Sediment Dating

Past Environmental Change ECGS-068

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Kruunuvuorenlampi:
2000 years?
800 years?
200 years?

Law of Superposition

- **Newer material stacks atop older material** (if undisturbed)

Nicolaus Steno (1677)

younger

older

Djúpivogur, Iceland


Karwendel, Austria

Geochronological Methods

Absolute

Geochemical

- ^{210}Pb
- ^{137}Cs, ^{241}Am
- ^{14}C
- Other radioactive isotopes

Physical

- Varves
- Luminescence
- Dendrochronology
- Corals
- Lichen in Rocks

Relative

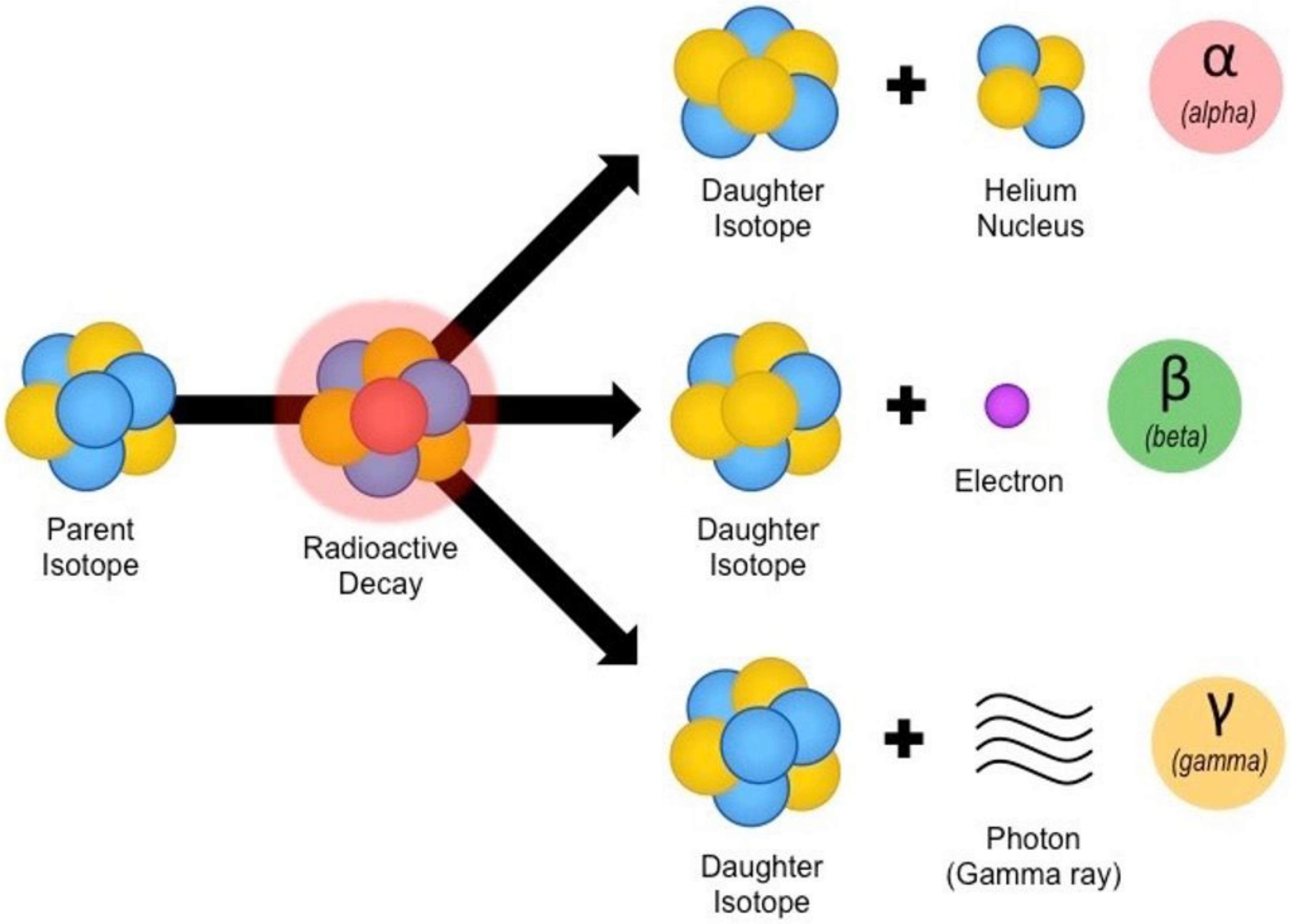
- Paleomagnetism
- Tephra
- Fossils
- $\delta^{18}O$
- SCPs

Lead (^{210}Pb)

Radioactive decay network

Radioactive Isotopes

- Isotopes are either **stable** or **radioactive**
- Unstable isotopes decay, forming new elements, until they reach stability
- **Radioactivity is a random process**, what we calculate is the probability that a nuclide will decay in a given time

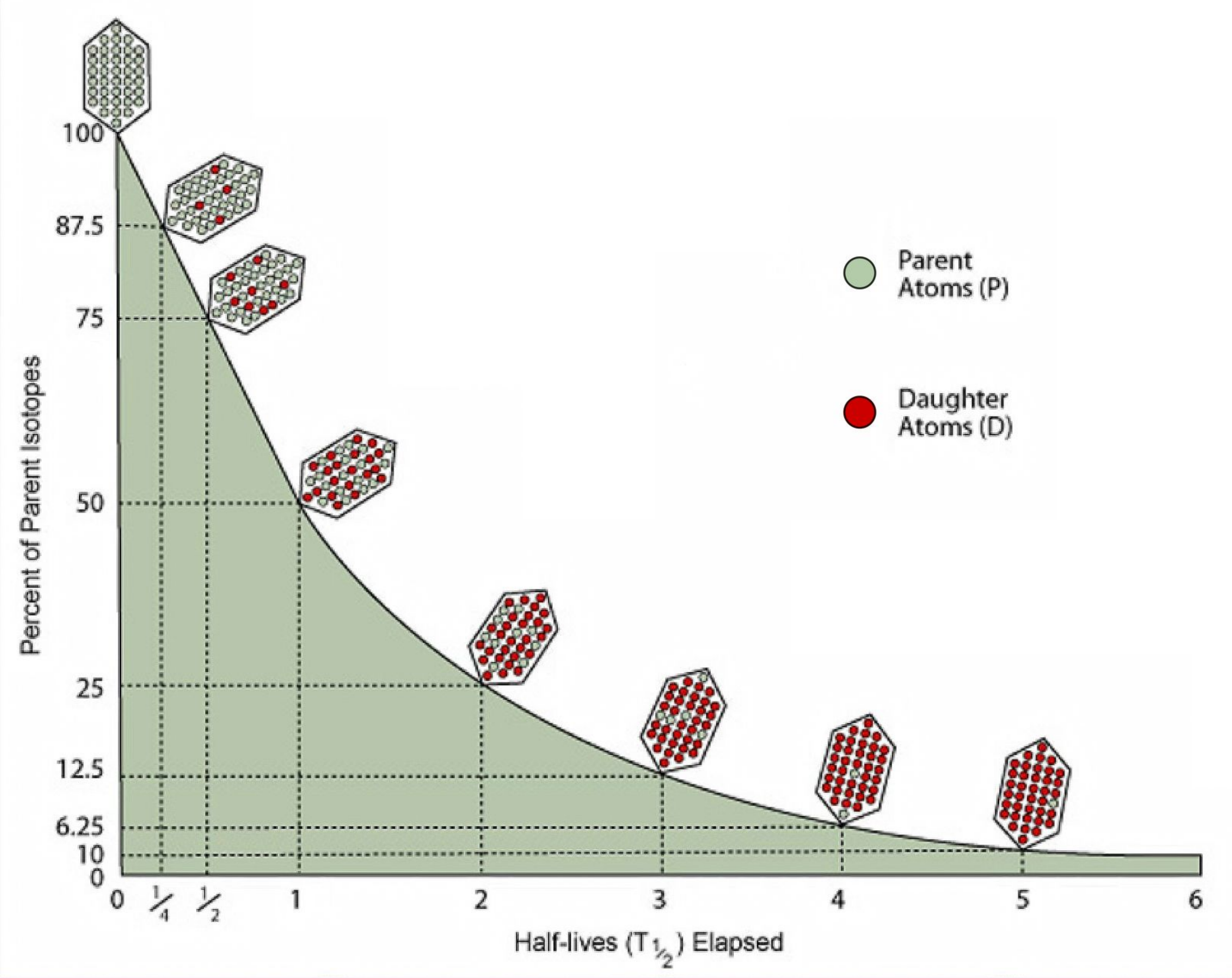


Radioactive Decay

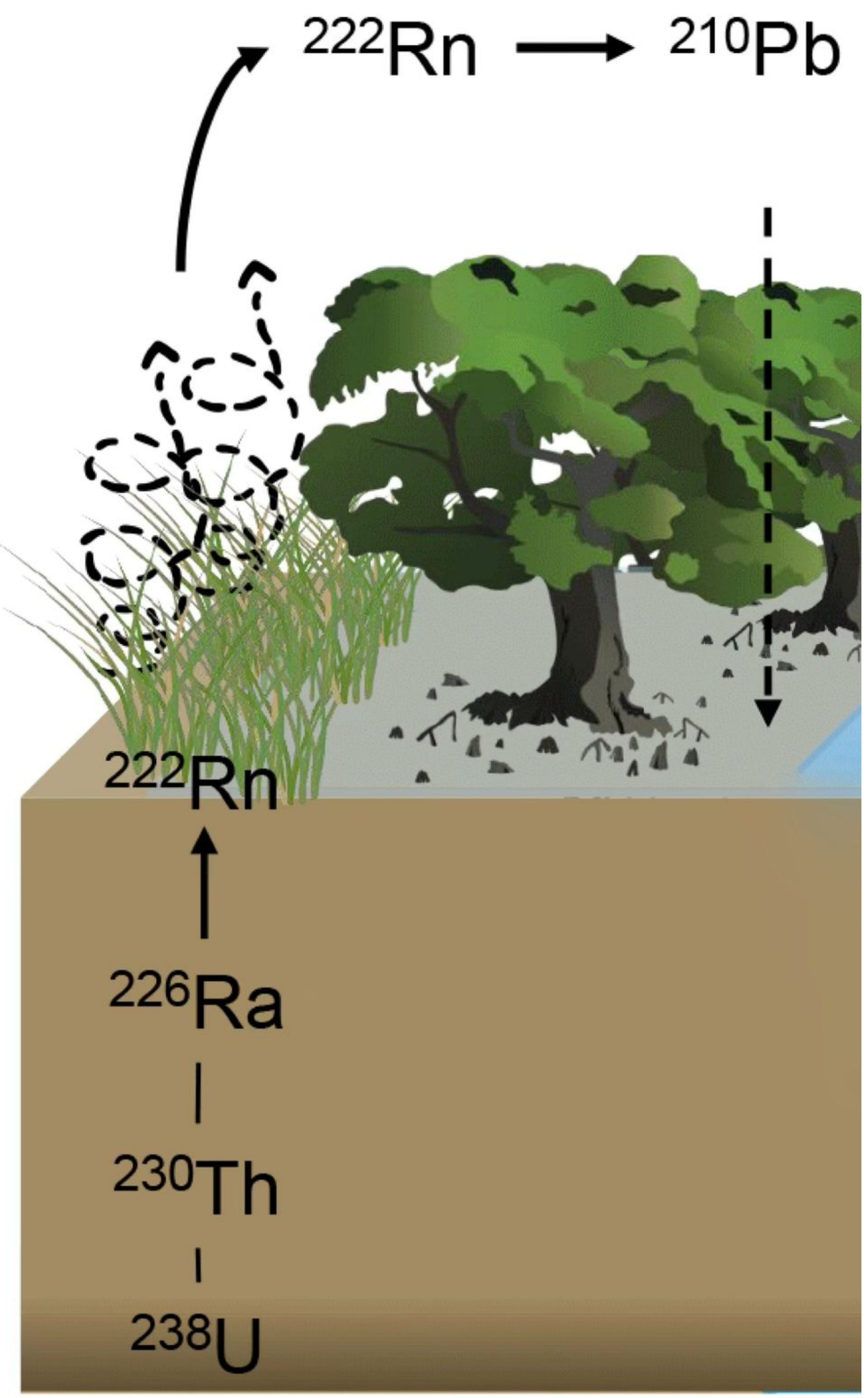
- The **half-life** determines the **speed of** radioactive **decay**

$$N = N_0 e^{-\lambda t}$$

$$t_{1/2} = \frac{ln2}{\lambda}$$



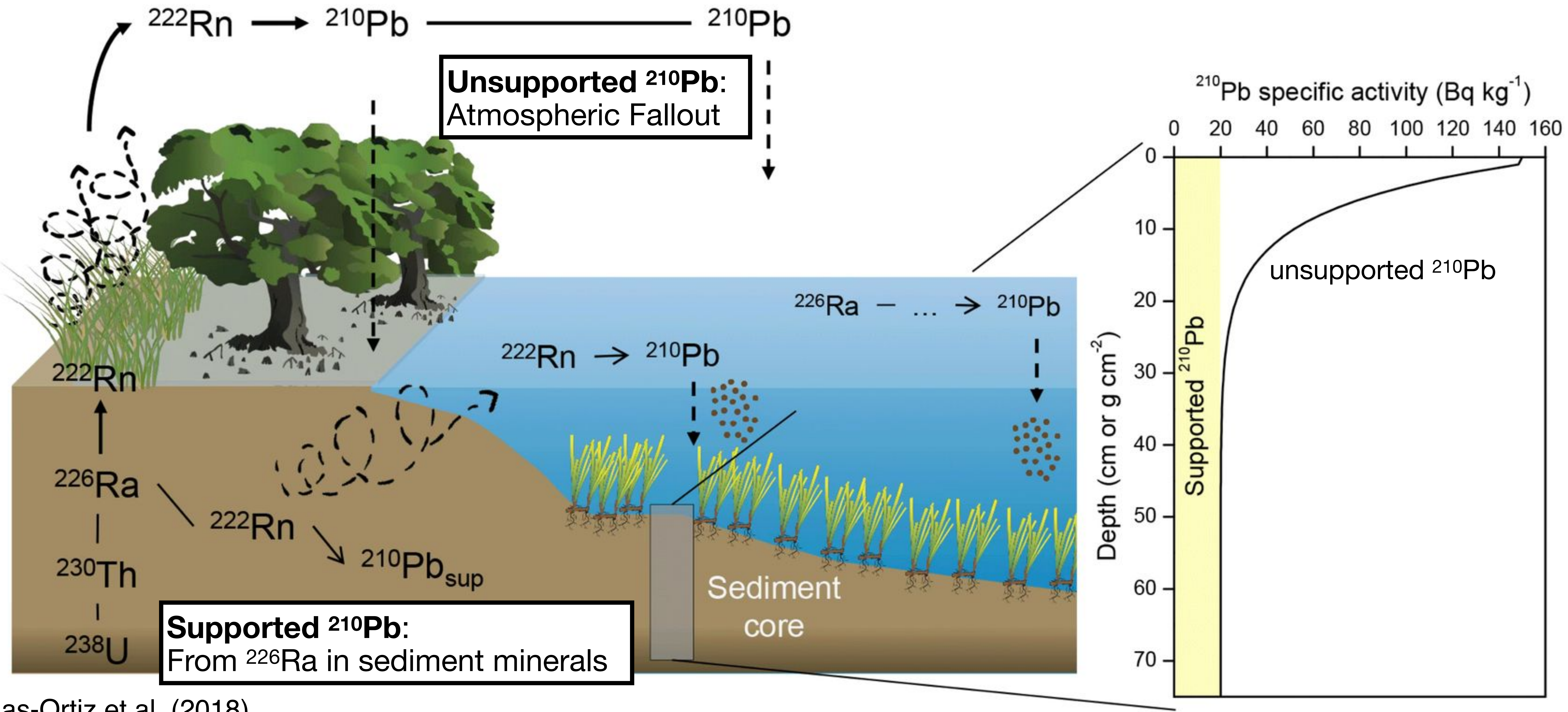
^{238}U Decay Series



Arias-Ortiz et al. (2018)

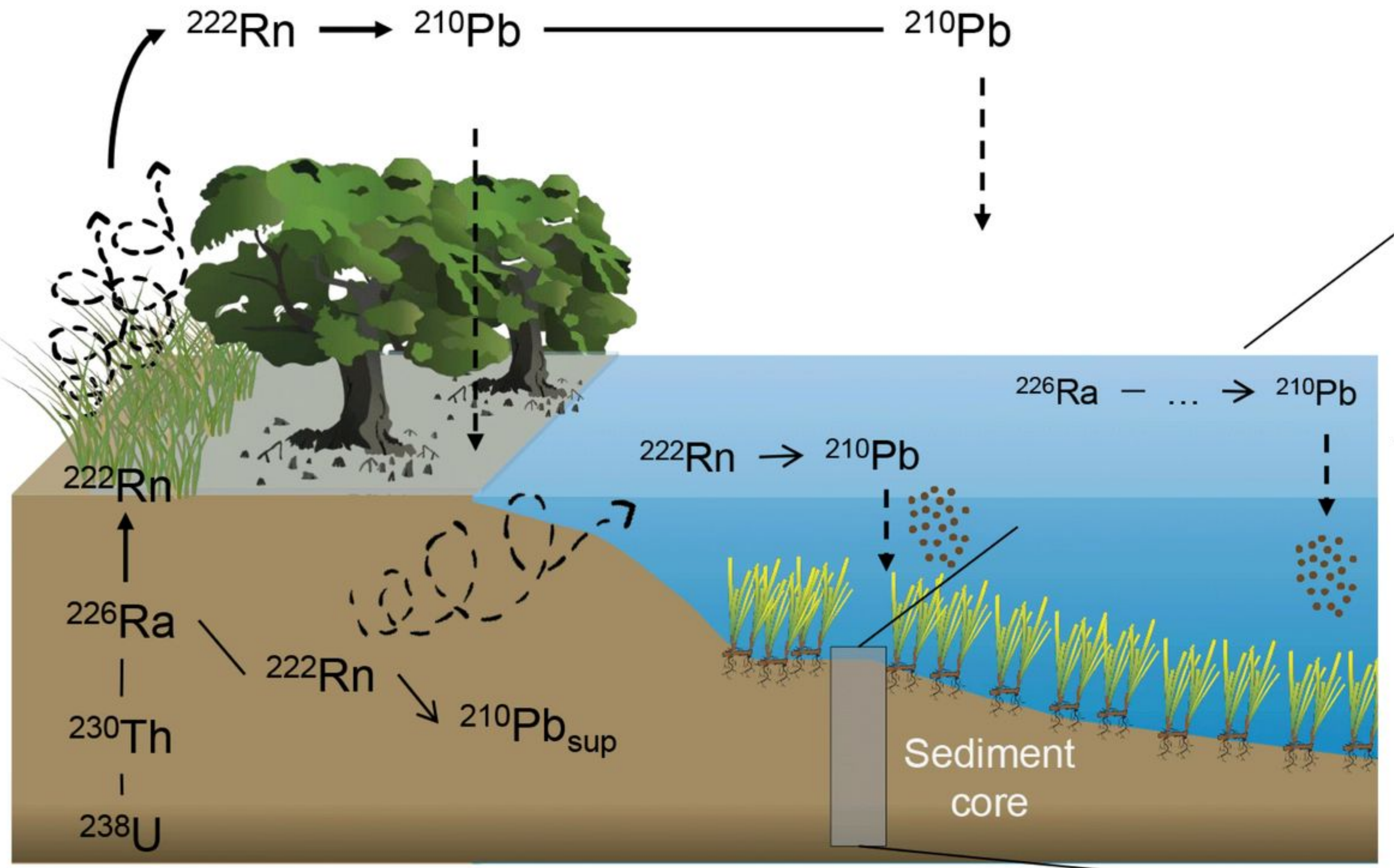
type of radiation	nuclide	half-life
α	uranium—238	4.5×10^{9} years
β	thorium—234	24.5 days
β	protactinium—234	1.14 minutes
α	uranium—234	2.33×10^{5} years
α	thorium—230	8.3×10^{4} years
α	radium—226	1590 years
α	radon—222	3.825 days
α	polonium—218	3.05 minutes
β	lead—214	26.8 minutes
β	bismuth—214	19.7 minutes
α	polonium—214	1.5×10^{-4} seconds
β	lead—210	22 years
β	bismuth—210	5 days
α	polonium—210	140 days
	lead—206	stable

Lead (^{210}Pb)



Arias-Ortiz et al. (2018)

Lead (^{210}Pb)



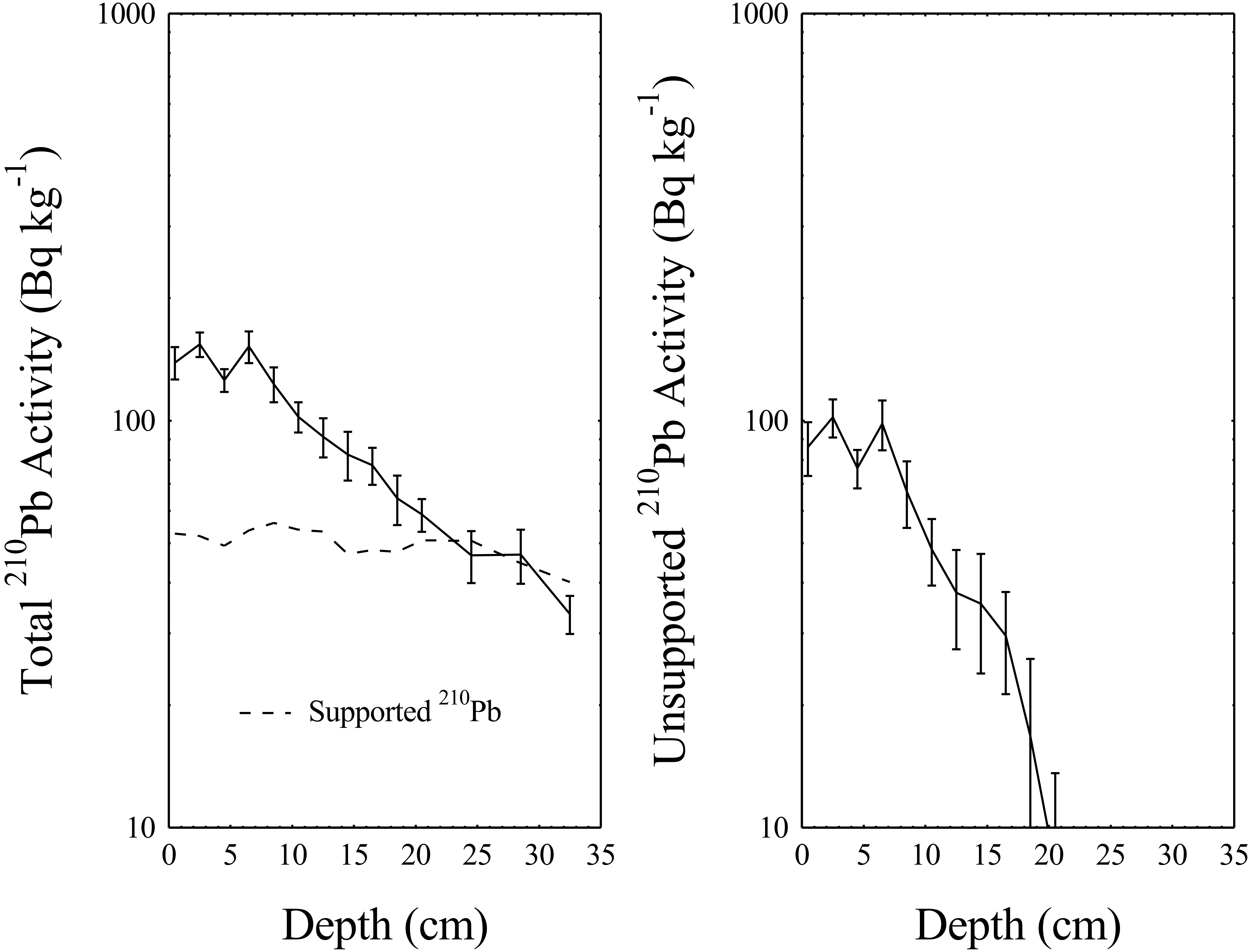
Arias-Ortiz et al. (2018)

Assumptions:

- **Constant** ^{210}Pb **deposition** from atmosphere
- ^{210}Pb **delay in water** is **constant**
- **No redistribution** in sediments


210Pb
137Cs
14C
18O

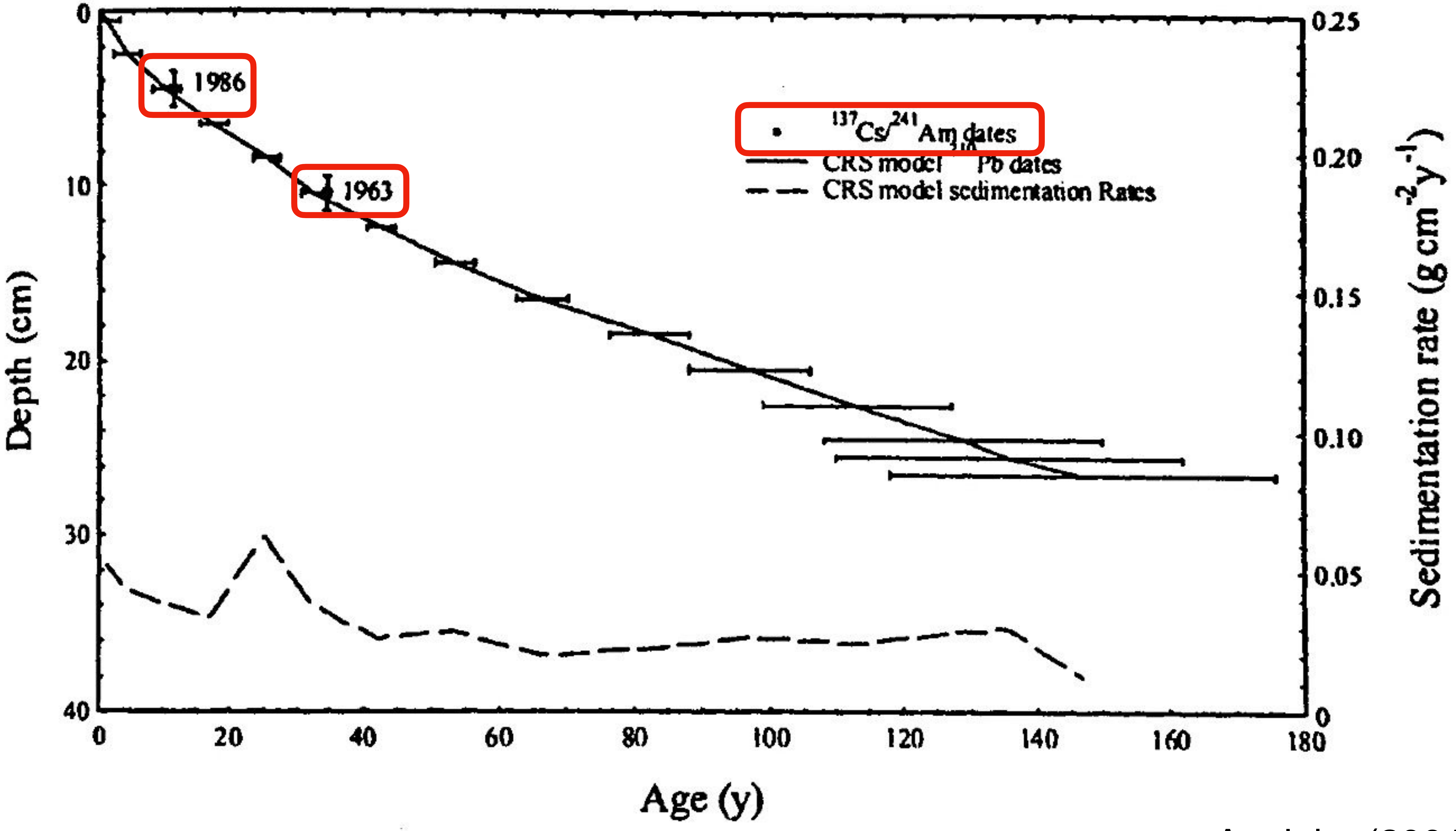
Lead (^{210}Pb)


1000
100
10
0 5 10 15 20 25 30 35
Total 210Pb Activity (Bq kg-1)
Supported 210Pb
Depth (cm)
Unsupported 210Pb Activity (Bq kg-1)
Depth (cm)

Lead (^{210}Pb)

Models:

- Constant Rate of Supply of Sediment Influx (**CRS**)
- Constant Initial Concentration (**CIC**)



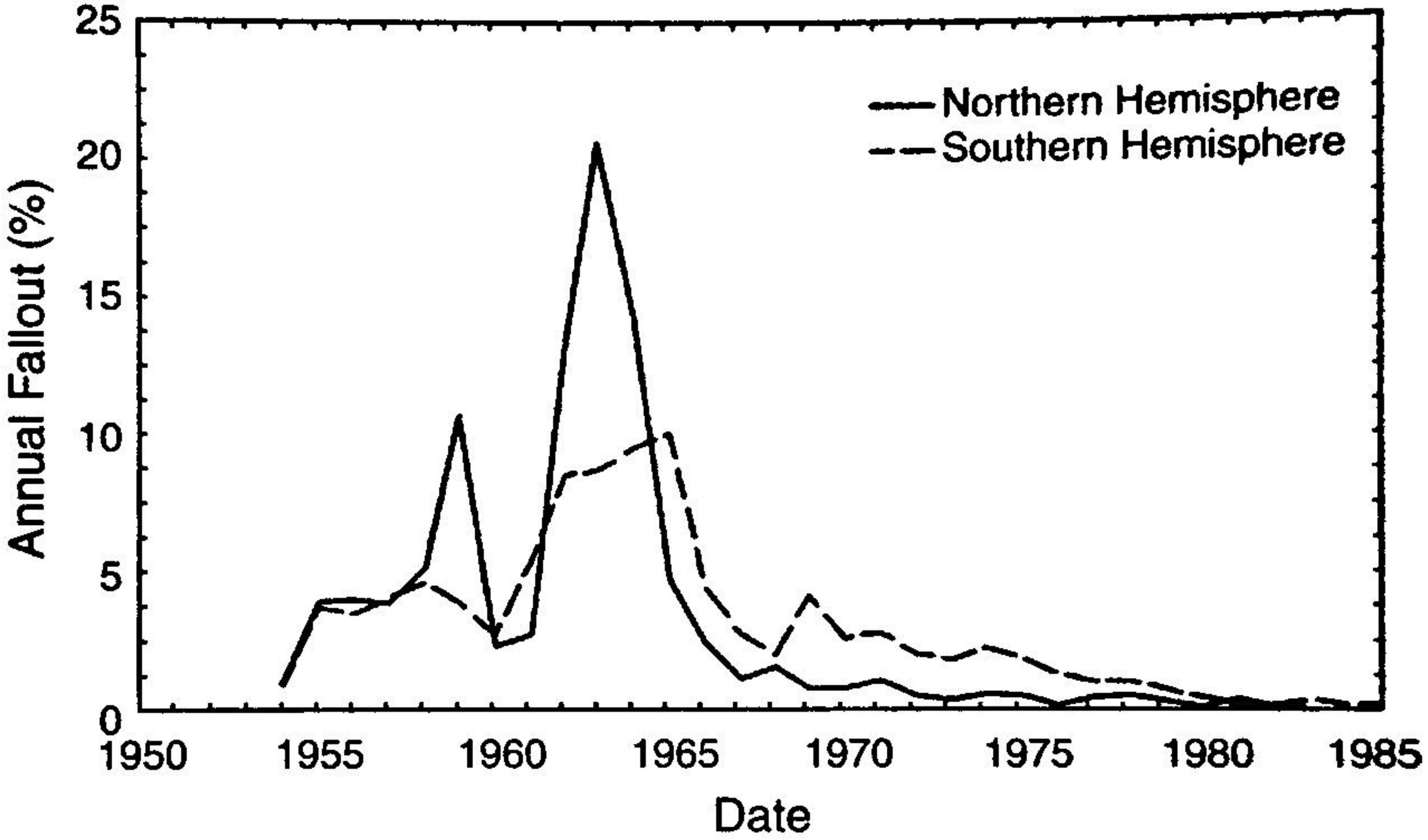
Appleby (2001)

Cesium (^{137}Cs)

Thermonuclear test “Baker”, Marshall Islands

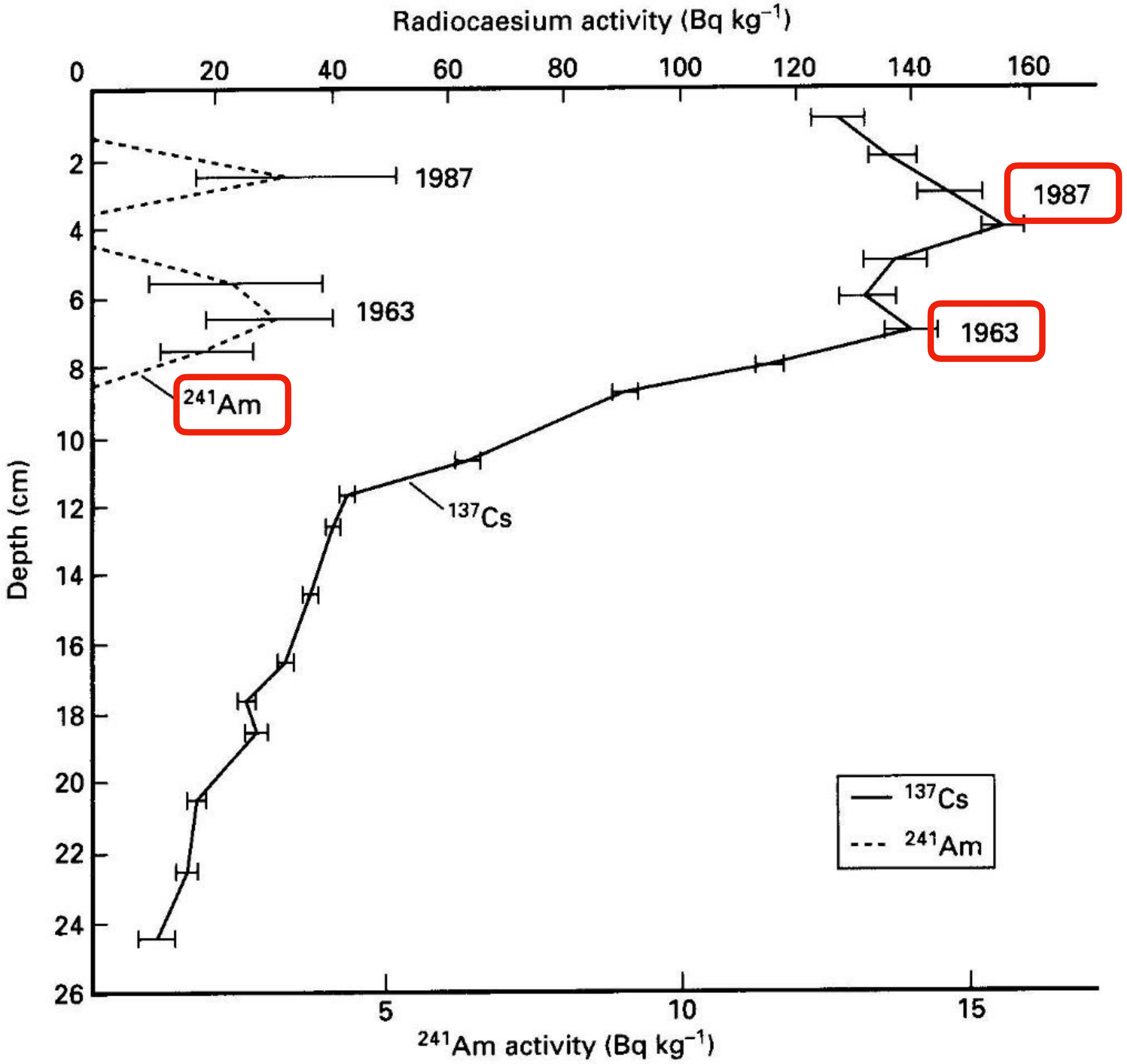
Cesium (^{137}Cs)

- Result of fission in nuclear reactors
- Marks **nuklear testing / disasters**
- **Complements ^{210}Pb** dating
- Unstable in sediments → migration



Appleby (2001)

Cesium (^{137}Cs)



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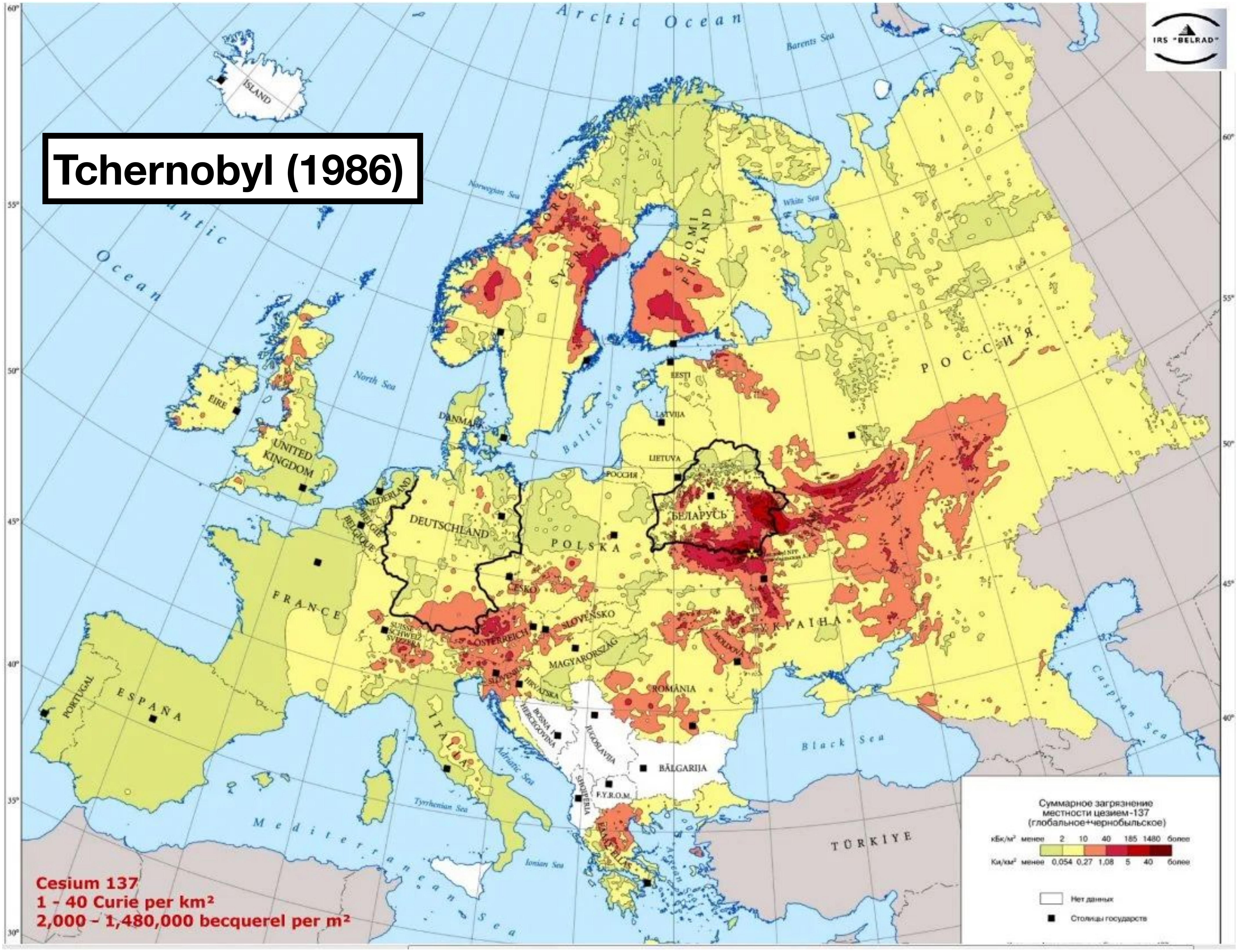
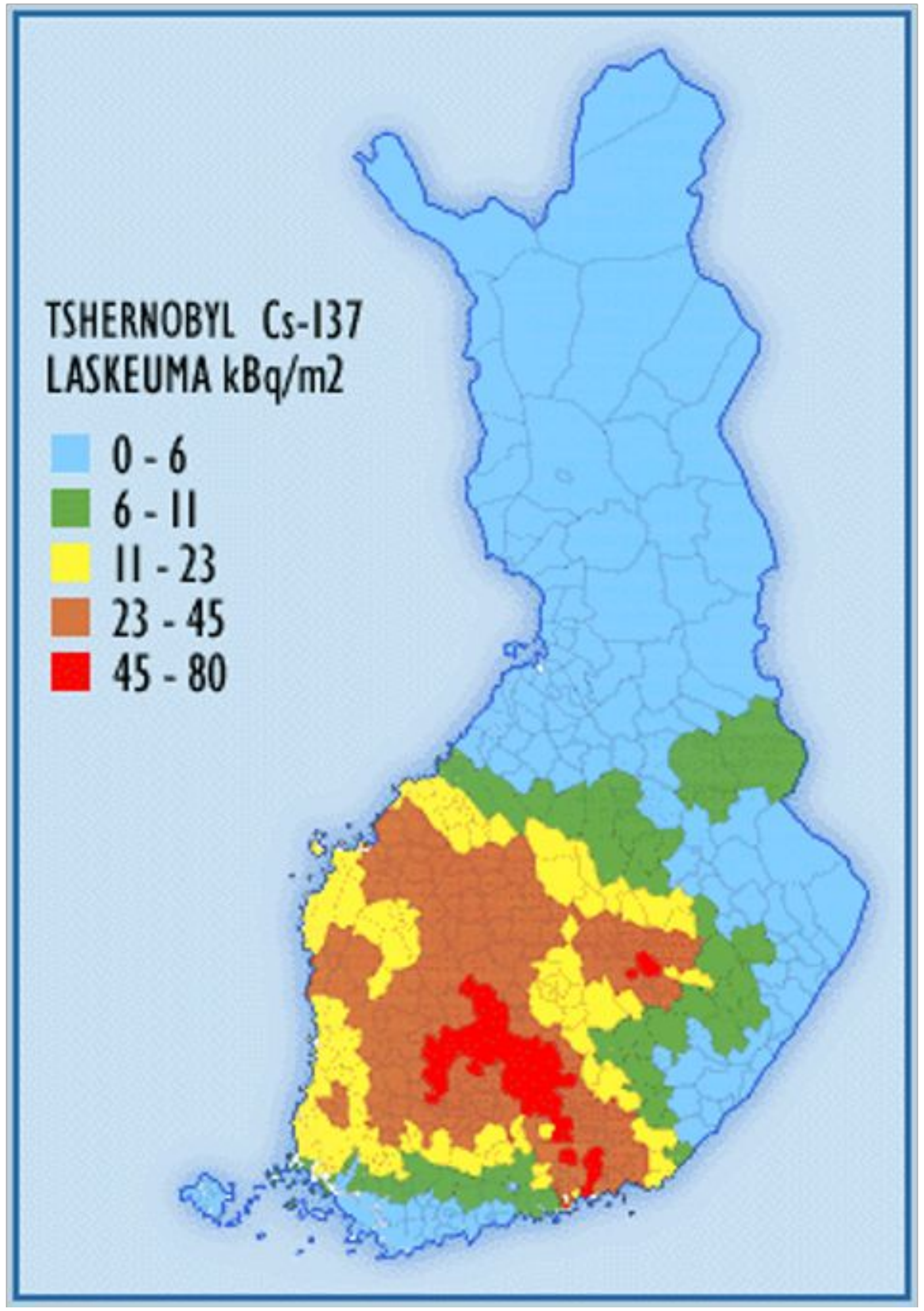
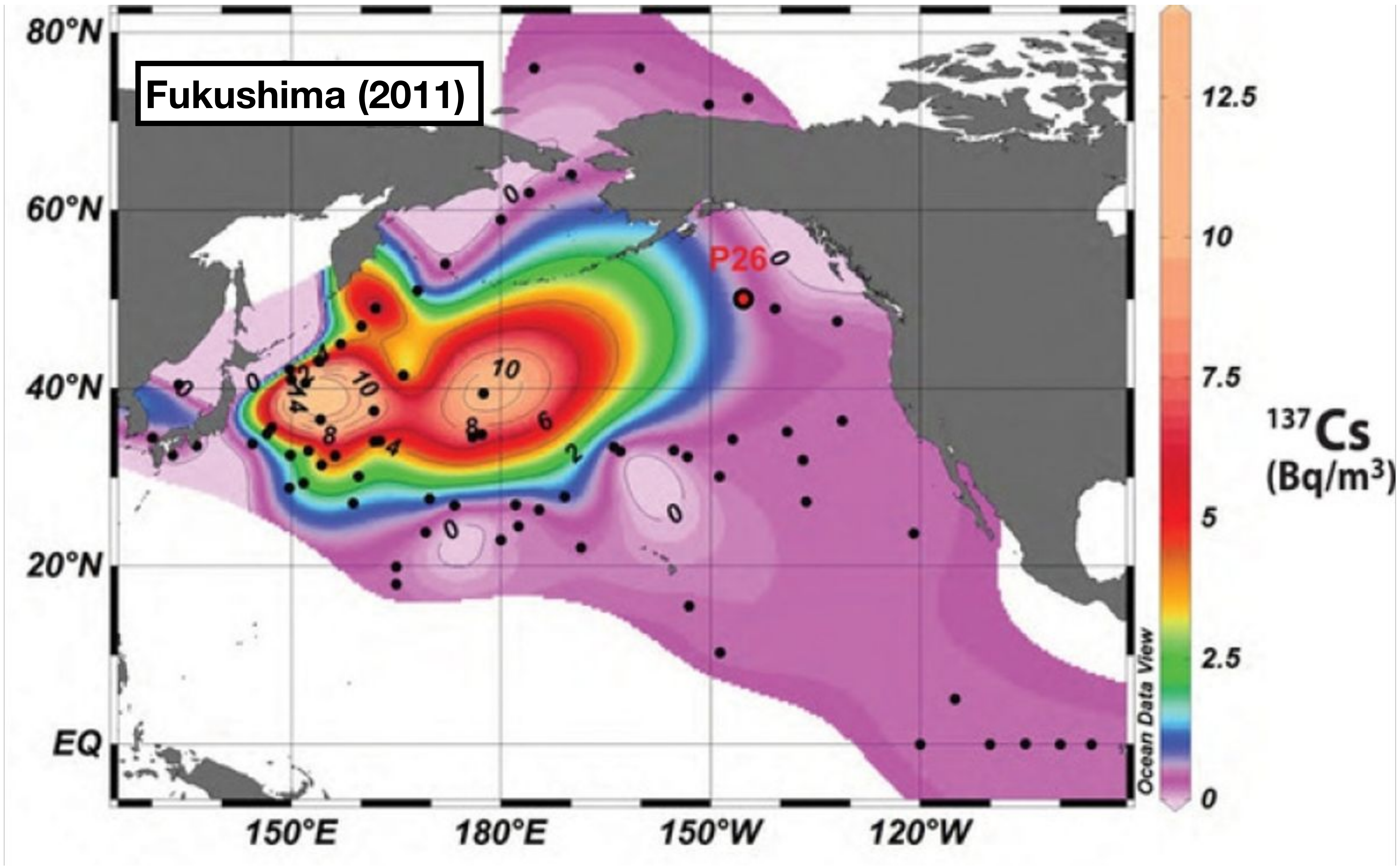




Cesium (^{137}Cs)



Aoyama et al. (2013)

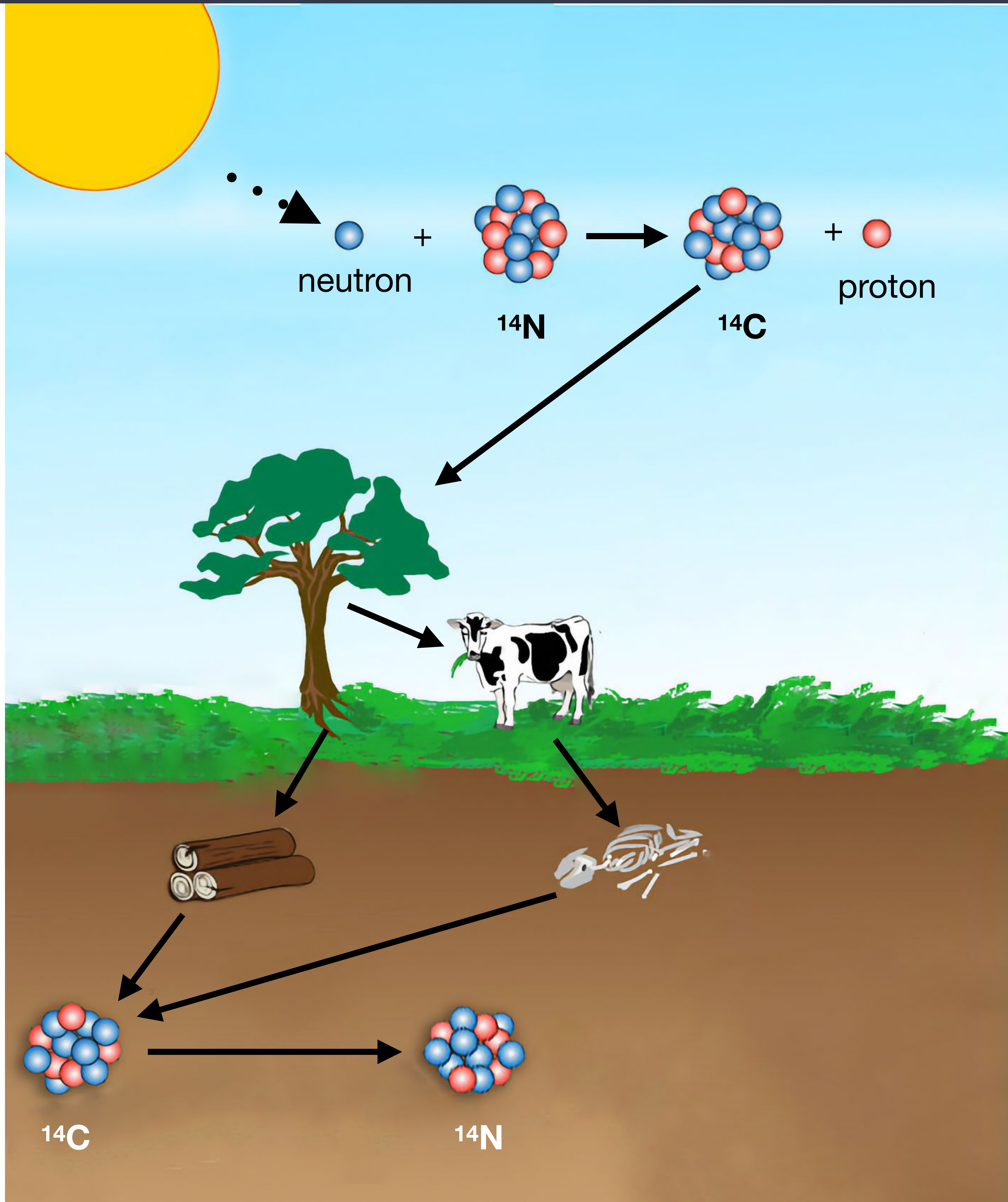
Radiocarbon (^{14}C)

Willard Libby (1960)

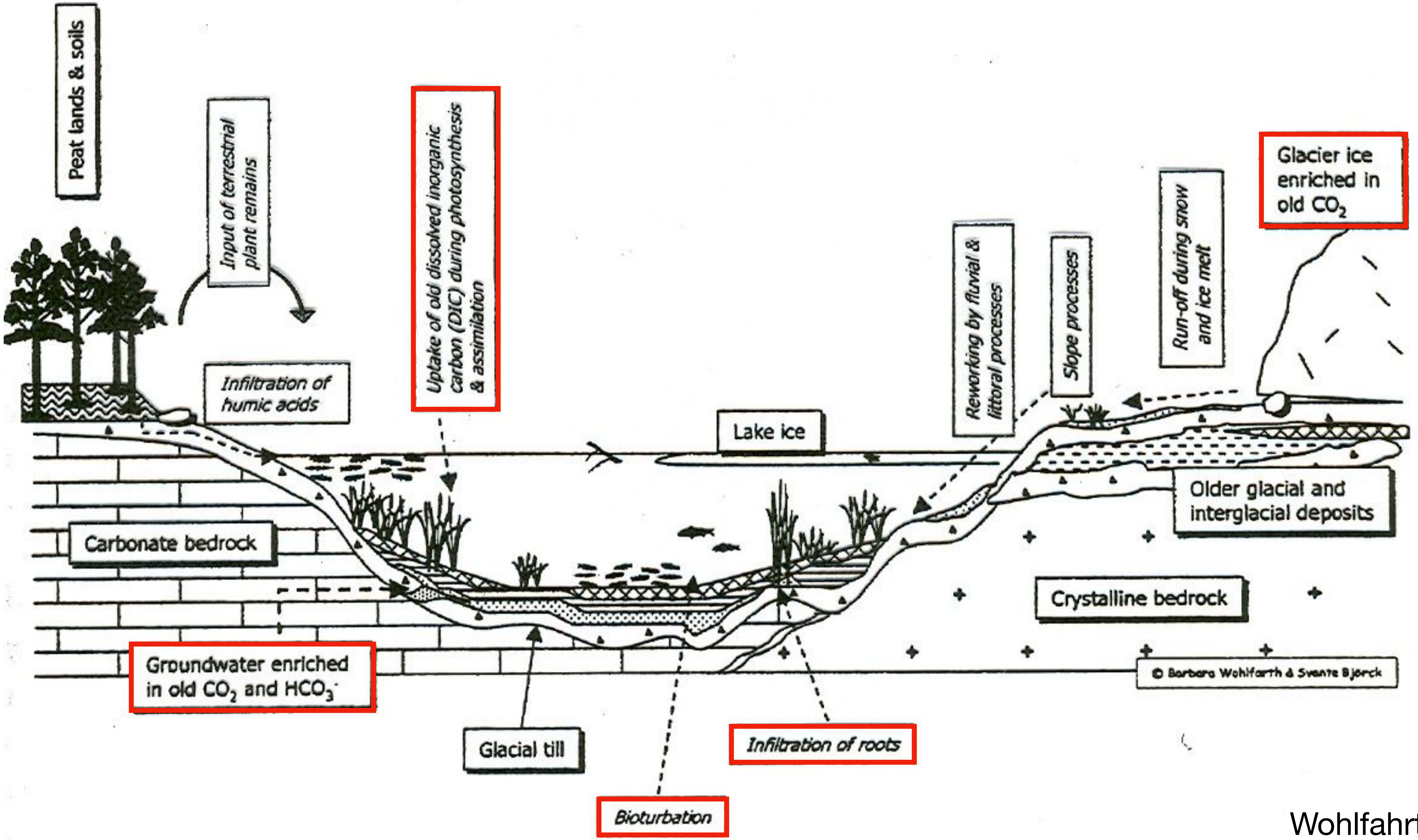
Acer ruburum seed macrofossil

Radiocarbon (^{14}C)

- Cosmic rays: $^{14}N \rightarrow {}^{14}C$
- ^{14}C in **equilibrium in living organisms**
- **After death**: no new overturn, only **decay** $^{14}C \rightarrow {}^{14}N$



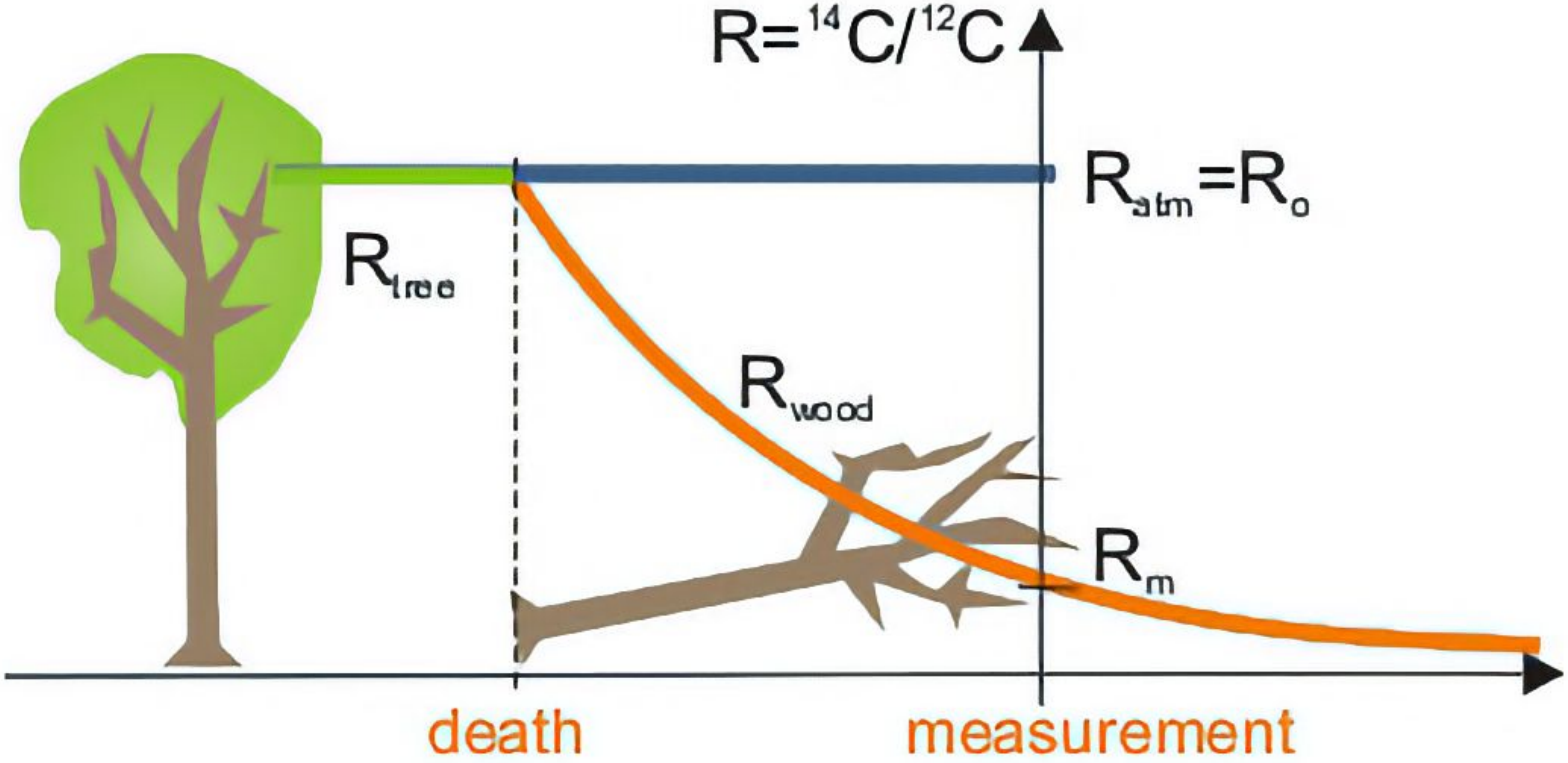
Radiocarbon (^{14}C)



Wohlfahrt and Björk (2001)

Radiocarbon (^{14}C)

^{14}C half-life: 5730±40 years



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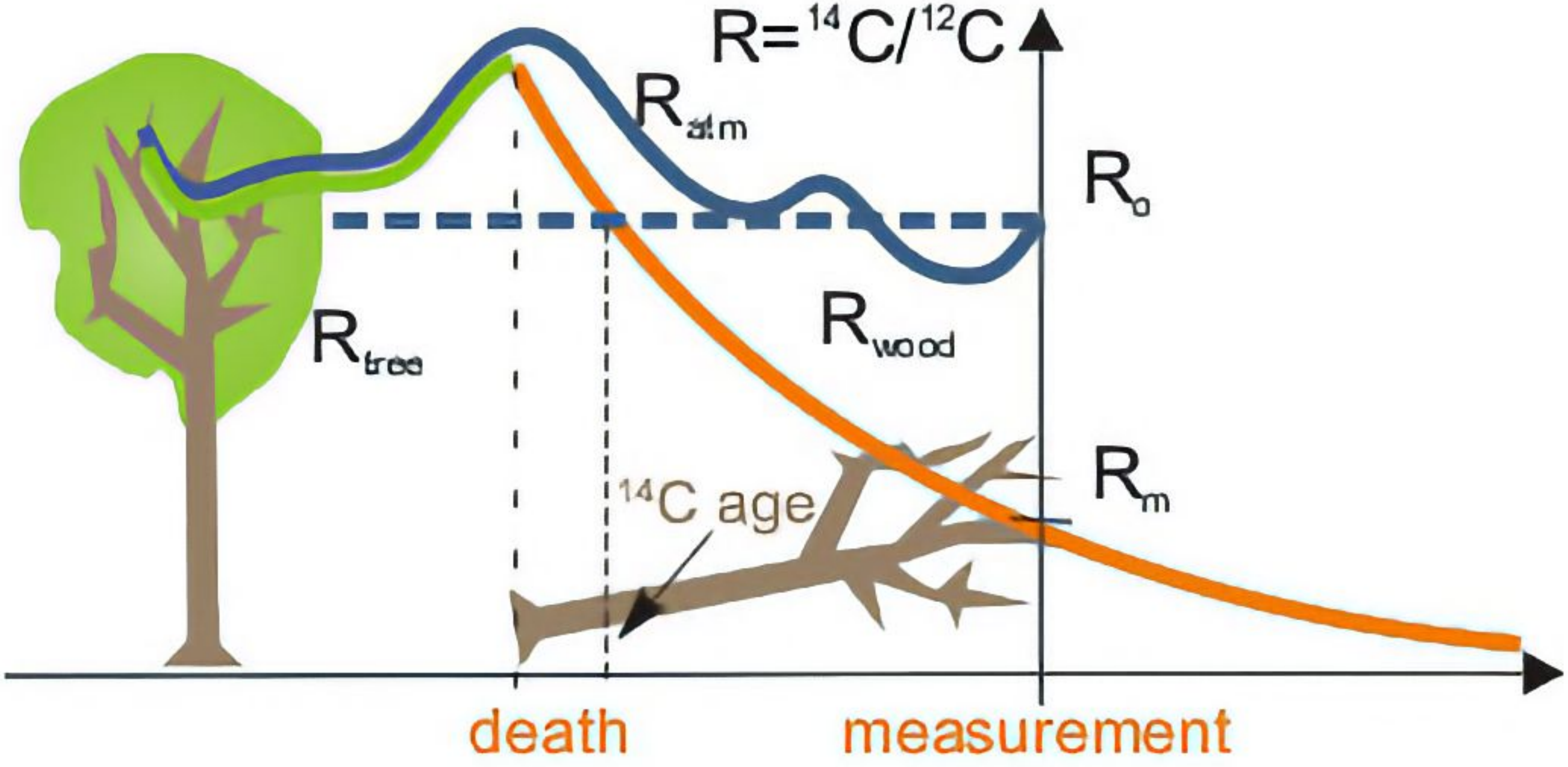
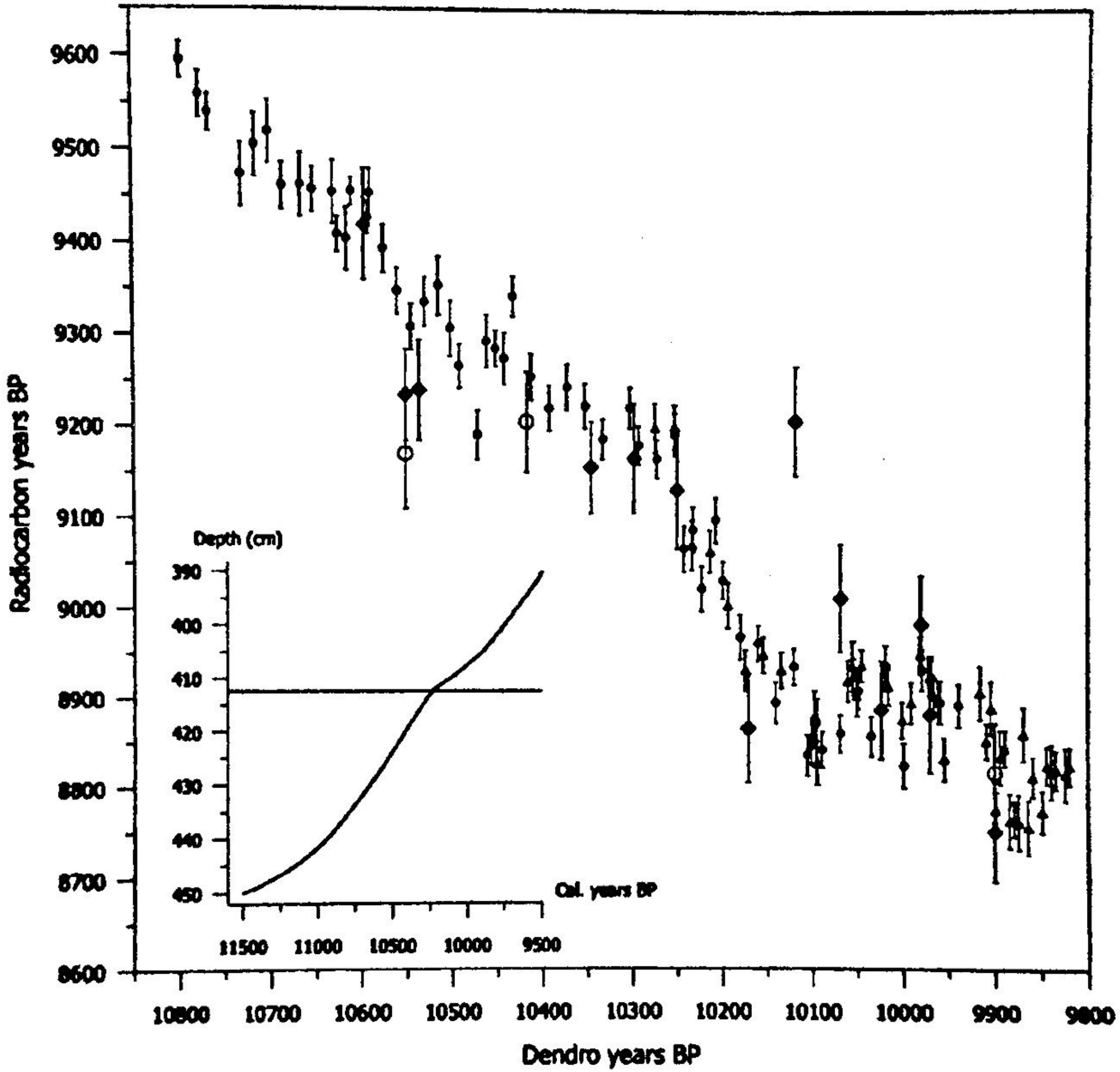
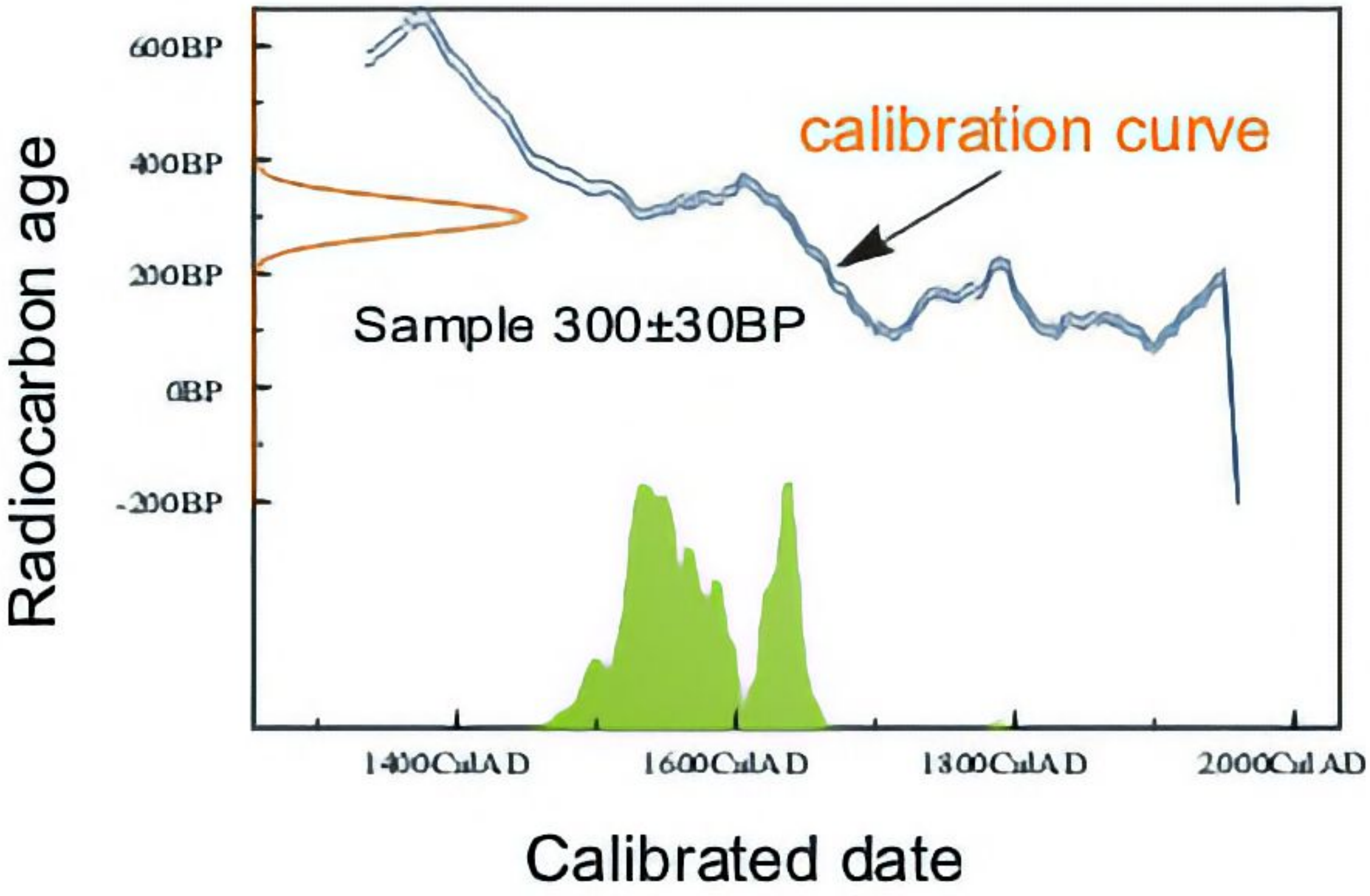




Wohlfahrt and Björk (2001)

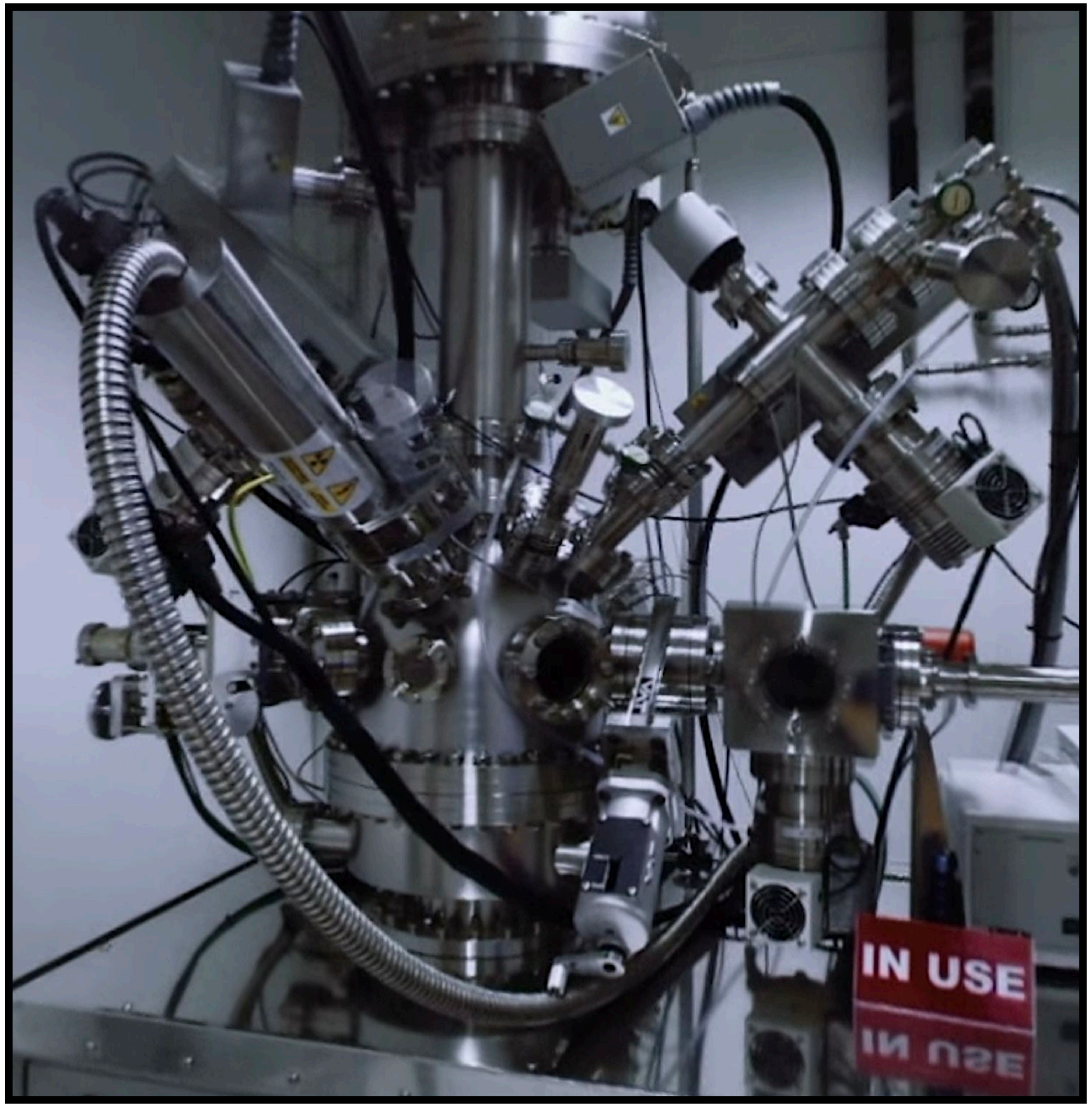
Radiocarbon (^{14}C)



Radiocarbon (^{14}C)

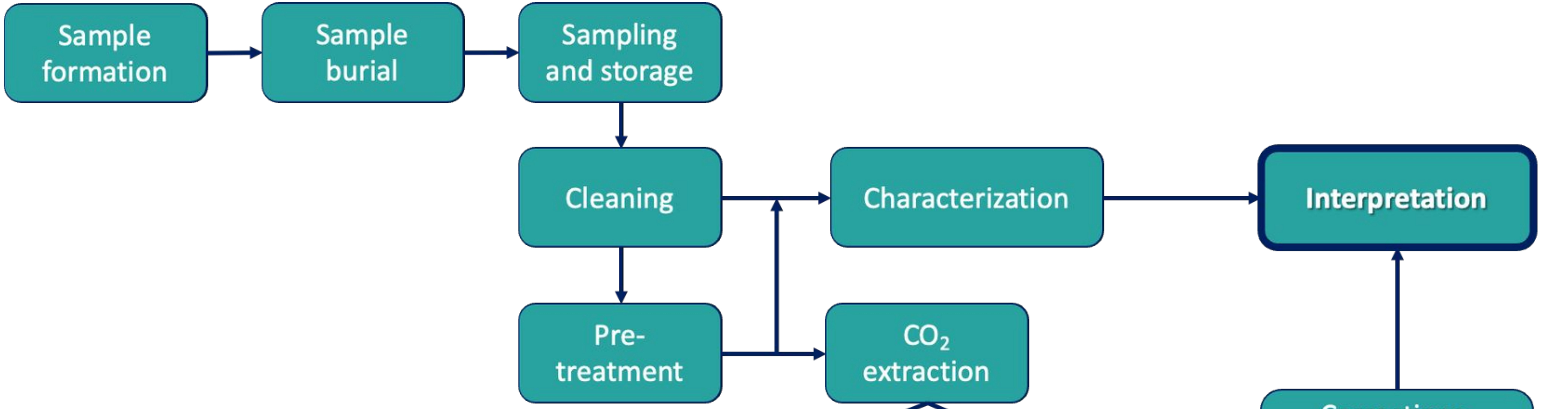
Accelerator Mass Spectrometry (AMS)

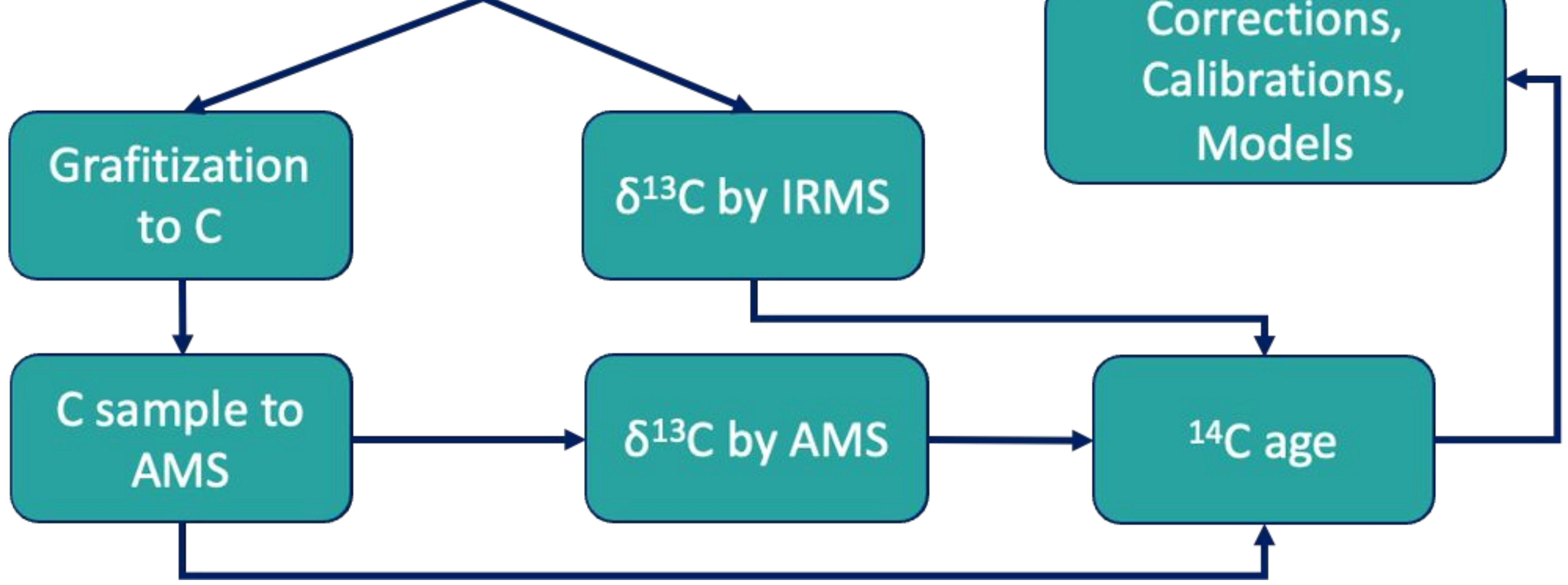
- **Small sample size** (≤ 1 mg C)
  → dating material can be chosen
- **Lower errors** → older samples
  (max. ≈ 60,000 years)
- Pre-handling of the sample more careful

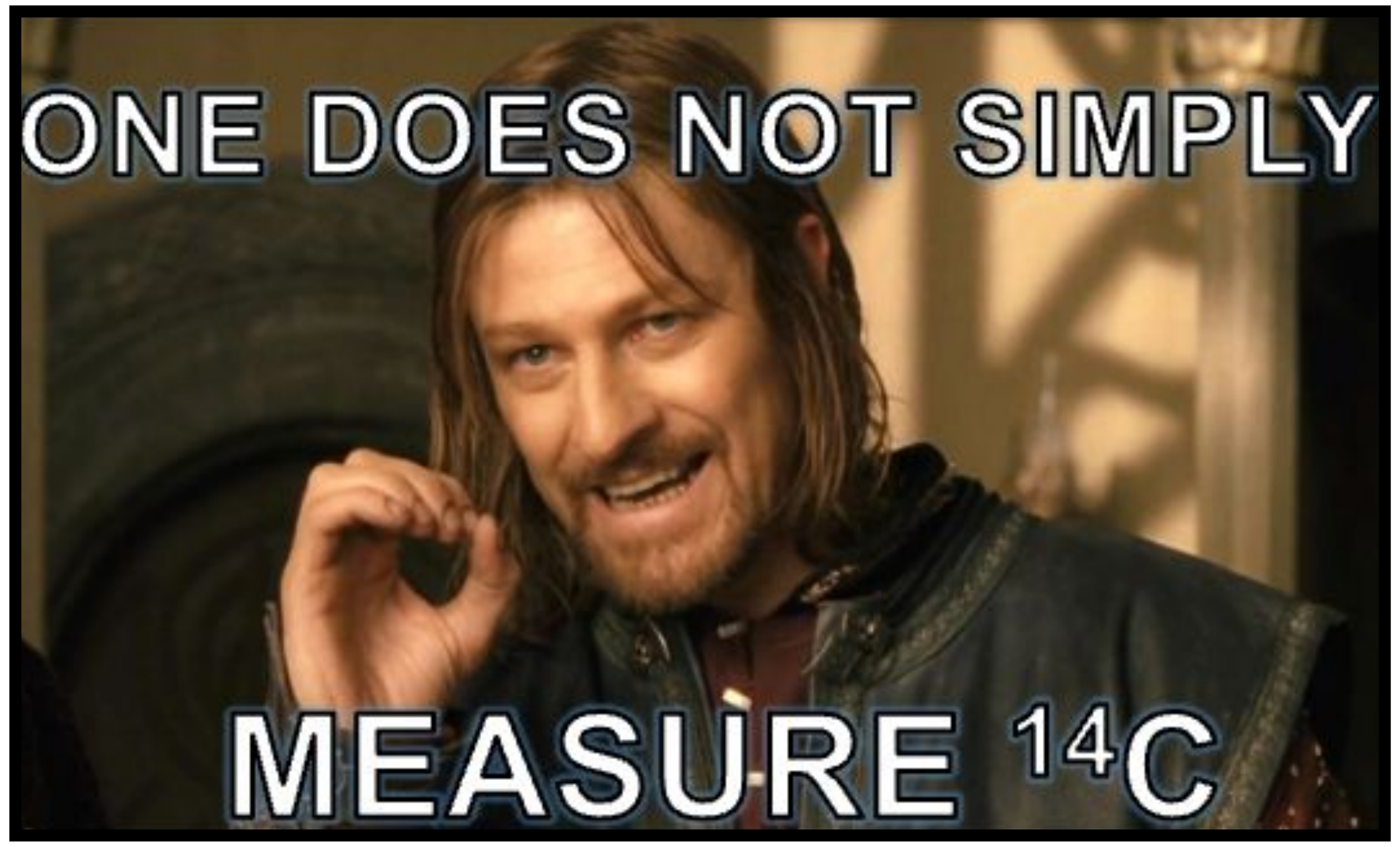


https://www.youtube.com/watch?v=jDVWwZG7O1Y

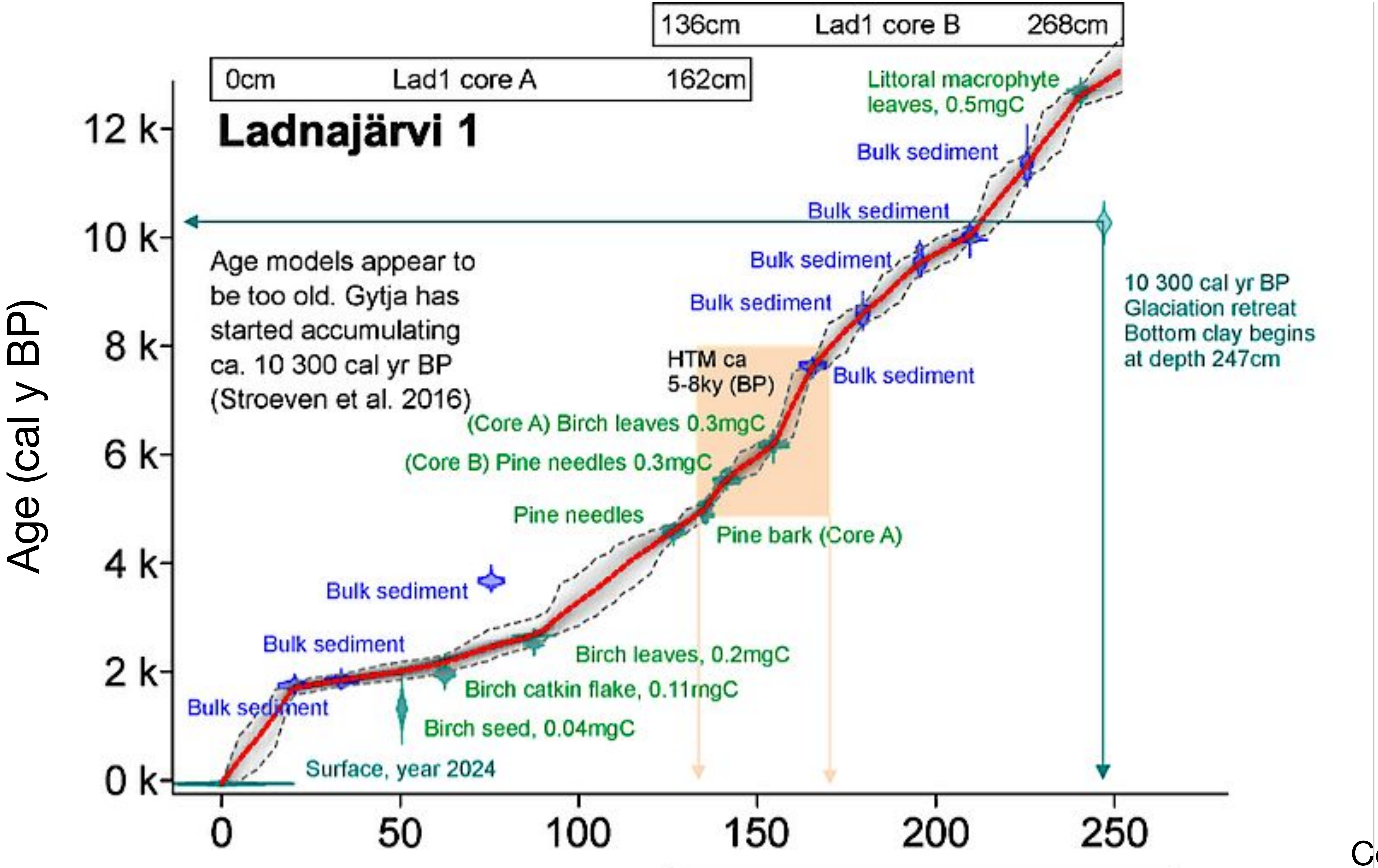
Radiocarbon (^{14}C)







Radiocarbon (^{14}C)



Courtesy of Ossi Keva

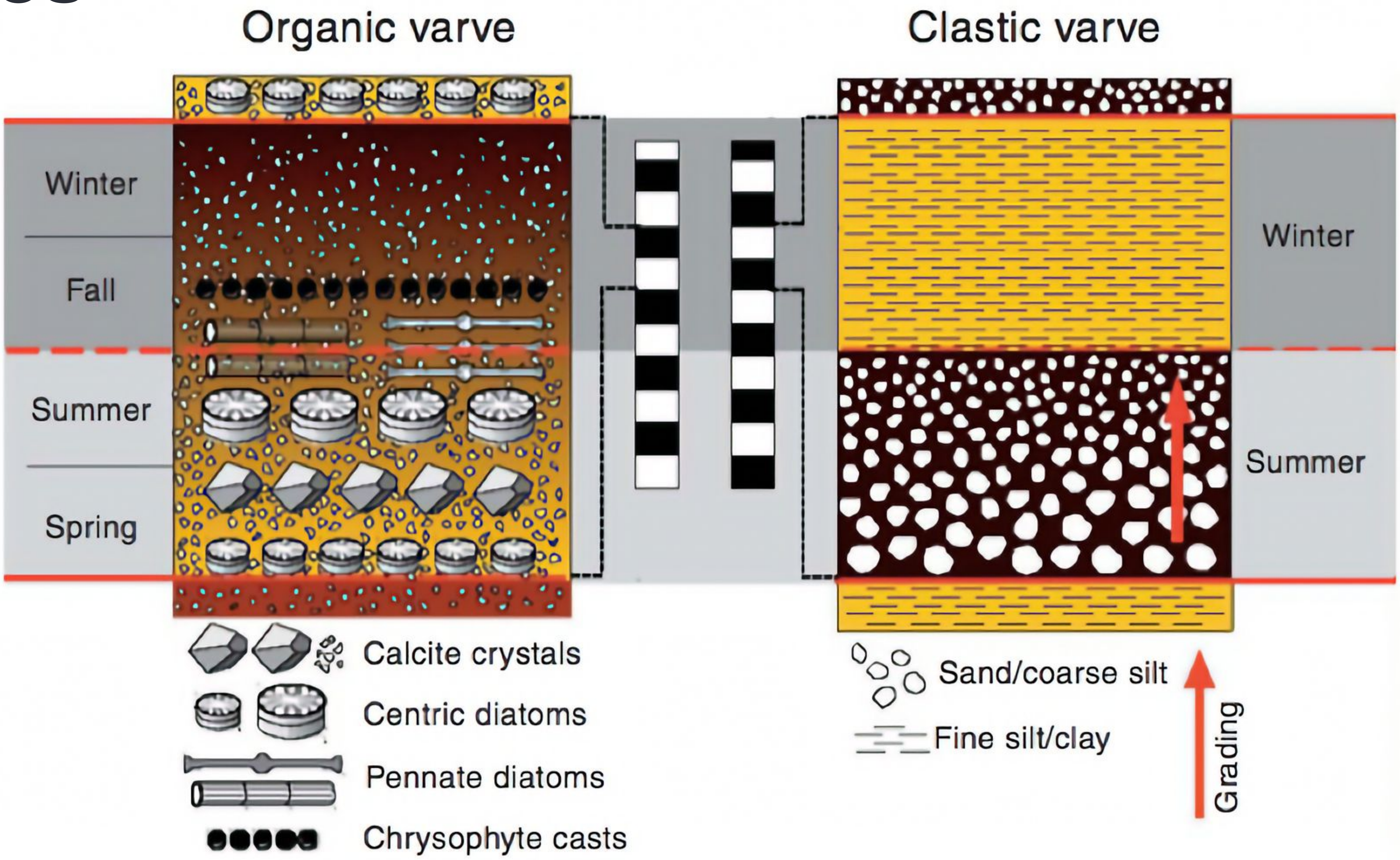
Varves

Geopark Indalsälven, Sweden

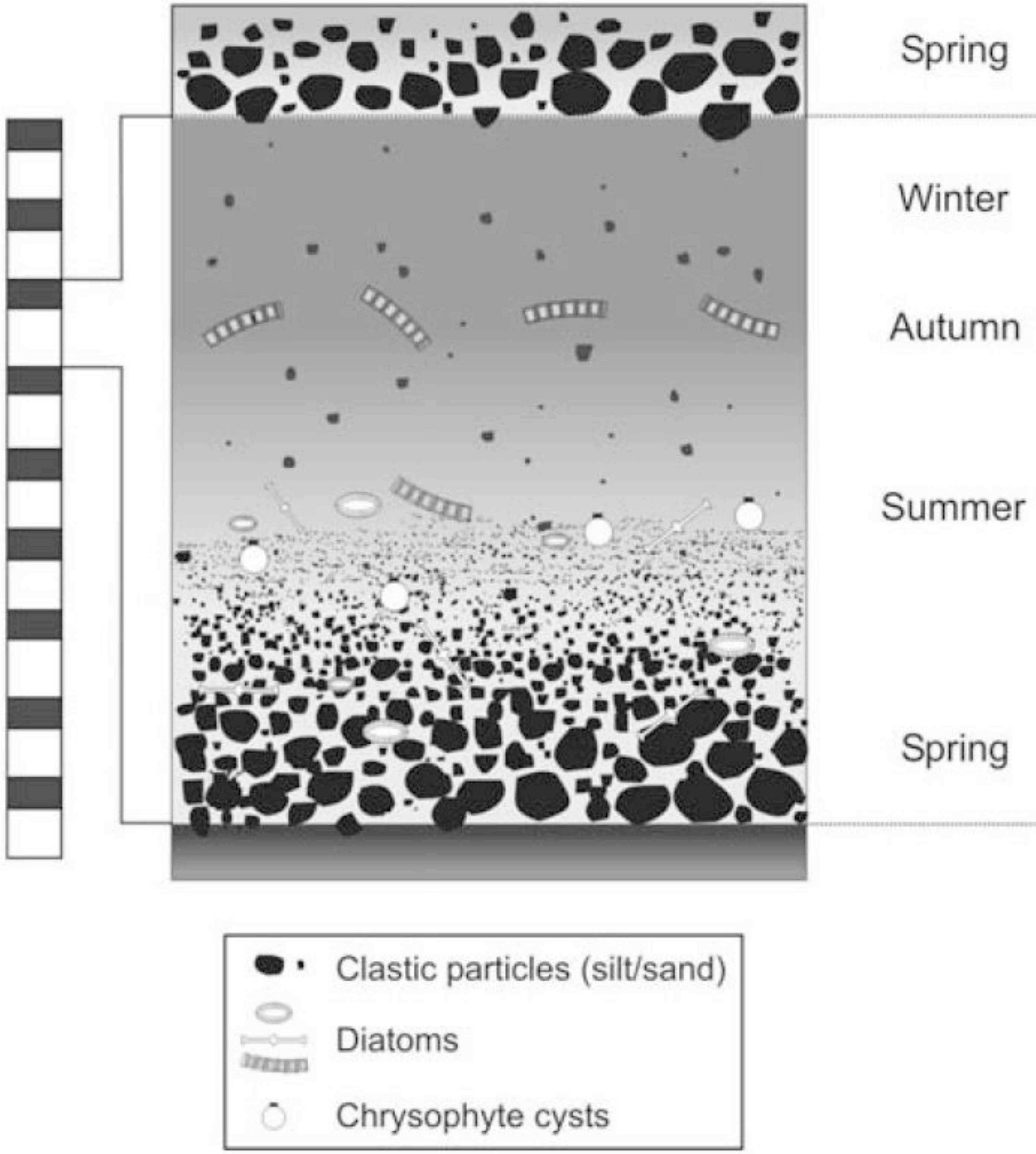
Varves

- Undisturbed conditions
- **Annual / seasonal** laminations
  - **Clastic**
  - **Biogenic**
- Laminae ≠ Varves!

Varves


Organic varve
Clastic varve
Winter
Fall
Summer
Spring
Winter
Summer
Calcite crystals
Centric diatoms
Pennate diatoms
Chrysophyte casts
Sand/coarse silt
Fine silt/clay
Grading

Varves



SEM BSEI
(AD 1980)

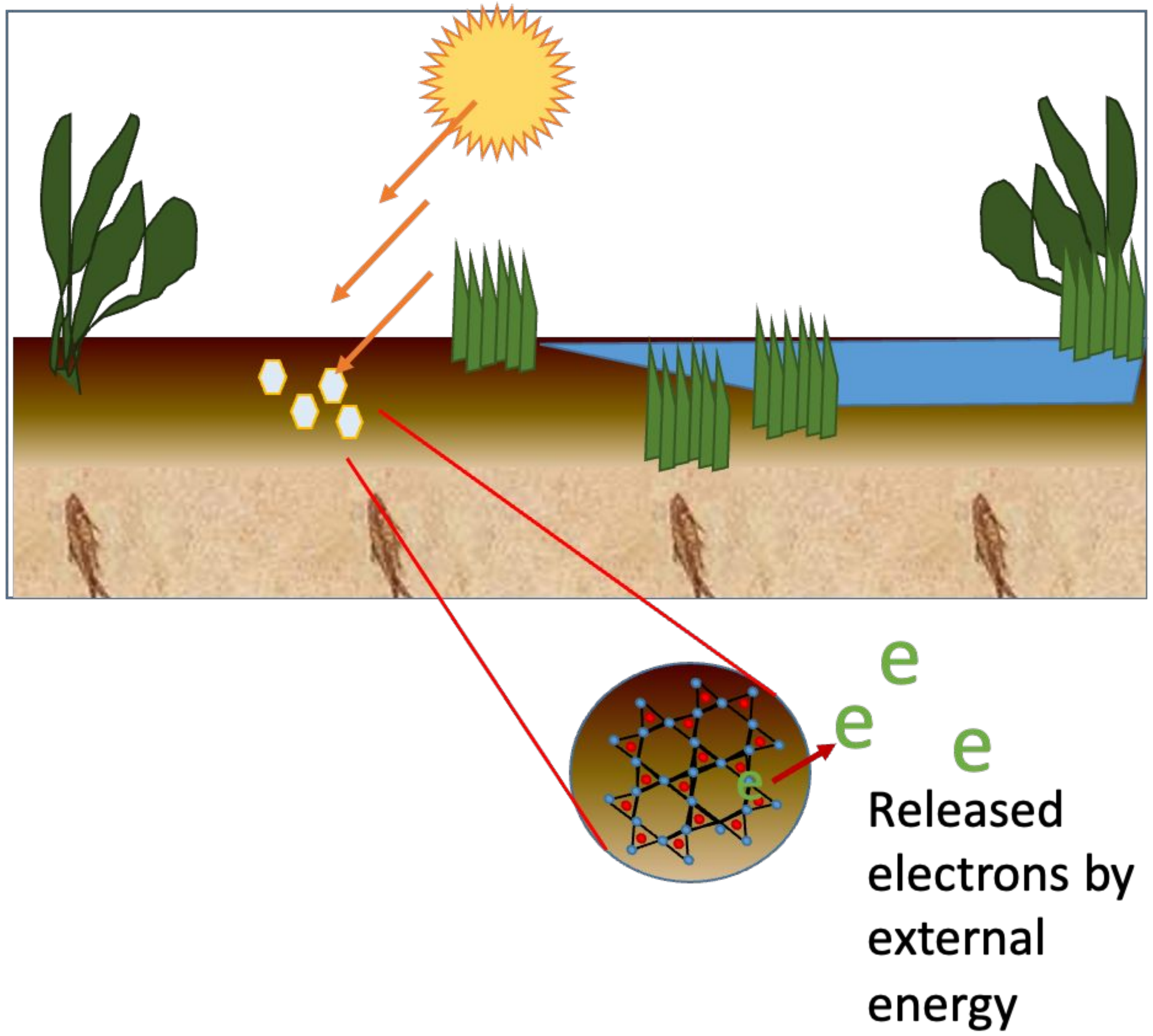
Ojala et al. (2013)

Luminescence

Quartz grains

Luminescence

- Mineral **grains store energy from natural radiation**
- **Sunlight / heat reset storage**
- After burial, storage fills up over time
- Luminescence / **energy stored** indicates when grains were **last exposed to light**



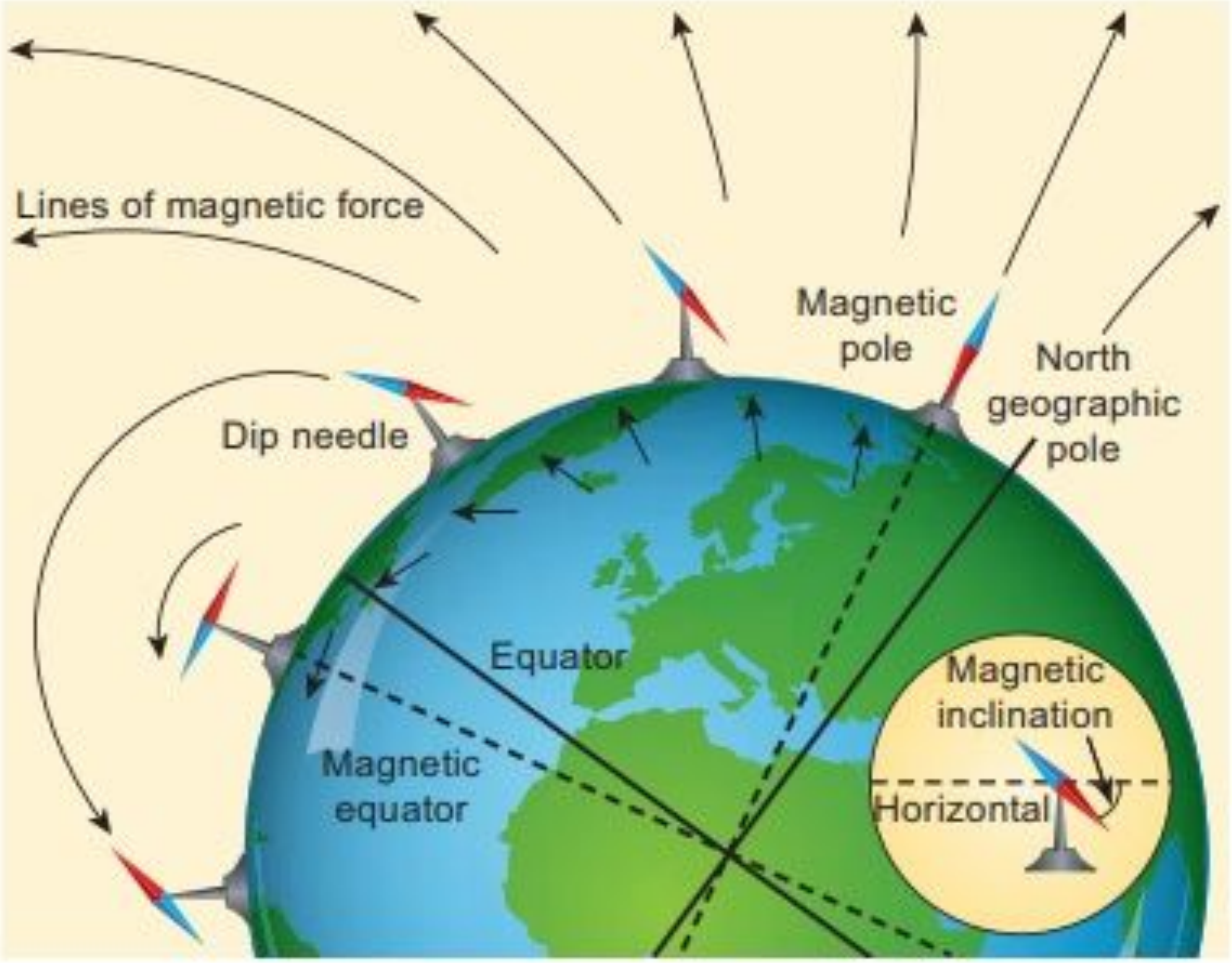
Courtesy of Lilia Orozco

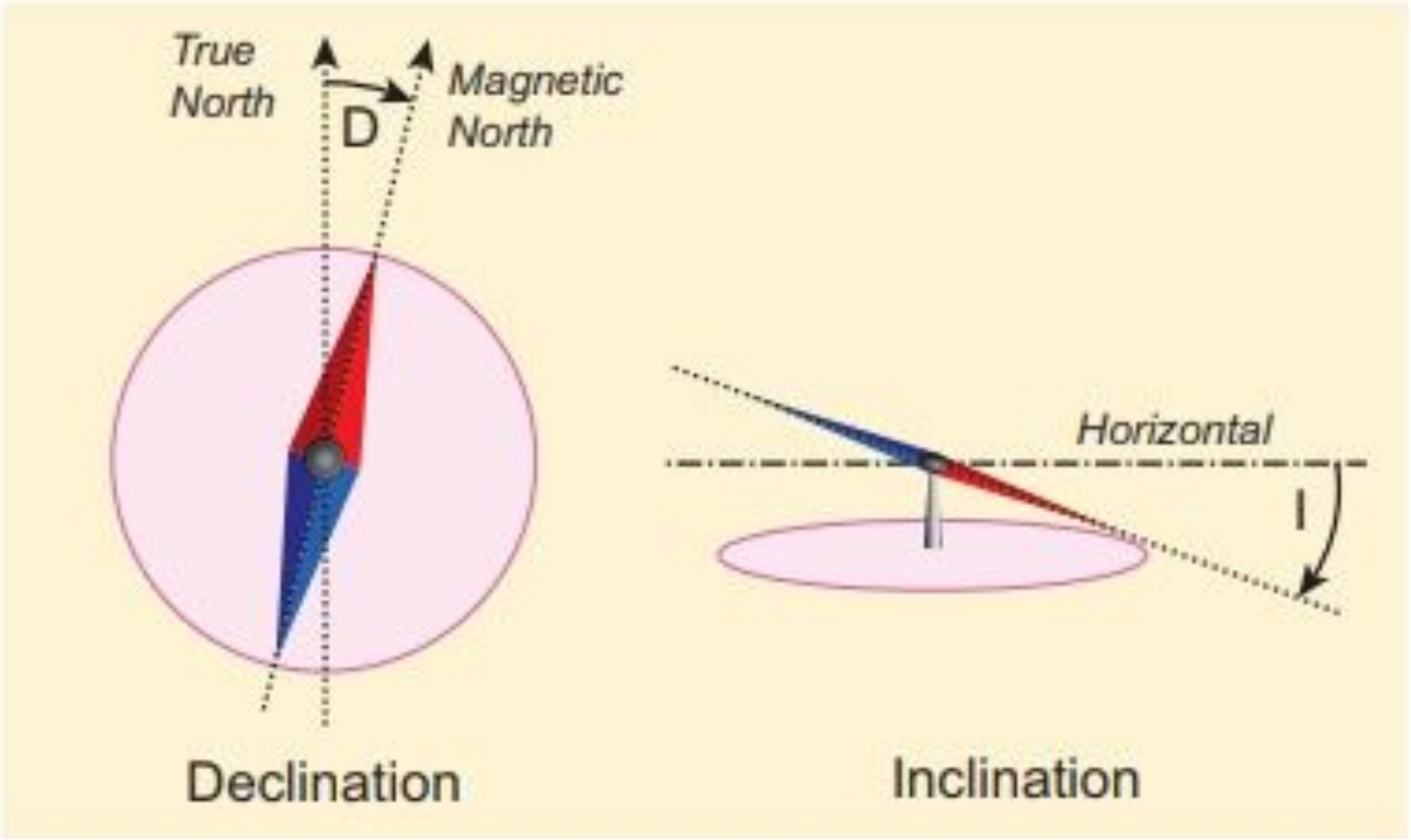
Paleomagnetism


CANADA
2020
2015
Magnetic north pole, 1900
Geographic North Pole
70° N
80° N
Arctic Ocean
GREENLAND

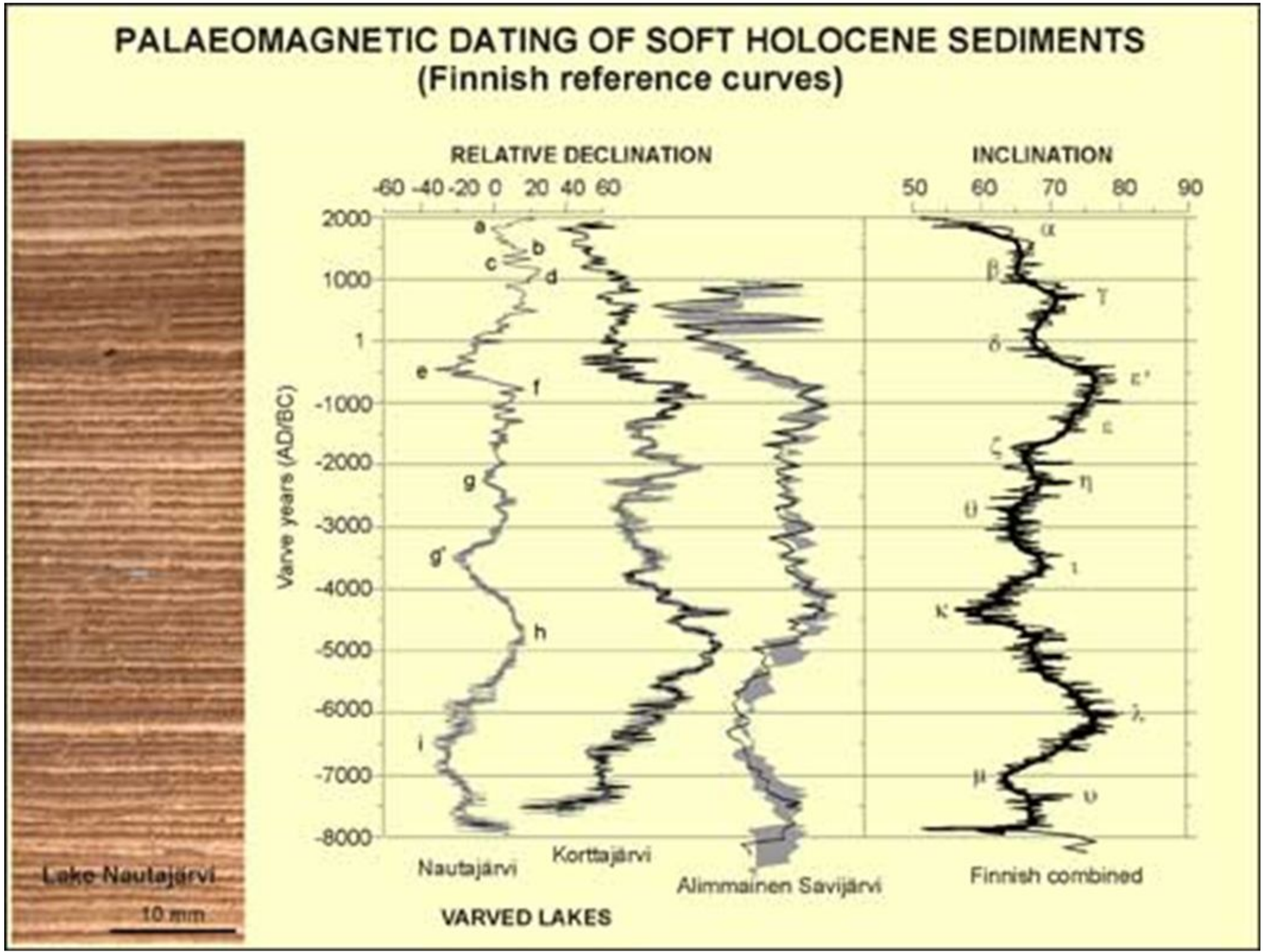
Paleomagnetism

- The Earth's **magentic field changes** over time
- Magnetic **minerals align with Earth's field**
- Magnetization locks in after deposition (declination + inclination)





Paleomagnetism



Tephras

Grimsvötn, Iceland

Tephras

- Pyroclastic **material from volcanic eruptions**

- Ash forms “time stamp” layer

- **Ash** identified by chemical fingerprint, **matched to known eruption date**

Mount St. Helens, USA

Tephras

Examples:

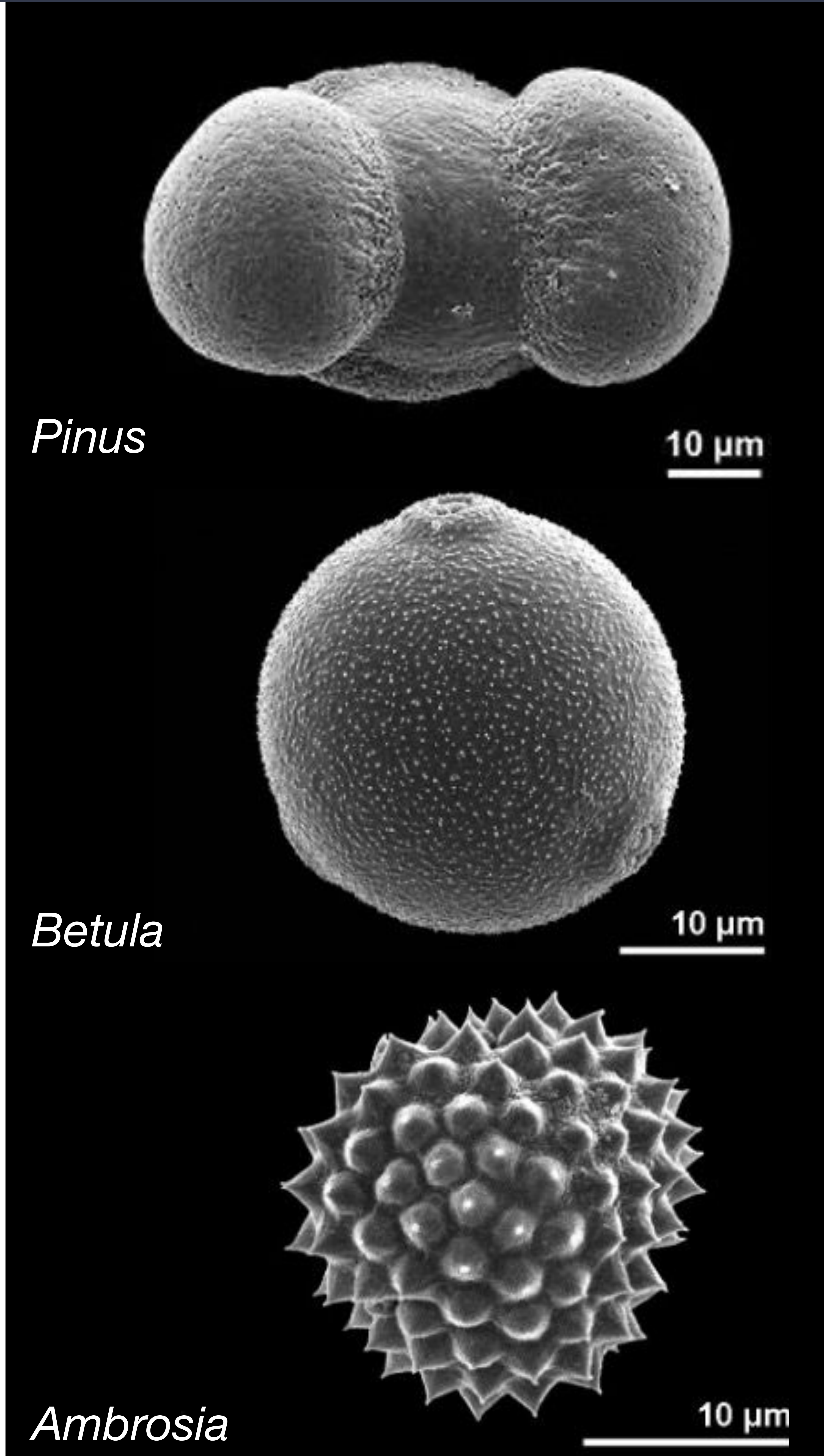
- Lacher-tephra Late-Glacial, 10 800 BP
- Vasset/Killian tephra in France 8230 BP
- Mazama ash 6600 BP
- Hekla, Vesuvius, Santorini eruptions

Fossils

Fossil pollen from central Asia

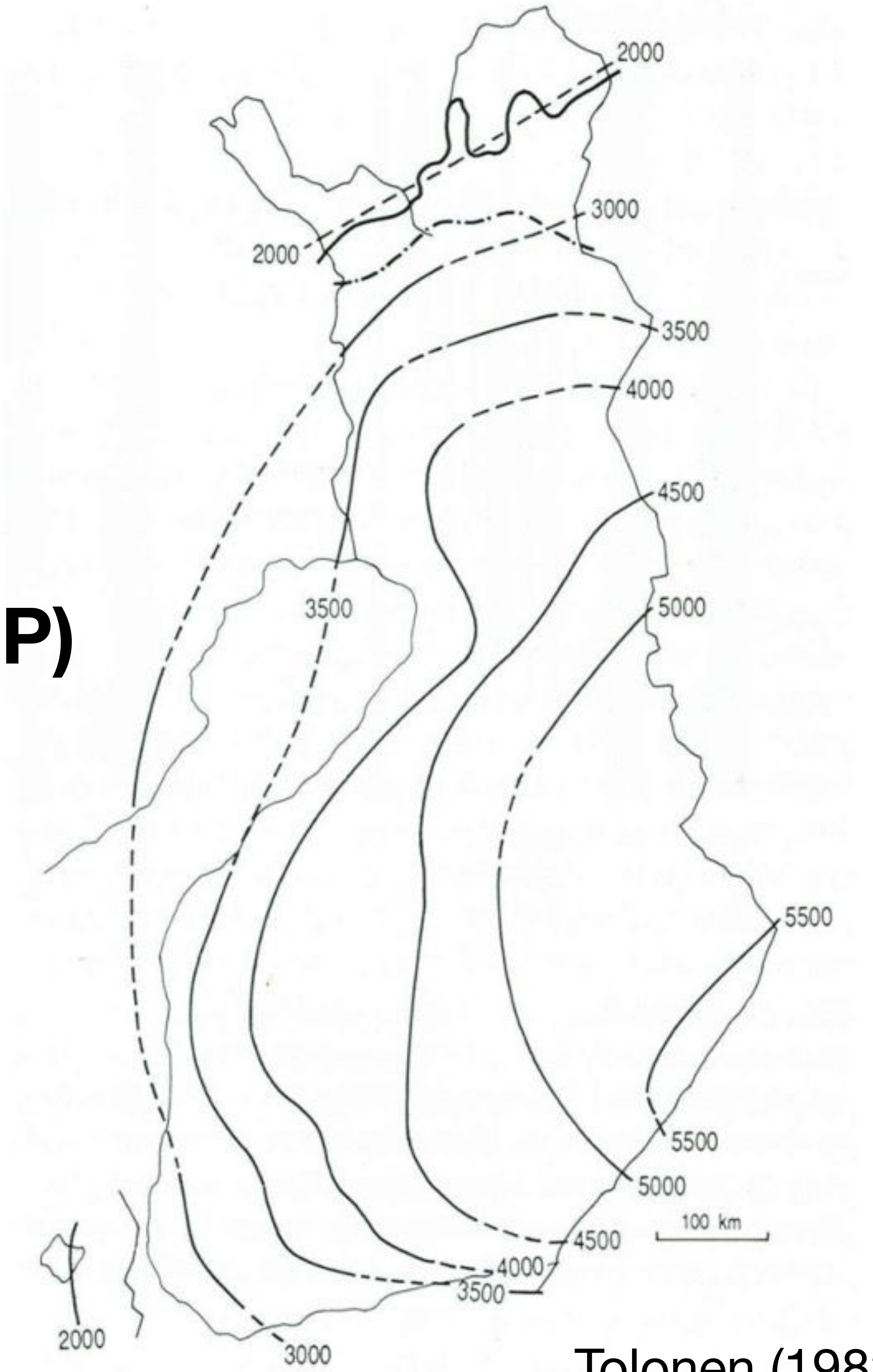
Fossils

- Some **species (dis-)appear at known times** / events
- Changes vegetation mark temporal episodes / sediment layers (esp. trees)
- Caveat: species timing varies by region, transport can blur signals

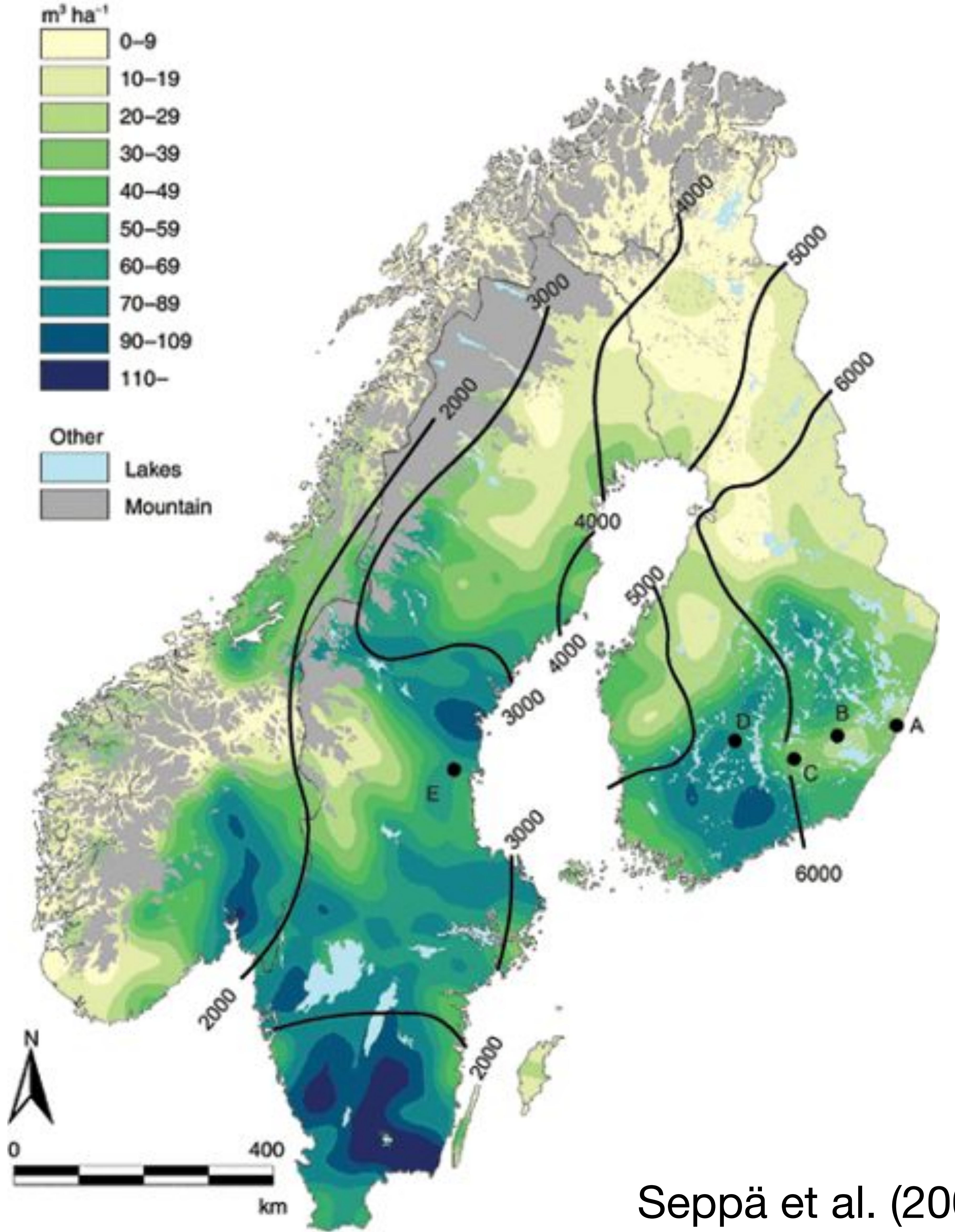


Fossils

Spruce expansion (yBP)

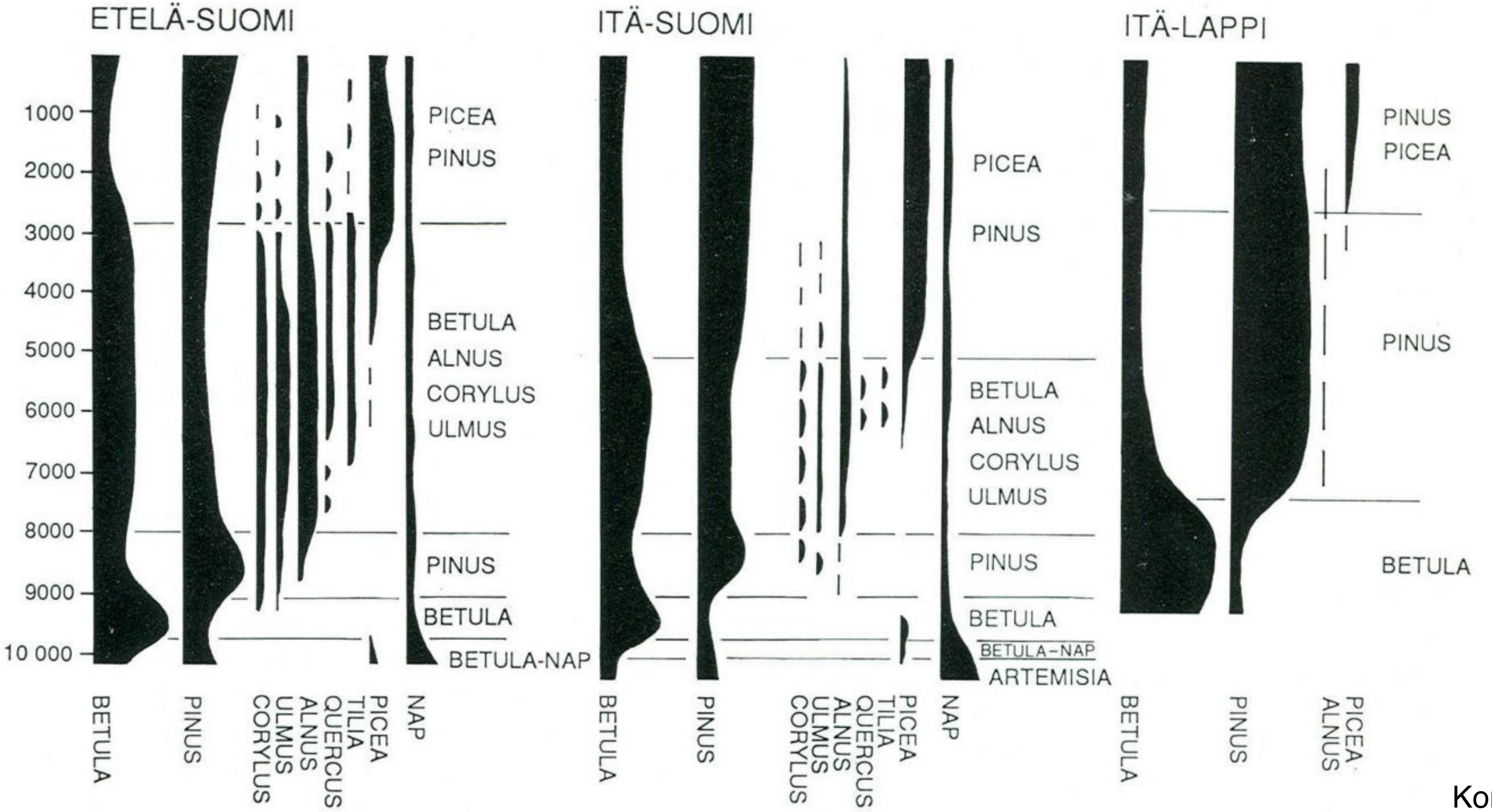


Tolonen (1983)



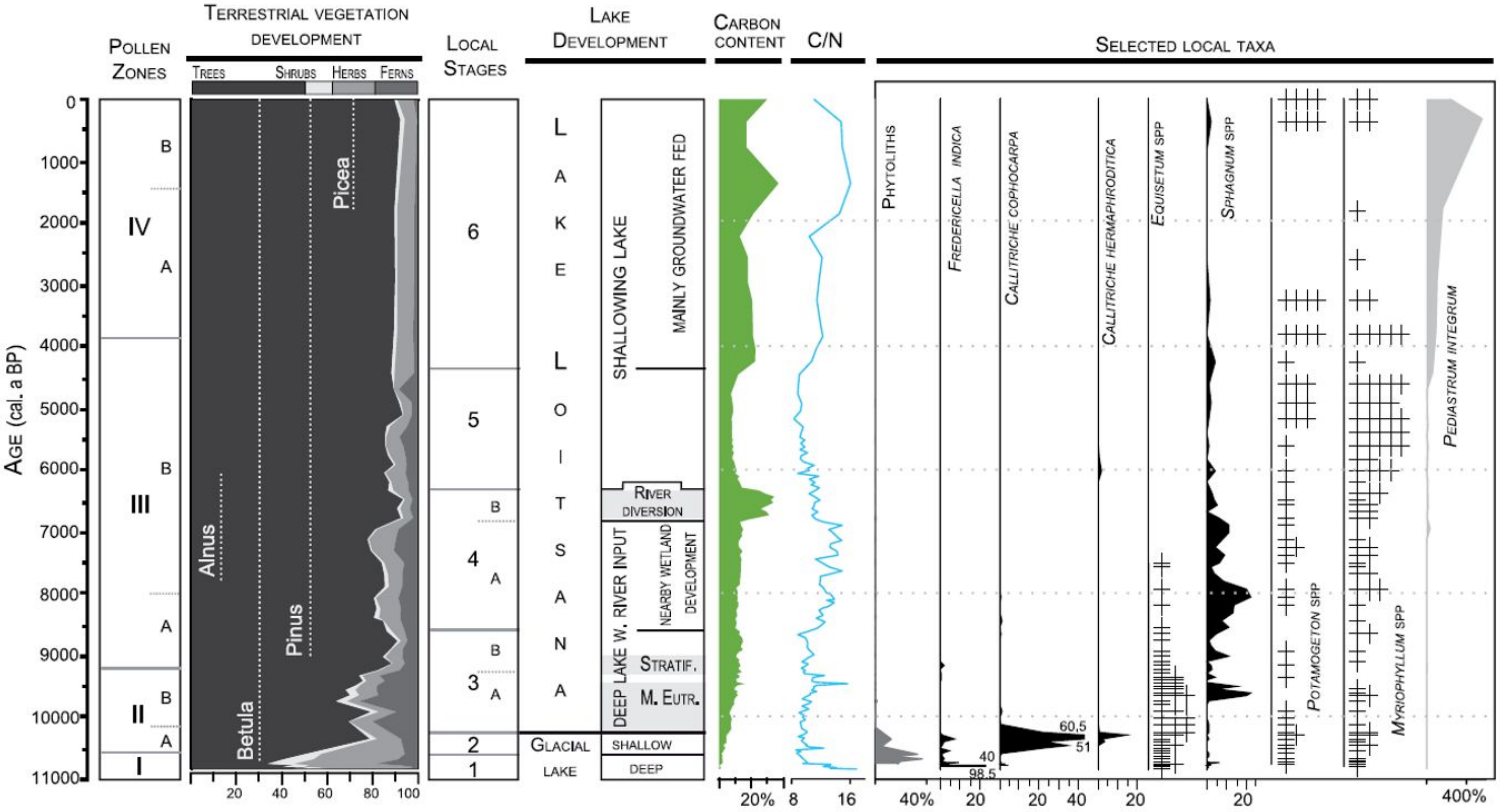
Seppä et al. (2009)

Fossils



Korhola (1990)

Fossils

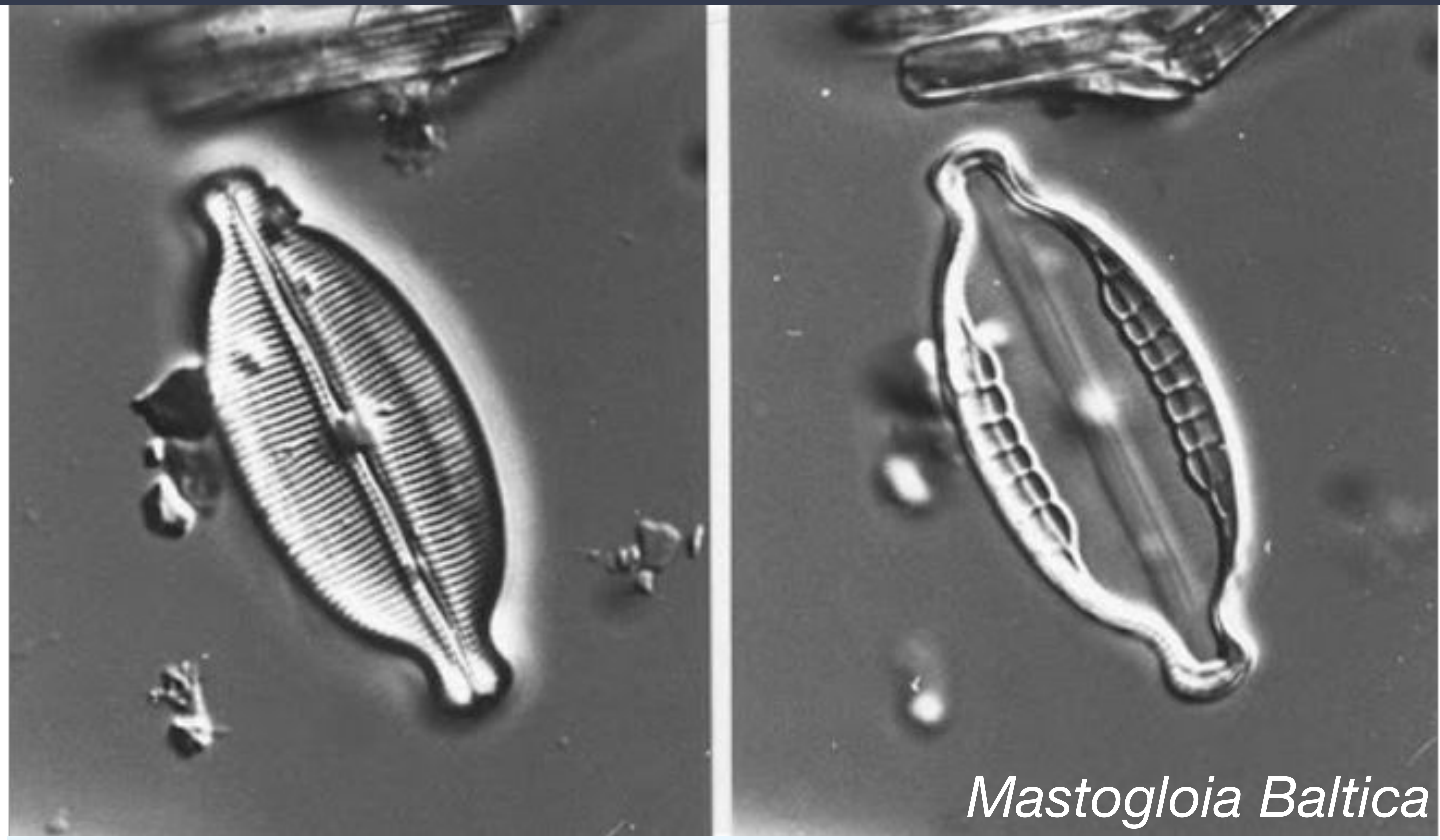


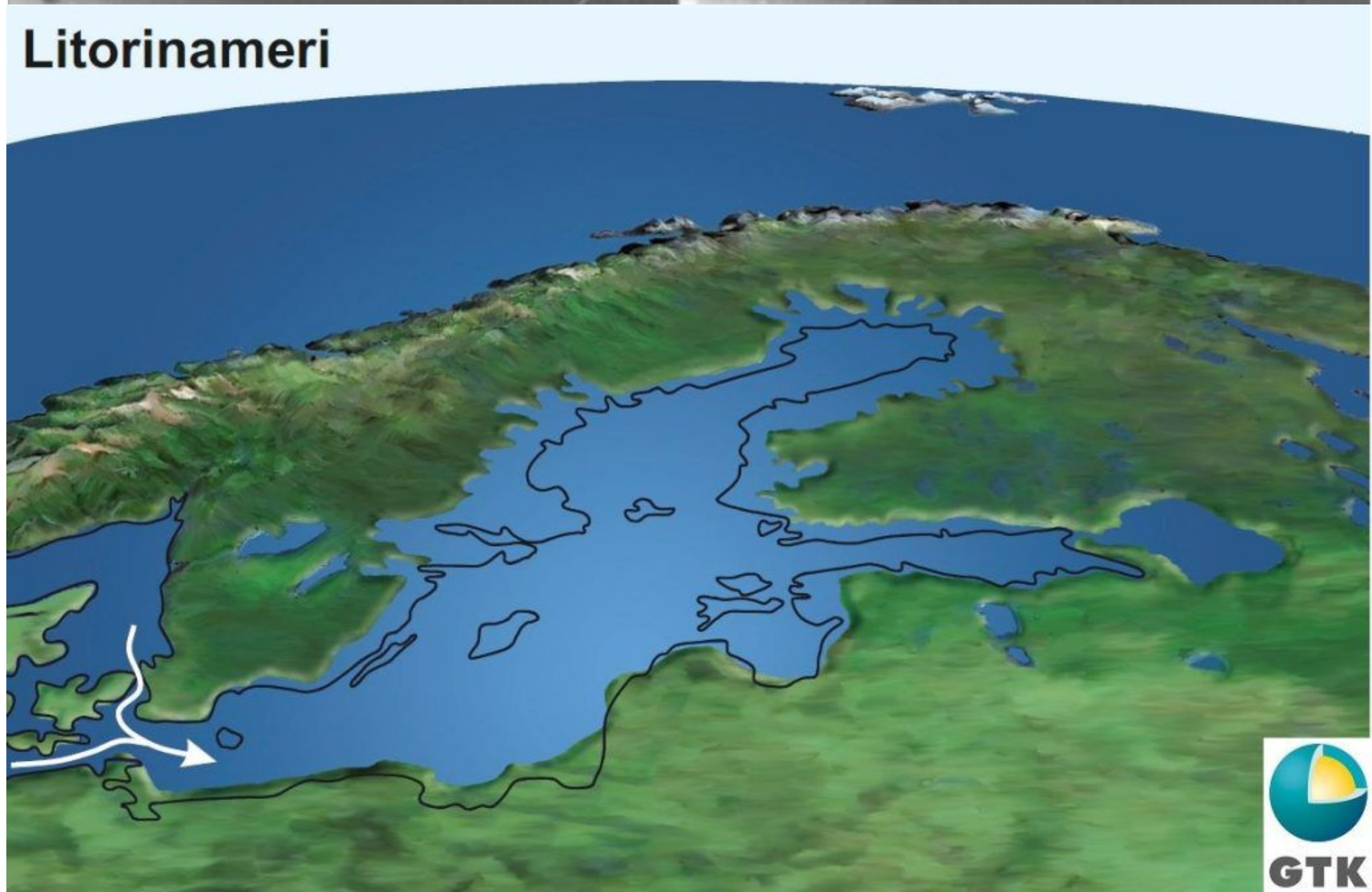
Shala et al. (2017)

Fossils

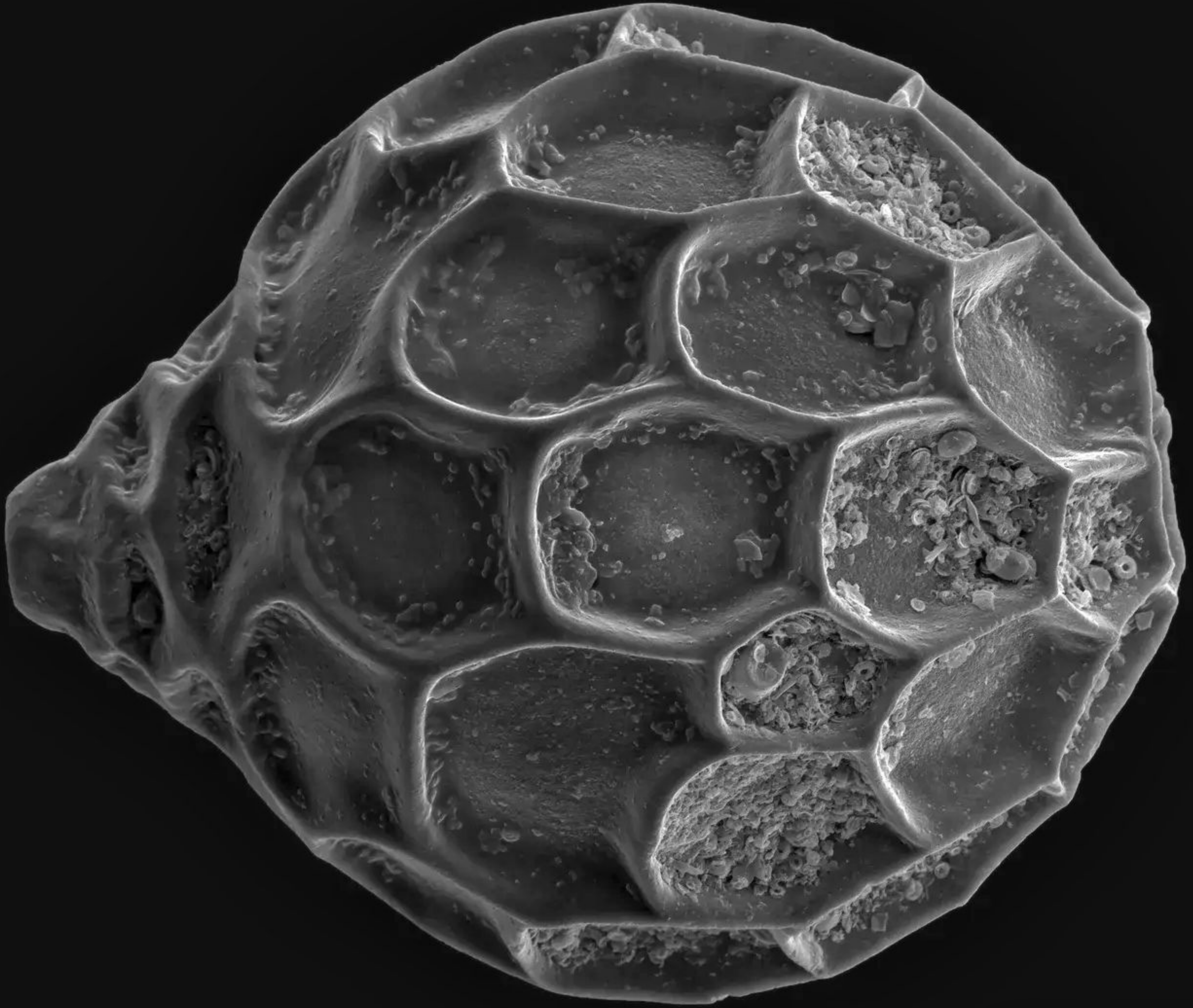
Diatoms (silica algae)

- Preserve well in sediments
- **Different species prefer different conditions** (salinity, nutrients, pH)
- Big environmental shifts can cause diatom “turnovers”


Mastogloia Baltica



$\delta^{18}O$

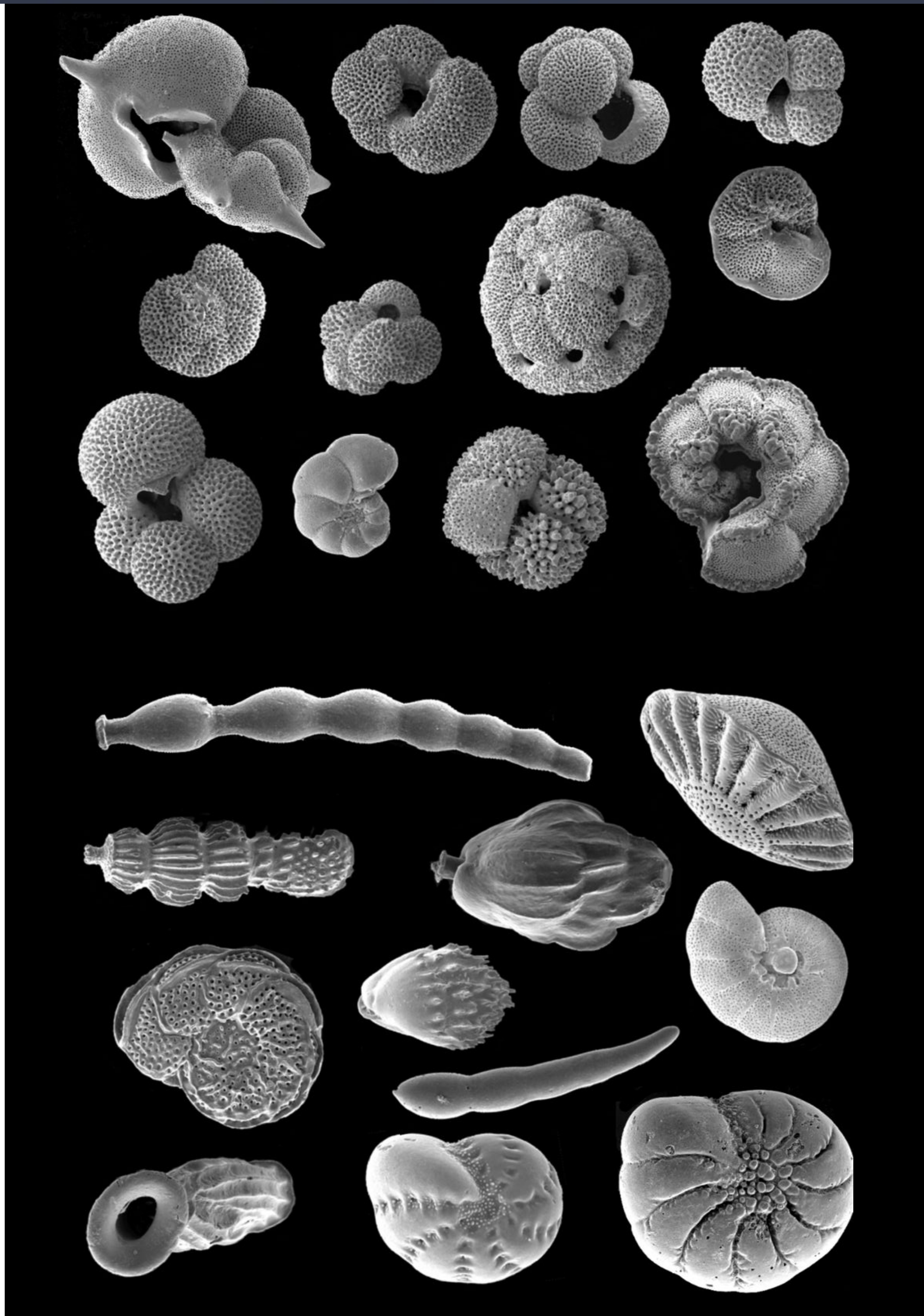


Foraminifera species *Favulina hexagona*

$\delta^{18}O$

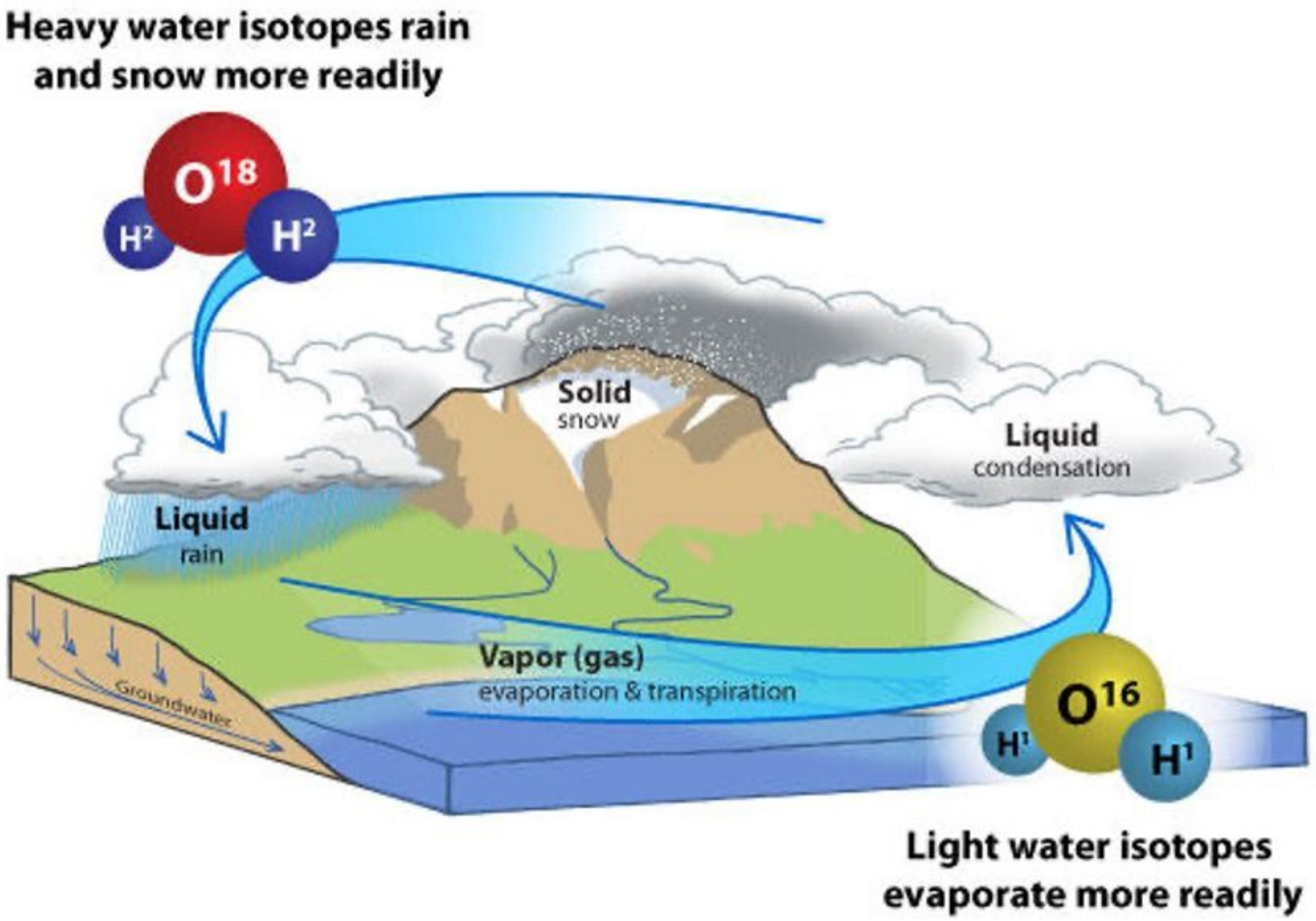
Foraminifera:

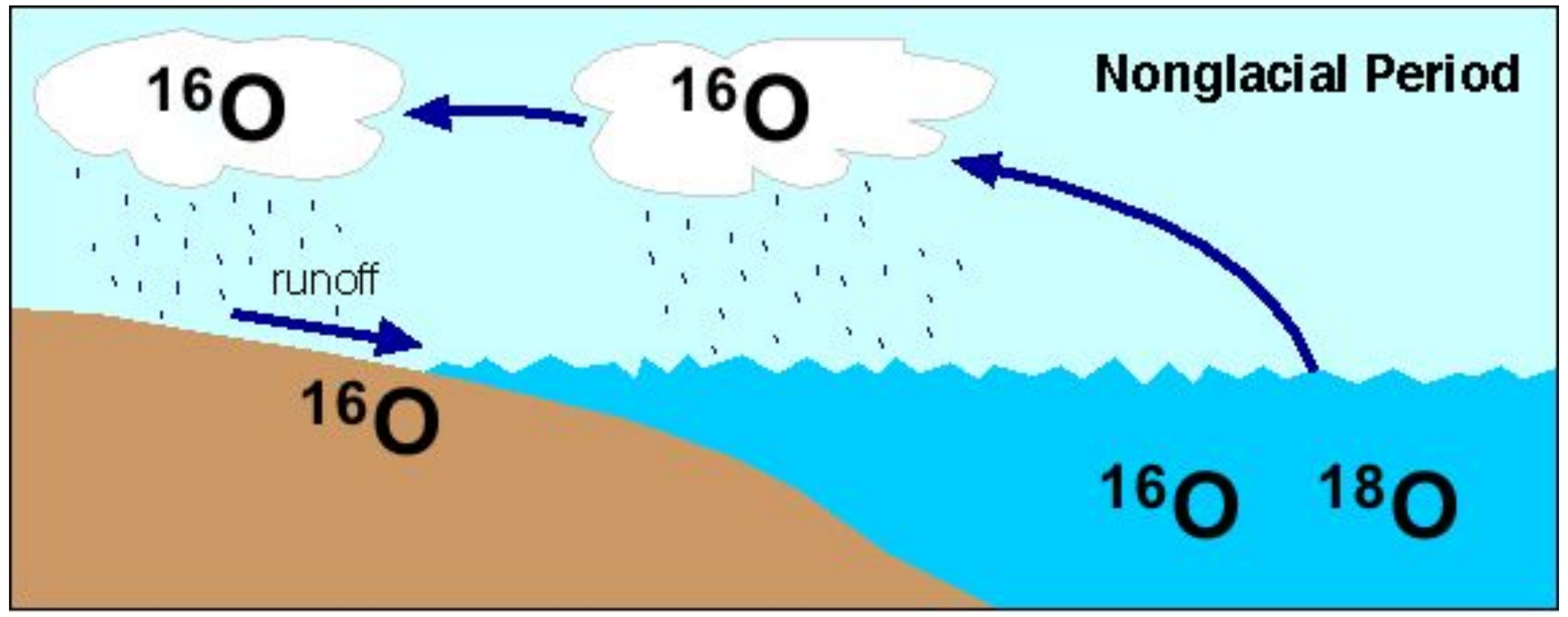
- Single-celled marine protists with **external shell**
- First fossils date to the Cambrian (541 ± 1Ma BP)
- **Chemistry of shell reflects seawater chemistry**

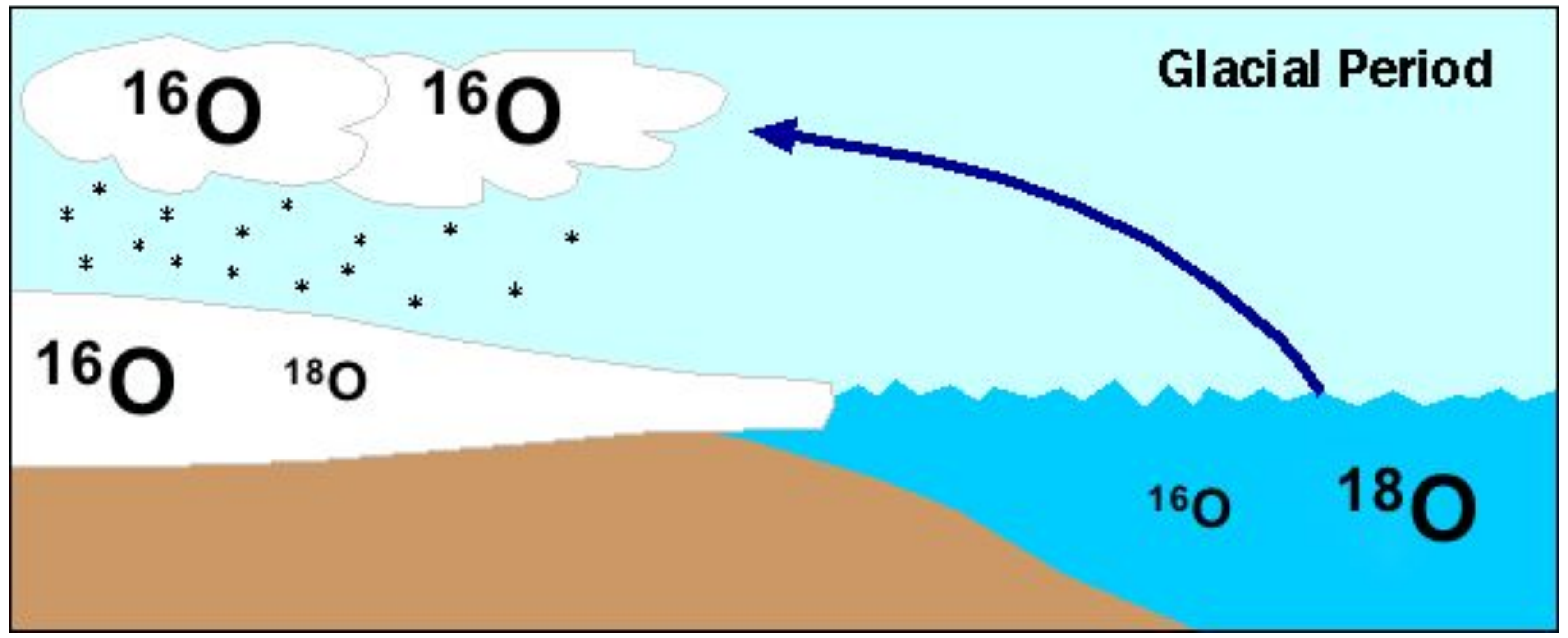


δ¹⁸O

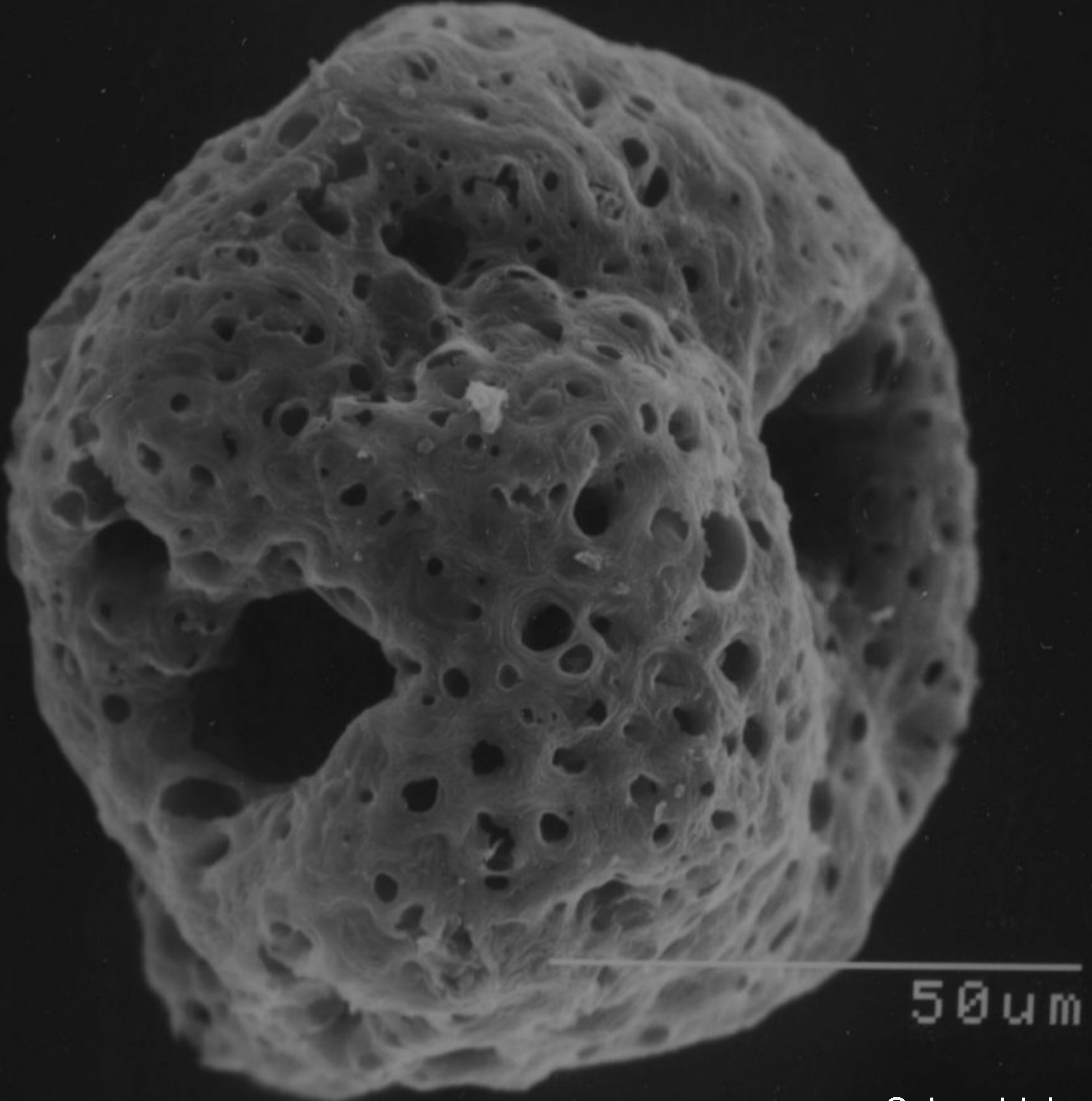
- Shell δ¹⁸O records seawater + temperature
- **higher δ¹⁸O: more global ice / colder**
- Produces **glacial-interglacial pattern** in marine sediments







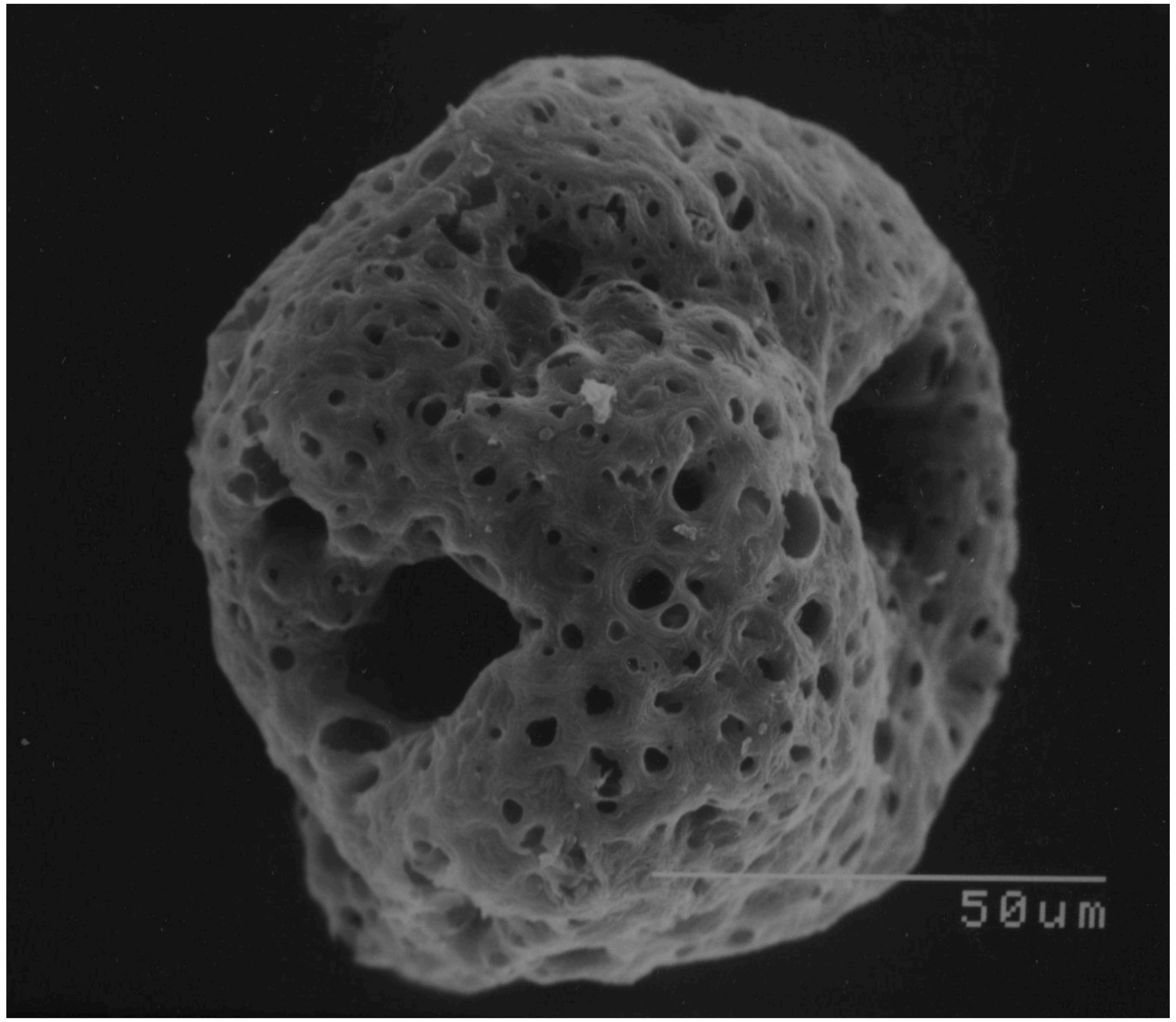
SCPs



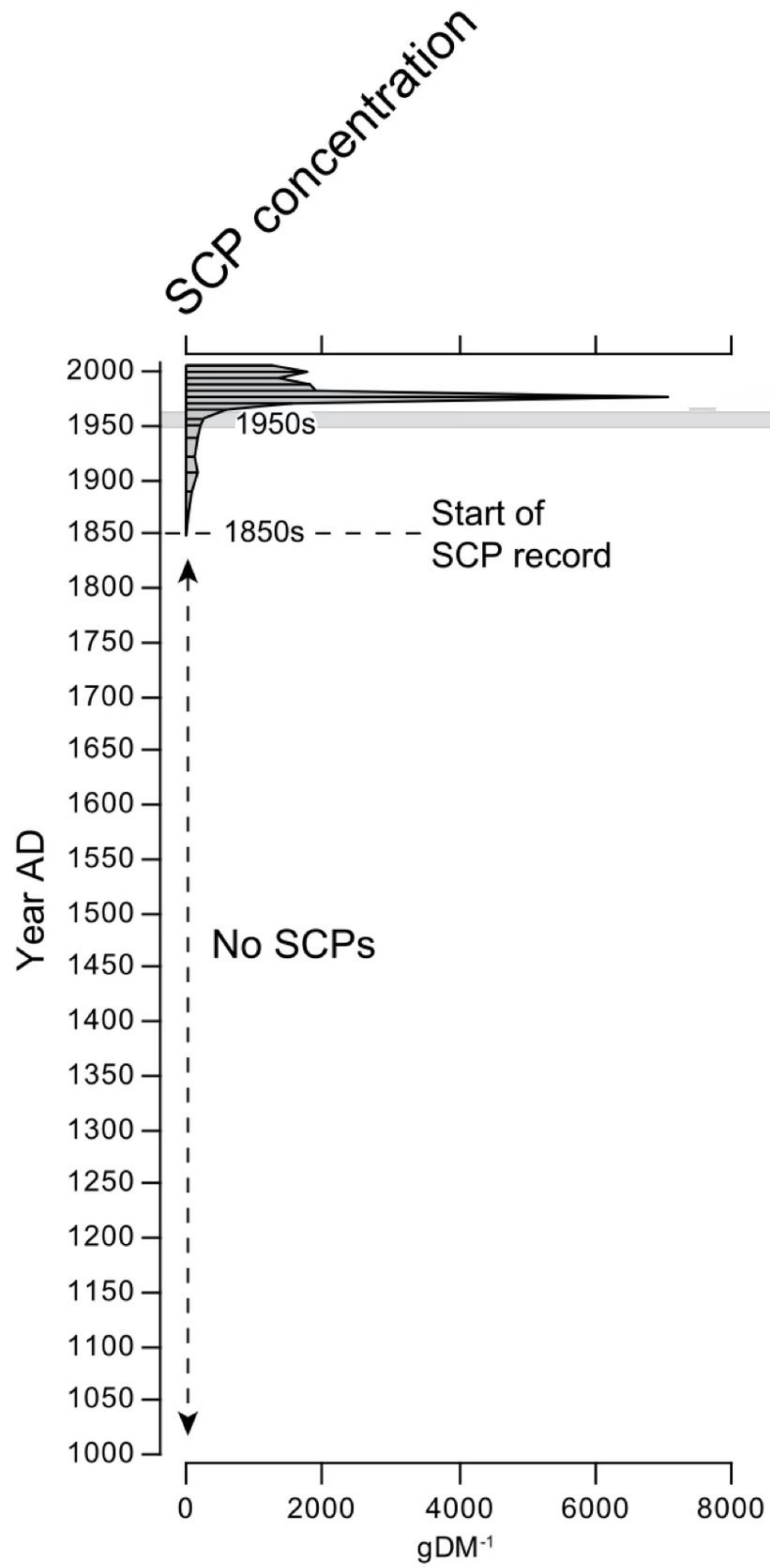
Spheroidal carbonaceous fly-ash particle

SCPs

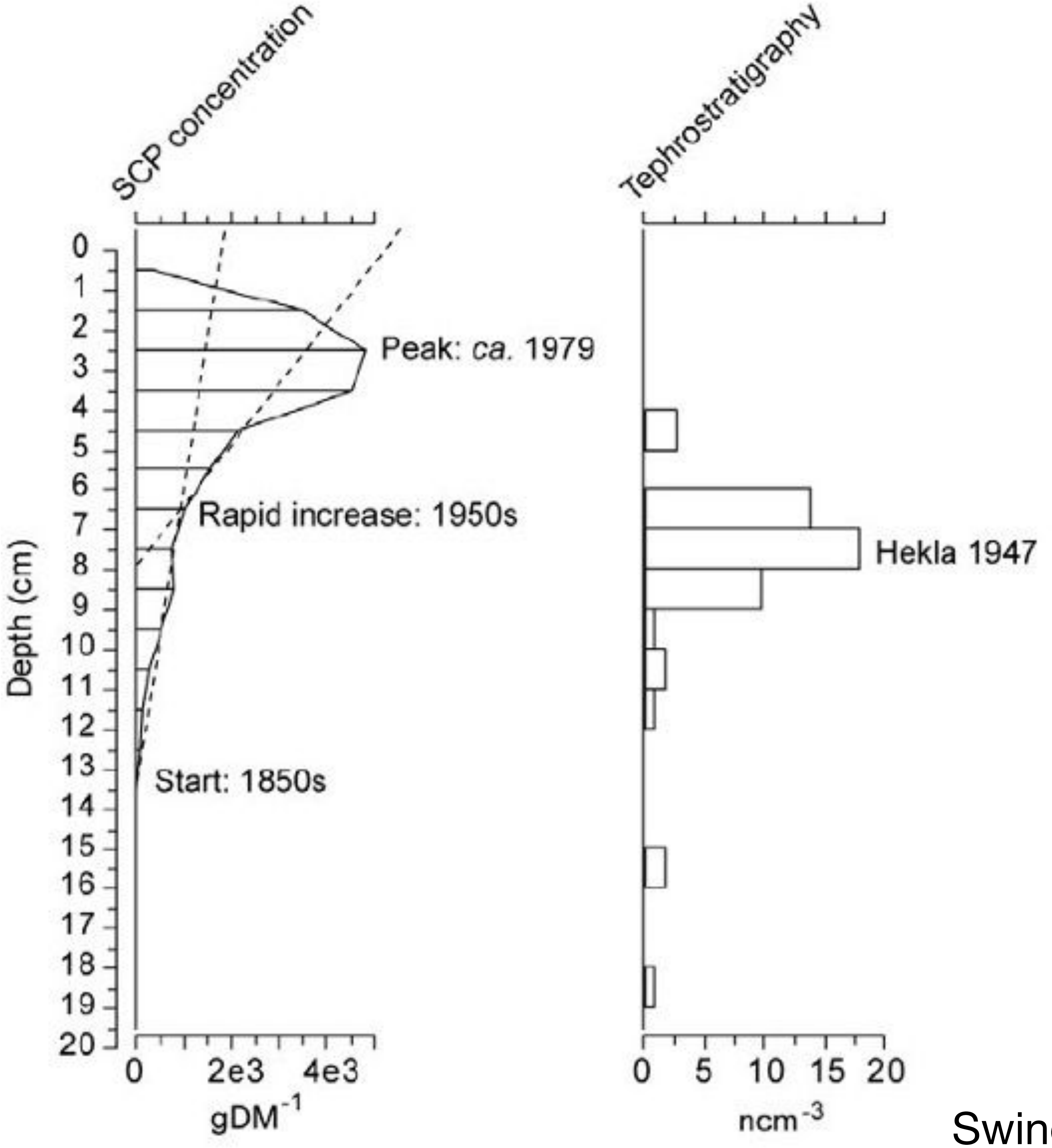
- Spheroidal Carbonaceous Particles
- **Formed during** high-temperature **fossil-fuel burning**
- Virtually **absent before industrialization** → “human-era” marker



SCPs



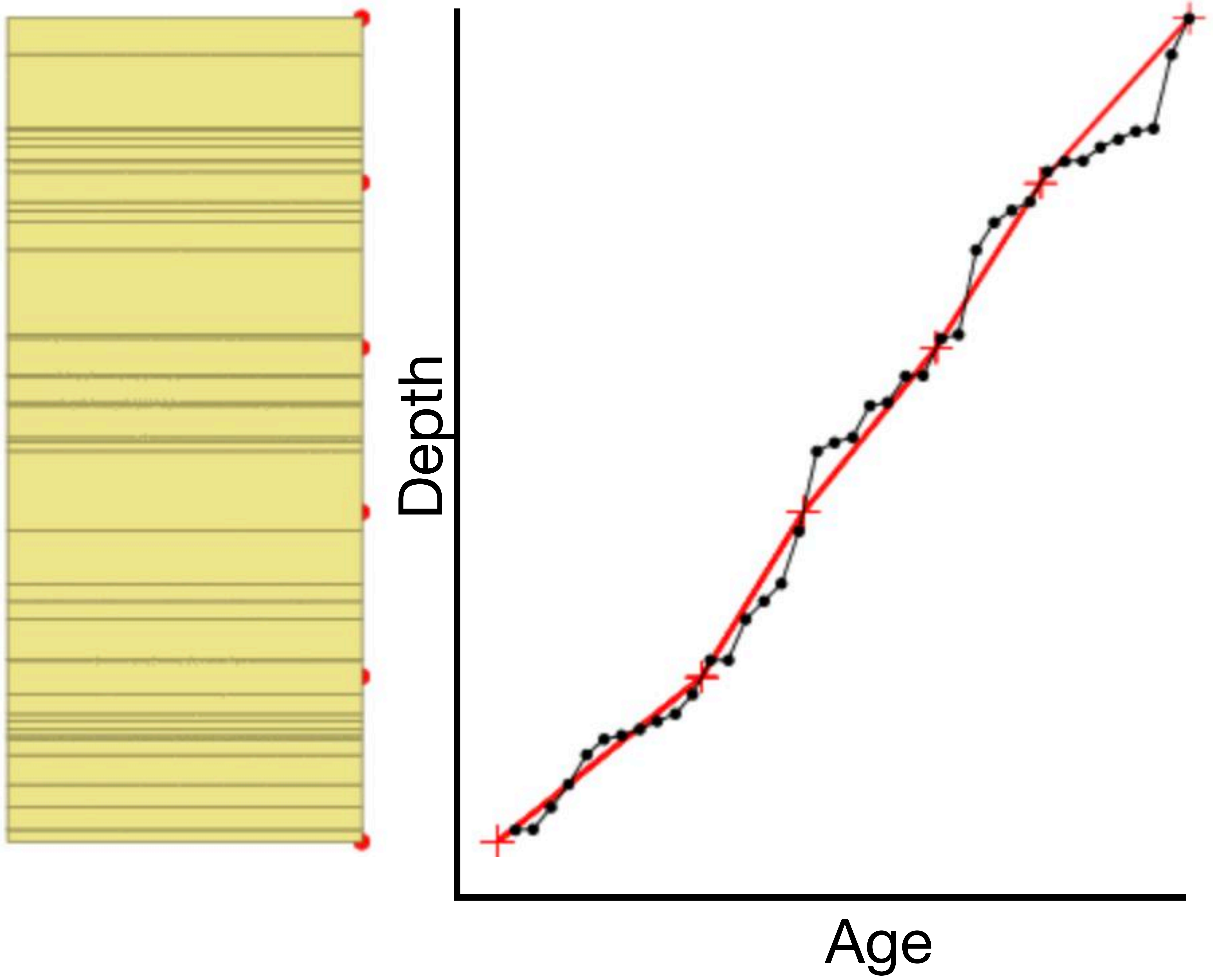
Swindles et al. (2015)



Swindles (2010)

Age-Depth Models

- Dating every slice is impractical
  → **only a few depths are dated**
- Ages and uncertainties needed for every depth
- Sedimentation rate changes
  → can't assume straight lines

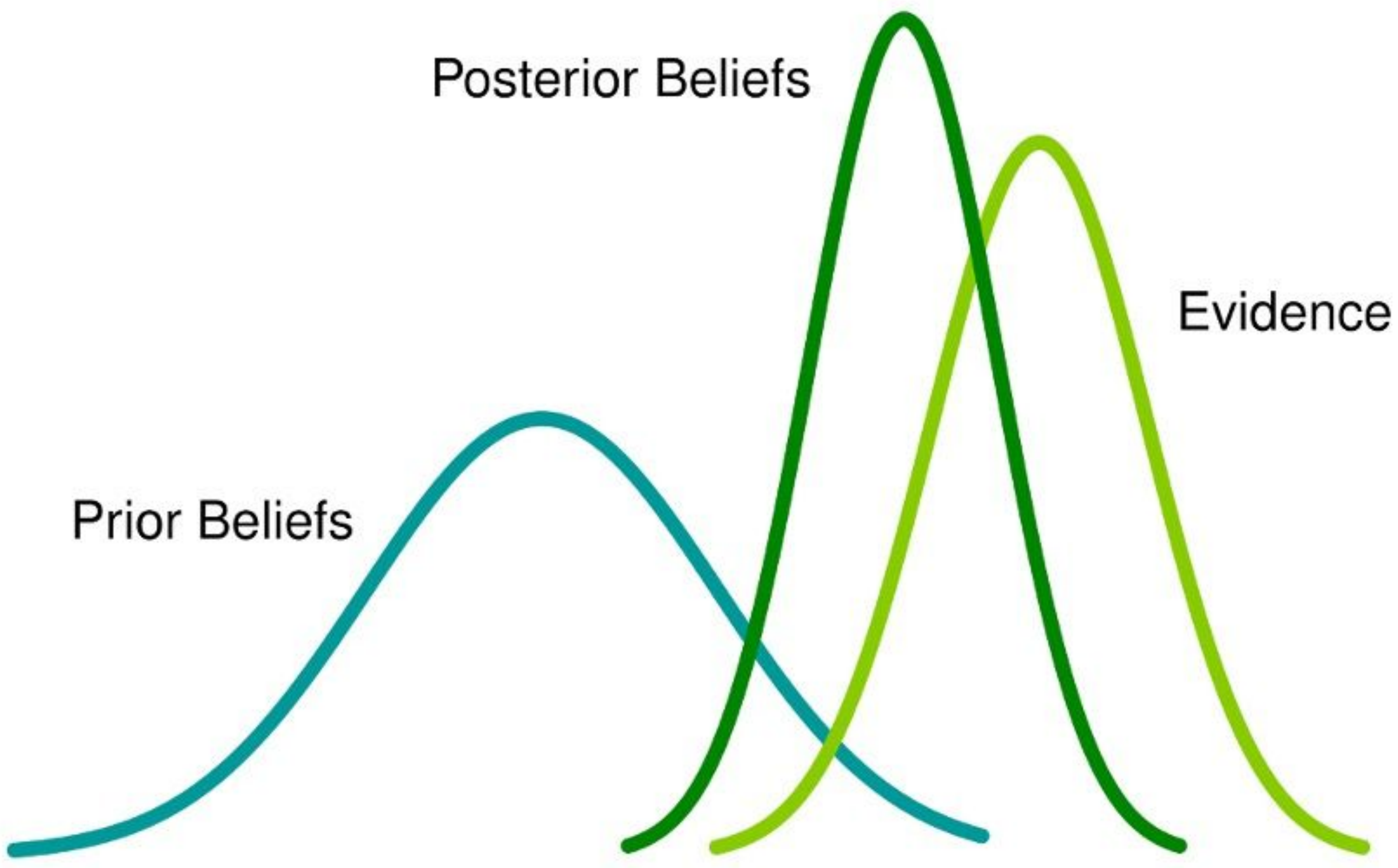


Age-Depth Models - Bayesian Statistics

- **Bayes' law:** The probability of an event is given by the existing evidence

- **Bayesian models:** Estimate most probable order of events, given the measurements and prior knowledge

- How likely is age-depth relationship based on:
  - ^{14}C dates (radiocarbon age)
  - Prior knowledge of atmospheric ^{14}C variations, sediment accumulation rate, ranges and variation…



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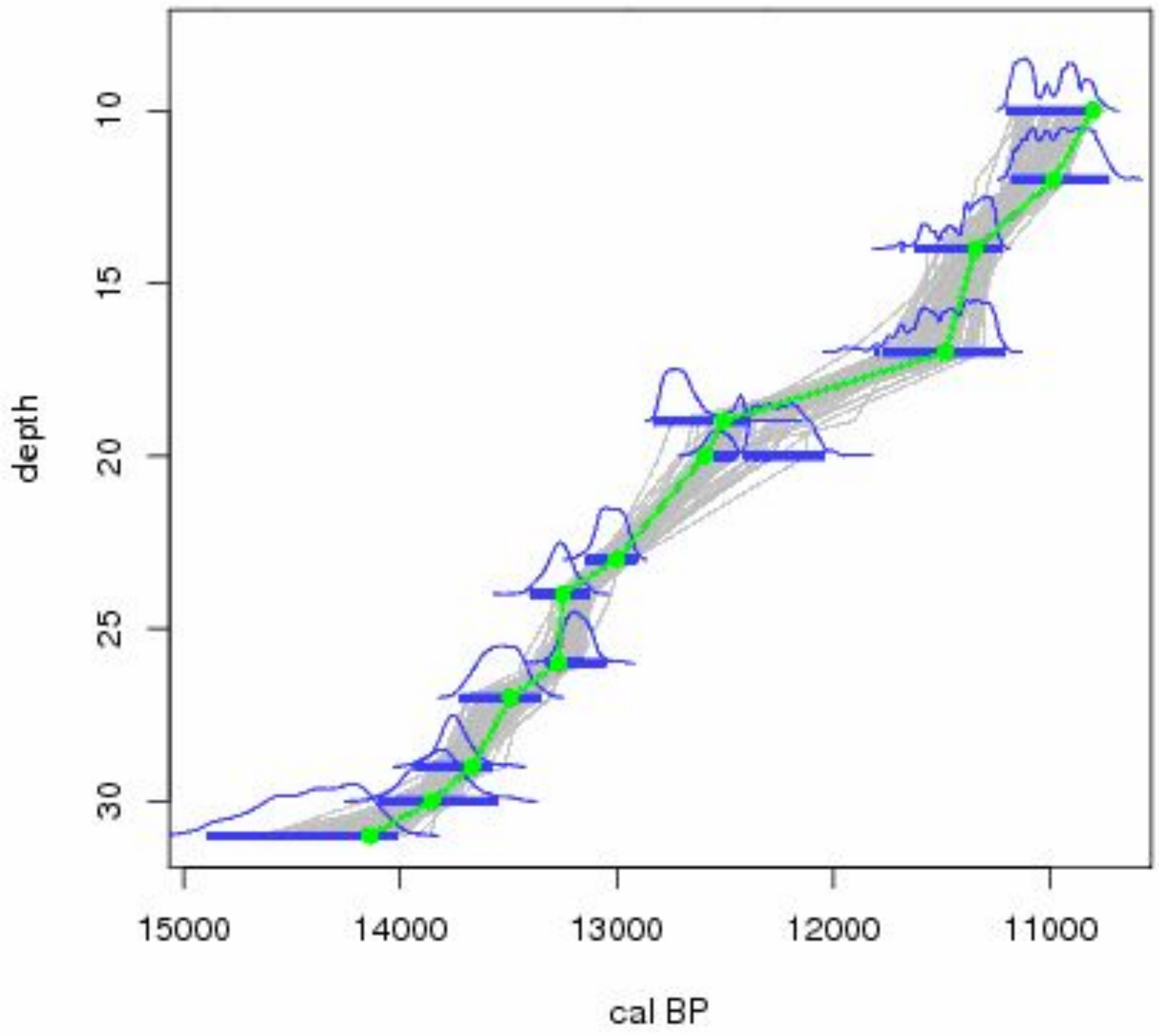
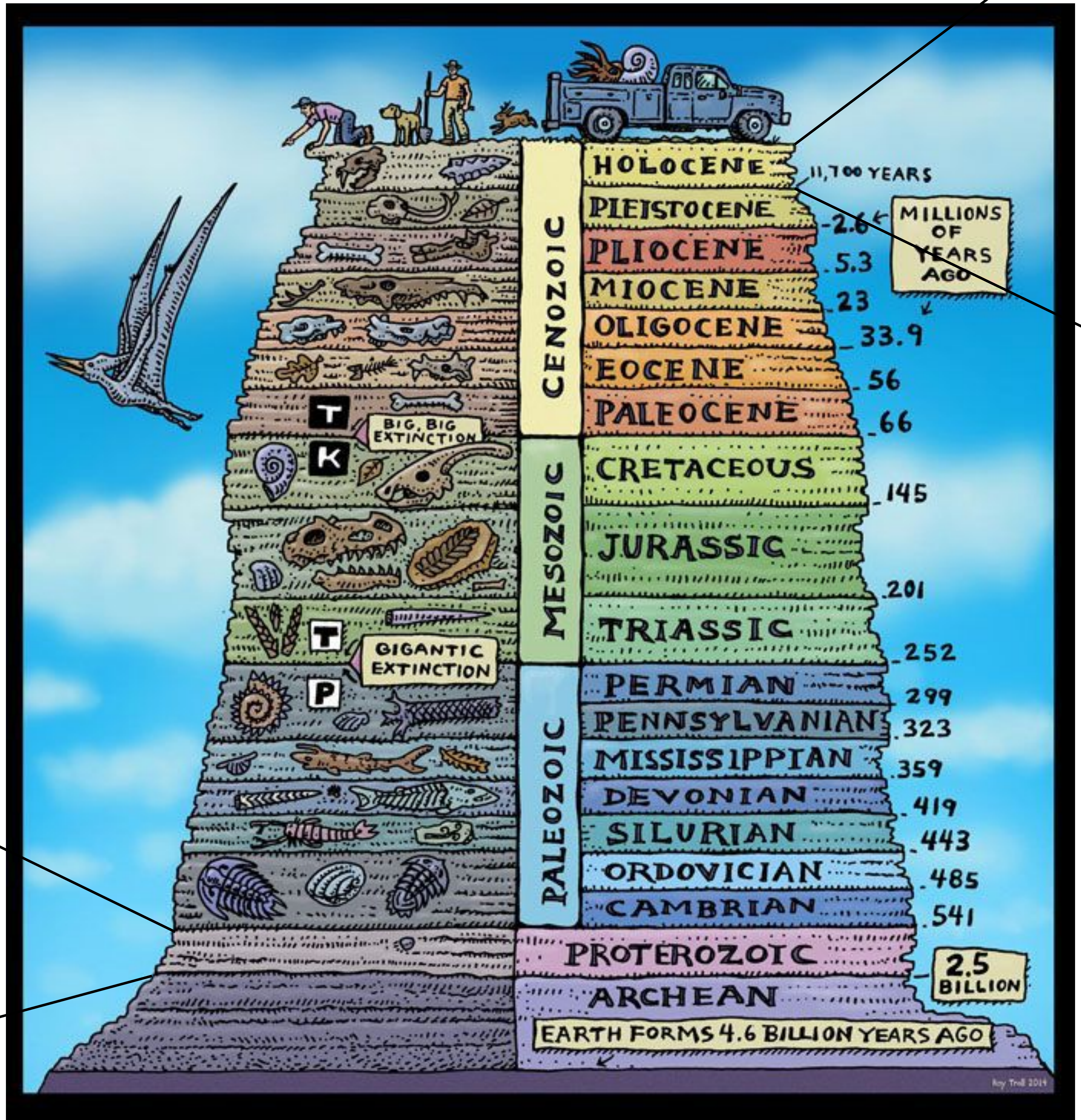


Which Method To Choose?

Which Method To Choose?



Which Method To Choose?

Which method(s) would you use to date the Kruunuvuorenlampi sediments?

^{210}Pb

^{14}C

Fossils

Tephra

Varves

SCPs

Paleomagnetism

Luminescence

$\delta^{18}O$

^{137}Cs