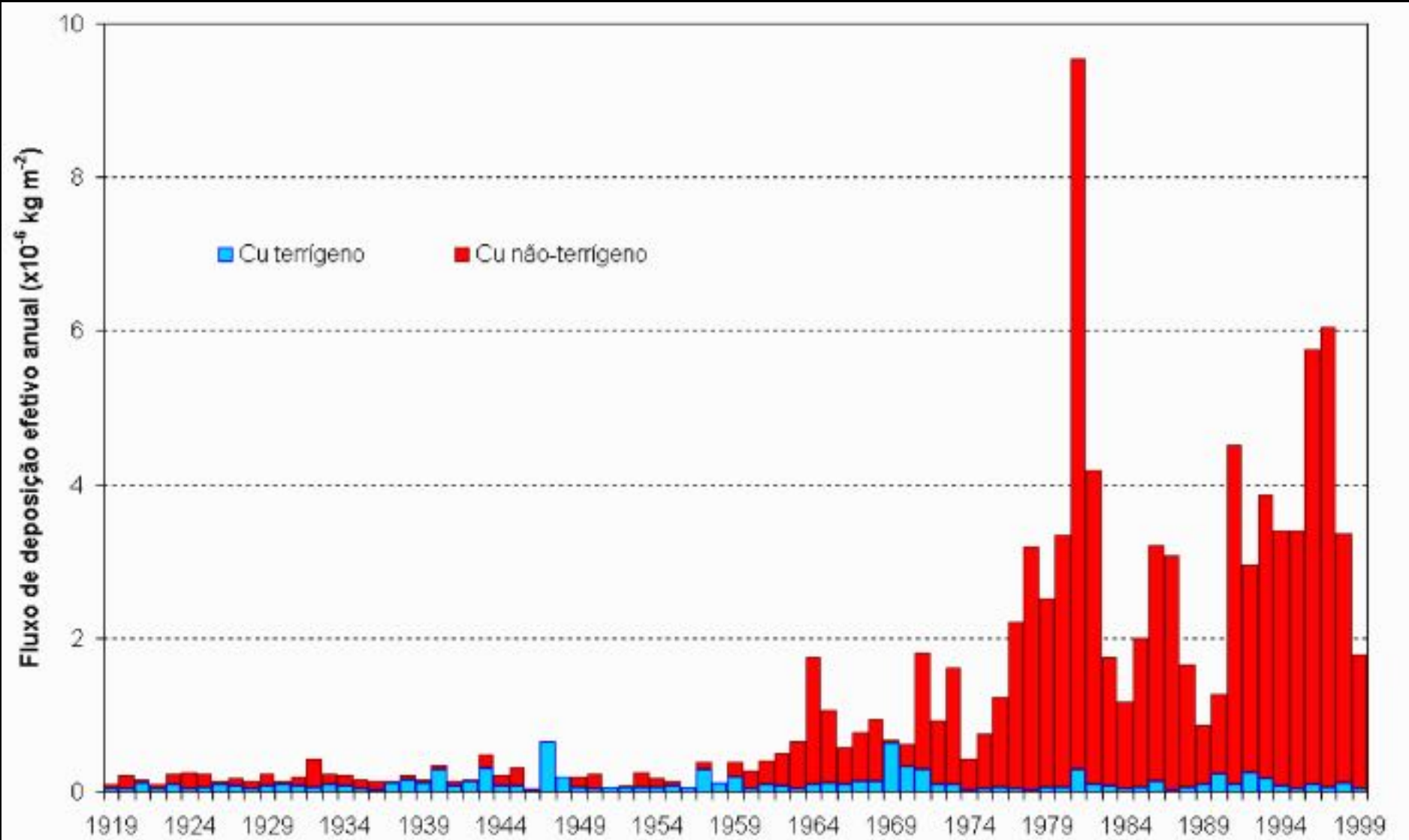


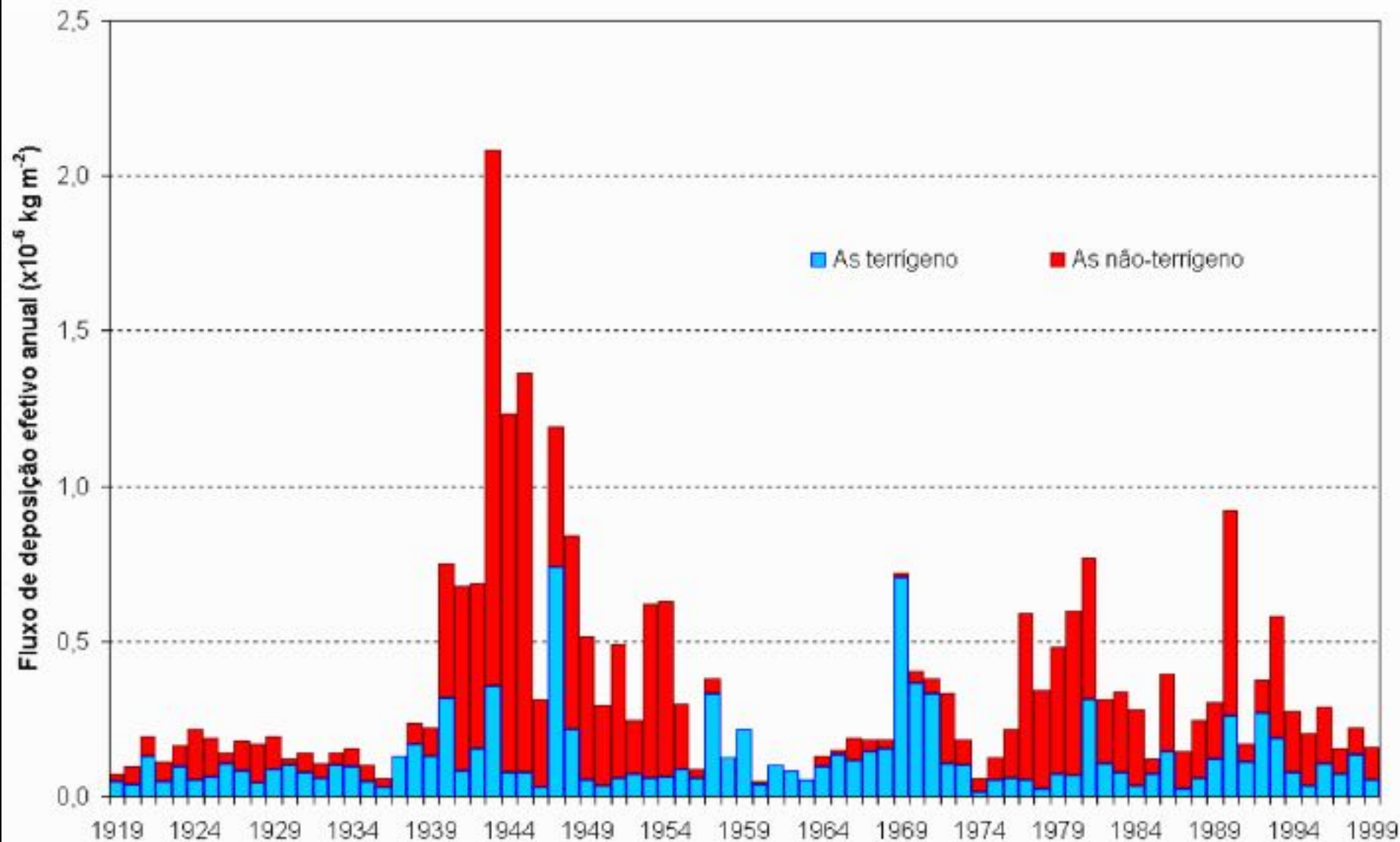


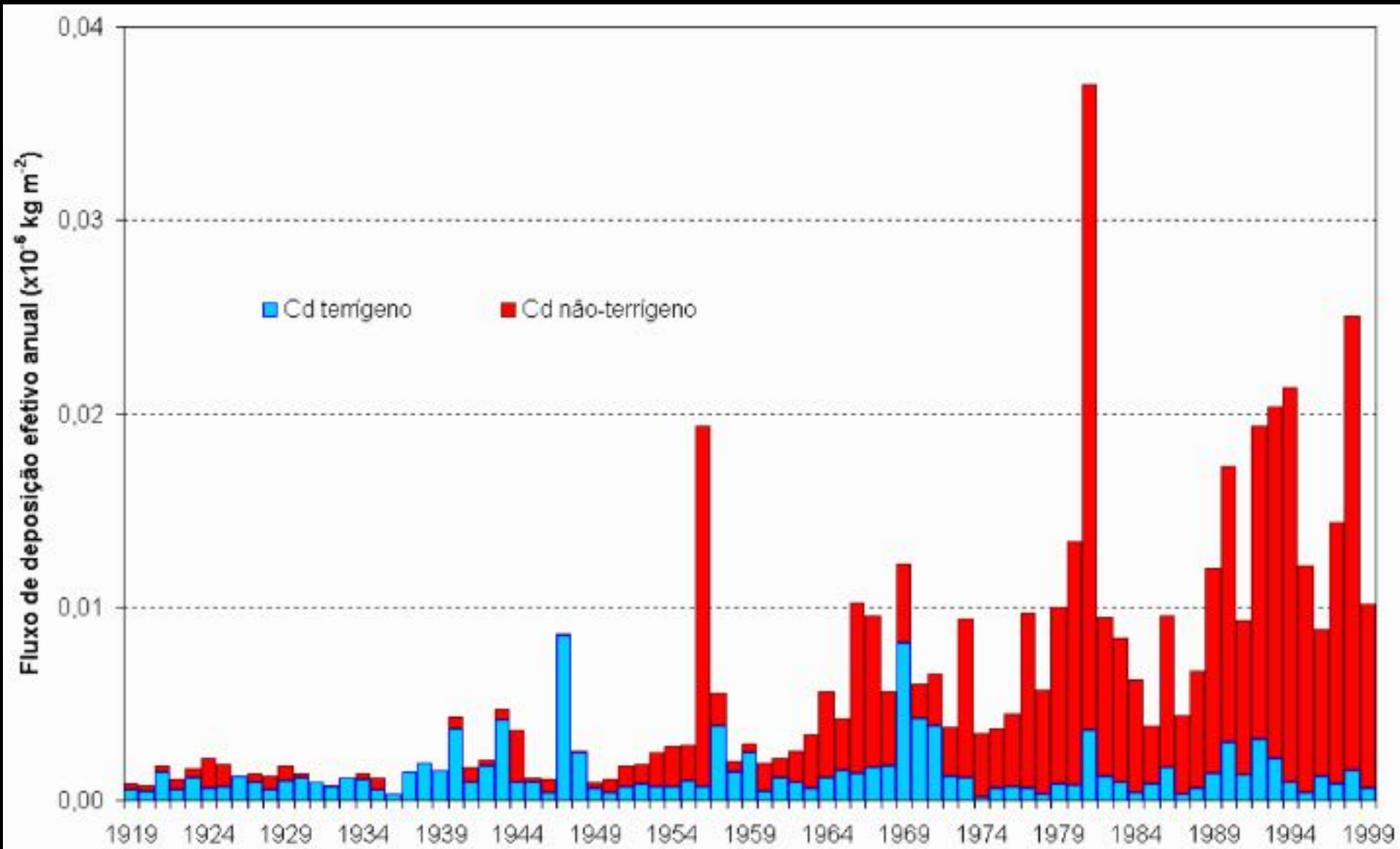


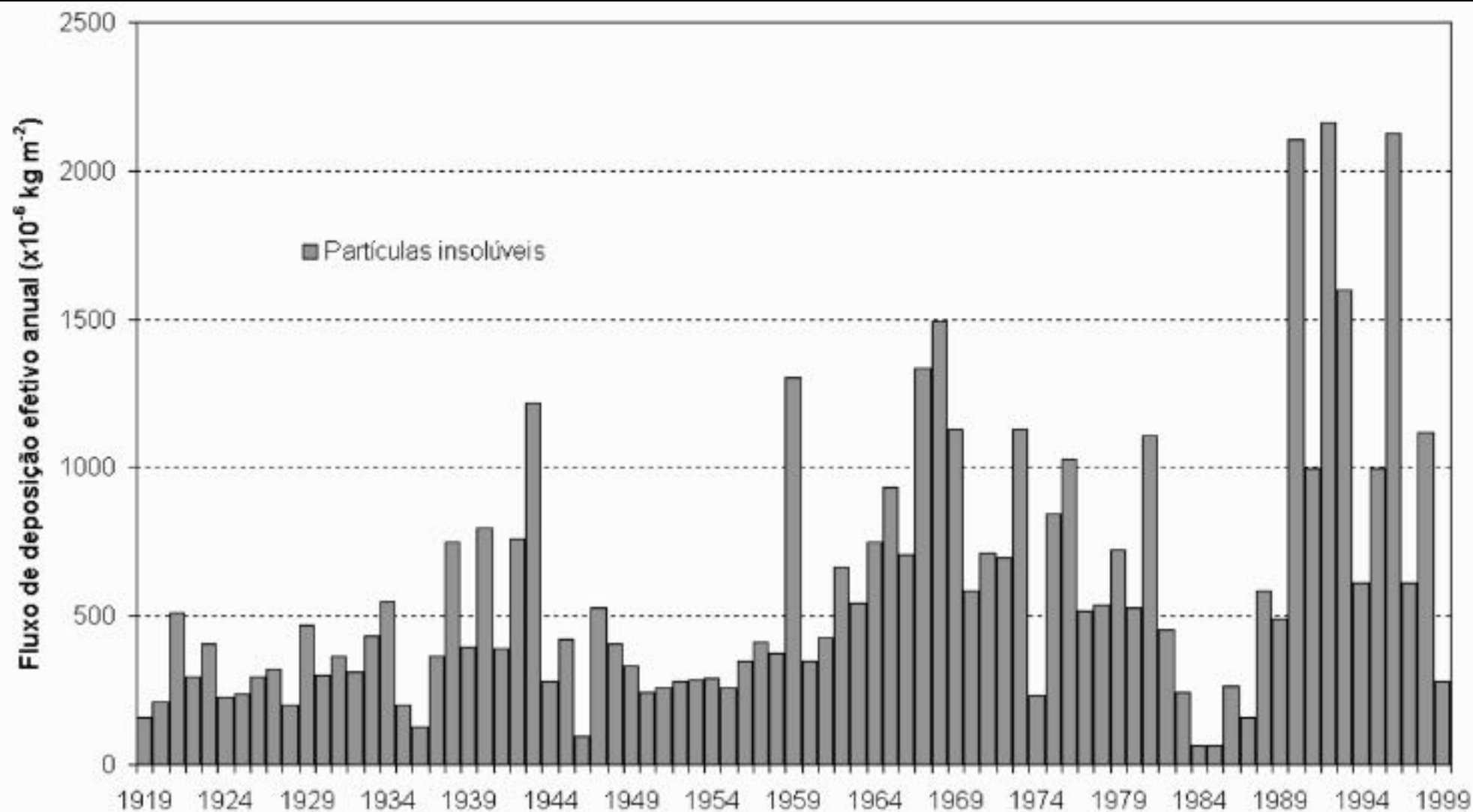


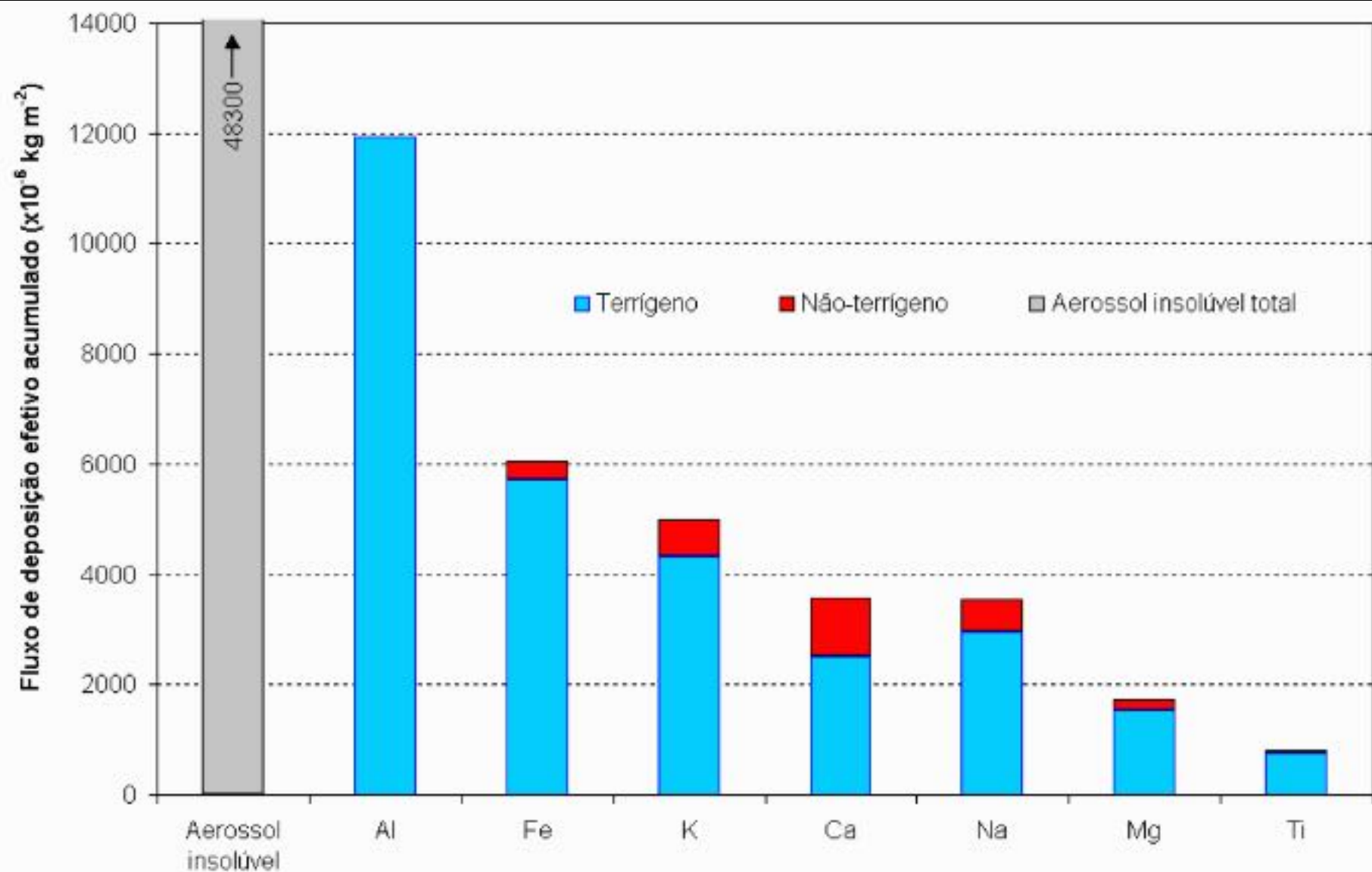


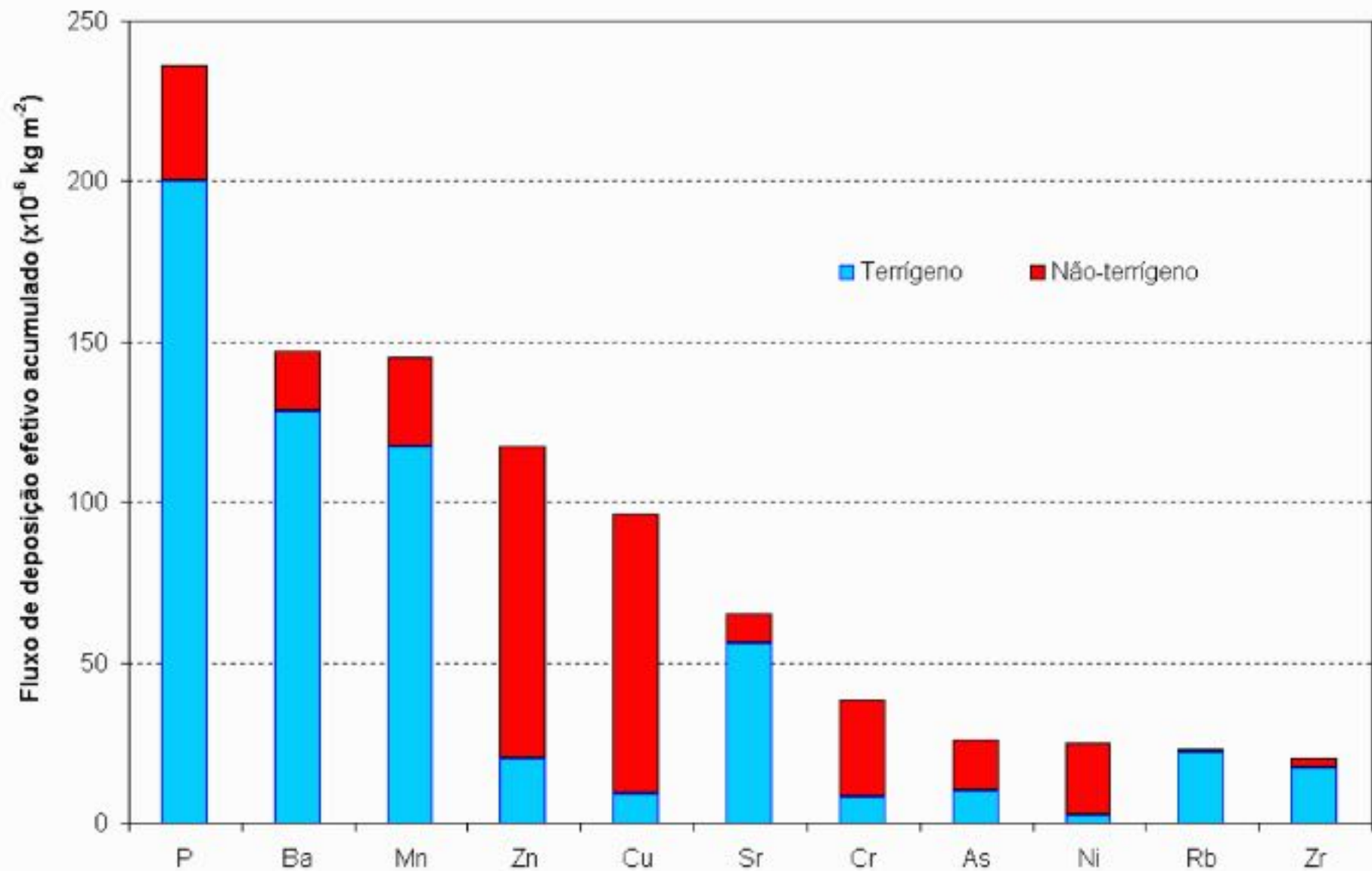




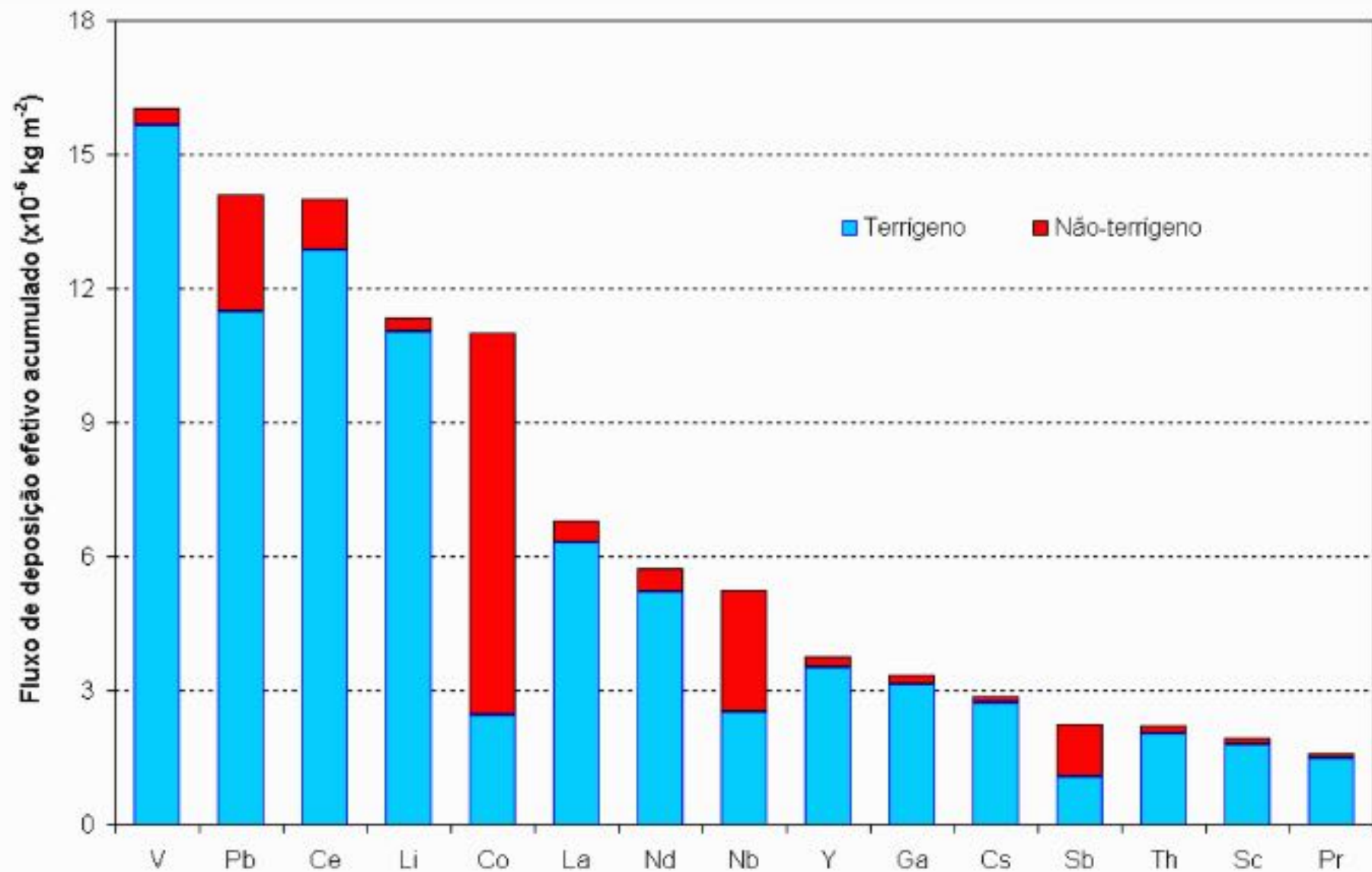












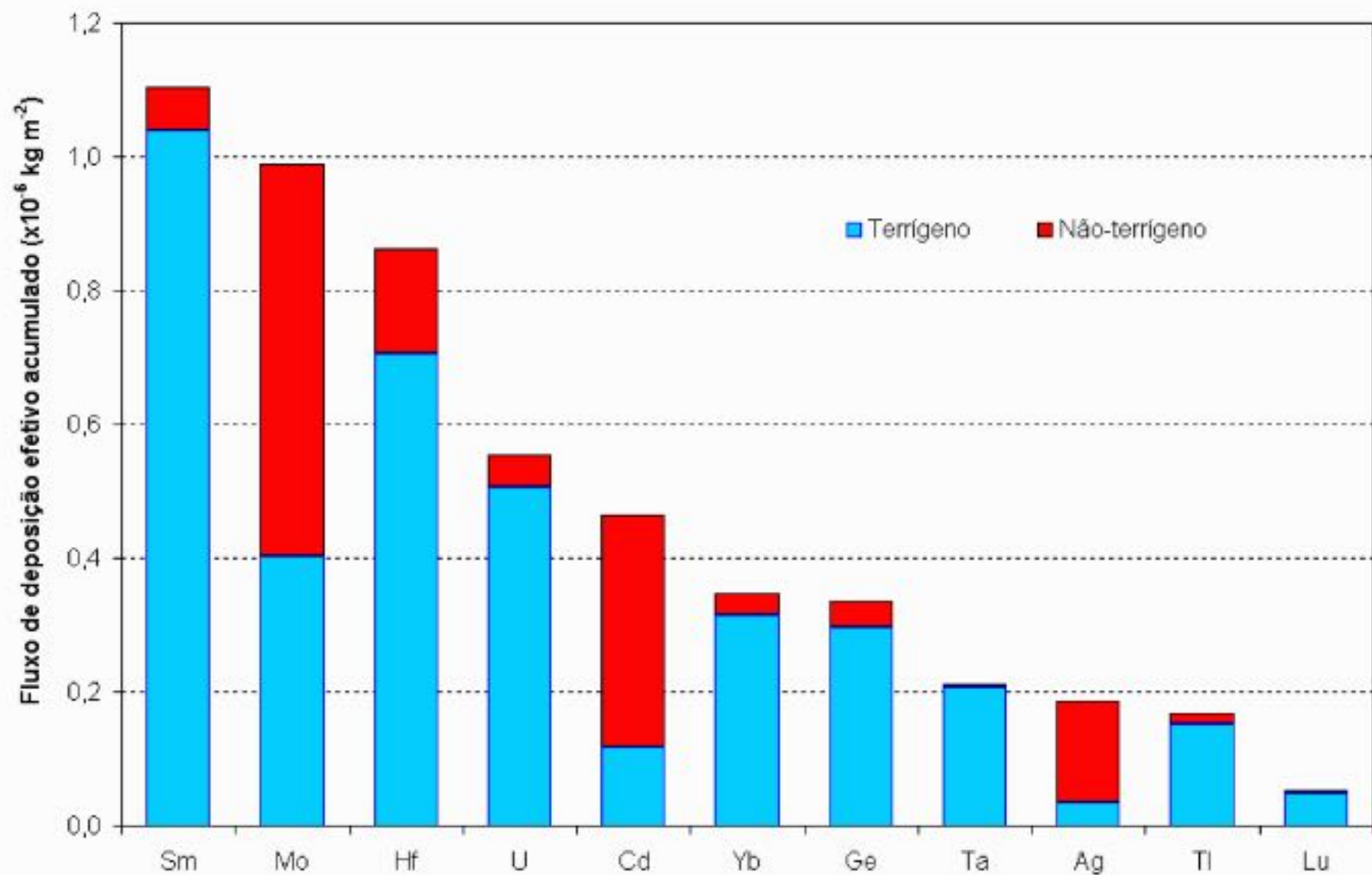
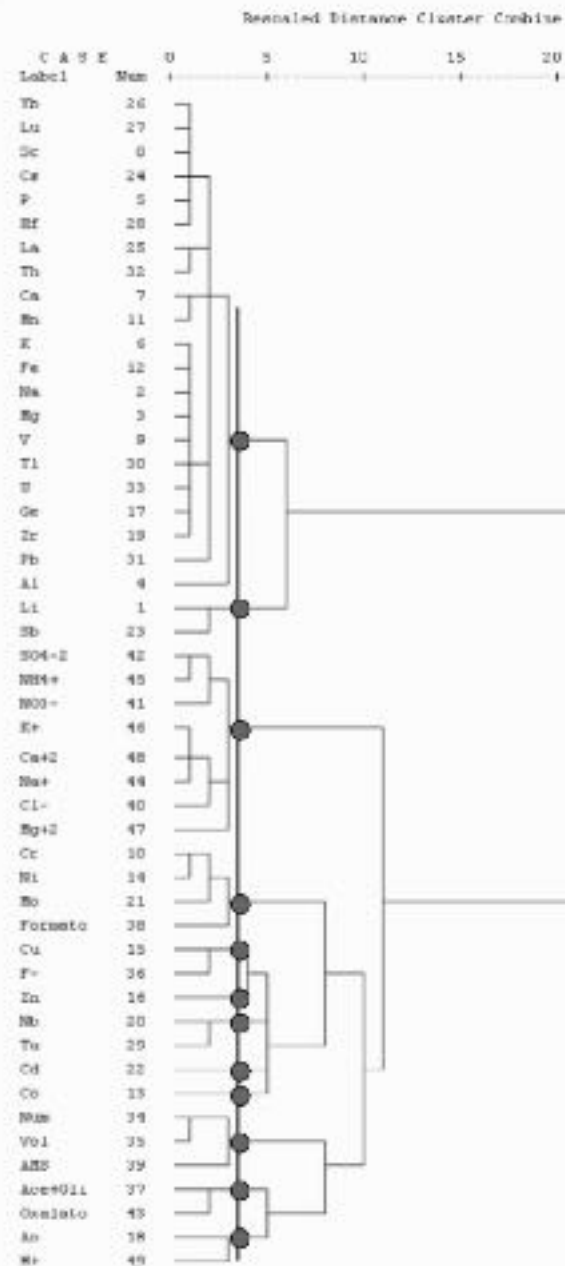
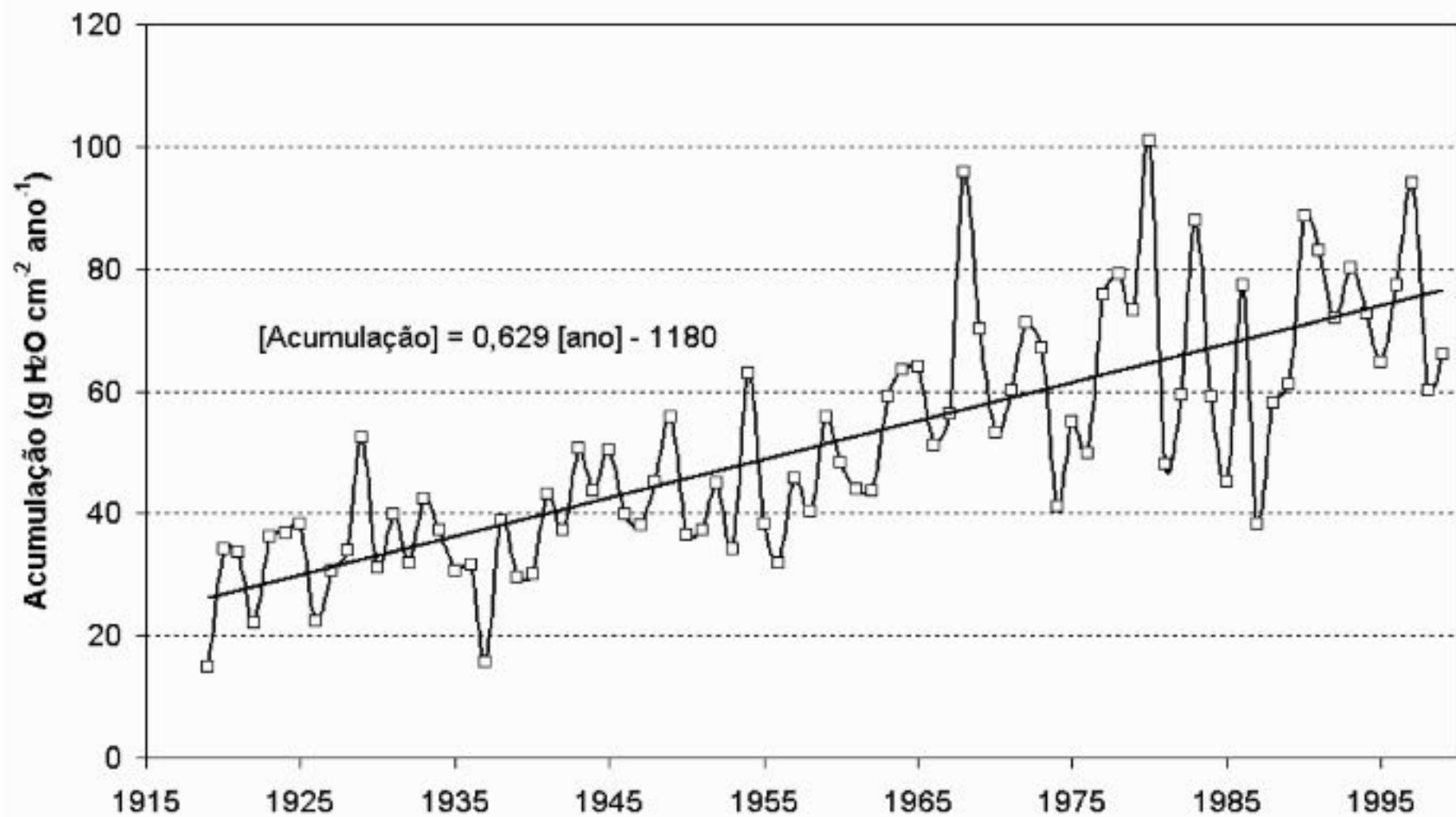


Tabela 4.11 - Assinatura elementar de fontes durante a estação seca (pg g<sup>-1</sup>).

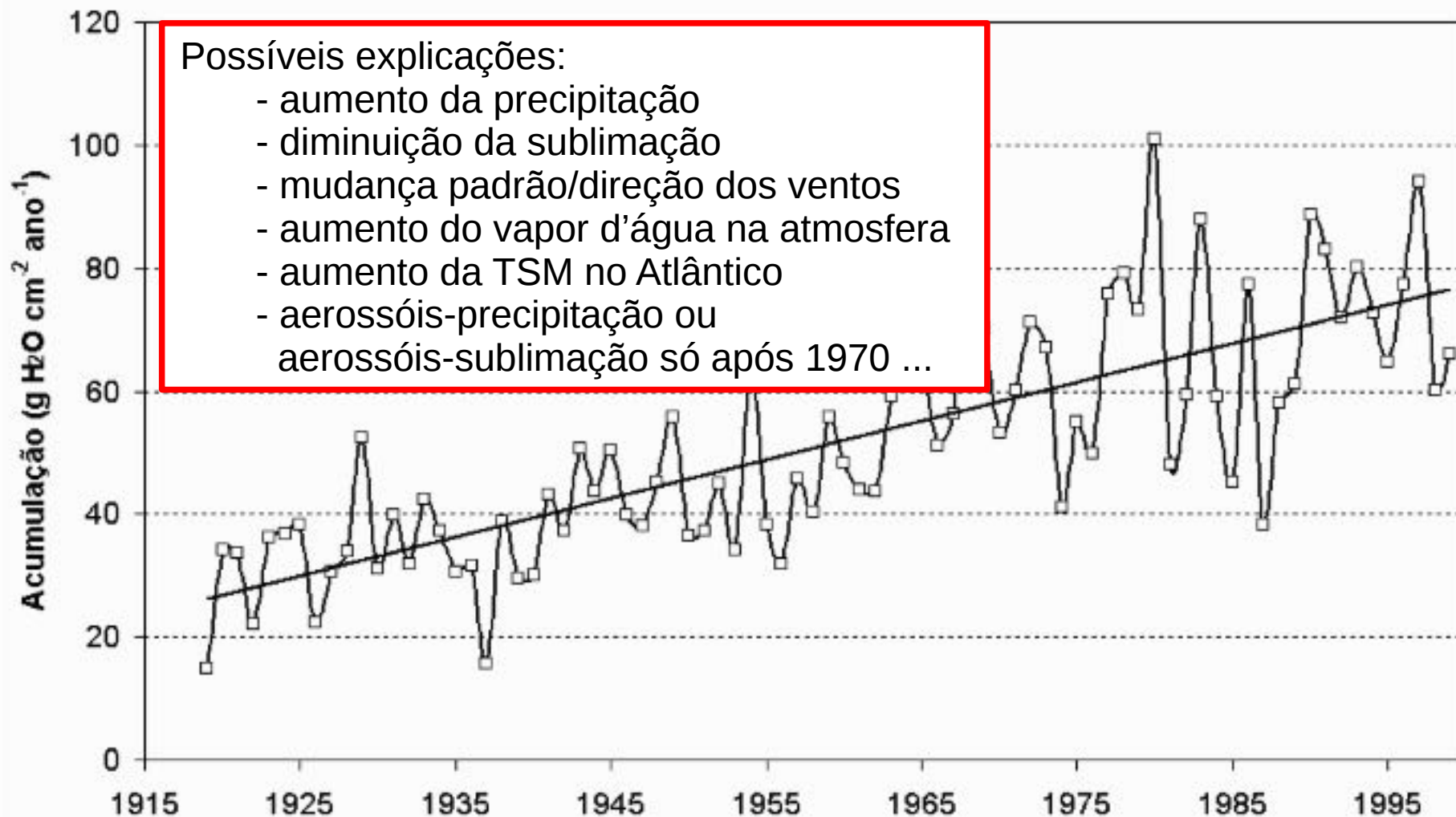
Espécie	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12
Li	439		14,3	13,1					952		14,0	21,5
Na	<b>157000</b>	44300	23600	1630	6750			10600	12000	344		1690
Mg	<b>81600</b>	23900	13100	808	5910			2420	5200	903		2460
Al	<b>889000</b>		310000	2500	132000	5840	57700	222000		85300	54700	
P	<b>10900</b>	5130	278	285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

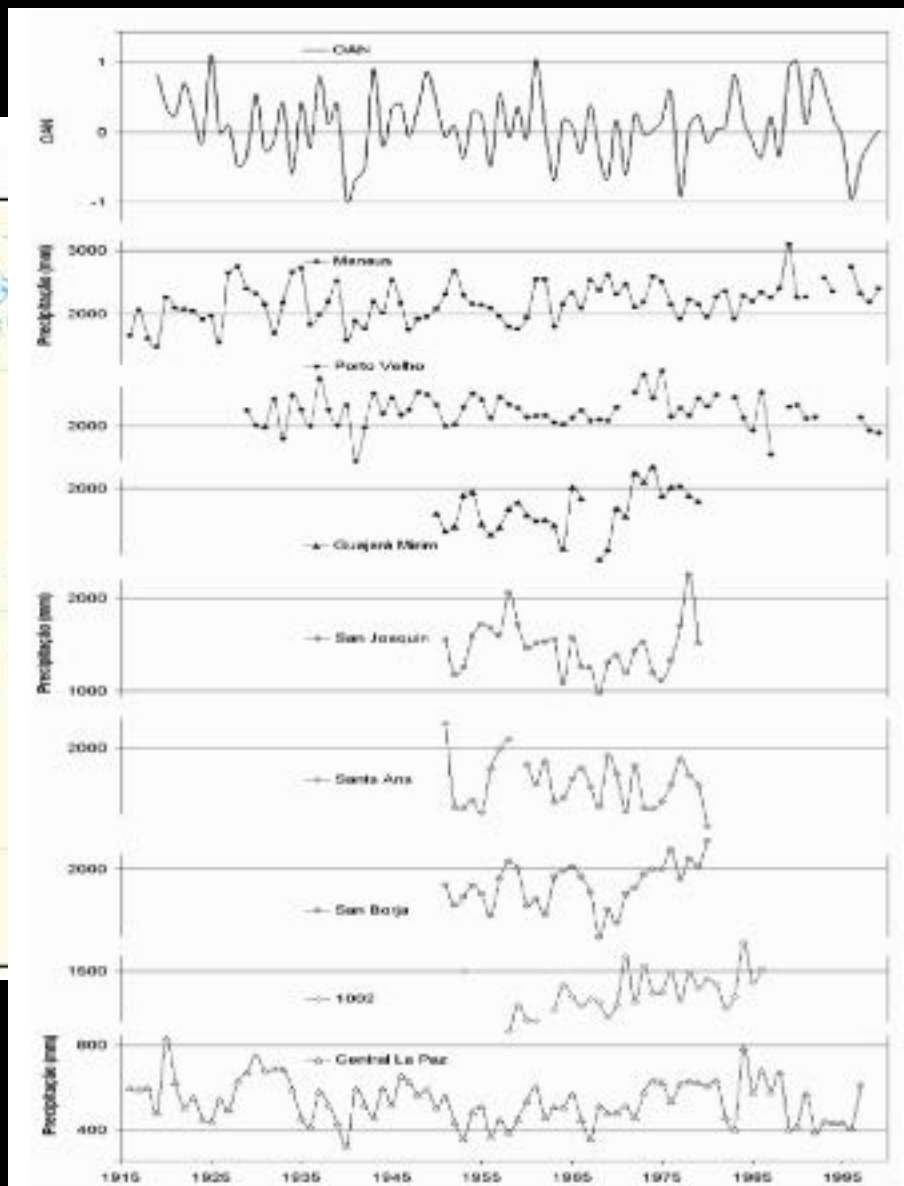


### Acumulação anual - Illimani



## Acumulação anual - Illimani





Cane et al. 1997:

Durante o século XX:

Atlântico Equatorial +0.3C

Atlântico Sul +1.0C



Mais umidade disponível

EOF TSM do Atlântico (Sutton et al. 2000)

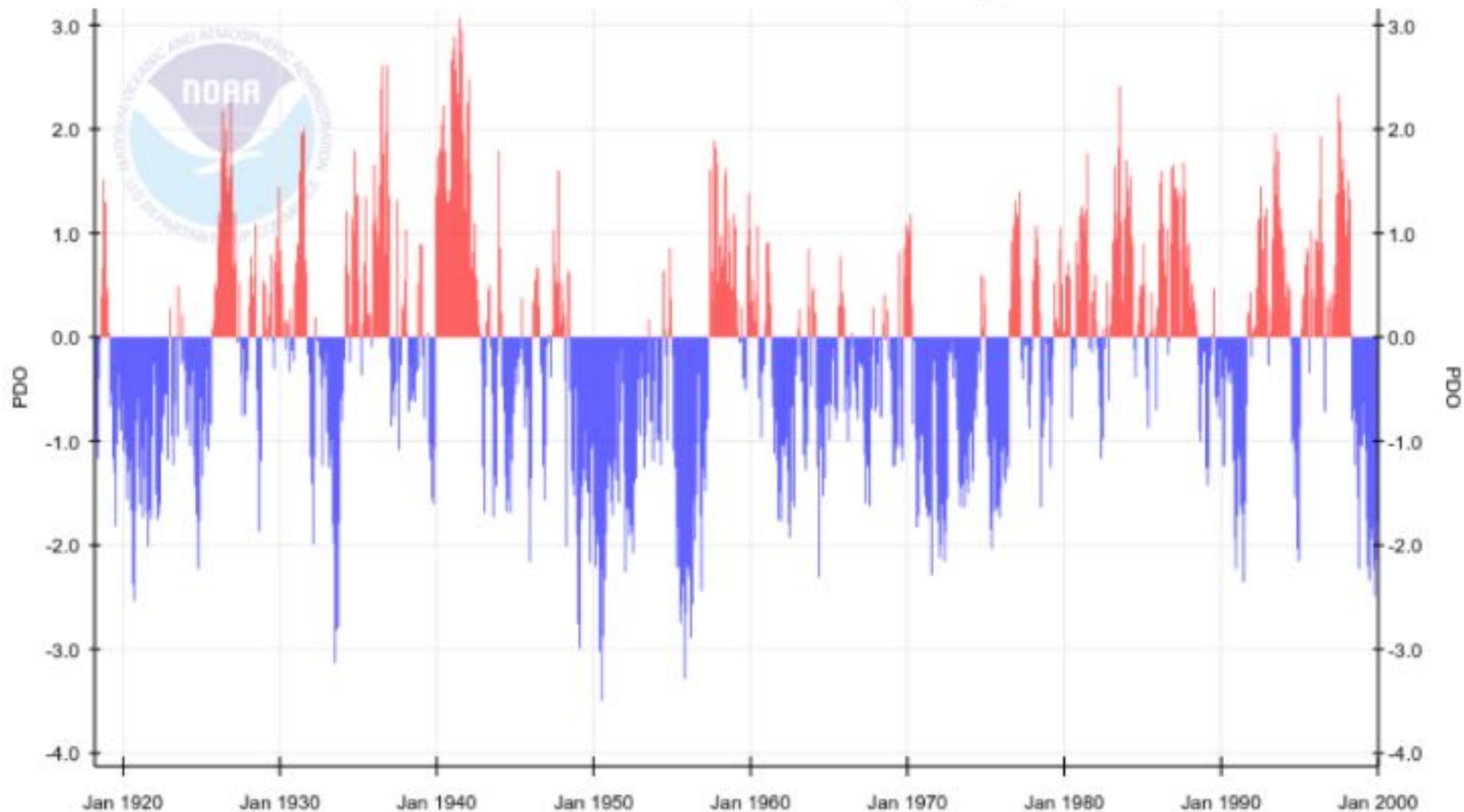
EOF TSM do Pacífico (Cardoso, 2001)



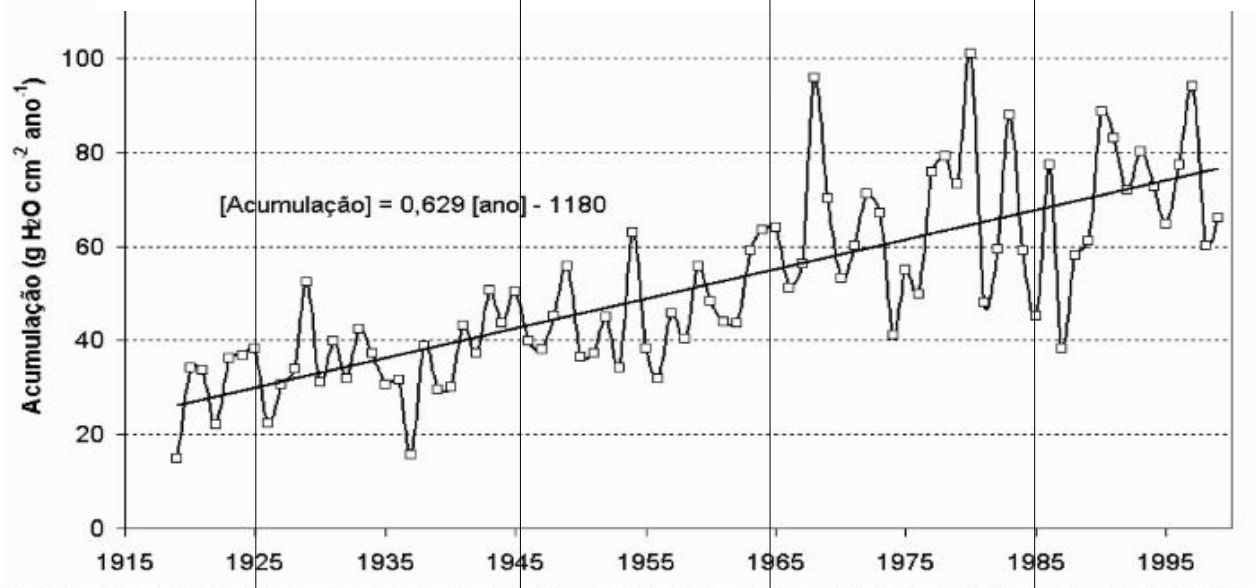
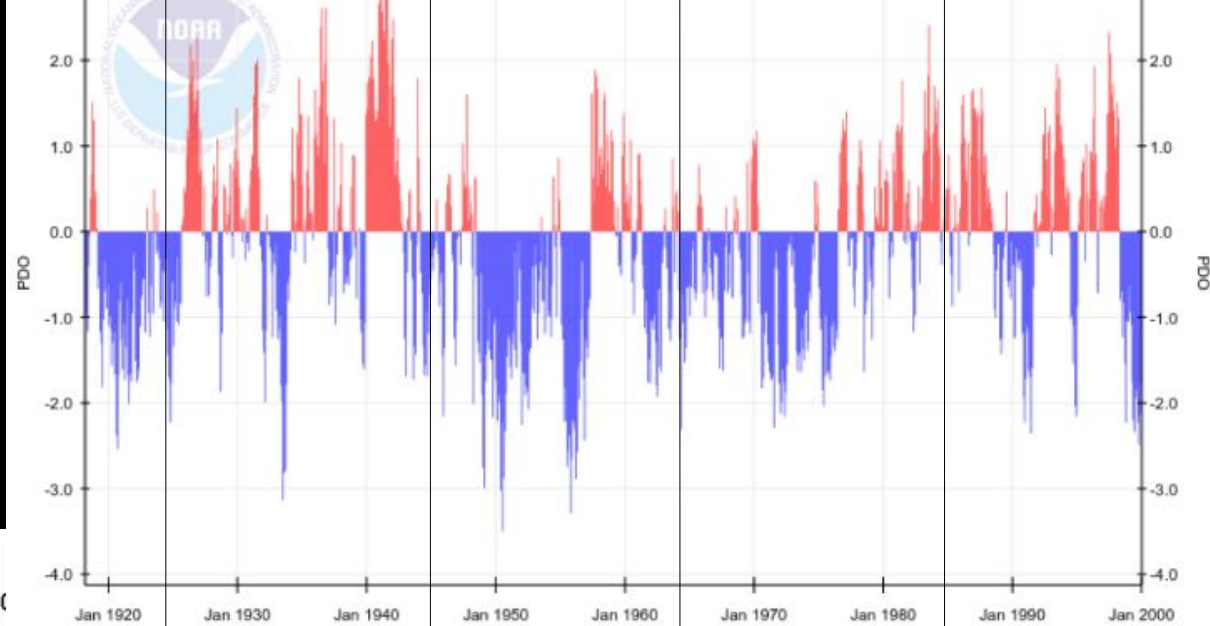
Tendências de longo prazo para alguns modos de oscilação

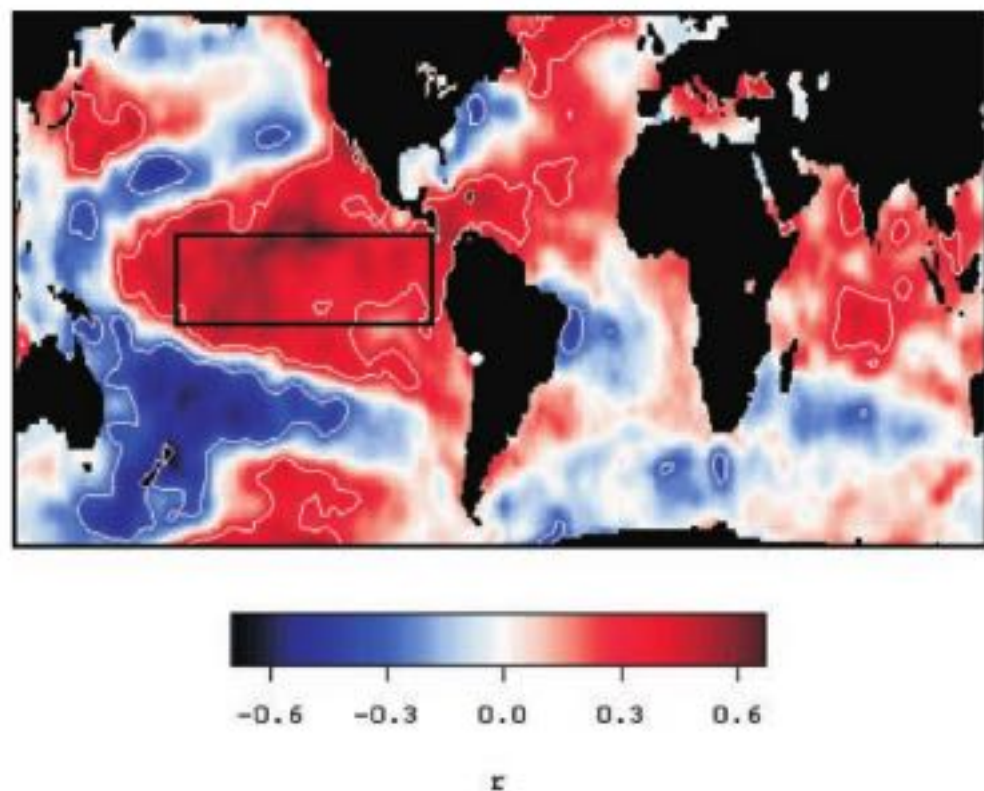
Oscilação Decadal do Pacífico ???

# Pacific Decadal Oscillation (PDO)

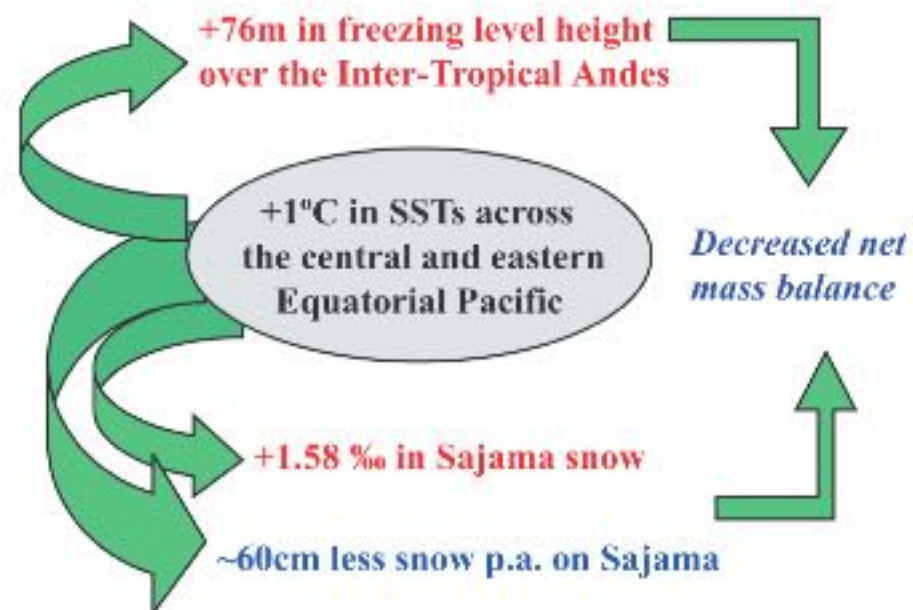






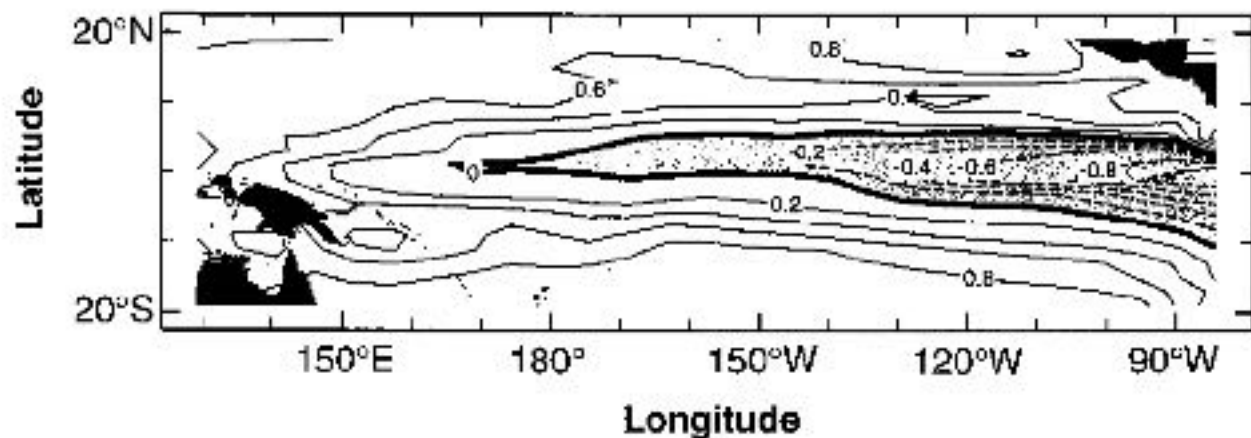


**Figure 1.** Correlation of global No<sub>x</sub>-February SSTs with net accumulation-weighted  $\delta^{18}\text{O}$  at Sajama, Bolivia (white dot), 1961–1997. Regions delimited by white line are correlated at the 95% significance level. The area used in



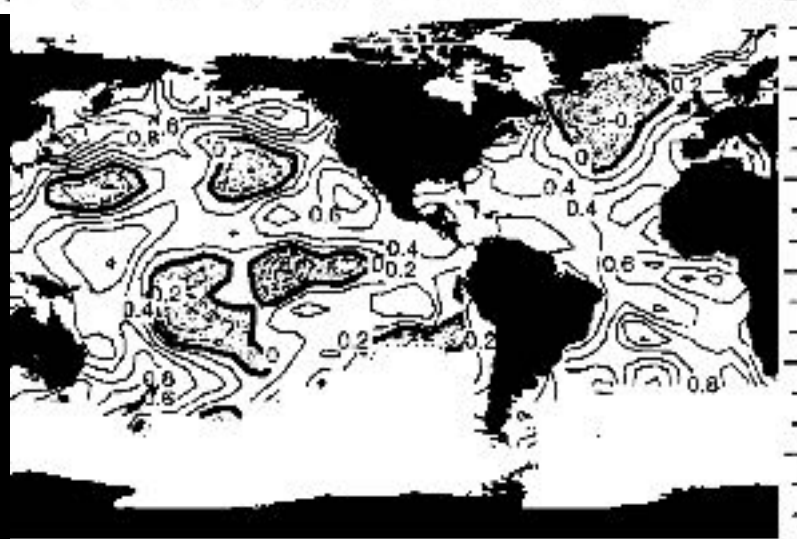
**Figure 4.** Schematic diagram summarizing links between central and eastern Equatorial Pacific SSTs, isotopic records at Sajama, and mass balance changes.

**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)]



958

SCIENCE • VOL. 275 • 14 FEBRUARY 1997 • <http://www.sc>



150°E 180° 150°W 120°W 90°W 60°W 30°W 0°

30°E 60°E 90°E 120°E 150°E 180° 150°W 120°W 90°W 60°W 30°W