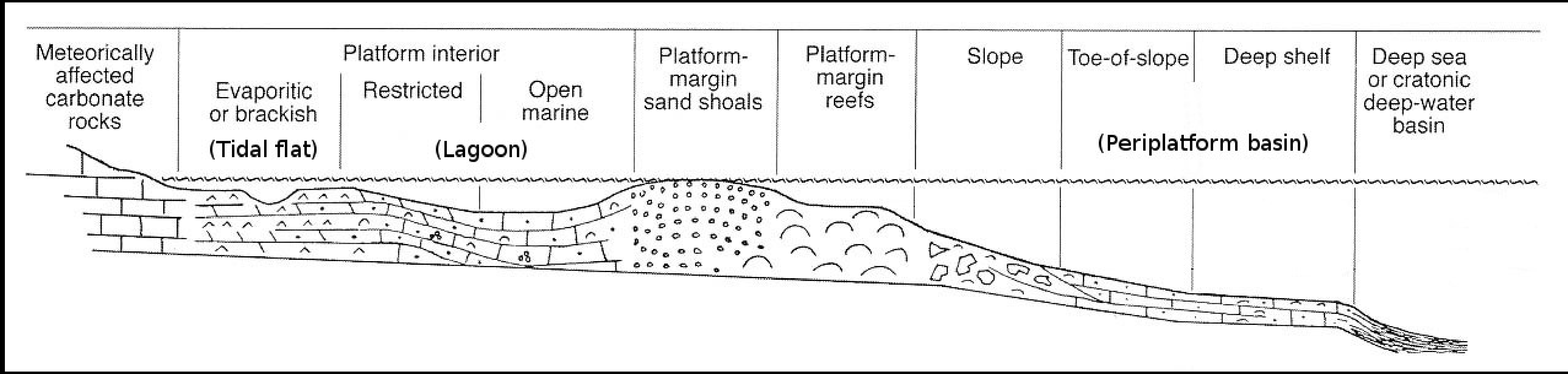
Carbonates at the optical microscope

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



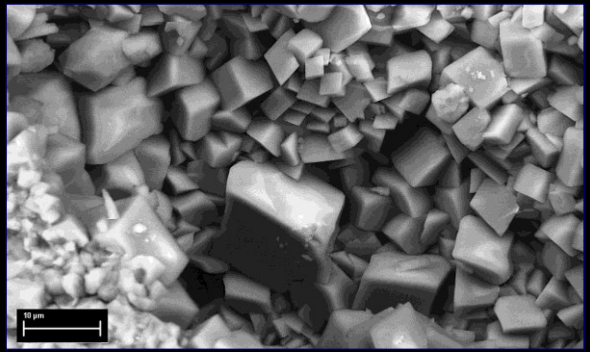
Flügel, 2004 (modified from Wilson)

Carbonates at the optical microscope

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

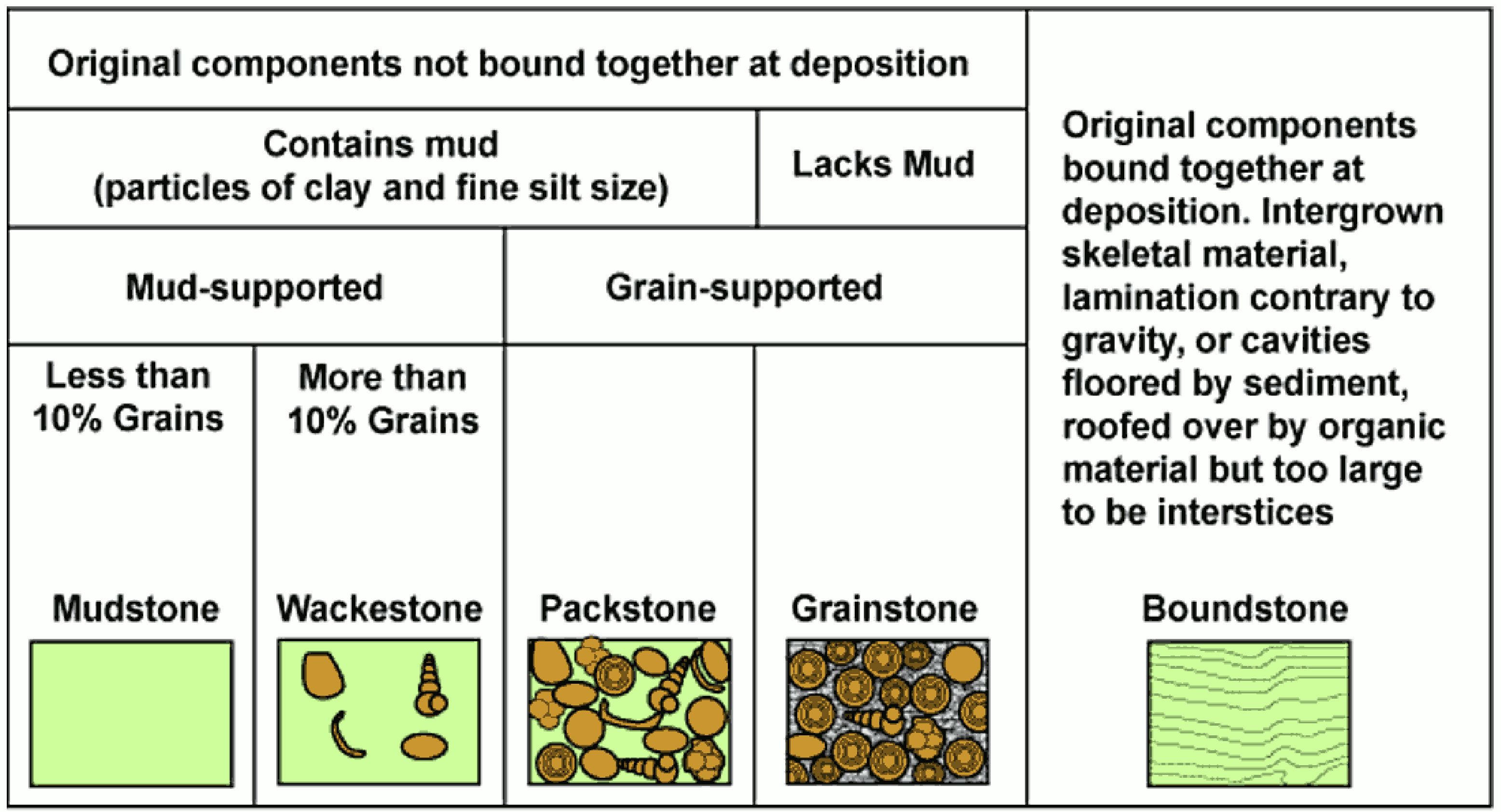
- **Boundstones** are rocks built by carbonate-secreting, in-situ sessile organisms. Use:
  → Embry and Klovan (1971)
  → Insalaco (1998)

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



Carbonates at the optical microscope

- **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)

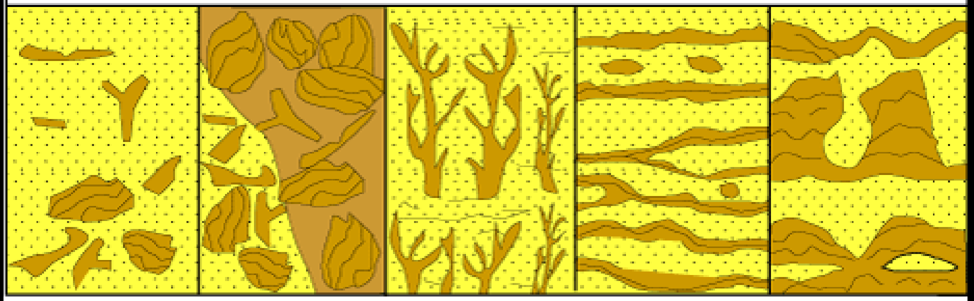


C. G. St. C. Kendall, 2005 (after Dunham, 1962, AAPG Memoir 1)

Carbonates at the optical microscope

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

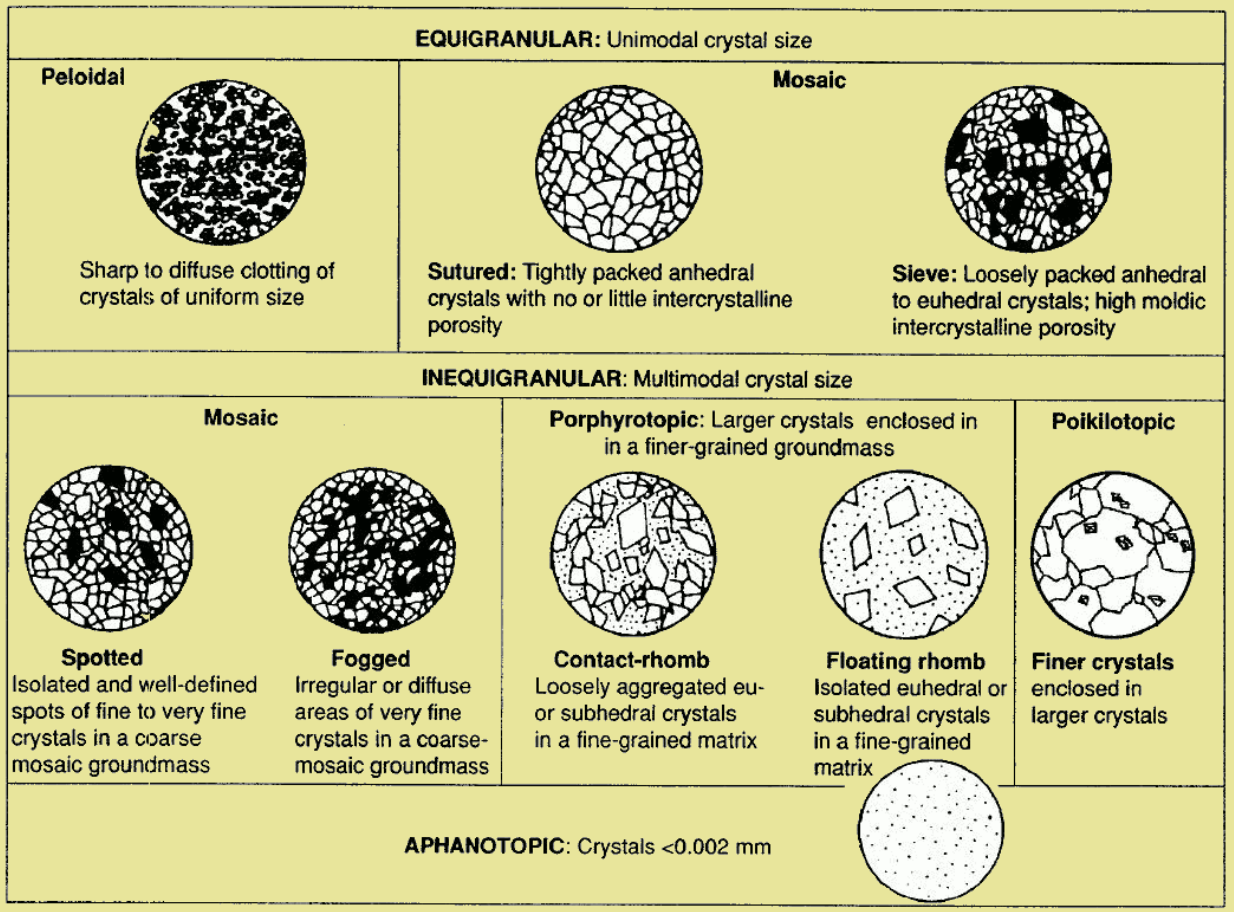
Allochthonous		Autochthonous		
Original components not bound organically at deposition		Original components bound organically at deposition		
>10%grains>2mm				
Matrix supported	Supported by >2mm component	By organisms that act as baffles	By organisms that encrust and bind	By organisms that build a rigid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



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

Carbonates at the optical microscope

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

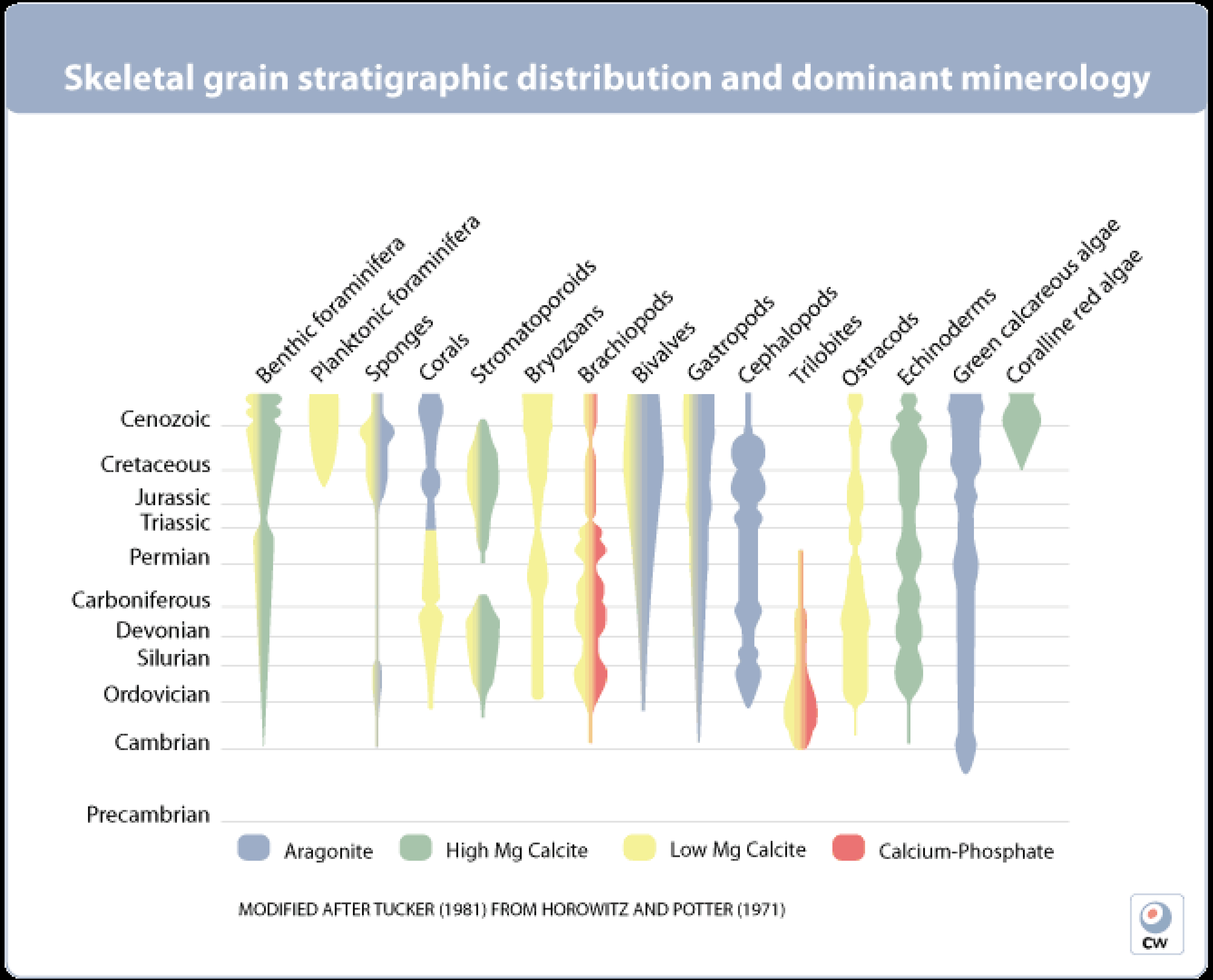


Types of carbonate grains

Carbonate grains are classified according to their origin:

- Non-skeletal grains
  - Ooids, pisoids
  - other coated grains
  - aggregate grains
  - peloids
  - intraclasts
- Skeletal grains

(i.e., grains deriving from shells and skeletons)



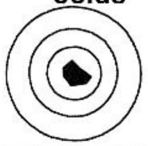
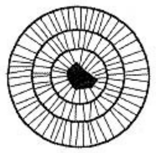
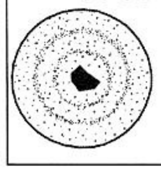
www.carbonateworld.com

Carbonates at the optical microscope

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

Carbonates at the optical microscope

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.

Carbonates at the optical microscope

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

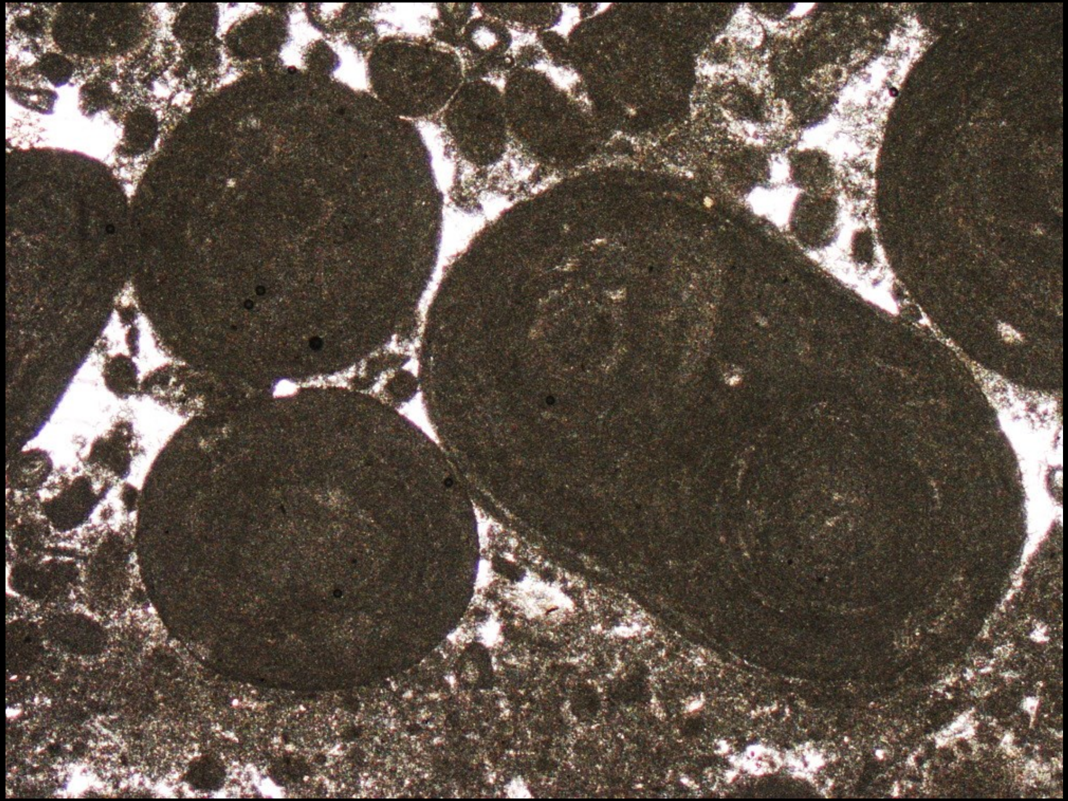
Significance:

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

Carbonates at the optical microscope

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?



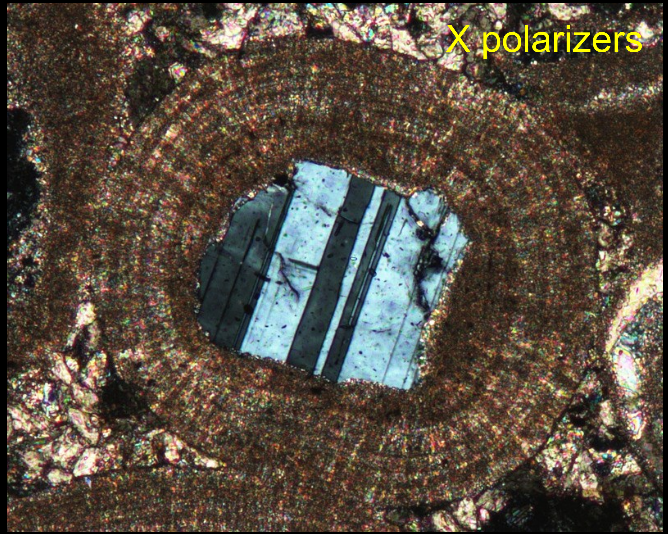
Original mineralogy:
- ?

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".

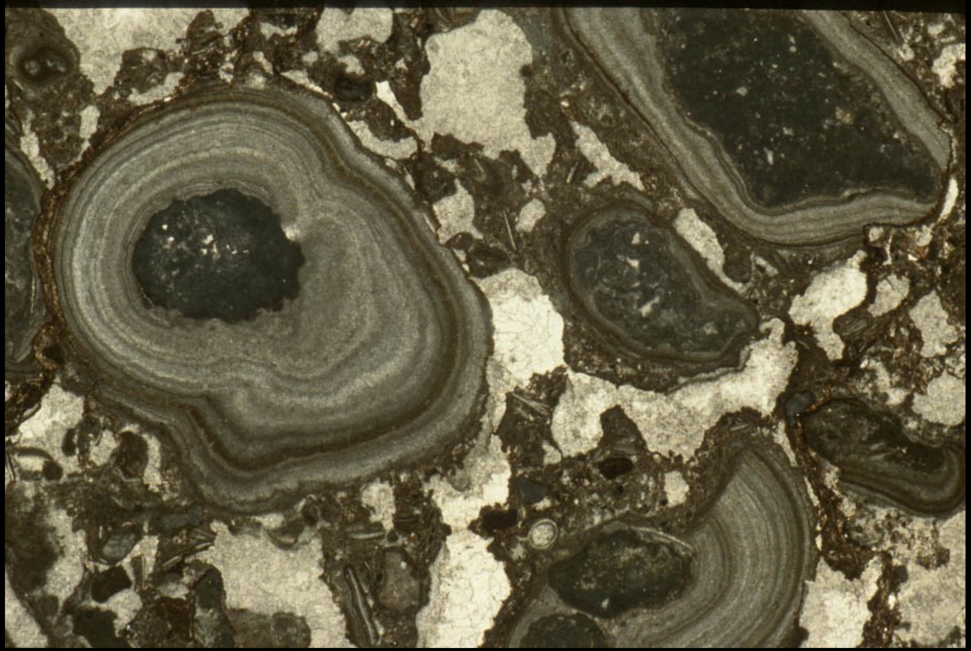
Significance:
- High energy shallow water marine environments, long residence time of sediments if formed by micritization

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

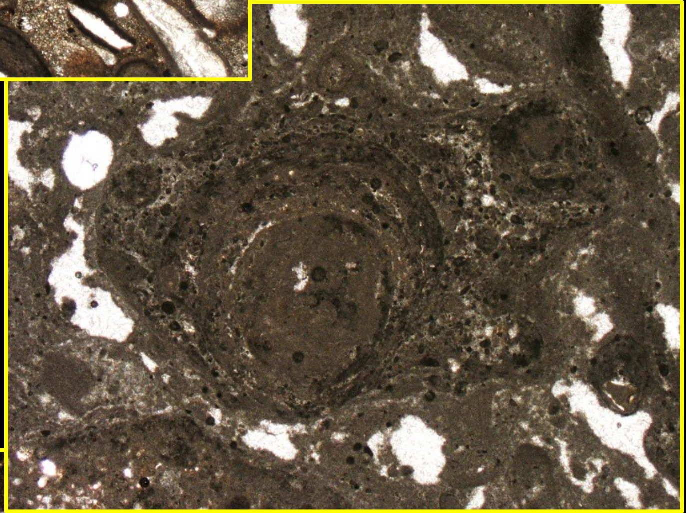
https://upload.wikimedia.org/wikipedia/commons/8/8b/Calcario2EZ.jpg

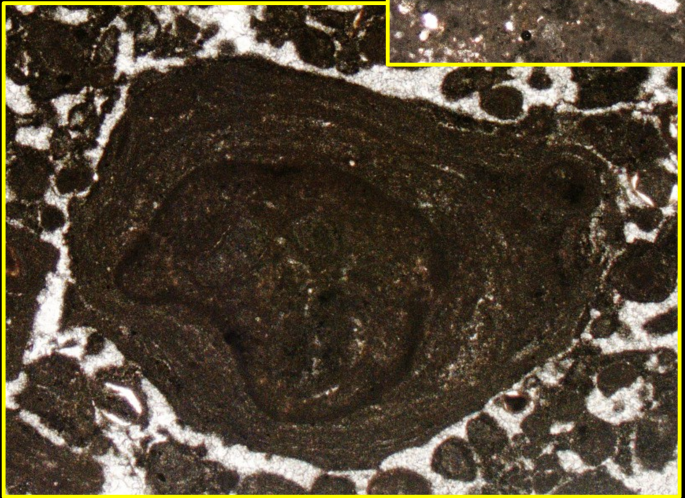
Original mineralogy:
- various

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:

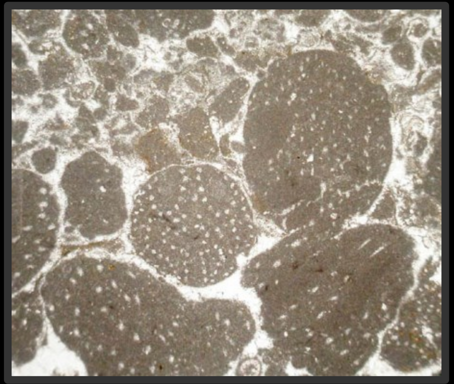
- Coatings are made of micrite or microsparite, plus sometimes encrusters (e.g., agglutinate foraminifera)
- Dimensions vary from microscopic to few cm
- The shape is usually irregular, the laminae are always irregular

Significance:

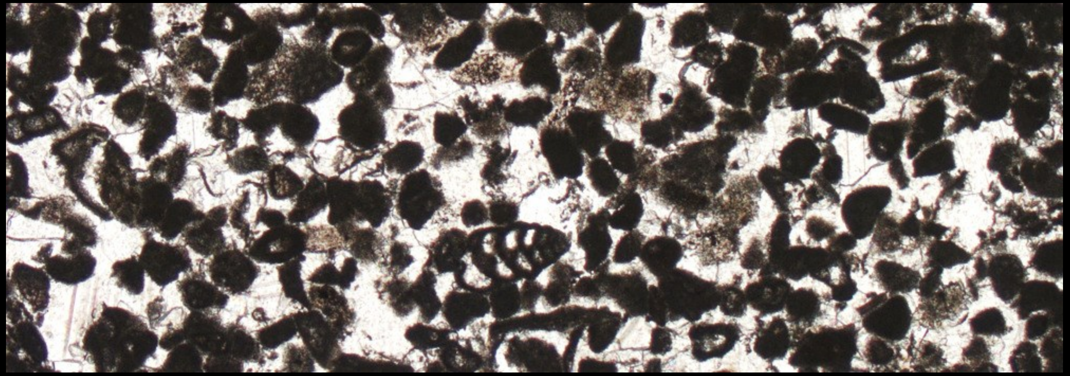
- Oncoids are a type of microbialite, and are almost absent since the beginning of the Cenozoic

Carbonates at the optical microscope

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



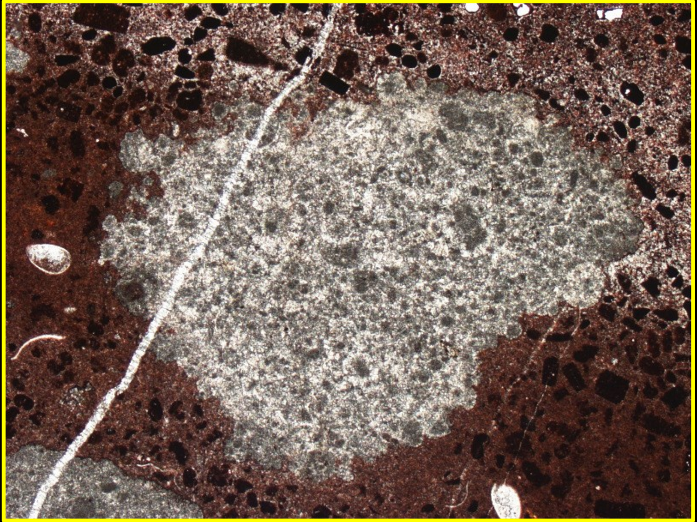
Original mineralogy:
- Various

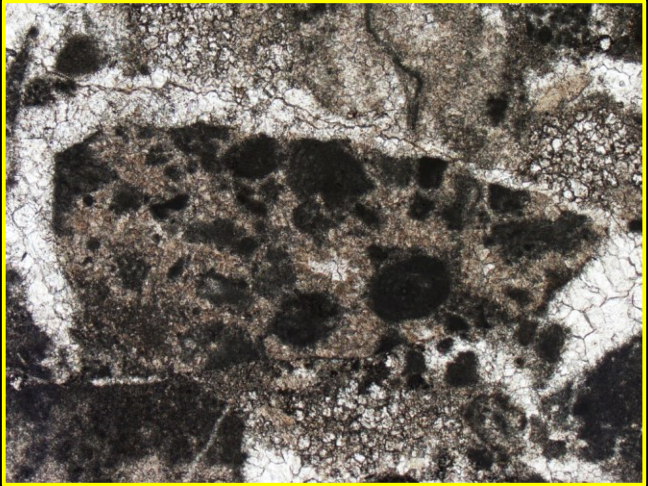
Diagnostic features:
- All carbonate grains made of micrite (or microsparite) which cannot find a place in other categories are called peloids
- In rare cases, peloids are recognized as micro-coproliths, in which case they are called fecal pellets

Significance:
- None

Carbonates at the optical microscope

Intraclasts





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

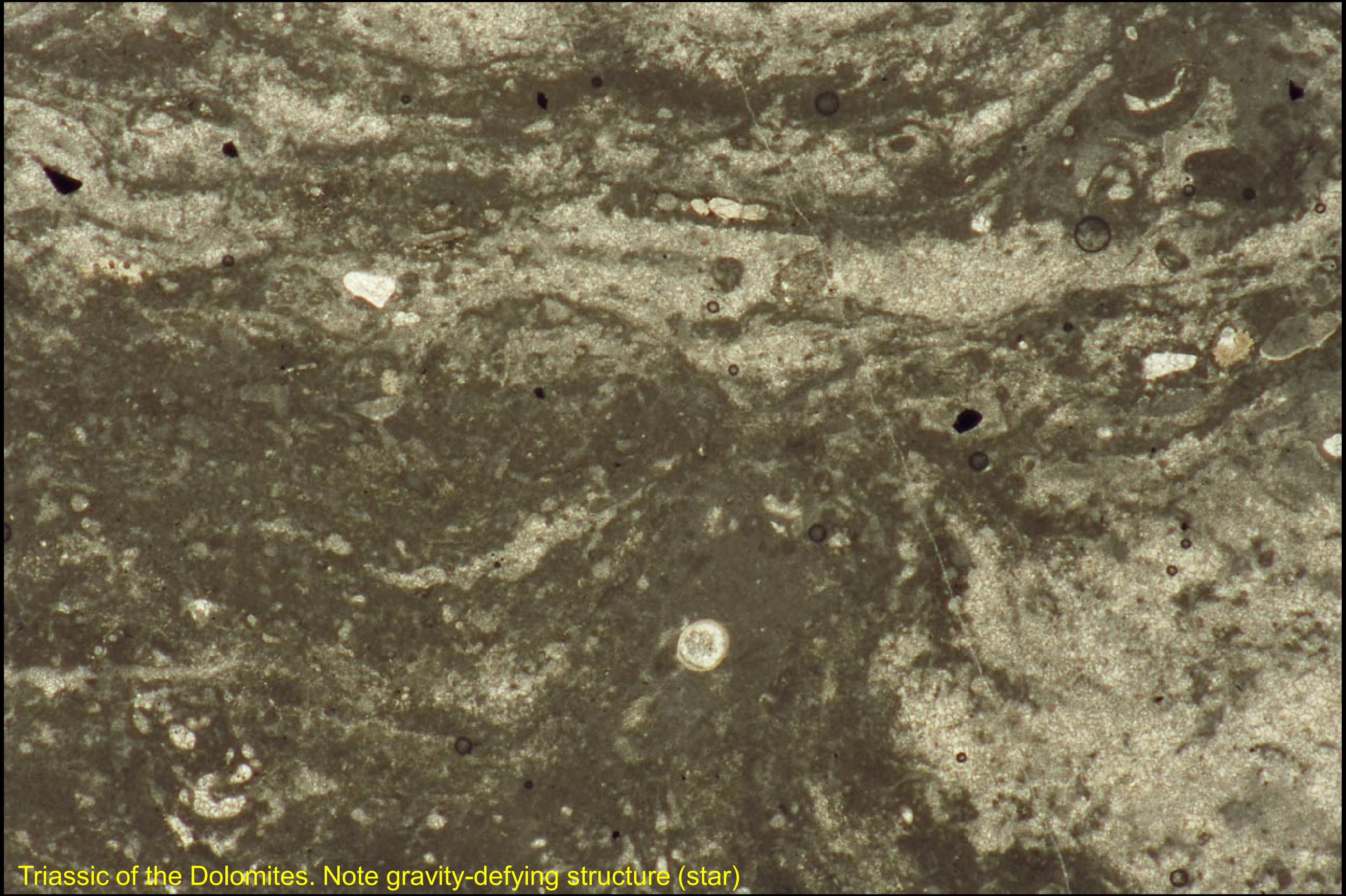
Original mineralogy:
- Various

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

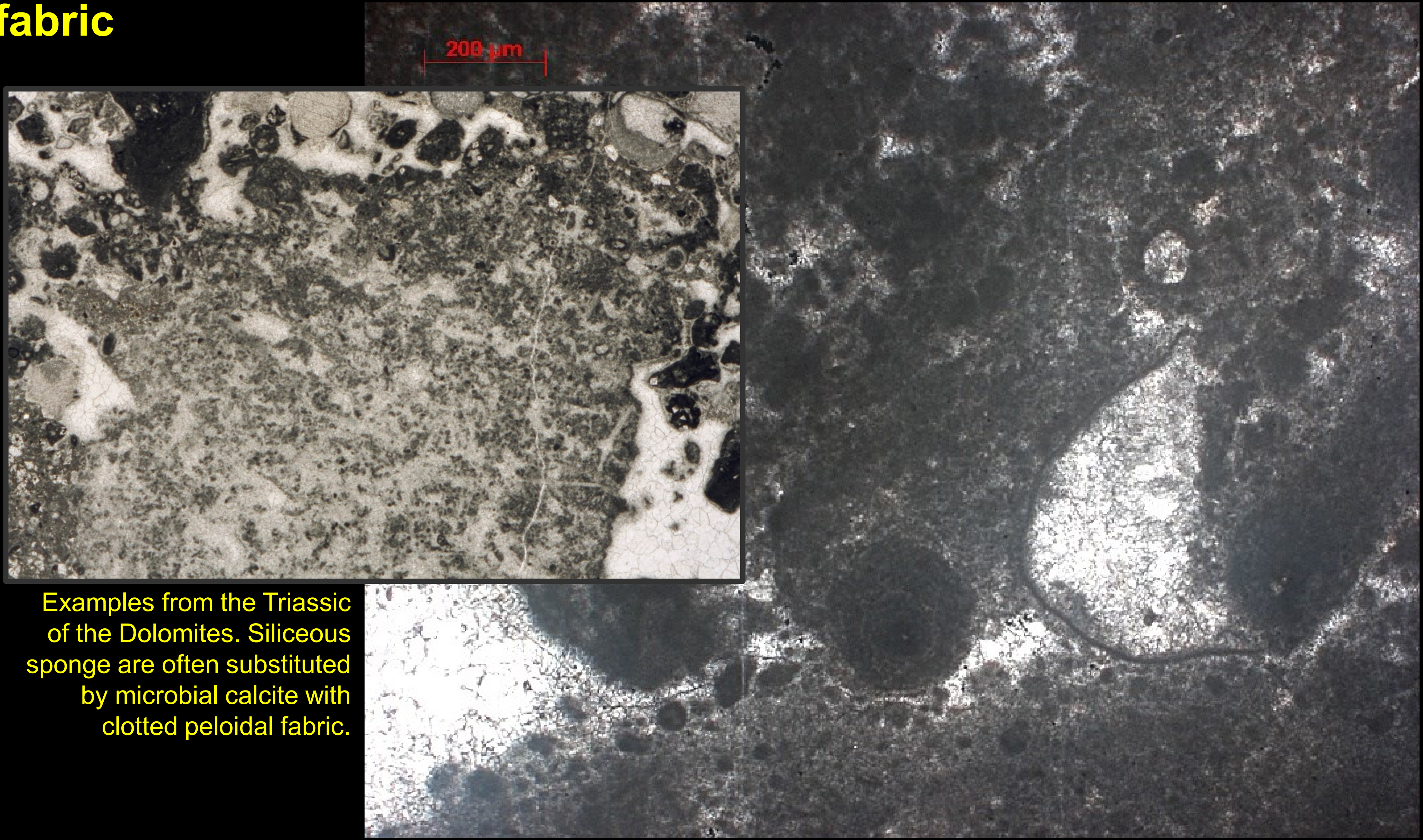
Carbonates at the optical microscope

Stromatolitic fabric


Triassic of the Dolomites. Note gravity-defying structure (star)

Carbonates at the optical microscope

Clotted peloidal fabric

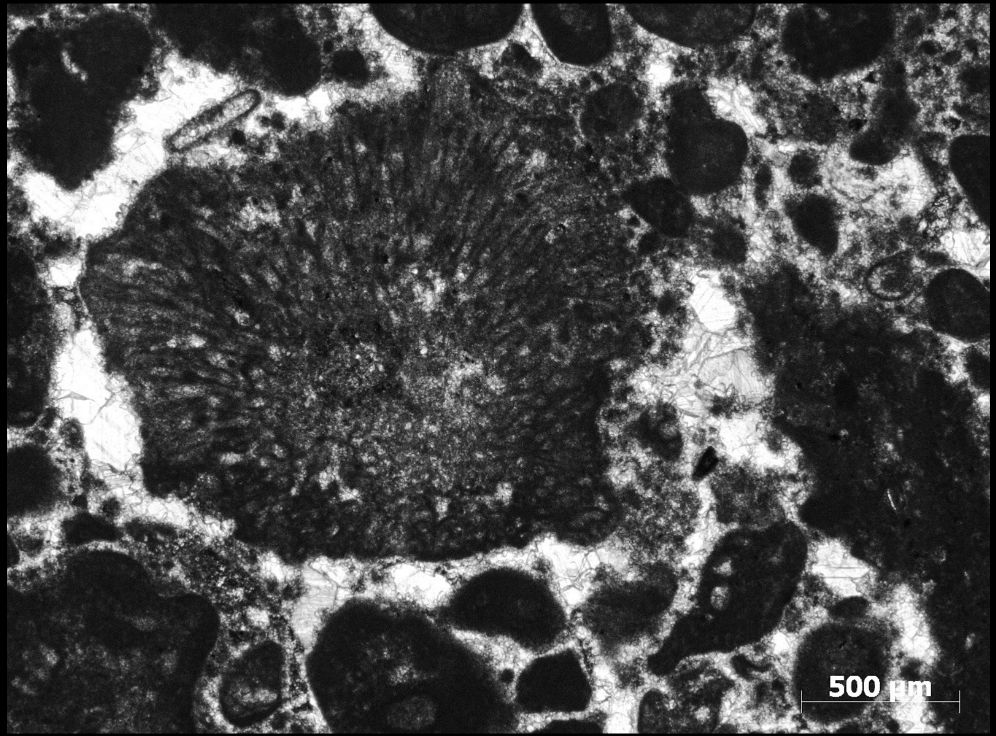


Examples from the Triassic of the Dolomites. Siliceous sponge are often substituted by microbial calcite with clotted peloidal fabric.

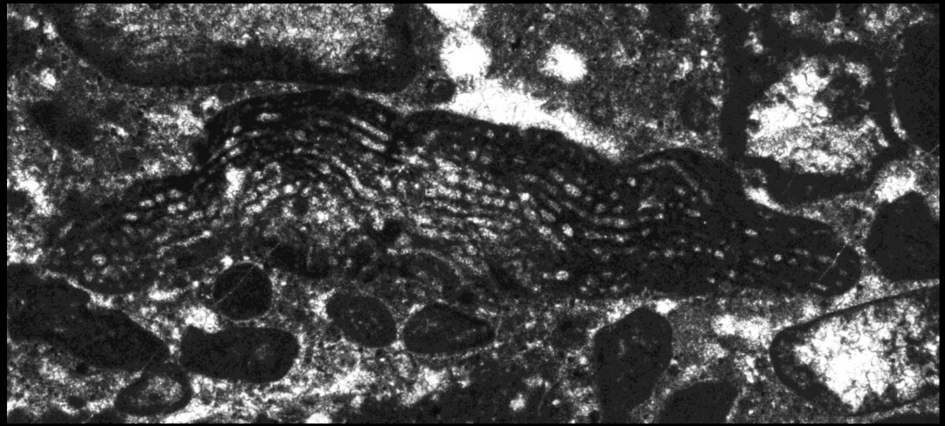
Carbonates at the optical microscope

Calcimicrobes

Calcimicrobes *sensu stricto* are fossils of cyanobacterial colonies.



Cayeuxia from the Early Jurassic of the lombardian Alps.



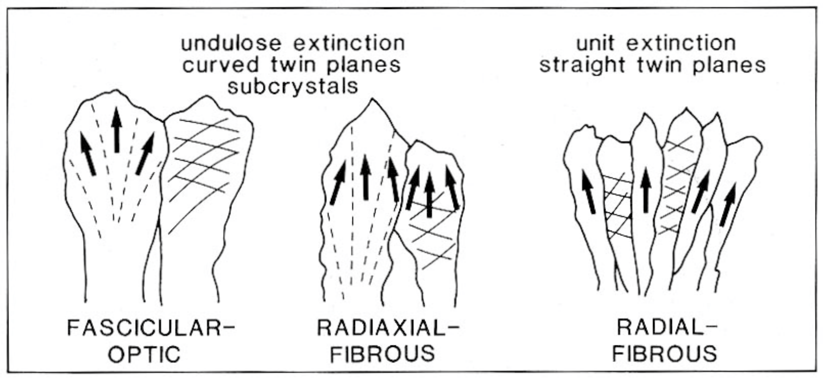
Cf. *Girvanella* forming a mat of tiny tubules. This fragment was probably encrustating a larger grain. Lower Jurarric, lombardian Alps. Scale as the other figures.

Another *Cayeuxia*, same locality, on a longitudinal cut.

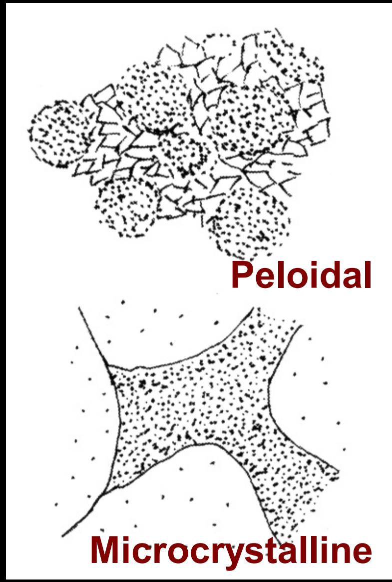
Morphology of cements

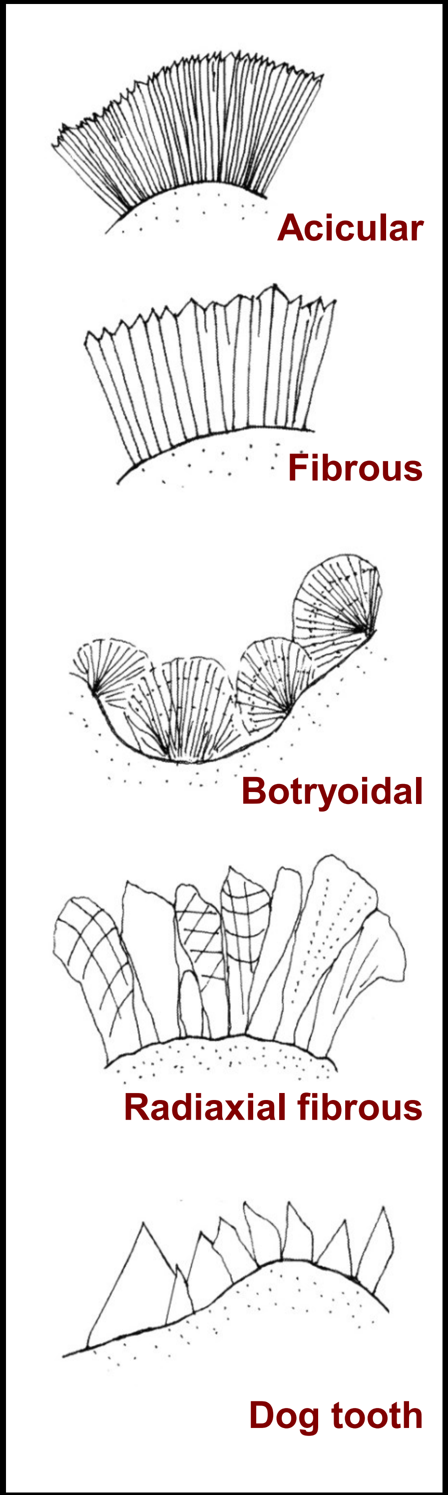
Cements are first of all described by the shape of their crystals and crystal aggregates.

- **Aragonite** forms needles with square terminations
- **Calcite** forms scalenohedrons with pointy terminations, but it is rarely idiomorphic.



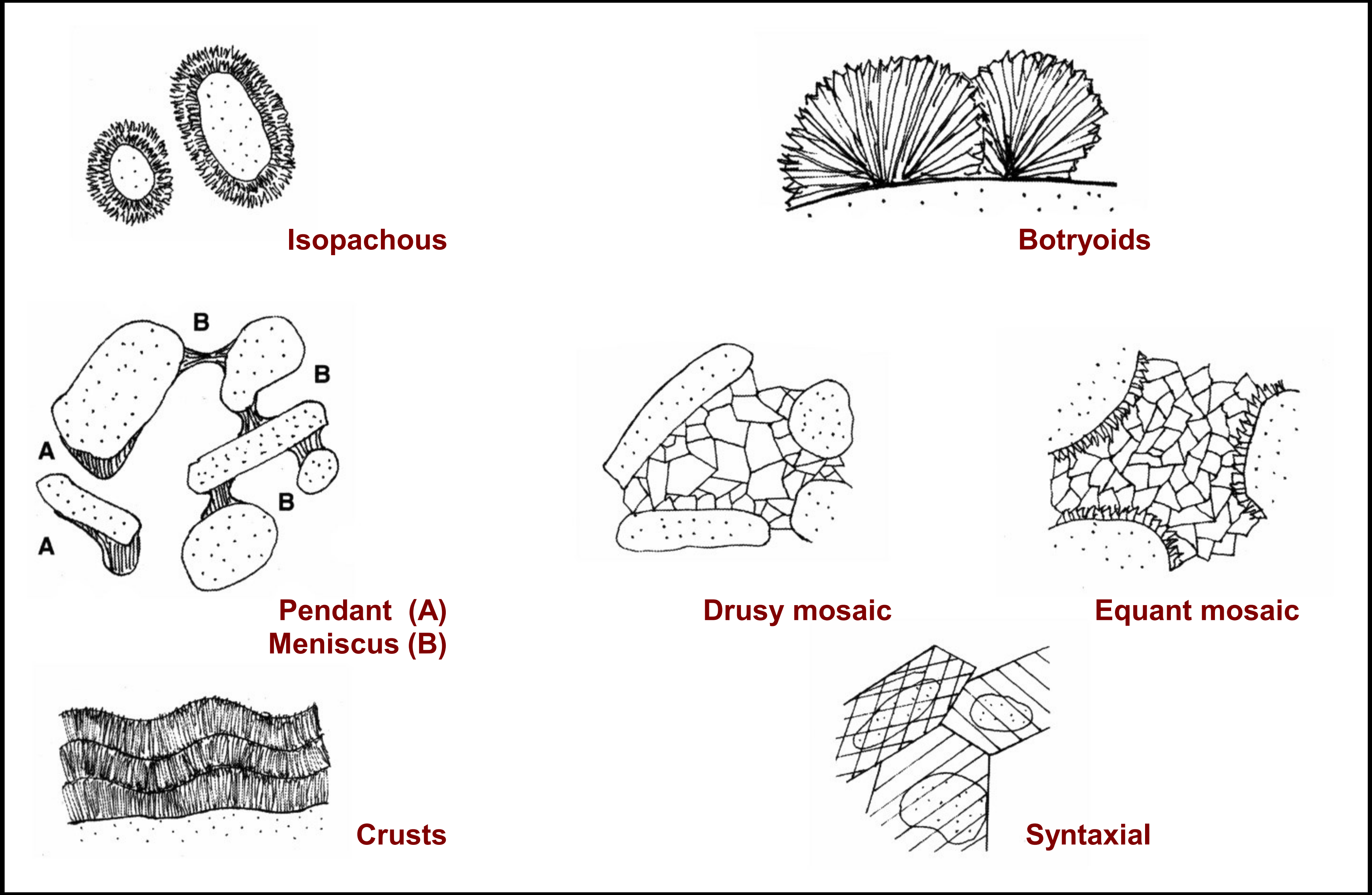
Radiaxial fibrous cement, and its variations, are calcite cements normally characterized by turbid appearance due to abundant inclusions. In the most common varieties, extinction is undulated. From Tucker and Wright, 1990





Flügel, 2004

Secondly, the relation between cement and grains should be described.



Flügel, 2004

Carbonates at the optical microscope

Cements

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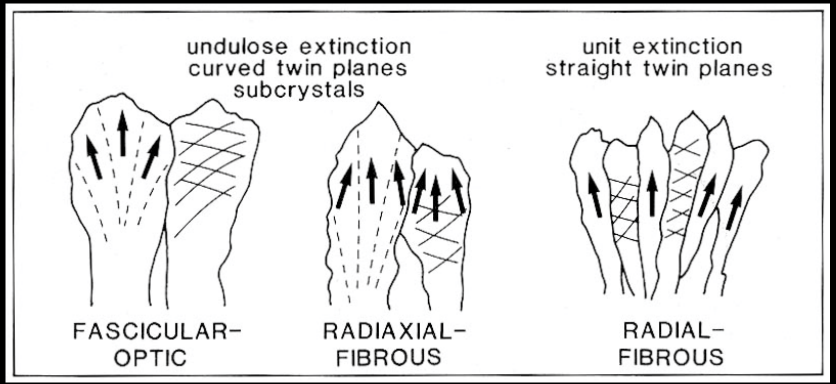
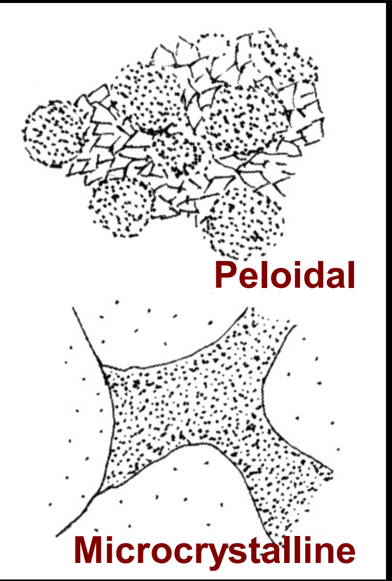
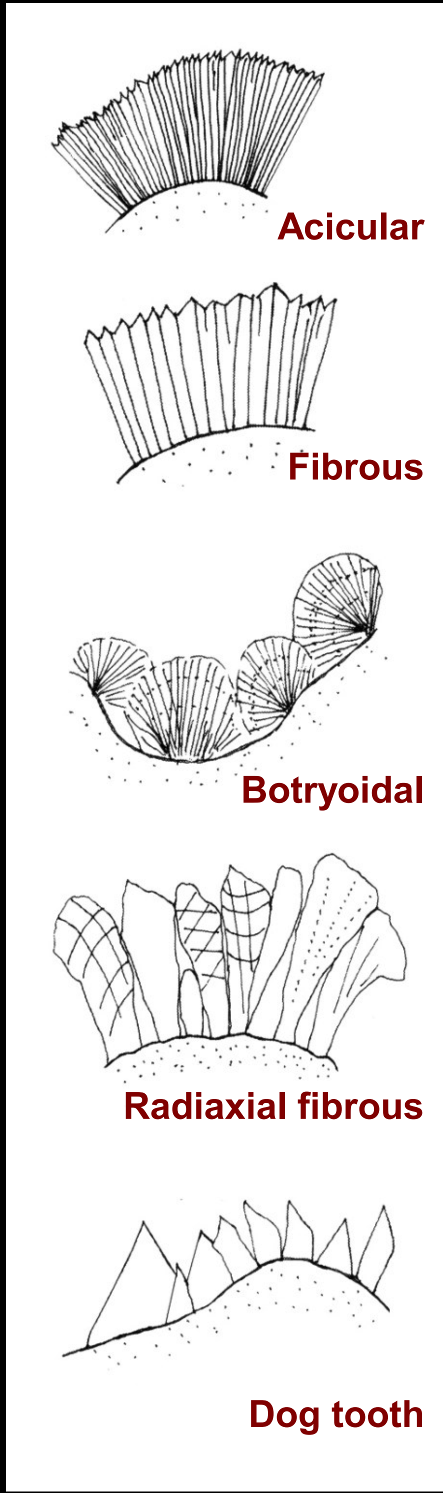


Radiaxial fibrous cement, and its variations, are calcite cements normally characterized by turbid appearance due to abundant inclusions. In the most common varieties, extinction is undulated. From Tucker and Wright, 1990





Flügel, 2004

Carbonates at the optical microscope

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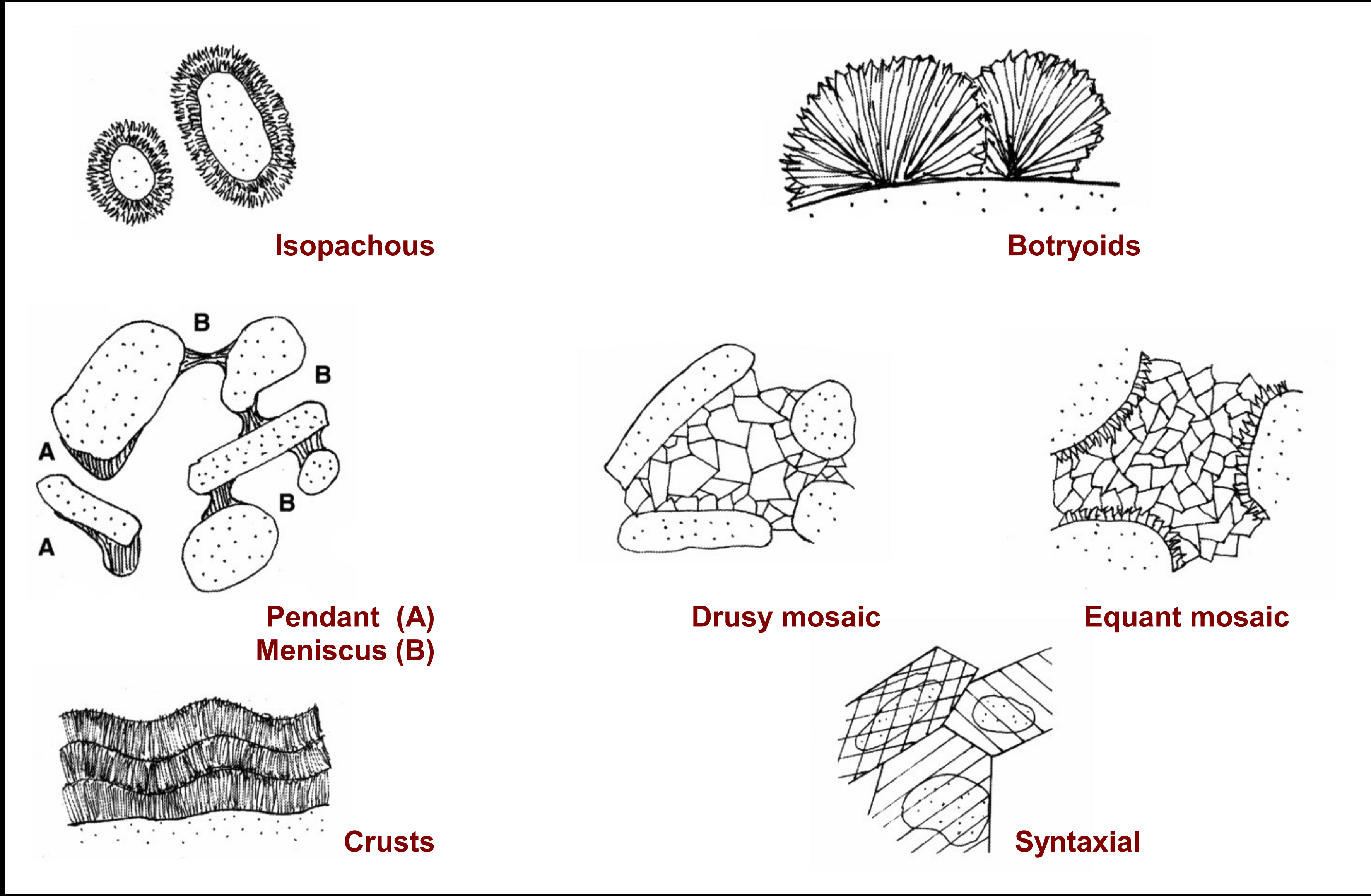


Flügel, 2004

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

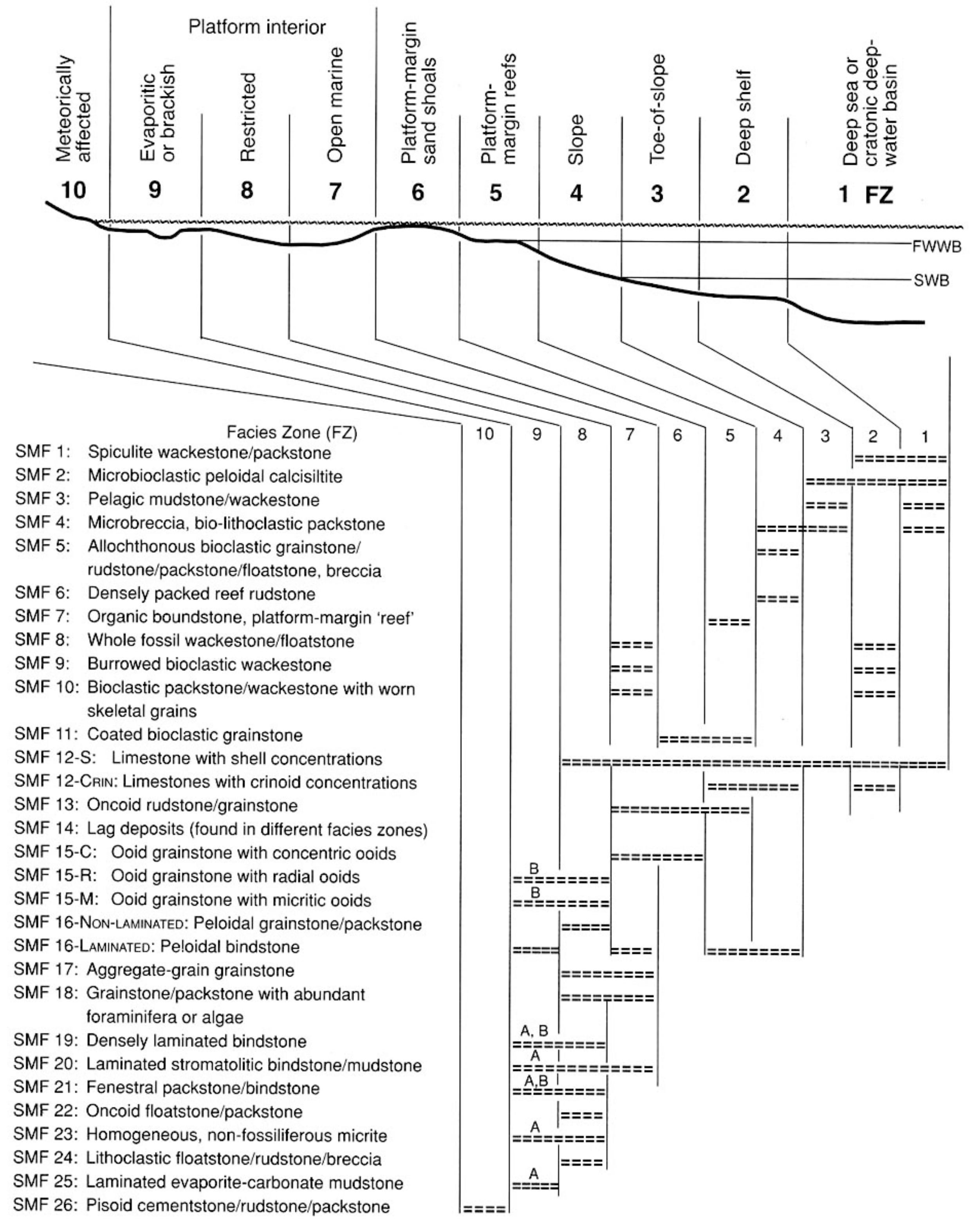
Box 14.4. *List of Standard Microfacies Types*. The order of the SMF numbers follows approximately the order of the Standard Facies Zones in the Wilson Model going from the basinal SMF Type 1 to SMF 26 that characterizes subaerial exposed areas.

- **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.

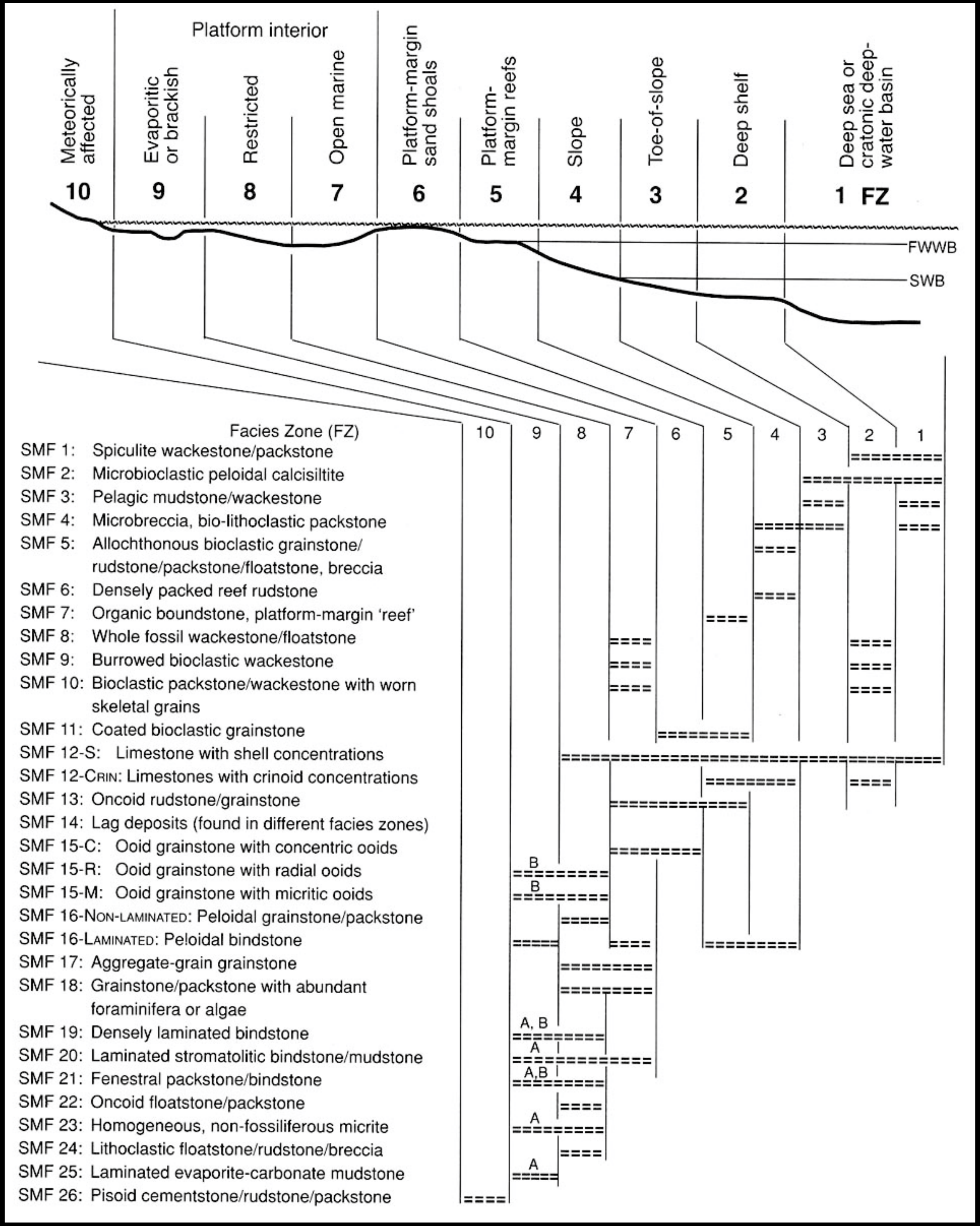


Flügel, 2004

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

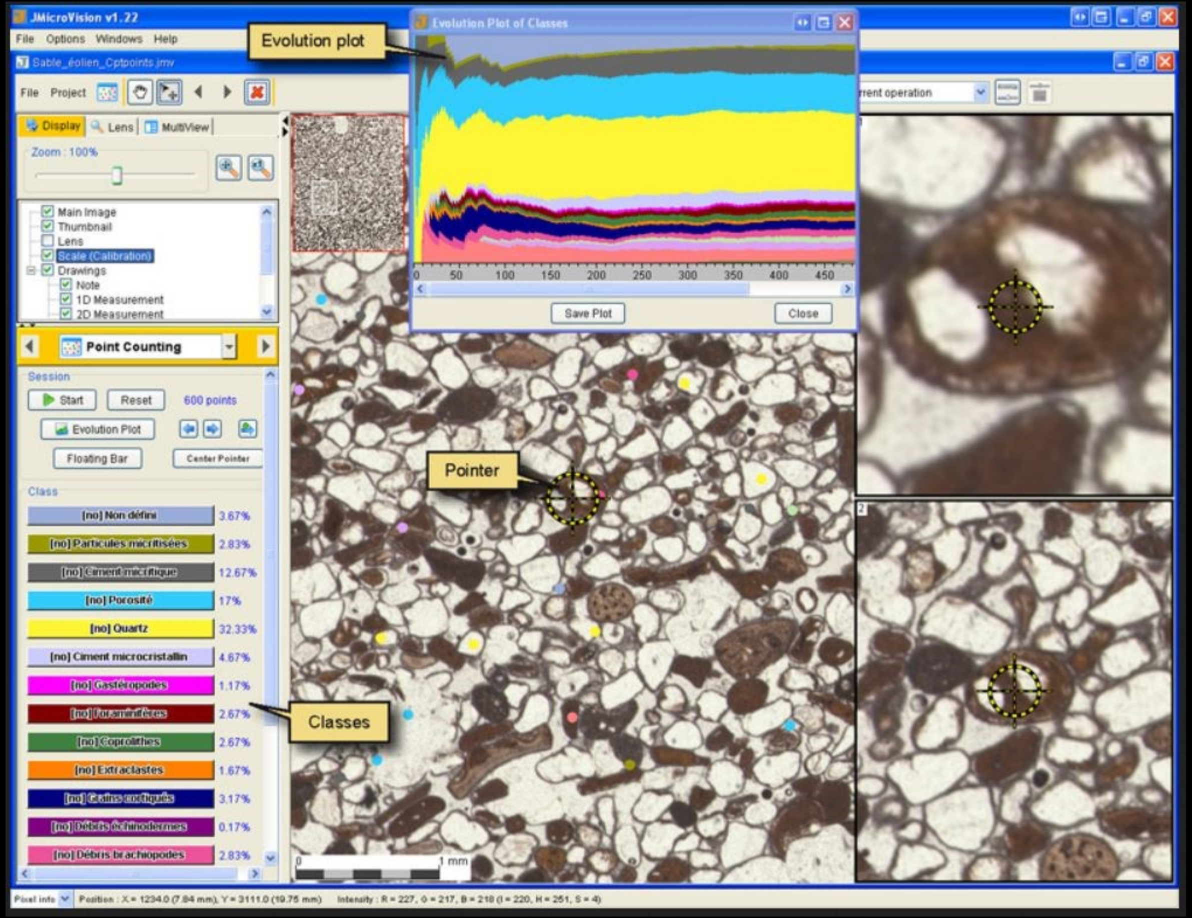
Observation of carbonates at the optical microscope does not only allow a quantitative description of the facies.

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.

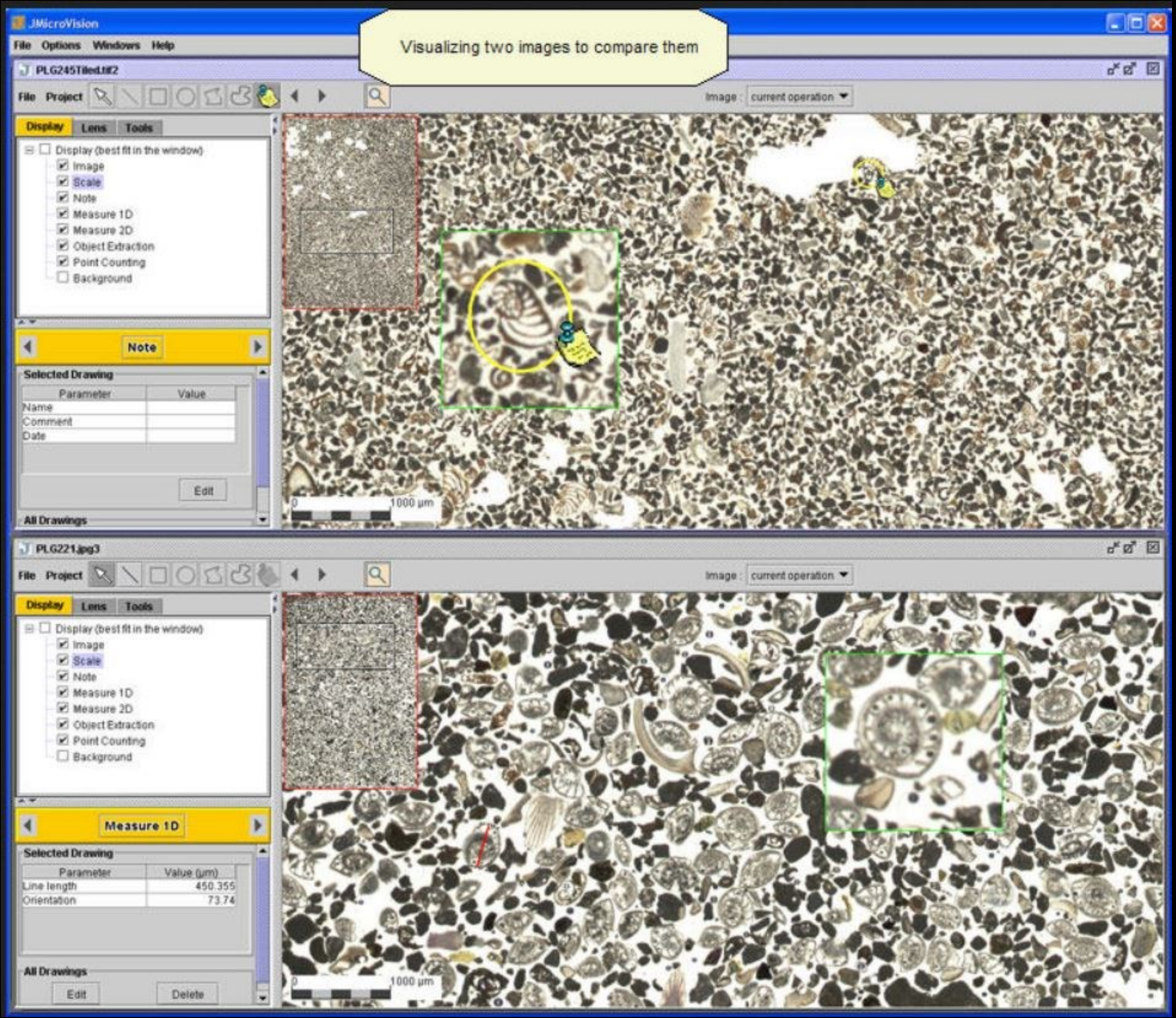
Quantative analysis on carbonates

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.

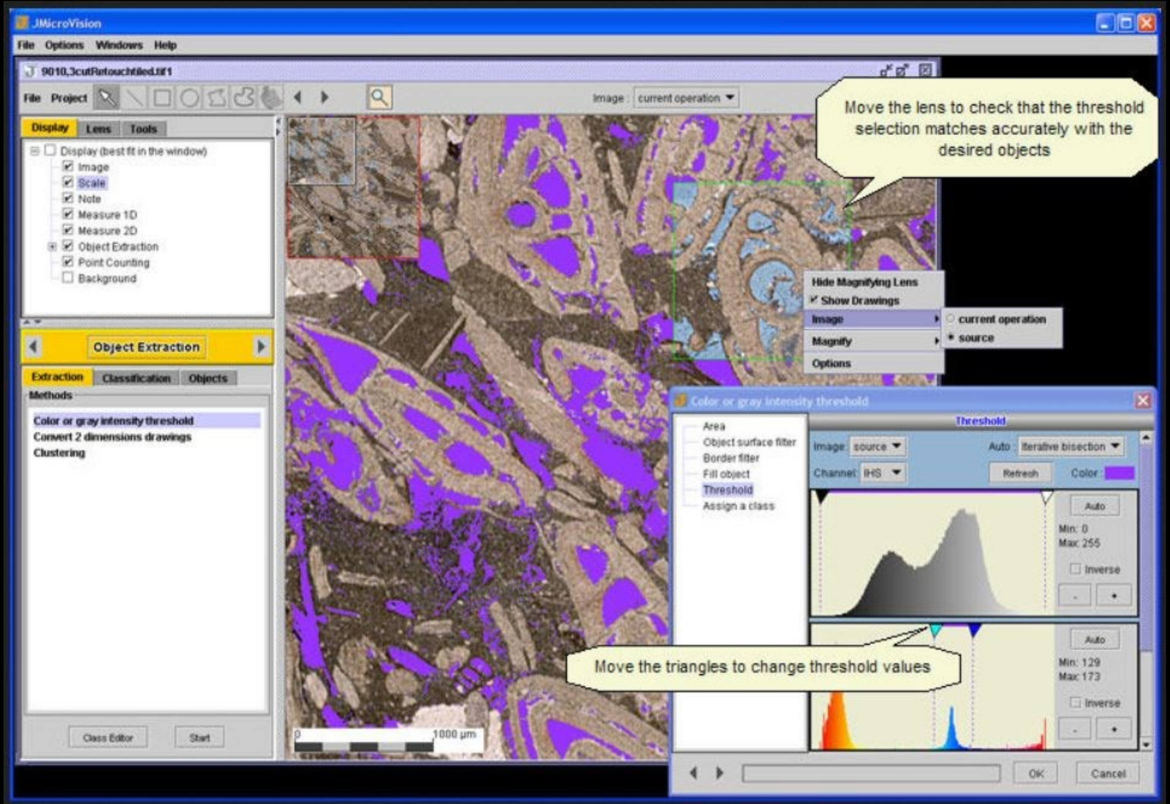


Example of sofwater for quantitative analysis of thin sections (including carbonates).
The software is J-Microvision.
The software imports a digital image of the thin section and a grid with number of points defined by the operator is set.
At this point the operator goes through the grid and identifies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

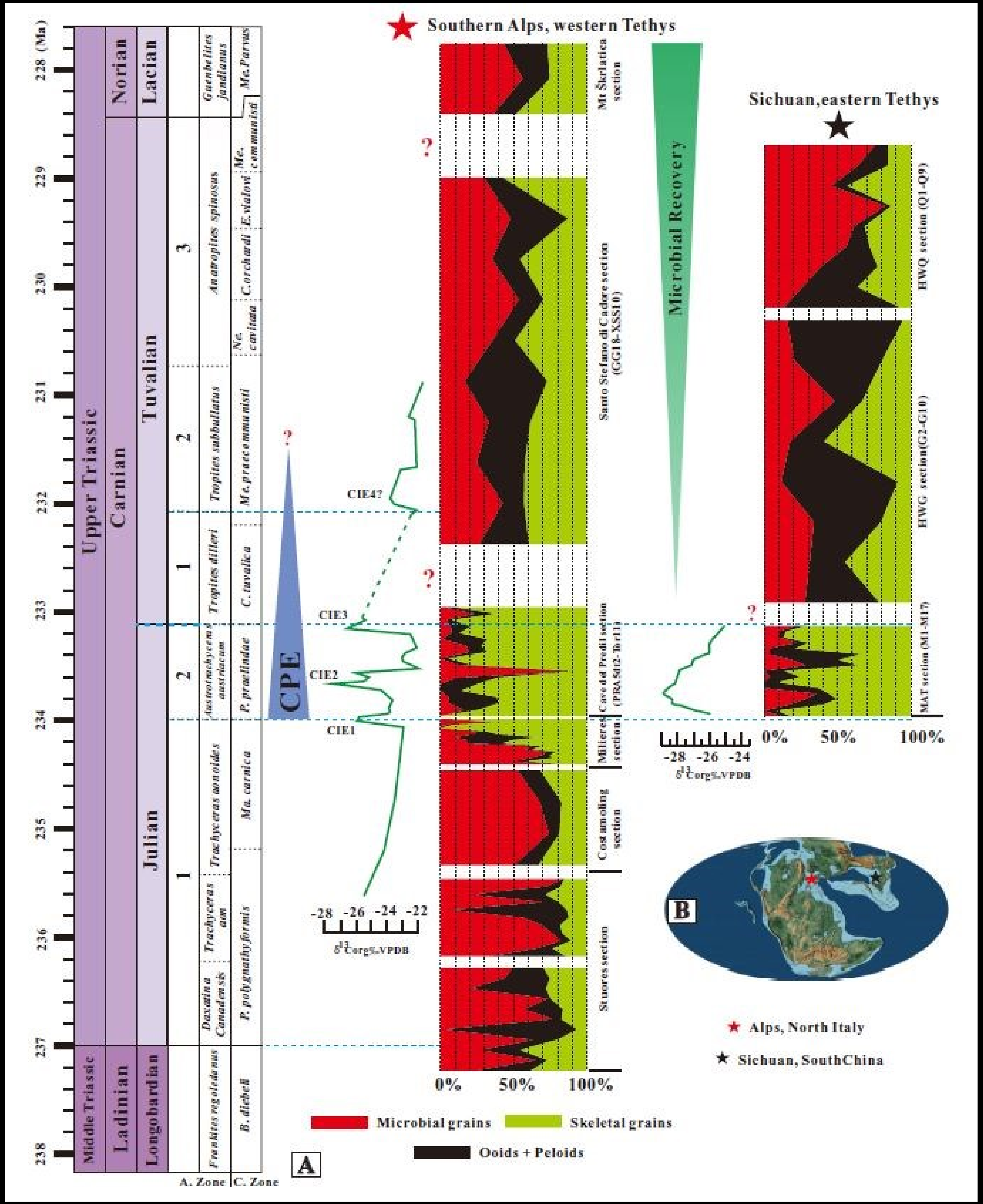
An example of point counting results

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).



CARBONATE SEDIMENTOLOGY

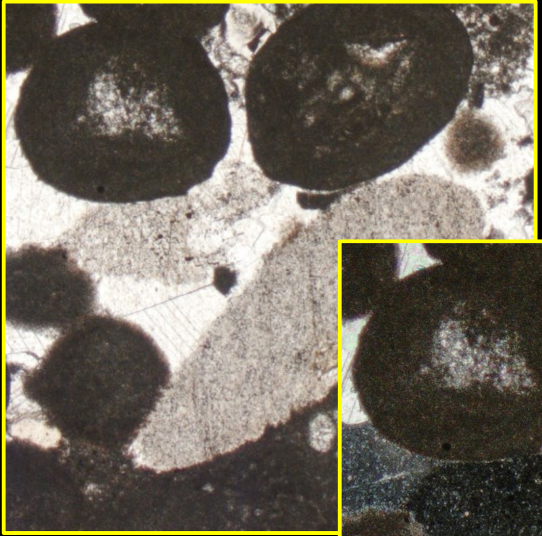
Carbonates at the optical microscope

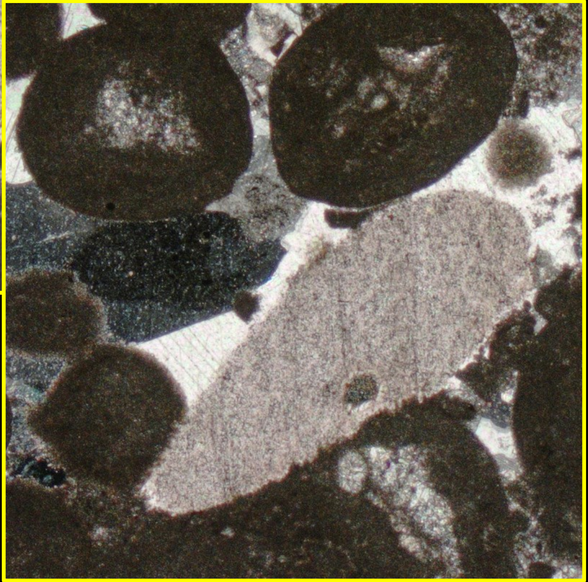
Echinoderms

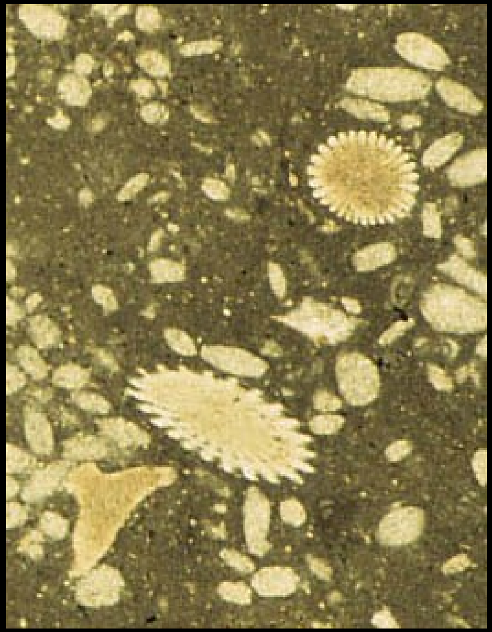
Original mineralogy:
- High-Mg calcite

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)


II polarizers


X polarizers



Carbonates at the optical microscope

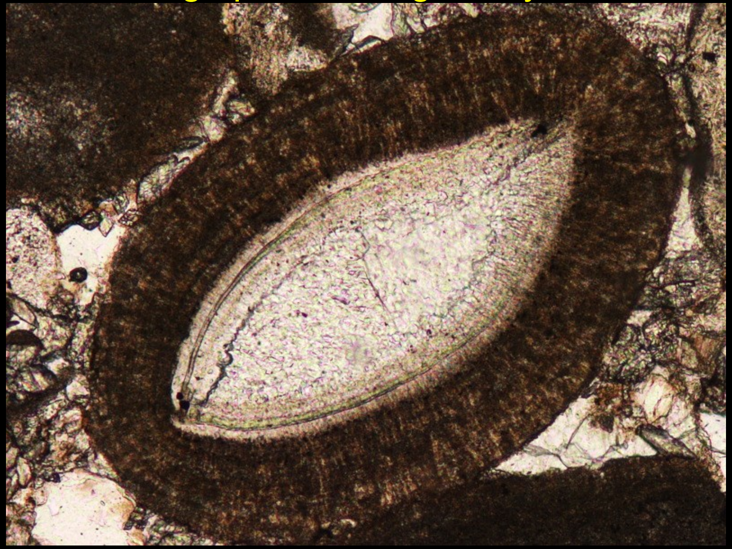
Ostracods

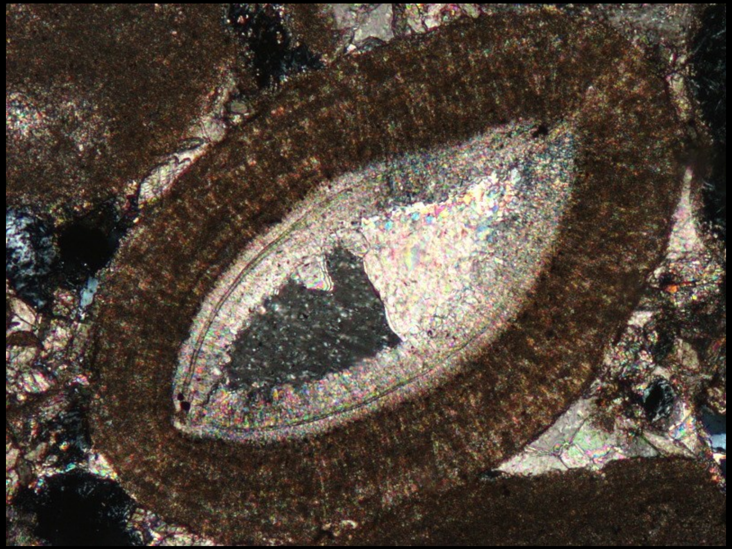
Original mineralogy:
- Low-Mg calcite

Diagnostic features:
- Bivalves, often articulated
- Small, almost never > 1 mm
- Fibrous calcite ultrastructure, with 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.

Carbonates at the optical microscope

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

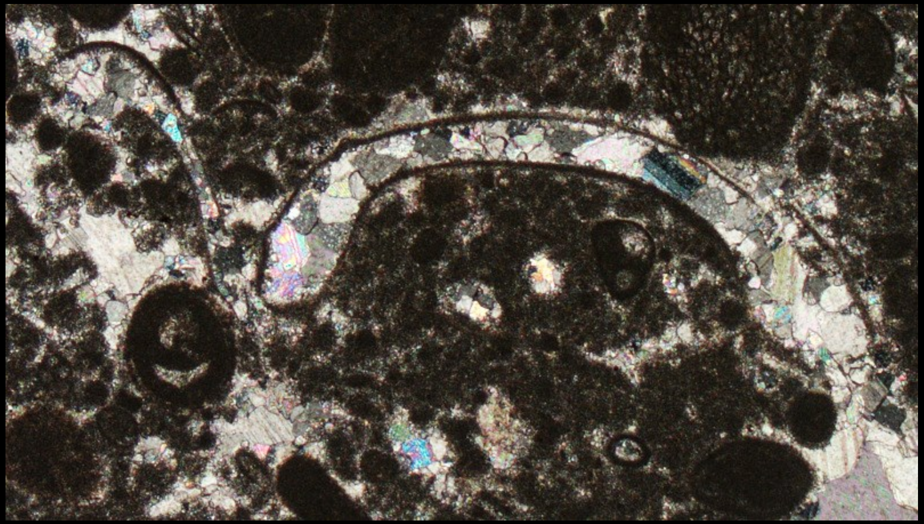
Aragonitic Bivalves

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 be distinguished from gastropods

Significance:
- Nearly always shallow water

X polarizers



Carbonates at the optical microscope

Prismatic Bivalves

Original mineralogy:

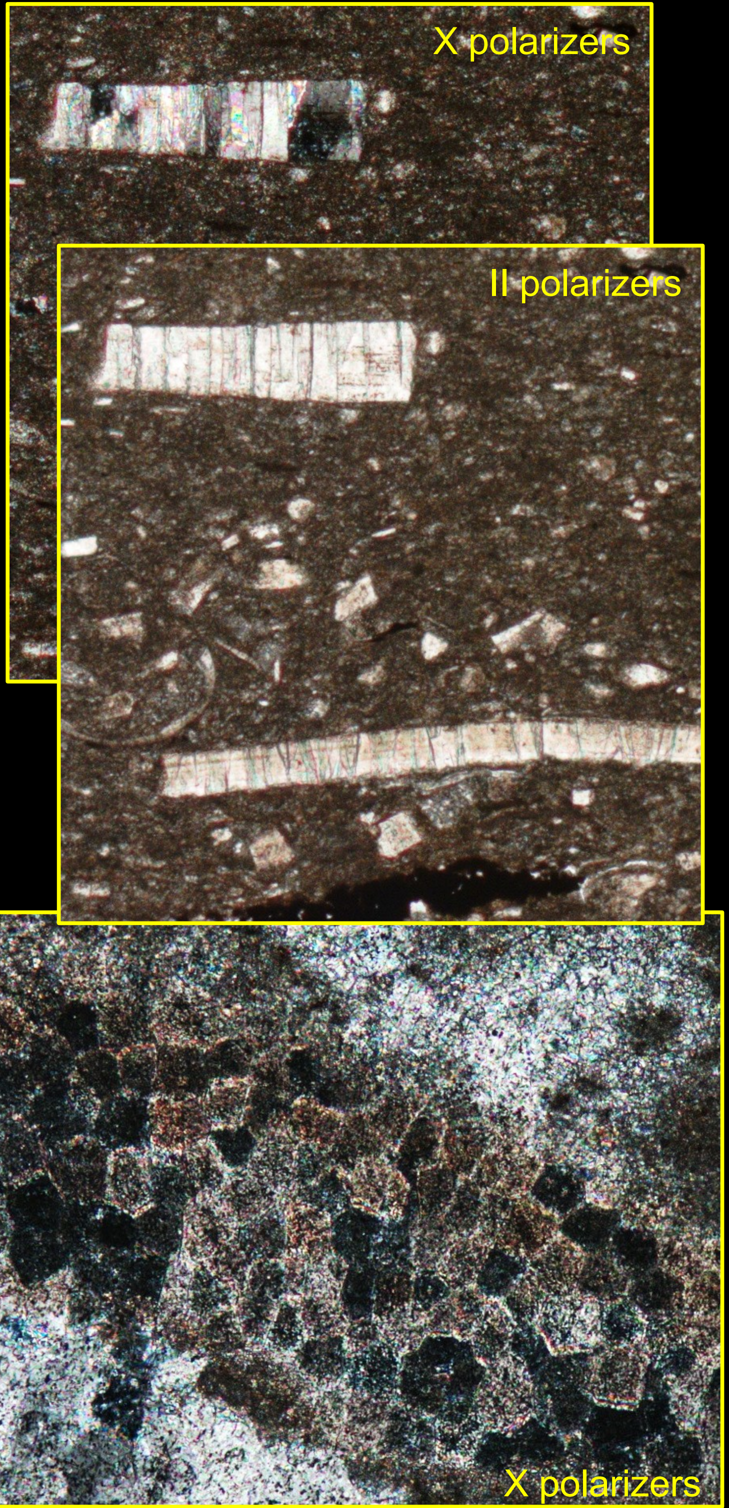
- Calcite (+ Aragonite)

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



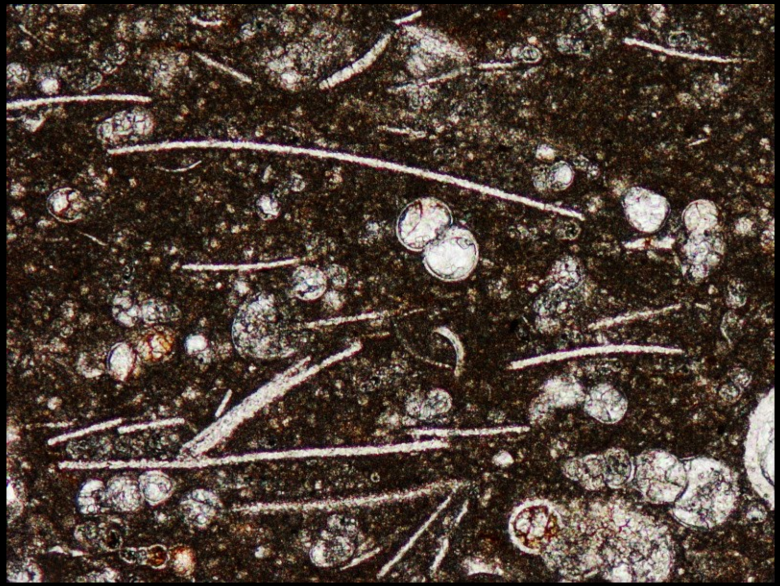
Carbonates at the optical microscope

Thin-shelled Bivalves

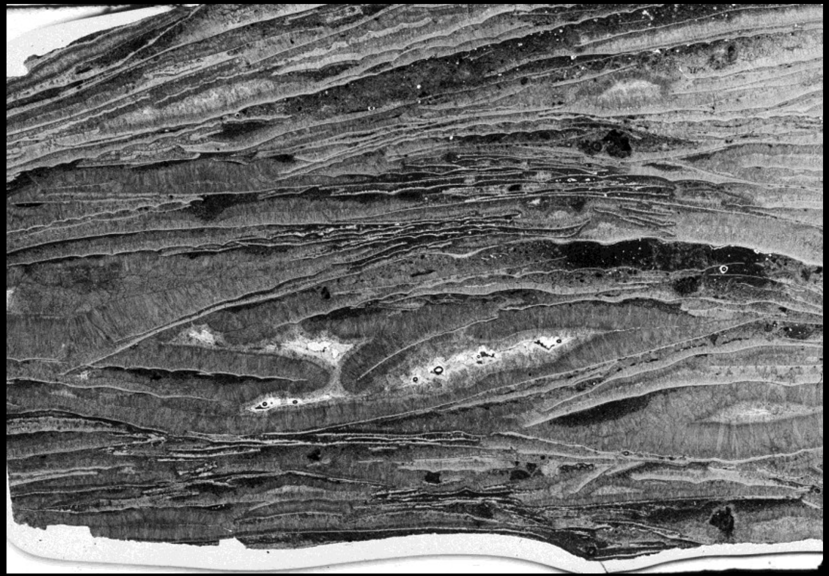
Original mineralogy:
- Calcite (+ Aragonite)

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.

Carbonates at the optical microscope

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 Bivalvia

Significance:
- Nearly always shallow water