

Looking into the past to predict the future

The planet is rich of natural archives storing the past climate history



Arctic and Antarctic Ice



Glaciers

Peat bogs and mires

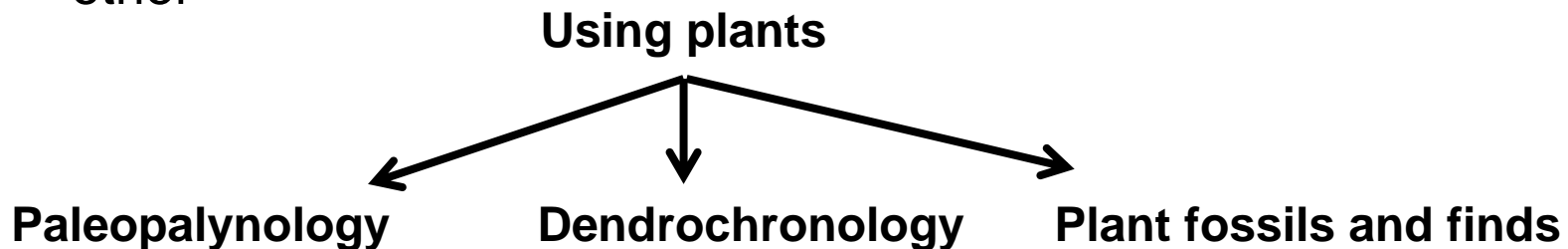


Marine and freshwater sediments



The analysis of sediments make use of many, integrated techniques to:

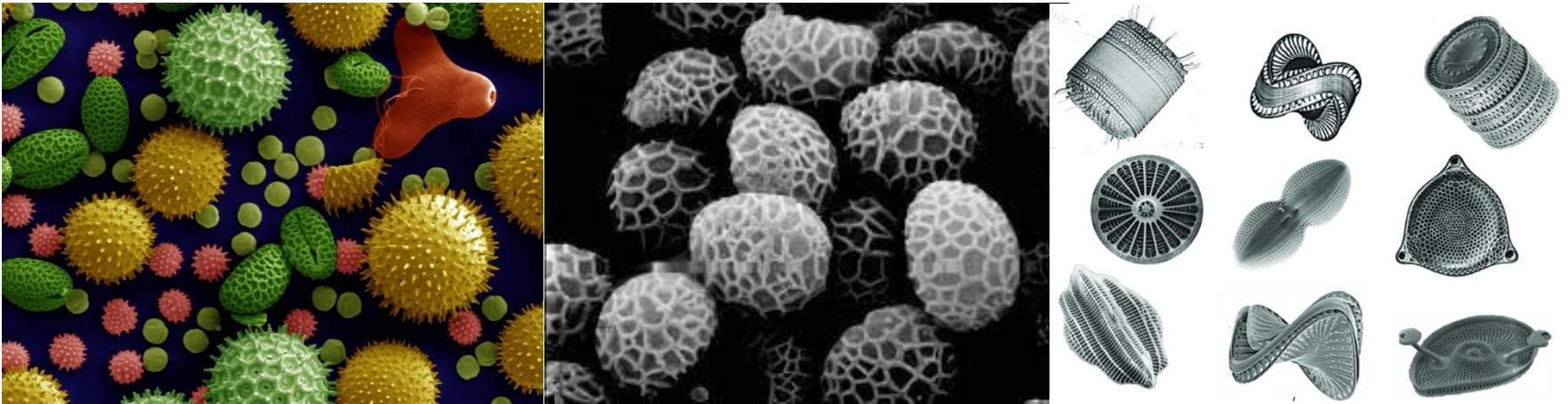
- Date the sediment layers
- Infer temperatures when the layer was deposited
- Date the organic component of the sediments (both plant and animal)
- Infer air composition
- Detect evidence of volcanic activity
- Reconstruct vegetation and its changes
- Estimate precipitations
- other



Palynology

Scientific discipline concerned with the study of **plant pollen, spores**, and certain **microscopic planktonic organisms**, in both **living** and **fossil form**.

Palynology = combination of the Greek verb palunein (παλύνειν, “to strew or sprinkle”), the Greek noun pale (παλη, in the sense of “dust, fine meal”) -> close to the Latin word pollen, meaning “fine flour, dust”)



The field is associated with the plant sciences as well as with the geologic sciences, notably those aspects dealing with stratigraphy, historical geology, and paleontology

Palinology involves:

a) Base research -> morphology, taxonomy, physical and chemical properties of pollen wall, correlation of palynology with other branches of biology, such as cytology, taxonomy, etc.; **e.g.** the analysis of morphology leads to the determination of pollen types (taxonomic comparisons) and identification keys (Morphopalynology).



b) Applied research -> taxonomic determination of pollen grains recovered from various substrates. Taxonomic identification aided by pollen atlases or libraries made of reference material.

Applications of Palinology:

- b) **Briopalynology**, study of the pollen landing on mosses and lichens and other plant organisms playing as natural traps;
- c) **Melissopalynology**, study of the pollen ending in honey (or in other bees' products) -> compliance of the honey with the label;

Are we sure it is a Dandelion (*Taraxacus sp.*) honey?



- d) **Pharmacopalynology**, study of pollen grains in drugs and herbal products;

Applications of Palinology:

- f) **Forensic palynology**, determination of pollen grains recovered from samples of crime scenes or related samples;
- g) **Archeopalynology**, study of pollen diversity from site inhabited by humans

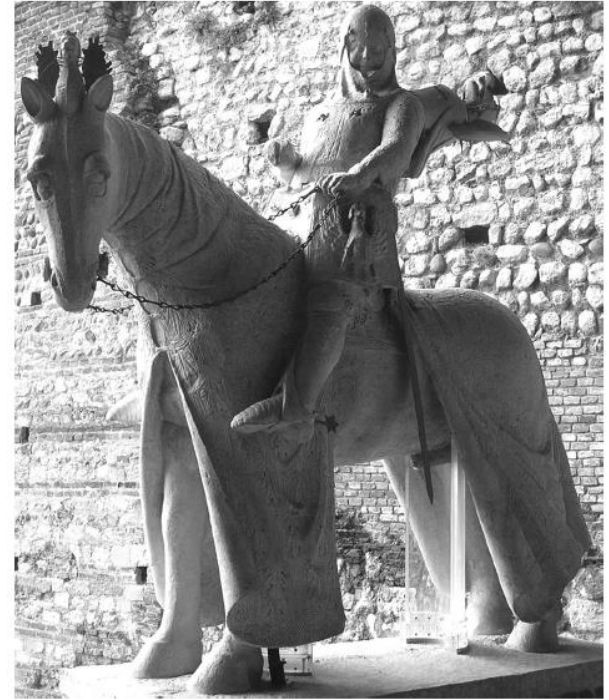


Fig. 1. The equestrian statue of Cangrande (Castelvecchio Museum, Verona).

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A medieval case of digitalis poisoning: the sudden death of Cangrande della Scala, lord of verona (1291–1329)

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CrossMark

"Palynological analyses demonstrated the presence of pollen grains of Digitalis sp./foxglove in the rectum content, along with Matricaria chamomilla/chamomille and Morus nigra/black mulberry."

f) **Paleopalynology**, study of fossil pollen and spores conserved in marine and freshwater sediments, peat bogs, soils, glaciers, etc.

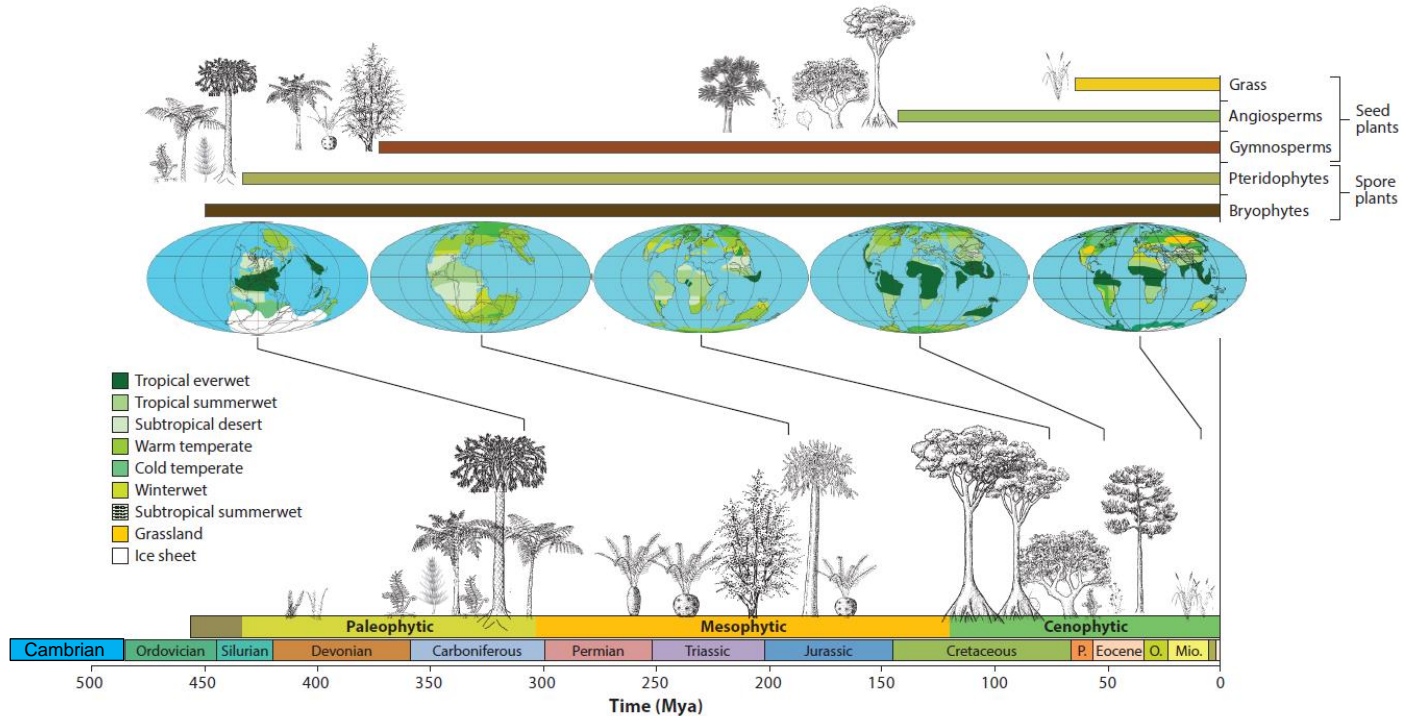


Figure 1

Time line of plant evolution demonstrating the estimated first occurrences of major plant groups [bryophytes, based on the time of origin of land plants, >450 Mya (139); pteridophytes, based on the time of origin of vascular plants, 433.5 Mya (139); gymnosperms, based on the time of origin of seed plants, 373.8 Mya; angiosperms, 143.8 Mya (139); and grasses, 65 Mya (148)], biomes through time (166), and the timing of the phases of plant evolutionary floras (Paleophytic, Mesophytic, and Cenophytic), modified from Reference 30. Plant illustrations from Reference 166 by Marlene Hill-Donnelly; used with permission. Geological timescale from the 2013 update by the International Commission on Stratigraphy. Abbreviations: Mio., Miocene; O., Oligocene; P., Paleocene.

Identification of pollen and spore microfossils has greatly aided delineation of the geographical distribution of many plant groups from early Cambrian time (some 541 million years ago) to the present

Pollen = male microgametophyte

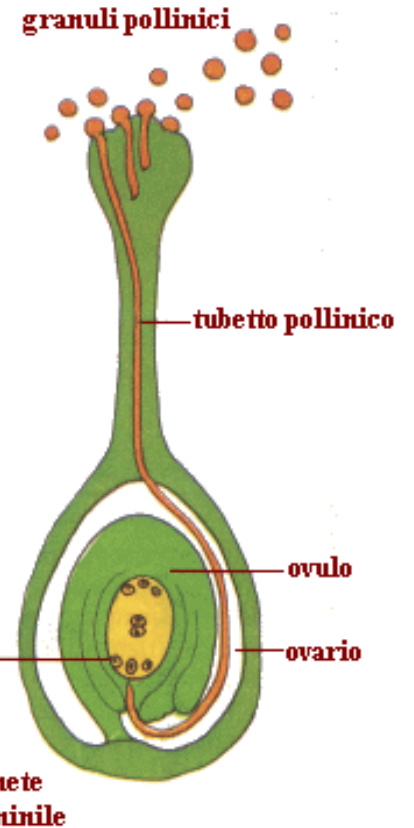
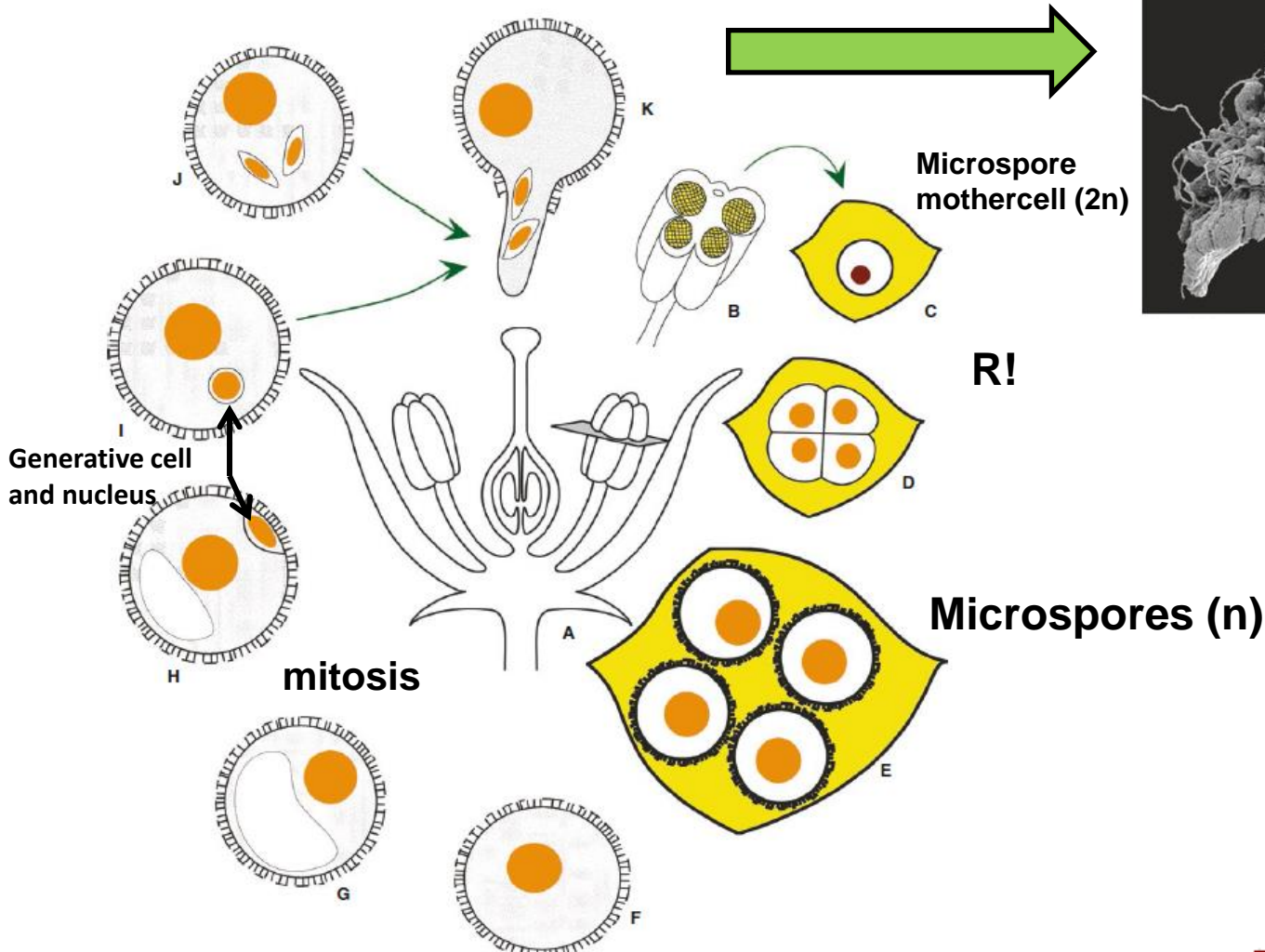
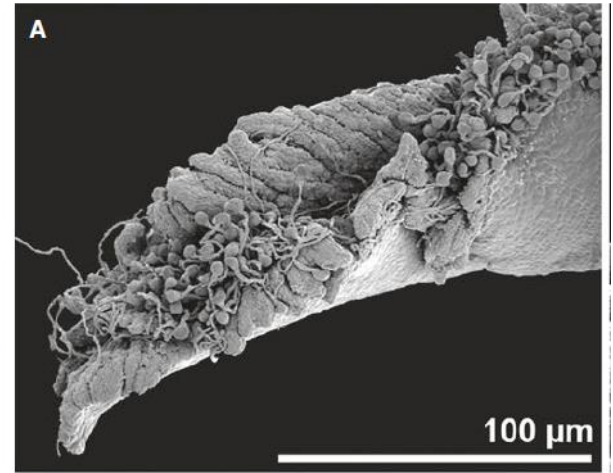
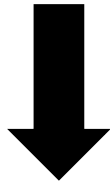


Fig. 1 Pollen development in angiosperms. A. Schematic illustration of an angiosperm flower. B. Cross section of anther. C. Pollen mother cell (PMC) enclosed in callose (diploid nucleus dark red). D. Tetrad of four haploid microspores enclosed in callose (haploid nucleus orange). E. Pollen wall formation and separation of microspores. F. A single free microspore with central haploid nucleus. G. Beginning of gametogenesis, formation of a central vacuole (white). H. First pollen mitosis, lens-shaped generative cell with generative nucleus attached to pollen wall. I. Two-celled pollen grain, generative cell detached from pollen wall. J. Three-celled pollen grain after second pollen mitosis, note two sperm cells with sperm nuclei. K. Germination can occur from either a two-celled pollen grain, followed by the formation of sperm cells, or from a three-celled pollen grain (pathways indicated by green arrows)

Pollen grains morphology

Among taxonomic groups they can exhibit tremendous variability:

- polarity
- shape (dry ≠ wet!)
- dimensions
- apertures
- ornamentation of the pollen wall
- Etc.

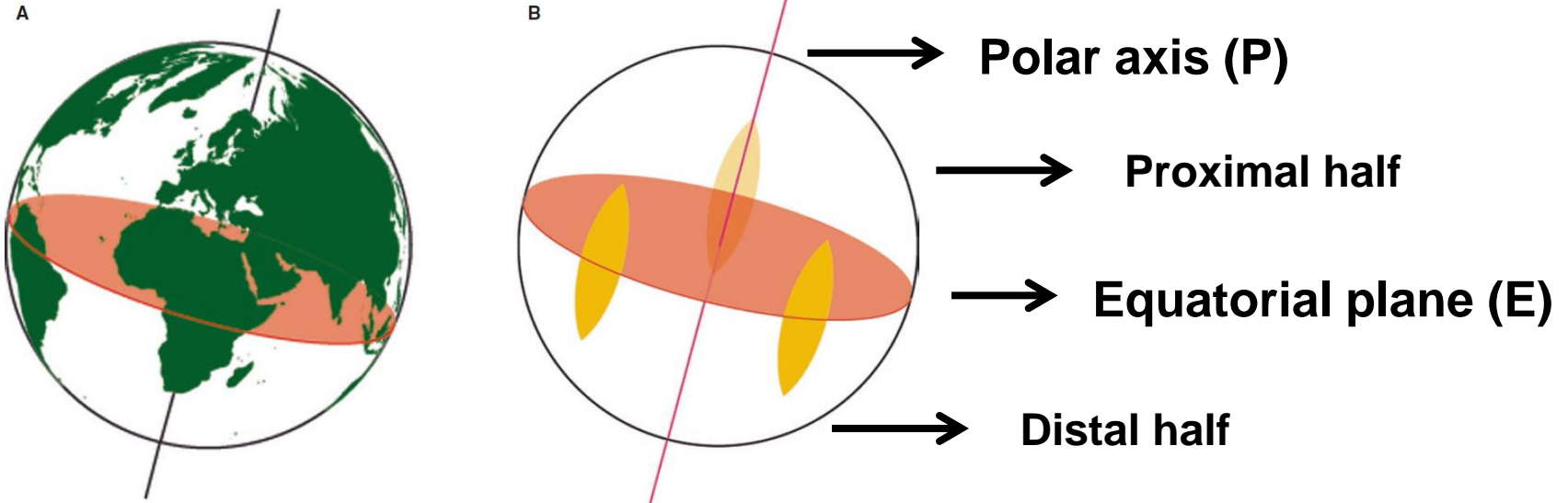
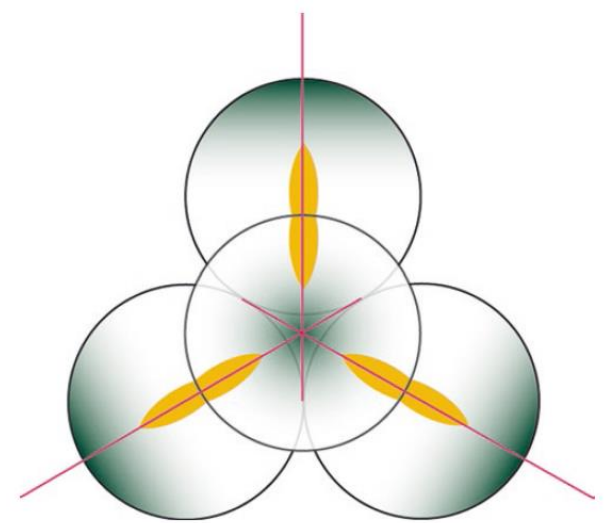


Diagnostic characters used to identify the belonging to a taxonomic group: **family**, **genus** or even **species**.



Polarity and pollen shape

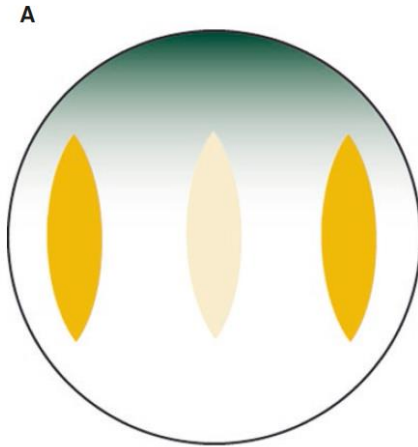
Pollen shape and aperture location relate directly to pollen **polarity**. The polarity is determined by the spatial orientation of the microspore in the meiotic tetrad and can be examined in the **tetrad stage**.



The **polar axis** of each microspore/ pollen runs from the **proximal pole**, orientated towards the tetrad center, to the **distal pole** of the microspore/pollen. The **equatorial plane** is located at the microspore's center, perpendicular to the polar axis (Fig. 2). Therefore, the **equatorial plane** divides the microspore/pollen into a proximal and a distal half

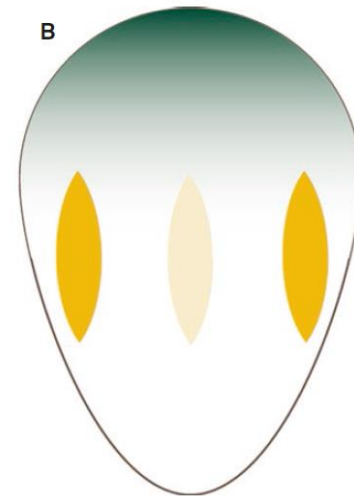
Isopolar pollen

has identical proximal and distal poles,
thus the equatorial plane is a symmetry
plane.



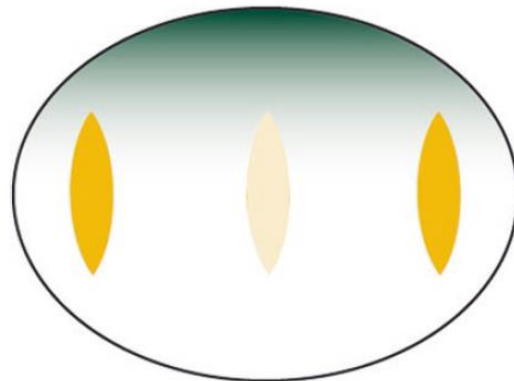
Heteropolar pollen

the proximal and distal halves differ

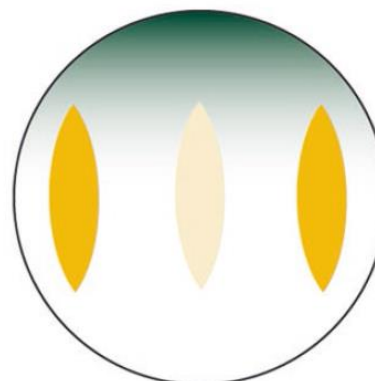


P/E ratio -> type of polarity

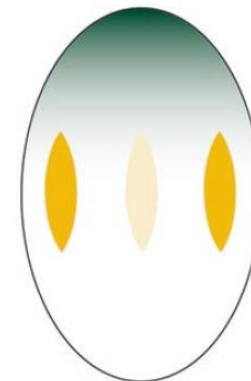
Oblate



Isodiametric



Prolate



Dicots vs monocots

Dicots : Isodiametric pollen; apertures along the equatorial plane

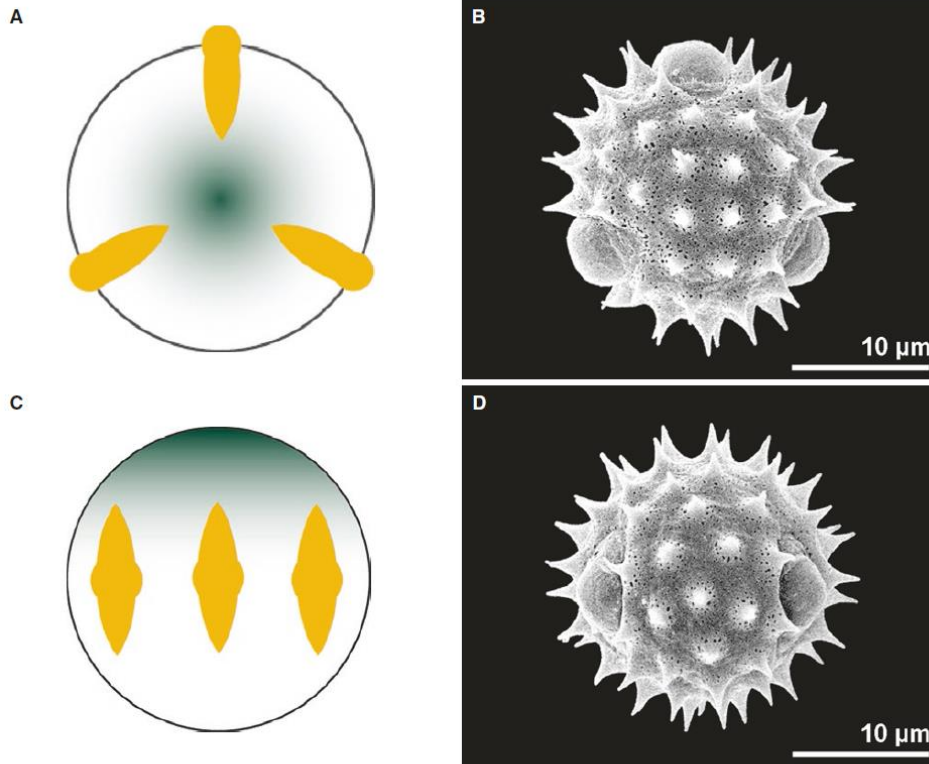


Fig. 3 Polarity of pollen in dicots. A-B. *Bellis perennis*, Asteraceae, polar view. C-D. *Bellis perennis*, Asteraceae, equatorial view

Monocots: Oblate pollen; aperture at the distal pole

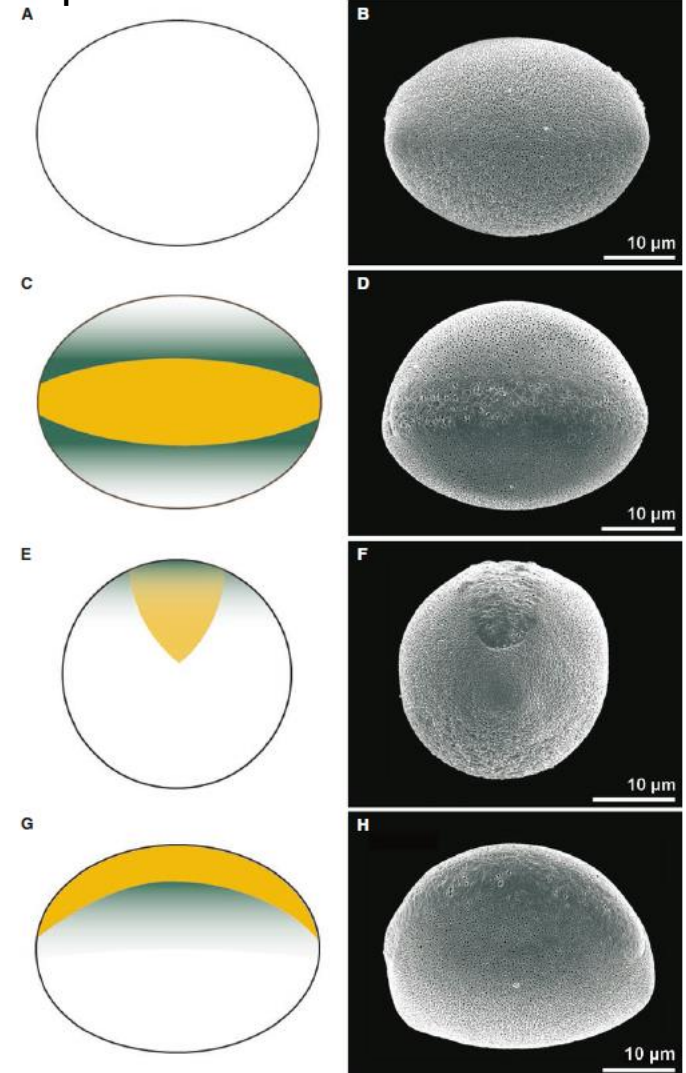


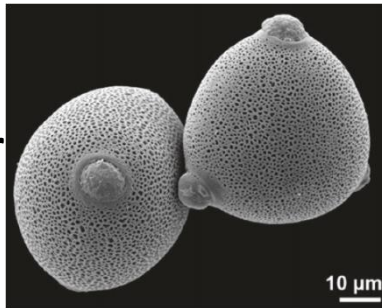
Fig. 4 Polarity of pollen in monocots (*Allium paradoxum*, Alliaceae). A-B. Proximal polar view. C-D. Distal polar view. E-F. Equatorial view (short axis). G-H. Equatorial view (long axis)

Apertures

An **aperture** is a region of the pollen wall that differs significantly from its surroundings in morphology and/or anatomy. The aperture is presumed to function as the site of germination

Circular apertures

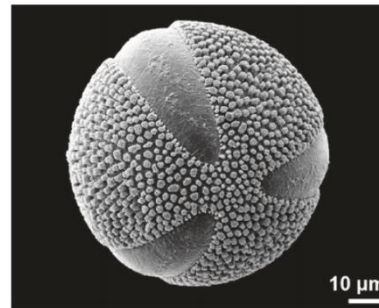
Porus/Porate



Positioned
equatorially or
globally

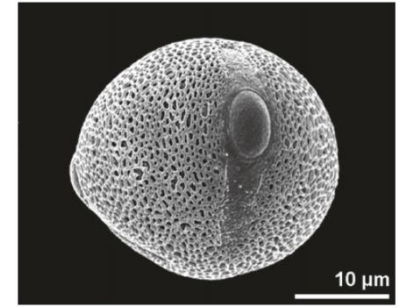
Elongated apertures

Colpus/Colpate

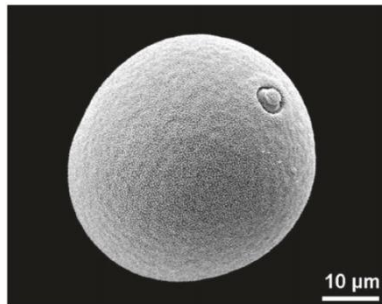


Hybrid apertures

Colporus/Colporate



Ulcus/Ulcerate



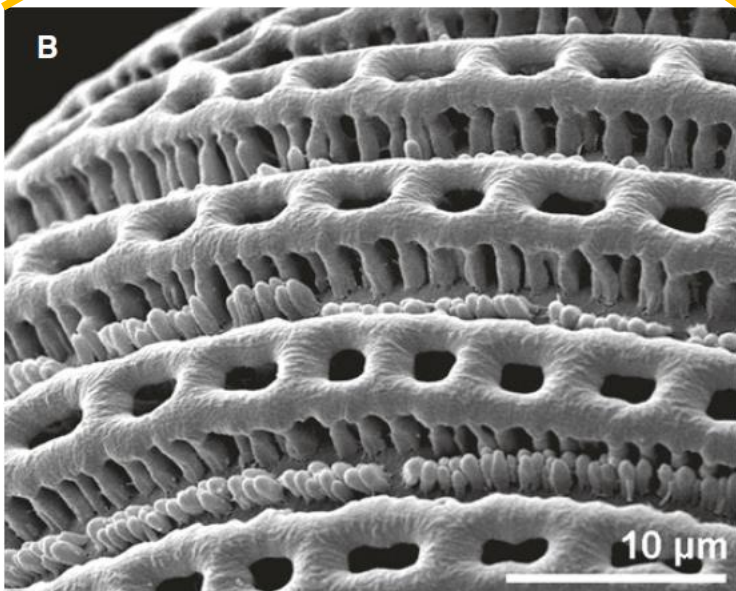
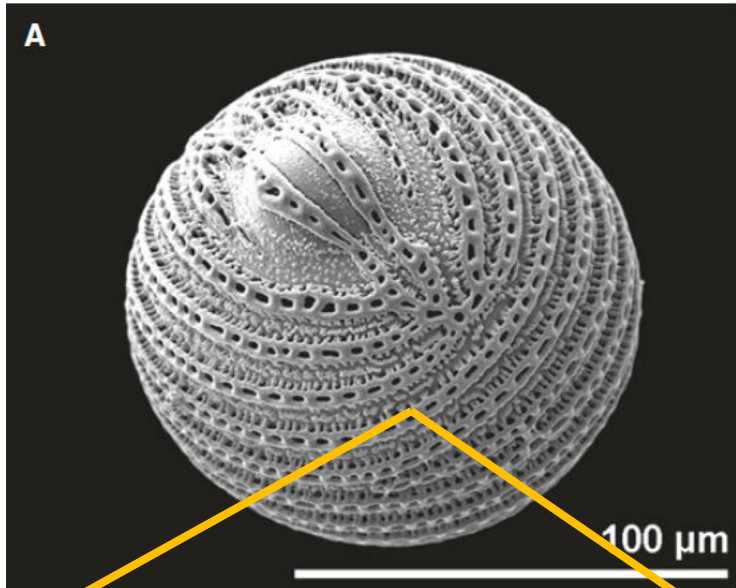
Positioned
distally

Sulcus/Sulcate

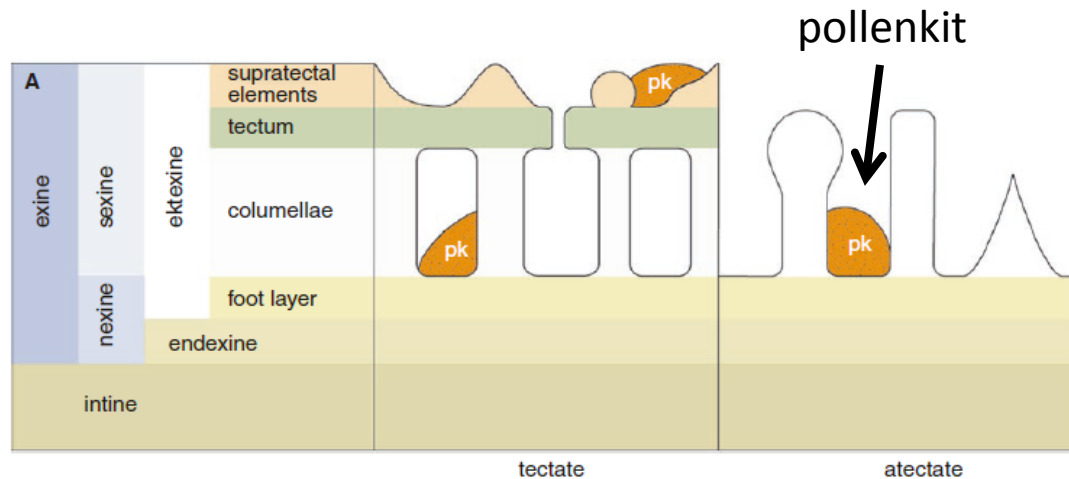


Inaperturate (without apertures) pollens are also present as well as **Heteroaperturate** pollens (different types of aperture on the same pollen grain)

Pollen wall and ornamentation



The **pollen wall (sporoderm)** of seed plants is formed by two main layers: the outer **exine** and the inner **intine** (Fig. 15).

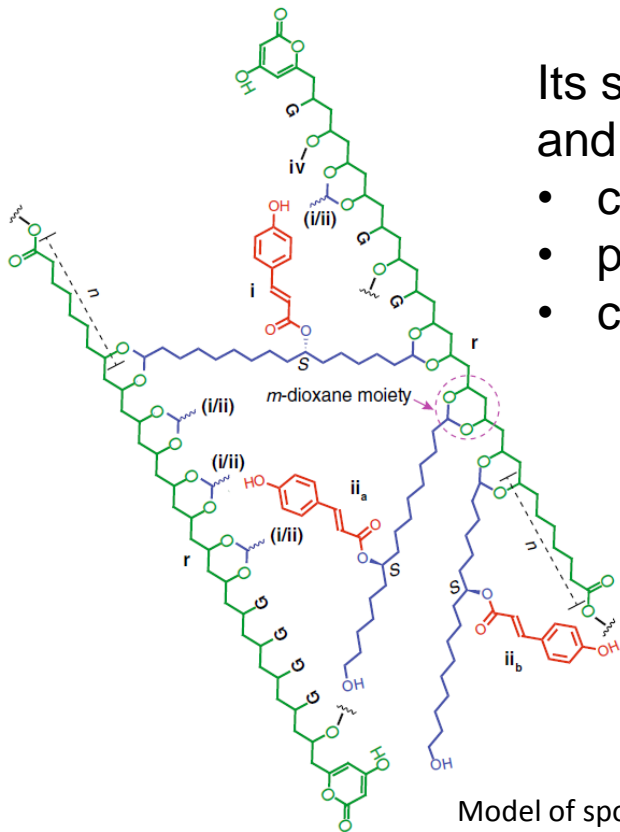


The exine consists mainly of **sporopollenin**. The intine is mainly composed of cellulose and pectin. Aperture regions are characterized by the reduction of exine structures or by a deviant exine, and a thick, often bilayered intine.

Sporopollenin

Zetsche et al. (1931) coined the term "sporopollenin", from the previous terms "pollenin" and "sporonin" used to indicate the resistant exine material of pollen and spores, respectively.

Sporopollenin is a complex biopolymer and **extremely resistant** to decay as well as to chemical and mechanical damage.

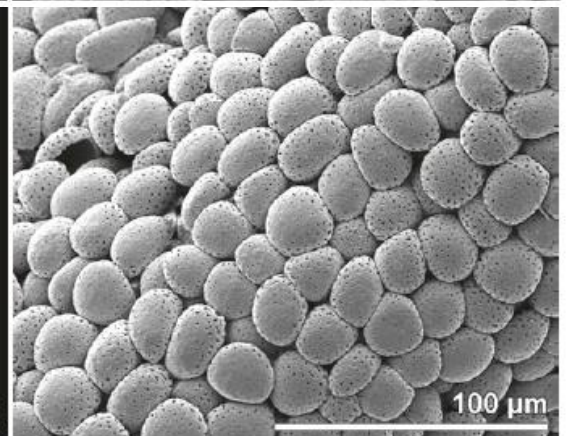
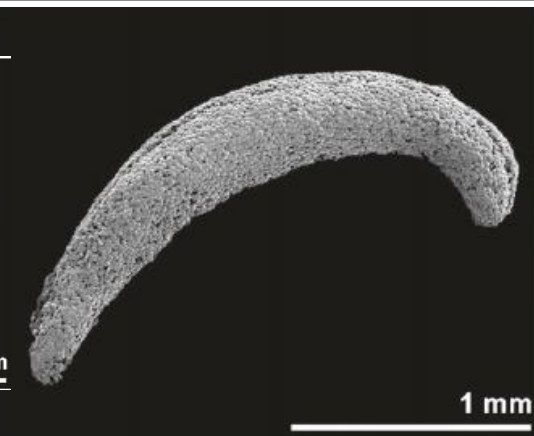
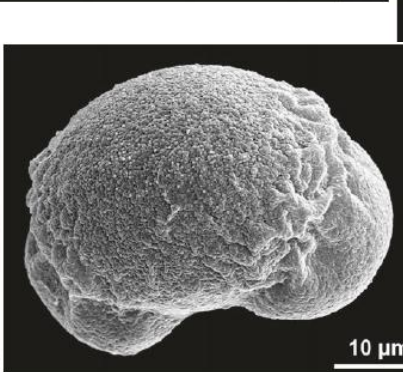
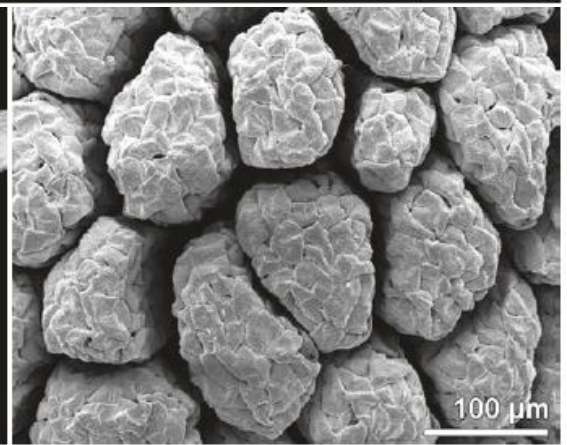
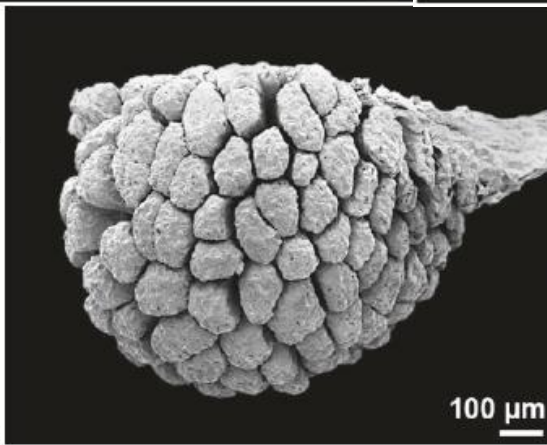
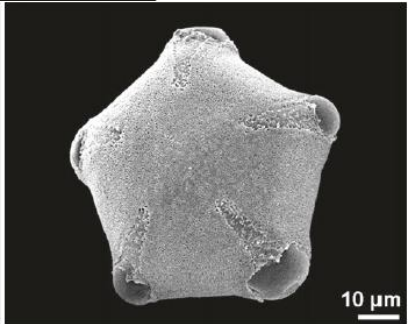
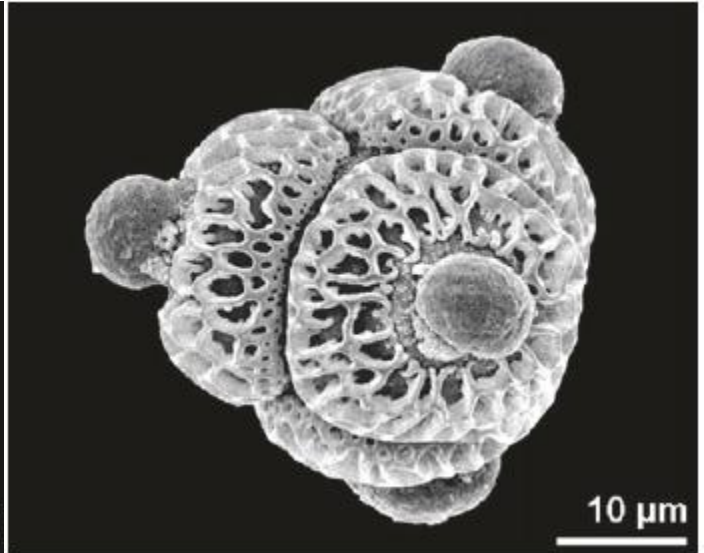
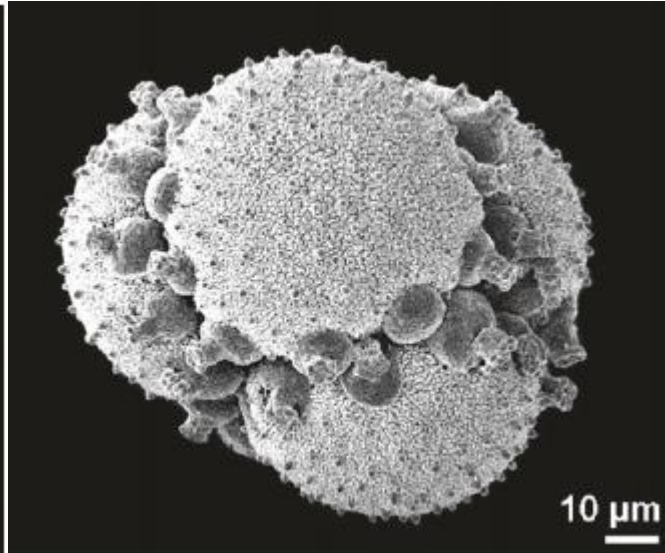


Its structure is composed by **aliphatic compounds** and **oxygenated aromatic compounds** including:

- carotenoids
- polyunsaturated fatty acids
- conjugated phenols

The term "**sporopollenins**" is the one commonly used because there are **many variation** in the structure, e.g. **between** sporopollenins of **angio-**, **gymnosperms** (in pollens) and **pteridophytes** (in spores).

Model of sporopollenin from *Pinus rigida* (Li et al. 2019)



The study of the fossil pollen (Paleopalynology) and spores from past geological ages is possible thanks to...

Sporopollenin... but only if conserved at specific conditions because it is not indestructible: **fungi and bacteria, (UV-) light, pH, high temperatures and O₂** can oxidize its chemical composition damaging the exine morphology with the final loss of the pollen.

However: under **anaerobic conditions** the sporopollenin remains stable:

Glaciers



**Vulcanic eruptions
(ashes coverings)**



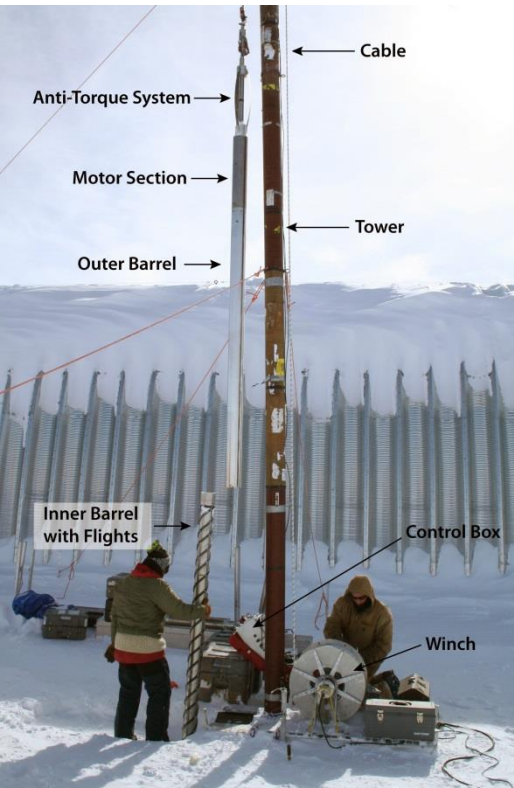
Peat bogs and mires



Marine and freshwater sediments



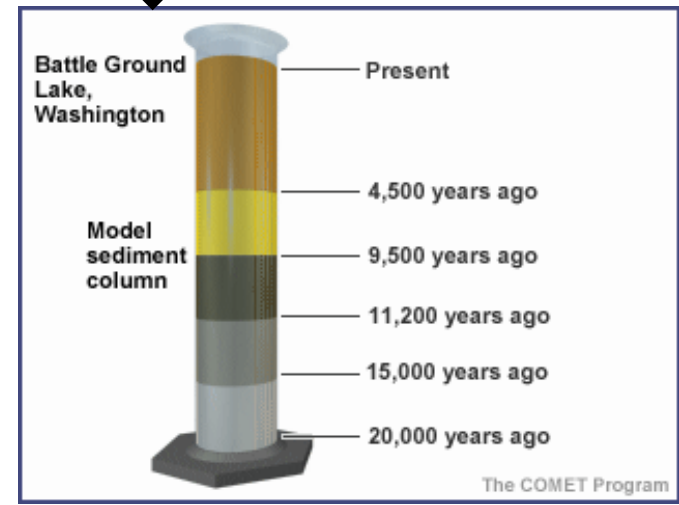
Fossil pollen is extracted from sediments



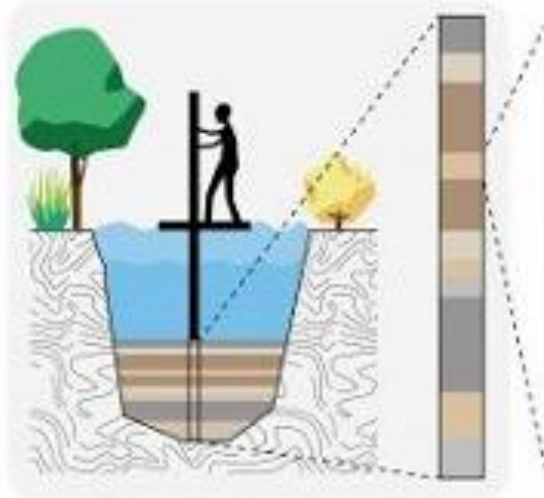
Cores



Dating



Find a lake and core it

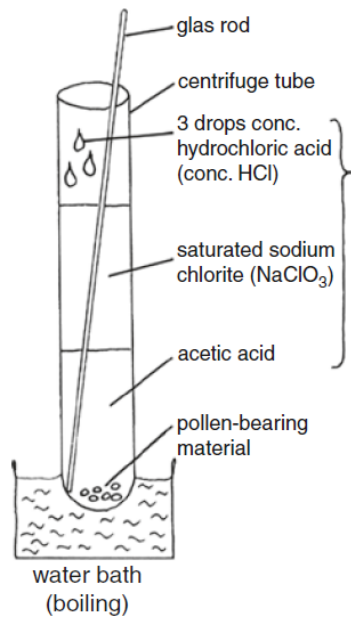


Preparation of fossil pollen: Acetolysation

Used to remove cellular content and intine while preserving and colouring exine and making more evident ornamentation (taxonomic character)

A

1. CHLORINATION (removes cellular content, intine)



when added → fluid stirred with a glass rod and heated for 3 min

chlorine appears immediately

causes bleaching within few seconds

3x rinsing in distilled water

1-2x rinsing in conc. acetic acid (dehydration)

B

2. ACETOLYSATION (colours pollen grains brown)

acetolysis mixture

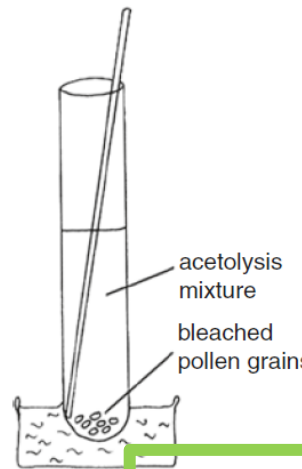
9 parts acetic anhydride
1 part conc. sulfuric acid

heat for 4 min

centrifugation & decantation

rinsing in acetic acid (dehydration)

rinsing in distilled water (minimum 3 times)



preparation for LM

SEM

storing

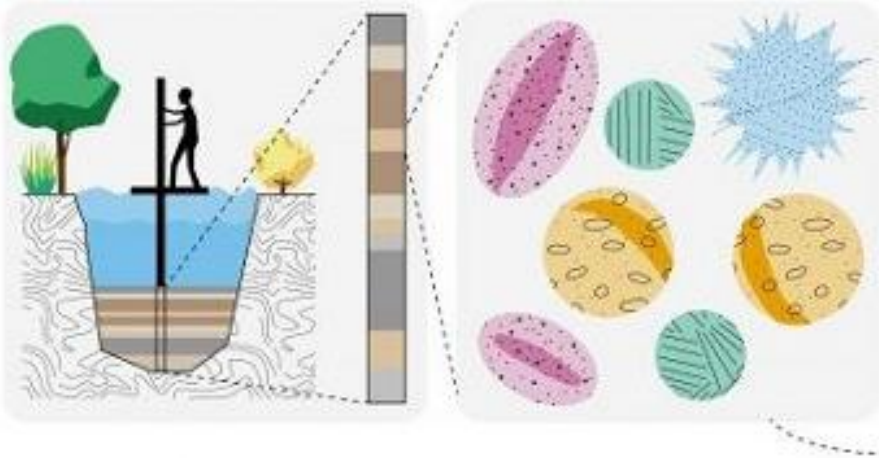
drop of glycerine

glycerin

1+2 -> fossil pollen; only 2 -> recent pollen

Find a lake and core it

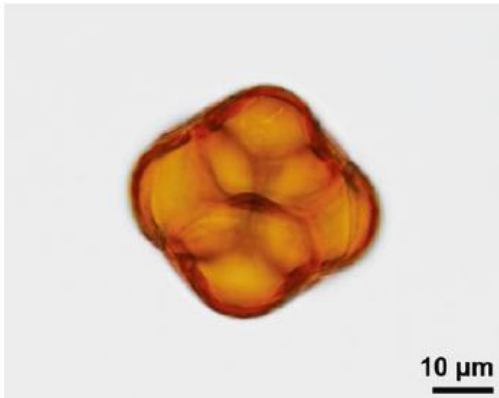
Count pollen in core



**For each stratigraphic layer
pollens are taxonomically
determined and counted**

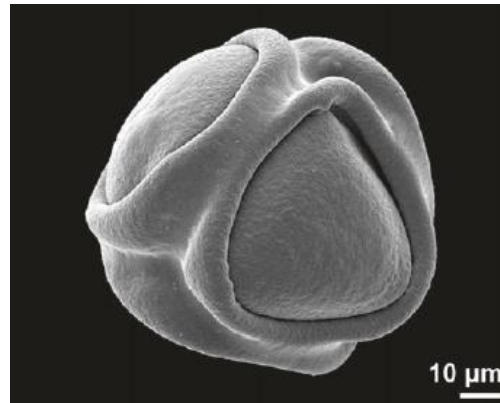
Only recent pollens

Light microscopy



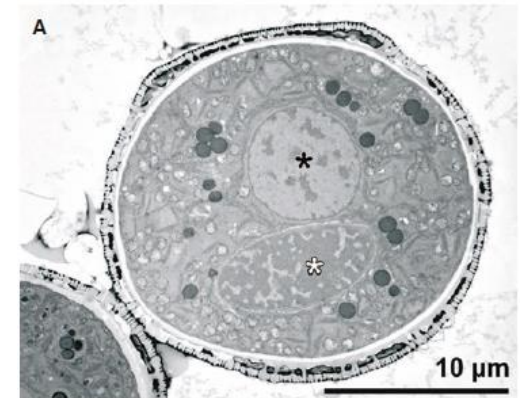
- Allows the comparison between hydrated and dehydrated pollen
- Provides information on endoapertures
- Only details at low magnifications

Scanning Electron Microscopy (SEM)



- Allows the observation of the ornamentation at high magnifications
- No insights on endoapertures

Transmission Electron Microscopy (TEM)



- Allows the observation of the pollen wall and cellular ultrastructure
- Very high magnifications

Pollen data from cores allow a time-resolved reconstruction of past vegetation

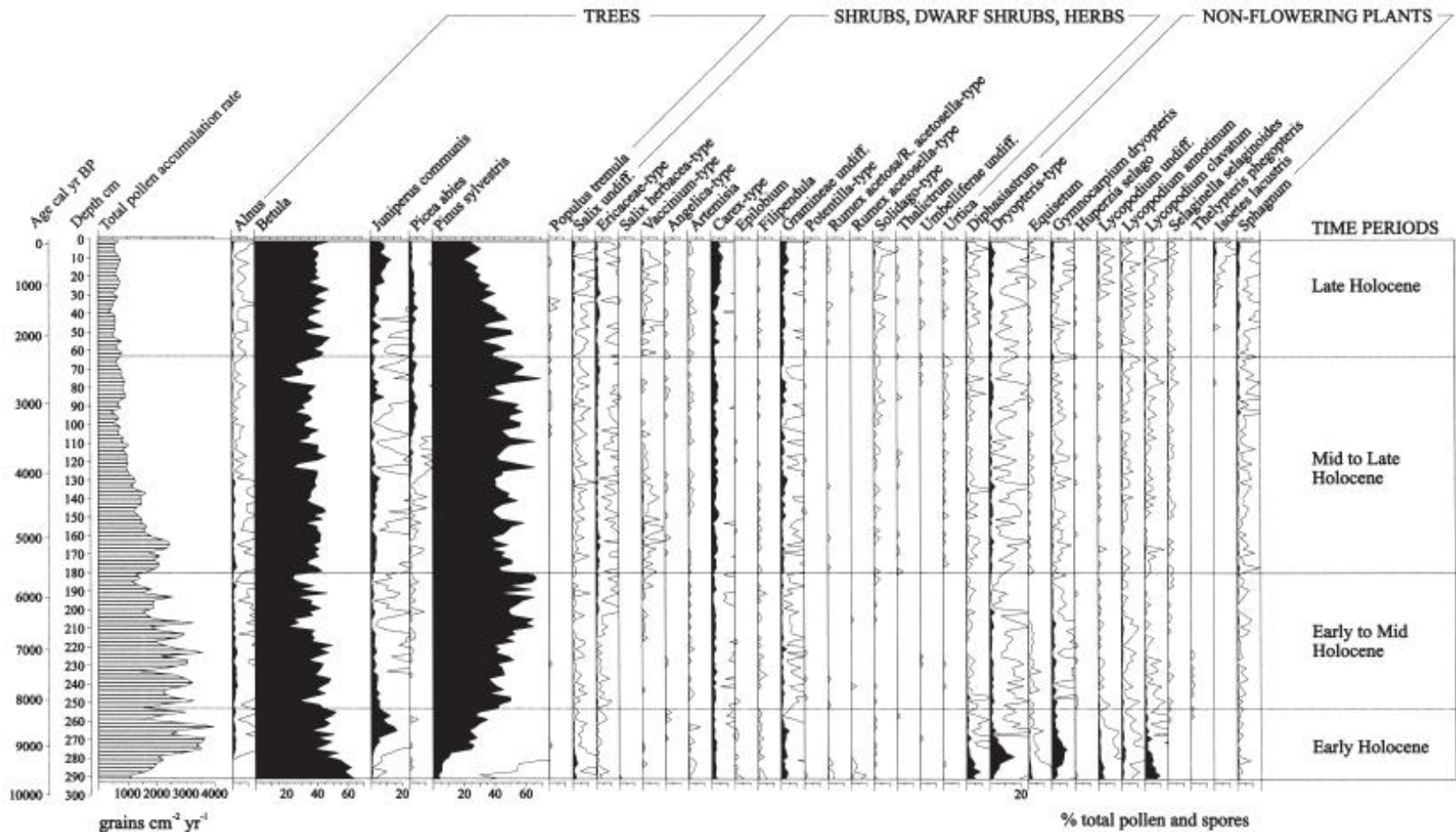
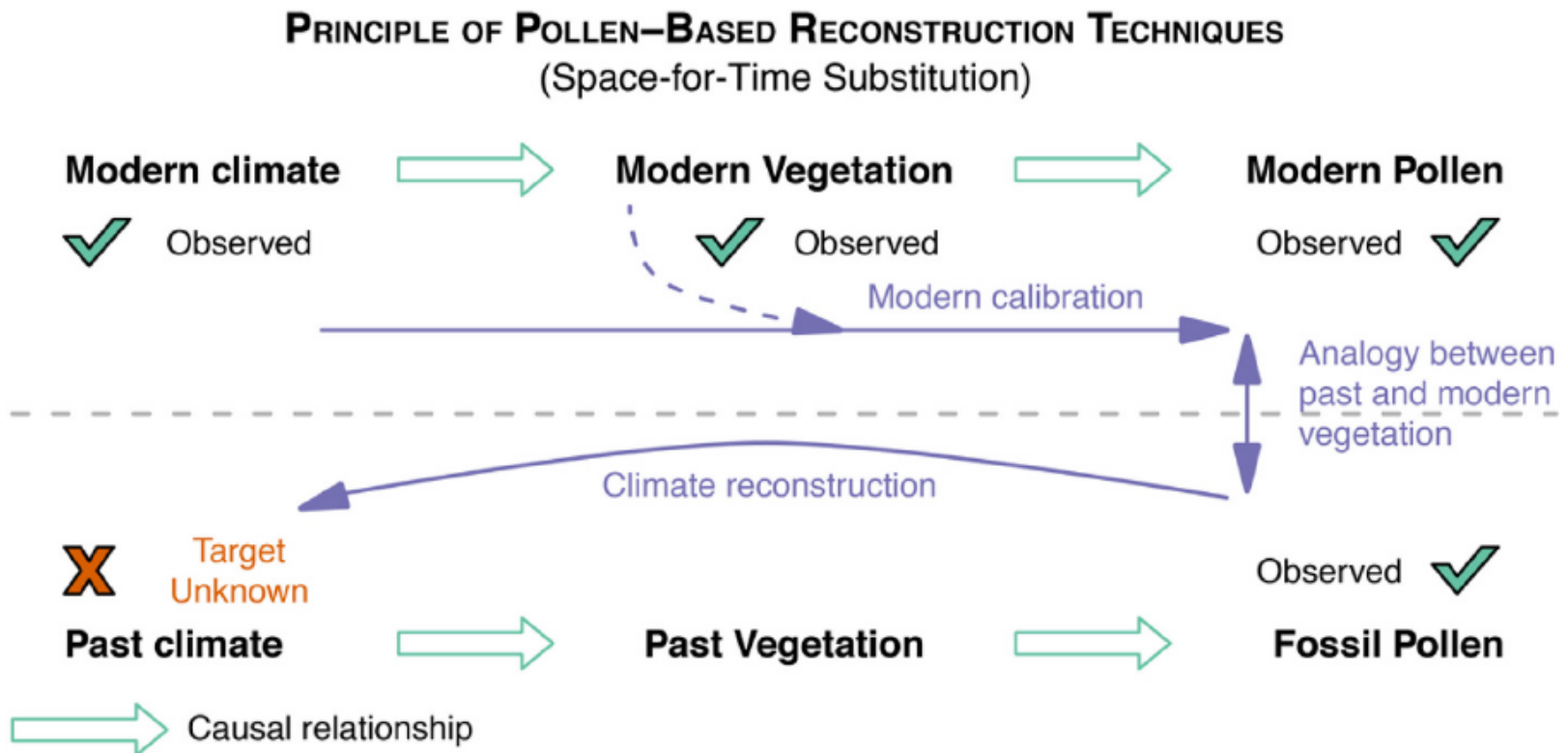


Figure 5 Summary pollen diagram from Tsuolbmajavri. The age scale in modelled calibrated years BP is shown along with the four phases discussed in the text. The total pollen- and spore-accumulation rate ($\text{grains-cm}^{-2}\text{-yr}^{-1}$) is also shown. The hollow silhouette curves denote the $10 \times$ exaggeration of the percentages.

Paleopalynology for past climate reconstruction

Most pollen-based climate reconstruction techniques aim at modelling/extracting the relationships between vegetation and climate from modern observations to reconstruct past climates, **under the assumption that the relationship between vegetation and climate has remained constant through time** (*i.e.* the **uniformitarian principle**).



Assumptions for a reliable past climate reconstruction

- 1. The taxa observed in both modern and past samples are systematically related to the climate in which they live.** This assumption assumes approximate dynamic equilibrium between the observed pollen assemblage and climate.
- 2. The climate variables to be reconstructed are important determinants, or systematically related to important determinants of the vegetation and the associated pollen.** This assumption assumes that the relationship has remained stable throughout the record (i.e. the uniformitarian principle).
- 3. Unstudied environmental variables have had a minor influence on the fossil data** over the studied period of time and at the spatial scale of the pollen record, **or their relationship with the variable of interest remained the same as in the calibration dataset.**

Assumptions for a reliable past climate reconstruction

4. The taxa in the modern calibration dataset are the same biological entities as in the fossil data, and their ecological responses have not changed over the studied period of time (**uniformitarian principle**).
5. The specified mathematical model has sufficient flexibility to represent the complexity of the ecological responses to the climate variables of interest.

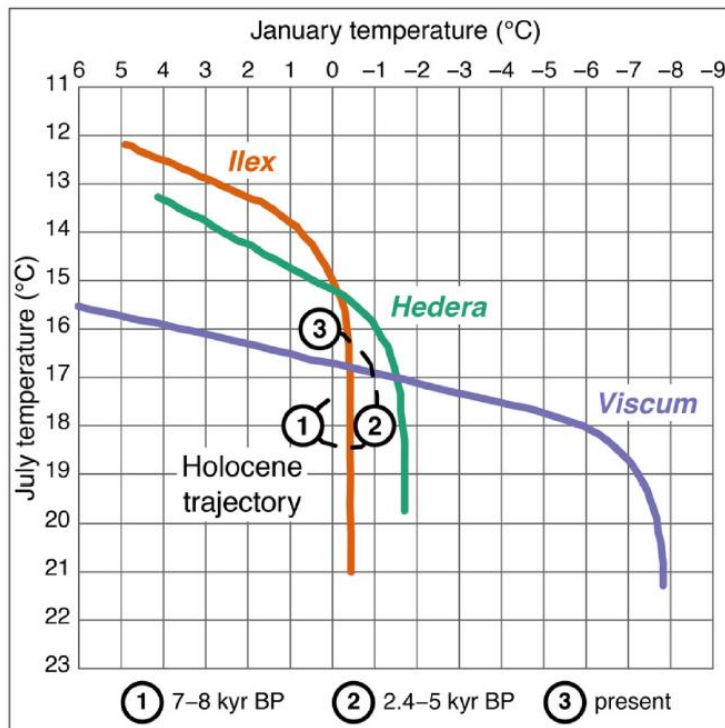


Fig. 2. Classic figure by Iversen (1944) representing the thermal niches of *Viscum*, *Hedera* and *Ilex* and how the combination of their presence (below their respective curve) or absence (above and to the right of their respective curve) in modern environments could be used to estimate past temperatures for the 'Atlantic' (1: 7-8 ka BP), 'Sub-Boreal' (2: 2.4-5 ka BP) and modern (3) phases of the Holocene.

A good comprehension of **the processes that govern the composition of pollen assemblages and their relationship with climate and the environment** is necessary

Pollen grains are produced in all environments where spermatophytes (*i.e.* seed-bearing plants) grow.

Each plant species adopts specific production and dispersal strategies, which can influence the representation and abundance of taxa in fossil pollen records.

Wind pollinated plants generally produce high amounts of pollen



Larch (*Larix*)

It can dominate the pollen assemblage even if it they are not the prominent species



Aspen (*Populus*)

They can be under represented even if they are prominent in their environment

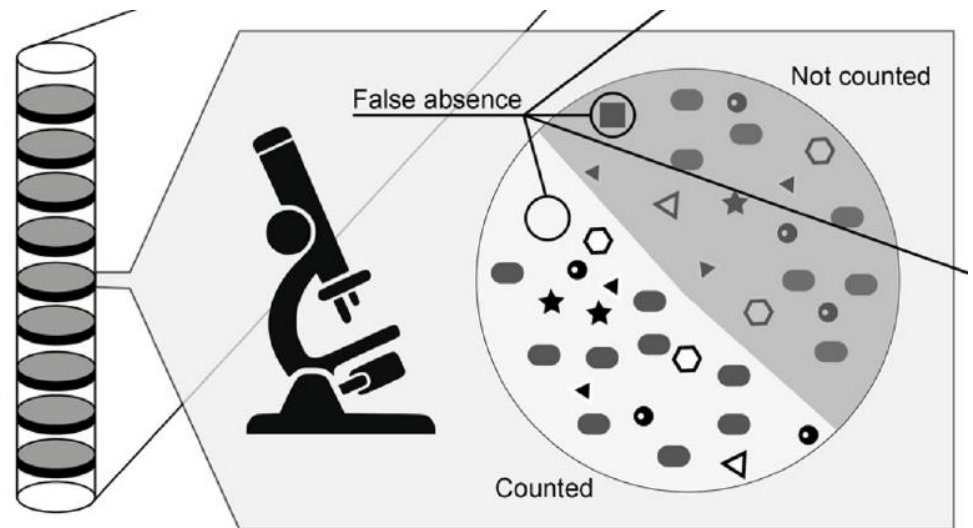
Contrary to plant macroremains that can generally only be used as presence/absence data, pollen grains are much more abundant in sediments and can be used to derive relative proportions of pollen taxa (eg. % of x taxon on the total pollen counted), which enables more refined statistical inferences about past climates.

The reliability of these percentages directly depends also on the number of counted pollen grains being counted



The optimal number of grains depends on the research aim, AIM of the study

Over representative taxa **might mask** the signal of rare but climatically informative taxa



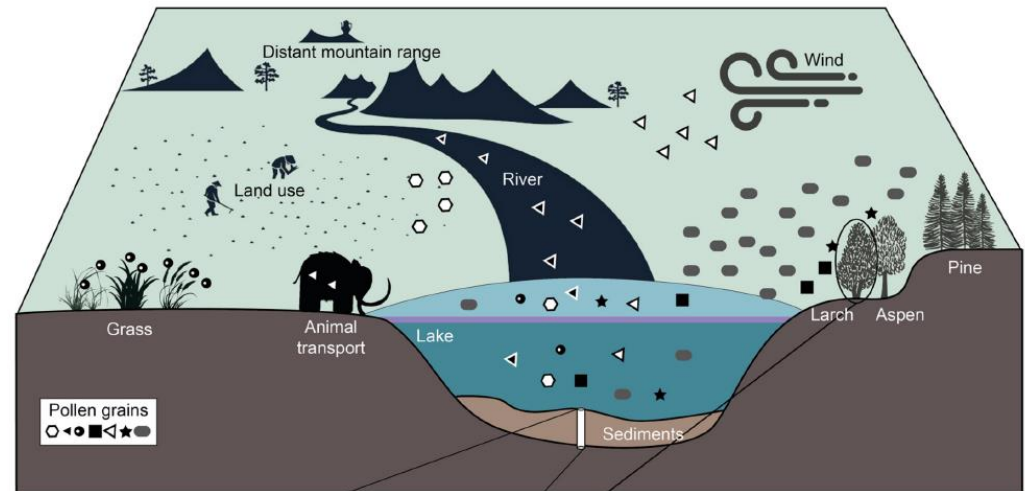
Counting 300 – 500 pollens is a good number but not always possible depending in certain environments or sediment types due to preservation or other taphonomic issues

Representativeness of a pollen sample

A pollen assemblage is not a direct measure of local vegetation composition, as many biological, climatic and environmental processes influence the production, dispersal and preservation of pollen grains

Pollen grains are transported by:

- Wind (mixes pollens)
- Streams and rivers
- Animals (foraging signal, rare)



Pollen assemblages thus represent a mix of locally and remotely produced pollen grains whose chances of being observed decrease with increasing distance of the plant source to the sampling location

The relative proportion of local and distant taxa is related to the catchment characteristics of the studied archive (site where pollen-containing cores are sampled).

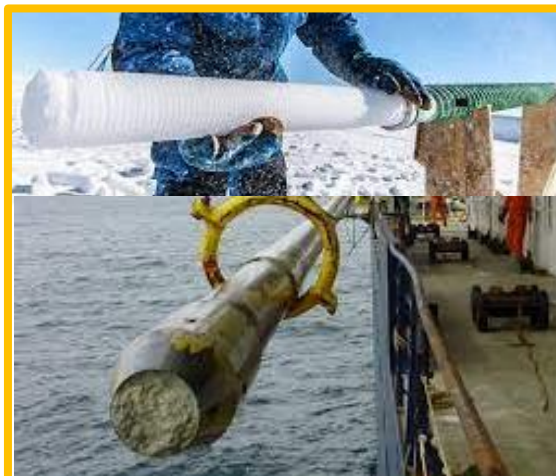
The environmental setting of a pollen archive can strongly influence the scale of climatic inferences that can be derived from a pollen record because...



Usually contain a stronger local signal (small pollen source area)



Act as regional integrators of pollen sources potentially very far



extreme endmembers of local vs regional pollen ratios as most of the pollen in these archives is not produced locally

When possible, characterizing the source archive and the likely area represented by pollen assemblages is important to defining the type and scale of climate inferences that can be drawn from a fossil pollen record

Environments with low pollen productivity can also be highly influenced by remote pollen producers

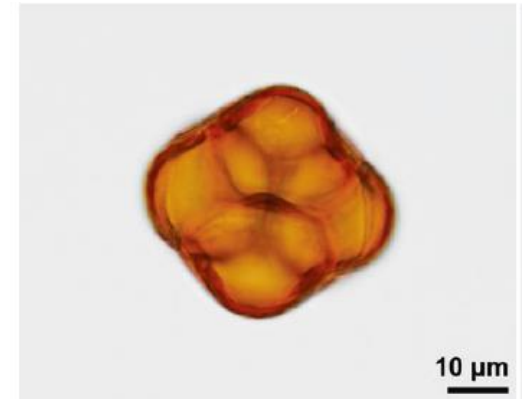
High arctic tundra



In such cases, **separating local from extra-local taxa can reduce the noise of the pollen data and improve the local climate signal**

Taxonomic resolution

Pollen grains are rarely identifiable to the species level using light microscopy



Increasing the taxonomic resolution of pollen analyses is useful for palaeoecological studies, especially in hotspots of botanical diversity where tens to hundreds of plant species with different climatic niches produce indistinguishable pollen grains (e.g. in Amazonia)

However, most reconstruction techniques use large compilations of modern pollen samples to estimate the relationship between pollen and climate
-> taxonomic improvements cannot be back-propagated to the existing compilations of modern pollen sample -> records with higher taxonomic resolution needs to be simplified or new compilations need to be produced

Human impact

Most terrestrial environments are or have been influenced to some extent by humans.

Human activities (e.g. deforestation or agriculture) modify vegetation structure, composition and diversity (e.g. replacement of a forested area by a field), which can obscure the observed relationships between pollen and climate

Note: climate reconstruction inferences are based on the relative abundances of pollens in the fossil records as compared to modern ones

The impact of human activity (e.g. land-use) on the pollen-climate relationship is expected but it is difficult to quantify

However, many reconstructions from such regions have been supported by non-botanical palaeoclimate proxies, indicating that modern climate reconstruction methods can – to some extent – cope with human impact

An example of quantification of human impact effect...

RESEARCH ARTICLE

The Bias and Signal Attenuation Present in Conventional Pollen-Based Climate Reconstructions as Assessed by Early Climate Data from Minnesota, USA

Jeannine-Marie St. Jacques^{1*}, Brian F. Cumming², David J. Sauchyn¹, John P. Smol²



In the American Midwest, **logging**, **fire suppression**, **deforestation** and **agriculture** have **greatly changed vegetation composition and the composition of its pollen rain** since Euro- American settlement in **the mid-1800s**

Minnesota is uniquely rich in **early climate stations** (instrumental recordings) from military forts which **predate** large-scale Euro-American settlement, allowing a rare opportunity to test whether or not the pollen-climate relationship is stationary in time, as has generally been assumed.

Fort Snelling (Minnesota)



An example of quantification of human impact effect...

To assess the significance of low-frequency signal distortion and bias introduced by human settlements

The climate reconstruction based on the modern pollen set was compared to the one obtained using an early post-settlement calibration set **for which instrumental data were available thanks to the recordings of the military fort**

The conventional inference method, based on modern pollen set, **produced significant low-frequency (centennial-scale) signal attenuation and positive bias** in the temperature pattern reconstruction of of **0.8-1.7°C**



Considering that the analysis involved a back propagation of the bias in the time frame covered by the sediment analyzed (back to 1116 AD)

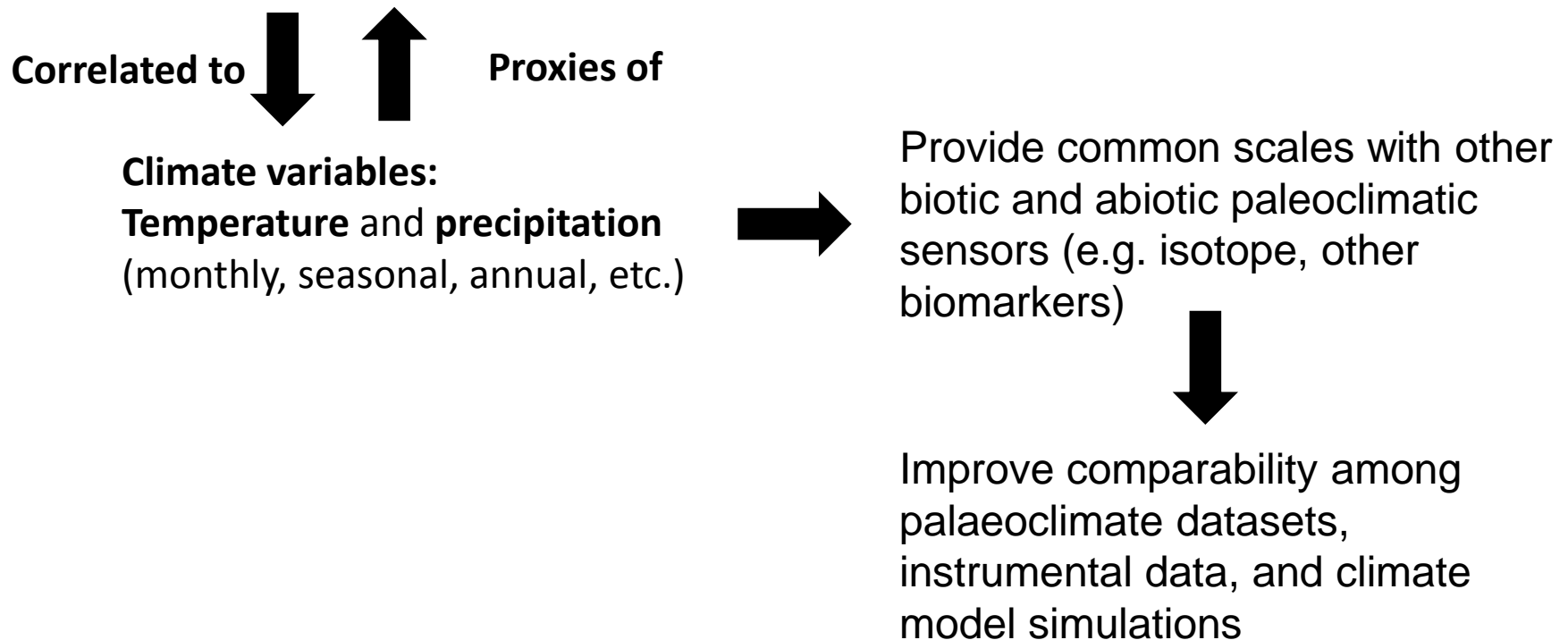


Little Ice Age (1300 – 1850 AD) temperature was overestimated and likely the extent and rate of anthropogenic warming in this region was underestimated.

Climate variable(s) that can be reconstructed from a fossil record

Plant growth, survival and reproduction and ultimately the presence/abundance or absence of plant species at a site are determined by a broad range of bioclimatic variables, such as:

- Min and Max temperatures
- Number of growing degree and frost days
- Length of the dry period or seasonality of rainfall and/or temperature





Late Miocene vegetation dynamics under monsoonal climate in southwestern China

Shu-Feng Li ^{a,b}, Li-Mi Mao ^d, Robert A. Spicer ^e, Julie Lebreton-Anberrée ^{a,b}, Tao Su ^a, Mei Sun ^{a,b}, Zhe-Kun Zhou ^{a,c,g}



mean annual temperature (**MAT**), maximum temperature of warmest month (**MTWM**), minimum temperature of coldest month (**MTCM**), mean temperature of wettest quarter (**MTWETQ**), mean temperature of driest quarter (**MTDRYQ**), mean temperature of warmest quarter (**MTWQ**), mean temperature of coldest quarter (**MTCQ**), mean annual precipitation (**MAP**), precipitation of wettest month (**PWETM**), precipitation of driest month (**PDRYM**), precipitation of wettest quarter (**PWETQ**), precipitation of driest quarter (**PDRYQ**), precipitation of warmest quarter (**PWQ**), and precipitation of coldest quarter (**PCQ**).

Climatic parameter	Wenshan	
	Late Miocene	Modern
MAT (°C)	16.6–17.5	18.1
MTWM (°C)	27.5–29.7	27.2
MTCM (°C)	2.4–5.5	6.5
MTWETQ (°C)	20.9–21.3	23
MTDRYQ (°C)	9.3–11.6	11.6
MTWQ (°C)	22.6–22.7	23
MTCQ (°C)	7.5–10.3	11.6
MAP (mm)	1432.3–1598.9	1038
PWETM (mm)	228.7–266	205
PDRYM (mm)	21.7–48.1	12
PWETQ (mm)	608.3–729.9	551.3
PDRYQ (mm)	76.1–178.9	45
PWQ (mm)	515.5–721.4	551.3
PCQ (mm)	89.5–192.6	45
MSI	11.3–17.1	18.6

Each paleofossil represents an entity or group of entities that has specific climate and environmental requirements (**environmental niche concept**).



For paleofossils, climate requirements are derived from ecology of the same species or from that of the **Nearest Living Relative**



The zone of **climatic-profile-overlap** which covers the most of fossil pollen taxa defines the most likely climate space for palaeoflora

Final consideration on the method

One consequence of Assumptions 2 and 3 is also that reconstructing climate is not always possible when **non-climatic factors** leave a stronger impact on the pollen assemblages than climate itself, e.g. **sea-level changes** at a coastal site that change the vegetation composition, **land use**, **levels of CO₂** as low [CO₂] increases the water use of plants.

The techniques to reconstruct climate will always provide estimates of the climatic variables and they do not identify those that drove the observed ecological changes

Performance indexes related to the techniques used, e.g. **spread of uncertainties associated with the fitted reconstruction model** can identify whether a variable is a poor predictor of the pollen data



Issue of covariate variables as they can be a source of bias if the relation is non-analogous between past and present (e.g. present vs past January and July T)