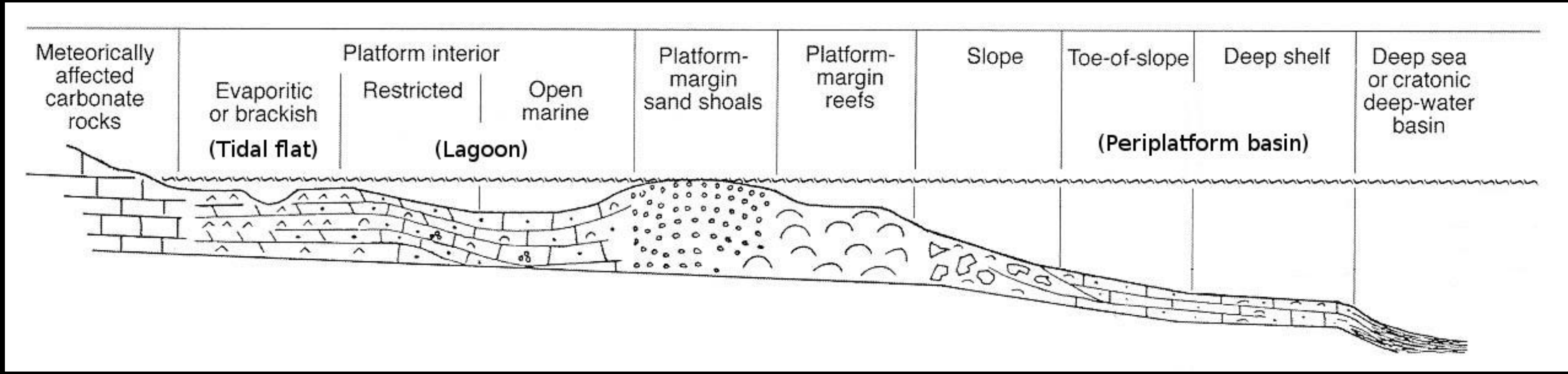
Carbonates at the optical microscope

- Identify the main carbonate grains – and learn where to look for to determine the others!
- Describe carbonate microfacies
- Interpret the sedimentary paleoenvironment



Flügel, 2004 (modified from Wilson)

Carbonate microfacies

Classification of sedimentary rocks

"...two fundamentally different kinds of sediment and sedimentary rock: (1) terrigenous clastic sedimentary rocks and (2) allochemical and orthochemical sedimentary rocks"

Encyclopaedia Britannica, https://www.britannica.com/science/sedimentary-rock

Classification of carbonate rocks: STEP 1

• **Clastic rocks** are formed by the deposition of grains derived from the physical erosion of a pre-existing rock

• **Chemical rocks** are formed by the precipitation of minerals from superficial waters (including seawater). They may be subdivided into:

  · **(ortho)chemical rocks**, that are strictly crystalline

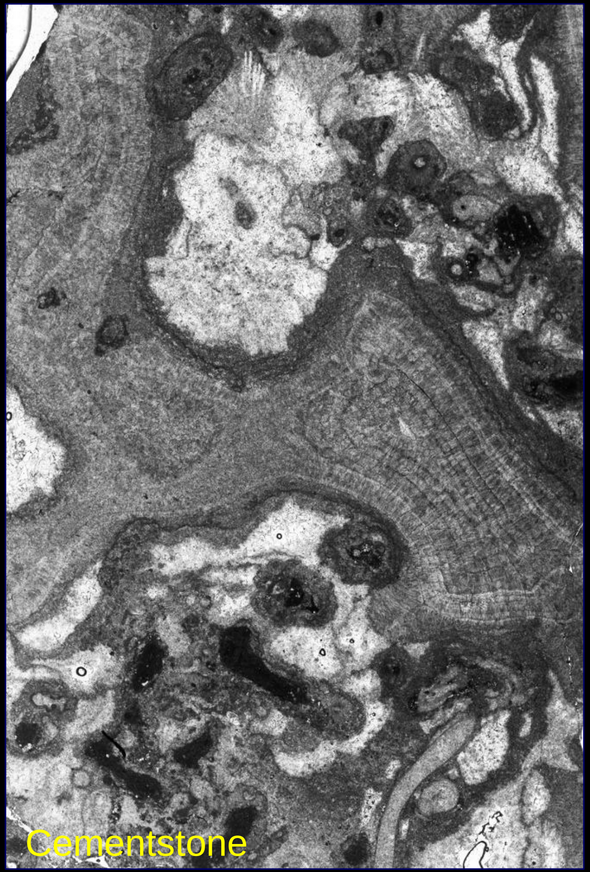
  · **biochemical rocks**, which main components are skeletal grains

• **Other sedimentary rocks** are, e.g., residual (bauxite), pyroclastic, organic (oil, coal)

Orthochemical VS biochemical:

The boundary is fuzzy

For some (yet common) carbonate rocks, the distinction between orthochemical and biochemical is not applicable. E.g.: oolites, travertines and calcareous tufa; cementstones...


Cementstone

More appropriately, then, (most) sedimentary rocks are either: clastic or chemical.

All limestones are chemical rocks


Oolitic limestone

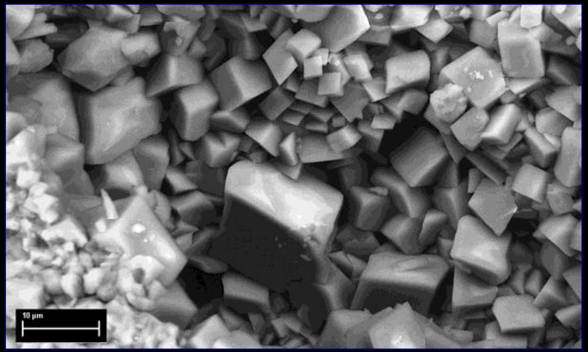

Fossiliferous limestone

Classification of carbonate rocks: STEP 2

- **Rocks with allochems** are rocks made of mobile carbonate grains. Use:
  - → Dunham (1962)
  - → Folk (1959)

- **Boundstones** are rocks built by carbonate-secreting, in-situ sessile organisms. Use:
  - → Embry and Klovan (1971)
  - → Insalaco (1998)

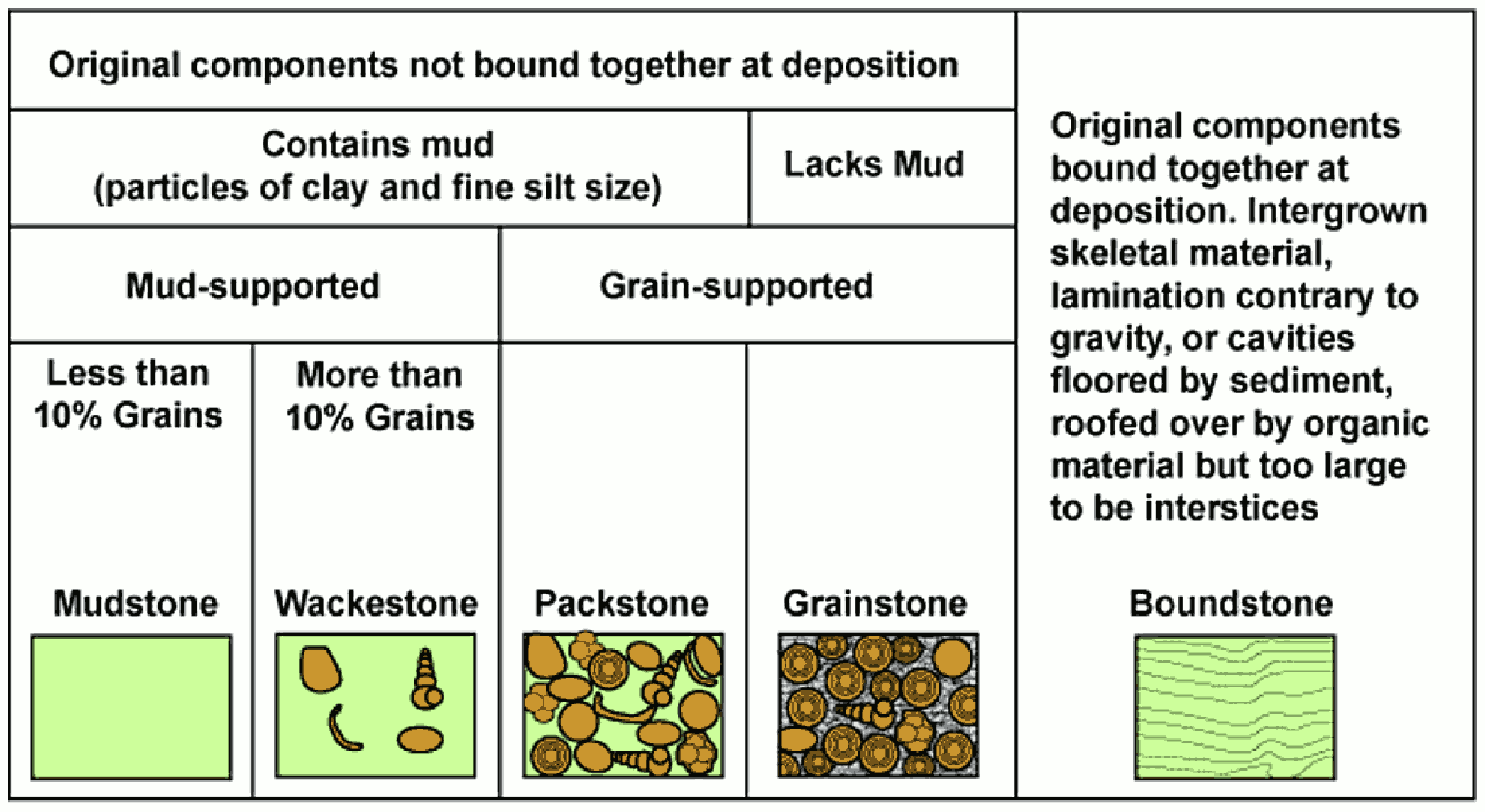
- **Crystalline carbonate rocks** are either produced by replacement or precipitation: dolomites, speleothems, marbles...
  - → Randazzo and Zachos (1983)
  - → Friedman (1965)



Classification of carbonate rocks:

- **Rocks with allochems** are rocks with chemical grains (allochems) which are free to be transported and deposited by physical processes as waves and currents.

  → Dunham (1962)

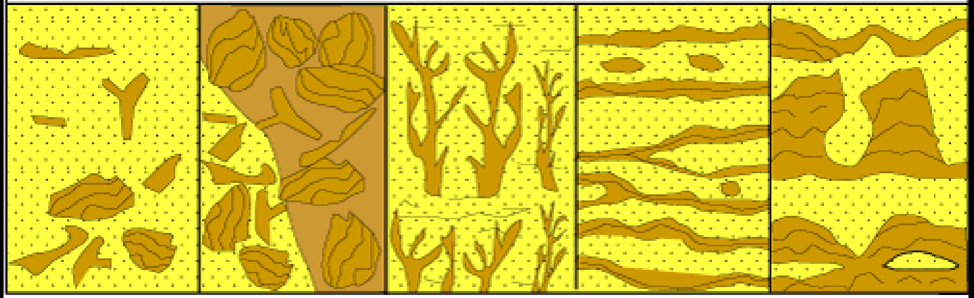


C. G. St. C. Kendall, 2005 (after Dunham, 1962, AAPG Memoir 1)

Classification of carbonate rocks:

• **Boundstones** are rocks built by carbonate-secreting, in-situ sessile organisms. Use:
→ Embry and Klovan (1971)

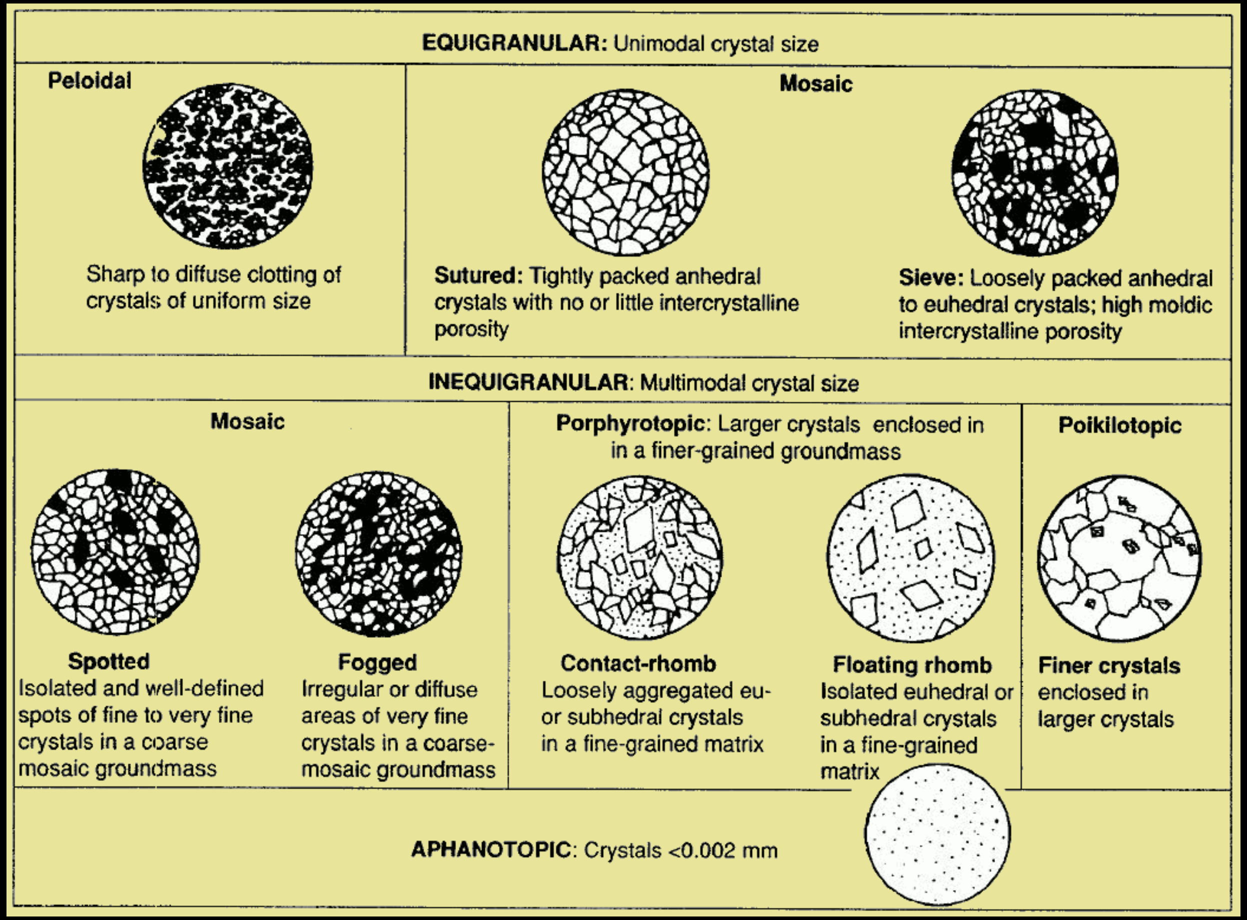
Allochthonous		Autochthonous		
Original components not bound organically at deposition		Original components bound organically at deposition		
>10% grains>2mm				
Matrix supported	Supported by >2mm component	By organisms that act as baffles	By organisms that encrust and bind	By organisms that build a rigid framework
Floatstone	Rudstone	Bafflestone	Bindstone	Framestone



Textural classification of reef limestones after Embry & Klovan (1971) and James (1984)

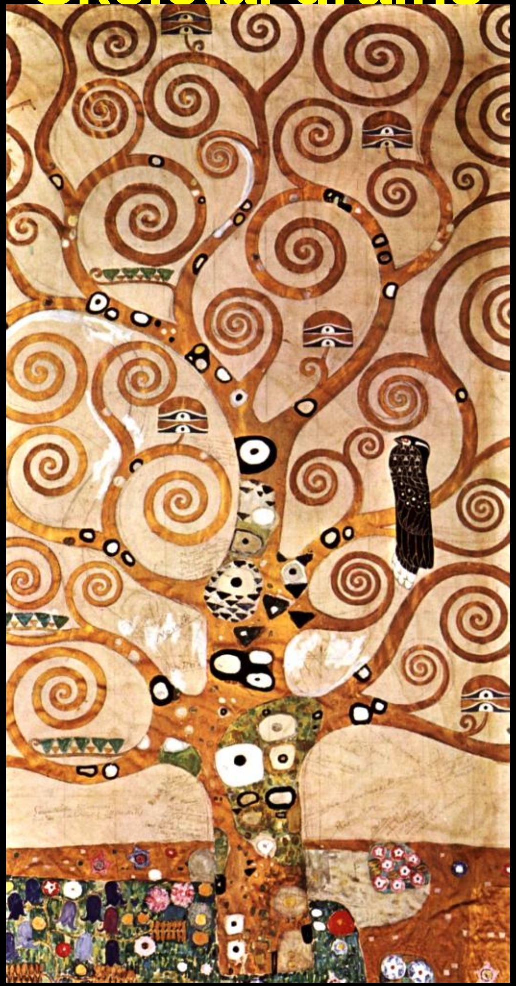
Classification of carbonate rocks:

• **Crystalline carbonate rocks** are mostly the dolomites and recrystallized limestones
→ Randazzo and Zachos (1983) (based on Friedman 1965)



Carbonate microfacies

Skeletal grains

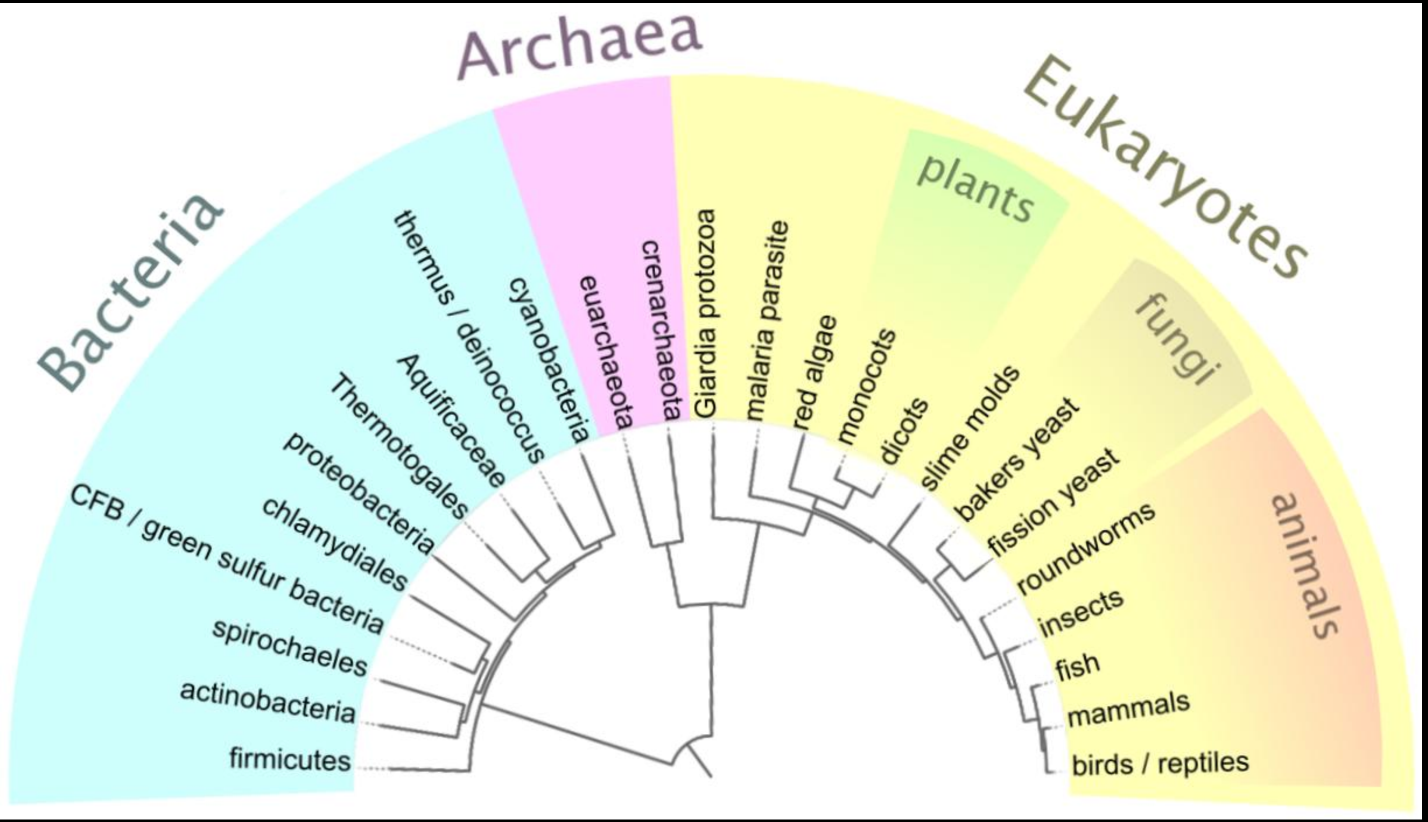


Gustav Klimt, the Tree of Life, 1909 (Museum of Applied Arts, Vienna)

What are skeletal grains?

It's simple: skeletal grains are microfossils or microscopic fragments of fossils.

Thus, when determining th skeletal grains, we are browsing the tree of life...

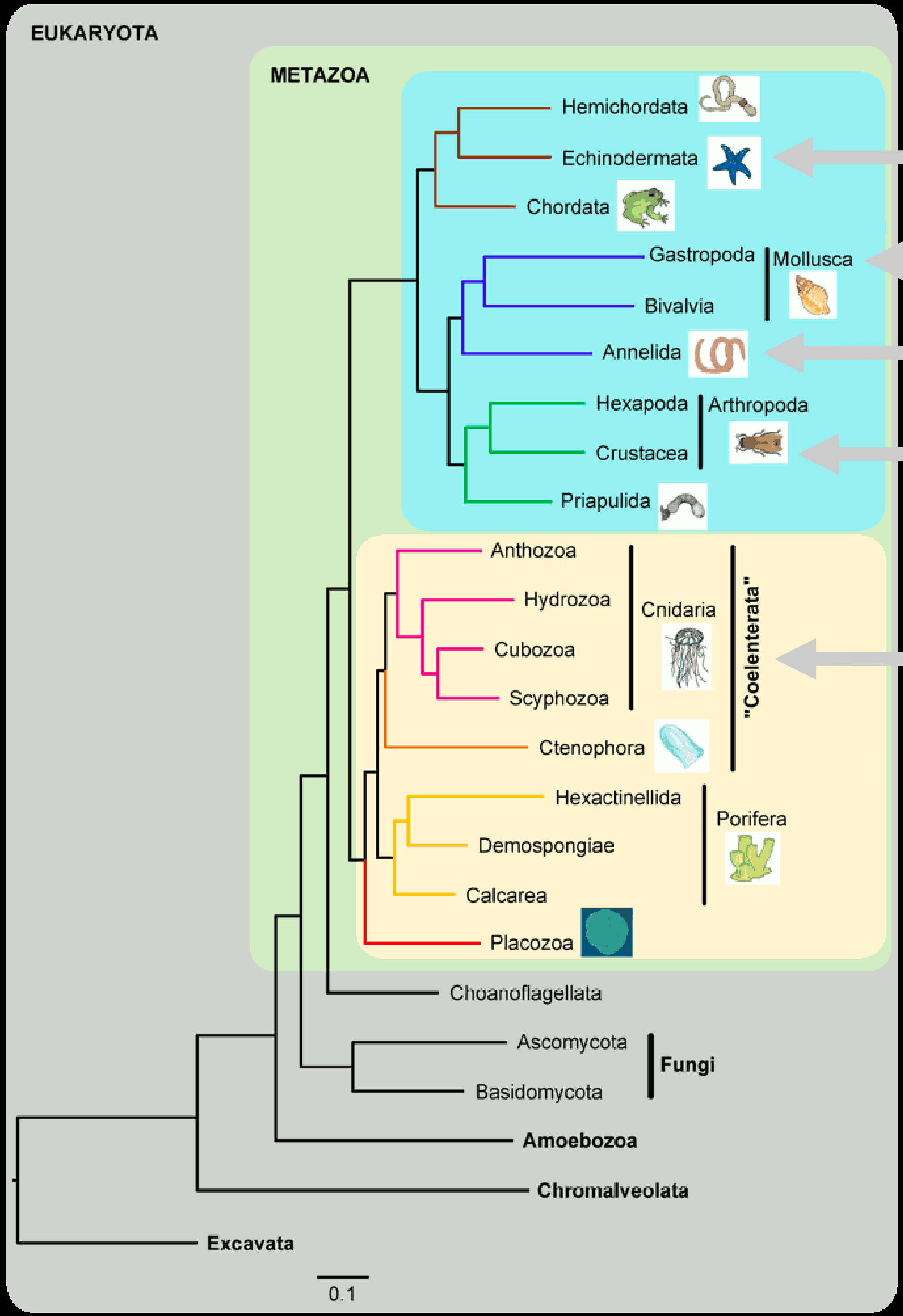


A comprehensive evolutionary tree of life (public domain image from Wikipedia). Bacteria and Archaea are prokaryota, i.e., their cells have no nucleus. Evolutionary speaking, **Eukaryota** (including us) are closer to **Archaea** than to **Bacteria**.

As a first approximation, calcified rests of Bacteria and Archaea belong to **microbialites**, while true skeletal grains are fossils of Eukaryota, from five main groups: **Rhodophyta** (red algae), **Plantae** (plants and green algae), "**Protista**" and **Metazoa** (multicellular animals).

"**Protista**" is actually a polyphyletic group that traditionally includes Foraminifera, Coccolithoforida and the dynoflagellates.

Which Eukaryota leave fossils?



Sea urchins, crinoids...

Gastropods, bivalves, ammonites...

Serpulids

Ostracods, trilobites, barnacles...

Corals

The evolutionary tree of Eukaryota, from Schierwater et al. (2009).

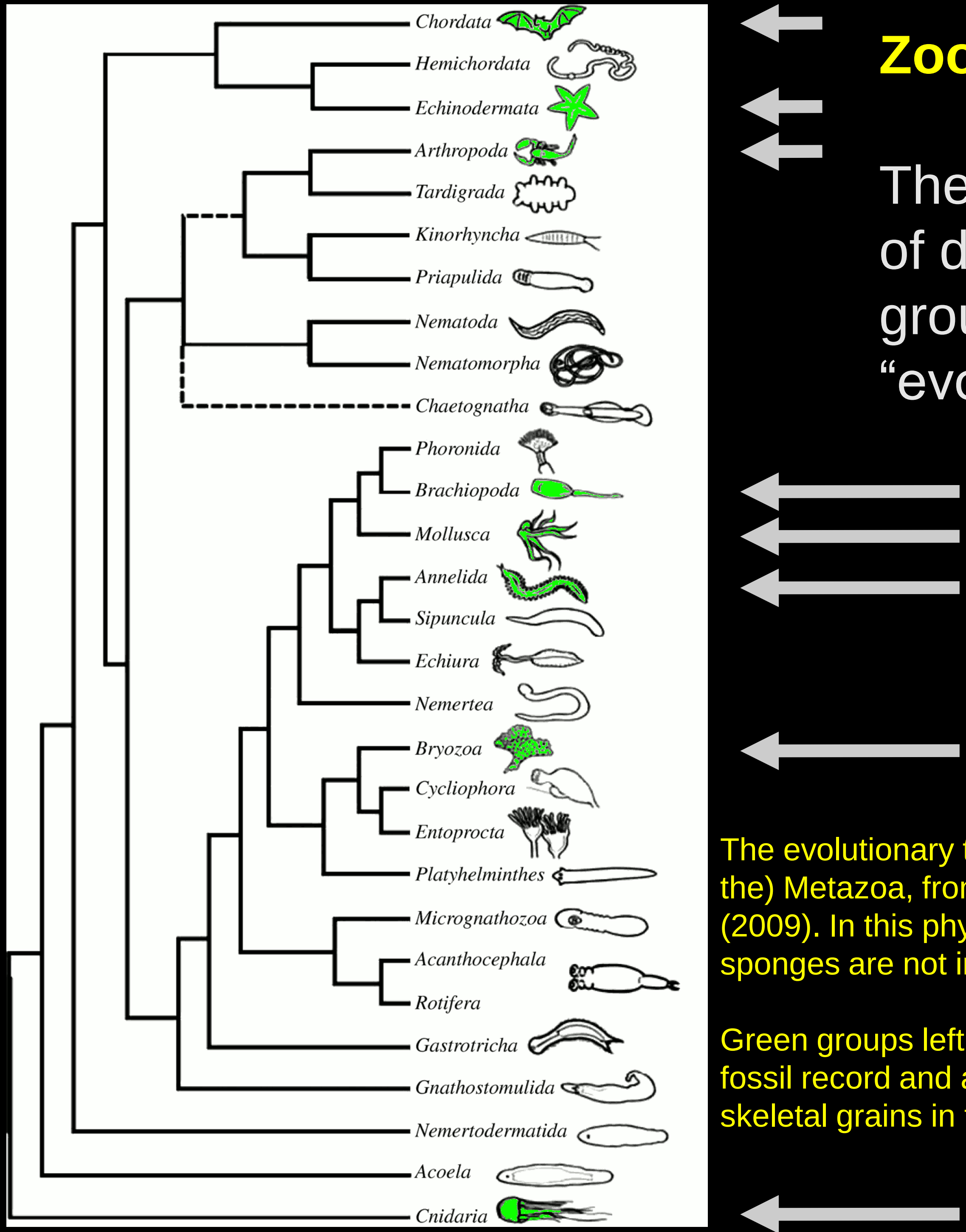
In this phylogeny, sponges are part of the Metazoa.

Sponges

“Protista”, “algae”...

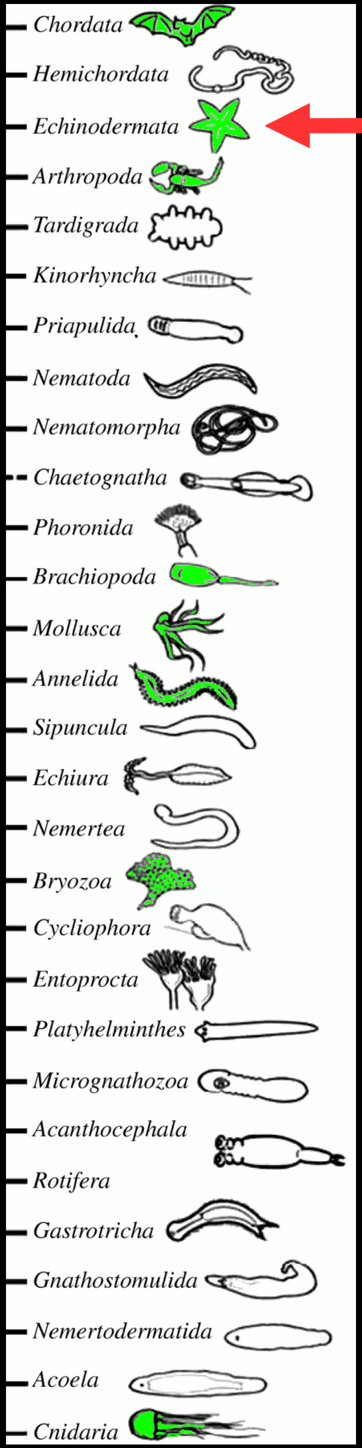
Zoom into the Metazoa!

The rest of the lecture is a series of data sheets on each main group. We'll follow an inverse "evolutionary time" sequence.



The evolutionary tree of (part of the) Metazoa, from Paps et al. (2009). In this phylogeny, sponges are not included.

Green groups left a significant fossil record and are found as skeletal grains in thin sections.

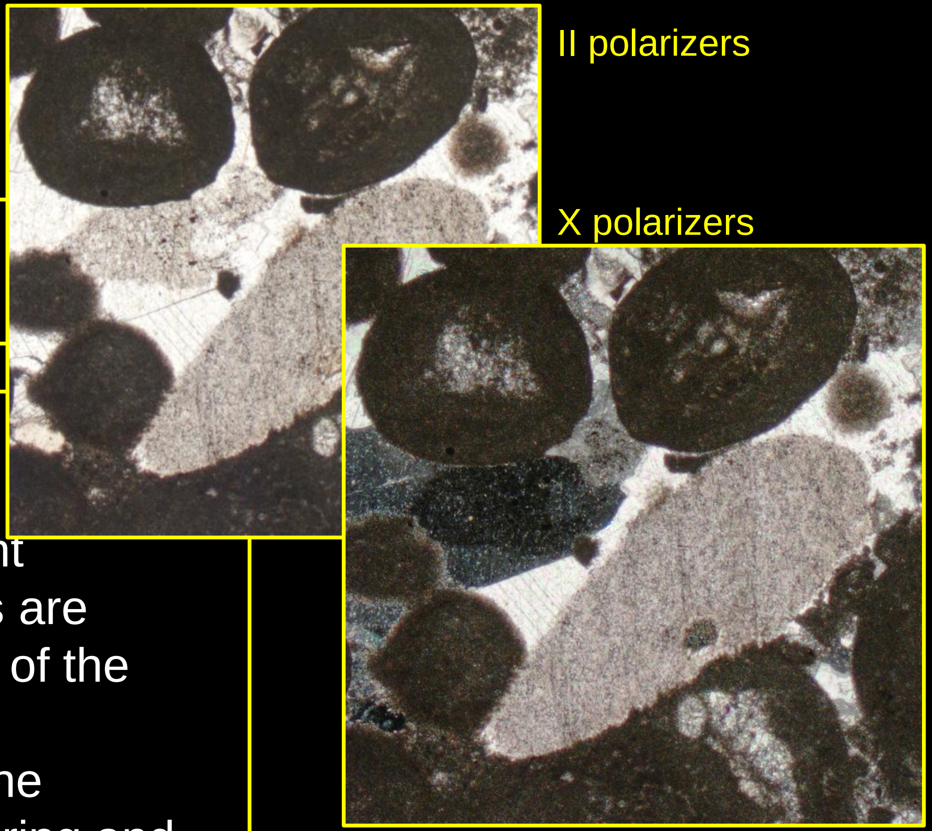


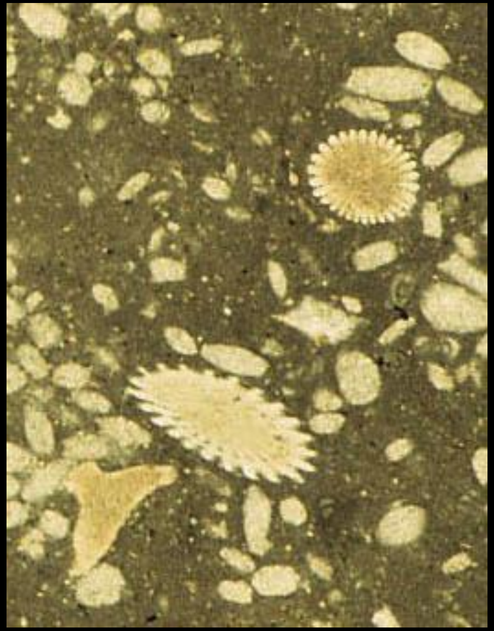
Echinoderms

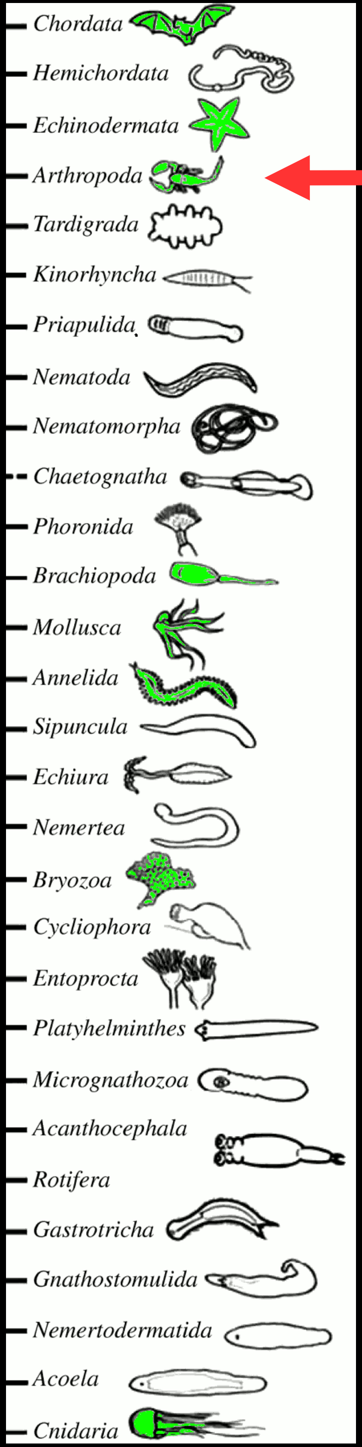
Original mineralogy:
- High-Mg calcite

Diagnostic features:
- Plain extinction
- Syntaxial calcite cement
- Microporous: impurities are captured within the framework of the skeleton
- Crinoid ossicles have the characteristic shape of a thick ring and may have a star-shaped section
- Echinoid spines may have a typical doily section (*doily = centrino*)

Significance:
- Strictly stenohaline, i.e., found only in normal seawater (ca. 35 ‰ psu)







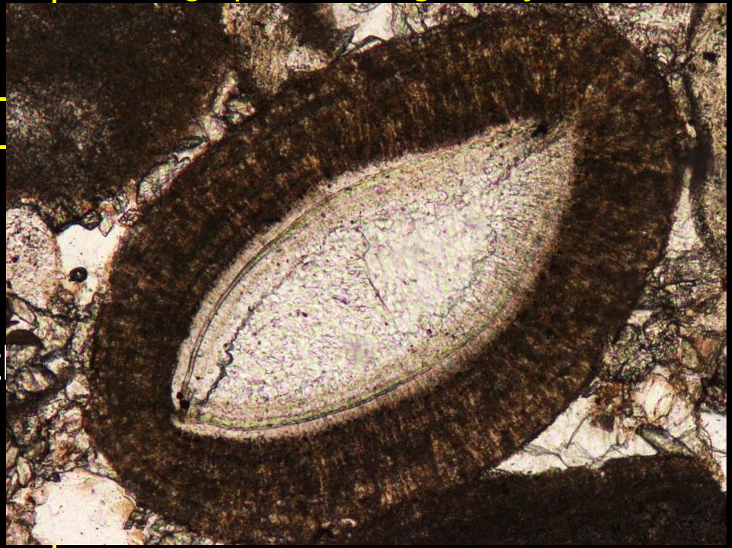
Ostracods

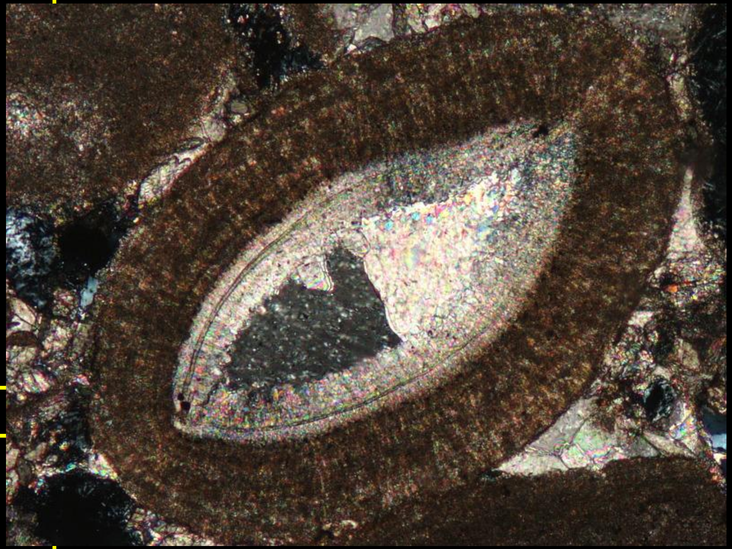
Original mineralogy:
- Low-Mg calcite

Diagnostic features:
- Bivalves, often articulated
- Small, almost never > 1 mm
- Fibrous calcite ultrastructure, wit fibers perpendicular to the shell
- May have a syntaxial calcite overgrowth, which is however not monocrystalline

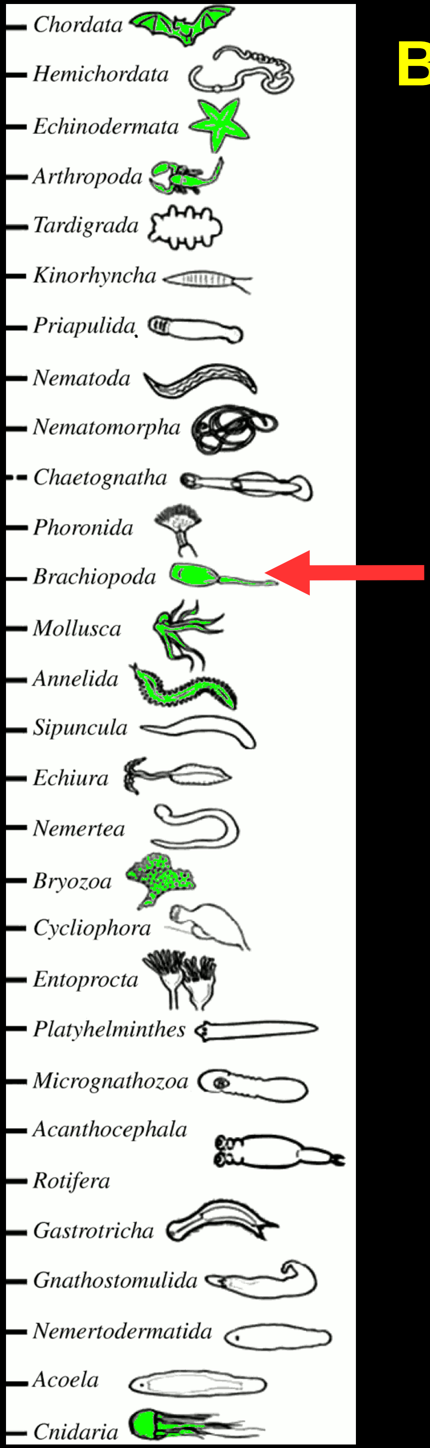
Significance:
- Euryhaline, from freshwater to hyperhaline

A ?radial ooid with an ostracod at the nucleus, and cement filling the space between its valves. This image polarized light only.





Same as above, X polarizers. Note a rim of syntaxial cement grown inside the shell. Last comes a blocky cement.



Brachiopods

Original mineralogy:

- Low-Mg calcite (rarely phosphatic)

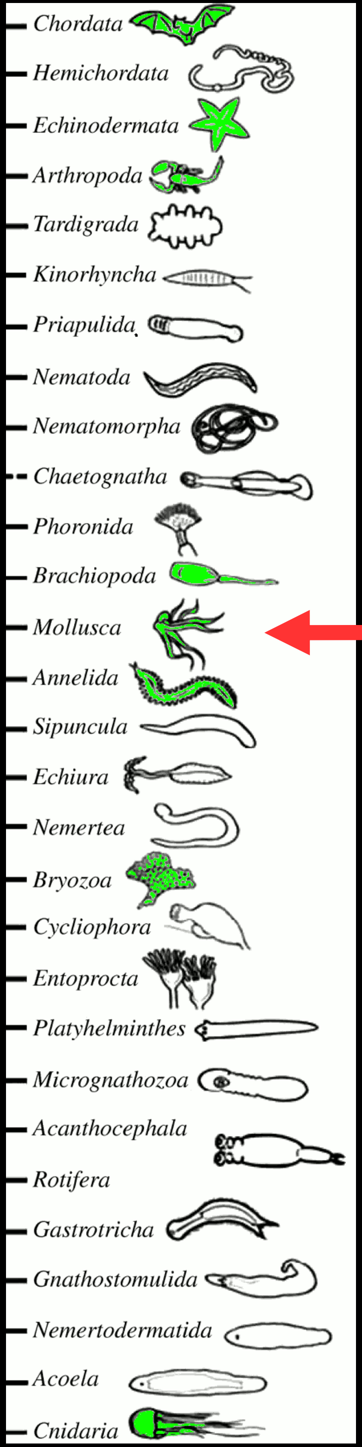
Diagnostic features:

- Bivalves, often articulated
- Inaequivalve (at the umbo or foramen)
- Can be large (many cm)
- Inner fibrous calcite skeleton, with fibers parallel to the shell or oblique
- Punctated and pseudopunctated brachiopods have perforations that cross throughout the inner layer
- The inner shell can have a complex shape (e.g., if the thin section cuts the brachidium)

Significance:

- Stenohaline, more common in the Paleozoic and Mesozoic

https://commons.wikimedia.org/wiki/File:Liospiriferina_rostrata_Noir.jpg



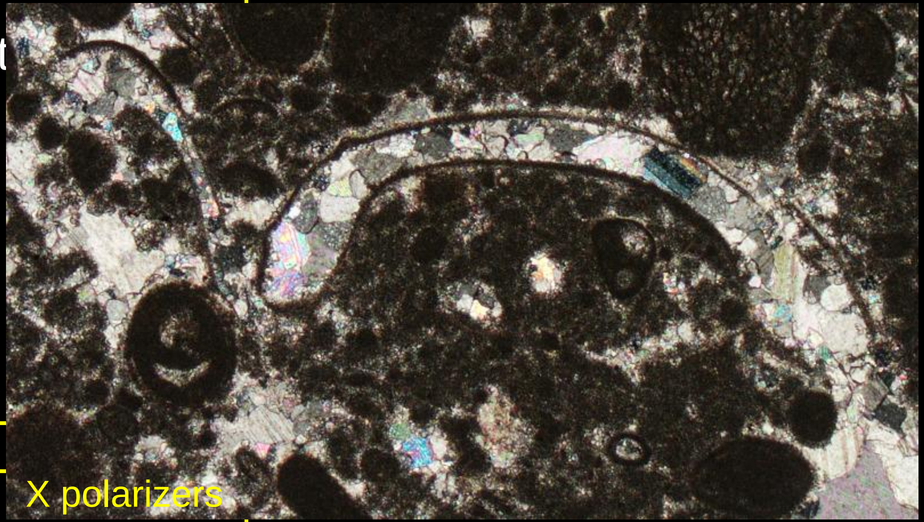
Aragonitic Bivalvia

Original mineralogy:

- Aragonite

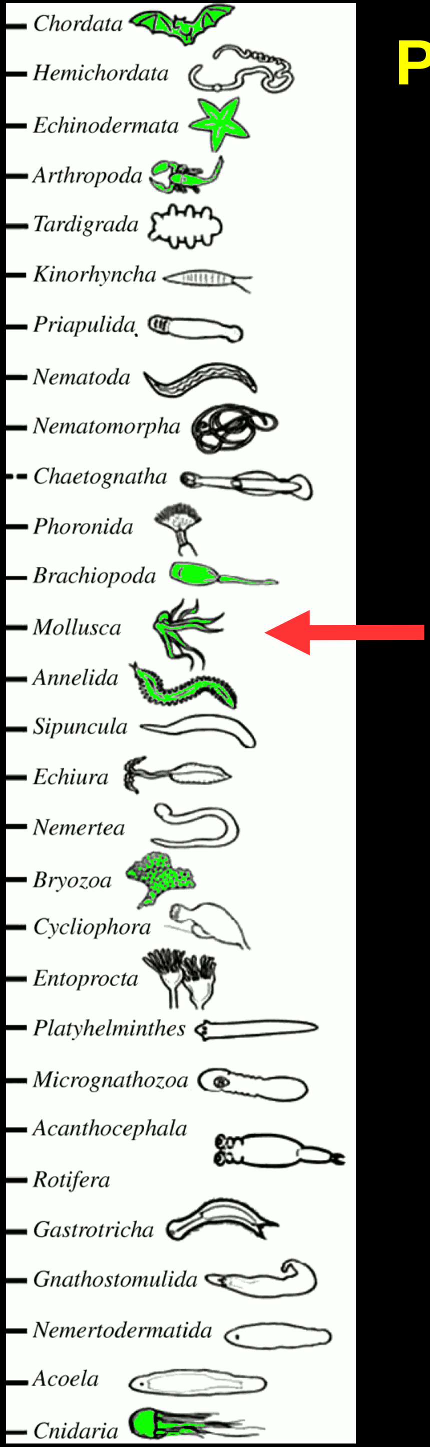
Diagnostic features:

- Bivalves, often disarticulated
- Often aequivalve
- Can be large (many cm)
- Nearly always dissolved or replaced by mosaic, drusy calcite cement
- Small fragments cannot distinguished from gastropods



Significance:

- Nearly always shallow water



Prismatic Bivalvia

Original mineralogy:

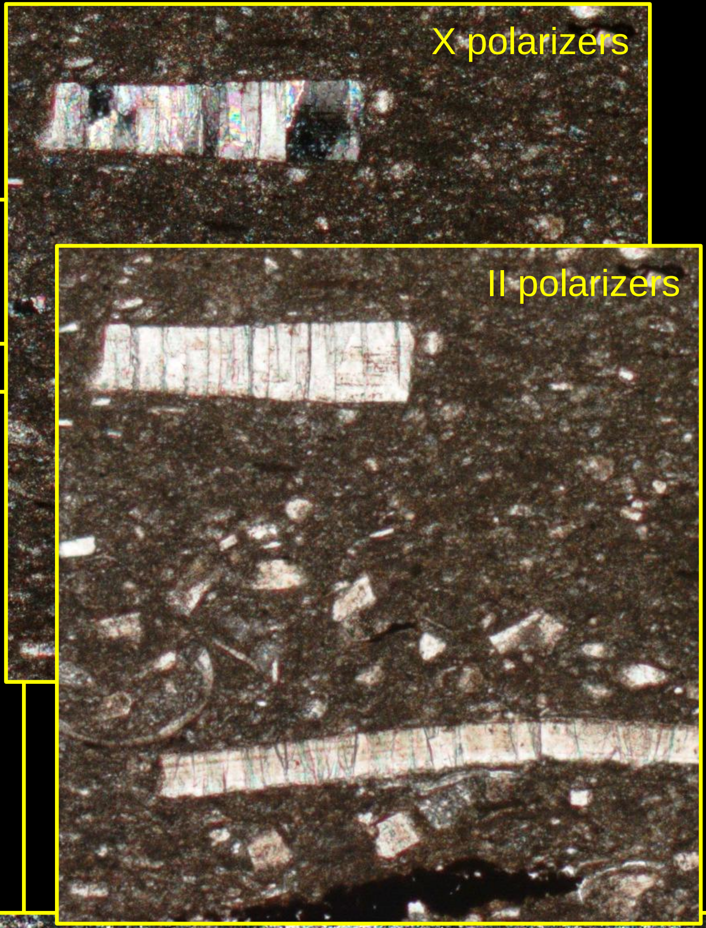
- Calcite (+ Aragonite)

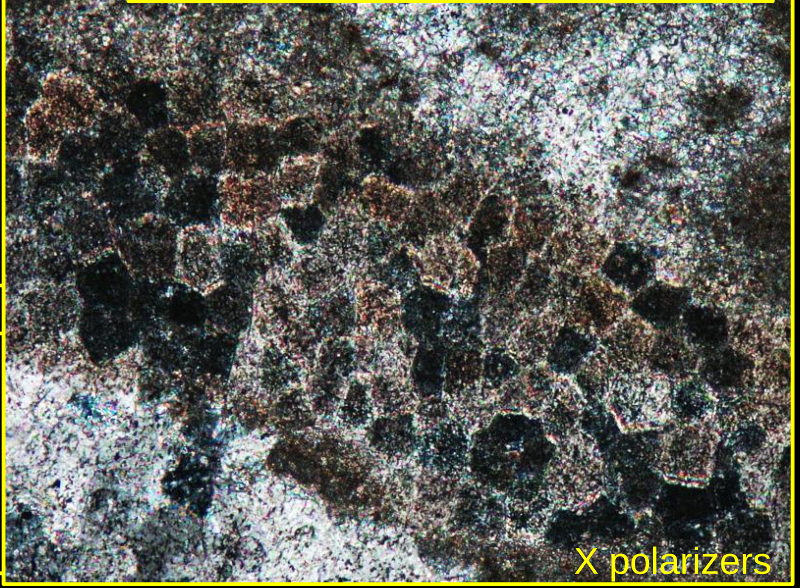
Diagnostic features:

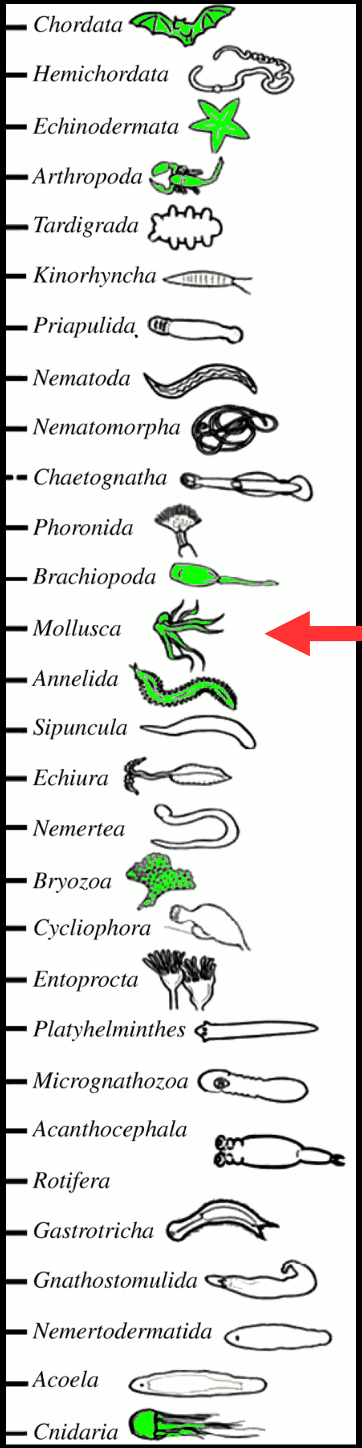
- Shells often broken into small fragments
- Can be large (many cm), but single prisms are always sub-mm
- Prisms have rectangular meridian sections and polygonal equatorial sections
- Some bivalves are bimineralic: an aragonitic inner layer and a prismatic outer layer

Significance:

- Common in the Mesozoic







Thin-shelled Bivalvia

Original mineralogy:

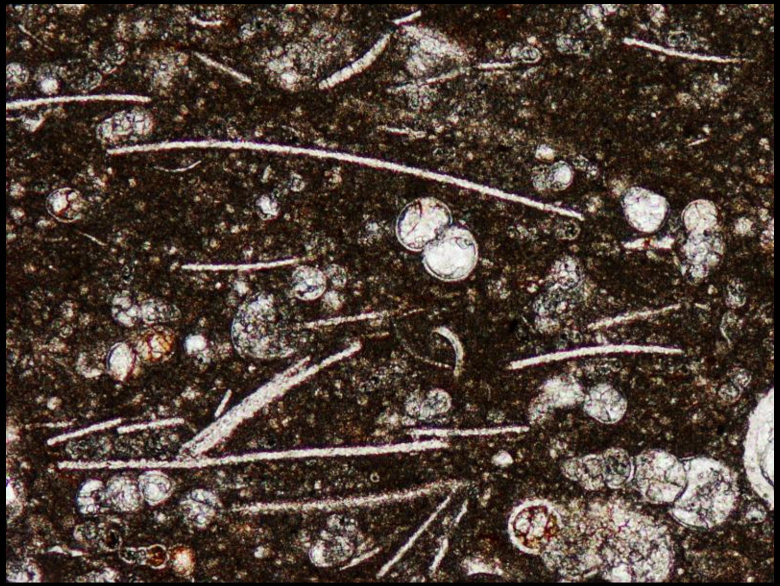
- Calcite (+ Aragonite)

Diagnostic features:

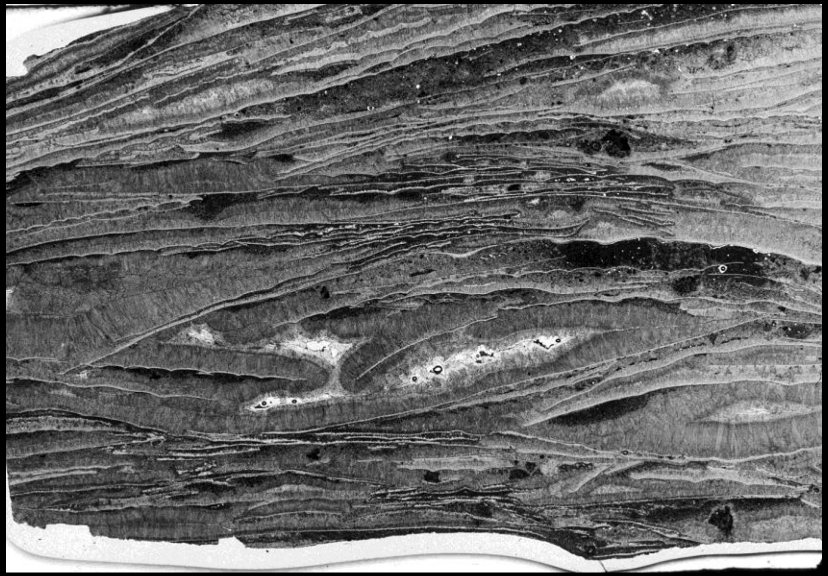
- Bivalves, often disarticulated
- Can be large (cm), the shell is extremely thin and flattish
- Made of fibrous calcite, fibers are parallel to the shell but hardly visible
- The facies in which they are found (micritic limestone with pelagic fossils) may suggest the determination

Significance:

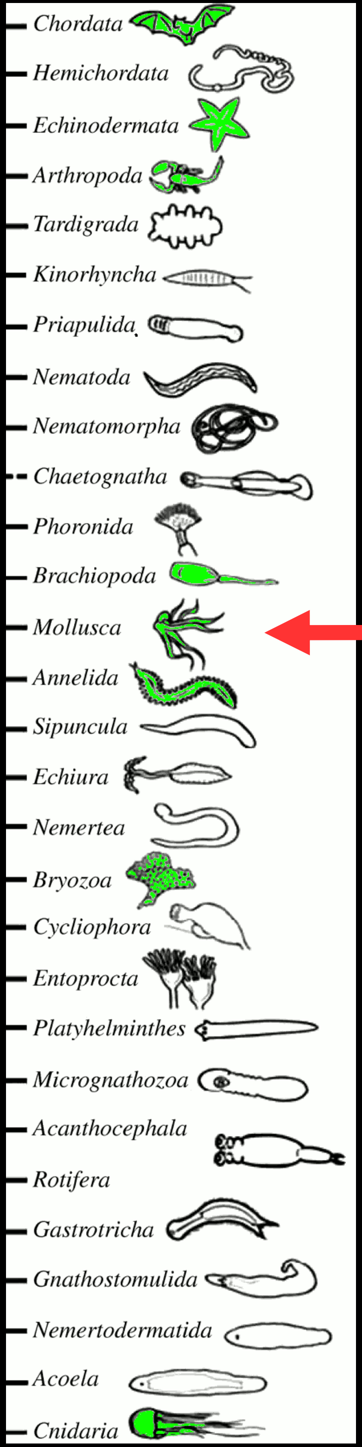
- Common in the Paleozoic and Mesozoic, are facies fossils for periplatform basins



Wackestone with thin-shelled bivalves and planktic foraminifera. Cretaceous, Berici Hills



Bivalve coquina and fibrous cement, upper Anisian, Latemar, Italy.

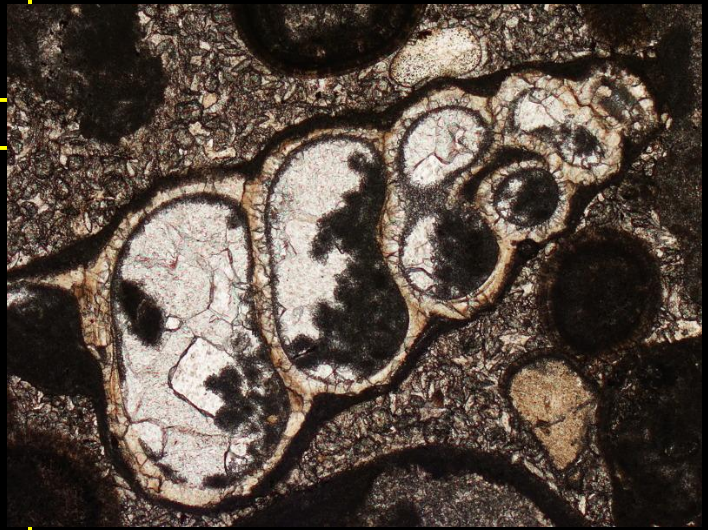


Gastropods

Original mineralogy:
- Aragonite

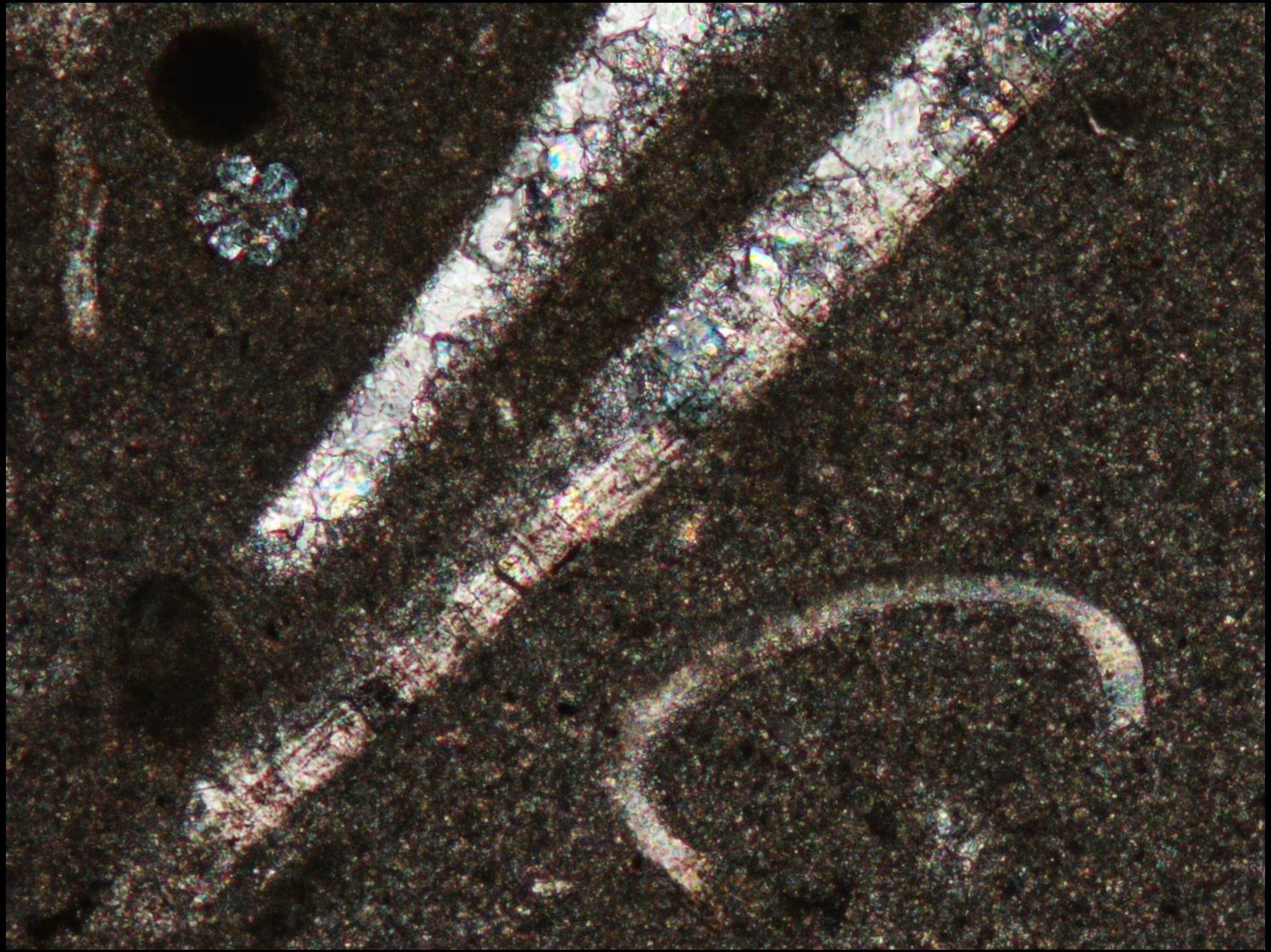
Diagnostic features:
- Have typical sections (see pictures)
- Can be large (many cm)
- Nearly always dissolved or replaced by mosaic, drusy calcite cement
- Small fragments cannot be distinguished from aragonitic Bivalv

Significance:
- Nearly always shallow water



Let's see if you got it...

What “bivalves” do we have here? (X nichols, 30 μm)



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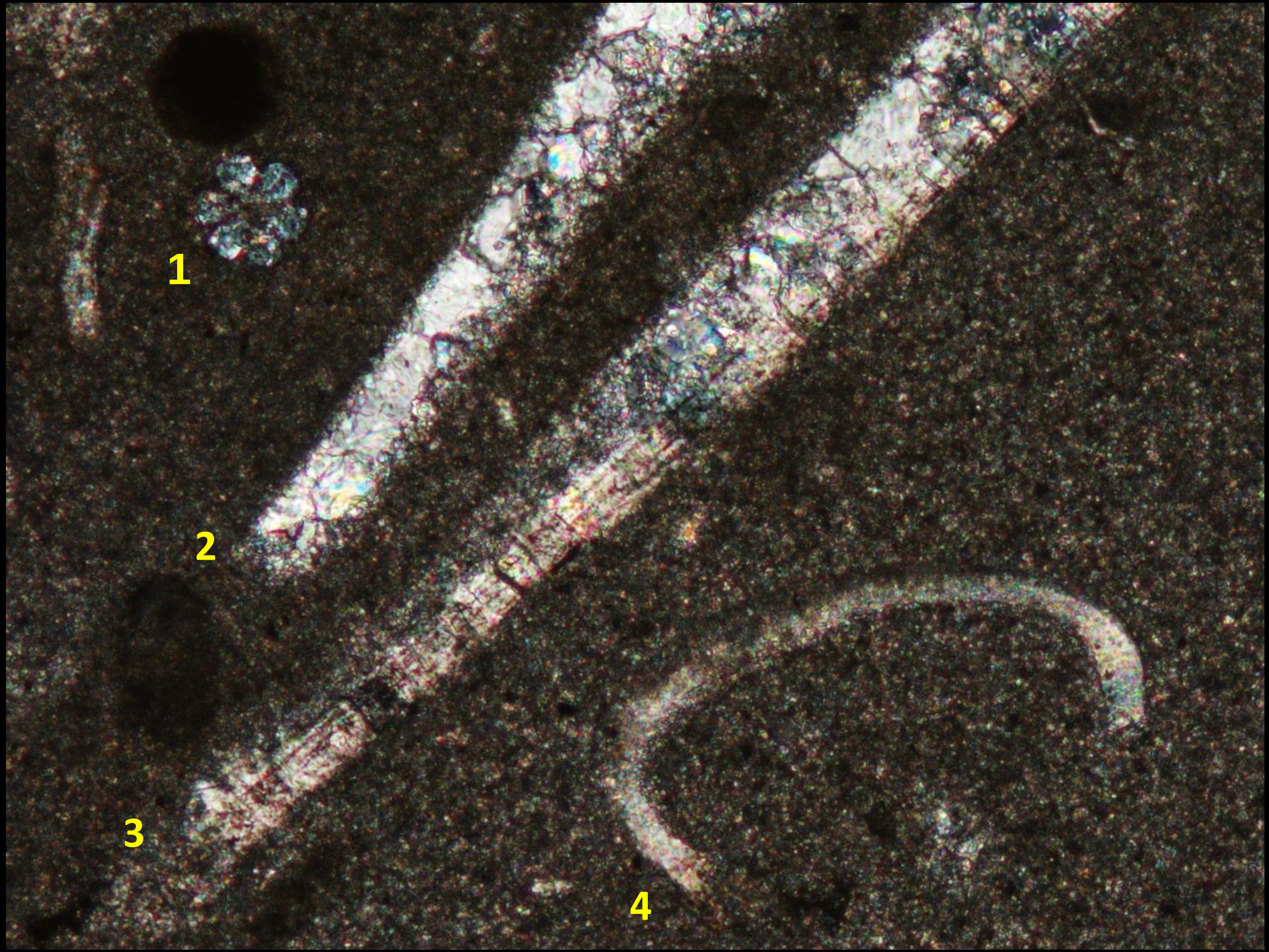
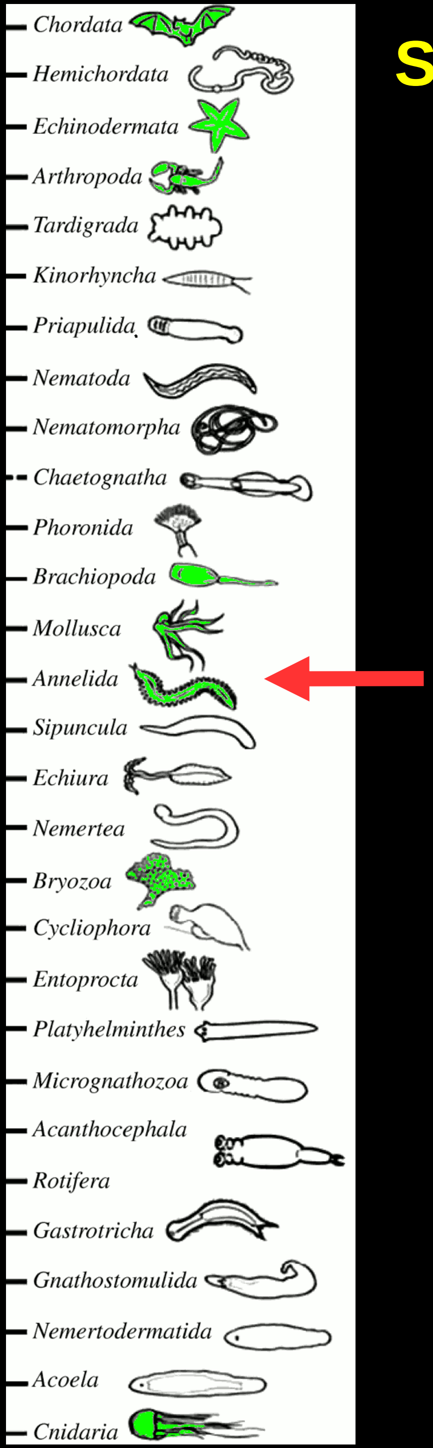


1) Echinoid spine (echinoderm): plain extinction, doily shape;
2) Aragonitic bivalve: replaced by mosaic calcite cement;
3) Bimineralic bivalve with a prismatic layer (right, some prisms are extinct) and an aragonitic layer (left);
4) Ostracod: small valve with wavy extinction, fibers perpendicular to the shell.



Serpulids

Original mineralogy:

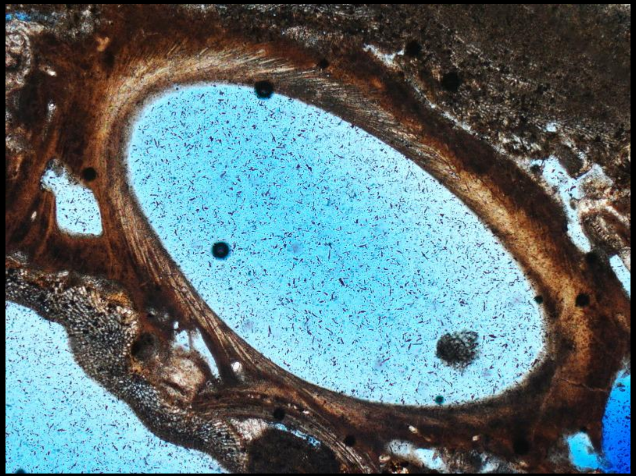
- Mixed, commonly low-Mg calcite.

Diagnostic features:

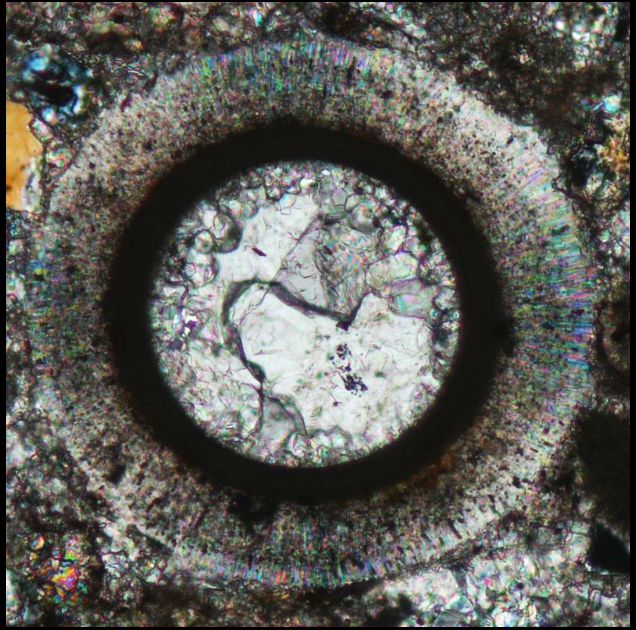
- Serpulids form tubes, thus, sections are open circles or ellipses
- Most of the times, they have a composite wall; however, the wall layers may be different between species
- There is always a calcitic part of the wall that preserves its ultrastructure
- May be encrusters of mollusk or other shells, or may be part of rhodoliths

Significance:

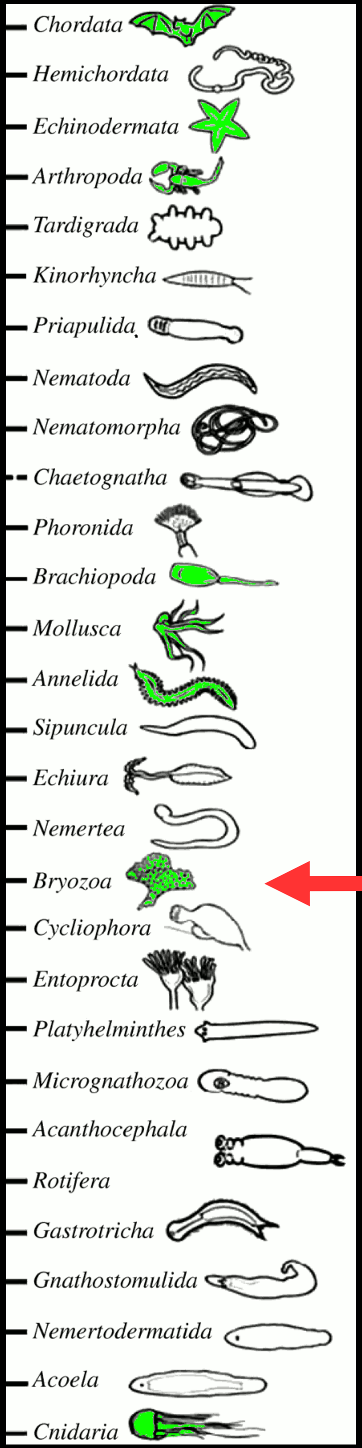
- Serpulids are often associated to mesotrophic - eutrophic conditions



Oblique section of a serpulid within a recent rhodolith. Blue staining fills the pores.



Serpulid from the Cenozoic of the Berici Hills, crossed polarizers.



Bryozoa

Original mineralogy:

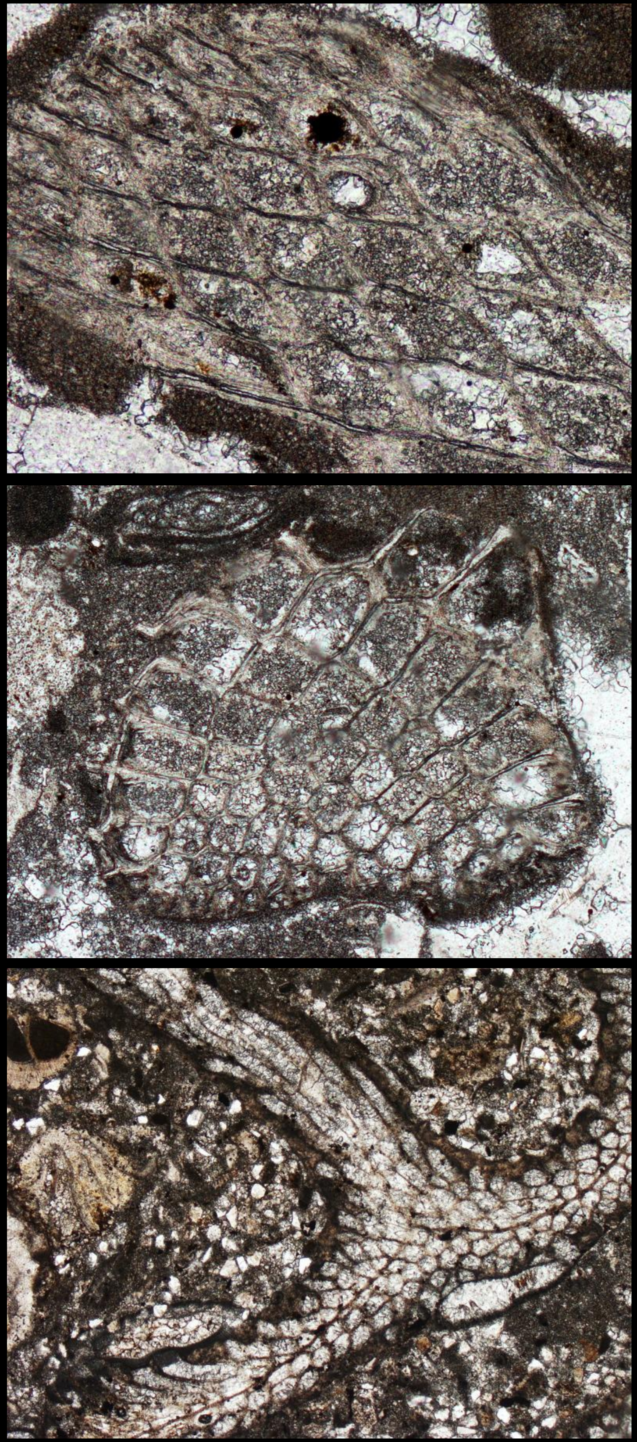
- Mixed, commonly low-Mg calcite.

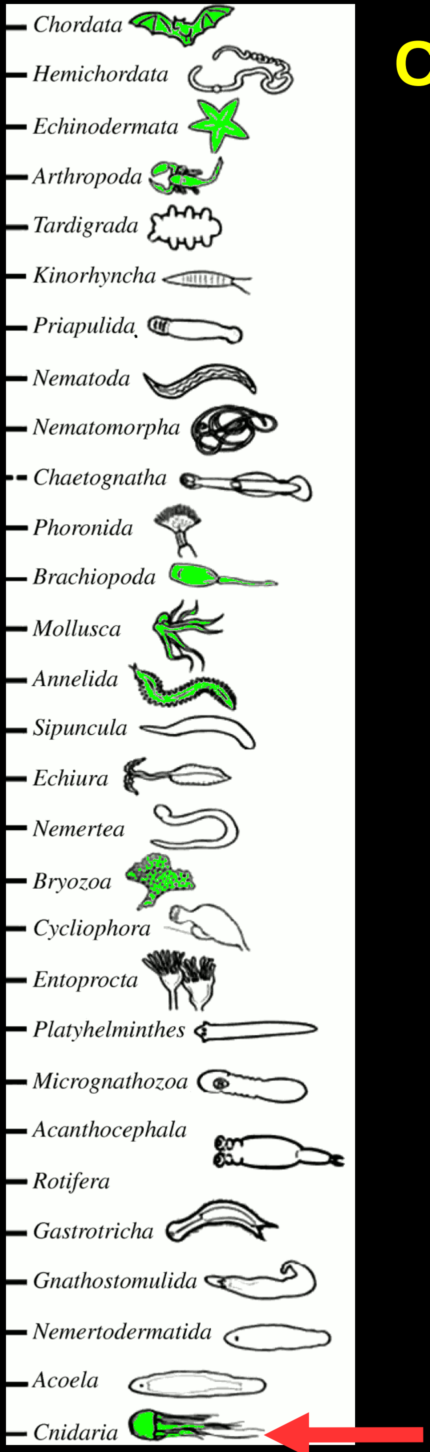
Diagnostic features:

- Made of cells separated by thin calcitic walls
- Cells have geometrical section and are elongated
- Can be confused with some Cenozoic larger foraminifera, but cells are much larger than walls, have more geometrical (e.g., rhombic) section and may form branching aggregates

Significance:

- May indicate eutrophic conditions or cold waters. Common in some Paleozoic facies, define the Bryomol skeletal ass.





Corals (Scleractinia)

Original mineralogy:

- Aragonite

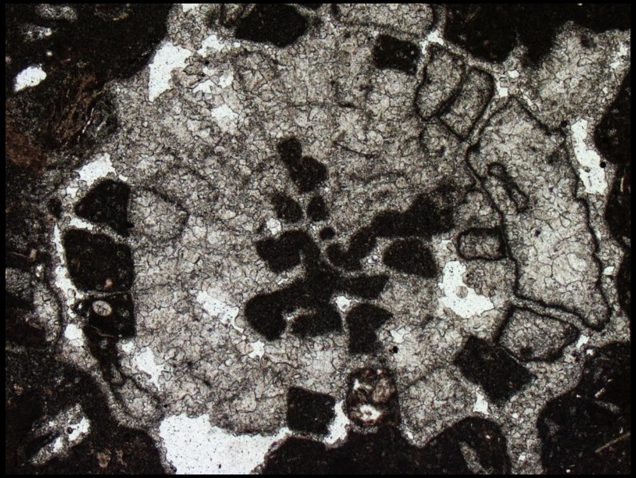
Diagnostic features:

- Have typical sections with septa encircled by a ticker wall
- Strongly modified by diagenesis, may transform into a circle fully replaced by a calcite mosaic, if the space between septa was not filled by sediment

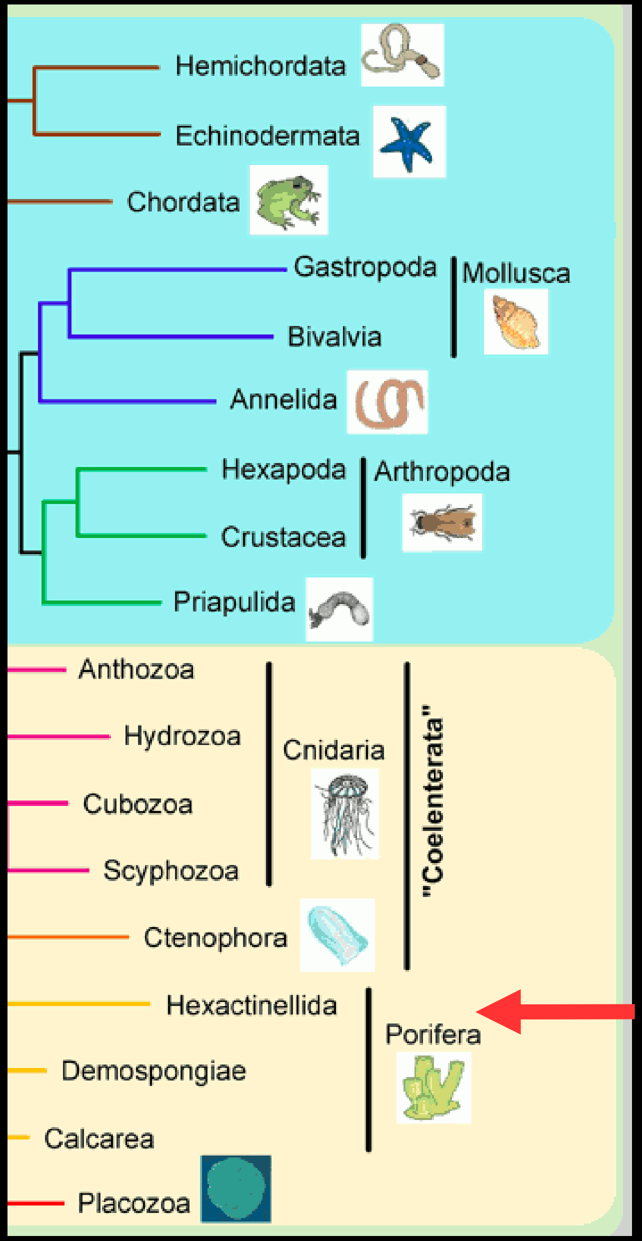
Significance:

- Most Cenozoic colonial corals indicate the photic zone. All colonial corals are reef builders.

Above: coral before diagenesis
Below: after aragonite replacement



Siliceous sponge spicules



Original mineralogy:

- Opal (amorphous silica)

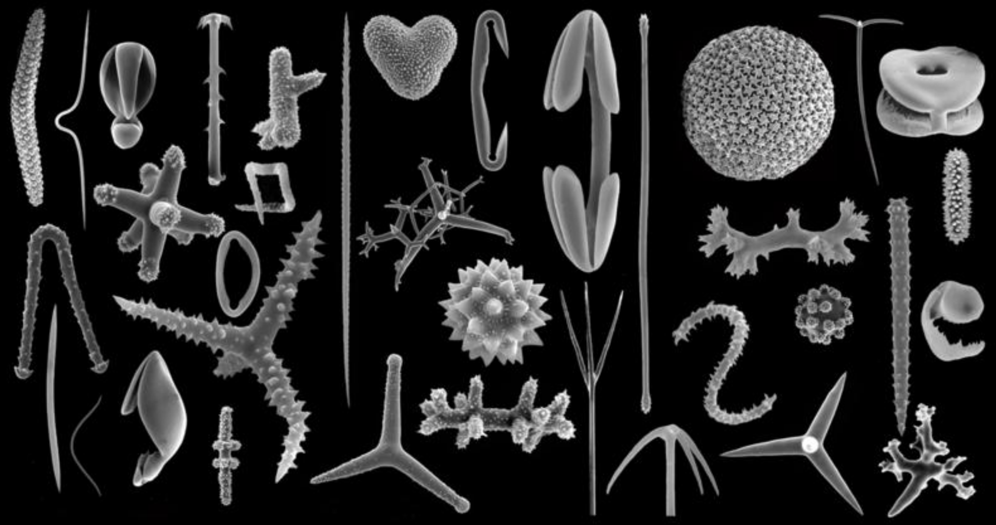
Diagnostic features:

- Are most typically replaced by mosaic calcite cement
- Always microscopic
- Sections are typically round or elliptical, or spiny. Rarer complex forms.
- A central pin (canal) may be visible, but is occluded in most cases

Significance:

- Deep or shallow water, hardly preserved in high-energy environments

Siliceous sponge spicules



From Van Soest et al., 2012

Original mineralogy:
- Opal (amorphous silica)

Diagnostic features:
- Are most typically replaced by mosaic calcite cement
- Always microscopic
- Sections are typically round or elliptical, or spiny. Rarer complex forms.
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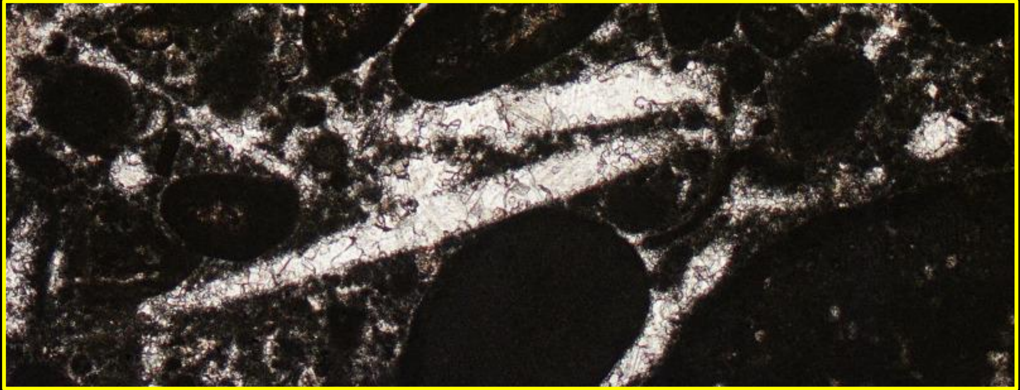
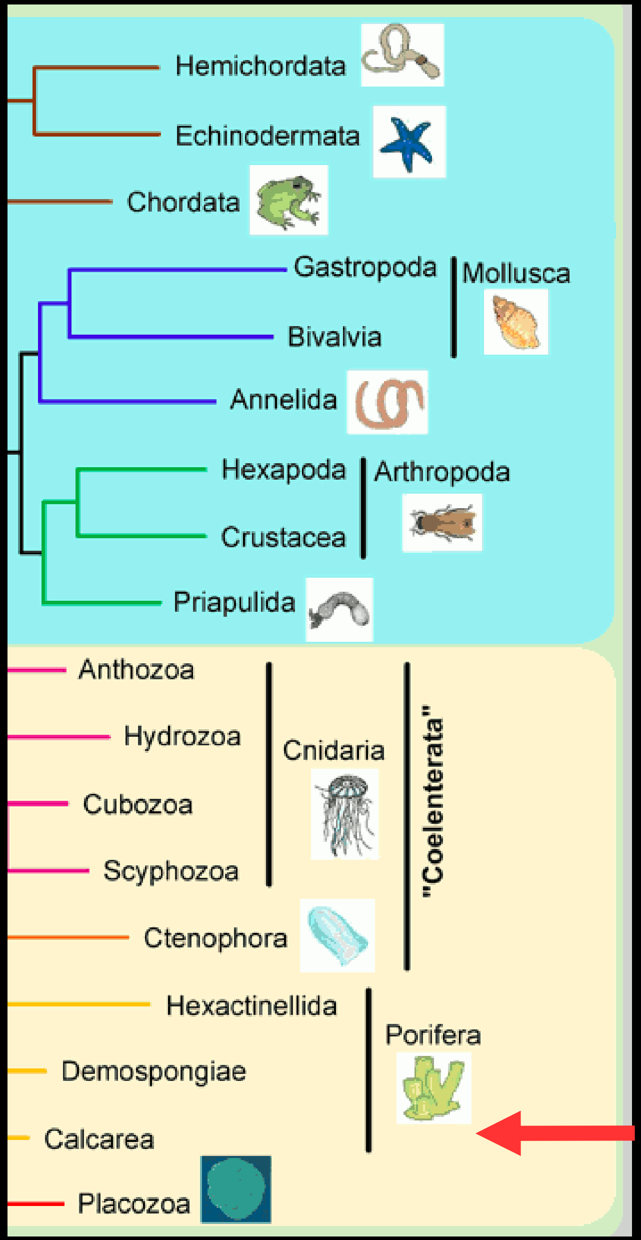


Siliceous sponge spicules (substituted by calcite) and echinoderms. In (1), the central canal is still visible.

Significance:
- Deep or shallow water, hardly preserved in high-energy environments

Calcareous sponges



Original mineralogy:

- Mostly aragonite

Diagnostic features:

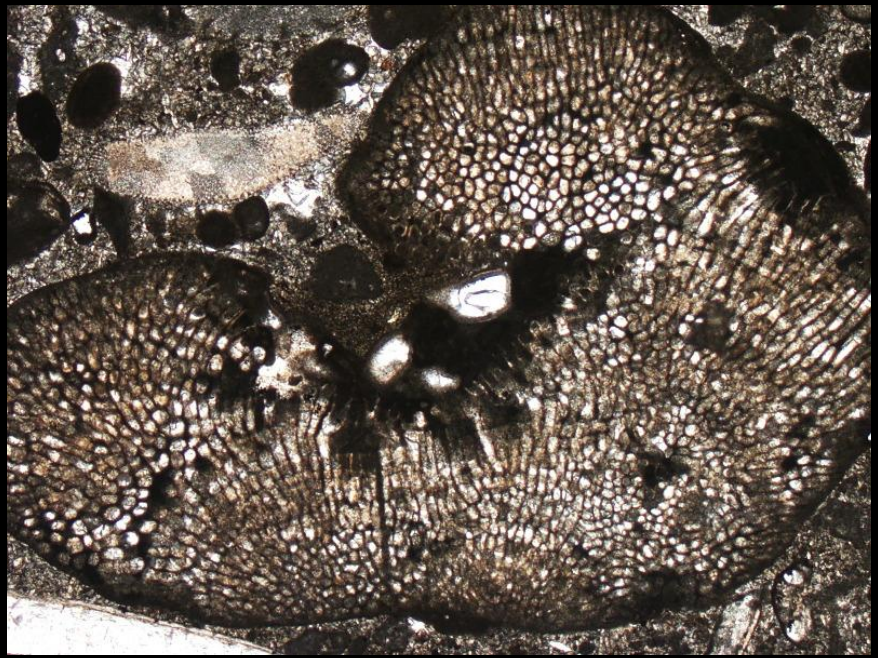
- Huge variety of forms and ultrastructures, it is nearly impossible to give a description!

 - Sphinctozoa are made by superimposed globular cells with a brain-like framework inside
- Stromatoporoids are made of pillars connected by “floors”
- Chaetetids are made of polygonal cells
- Many other forms exist

Significance:

- Common reef builders in the Paleozoic and for parts of the Mesozoic

Variety of calcareous sponges

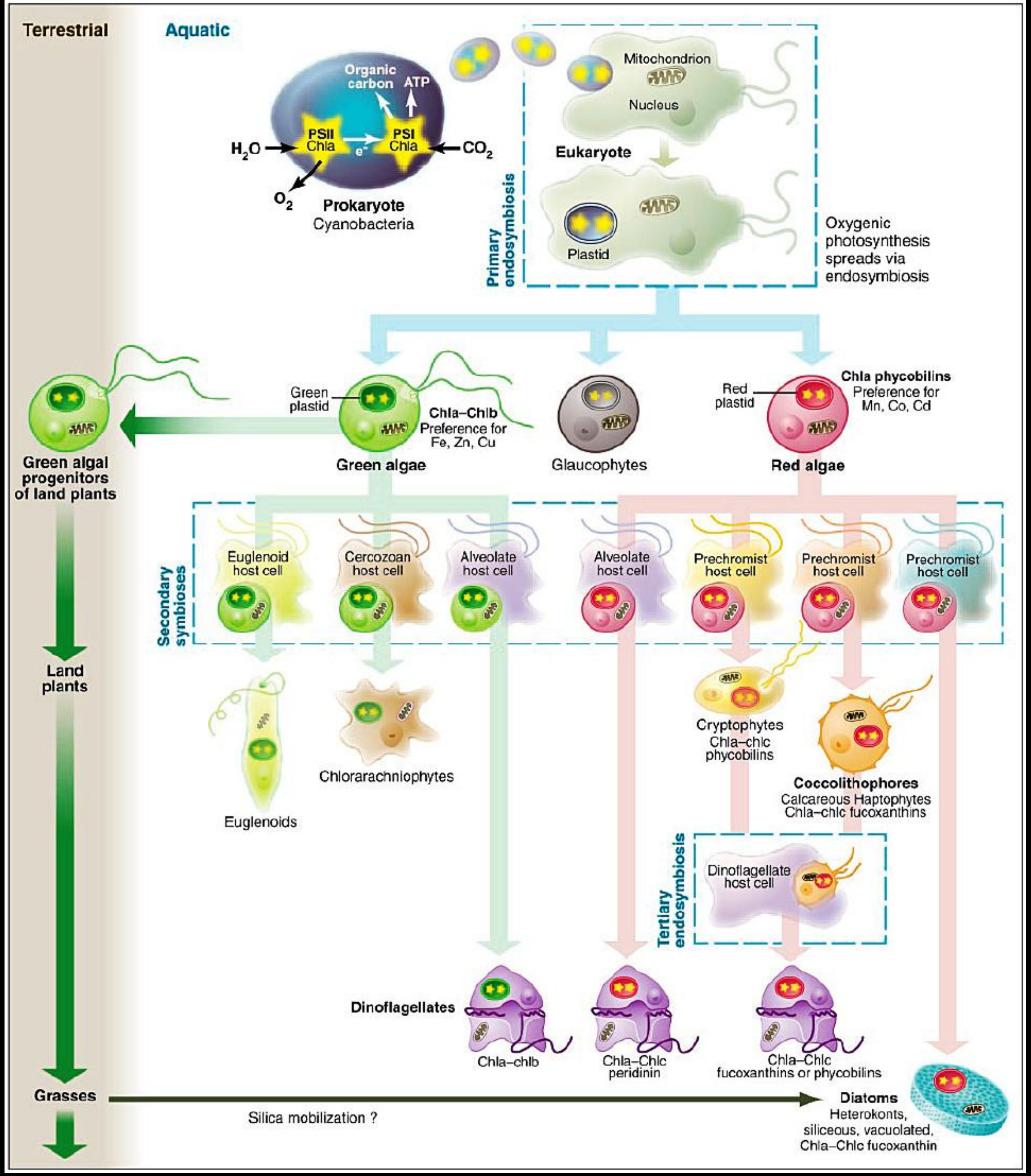


Chaetetid sponge

Stromatoporoid structure (Aragonite preserved)

Sphinctozoan sponge

Taxonomy of photosynthesizing organisms



There is no simple order in the evolution of “algae” and plants. Multicellular photosynthesizing organisms are a strongly polyphyletic group.

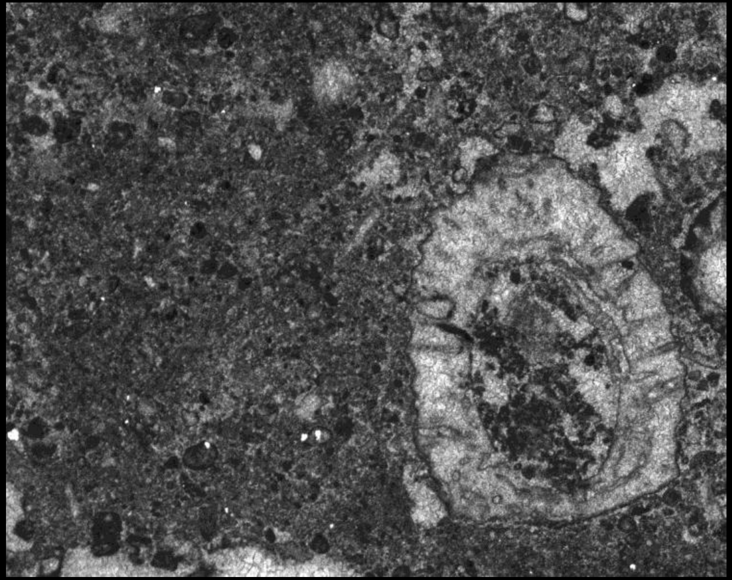
A simplified representation of the evolution of photosynthesizing organisms, from Falkowski et al. (2004).

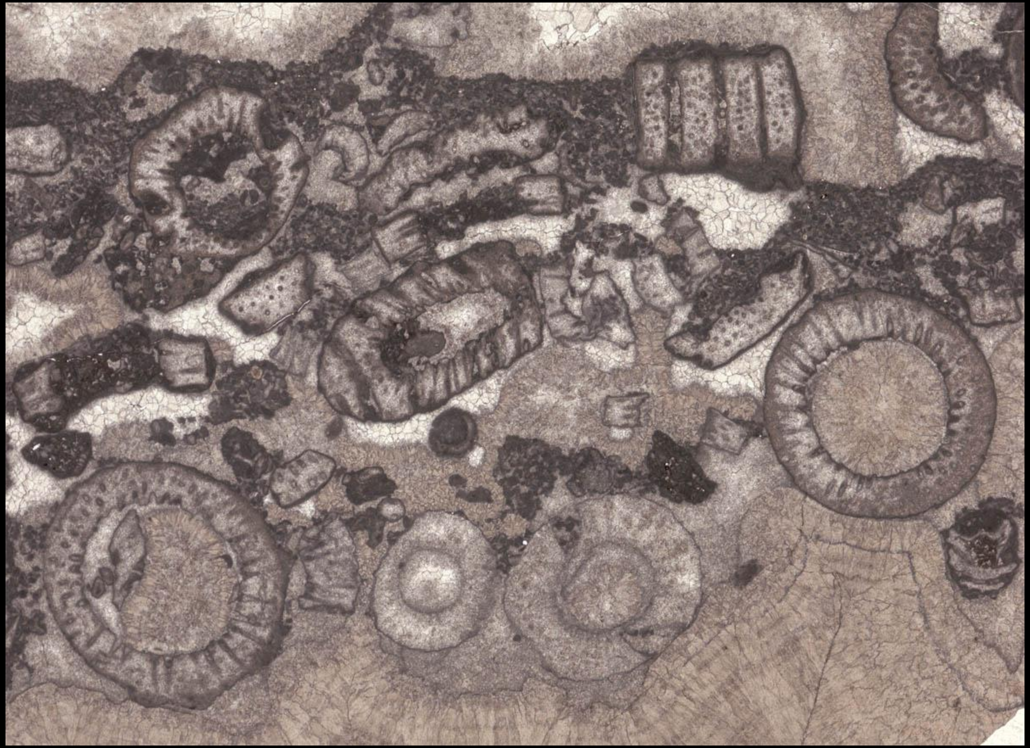
The evolution of this wide group of organisms is complex, because it involves strict symbiotic relationships that evolved into taxa (e.g., organelles as the chloroplasts are actually cyanobacteria that survived phagocytosis by heterotrophic single-celled organisms), and is thus not in the form of a tree.

This implies, among other complications, that:

- Dynoflagellates are a polyphyletic group
- Green “algae” have a common ancestor for what the photosyntesizing organelles are concerned, but different ancestors for the rest of the cell;
- Red algae are well separated from green algae, but both are ancestors of dynoflagellates

Dasycladacean algae





Original mineralogy:

- Aragonite

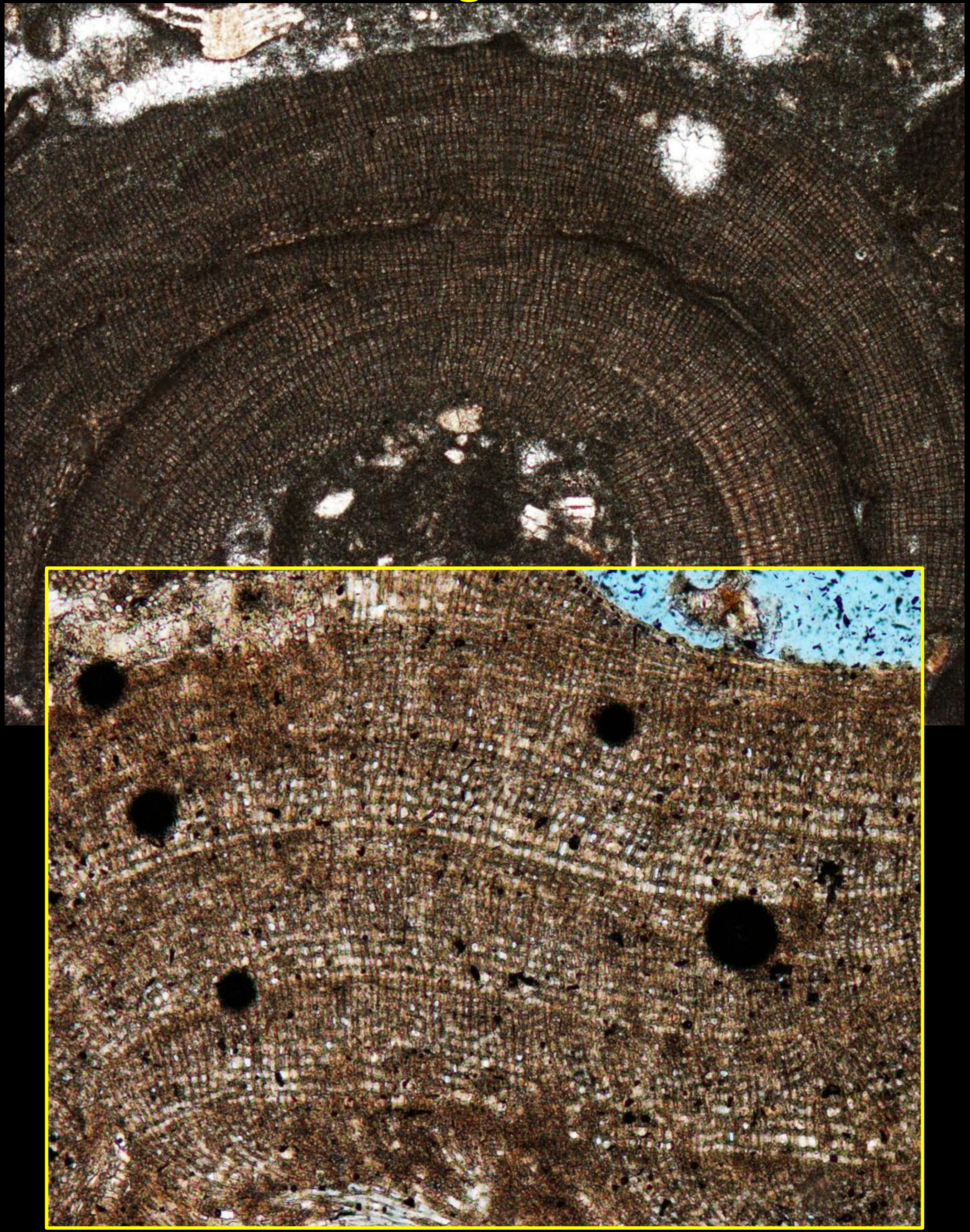
Diagnostic features:

- Each element of the stem is a ring, perforated by pores.
- Almost always sub-centimetric
- Typical sections are round, elliptic or double square
- Elements may be found in anatomical connection

Significance:

- Indicate the euphotic zone

Cenozoic red algae and rhodoliths



Original mineralogy:

- High-Mg calcite

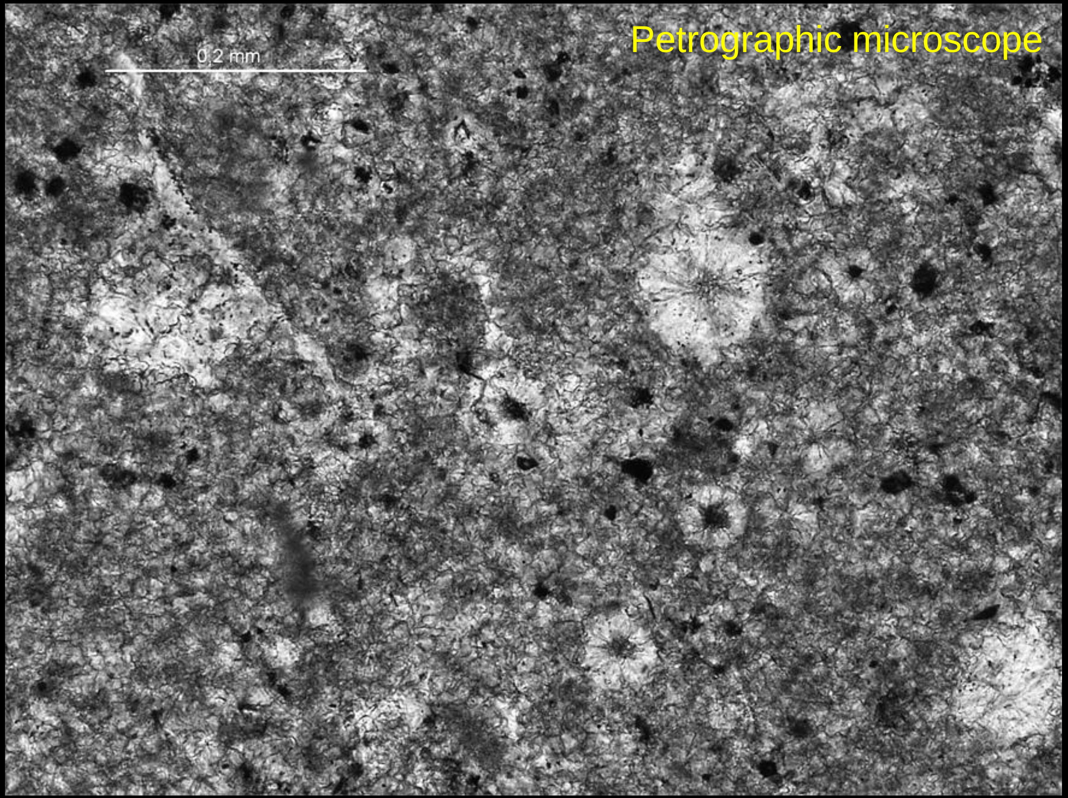
Diagnostic features:

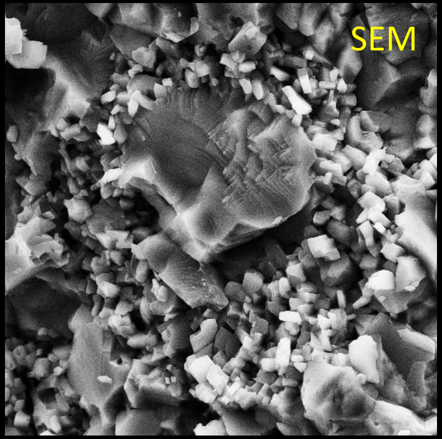
- The ultrastructure is made by small (tens of microns) cells with micritic walls and squared section
- Form crusts, branches, or rounded aggregates (rhodoliths) that can be as large as > 10 cm

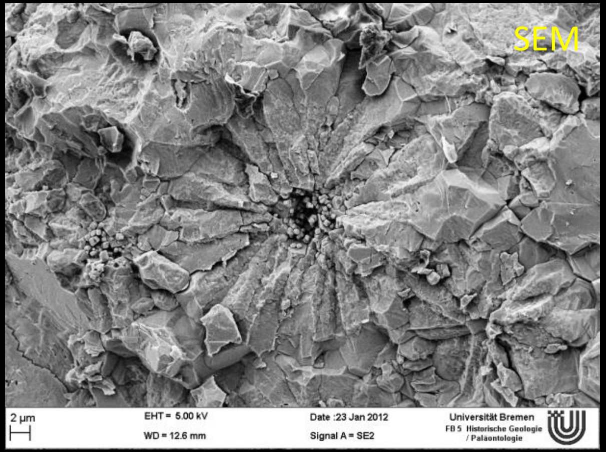
Significance:

- Become common only in the Cenozoic, most commonly indicates oligophotic conditions

“Calcispheres” (including some nannoliths)







Original mineralogy:

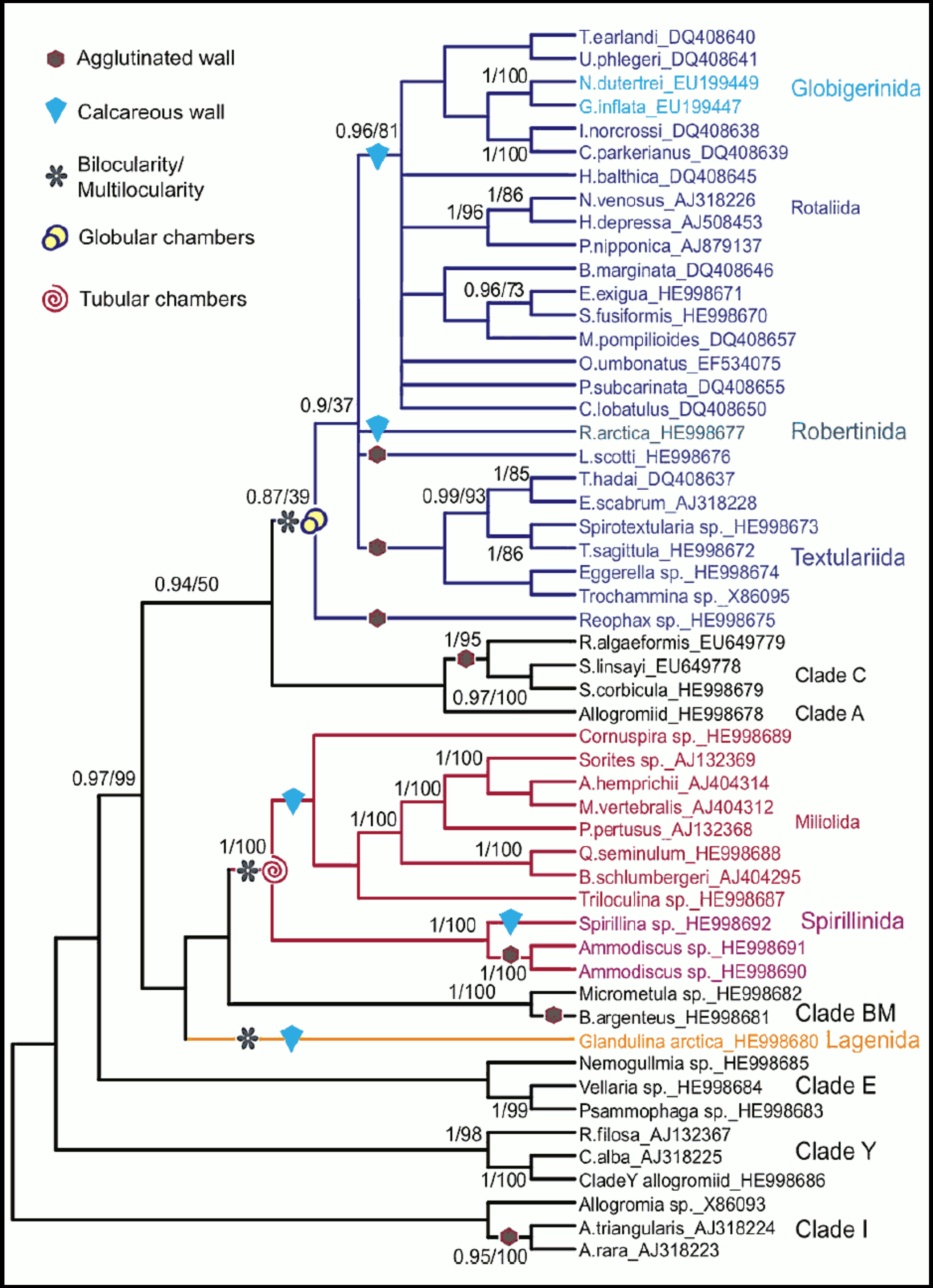
- Low-Mg calcite

Diagnostic features:

- The morphological term “calcisphere” refers to a variety of presumably planktic, usually spherical, usually *incertae sedis* organisms with diameters of ca. 5-100 μm
- Rarely visible under the optical microscope, and only at the highest magnifications (20x lens or more)
- Not to be confused with calcified radiolaria, which are siliceous and replaced by mosaic calcite. True calcispheres instead preserve a ultrastructure.

Significance:

- Pelagic or hemipelagic facies, more common in the Mesozoic



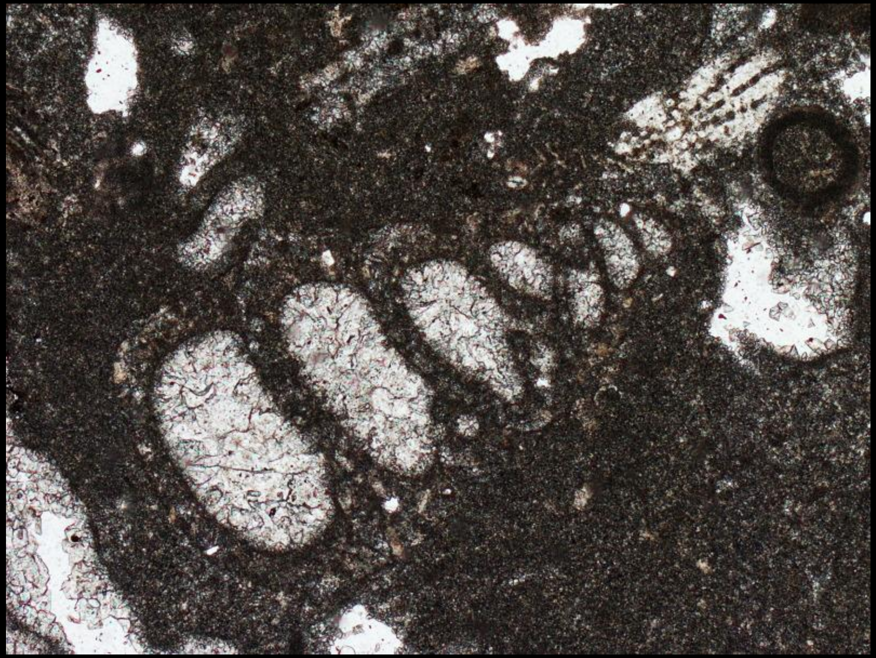
Taxonomy of foraminifera

There is no way to a morphological or textural determination of high-rank foraminiferal taxa.
Foraminifera in thin section are described with structural – not taxonomical – groups.

An evolutionary history of foraminifera, based on genome similarity or extant species and the fossil record (From Pawlowski et al., 2013).
Differently for photosynthesizing organisms, foraminifera have a single common ancestor and a strictly hierarchical taxonomy. However, no morphological, structural or mineralogical character exists that can be used as a proxy for the high-rank taxonomy.
For example, consider the mineralogy of the test: agglutinate foraminifera do not form a single branch of the evolutionary tree; instead, the agglutinated test keeps appearing in all main taxonomic groups at different (evolutionary) times. The same holds, for example, for the character of multilocularity.

Foraminifera are thus described and classified, in thin section, in a way that has no evolutionary meaning.

Agglutinated foraminifera



Original mineralogy:

- (sediment)

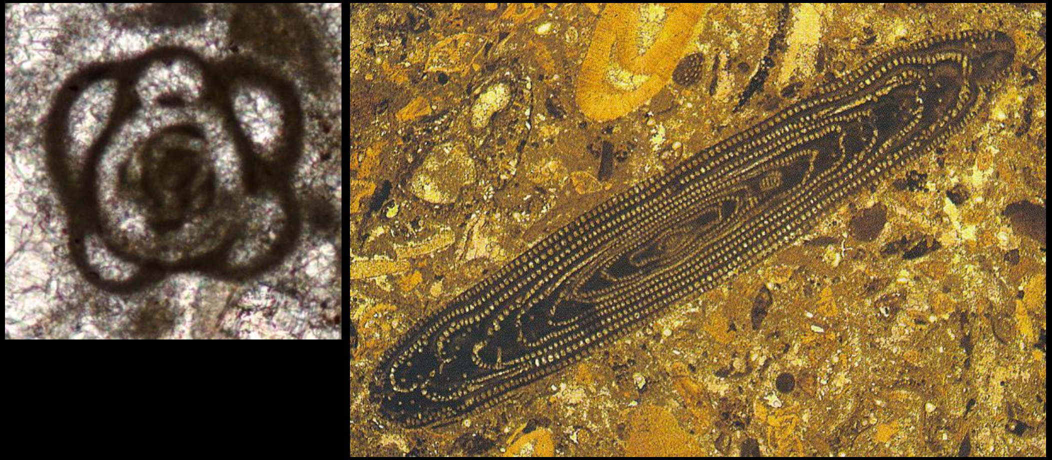
Diagnostic features:

- In silty or sandy sediments, the test is made of grains
- In muddy sediments, the test is made of fines, but it can be distinguished from porcelanous tests because it is ticker and irregularly dark
- Only rarely they have a complex arrangement of chambers (but uniseriate and biseriate forms are common).

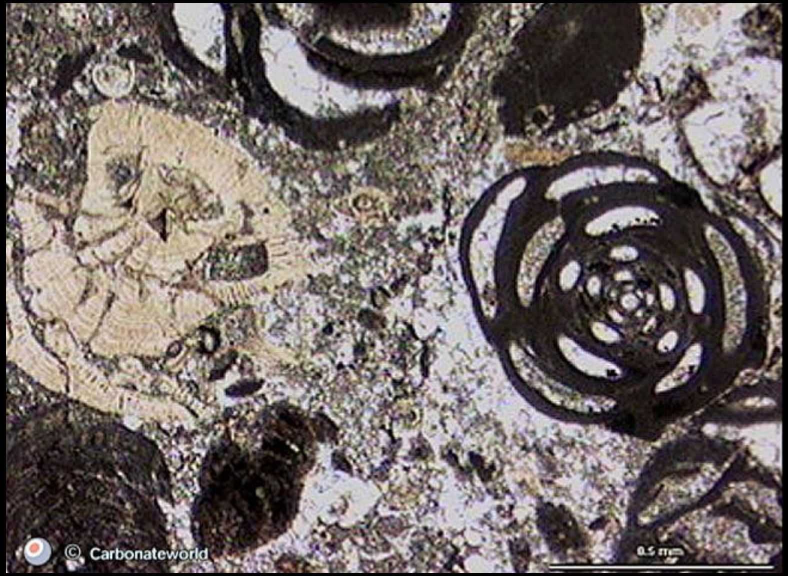
Significance:

- Benthic

Porcelanous foraminifera



Alveolina, a larger porcelanous foraminifer of the Cenozoic. From Adams and MacKenzie, 1998



Rotalinid, hyaline (left) and miliolid, porcelanous (right) foraminifera. Image from www.carbonateworld.com

Original mineralogy:

- High-Mg calcite

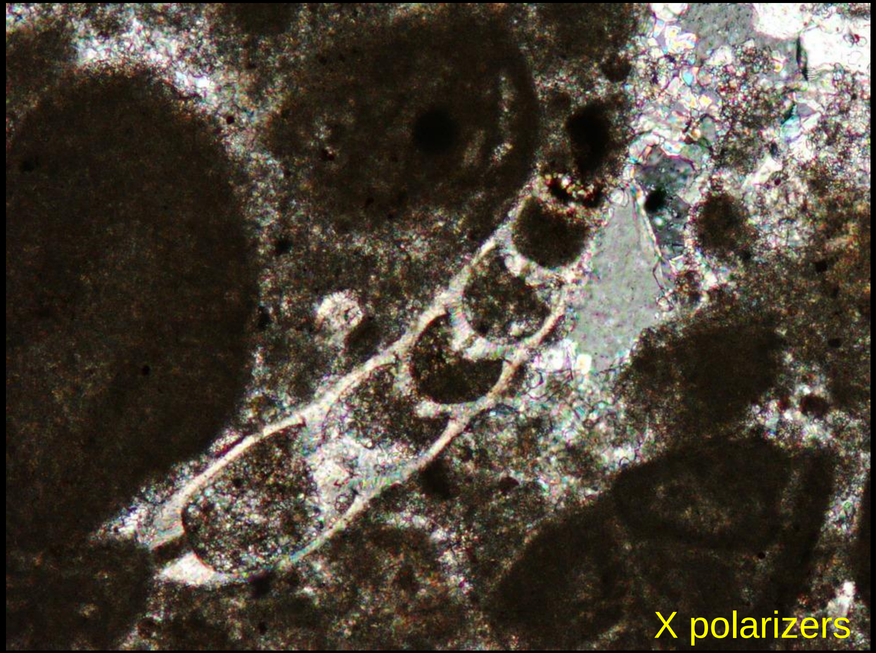
Diagnostic features:

- The test is made of densely packed ultra-fine (<1 μm) calcite crystals that give the test a dark, nearly opaque appearance under transmitted light
- Most forms are small (< 1 mm), with few exceptions in specific time intervals
- Always multiloculated, typical forms are generated by a “ball of wool” coiling, as in genera *Pyrgo*, *Triloculina*, *Quinqueloculina*

Significance:

- Benthic, usually in the most internal part of carbonate platforms

Hyaline foraminifera



Original mineralogy:

- Low-Mg calcite

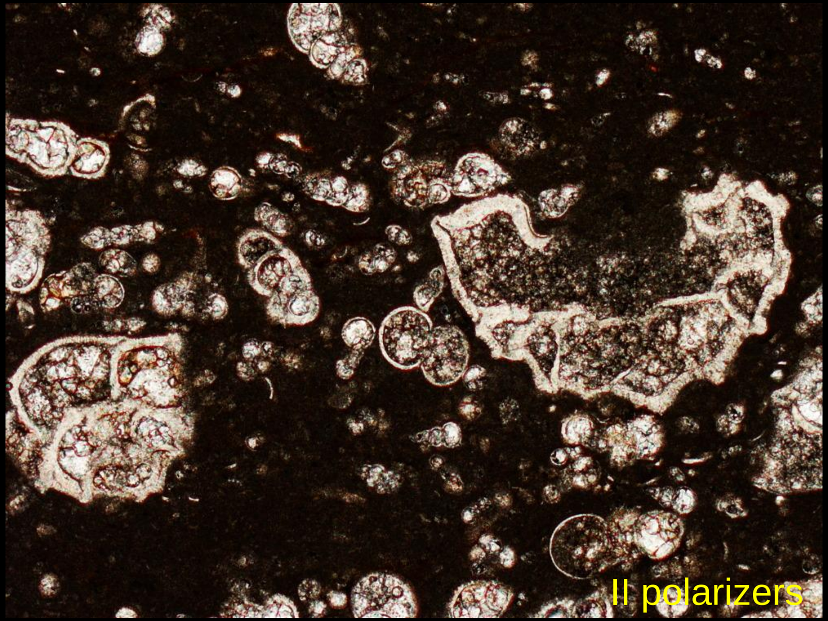
Diagnostic features:

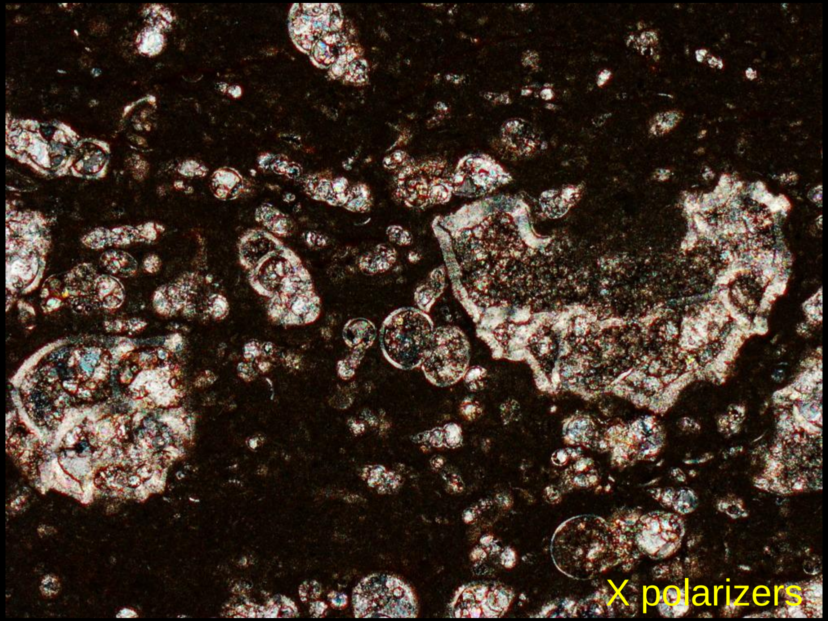
- The test is made of calcite fibers perpendicular to the wall, implying a undulose extinction
- The test is thin in most forms
- Chambers are arranged in all possible combinations, from uniloculated to the most complex coilings of numerous chambers
- They have a perforated wall (unlike porcelanous foraminifera), although perforations may be sometimes invisible

Significance:

- Forams with a hyaline test occur in all possible marine environments

Planktic foraminifera (hyaline wall)





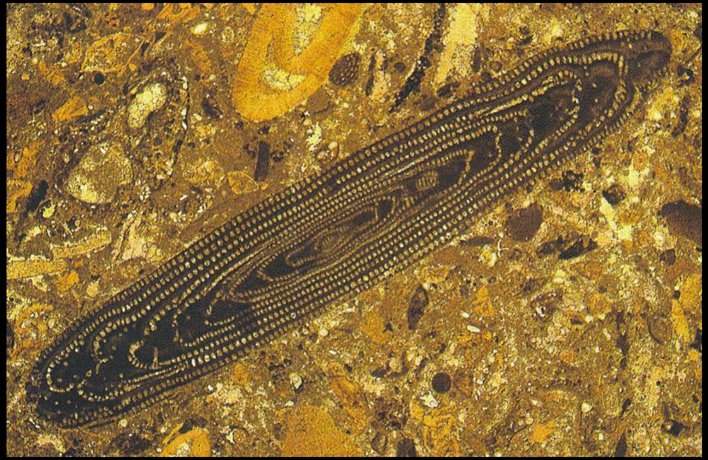
Original mineralogy:
- Low-Mg calcite

Diagnostic features:
- Planktic foraminifera are perforated foraminifera with a hyaline test.
- With respect to benthic forms, they have a thinner wall, and (evident in Cenozoic forms) large wall perforations
- Nearly always associated with the occurrence of fines, may form wackestones and may be associated with other deep water fossils (e.g., thin-shelled bivalves, calcified radiolaria)

Significance:
- Pelagic, hemipelagic facies or outer ramp facies, they are common only since the Cretaceous

Larger foraminifera (hyaline or porcelanous wall)

Alveolina, from Adams and MacKenzie, 1998



Nummulites (above) and *Discocyclina* (on the right)

Original mineralogy:
- Low-Mg calcite (rarely, High-Mg)

Diagnostic features:
- Visible at the naked eye
- Always with a huge number of chambers
- Mostly hyaline, with few exceptions, e.g.: *Fusulina* in the Paleozoic; *Orbitopsella* in the Jurassic; *Alveolina* in the Cenozoic
- The wall is often much thicker than the chambers

Significance:
- In the Cenozoic, different groups mark different parts of carbonate ramps

Carbonate microfacies

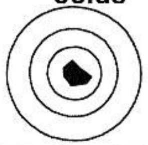
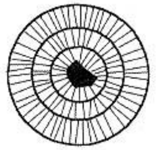
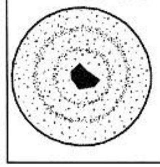
Inorganic grains: reloaded

Robert Delaunay, Premier Disque, 1913

Ooids

They have a nucleus and three main ultrastructures:

- Tangential ooids have crystals elongated parallel to laminae
- Radial ooids have crystals perpendicular to the laminae
- Micritic ooids are made of micrite (fine carbonate, < 4 mm)

	Microfabric of the cortex	Mineralogy, modern examples		Environment
Concentric (tangential) **ooids** 	Concentric laminae consisting of tangentially arranged crystals whose long axes are aligned to the surface of the laminae. High microporosity	Aragonite:	Bahamas, Yucatan, Abu Dhabi, Persian Gulf	Very shallow, warm low-latitudinal seas; *common in high-energy settings*
			(Great Salt Lake/Utah)	Lacustrine-hypersaline
		Low-Mg calcite: Caliche ooids*		Terrestrial
Radial (radial-fibrous) **ooids** 	Laminae consisting of radially arranged crystals; long crystal axes perpendicular to the laminae surface	Aragonite:	Persian Gulf, Great Barrier Reef, (Yucatan, Shark Bay, Mediterranean)	Shallow marine, *common in low-energy settings*
			Gulf of Aqaba	Sea-marginal hypersaline pool
			Great Salt Lake/Utah	Lacustrine-hypersaline
		Mg-calcite:	(Baffin Bay/Texas)	Marine-hypersaline
		Calcite and Low-Mg calcite:	e.g. Cave pearls*	Non-marine
Micritic (random) **ooids** 	Laminae composed of randomly arranged microcrystalline crystals or Laminae obliterated or absent, due to a pervasive micritization of the cortex	Aragonite:	Bahamas	Shallow-marine

Flügel, 2004

Tangential ooids

Modern tangential ooids from the Bahamas. Below, blue staining was used to highlight that laminae of aragonitic ooids are porous.

Fossil aragonite ooids should be replaced by a mosaic of blocky calcite (lower Jurassic, Lombardy).

Original mineralogy:

- Aragonite

Diagnostic features:

- The coatings are crystalline and appear laminated
- Are substituted by a mosaic of blocky calcite in nearly all geological examples
- Vertical bioerosion traces and the growth of secondary, radial calcite crystals may give the ooid a radial appearance

Significance:

- High energy shallow water marine environments – common today, rare in the fossil counterparts.

Radial ooids

Original mineralogy:

- Low-Mg calcite (?)

Diagnostic features:

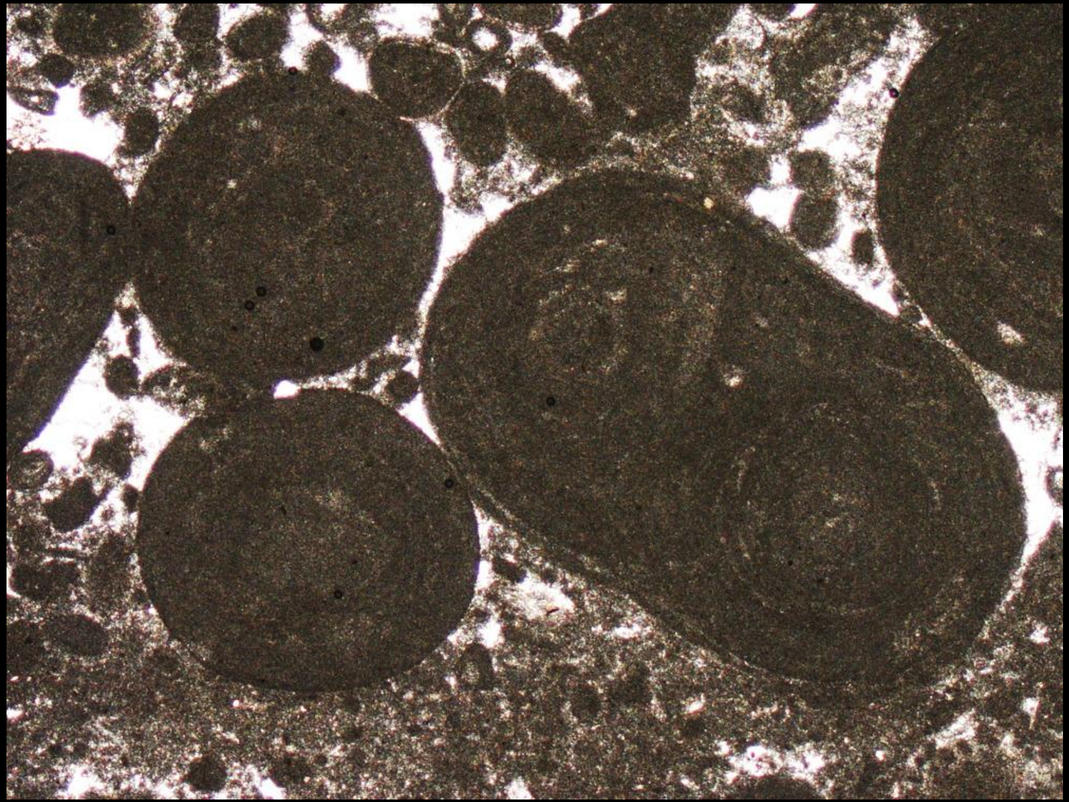
- Coatings are crystalline, often laminated, with fibrous crystals disposed radially
- They have a typical cross (ondulose) extinction pattern
- Vertical bioerosion traces occur as in tangential ooids

Significance:

- High energy shallow water marine environments, lakes, caves, gaysers...

Micritic ooids

This ooid has a peloid as a nucleus; a first coating that is radial, and an external part that is micritic. Is this micritization or a primary micritic layer?



Original mineralogy:

- ?

Diagnostic features:

- Coatings are made of micrite or microsparite
- Lamination may or may not occur
- Bioerosion traces cannot be distinguished
- They often originated from the micritization of other types of ooids. However, there might be primary micritic ooids. This primary variety has been also called “micro-oncoids”.

Significance:

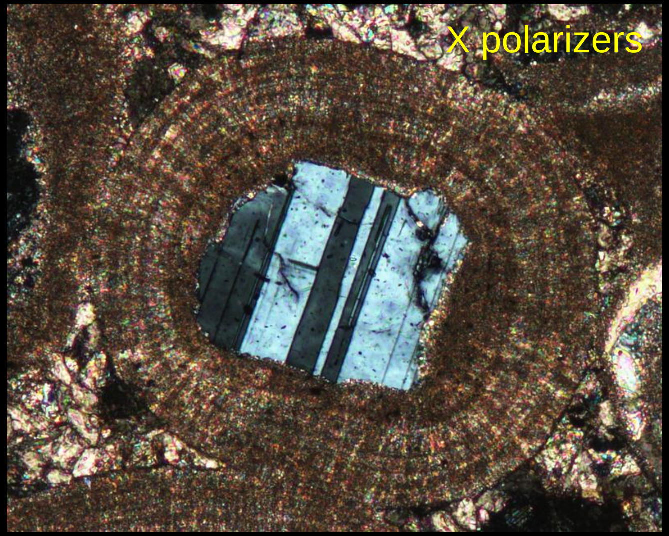
- High energy shallow water marine environments, long residence time of sediments if formed by micritization

Ooids: caveats

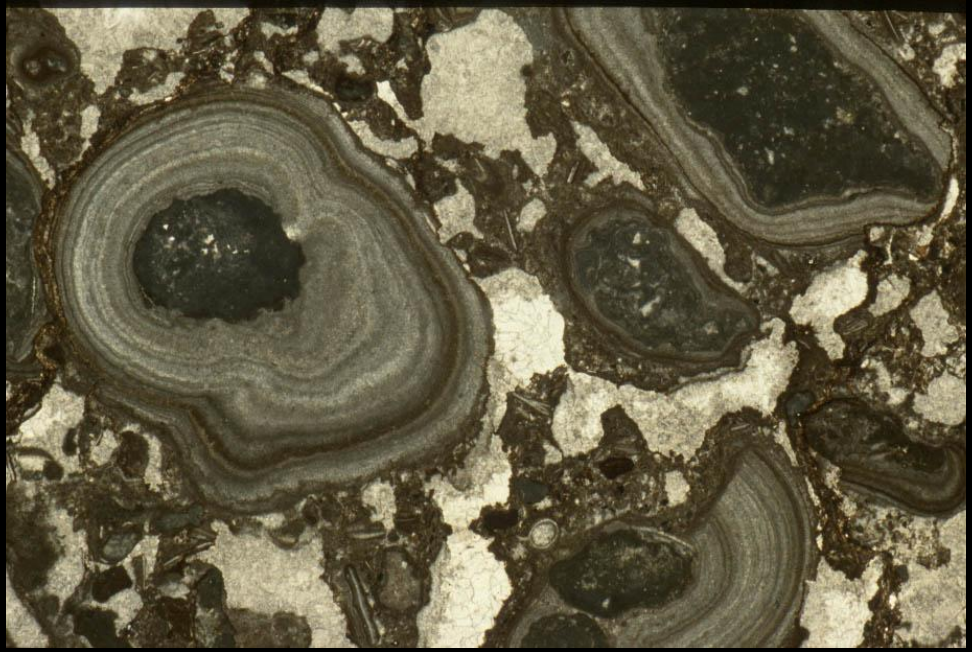
- micritic ooids are often micritized tangential or radial ooids

- Ooids with abundant bierosion traces loose their original extinction pattern. Interpretation of the ultrastructure is thus ambiguous. Ooids as in the figure below are usually determined as radial ooids

- This is the most common appearance of ooids in the geological record, i.e., most fossil marine ooids are radial. But modern marine ooids are (almost) all tangential.



Pisoids



Marine pisoids, Latemar platform, Anisian

https://upload.wikimedia.org/wikipedia/commons/8/8b/Calcario2EZ.jpg

Original mineralogy:

- various

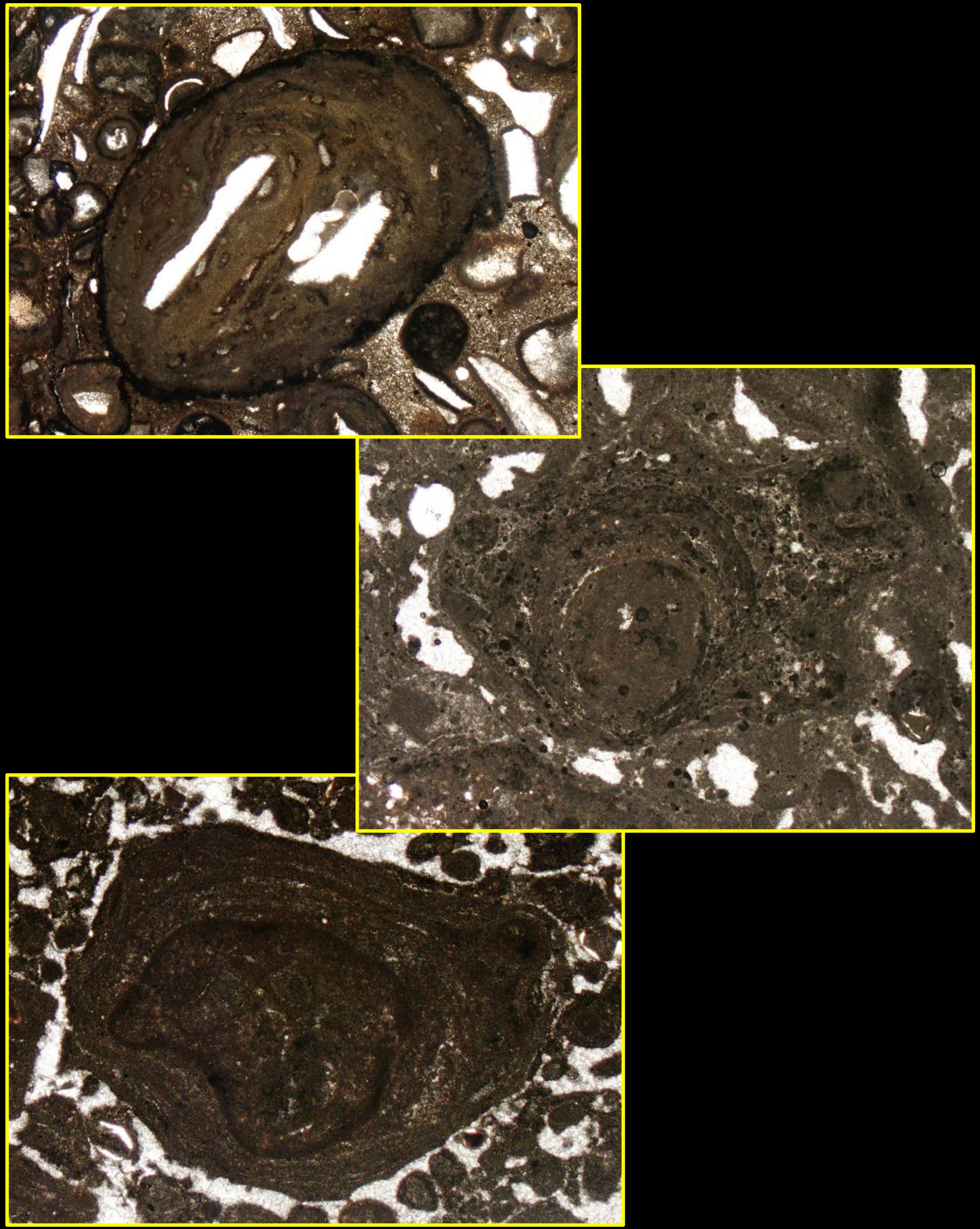
Diagnostic features:

- The coatings are crystalline, but are often replaced by microsparite
- They might have radial crystalline coatings, they are never tangential
- They are often not perfectly spherical, reflecting lower energy conditions compared to ooids
- Non-carbonate varieties exist (e.g., in soils), and in these cases the term “pisoid” is always appropriate

Significance:

- Low energy restricted marine environments, lakes, caves, gaysers... with short episodes of high energy.

Oncoids



Original mineralogy:

- High-Mg calcite (?)

Diagnostic features:

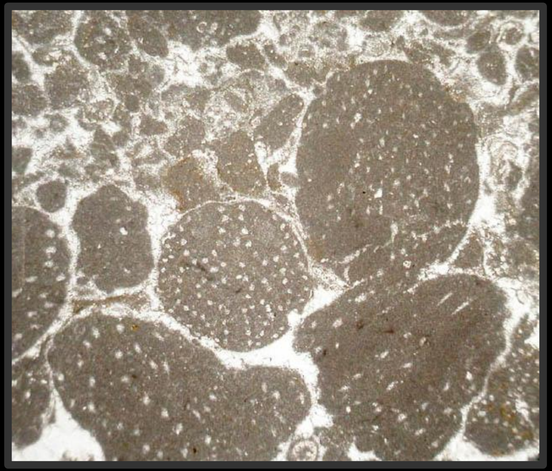
- Coatings are made of micrite or microsparite, plus sometimes encrusters (e.g., agglutinate foraminifera)
- Dimensions vary from microscopic to few cm
- The shape is usually irregular, the laminae are always irregular

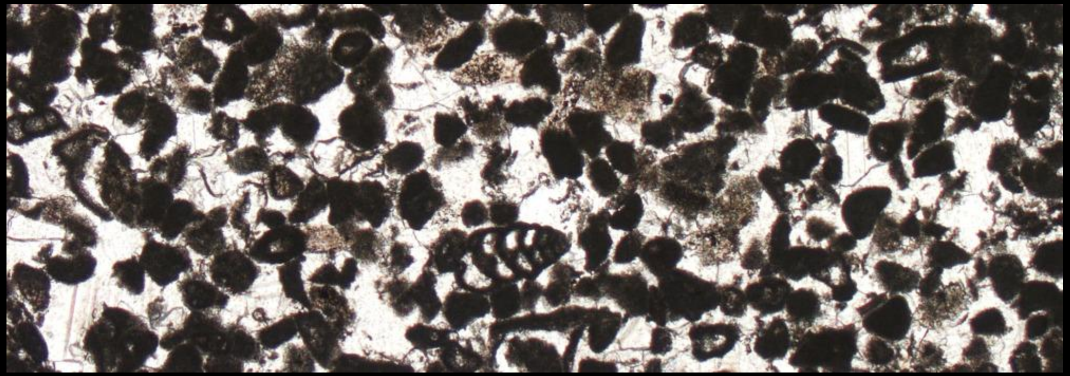
Significance:

- Oncoids are a type of microbialite, and are almost absent since the beginning of the Cenozoic

Peloids

Favreina (on the right) is a type of fecal pellet. From: http://147.94.111.32/ Collection/per_cretace_inf.php?page=micro-fossils





Original mineralogy:

- Various

Diagnostic features:

- All carbonate grains made of micrite (or microsparite) which cannot find a place in other categories are called peloids
- In rare cases, peloids are recognized as micro-coproliths, in which case they are called fecal pellets

Significance:

- None

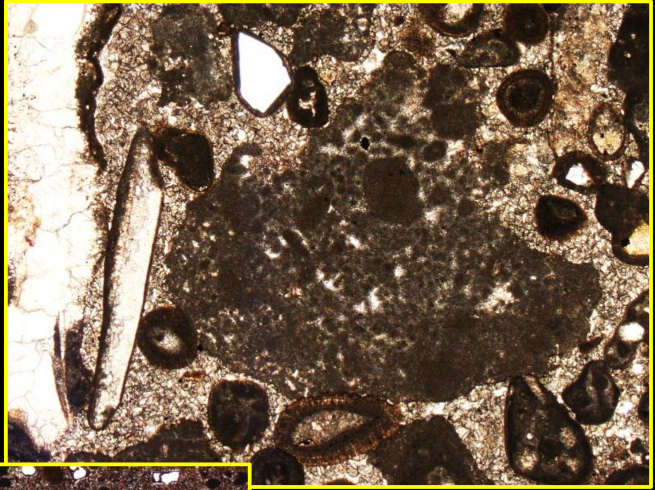
Peloids

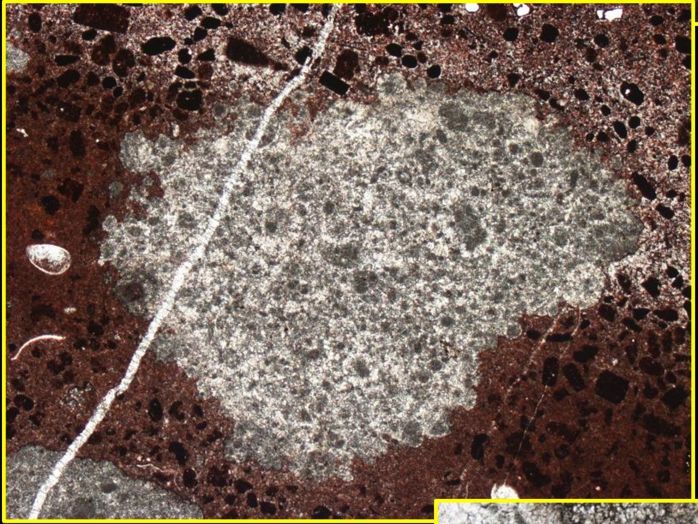
Processes that can form peloids are many. Probably, the most common process is micritization of other carbonate grains.

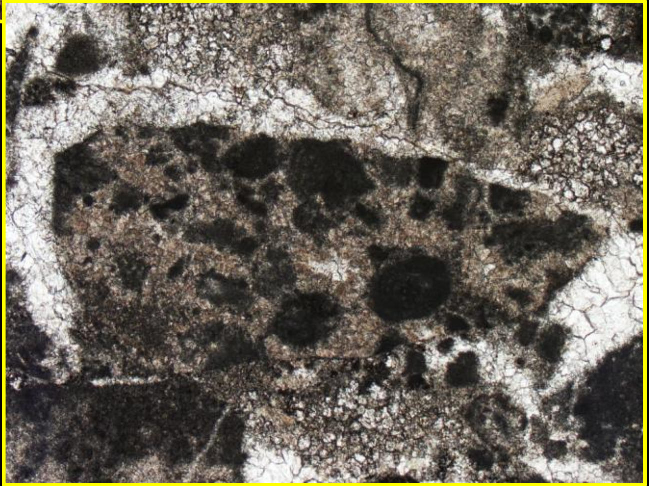
Origin		Types	Diagnostic criteria
Biotic Origin	Lithified organic excrements	1 **Fecal pellets**	Rounded elongated, rod-shaped or ovoid dark-colored micritic grains, rarely spherical. Commonly homogeneous or with silt-sized inclusions; rarely with defined internal structures. Sizes <100 μm to several millimeters. Sometimes associated with bioturbation structures . . . . Pl. 136/8
	Abrasional products of algae and calcimicrobes	2 **Algal peloids**	Irregularly shaped, rounded micritic grains, exhibiting gradations from grains with relicts of algal structures to homogeneous grains. Size <20 μm to ~2 mm . . . . Pl. 136/4
	Grains resulting from hard-part-boring and rasping activity of organisms	3 **Bioerosional peloids**	Scoop-shaped subrounded and angular grains. Sizes from 20 μm to 100 μm
Reworking of Mud and Grains	Synsedimentary and post-sedimentary reworking of carbonate mud and micrite	4 **Mud peloids** (Lithic peloids)	Variously shaped micritic grains, commonly without internal structures. Wide size ranges, poor sorting. Frequent occurrence within distinct beds or laminae . . Pl. 10/2, Pl. 121/2
	Internal micritic molds of bivalved shells	5 **Mold peloids**	Ovoid micritic grains, sometimes with relicts of still undissolved shells (ostracods, small bivalves). . . . . . . Pl. 132/8
Alteration of Grains	Ooids and rounded skeletal grains whose microstructures have been lost through micritization	6 **Bahamite peloids**	Round micritic grains, some of which with relicts of the primary microstructures. Association of peloids, aggregate grains and ooids. Transition of micritized bioclasts to peloids of the same size. Larger than algal peloids . . . . . Pl. 10/3, Pl. 43/1
	Ooids and skeletal grains; microstructures destroyed by recrystallization	7 **Pelletoids**	Microcrystalline grains, in places exhibiting vague residual internal structures. Diffuse outlines due to amalgamation and compaction . . . . Pl. 38/6
In-situ Formation	Biochemical precipitation triggered by microbes and organic substances	8 **Microbial peloids**	Rounded micritic grains associated with laminated and clotted fabrics. Sizes from <80 μm to >600 μm . . . . . . Pl. 8/6, Pl. 10/1
	Chemical precipitation of carbonate cements with or without organic controls	9 **Precipitated peloids**	Tiny peloids within carbonate cements; consisting of a cloudy micritic center sourrounded by clear exterior rims of crystals. Occurrence in cavity fill precipitates (e.g. in reefs) . . . . Pl. 8/5

Flügel, 2004

Intraclasts







As opposed to intraclasts (above), carbonate lithoclasts (on the right) may have angular shape and boundaries that cut through grains, textures and cement

Original mineralogy:

- Various

Diagnostic features:

- There are no strict diagnostic features for intraclasts, the definition being a genetic one: Intraclasts are early cemented carbonate aggregates or grains that are remobilized, within the carbonate depositional system, before lithification is completed.
- Intraclasts may have concave outlines, and normally do not show sign of breaking
- They can show deformation due to incomplete cementation

Significance:

- Common in most carbonate depositional environments

Standard Microfacies types (SMF)

Carbonate microfacies can be classified in homogeneous groups, characterized by skeletal associations and textures (e.g., matrix-grains relationships after Dunham), that repeat throughout geologic time. Recognizing this pattern, Wilson (1975) created 24 **standard microfacies types** (**SMF**).

- SMF are defined on the base of simple, non-quantitative criteria.
- Their definition is based on a few dominant characteristics

Criteria for the definition of a SMF:

- Grain types, relative frequencies, skeletal associations
- Matrix type
- Fabric (lamination, gradation, bioturbation...)
- Fossils, in terms of higher taxonomical groups
- Textural classification after Dunham

List of Standard MicroFacies types (Flügel, 2004)

Flügel, 2004

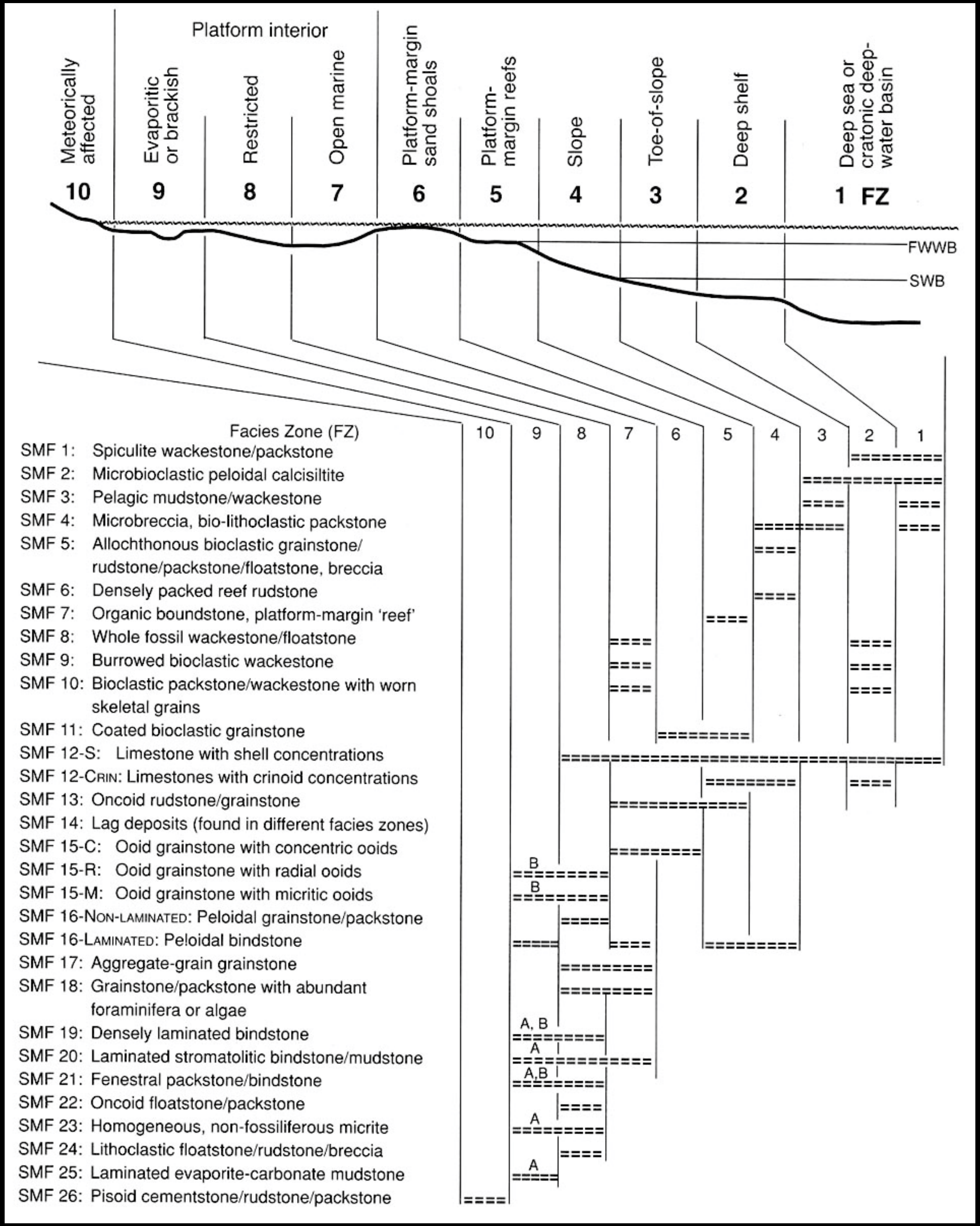
Box 14.4. *List of Standard Microfacies Types*. The order of the SMF numbers follows approximately the order of the Standard Facies Zones in the Wilson Model going from the basinal SMF Type 1 to SMF 26 that characterizes subaerial exposed areas.

SMF 1: Spiculitic wackestone or packstone, often with calcisiltite matrix. Subtype emphasizes burrowing.
SMF 2: Microbioclastic peloidal calcisiltite with fine grainstone and packstone fabrics.
SMF 3: Pelagic lime mudstone and wackestones with abundant pelagic microfossils. Subtypes differentiate the groups of planktonic organisms.
SMF 4: Microbreccia, bio- and lithoclastic packstone or rudstone.
SMF 5: Allochthonous bioclastic grainstone, rudstone, packstone, floatstone, breccia with reef-derived biota.
SMF 6: Densely packed reef rudstone.
SMF 7: Organic boundstone. Subtypes try to differentiate the kind of contribution by potential reefbuilders to the formation of reefs and other buildups.
SMF 8: Wackestones and floatstones with whole fossils and well-preserved endo- and epibiota.
SMF 9: Strongly burrowed bioclastic wackestone.
SMF 10: Bioclastic packstone and wackestone with abraded and worn skeletal grains.
SMF 11: Coated bioclastic grainstone.
SMF 12: Limestone with shell concentrations. Subtypes characterize shell-providing fossils.
SMF 13: Oncoid rudstone and grainstone.
SMF 14: Lag deposit.
SMF 15: Oolite, commonly grainstone but also wackestone. Subtypes highlight the structure of ooids.
SMF 16: Peloid grainstone and packstone. Subtypes differentiate non-laminated and laminated rocks.
SMF 17: Grainstone with aggregate grains (grapestones).
SMF 18: Bioclastic grainstone and packstone with abundant and rock-building benthic foraminifera or calcareous green algae. Subtypes describe the systematic assignment of the various groups.
SMF 19: Densely laminated bindstone.
SMF 20: Laminated stromatolitic bindstone/boundstone.
SMF 21: Fenestral packstone and bindstone. Subtypes characterize fenestral voids and the contribution of calcimicrobes.
SMF 22: Oncoid floatstone and wackestone.
SMF 23: Non-laminated homogenous micrite or microsparite without fossils.
SMF 24: Lithoclastic floatstone, rudstone or breccia.
SMF 25: Laminated evaporite-carbonate mudstone.
SMF 26: Pisoid cementstone, rudstone or packstone.

SMF: Motivation

Some microfacies are typical of specific parts of a carbonate platform.

Microfacies play, in carbonate sedimentology, a role similar to sedimentary structures for clastic sedimentology.



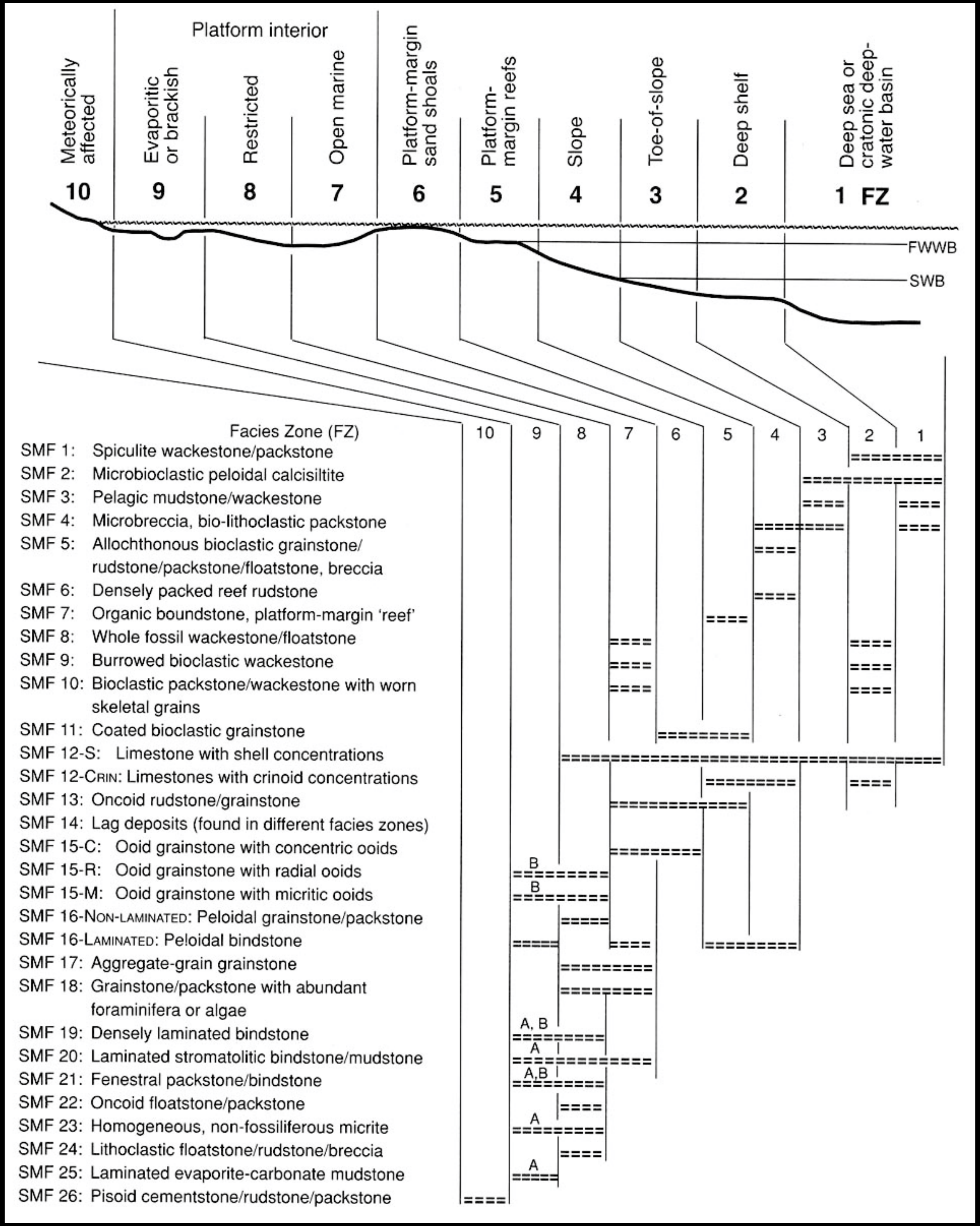
Flügel, 2004

A place for SMF in the Wilson model

The standard microfacies types (SMF) are those microfacies that you should find in a fossil platform that obeys the Wilson Model.

Each SMF is found in a specific part of the platform, and is thus strongly indicative of a depositional environment.

Flügel, 2004



Quantative analysis on carbonates

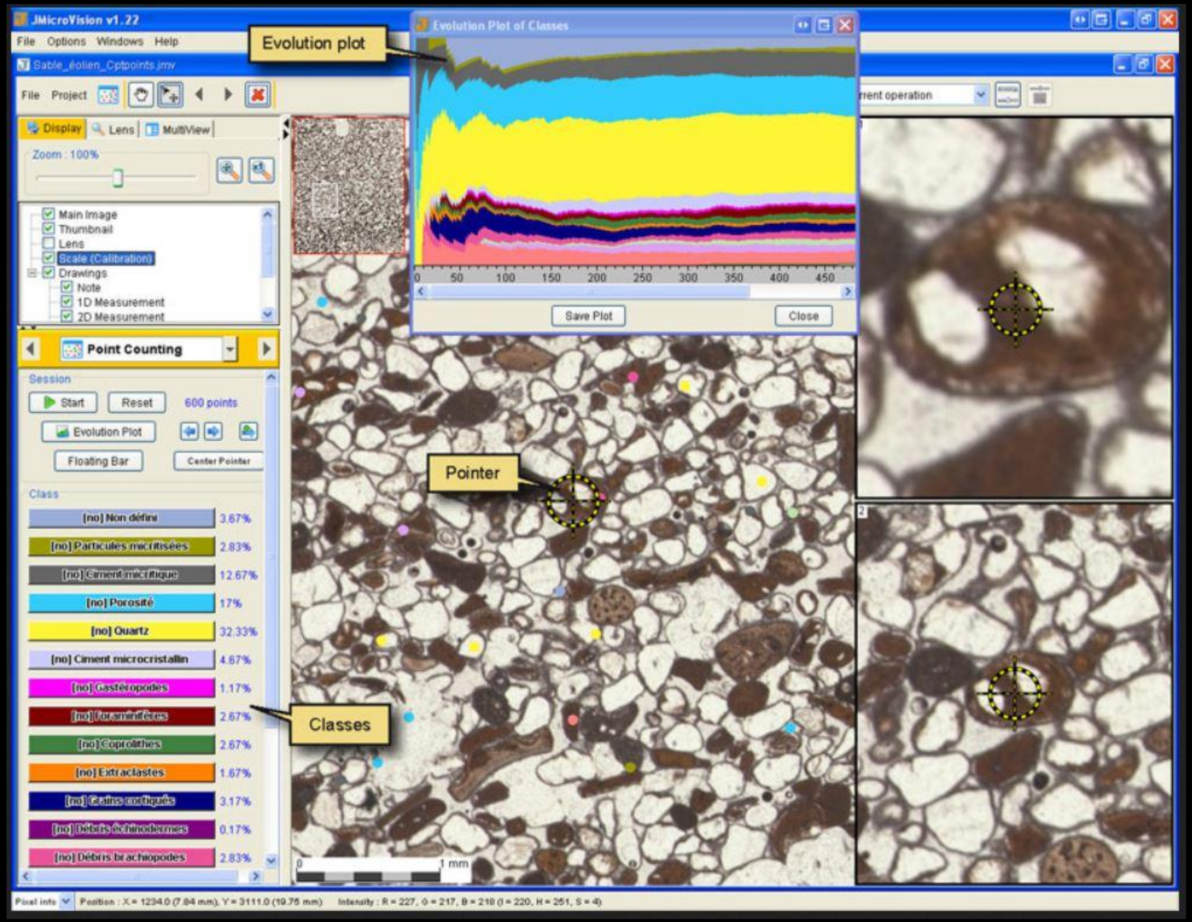
Observation of carbonates at the optical microscope does not only allow a quantitative description of the facies.

There are methods that allow extracting quantitative information.
One of them in point counting in which the proportion of an area that is covered by some objects of interest is determined.

The principle of point counting is cover the area of interst by a grid of points. Then for each of these points, the underlying object is identified to estimate for the proportion of the area covered by the type of object.

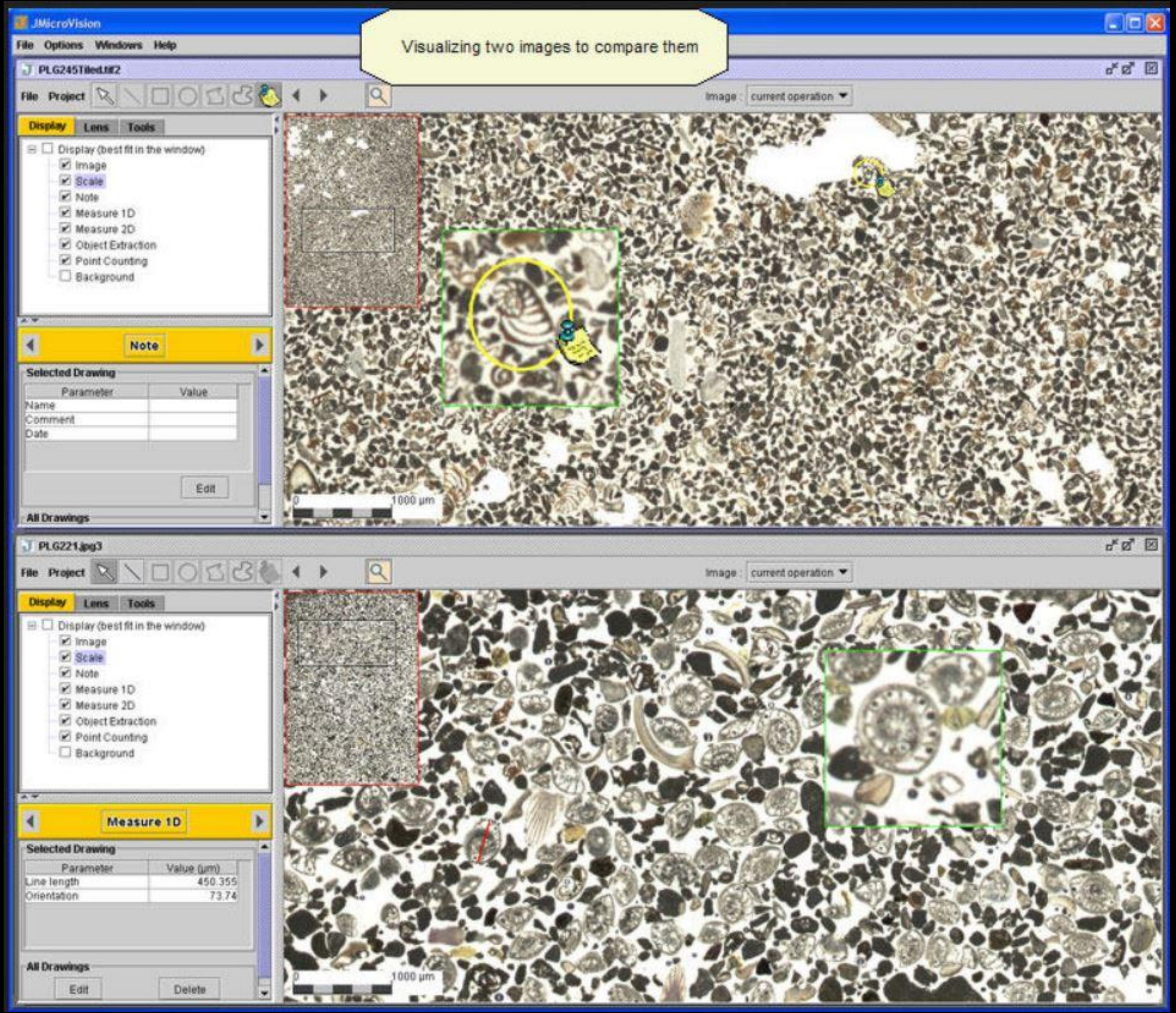
Quantative analysis on carbonates

Several software exist to perform this operation semi-authomatically.
They normally work on digital pictures of the thin section, therefore the operator normally works with the computer connected to a digital camera and uses the optical microscope to classify the points of the grid.

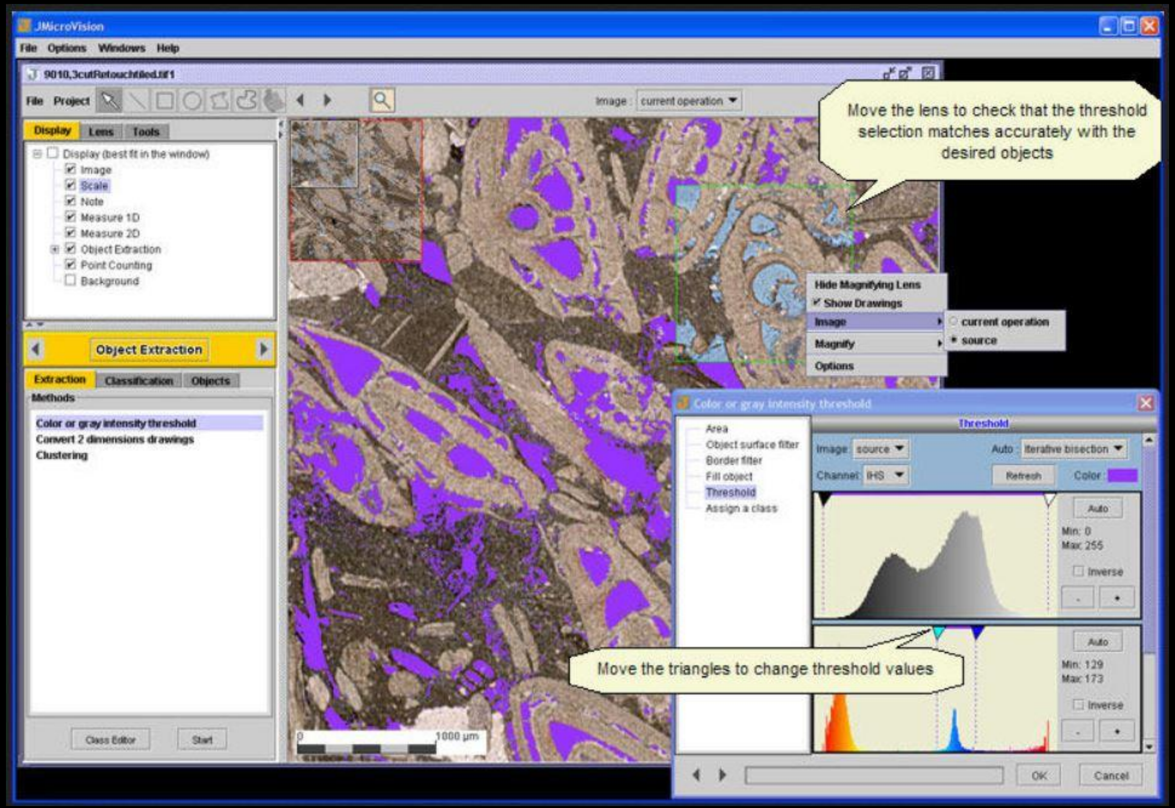


Example of sofwater for quantitative analysis of thin sections (including carbonates).
The software is J-Microvision.
The software imports a digital image of the thin section and a grid with number of points defined by the operator is set.
At this point the operator goes through the grid and identifies what the viewfinder is pointing at, assigning the desired class

Quantative analysis on carbonates



Comparison of two thin sections digital images in J-Microvision



Estimation of pores volume in J-Microvision

Quantative analysis on carbonates

An example of point counting results

From Jin et al., 2020

Comparison of modal abundance of skeletal and microbial grains (excluded other components) in carbonates from Ladinian to Norian in Alpine regions (western Tethys) and Sichuan Basin (eastern Tethys).

The published data from Stuores Wiesen section (Preto, 2012) and Milieres and Costamoling section (Dal Corso et al., 2015) are merged with the new results of this study.
The point-counting data of studied sections were selectively illustrated here according to their comparable biochronology.

The sharp decrease of abundance in microbial grains coinciding with the negative CIE is observed in both the Alpine region and Sichuan Basin, as well as the recovery of microbial grains is in late Carnian to earlier Norian. δ13Corg record of Alpine regions are from Dal Corso et al. (2018b) and of Sichuan Basin are from Shi et al. (2019). B). Locations of Southern Alps and Sichuan Basin during the Carnian, paleogeographic map of Carnian from Scotese (2014).