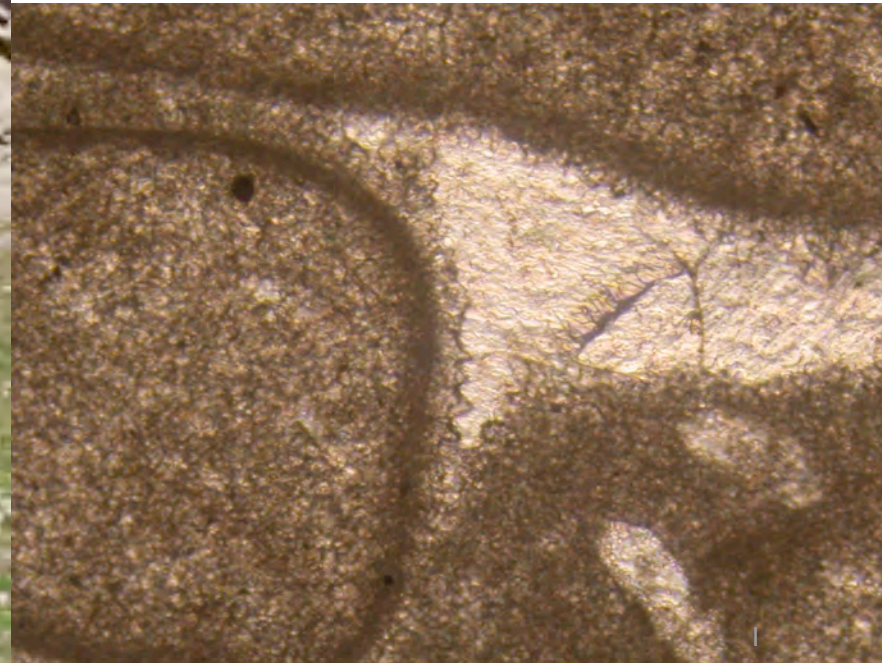


MICROFACIES OF CARBONATE ROCKS AND DEPOSITIONAL ENVIRONMENTS

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Prof. Alain Pr  at
Free University of Brussels



PETROGRAPHY OF CARBONATES

1. MATRIX

2. CEMENT

3. GRAINS

**A carbonate grain tells a story \neq A clastic grain
('highly sensitive' > < 'inert')**

Erik Flügel

MICROFACIES OF CARBONATE ROCKS

Analysis,
Interpretation
and
Application

2004

 Springer



ERIK FLÜGEL was born in Austria and obtained his Ph.D. degree from the University of Graz. After working as a curator at the Natural History Museum in Vienna, he spent ten years at the Technical University of Darmstadt and subsequently held the chair at the Institute of Paleontology at the University of Erlangen-Nürnberg from 1972 to 1999. His research on microfacies and facies analysis of limestone and the investigation of Paleozoic and Mesozoic reefs and reef-building fossils has enabled many ancient environments to be reconstructed. Springer published his textbooks *Microfacies Analysis of Limestones* in 1978 and 1982. He co-edited the SEPM Special Volume *Phanerozoic Reef Patterns* published in 2002 and led a Priority Research Program funded by the German Research Foundation, devoted to *The Evolution of Reefs through Time*. Flügel also held courses and workshops dealing with microfacies and facies models in Europe and Africa. He was an Honorary Member of the GSA and Professor Emeritus at the Erlangen Institute of Paleontology.

Flügel ■ MICROFACIES OF CARBONATE ROCKS



with CD-ROM

The book brings together the methods used in microfacies analysis and details the potential of microfacies in evaluating depositional environments and diagenetic history, and, in particular, applying microfacies data to the study of carbonate hydrocarbon reservoirs and the provenance of archaeological materials. The first part of the book introduces microfacies analysis; the second part deals with the interpretation of the microfacies data; and the third part explores the practical use of microfacies. This last part focuses on the facies controls of reservoir and host rocks, the importance of microfacies and diagenesis for understanding the technological properties of carbonate rocks and the destruction and conservation of carbonate objects, and discusses the potential of microfacies for archaeometrical studies. Nearly 400 instructive plates and figures (30 in color) showing thin-section photographs with detailed explanations form a central part of the content.

ISBN 3-540-22016-X



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springeronline.com

PETROGRAPHY OF CARBONATES

3. CARBONATE GRAINS

- ✓ various organic and non-organic particles of limestones that are larger than the groundmass = ‘grains’, ‘particles’, ‘constituents’, ‘allochems’ (the last term –Folk 1962- for mechanically deposited grains that have undergone transportation => = ‘intraclasts’),
- ✓ the final useful subdivision is between NON-SKELETAL grains and SKELETAL grains
 - = > skeletal grains comprise complete or fragments fossils (= ‘bioclasts’)
 - = > non-skeletal grains are peloids, various ‘coated grains’ (ooids, oncoids, ...), grain aggregates and clasts,
- ✓ **interest** : grain types are palaeoenvironmental proxies both from non-marine and marine carbonates (e.g. water energy levels, sedimentation rates ...).
Grain association patterns also allow reconstitution of paleoclimate and paleolatitudinal zones.
Grain type, mineralogy and spatial variations in their distribution are major control on the porosity development of reservoir rocks.

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.1 BIOCLASTS

- ✓ cf. first part of the course ('invertebrate fossils in rocks and thin sections')
= **skeletal grain** or **bioclast** ('organoclast', 'phytoclast', 'zooclast')
- ✓ their record is strongly controlled by
 - the primary skeleton mineralogy : $\pm 50\%$ = carbonate, other are phosphate and silica
 - taphonomic and diagenetic processes : transport (with or without breakdown) and/or dissolution
 - = > many skeletal grain types have specific preservation potential...
 - = > nb : dolomitization...
 - methodological bias : thin sections do not document the total record of skeletal grains
 - => some very small grains may be missed, 'non skeletal' grains are definitively lost.
- ✓ dating : they are the most valuable grain types to determine the age of limestone samples
 - => forams, sometimes algae

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.1 BIOCLASTS

Primary skeletal mineralogy of organisms

● dominant

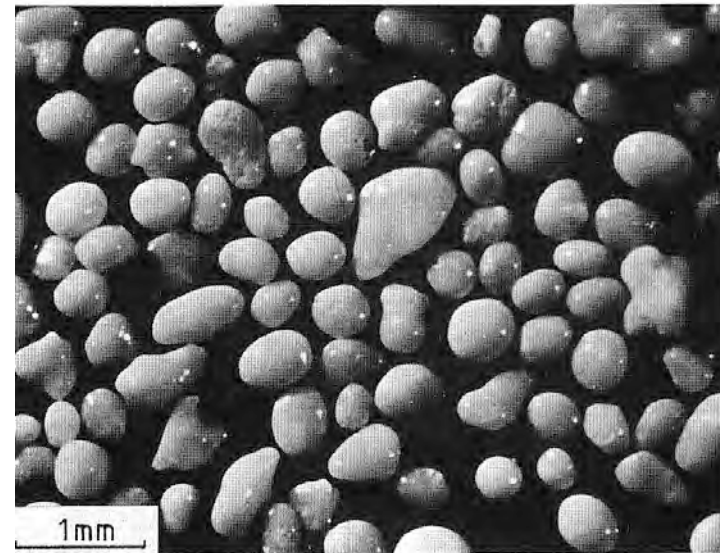
○ less common

| | | Aragonite | Low-Mg Calcite | High-Mg Calcite | Aragonite + Calcite | Ca-Phosphates | Silica |
|---------------|----------------------|--------------|----------------|-----------------|---------------------|---------------|--------|
| Cyanobacteria | | ○ | ● | ○ | | | |
| Pyrrhophyta: | Calciadinoflagellata | | ● | | | | |
| Chrysophyta: | Diatoms | | | | | | ● |
| | Coccolithophorida | | ● | | | | |
| Chlorophyta: | Dasycladaceae | ● | | | | | |
| | Udoteaceae | ● | | | | | |
| | Gymnocodiaceae | ● | | | | | |
| | Charophyceae | | ● | ● | | | |
| Rhodophyta: | Solenoporaceae | ● | | | | | |
| | Squamariaceae | ● | | | | | |
| | Corallinaceae | | | ● | | | |
| Radiolaria | | | | | | | ● |
| Foraminifera | | ○ | ● | ● | | | |
| Ciliata: | Calpionellida | | ● | | | | |
| Sponges: | Demospongea | | ○ | | | | ● |
| | Calcarea | | ○ | | | | |
| | Sphinctozoa | ● | ● | | | | |
| | Stromatoporoidea | ○ | ● | ● | | | |
| | Chaetetida | ● | ● | | | | |
| | Archaeocyathida | | ● | | | | |
| | Hexactinellida | | | | | | ● |
| Scyphozoa: | Conulata | | | | | ● | |
| Hydrozoa | | ● | ○ | ○ | | | |
| Corals: | Octocorallia | ○ | ○ | ● | ○ | | |
| | Rugosa | | ● | ○ | | | |
| | Heterocorallia | | ● | | | | |
| | Tabulata | ○ | ● | ○ | | | |
| | Scleractinia | ● | | | | | |
| Bryozoa | | ○ | ● | ○ | ● | ○ | |
| Brachiopoda: | Articulata | | ● | ○ | | | |
| | Inarticulata | | | | | ● | |
| Mollusca: | Monoplacophora | ● | | | ● | | |
| | Polyplacophora | ● | | | | | |
| | Scaphopoda | ● | | | | | |
| | Bivalvia | ● | ● | | ● | | |
| | Gastropoda | ● | ● | | ○ | | |
| | Nautiloidea | ● | ○ | | ○ | | |
| | Ammonoidea | ● | ● Aptychus | | | | |
| | Belemnoides | ● | | | ● | | |
| Tentaculitida | | ● | | ● | | | |
| Annelida: | Serpulida | ● | ● | ○ | ○ | ○ | |
| Arthropoda: | Trilobita | | ○ | | | ● | |
| | Ostracoda | | ● | ○ | | | |
| | Cirripedia | ○ | ● | ● | | | |
| | Decapoda | | ● | ● | | | |
| Echinodermata | | | | ● | | | |
| Tunicata | | ● | | | | | |
| Vertebrata | | ○ (otoliths) | | | | ● | |
| Conodonts | | | | | | ● | |

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.2 OOLIDS

OOIDS ARE SPHERICAL PARTICLES WITH CONCENTRIC LAMINAE COATING A NUCLEUS



Dean & Fouch 1983



Bars of oolites, parallel to the shoreline Great Salt Lake



Spill-over lobes, backside of an active ooid shoal
(clean, crossbedding, Great Bahama Bank)

Halley et al 1983

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.2 OIDS

OOIDS ARE SPHERICAL PARTICLES WITH CONCENTRIC LAMINAE COATING A NUCLEUS

Clean sands on an active sand shoal.
Well-sorted, medium sand-size ooids
in slightly dipping laminae.
Thicker laminae with coarse grains
(algae, forams, aggregates), loose-packing
Joulters ooid shoal, Great Bahama Bank
Halley et al 1983.



PETROGRAPHY OF CARBONATES

3. GRAINS = 3.2 OOLIDS

OOIDS ARE SPHERICAL PARTICLES WITH CONCENTRIC LAMINAE COATING A NUCLEUS

- ✓ known since Sorby 1879 and Kalkowsky 1908 => 'intriguing constituent'
- ✓ for a long time, they were regarded as 'inorganic' grains
 - => strong biological controls have been highlighted : cumulative processes by biofilm attachment and subsequent carbonate (mostly aragonite) encrustation
 - = = > 'microbial' contact (coccolith cyanobacteria and diatoms)
 - = = > also inorganic ooids = hydrodynamic control (Bahamian ooids/oolites)?
- ✓ microfabrics, mineralogy, abundance and size reflect physical and chemical conditions of the depositional environments in marine and non-marine settings
 - => ooids = proxies for water energy, temperature, salinity, water depths...
- ✓ present-day marine Bahamian-type ooids formed in turbulent environments,
 - => not necessarily analogues of ancient ooids
 - => moreover, the transport of ooids from the areas in which they were produced to the depositional areas is often underestimated
 - => changes in mineralogy and abundance over time have been correlated to changes in CO₂atm or to the rate of sea-level change => also a relation with climates.
- ✓ **oolites (carbonate rocks composed of ooids) formed on marine PF and ramps comprise > 50% of the world's carbonate hydrocarbon reservoirs.**

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.2 Ooids

DEFINITION : Ooids are spherical and egg-shaped carbonate or non-carbonate (iron-ooids) coated grains exhibiting a **nucleus** surrounded by an external **cortex**, the outer part of which is concentrically smoothly laminated.

Most ooids are smaller than 2 mm in diameter, many ooids between 0.5-1 mm in size

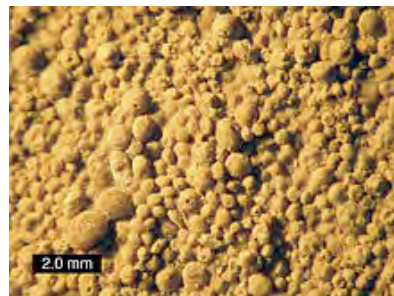
Modern ooids = ARAG and/or CALCITE.

The cortices exhibit a variety of microfabrics caused by different orientations of carbonate crystals in the laminae

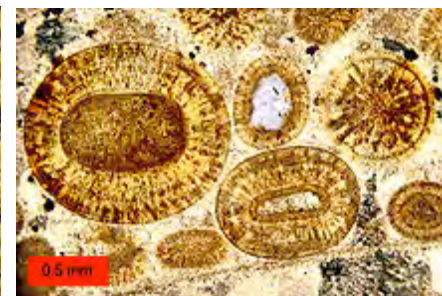
- TANGENTIAL or CONCENTRIC Ooids : tangentially or randomly arranged crystals
- RADIAL or RADIAL-FIBROUS Ooids : radially arranged HMC and/or ARAG crystals
- MICRITIC Ooids : spherical grains with a nucleus and micritic cortex
- SPHEROIDS : radially arranged fibrous crystals



Modern ooids from a beach on
Joulter's Cay, The Bahamas



Ooids on the surface of a limestone
Middle Jurassic, southern Utah



Thin-section of calcitic ooids
Jurassic, southern Utah

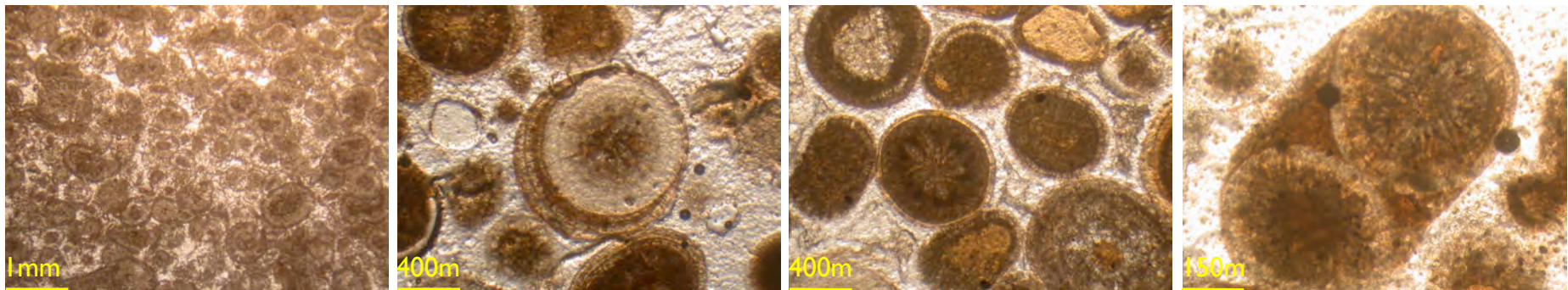
Wikipedia 2013

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.2 OOLIDS

KEY INTERPRETATION

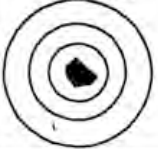
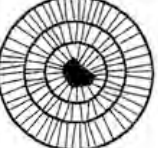
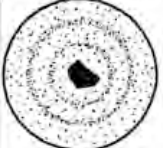
- TANGENTIAL TANGENTIAL or CONCENTRIC OOLIDS = **HIGH-ENERGY**
- RADIAL or RADIAL-FIBROUS OOLIDS = **MODERATE to LOW-ENERGY**
if well-preserved in geological series => HMC => LMC
- MICRITIC OOLIDS = obliteration/recrystallization of previous ones
- SPHEROIDS : radially arranged fibrous crystals



Neoproterozoic, Bas Congo, Delpomdor, Pr  at, Van Vliet 2011

PETROGRAPHY OF CARBONATES

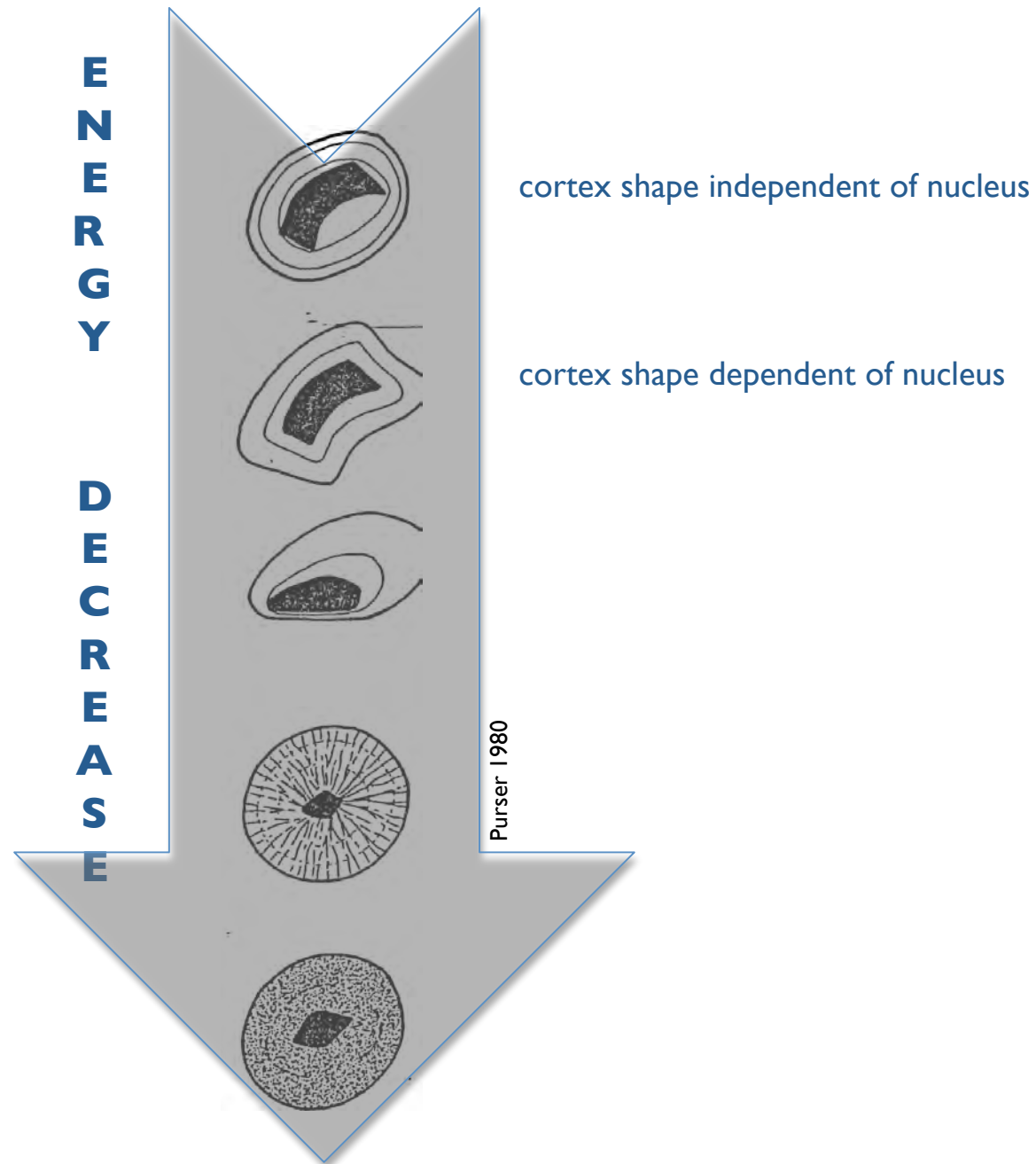
3. GRAINS = 3.2 OIDS

| | 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 (Great Salt Lake/Utah) | Very shallow, warm low-latitude seas; <i>common in high-energy settings</i> 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) Gulf of Aqaba Great Salt Lake/Utah | Shallow marine, <i>common in low-energy settings</i> Sea-marginal hypersaline pool 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

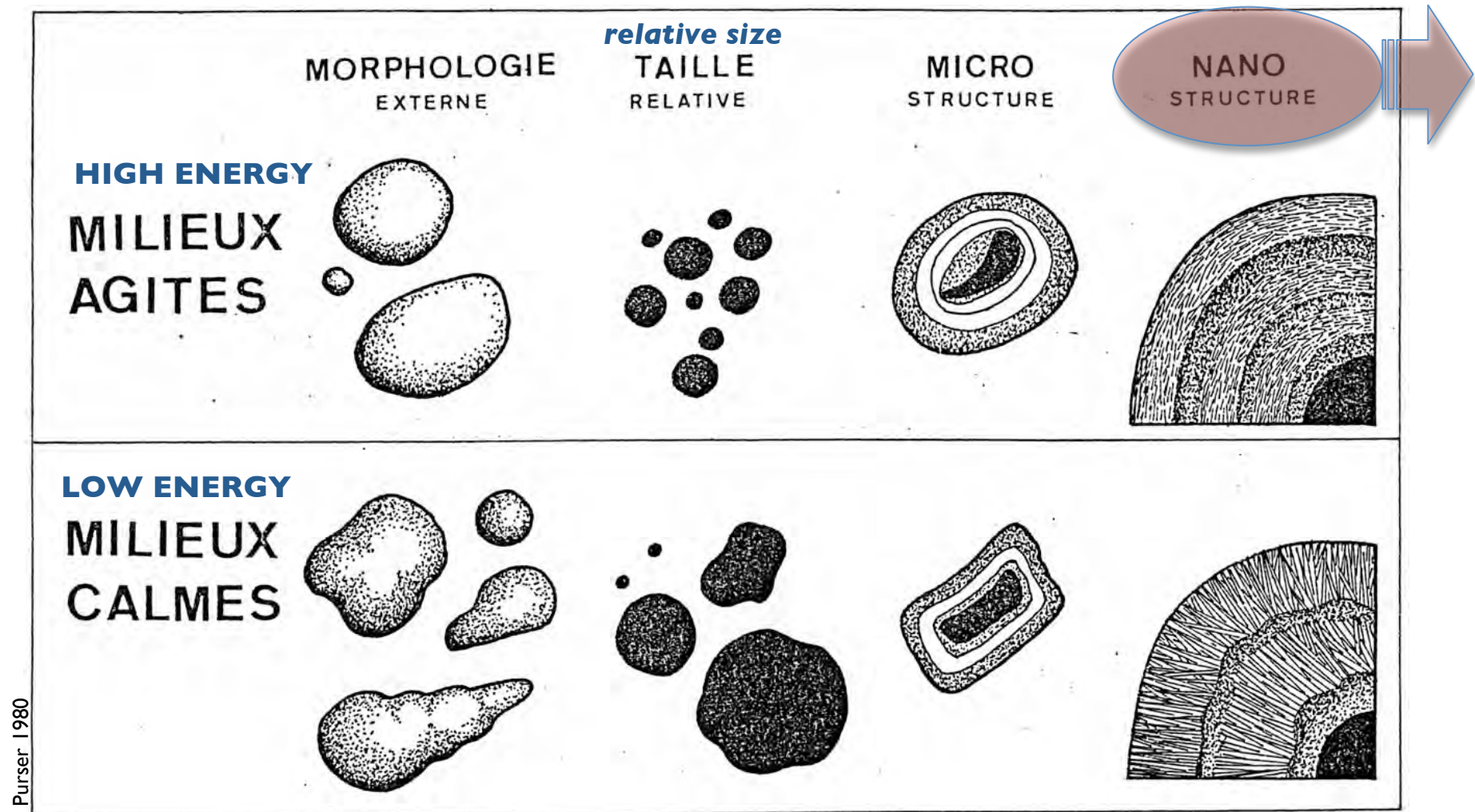
PETROGRAPHY OF CARBONATES

3. GRAINS = 3.2 OOLIDS



PETROGRAPHY OF CARBONATES

3. GRAINS = 3.2 OOIDS

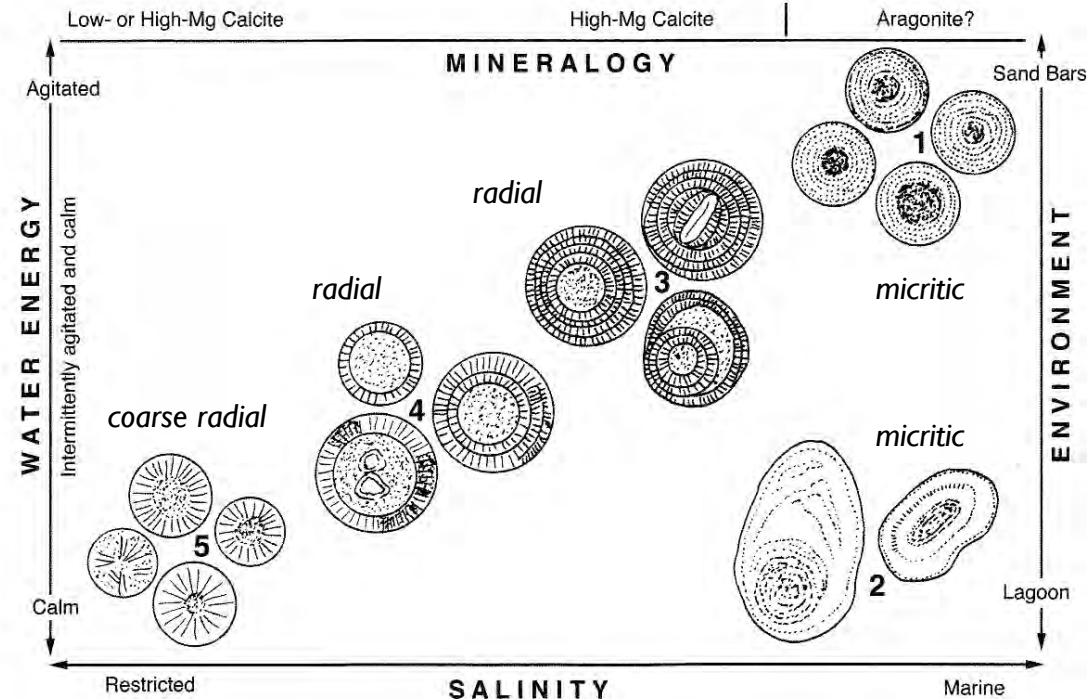


Purser 1980

PETROGRAPHY OF CARBONATES

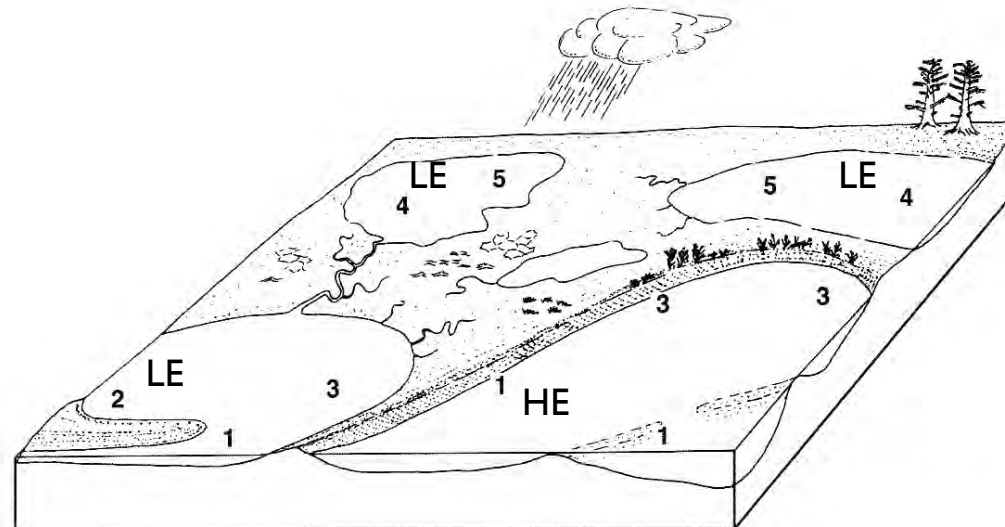
3. GRAINS = 3.2 OIDS

Depositional sites
and environmental
controls of ooids.
Purbeck facies,
lowermost Cretaceous,
Swiss, France
Jura mountains
(Strasser, 1986).



Shallow
sub-
inter-
supratidal

normal marine
brackish
freshwater
hypersaline

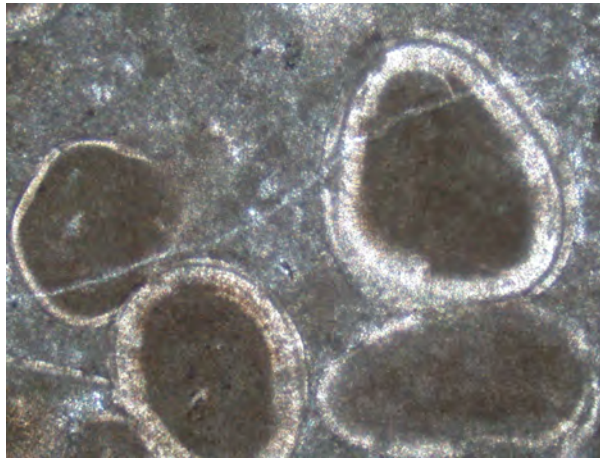


Ooid packstone

Radial ooid partially replaced in a pre-evaporitic supratidal environment.

Middle Devonian (Givetian), France, Pr  at.

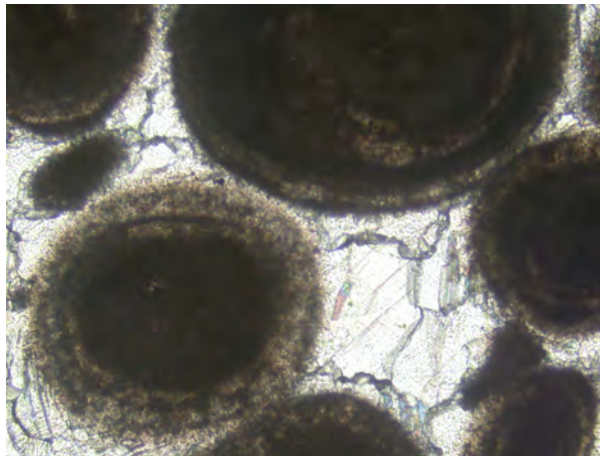
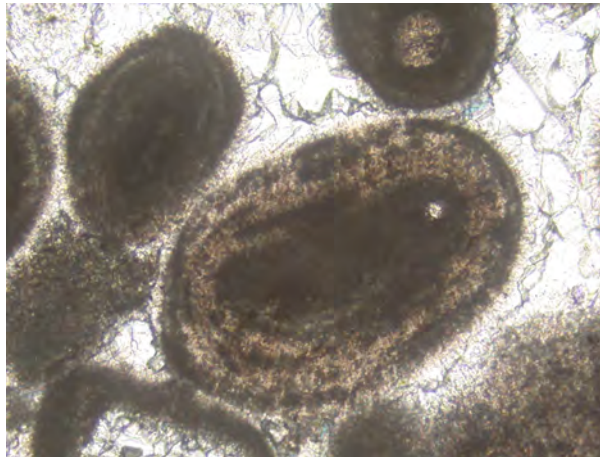
Ooid sizes : 200-300  m



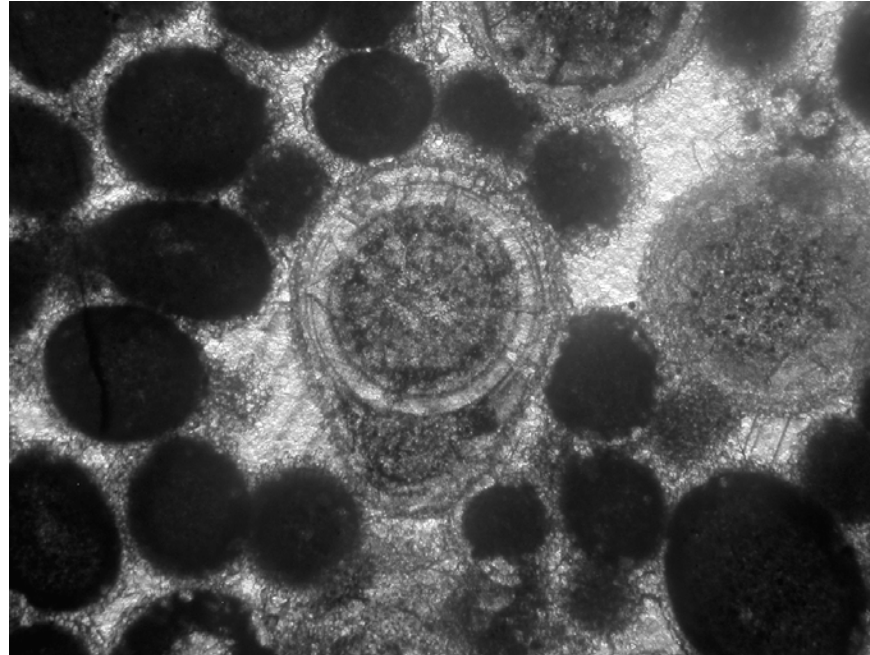
Ooid grainstones in a vadose freshwater-influenced back shoal area. Radial partially micritized ooids, bladed HMC with needle (former aragonite) inclusions, equant clear calcite and meniscus calcite cements. Intertidal setting.

Givetian, Belgium, Pr  at.

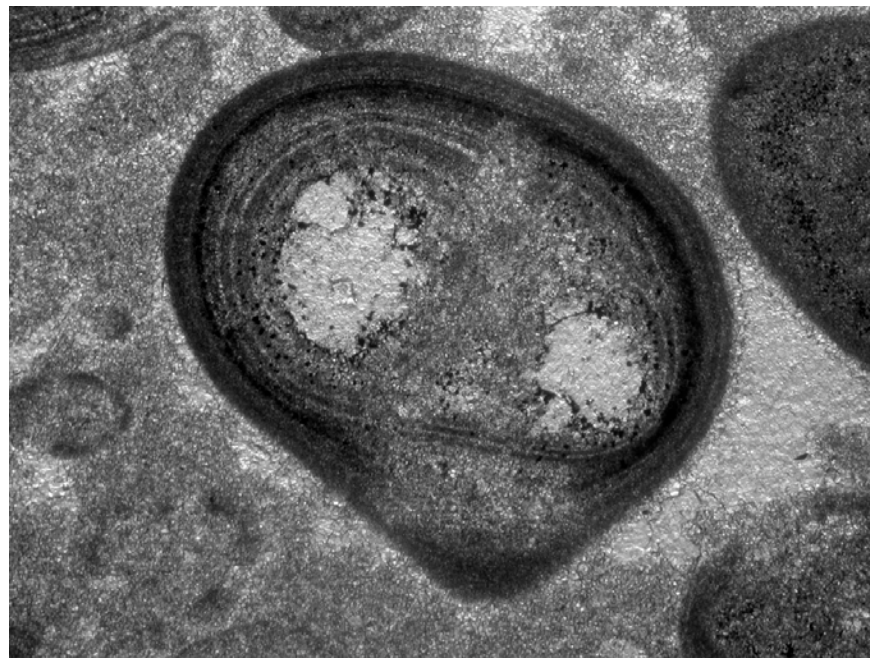
Ooid sizes 100-300  m



OOIDS IN VADOSE EVAPORITIC ENVIRONMENT NEOPROTEROZOIC, CONGO-BRAZAVILLE, Pr  at 2012



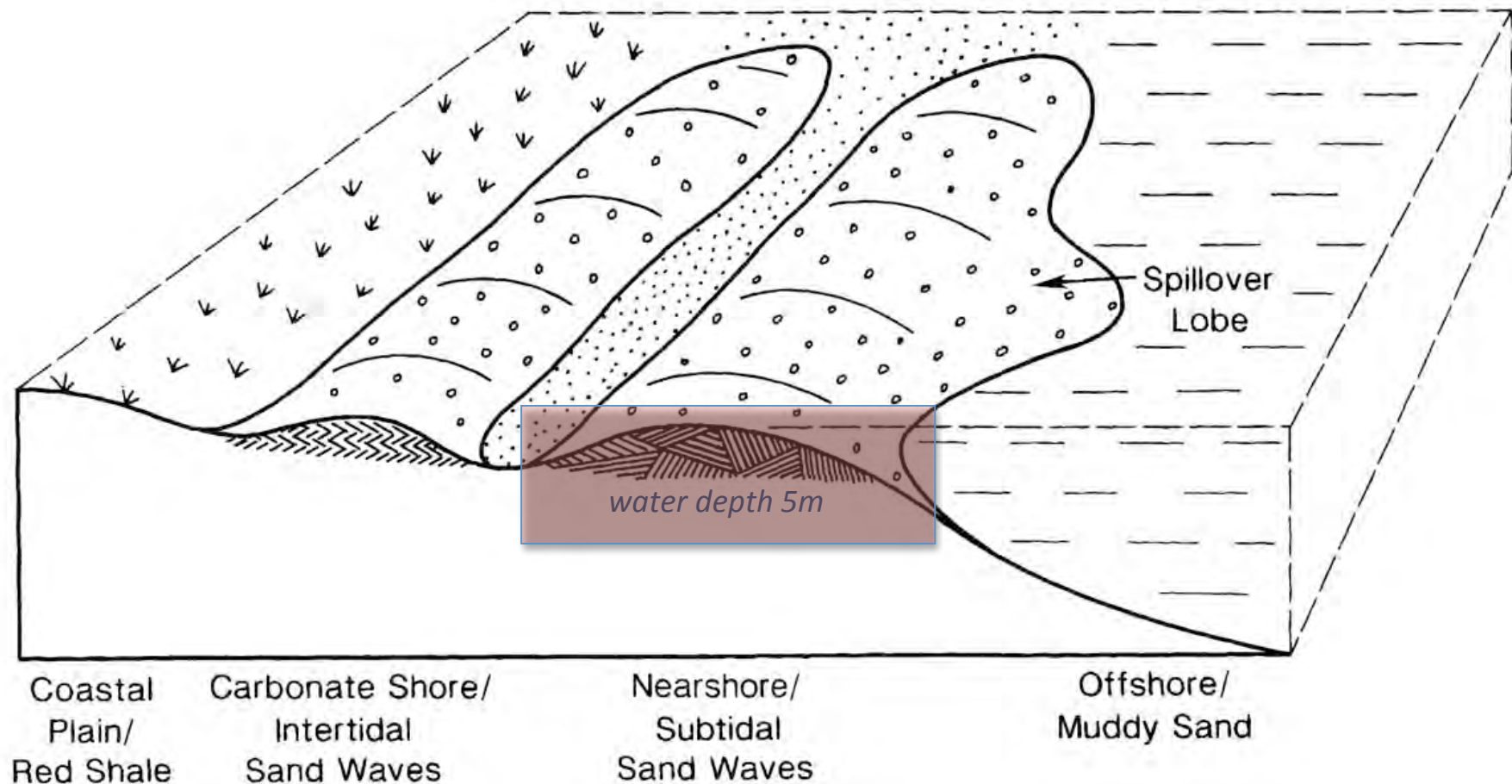
Diameters of ooids
 $\pm 0,5$ mm



PETROGRAPHY OF CARBONATES

3. GRAINS = 3.2 OOLIDS

OOLITIC TIDAL-BAR RESERVOIRS, MISSISSIPPIAN, WEST VIRGINIA



Smosna & Koehler 1993

Depositional model of the Pickaway ramp, Mississippian, West Virginia.

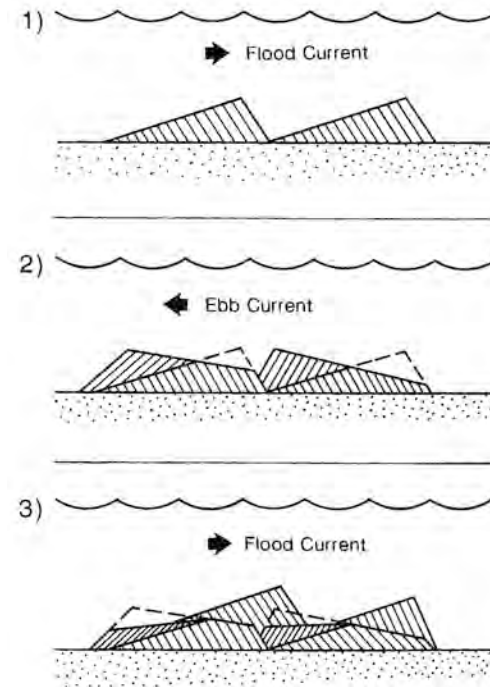
Small intertidal sand waves, large subtidal sand waves, offshore spillover, offshore muddy sands.

OOLITIC TIDAL-BAR RESERVOIRS, MISSISSIPPIAN, WEST VIRGINIA

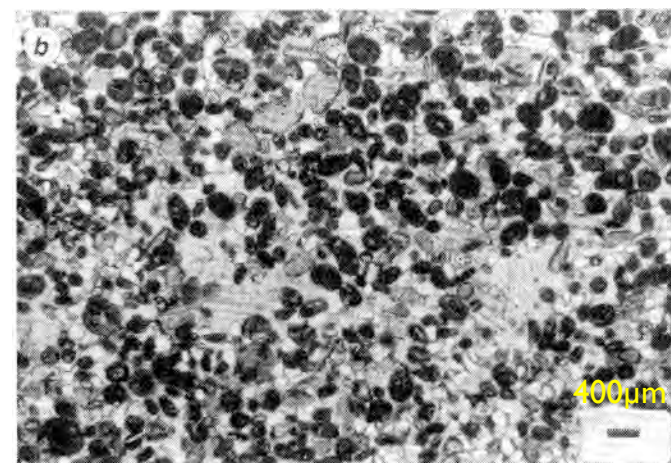


Smosna & Koehler 1993

Sets of wedge shaped cross-strata with planar bounding surfaces

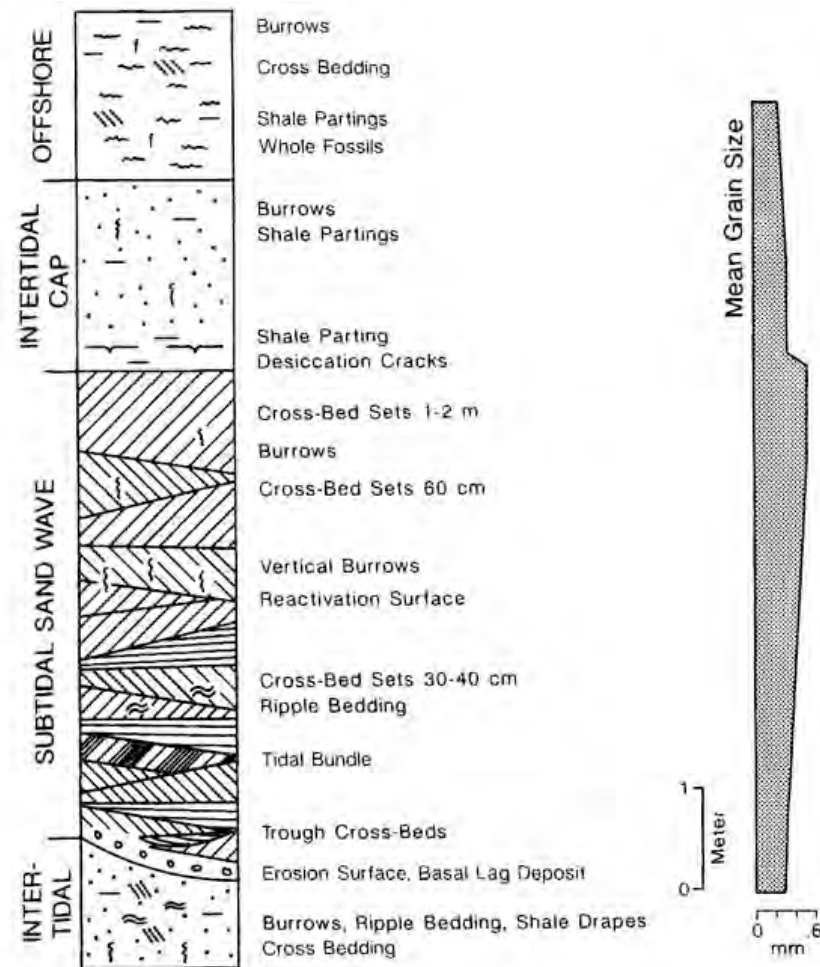
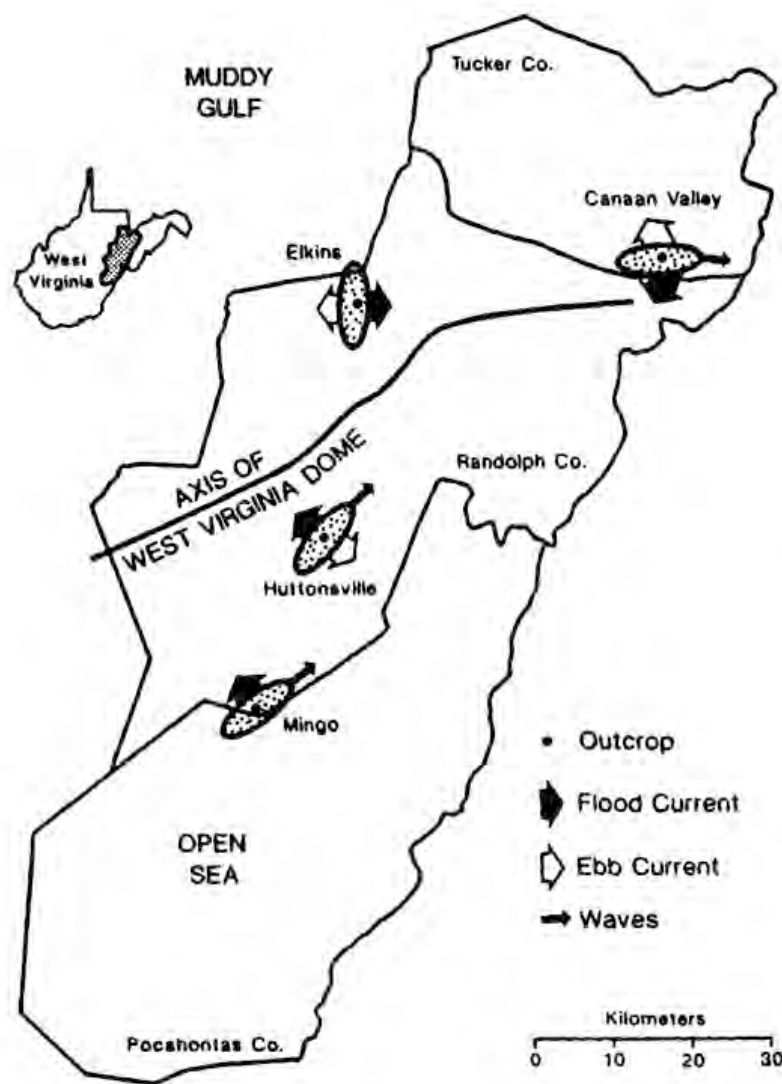


Wedge shaped cross-strata with bidirectional foresets that formed when sand waves migrated under the influence of reversing tidal currents



Grainstone with peloids, quartz, OOLIDS, bioclasts

OOLITIC TIDAL-BAR RESERVOIRS, MISSISSIPPIAN, WEST VIRGINIA

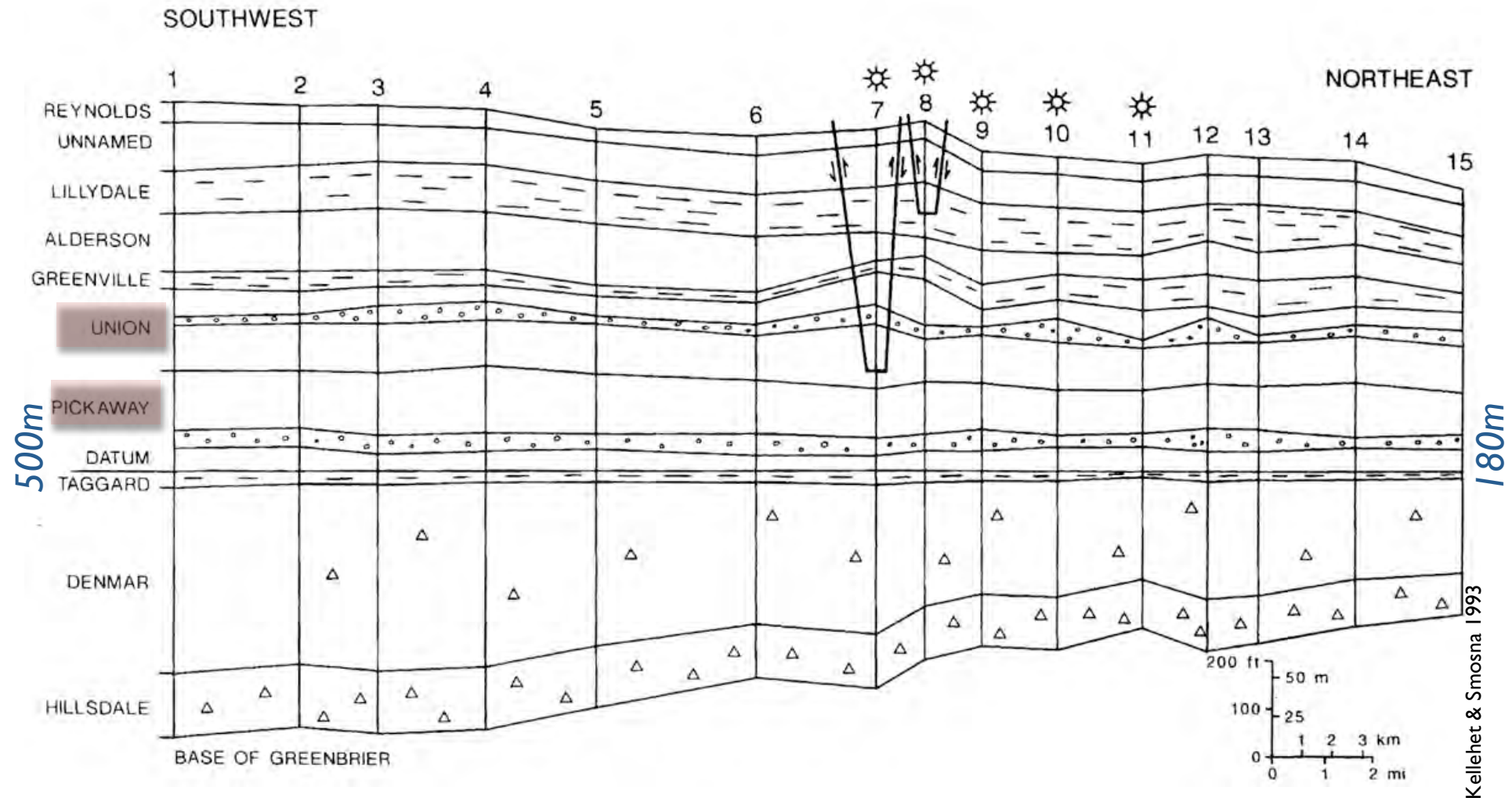


Stratigraphic succession of facies from Huttonsville. Basal erosion surface and lag deposit.

Smosna & Koehler 1993

Paleogeography around the axis or crest of the West Virginia dome. Flood and ebb tidal currents flowed perpendicular to the axis and waves came from W-SW.

Individual ooid tidal bars : 4.6-9.1m, porosity >6%

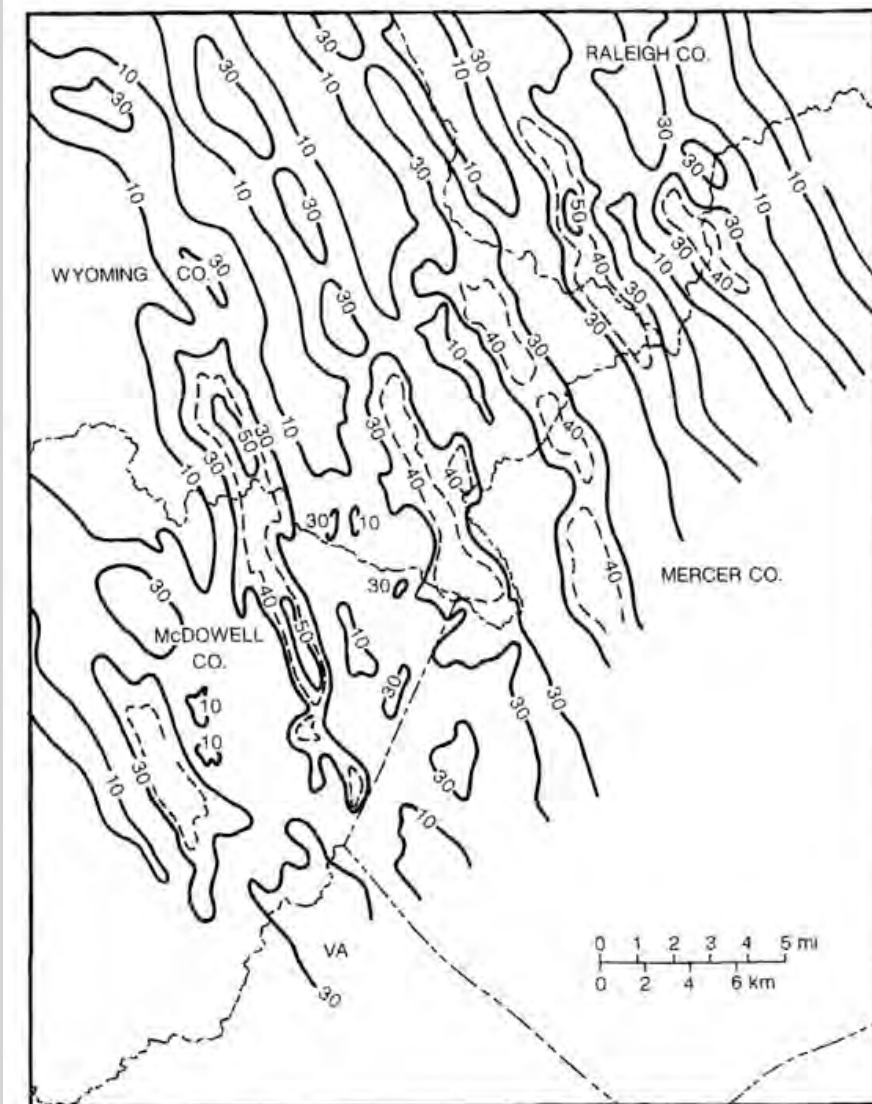


Producing zones in grainstones with porosity 9.5% and K 0.15md

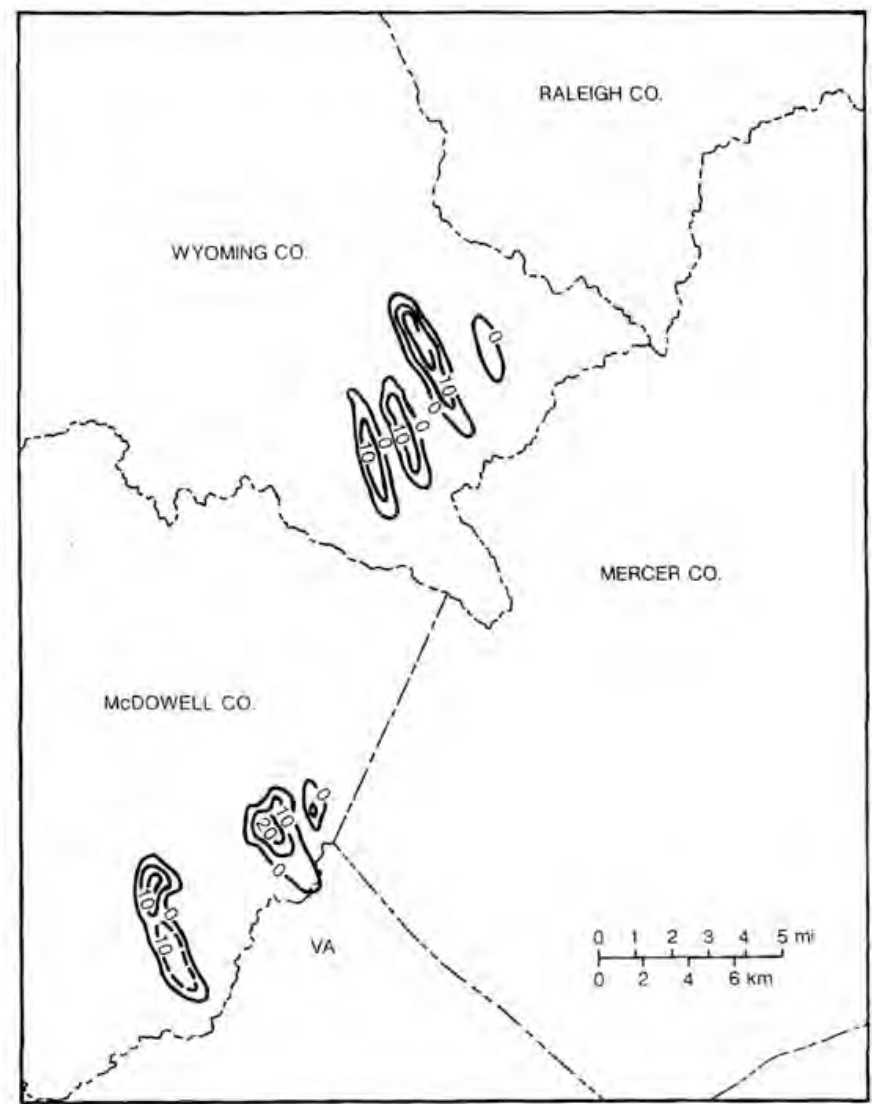
Ooids altered during meteoric diagenesis => high inter/intra-granular microporosity

K enhanced by chemical compaction => long contacts between microporous grains

OOLITIC TIDAL-BAR RESERVOIRS, MISSISSIPPIAN, WEST VIRGINIA



Isopach map, Union Oolite Member.
NW-trending tidal bars, 12m-thick (av.),
1.4km in width and 32km in length



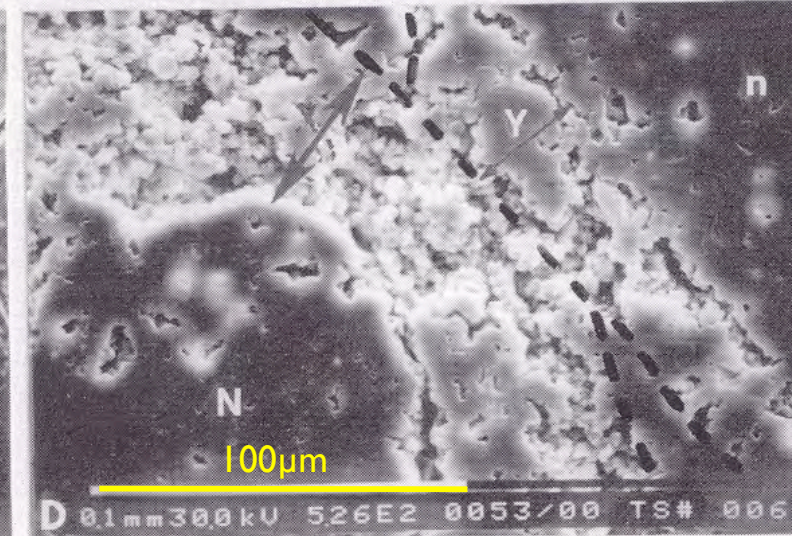
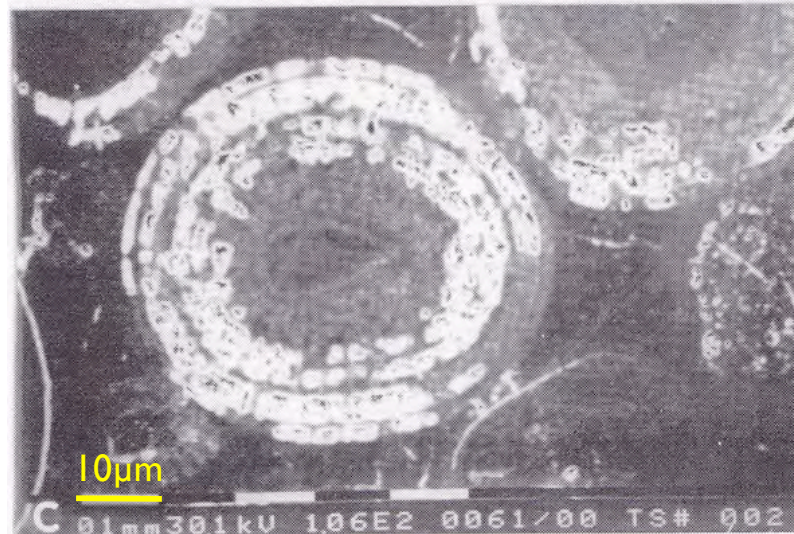
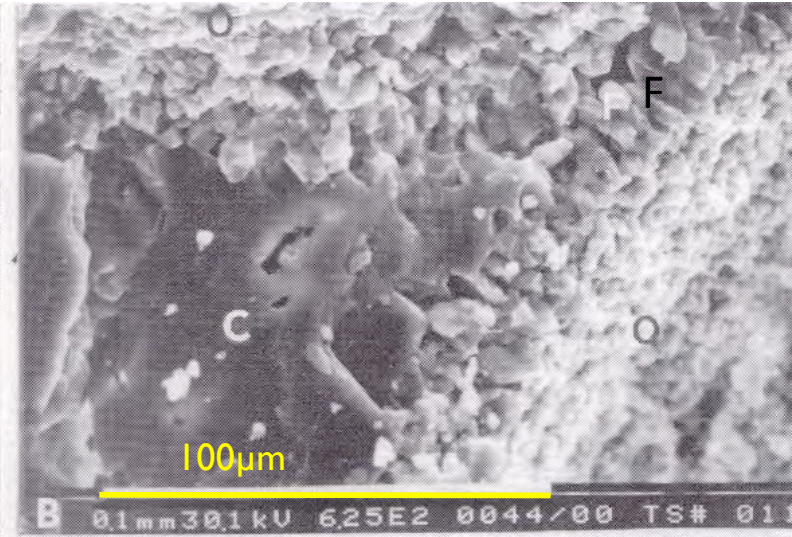
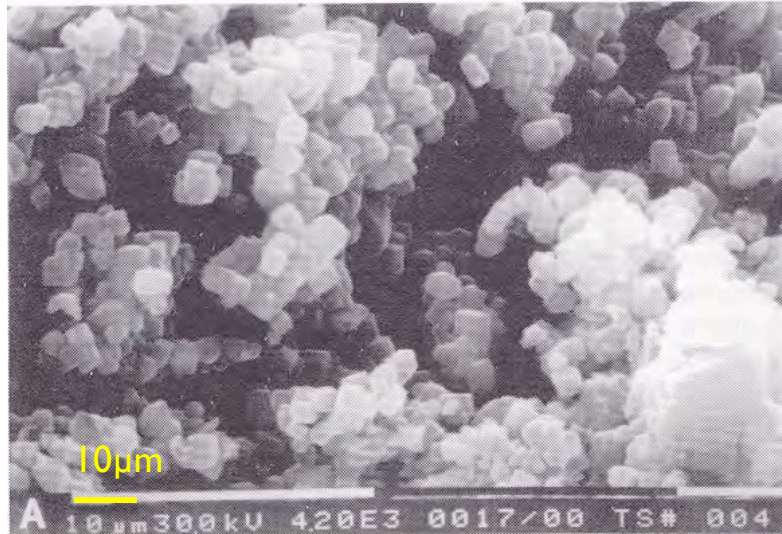
Isopach map, Union Pickaway member.
Net pay zone (porosity = ou > 6%)

Kellehet & Smosna 1993

OOLITIC TIDAL-BAR RESERVOIRS, MISSISSIPPIAN, WEST VIRGINIA

microLMC (meteoric diagenesis)
intraooid microporosity (high
pores with large throats and interconnections

parts of two ooids (O)
isopachous fringe cement (F) followed by
coarse void-filling LMC cement (C)

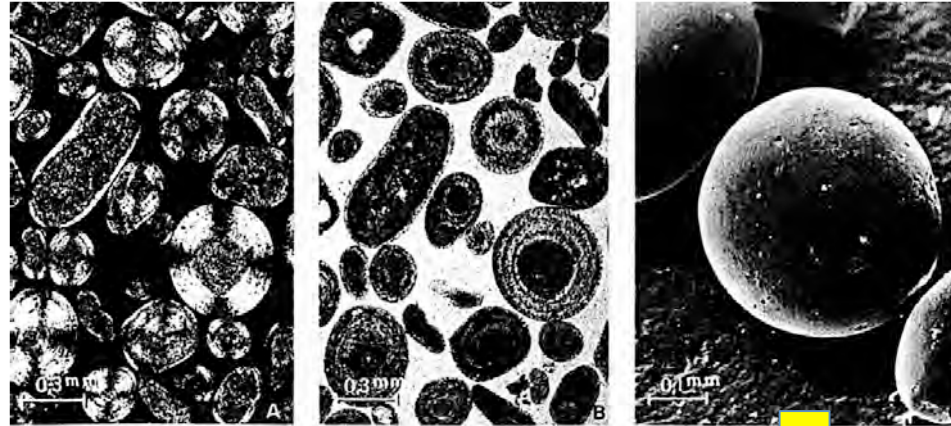


microporosity (white areas) along dissolved
laminae of the cortex

polished section, long interconnection (fitted fabric)
between two ooids (N and n = nucleus, Y = porous
cortex, dashed line = boundary between the ooids)

Kellehet & Smosna 1993

BAHAMAS Loreau 1982



Agitated environments

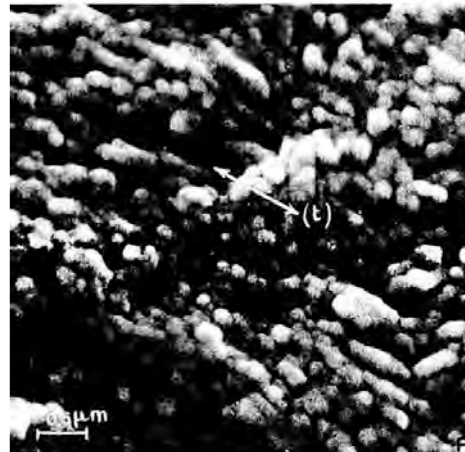
subhedral needles
 0.2×1 to $2.5 \mu\text{m}$



elongated and
subrounded
(tangential)
rods
 $0.13-0.3$
 \times
 0.5×1 to $1.7 \mu\text{m}$



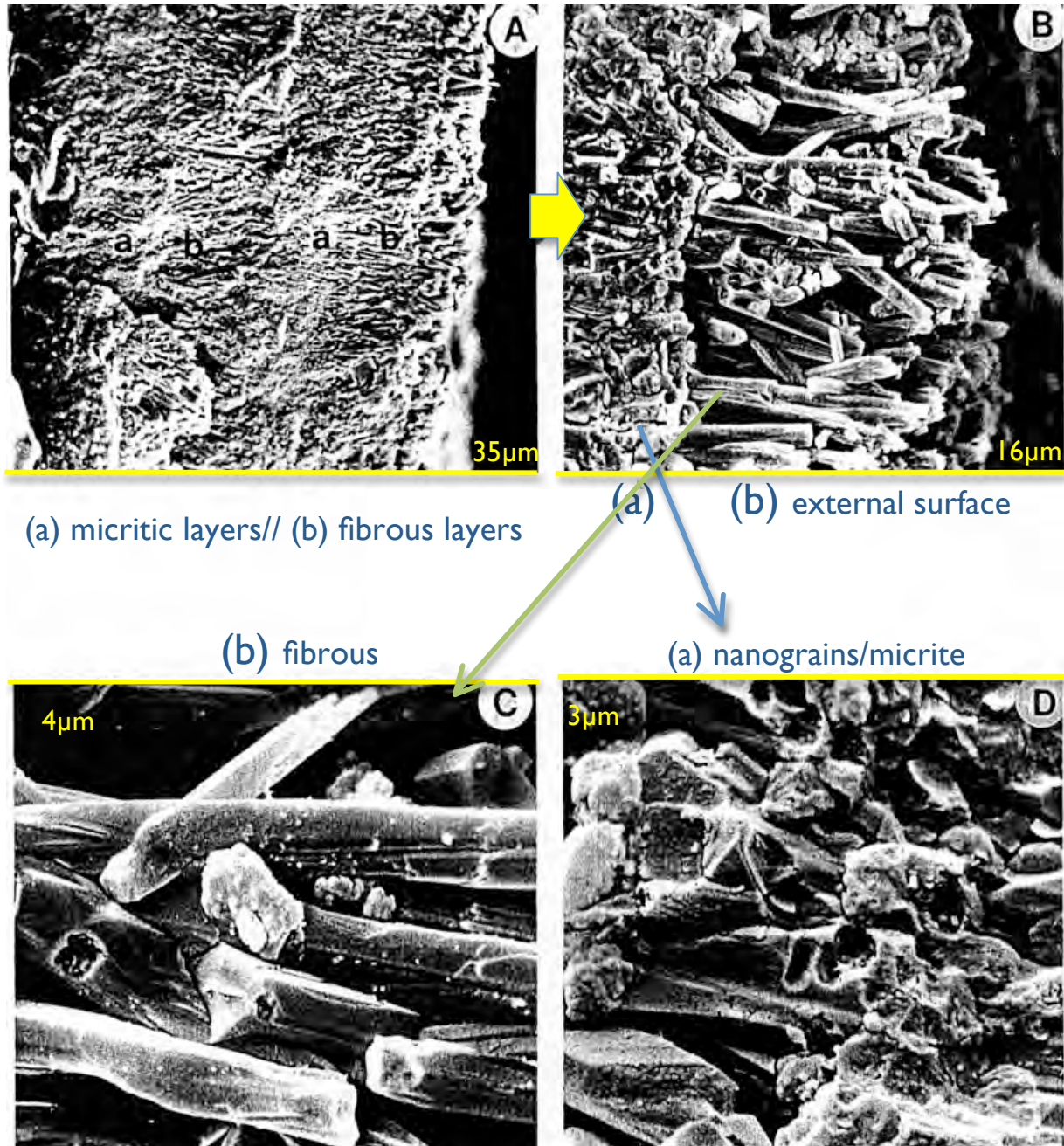
TANGENTIAL
STRUCTURE



radial nanocrystals
 $< 1 \mu\text{m}$

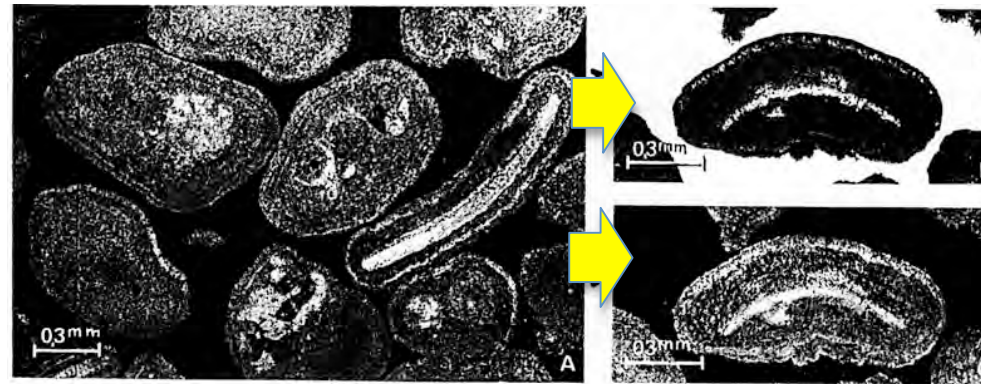


Quiet environments : nanostructure of the cortex



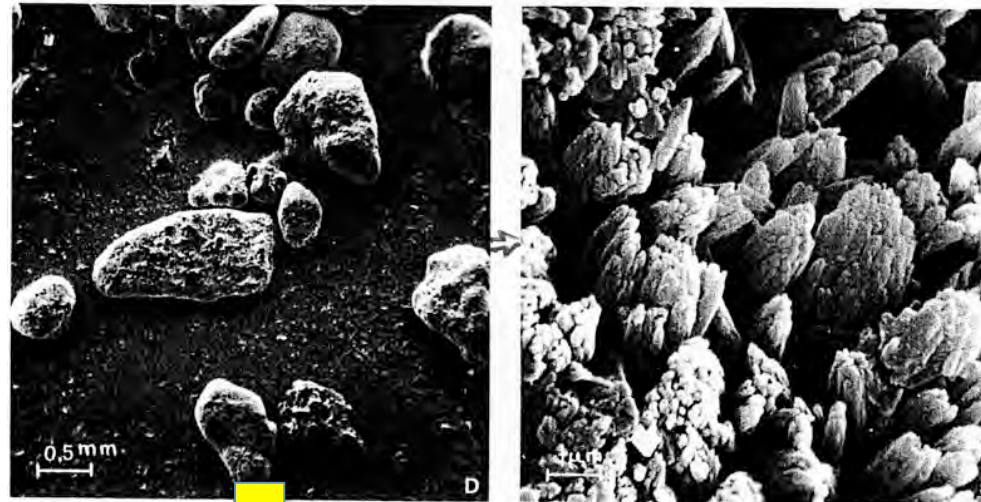
PERSIAN GULF Loreau 1982

'protected' ooids
in intertidal-
supratidal lagoon ...



...with' microstalactitic '
cement'

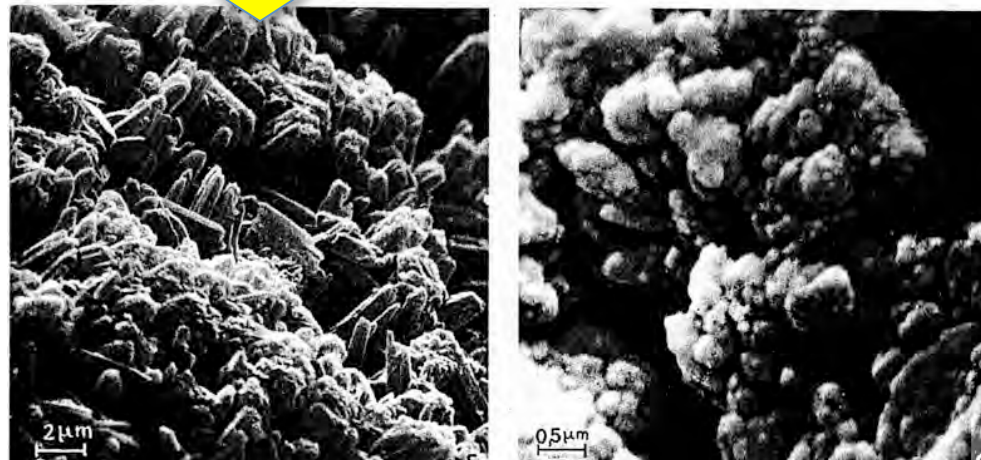
irregular lagoonal
ooids



tiny crystals
0.2-0.4
x
2-4µm
forming
2-5µm-thick bundles

with

thicker 'radial' crystals
2-4µm

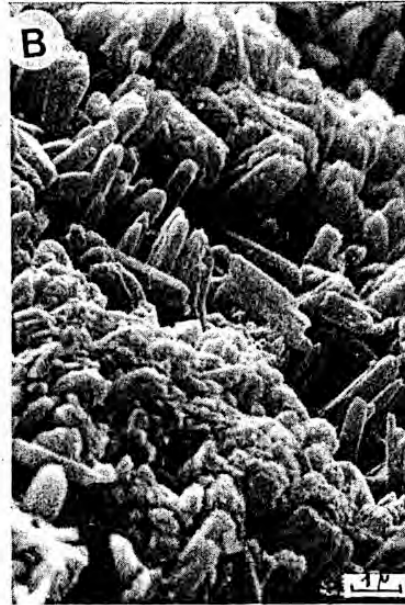


oid with stacked
nanograins
0.1-0.6µm

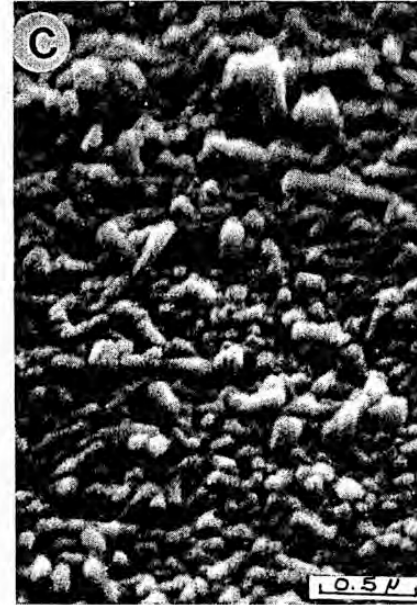
NANOSTRUCTURES OF CORTEX (MARINE OOLIDS)



loose arrangement, subhedral rods



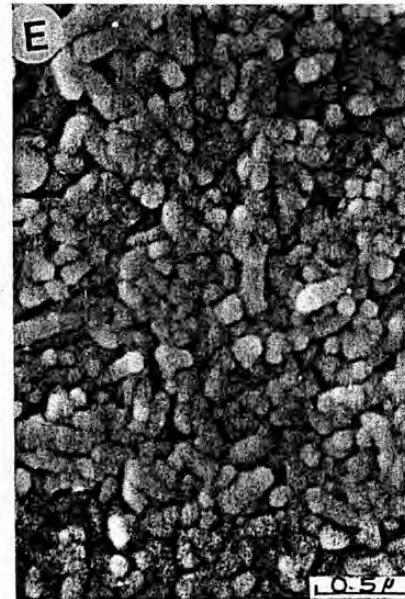
radial, euhedral



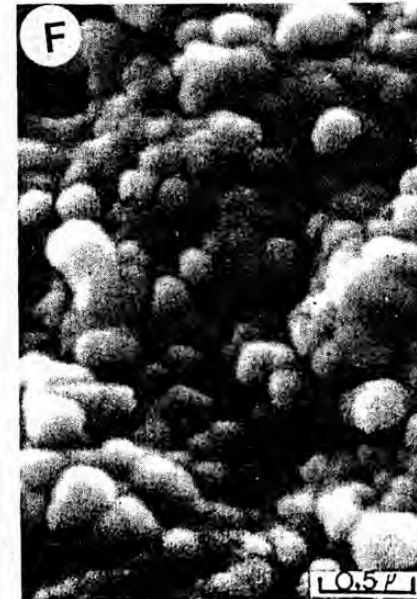
compact



euhedral, tangential



nanograins, compact

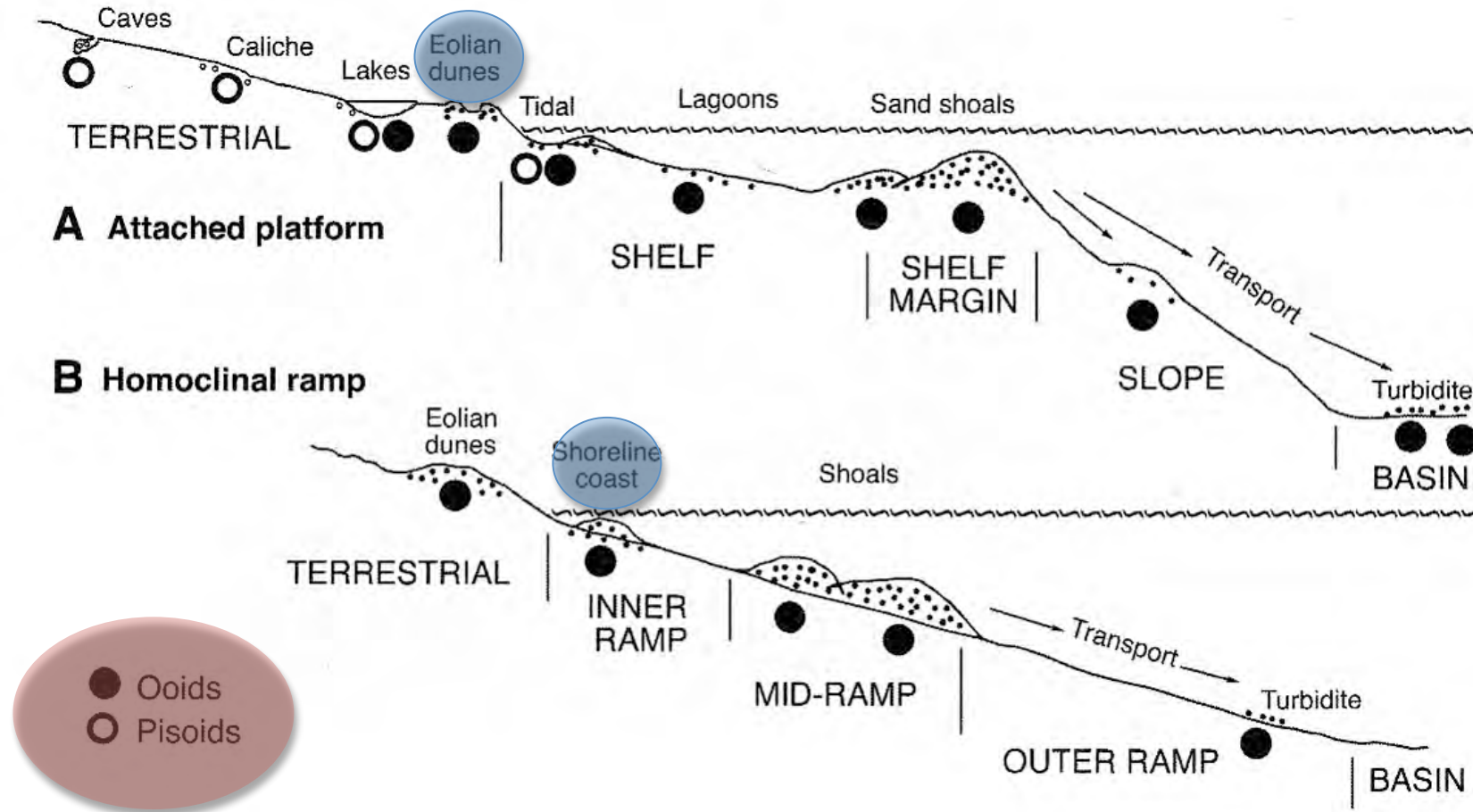


nanograins, anhedral

Purser 1980

PETROGRAPHY OF CARBONATES

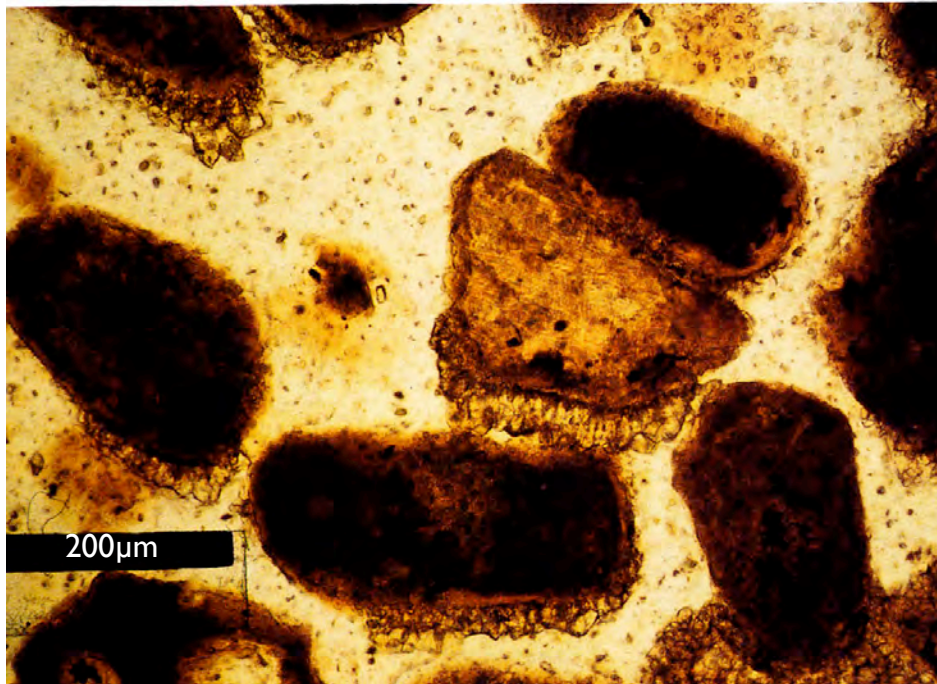
3. GRAINS = 3.2 Ooids



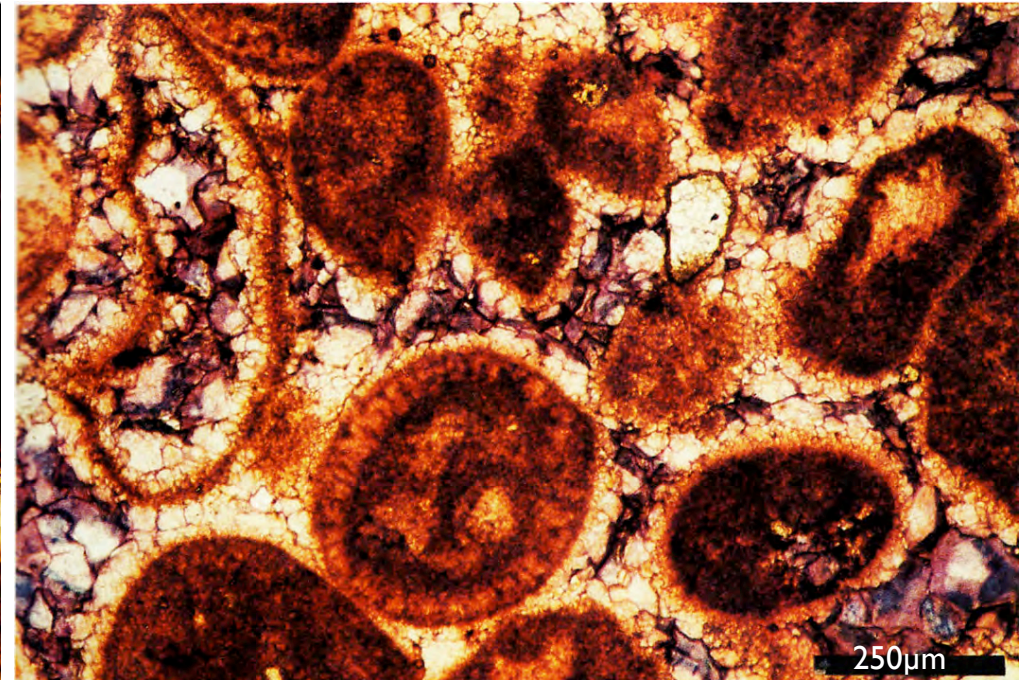
Sites of ooid and pisoid formation : autochthonous = eolian dunes, marine shoals, banks, sheet-like bodies, allochthonous accumulations = turbidites, debris flows on slopes and in basins (from Flügel 2004).

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.2 OOIDS

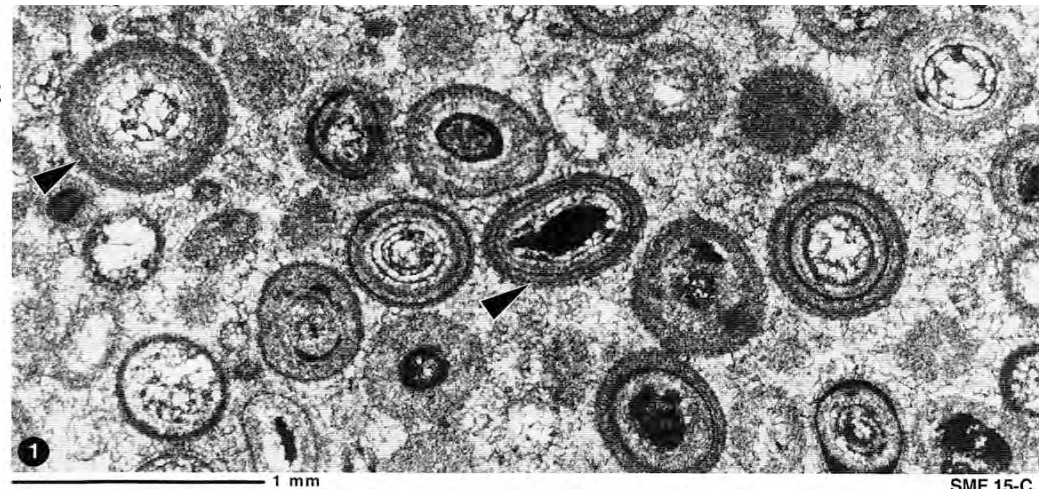


Pendulous cement, Holocene **eolianite**,
Isla Blanca, Yucatan Peninsula
McKee & Ward 1983

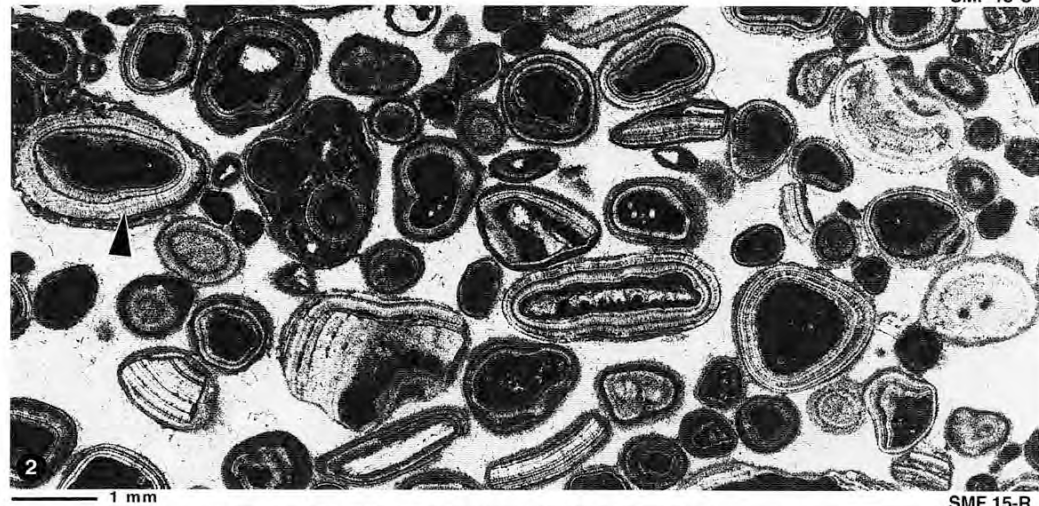


Well sorted oolite-intraclast lime grainstone,
Fe-free bladed and equant spar, later Fe-rich equant
spar (purple), **barrier beach**, Mississippian, Kentucky
Inden & Moore 1983

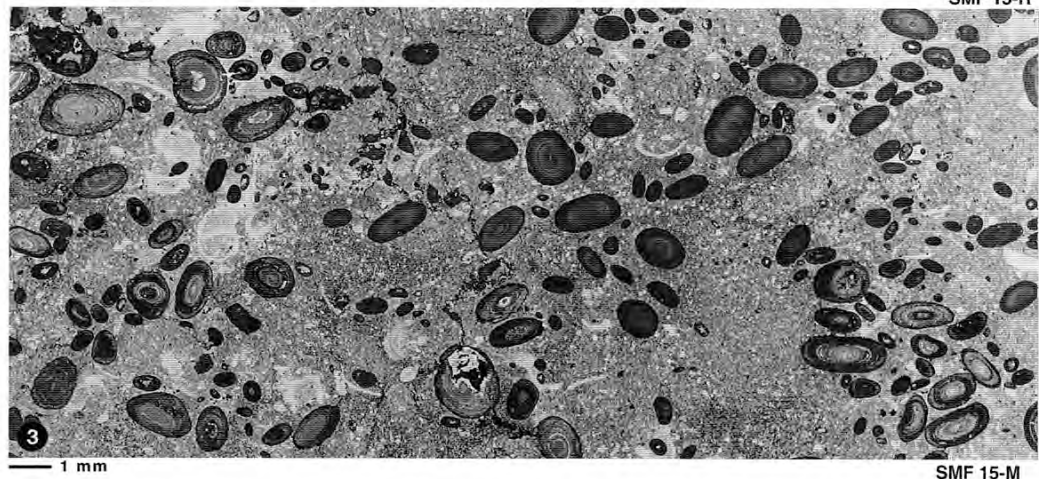
Ooid grainstone (**drusy cement**) with concentric ooids, multiple-coated, well sorted. Some are micritized and dissolved. *Late Triassic, N Alps, Austria* [arrows = tangential structures]



Ooid grainstone with radial ooids [arrows], multiple-coated, poorly sorted, irregularly shaped, reworked and broken. Also composite ooids, *Early Cretaceous, Apennines*.



Quartz-bearing ooid wackestone with micritic ooids. Poorly sorting and Fe-coatings (black). Ooids are allochthonous redeposited in a deep outer ramp, *Oxfordian, Spain (Zaragoza)*.



PETROGRAPHY OF CARBONATES

3. GRAINS = 3.2 OIDS

SHAPE and SIZE : Ooids occur as single or compound (**complex**) ooids
= 'poly-oid' i.e. two or more ooids bound together.

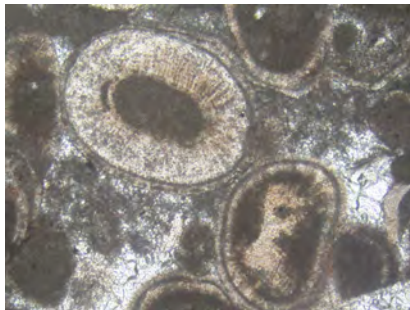
'Multiple ooids' result from the intergrowth of several ooids

....

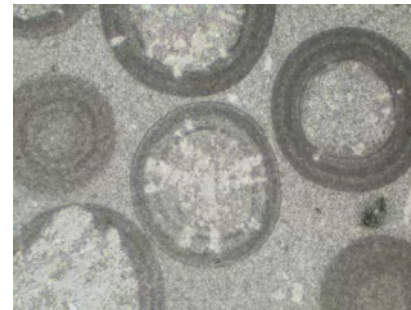
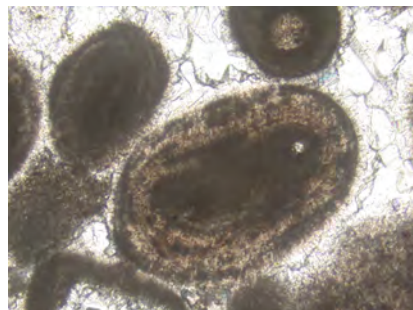
Most ooids are spherical, the shape often results from the shape of the nuclei,
Size and sorting = clues to the hydrodynamic condition

THE CORTEX OF MODERN OIDS CONSISTS OF ARAGONITE, HMC or LMC
Aragonite and HMC can co-occur in alternating laminae (Precambrian and much of the Paleozoic)

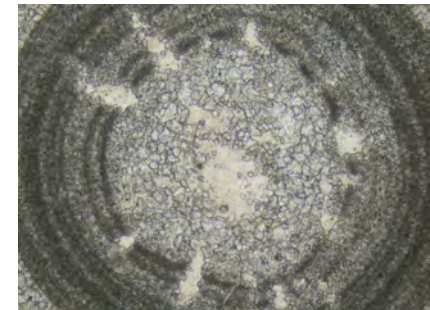
Most MODERN ARAGONITIC OIDS FORMED IN THE MARINE ENVIRONMENT
exhibit a concentric-tangential microfabric, rarely preserved in ANCIENT ONES



Neoproterozoic, Congo-Brazzaville, Pr  at 2012



Neoproterozoic, Gabon, Pr  at 2008



PETROGRAPHY OF CARBONATES

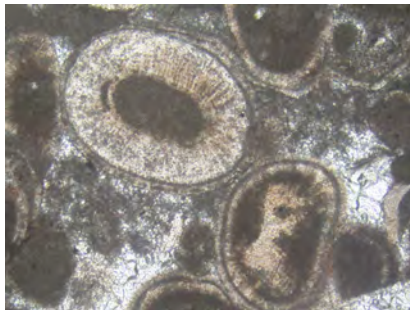
3. **GRAINS = 3.2 OIDS**

MARINE LOW-ENERGY OIDS = RADIAL-FIBROUS FABRIC
ALSO KNOWN FROM HYPERSALINE ENVIRONMENTS

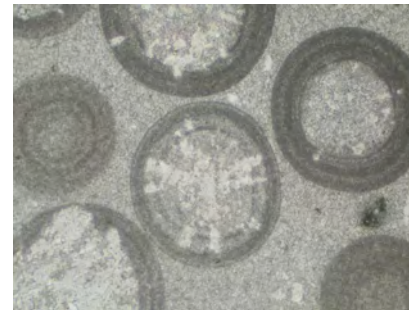
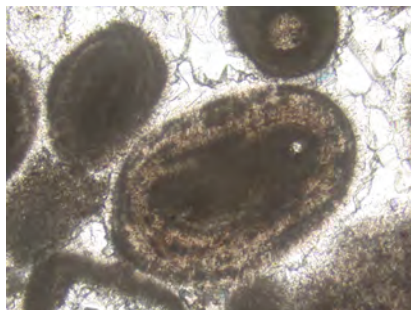
LMC OIDS FORMED IN FRESHWATER ENVIRONMENTS

Original mineralogy of ancient ooids is inferred from preserved fabrics (diagenesis)

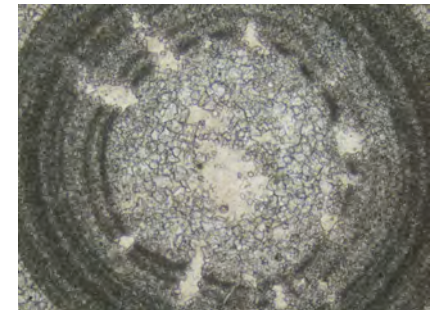
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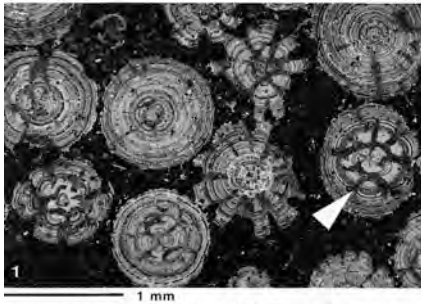
Neoproterozoic, Congo-Brazzaville, , Pr  at 2012



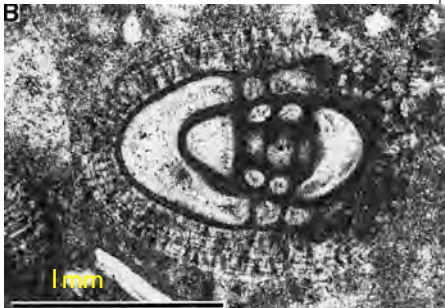
Neoproterozoic, Gabon, , Pr  at 2008



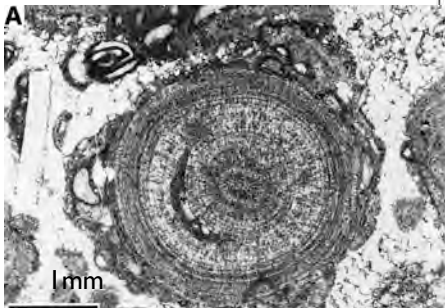
Common specific ooids (Flügel 2004)



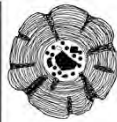
Tangential, primarily HMC
'cerebroid', Early Triassic (playa
lake), Kalkowsky 1908



Nucleus = Endothyrid benthic
foram, Early Carboniferous, Austria



Encrusting forams (mobile sands)
Late Triassic, Austria



Cerebroid ooids (Graf and Lamar 1960; Carozzi 1962)

Criteria: Indented periphery. Mottled appearance of the cortex. Sectors made of tangentially arranged laminae and radial micritic sectors which often start at former depressions of the nucleus surface.
Occurrence: Marine and non-marine. Often associated with stromatolites.
Interpretation: The indented periphery of the ooids has been explained as a result of a peripheral replacement. The formation of the micritic sectors is ascribed to bacterial dissolution and precipitation (Kahlke 1974).



Asymmetrical and eccentric ooids (Gasiewicz 1984)

Criteria: Small spherical and ovoid composite grains consisting of superficial ooids acting as eccentric nuclei for successively formed ooids whose growth takes place preferentially upward. Alternation of very thin oolitic laminae (white) and micrite envelopes (black). Ooid size commonly < 0.30 mm. Rare in wackestones and grainstones, common in packstones, associated with abundant peloids. Eccentric ooids should not be confused with oomolds with eccentric nuclei.

Occurrence: Low-energy shallow-marine lagoonal and lacustrine environments, periodically without agitation.

Interpretation: The ooid laminae are explained as resulting from short periods of water agitation, the micritic envelopes correspond to longer non-turbulent periods. Eccentric growth is controlled by changes from suspension to saltation and traction processes at the sea floor. Top: A superficial ooid formed in suspension and deposited on the sea floor is the base of a micrite envelope and forms the eccentric nucleus of a subsequent new superficial ooid. Bottom: Ongoing ooid formation subsequent to rolling and turning.



Broken and regenerated ooids (Carozzi 1961a)

Criteria: Fragments of radial or tangential ooids that act as nuclei for new ooids are surrounded by ooid laminae. The ooids are characterized by alternating concentric ooid laminae and micritic laminae (white).
Occurrence: Common in high- and low-energy settings, occurring together with partly cracked ooids and regular ooids.

Interpretation: These ooids indicate multiple syndimentary reworking and breaks in the formation of ooids, commonly associated with redeposition. Also known from ferruginous ooids ('hiatus ooids', Berg 1944).



Distorted ooids (Carozzi 1961b; Conley 1977)

Criteria: Characterized by notched and stretched, sometimes flattened ooid grains, or grains connected by narrow apophyses, or series of grains linked in zigzag chains parallel to bedding. The distortion has commonly preceded cementation and strong compaction. These ooids co-occur with other distorted grains (e.g. micritized intraclasts) in irregular pockets or in zones parallel to the bedding.

Occurrence: Restricted to specific limestone horizons, affected by strong waves or currents. Common also in non-carbonate oolitic deposits.

Interpretation: The shapes of distorted ooids illustrate a complete gradation from initial rupture and plastic deformation of soft grains to the rupture of rigid bodies. Explanations include fracture and plastic alteration of soft ooids in a turbulent environment, sediment sliding, or compaction. Deformation occurs when uncemented or poorly cemented ooids are buried (Pl. 13/8, Pl. 36/5). The term also is used for pitted ooids and cracked ooids which result from mechanical distortion and pressure solution. These ooids exhibit displaced and sometimes broken laminae (Pl.150/2).



Half moon and shrunken ooids (Wherry 1916; Mazzullo 1977)

Criteria: Ooids in which the interior cores have dropped to the bottom of the concentric outer layers, forming a geopetal fabric. Cross sections commonly exhibit a 'half-moon' aspect characterized by an internal dividing line convex upward which separates an upper light part (frequently calcite-filled) and a lower dark part.

Occurrence: Rare in carbonate-evaporite series, but also known from meteorically influenced carbonates.
Interpretation: These ooids may be products of evaporite-carbonate or aragonite solution diagenetic processes (Carozzi 1963) and may indicate vanished evaporites in associated rocks (Folk and Pittman 1971; Folk and Siedlecka 1974). Geopetal ooids, however, can also result from the selective aggrading recrystallization of the ooid nuclei during a period of meteoric diagenesis (Mazzullo 1977).

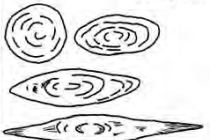


Spiny ooids (Davaud et al. 1990)

Criteria: Characterized by external cortices exhibiting spines. The external cortices are detached from the underlying cortices near the points of contact between ooid grains, suggesting a postdepositional origin for the spines. The external cortices (white) are not stretched or broken and fit perfectly into the underlying cortices (densely arranged laminae) in undeformed areas.

Occurrence: Lagoonal beach sands cemented in a vadose environment.

Interpretation: The ooids are explained by tangential compressive deformation due to crystal growth in the outer cortices during early subaerial deformation. Spiny ooids differ from distorted ooids formed during burial compaction; these ooids display convex forms pointing into the pore space.



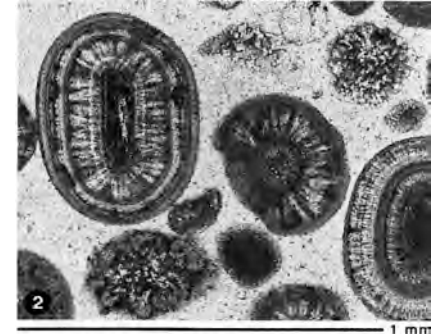
Deformed ooids (Cloos 1947; Nissen 1964; Badoux 1970)

Criteria: Originally spheroidal ooids are distinctly elongated, flattened and stretched. Microfabric structures recognizable in traces only or completely destroyed.

Occurrence: Described from folded carbonate series. Indicate tectonic style and timing of plastic deformations.

Interpretation: Intensive tectonic stress results in elongations parallel to the schistosity planes.

Modern arag radial and radial-concentric, Great Salt Lake, Utah



PETROGRAPHY OF CARBONATES

3. GRAINS = 3.2 OIDS

Modern ooids

Three main microfabrics

TANGENTIAL

aragonite rods

without crystal terminations

$1\mu\text{mL}$ (max $3\mu\text{m}$) $\times 0.1-0.3\mu\text{m}$

RADIAL

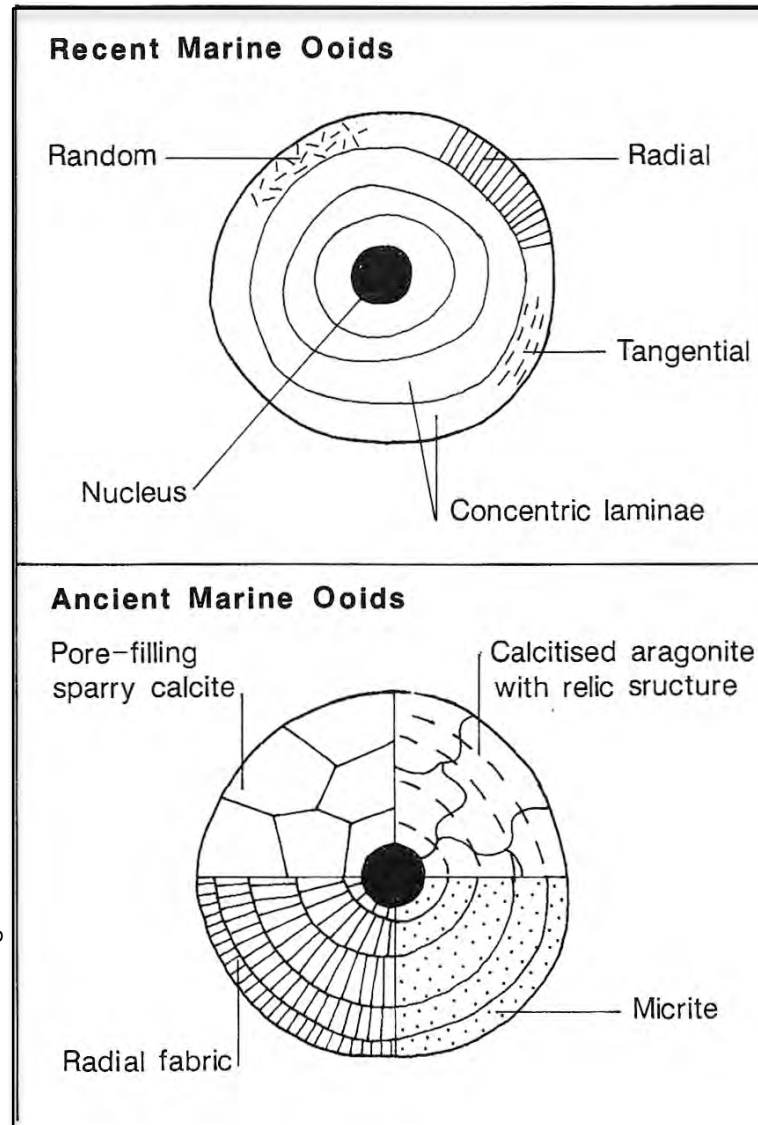
fibrous/bladed arag-LMC-HMC

needles $10-50\mu\text{mL} \times 2-5\mu\text{m}$

less common

RANDOM

arag rods or equant grains
(and microbial micritization)



Ancient ooids

more complex

DIAGENESIS

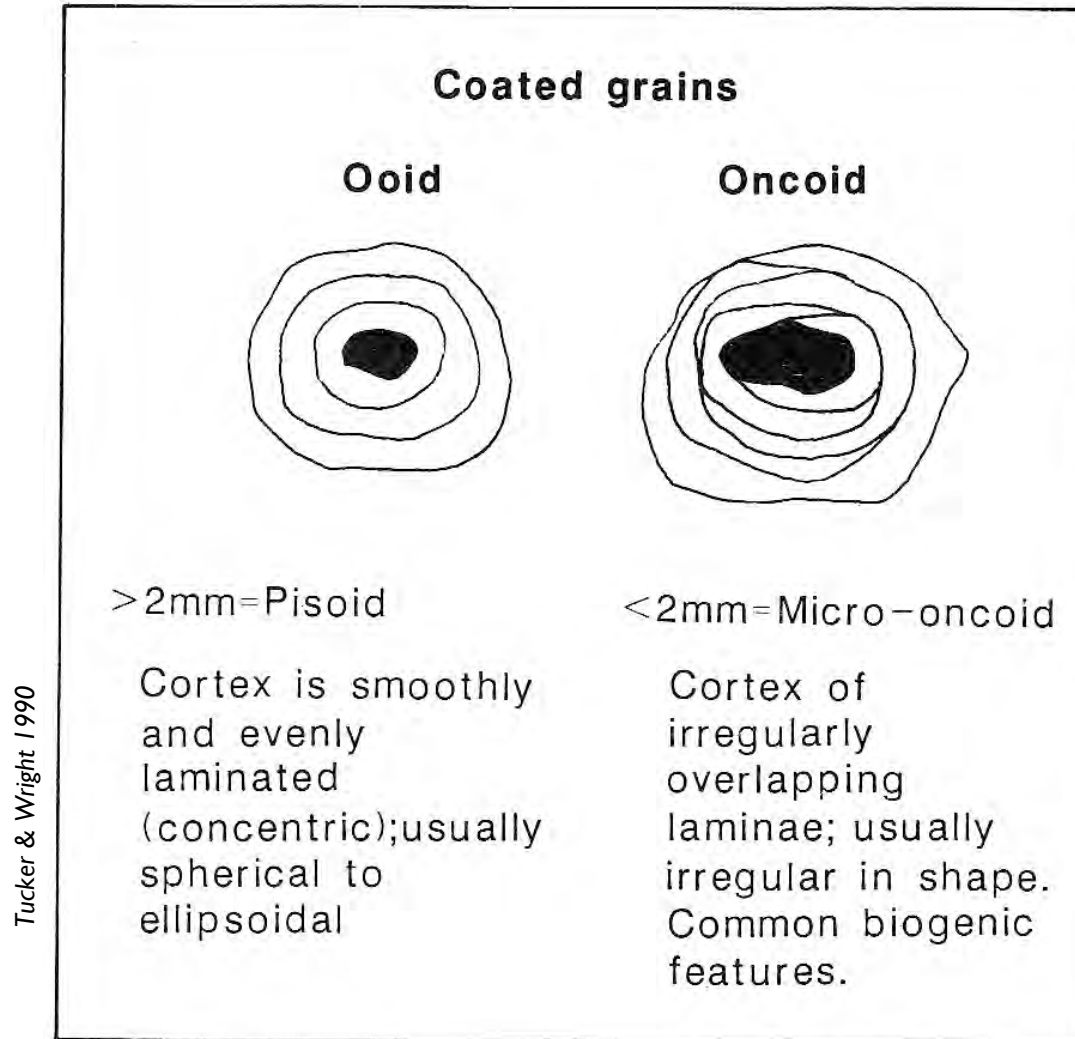
vs

PRIMARY

...

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.2 OOLIDS



PETROGRAPHY OF CARBONATES

3. GRAINS = 3.3 ONCOIDS

ONCOIDS ARE mm- to cm-sized **ROUNDED** or **IRREGULARLY** GRAINS WITH A **LAYERED MICRITIC CORTEX** AND A **BIO-** or **LITHOCLASTIC NUCLEUS**

✓ the term is not genetic => purely descriptive

✓ = pisoid or 'pisolith' in America!

=> also other ancient names: 'algal balls', 'algaly-coated grains', 'osagid grains' ...

✓ formed by microbes, algae and other encrusting organisms

=> common in platform, reef and slope environments

✓ TWO MAJOR CATEGORIES

=> ONCOIDS formed by calcibionts and algae

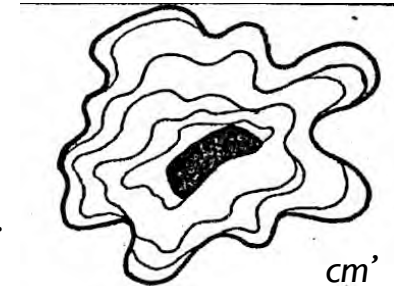
=> RHODOIDS formed by calcareous red algae (Late Mesozoic to Cenozoic)

✓ present-day oncoids => wide variety of environments (≠ ooids)

=> freshwater lakes, streams, marshes to marine inter- and subtidal conditions

=> the concentric laminae are formed by adhesion of fine grains of sediment to the mucilaginous surface of algal mats AND also by precipitation of CaCO_3 by algae as a result of the photosynthesis)

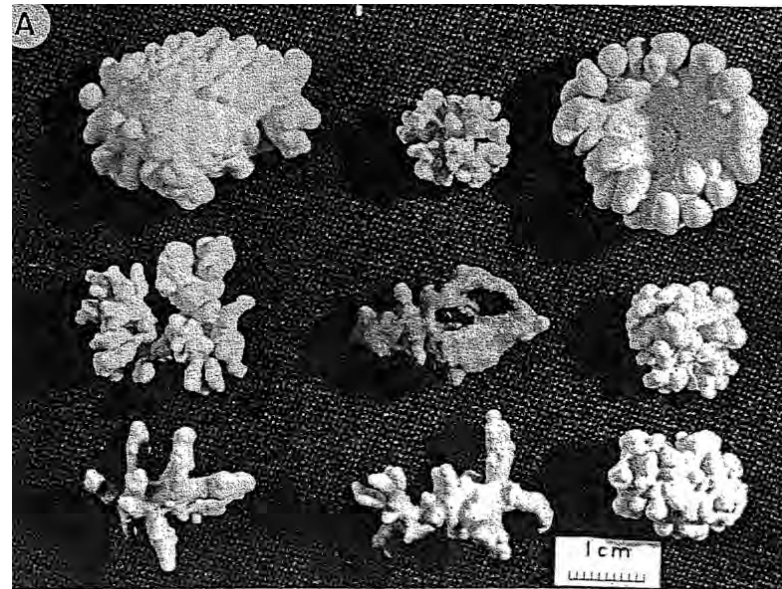
=> common sizes 1cm-10cm (up to 25cm). Ancient oncoids have about the same size.



PETROGRAPHY OF CARBONATES

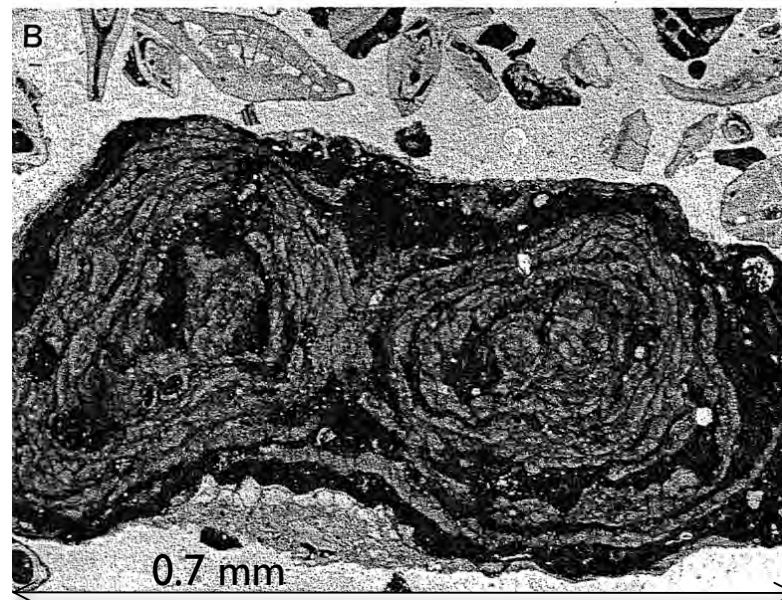
3. **GRAINS = 3.3 ONCOIDS**

Rhodoids
with different
morphologies



PERSIAN GULF

Section through
one of these rhodoids



Purser 1980

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.3 ONCOIDS

ONCOIDS ARE mm- to cm-sized **ROUNDED** or **IRREGULARLY** GRAINS WITH A **LAYERED MICRITIC CORTEX** AND A **BIO-** or **LITHOCLASTIC NUCLEUS**

✓ TERMINOLOGY : 'CONFUSED'

=> SPONGIOSTROMATE vs POROSTROMATE ONCOIDS

Spongiostromata (from Carboniferous of Belgium) = nodules with defined growth forms but without (or rarely) visible organic structures => microbial (cyanobacterial? origin + diagenesis)

Porostromata exhibiting preserved tubular microstructures

= => spongiostromate oncoïd and porostromate oncoïd : laminated dense micritic or spongy fabric without or with fine micritic –walled tubes < 100µm in size

=> ONCOIDS and STROMATOLITES, unattached vs attached, related to 'algal' mats = 'microbialites' ...

=> CYANOLITE or CYANOÏD: cortex with calcified filamentous and coccoid cyanobacteria

=> RHODOLITE or RHODOÏD : cortex predominantly with coralline algae

=> NON-ALGAL ONCOIDS and MACROOIDS : cortex with bryozoans, serpulids, forams (sessile) ...

=> COMPOSITE ONCOIDS : cortex = association of different (micro)-organisms

=> MICRITIC ONCOIDS : no distinct lamination but comparable in shape to other oncoïd types

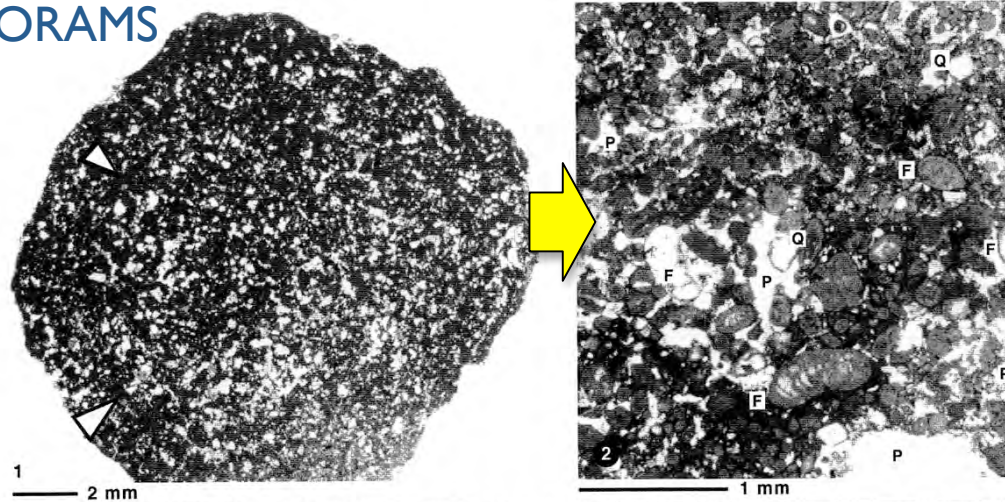
=> ...

✓ SIZE CATEGORY : MICROÏD (<2mm), PISO-ONCOÏD (2-10mm), MACROOIDS (>10mm)

✓ NON-CARBONATE ONCOIDS : phosphatic oncoïds (Mesozoic pelagic swell), Fe-Mn oncoïds (Jurassic of Italy, Spain ...) associated with hardgrounds, also pyrite oncoïds (pelagic)

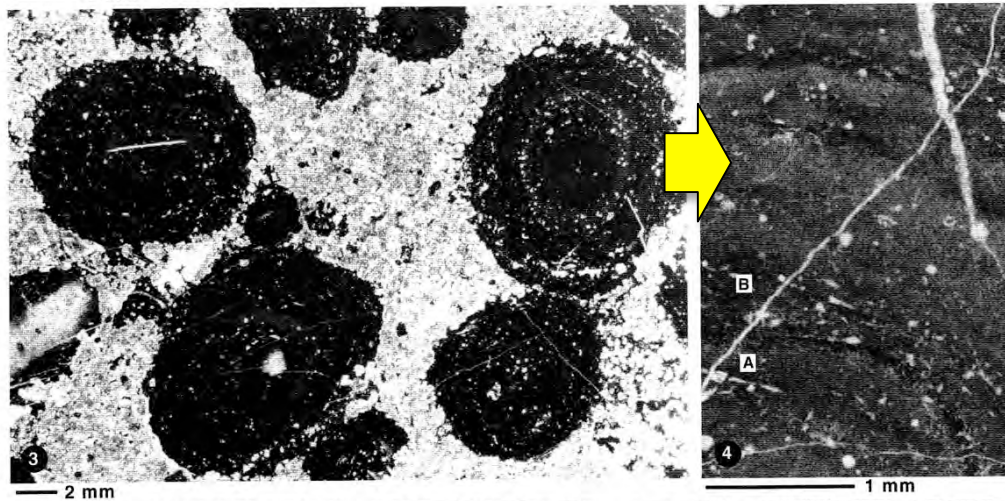
ONCOID –MICROBES/FORAMS

Micritic oncoïd with a poorly developed laminar fabric (arrows)
from a quartz bearing sand
Red Sea, Sinai, Egypt



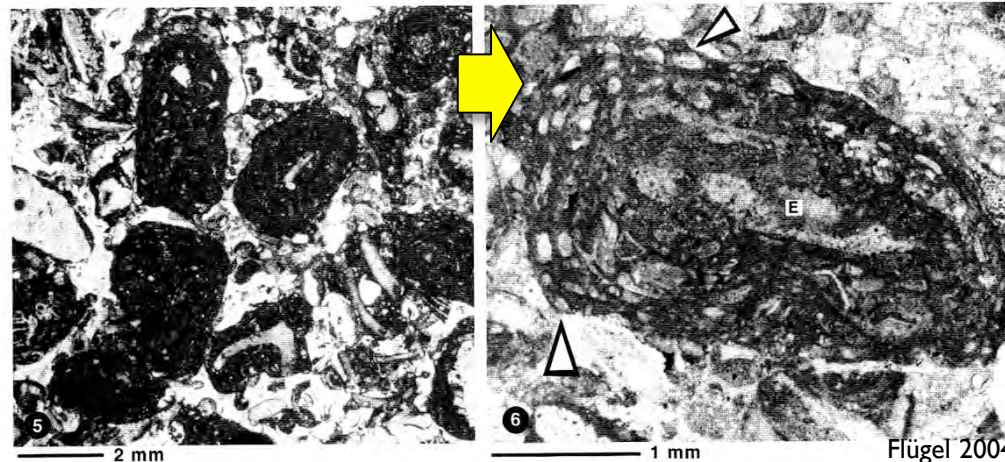
Sediment-trapping
on the slimy surface
of microbial film
Q = Qz
F = foram
P = open interparticle
porosity

Spheroidal spongiost/porostr oncoïds
Intergranular pores are occluded
sparitized LMC rhombs after
dedolomitization processes
Jurassic, Slovenia



B = horizontally
growing *Girvanella*-like
tubes

Foraminiferal oncoïds in a
bioclastic grainstone,
*High energetic shoals,
Bajocian, Bourgogne, France*



Nubecularia oncoïd
E = echinoderm
fragment (nucleus)
Arrows: chambers of
foram

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.3 ONCOIDS

Oncoid around a gastropod-shell
Concentric annual couplets (porous/dense)
Ore Lake, Michigan



Oncoid around a gastropod-shell
Flagstaff Limestone, Paleocene-Eocene



Oncoid, Flagstaff Limestone, Green River Formation, Paleocene-Eocene
Weiss 1969

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.3 ONCOIDS

ONCOIDS ARE mm- to cm-sized **ROUNDED** or **IRREGULARLY** GRAINS WITH A **LAYERED MICRITIC CORTEX** AND A **BIO-** or **LITHOCLASTIC NUCLEUS**

✓ INTERPRETATION : key parameters

=> the shape, internal structures and biotic compositions = paleoenvironmental conditions (e.g. water energy, sedimentation rates, redox potential), salinity) and specific settings

Example : water-energy levels

- stationary growth => asymmetrical shapes and asymmetrical widths of laminations
- rolling => subspherical shapes, well-laminated cortices, concentric symmetrical growth patterns, abrasion of algal or cyanobacterial structures
- cessation of rolling => strongly encrusted laminae surfaces
- lack of rolling => branched and lobate oncoïd shapes
- common rolling to less frequent rolling: multistage oncoïds, laminar => lobate
-
- redeposition: smoothing and breaking
-



✓ FACIES : predominantly wackestones, packstones and floatstones in various settings

✓ RESERVOIR ROCKS : micritic oncoïd limestones are poor reservoirs (but they are exceptions...).

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.3 ONCOIDS

✓ **ANCIENT ONCOIDS**

Most consist of calcite, sometimes with minor admixtures of clays, quartz and organic matter.
They are MARINE or NON MARINE

- **Non marine oncoids**

- lakes (since Precambrian) including soda lakes (Tertiary) or hypersaline lakes

=> insights into regional climate and lake level fluctuations

=> common sizes: 1.5cm-20cm

(freshwater and saline oncoids can be separated by different types of bioclastic nuclei)

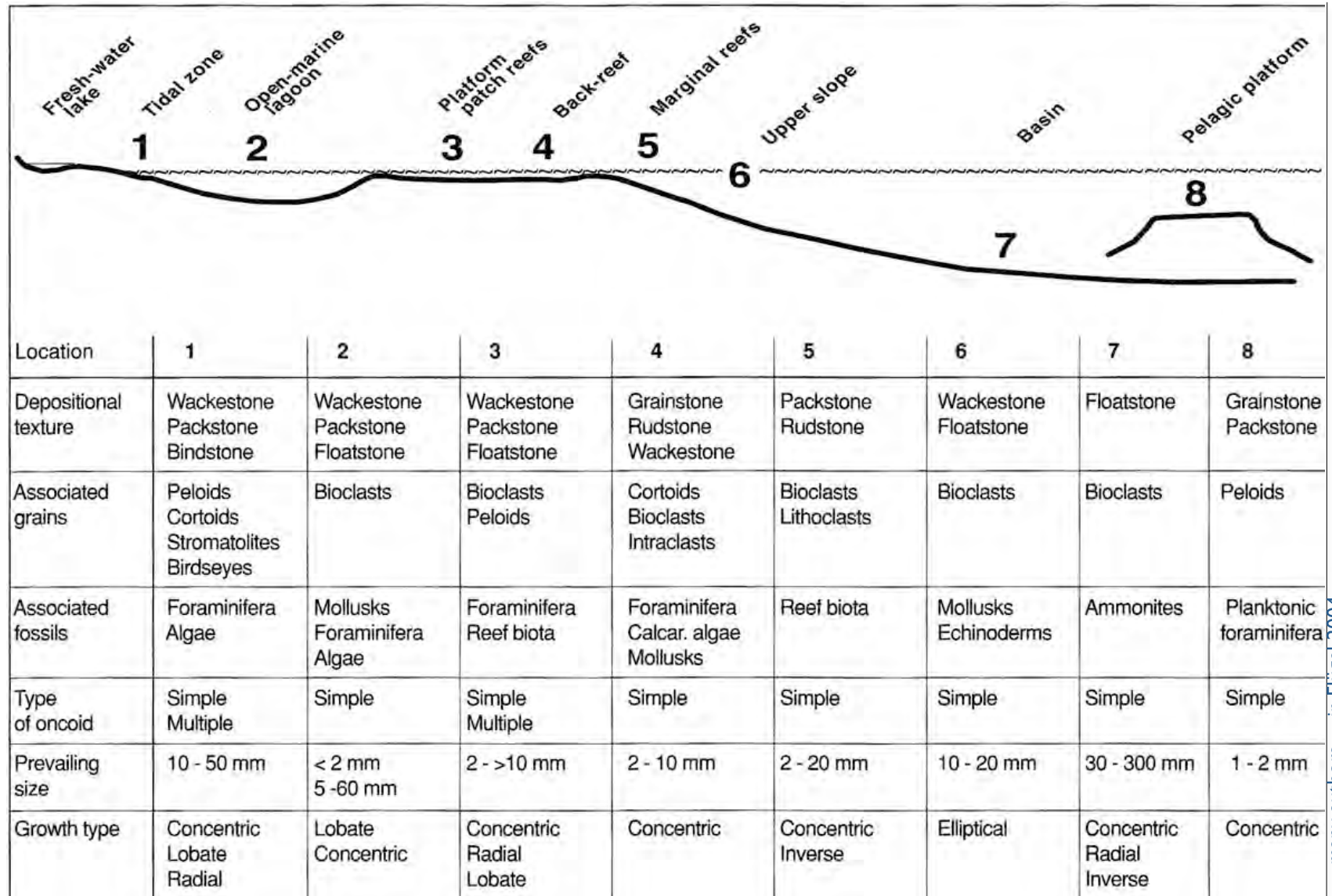
- near-shore environments
=> often with high energy mixed siliciclastic-carbonates
- fluvial channels
- ponds
- deltaic settings (boundary continent/sea)

- **Marine oncoids**

- tidal influenced marginal-marine
- open-marine shelf lagoons
- platform patch reefs
- back-reef areas
- platform margin reefs
- upper slope
- basin
- pelagic platforms

PETROGRAPHY OF CARBONATES

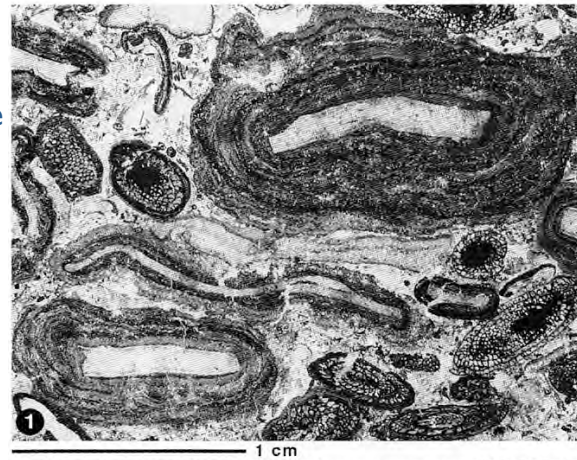
3. GRAINS = 3.3 ONCOIDS



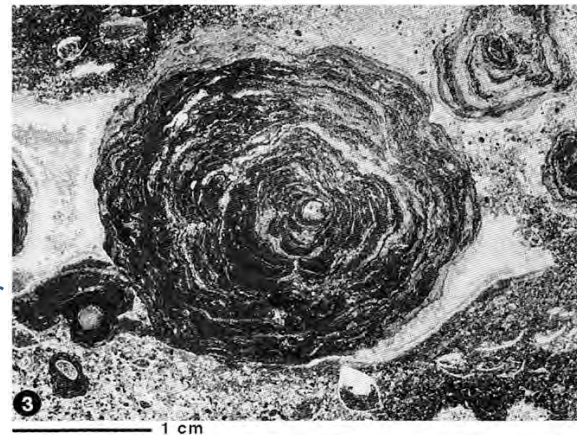
many authors... in Flügel 2004

Depositional environments and characteristics of Late Jurassic (Oxfordian-Kimmeridgian) oncoïds.

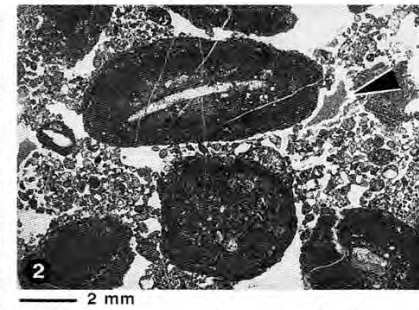
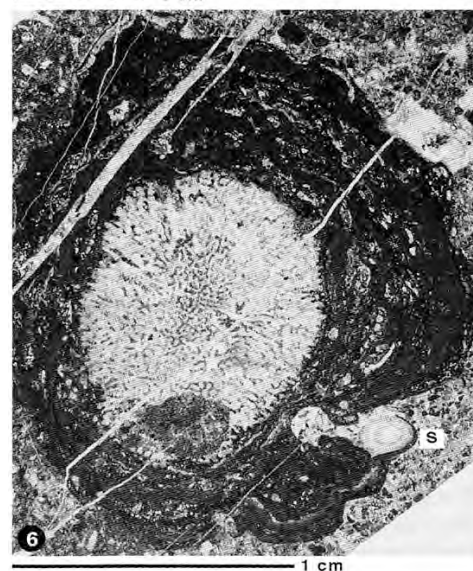
Cyanoids (calcified porostromate cyanobacteria). Irregular discoidal, breaks in growth layers. Cores are platy phylloid calcareous algae. *Early Permian, Carnic Alps, Austria and Italy*



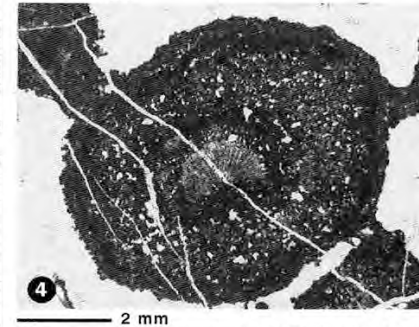
Porostromate oncoids (?green-algae or cyanobacteria). *Fore-reef slope, Late Devonian (Frasnian), Canning basin, Australia.* Commonly associated with lamellar stromatoporoids.



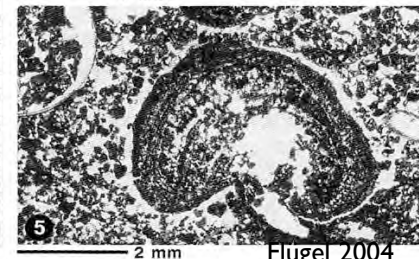
Rhodoid spheroidal, laminar corallinaceae (black)/encrusting foram (white chambers) and serpulid worms (S). Nucleus = poritid coral. *Shallow subtidal back-reef, Early Tertiary, Austria*



Micrite oncoids = micritization of microbial oncoids, aggregates, peloids. Nuclei = shells and forams. *Open marine platform, Early Jurassic, Greece*



Two-stage oncoids Microbial laminae (*Bacinnella*), nucleus = coral+sponge, *High energy subtidal env., Late Jurassic, Austria.*



Modern soft lacustrine oncoid : cyanobacteria and algae, asymmetrical growth... *in 0.5-1.5 m water, Lake Constance, S Germany*



Brackish-water oncoids : cyanobacteria and algae, elliptical. Discontinuous laminae and shrinkage structures. *Coastal pond, Late Jurassic, Portugal.*

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.4 PISOIDS-VADOIDS

GRAINS similar to ooids, but have a DIAMETER > 2mm
CARBONATE or NON-CARBONATE

✓ DIFFERENT NAMES FOR THE 'PISOIDS' from *pisum* = Latin for pea

- diagenetic ooids
- cave pearls in speleothems
- caliche ooids
- vadose ooids or vadoids => influence of freshwater vadose or marine vadose environment
=> specific cements
- coniatoids : carbonate crusts of uniformly thick coatings of ARAG lamellae, supratidal zone, Persian Gulf
- macrooids
-

✓ CHARACTERISTICS

- generally larger than most marine ooids, dense or irregular laminations around a NON-skeletal nucleus
- generally no encrusting biota (≠ oncoids)
- **Shape cf. energy**
 - HE : increasing roundness in continuously agitated water
=> cave pearls, geyser waters
 - LE : irregular layers and strong deviations from the spherical shape in quiet-
=> asymmetrical, downwarp or upward thickening, lateral elongation = 'in-situ' growth
 - HE/LE => broken and recoated pisoids (alternating periods of fracturing/reworking/growth)
- **Nucleus**
 - fragment of pisoids, cement crusts, lithoclasts, mineral grains
 - sometimes more than one nucleus
- **Cortex**
 - concentric of very densely spaced dark [=? microbial] and light [=microspar] laminae

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.4 PISOIDS-VADOIDS

GRAINS similar to ooids, but have a DIAMETER > 2mm
CARBONATE or NON-CARBONATE

✓ MODERN PISOIDS : various climate zones

- hypersaline settings (Persian Gulf) = ARAG and/or HMC
- chemical precipitation from carbonate-saturated agitated water (cave pearls or 'thermic pisoids' [Mammoth Hot Springs, Yellowstone])
- chemical and biochemical precipitation in low-energy environment (vadose, fluvial, hypersaline ...)
- concretionary growth in arid and semi-arid pedogenic layers (caliche)
- ...

✓ ANCIENT PISOIDS

- FROM PRECAMBRIAN to PLEISTOCENE
- generally altered by diagenesis => sparitic laminae caused by meteoric-phreatic inversion of originally aragonitic laminae into granular calcitic laminae without a distinct dissolution phase
=> **'brick-like microfabric'**
=> **primary marine pisoids** are known from Paleozoic and a few Triassic and Jurassic occurrences
=> in contrast to the scarce Paleozoic marine pisoids, those **in Proterozoic are abundant** and associated with ooids, stromatolites, intraformational conglomerates =? different degree of carbonate supersaturation...

✓ NON-CARBONATE PISOIDS

- feruginous (Fe related to volcanism and weathering), phosphatic and siliceous
=> laterite and bauxite profiles ...

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.4 PISOIDS-VADOIDS

GRAINS similar to ooids, but have a DIAMETER > 2mm
CARBONATE or NON-CARBONATE

✓ IMPORTANT POINTS

- concerning **texture** : inverse grading is common in authochtonous pisoids formed *in situ*
- common association with fenestral carbonates, tepees, diagenetic grainstones, vadose crusts
- **sea-level fluctuations** : pisoids may indicate breaks in sedimentation caused by drops in sea level
=> association with karstification phases (supra- and intertidal members, shallowing-upward cycles)
- **paleoclimate** : cave and caliche pisoids reflect seasonal changes and longer term climatic changes
- ...

✓ ECONOMIC IMPORTANCE

- **Pisoid limestones are important reservoir rocks (Permian of West Texas, Mississippian of North Dakota. Porosity is enhanced by subaerial and vadose dissolution related to pisoid formation.**

PISOIDS

in Flügel 2004

Vadose-marine pisoids,
accretionary growth on a shelf
crest within shoaling upwards
sequence in a protected hypersaline
environment. White areas =
neomorphic carbonate.
Late Permian, New Mexico, USA

Broken and reworked pisoids
Cretaceous, Apennines, Italy

‘Coniatoids’ with large
non-skeletal nucleus
*Early Carboniferous, Cracow area,
Poland*

Siliceous pisoids
Bauxite paleokarst surface, with
shrinkage pores (arrows)
*Cretaceous, Subsurface Ras al
Khaimah, U.A.E.*

‘Coniatoids’

Irregular, non-spheroidal
grains with marine nuclei
(aggregate grains).
Supratidal.

*Early Carboniferous, Cracow area,
Poland*

Vadose pisoids

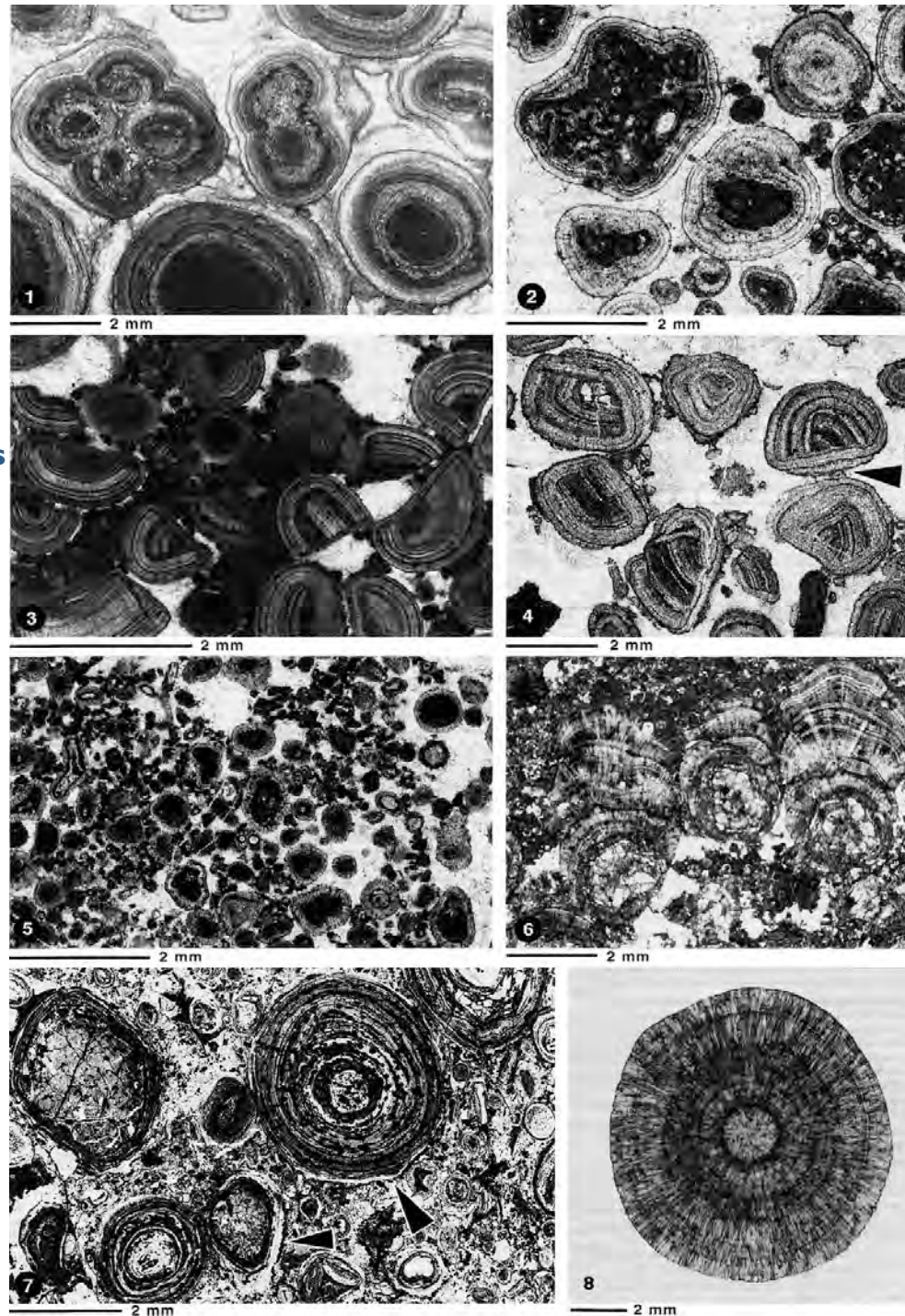
meniscus cement (arrow)
*Late Permian (Zechstein),
Subsurface, N Germany .*

Caliche pisoids

top of lacustrine
stromatolites.
Upward growth,
vadose and phreatic
Early Permian, Germany

Cave pearl

of a modern speleothem,
vadose and phreatic,
Subrecent, Austria

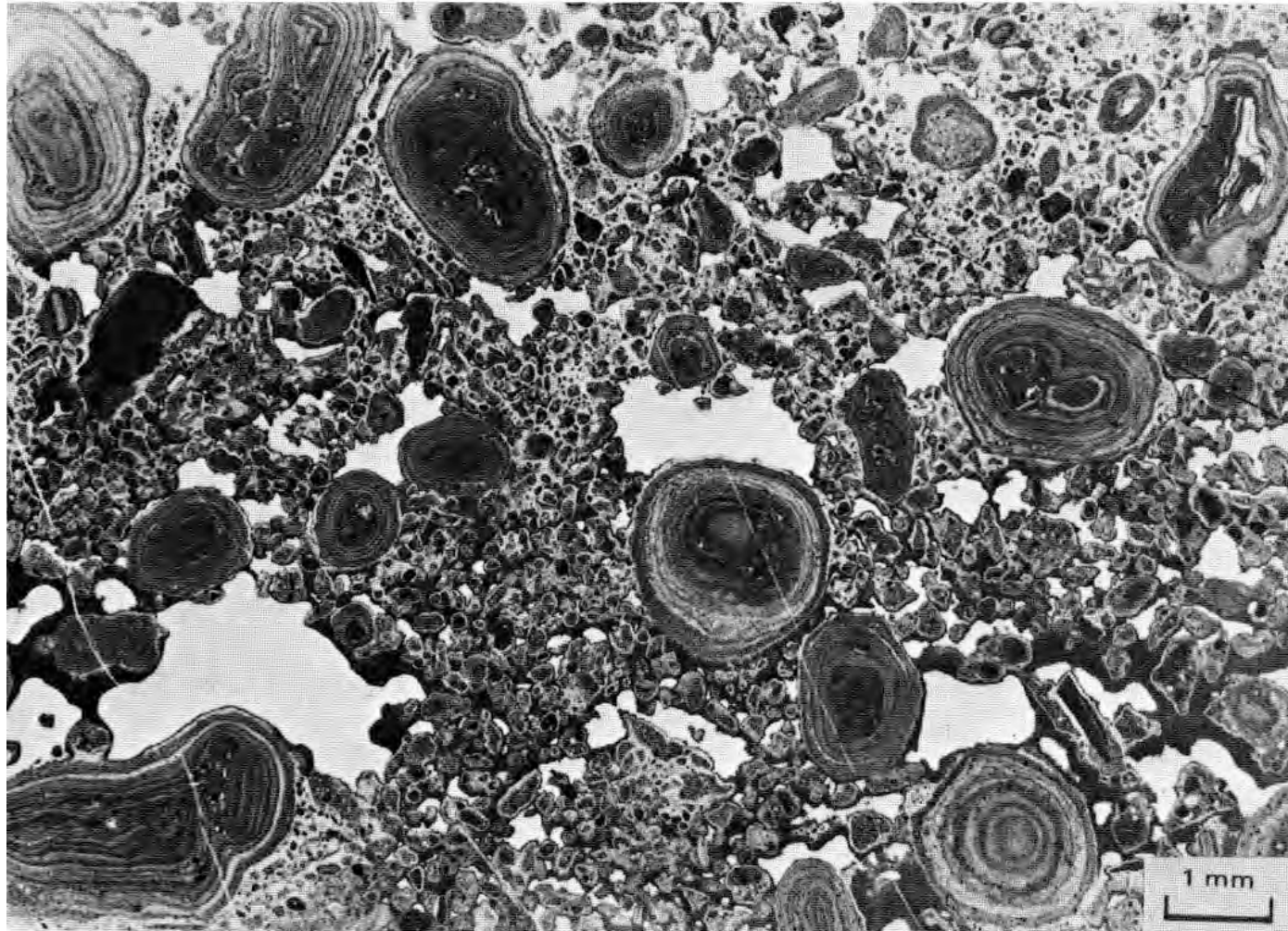


PETROGRAPHY OF CARBONATES

3. GRAINS = 3.4 PISOIDS-VADOIDS

GRAINS similar to ooids, but have a DIAMETER $> 2\text{mm}$

CARBONATE or NON-CARBONATE

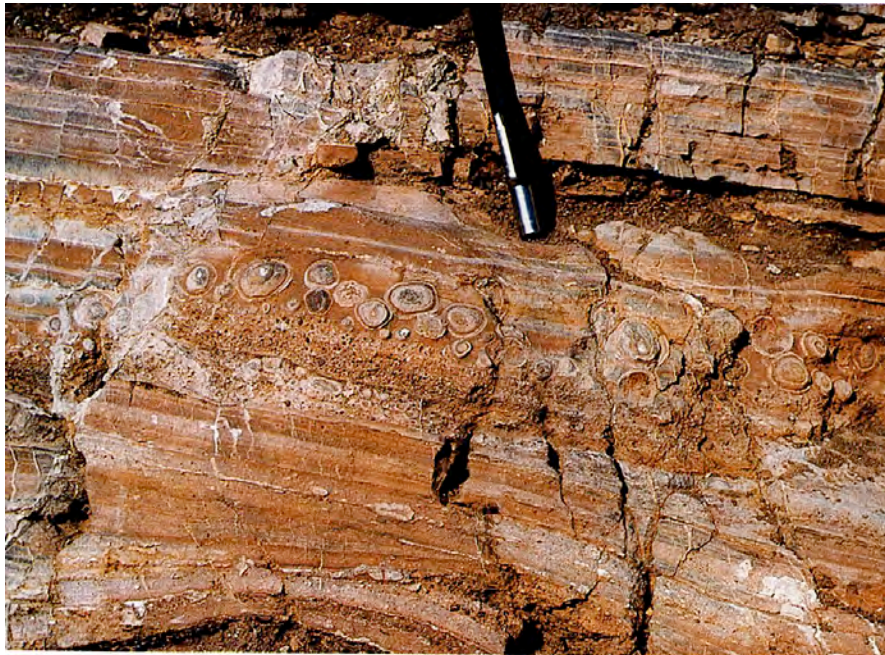


Asymmetrical (vadose) caliche (pisoid). Some pisolites are composite
Elf Aquitaine, 1975

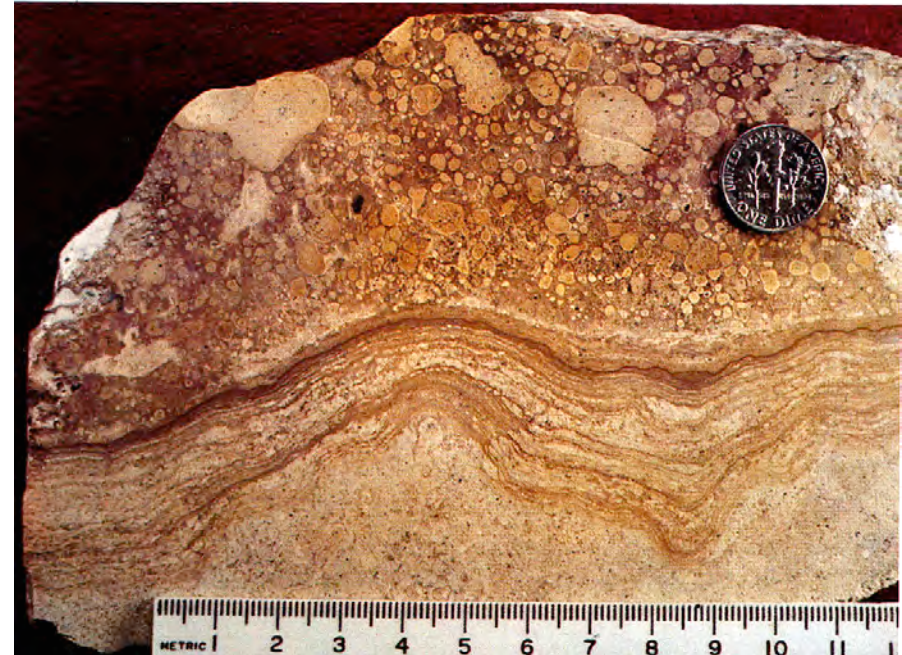
PETROGRAPHY OF CARBONATES

3. GRAINS = 3.4 PISOIDS-VADOIDS

GRAINS similar to ooids, but have a DIAMETER $> 2\text{mm}$
CARBONATE or NON-CARBONATE



Cave pearls and laminated cavern sediment with **reverse-grading** (coarsening upward grain size arrangements). Esteban & Klappa 1983.



Caliche layers, Pleistocene eolianite, Yucatan Peninsula. Micritized eolianite is overlain by conglomeratic layer with **crude reverse-grading**. McKee & Ward 1983.

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.5 AGGREGATES

=grapestones-lumps-composite grains

COMPOSITE GRAINS of ooids, skeletal material and peloids

✓ **AGGREGATE GRAINS** first studied in the Bahama => '**BAHAMITES**'

- common on shallow-marine carbonate platforms in lagoonal settings
- the grains are bound together by organic films and ARAG or HMC cements
- typical lobate shapes
- encrusted by forams, algae or serpulids (worms)

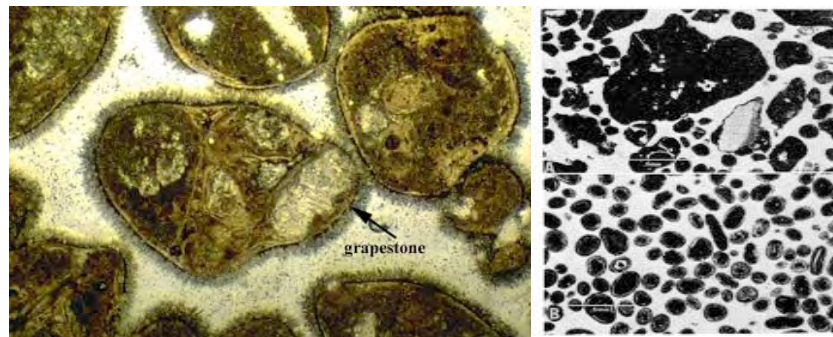
✓ **GENESIS**

- stabilization of the individual particles during reduced phase of deposition in environments with restricted circulation
 - => cementation on the sea bottom and periodical reworking
 - => biofilms, microbially induced early cementation between particles
 - = > absence of mud



✓ **CARBONATE CLASSIFICATION**

- included aggregate grains in the intraclast or lithoclast categories...



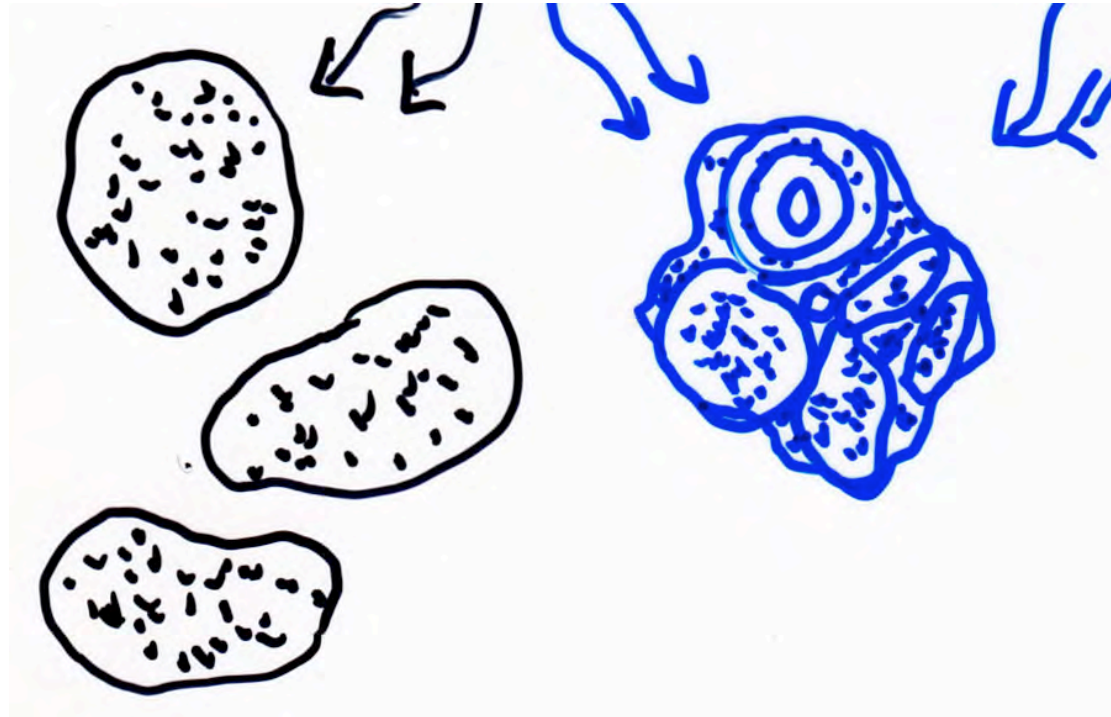
Bahama Banks, intermittent agitation

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.5 AGGREGATES

=grapestones-lumps-composite grains

COMPOSITE GRAINS of ooids, skeletal material and peloids



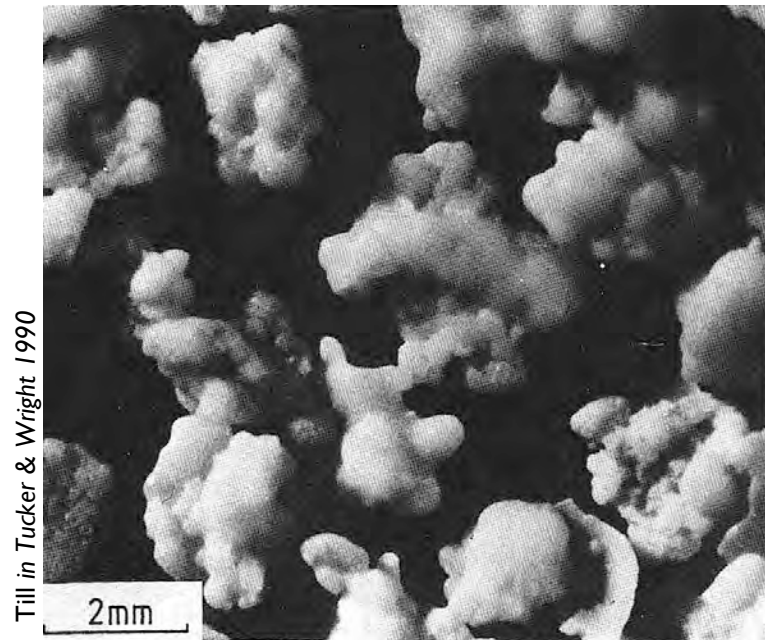
'BAHAMITE' Illing 1955

PETROGRAPHY OF CARBONATES

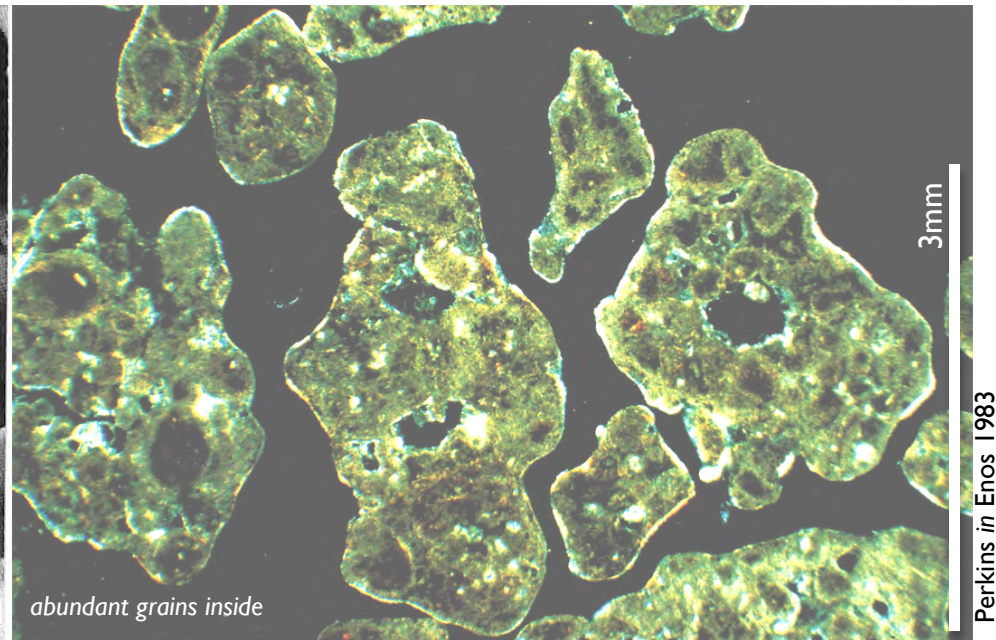
3. GRAINS = 3.5 AGGREGATES

=grapestones-lumps-composite grains

COMPOSITE GRAINS of ooids, skeletal material and peloids



Grapestones = aggregate grains of bioclasts and peloids cemented by micritic aragonite



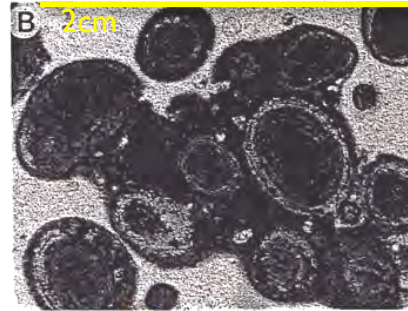
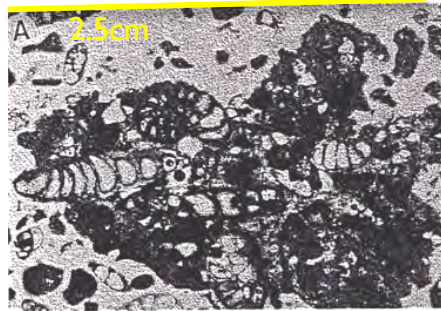
Grapestones from the Great Bahama Bank (cross polarized light)

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.5 AGGREGATES

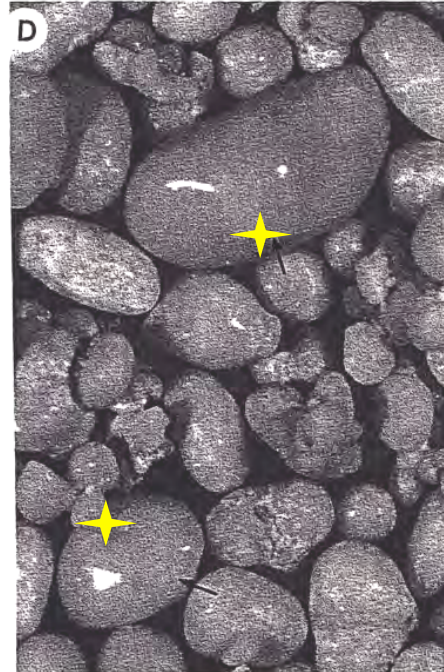
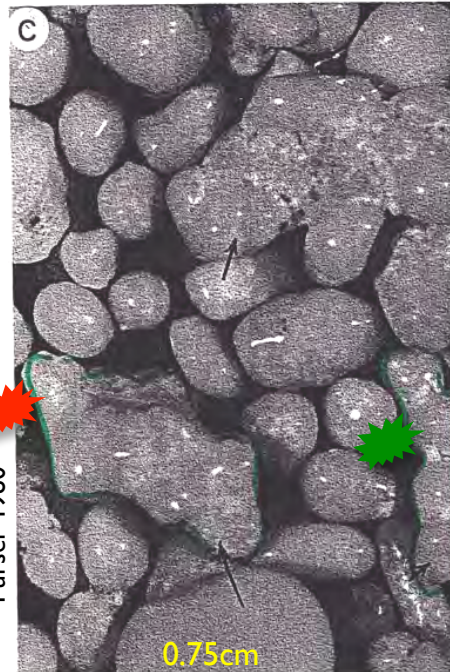
=grapestones-lumps-composite grains

COMPOSITE GRAINS of ooids, skeletal material and peloids



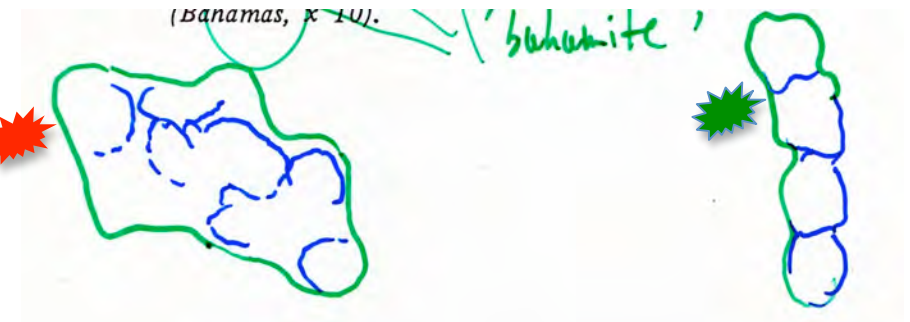
- A. aggregate of cemented forams, Abu Dhabi
- B. aggregate of oolites, Bahamas
- C. aggregate of oolites with typical **grapestones** Bahamas
- D. aggregate covered by an oolitic cortex
★ = 'botryoidal lump' (scale as C.)

LUMPS - GRAPESTONES = AGGREGATES



Purser 1980

'BAHAMITES'



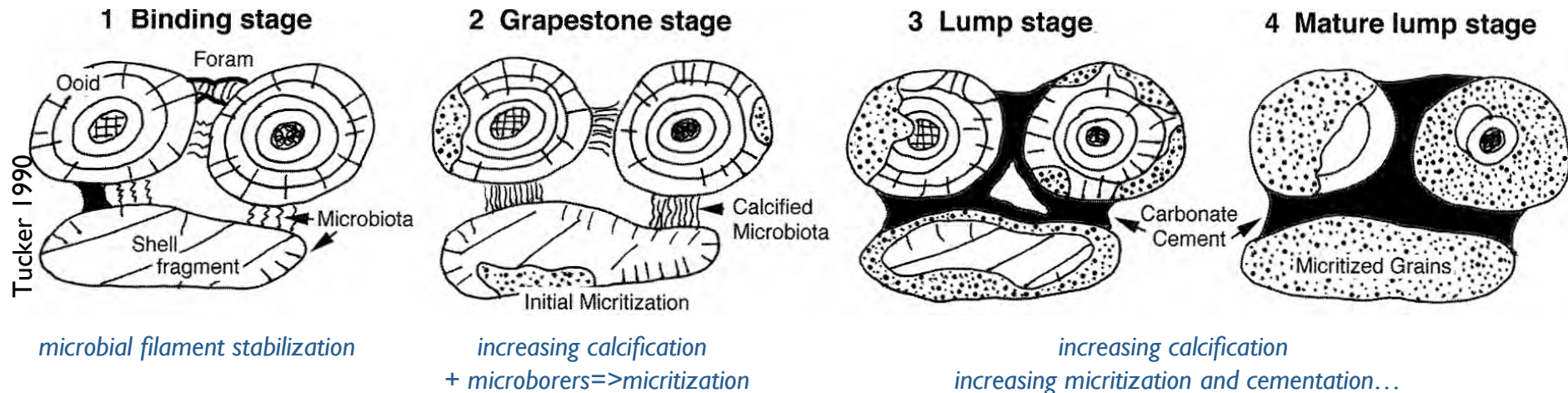
PETROGRAPHY OF CARBONATES

3. GRAINS = 3.5 AGGREGATES

=grapestones-lumps-composite grains

COMPOSITE GRAINS of ooids, skeletal material and peloids

Multi-stage formation of aggregate grains (grapestones and lumps)

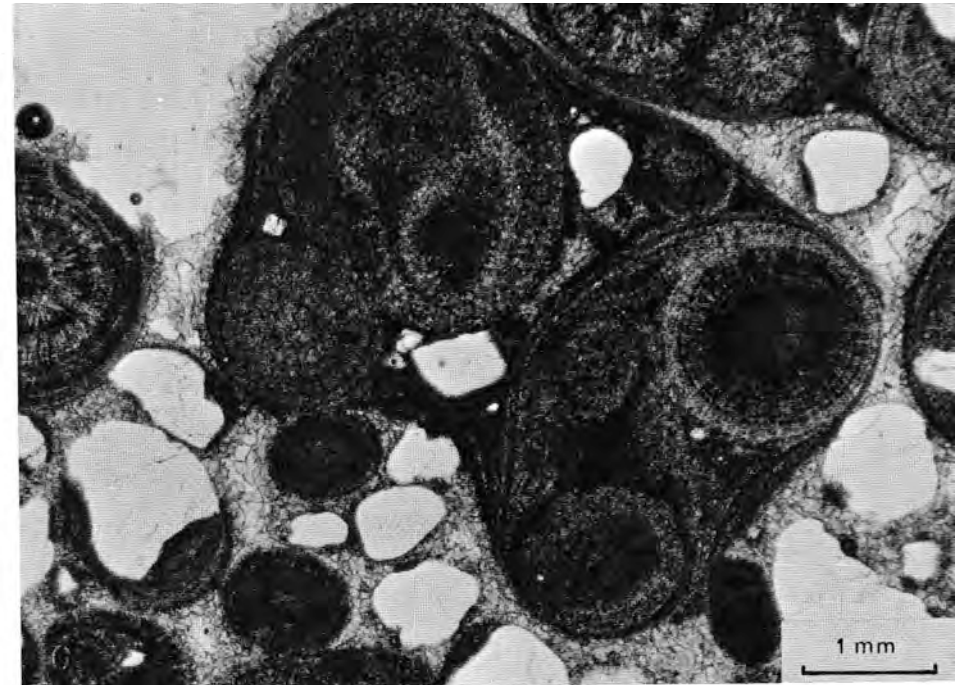
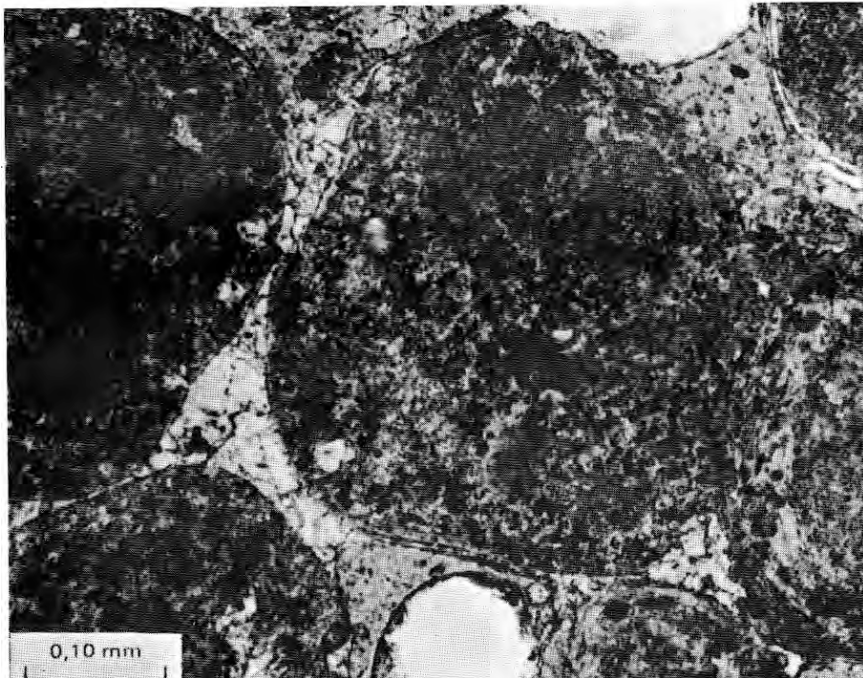


PETROGRAPHY OF CARBONATES

3. **GRAINS = 3.5 AGGREGATES**

=grapestones-lumps-composite grains

COMPOSITE GRAINS of ooids, skeletal material and peloids



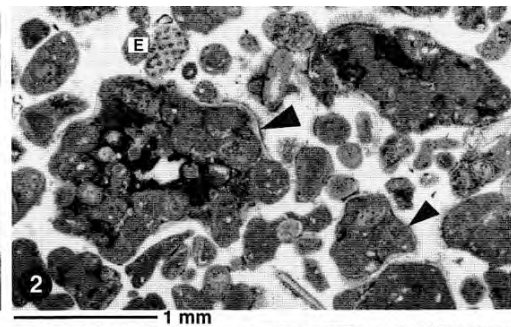
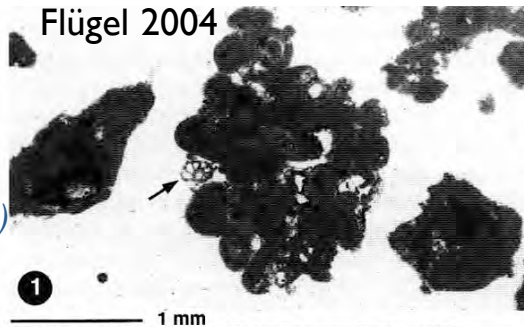
Aggregates of ooids with micritic cement and a thin external film (microbial or? algal).

Aggregates enclosed rare grain quartz .

Elf Aquitaine, 1975

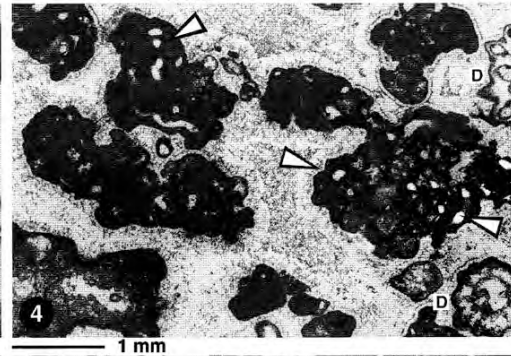
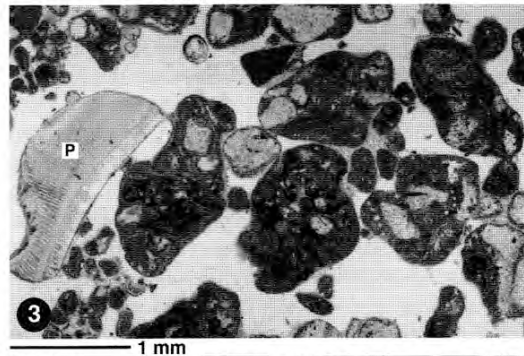
Flügel 2004

Modern aggregate ('grapestone')
with ooids, peloids, forams,
Great Bahama Bank (3-15m depth)



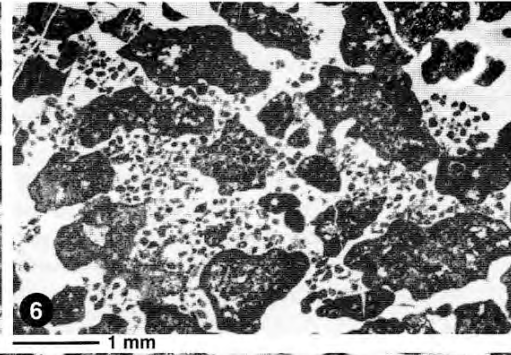
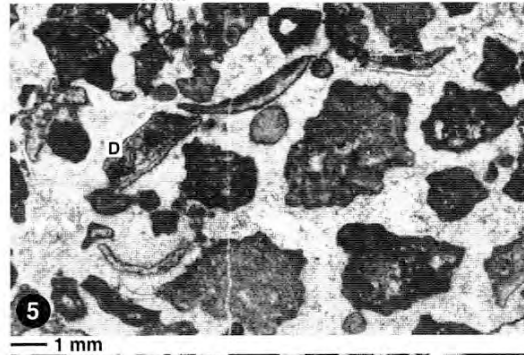
Pleistocene aggregate grains
forming weakly lithified sands.
Thin cements on grains (arrows)
E= Echinoid.
San Salvador Island, Bahamas

Pleistocene aggregate grains
(‘lumps’ due to ab micrite)
with ooids,, forams).
P = pelecypod (LMC) shell
San Salvador Island, Bahamas



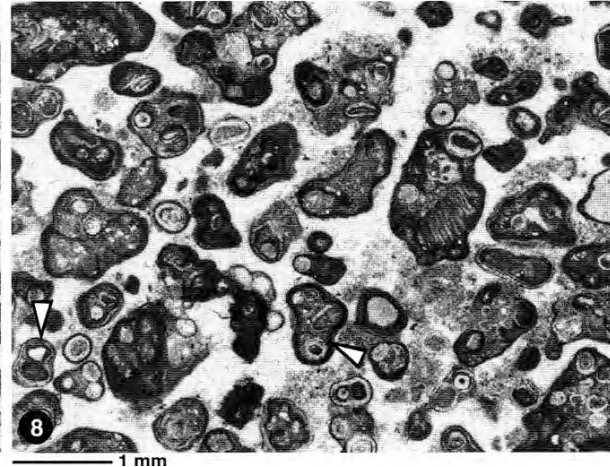
Encrusted (forams/chambers)
aggregate grains
Very irregular outlines
D= Dasyclad green alga
with ooids, forams).
Middle Permian, Croatia

Microbial lumps and micritized
Dasyclad algae (D).
Middle Triassic, Italy



Aggregate grains (lumps)
with loose peloids
(‘lumps’ due to ab micrite)
Early Jurassic, Tunisia

Aggregate grains of
(abundant) reefal biota.
Late Triassic, Austria



Aggregate-grain grainstone
= ‘grapestones’ of ooids and
fossils. Thin oolitic coating
(arrows, ‘botryoidal lumps’)
Middle Triassic, Italy

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.5 AGGREGATES

=grapestones-lumps-composite grains

COMPOSITE GRAINS of ooids, skeletal material and peloids

✓ ANCIENT AGGREGATE GRAINS

- from Precambrian
- Phanerozoic records of limestones with abundant aggregates = platforms
 - => they are concentrated in specific time intervals: Dev, Late Permian, Middle-Late Triassic, Jurassic, Cretaceous
 - => behind and adjacent to shelf-margin reefs AND transitional areas on the seaward side of ooid shoals and green algal-foraminiferal sands and the landward side
- indicate low to moderate and changing water energy levels, tropical and sub-tropical warm water conditions, low nutrient environments and low sedimentation rates
- generally associated with attached or isolated platforms (during sea level highstand phases).

✓ ECONOMIC POTENTIAL

- **good reservoir rocks in association with oolites (Cretaceous of the Near East)**

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.6 PELLETS and PELOIDS

micron-mm sized ±STRUCTURELESS SUBROUNDED micritic grains

- ✓ **PELLETS** = grain of fecal origin => subrounded or rounded, marine or non-marine
 - common on shallow-marine carbonate platforms in lagoonal settings
 - dimensions => silt- to fine-sand-sized, a few mm, generally > 500 µm and diameters < 200 µm smaller than ooids, pisoids, oncoids
 - UNIFORM SHAPES (+ carbon, phosphorus....)
 - typical of certain organisms (mollusks, crustaceans = *Favreina*, *Callianassa*, worms, holothurians, gastropods, etc



- ✓ **PELOIDS**
 - polygenetic grains composed of micro- and cryptocrystalline carbonate (micrite) with fine-grained skeletal debris and other grains
 - constitute grain- or mud-supported fabrics (wackestone, packstone, grainstone)
 - isolated or amalgamated, within layered or **clotted** textures
 - common in shallow—marine tidal and subtidal shelf carbonates, in reef and mud mounds, also deep-water
 - absent or rare in non-tropical cool-water carbonates.

✓ CARBONATE CLASSIFICATION

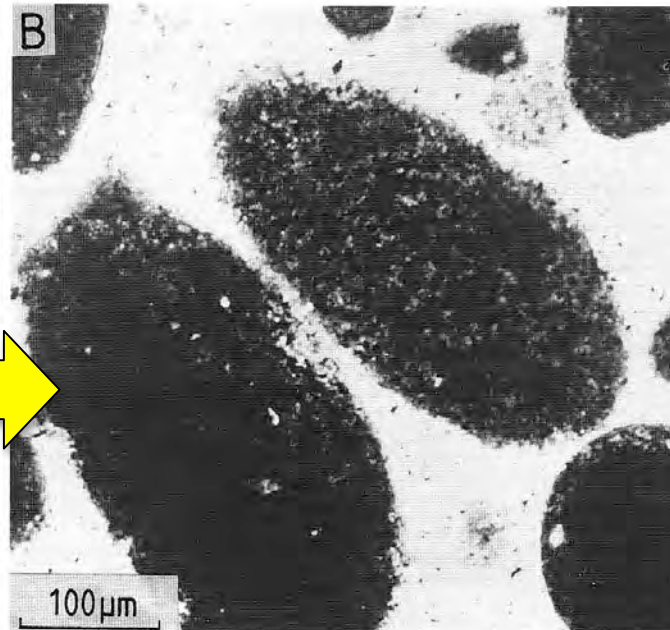
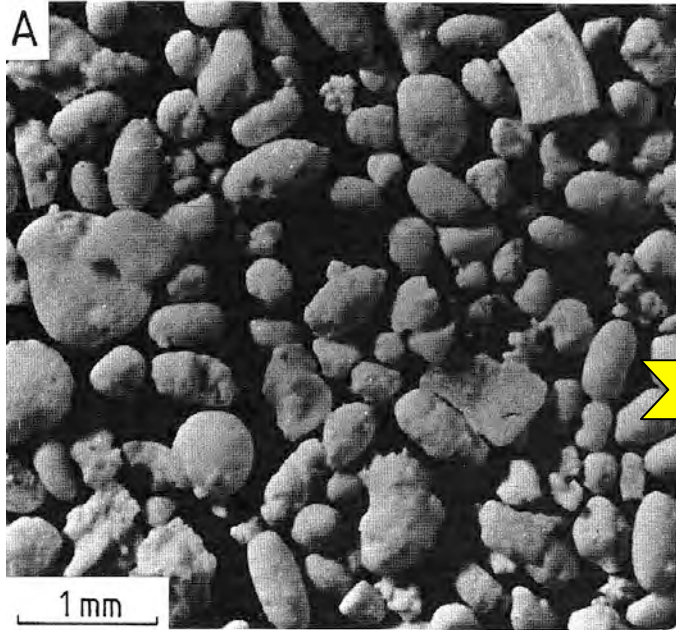
- included aggregate grains in the intraclast or lithoclast categories...

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.6 PELLETS and PELOIDS

micron-mm sized \pm STRUCTURELESS SUBROUNDED micritic grains

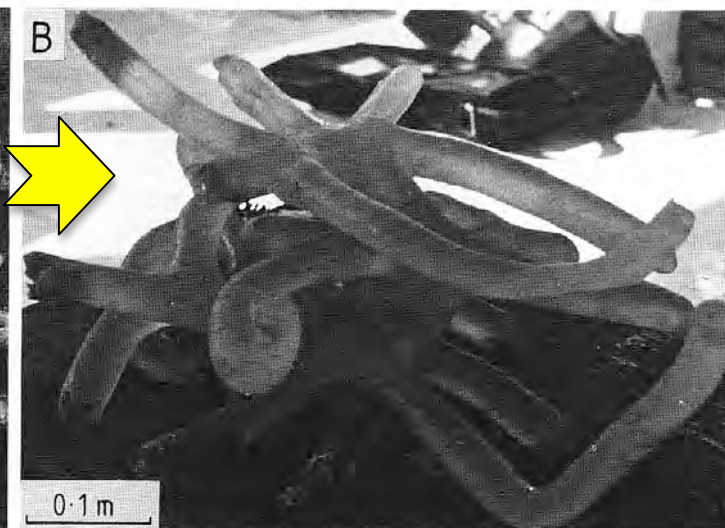
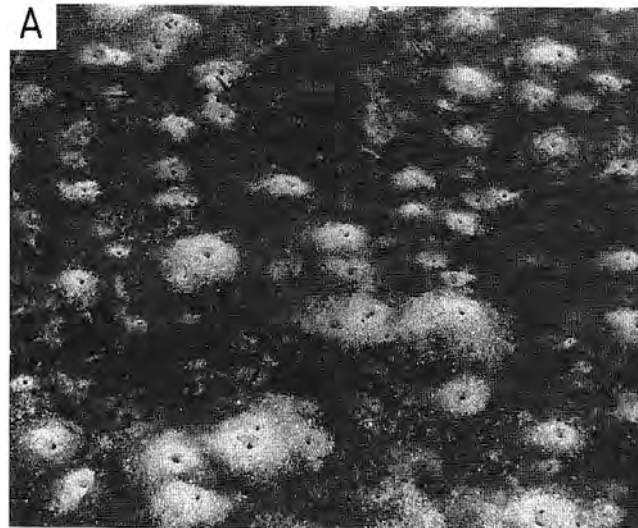
Peloidal skeletal sand washed out of sandy mud Bahamas



peloid displaying homogeneous micrite



Conical mounds 0.1-0.2m across produced by *Callianassa* (crustacean) in 0.5m water depth. Also thin dark surficial microbial mat. Lagoon. Bahamas



Burrow system of *Callianassa* preserved in resin

Till in Tucker & Wright 1990

Worm 'fecal' production in quartzose silty (present-day) sediment, Brittany, France



PETROGRAPHY OF CARBONATES

3. GRAINS = 3.6 PELLETS and PELOIDS

micron-mm sized ±STRUCTURELESS SUBROUNDED micritic grains

✓ FECAL PELLETS

- produced by organisms that eat mud, digest organic matter from the mud and excrete the non-digested lime-mud
- the dark color of the grains or the peripheral rim is caused by the high content of organic matter or iron sulfides
- fossilization requires bacterial decomposition of the organic mucus and **intragranular** cementation by HMC or ARAG => warm shallow waters that are supersaturated with respect to CaCO_3 .
- non-marine fecal pellets => salt lakes, freshwater lakes, soils.

✓ THE PELOIDAL QUESTION?



THE ORIGIN OF ANCIENT PELOIDS IS OFTEN IN DOUBT

=> difficult to distinguish fecal pellets, *in situ* precipitation or 'alteration' of former micritic grains...

- constitute grain- or mud-supported fabrics (wackestone, packstone, grainstone)

=> different subcategories have been established

The term 'peloid' is only **descriptive**, until thin-section studies provide genetic information

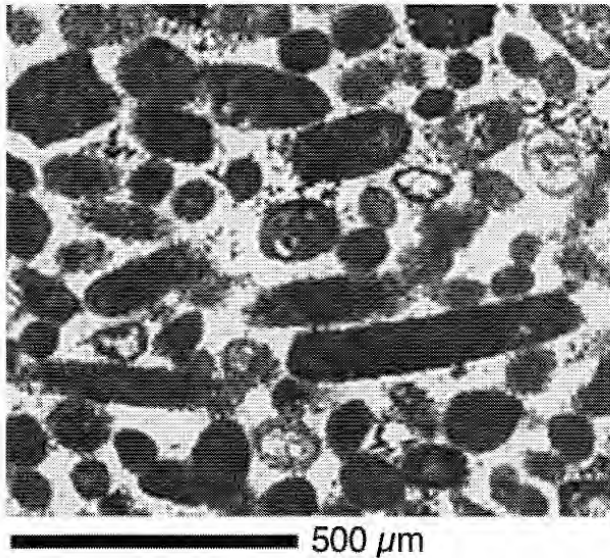
| Origin | | Types | Diagnostic criteria |
|-----------------------------|--|---------------------------------------|--|
| Biotic Origin | Lithified organic excrements | 1 Fecal pellets | Rounded elongated, rod-shaped or ovoid dark-colored micritic grains, rarely spherical. Commonly homogeneous or with 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 surrounded by clear exterior rims of crystals. Occurrence in cavity fill precipitates (e.g. in reefs) Pl. 8/5 |

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.6 PELLETS and PELOIDS

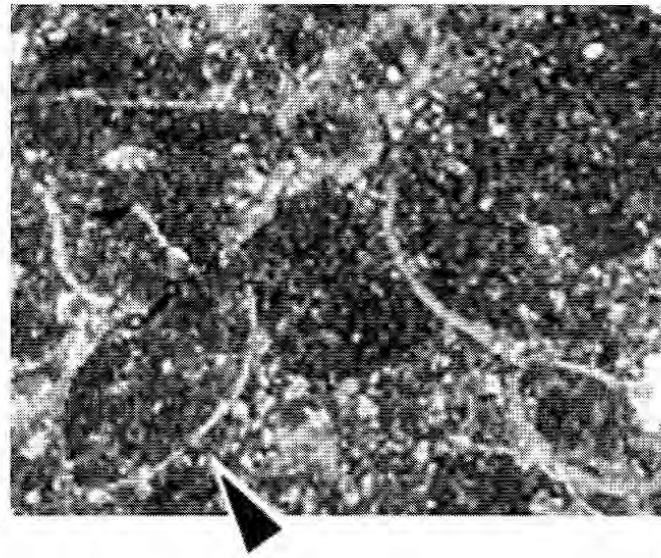
micron-mm sized \pm STRUCTURELESS SUBROUNDED micritic grains

Fecal pellets



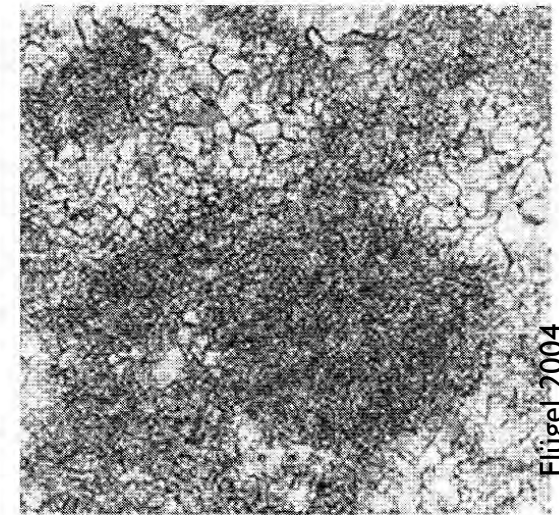
Early Cretaceous lagoonal limestone, rounded, elongated fecal pellets of different size.

Mold peloids



Middle Devonian shelf limestone, molds peloids are steinkerns of ostracods whose valves have been dissolved.

Pelletoids



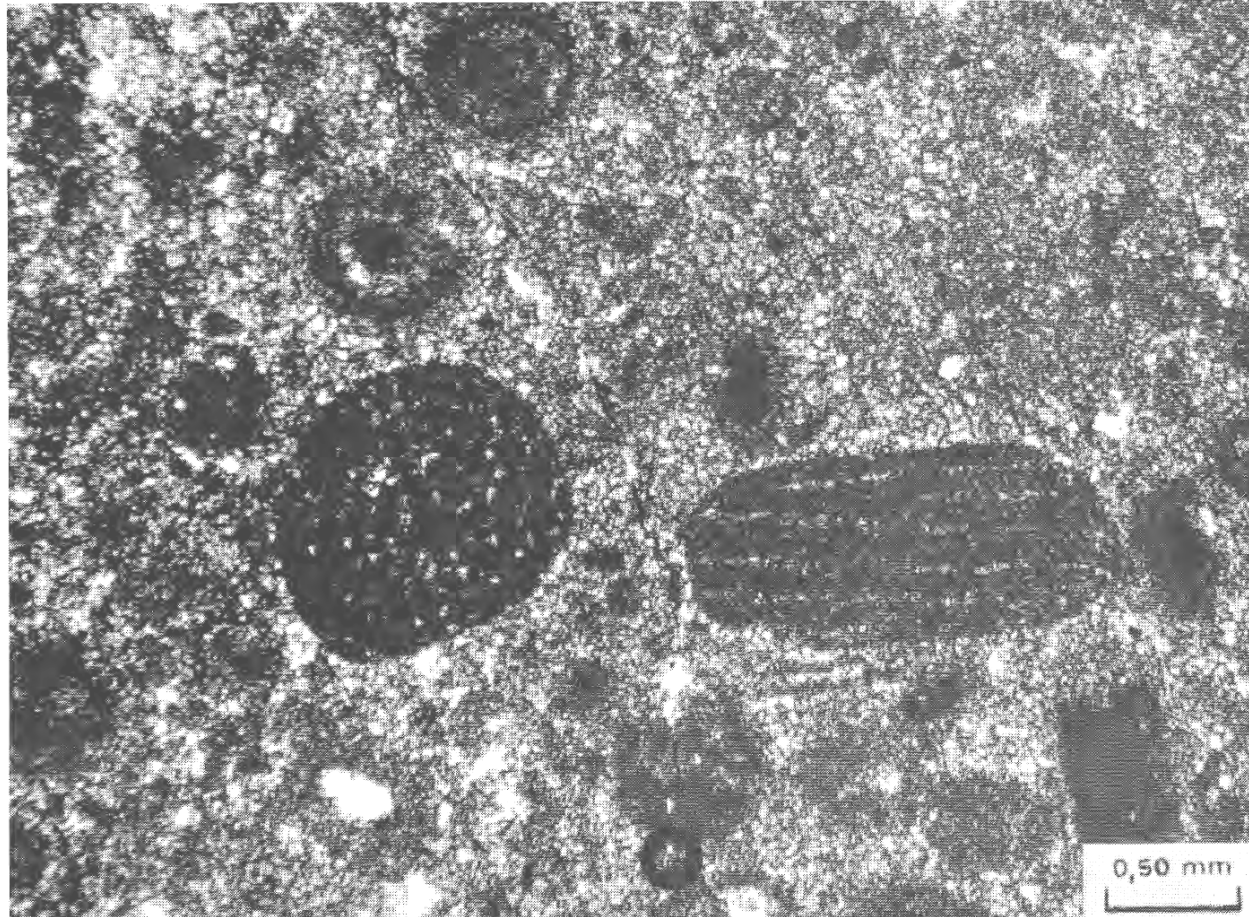
Carboniferous, strongly recrystallized limestone with round micritic pelletoids and spar-filled intergranular pores.

Flügel 2004

PETROGRAPHY OF CARBONATES

3. **GRAINS = 3.6 PELLETS and PELOIDS**

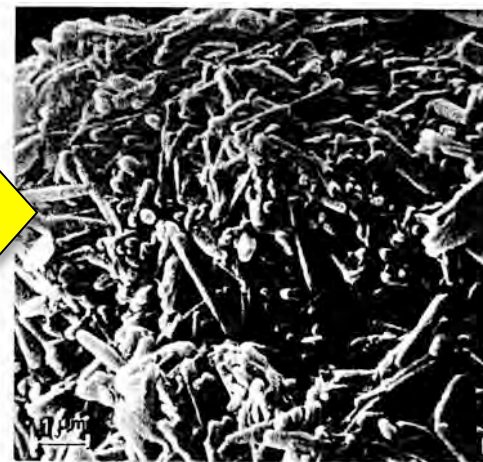
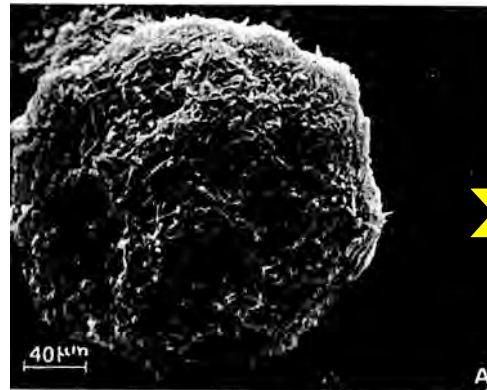
micron-mm sized ±STRUCTURELESS SUBROUNDED micritic grains



Crustacean coprolites in cross section (rounded) and longitudinal section
Elf Aquitaine, 1975

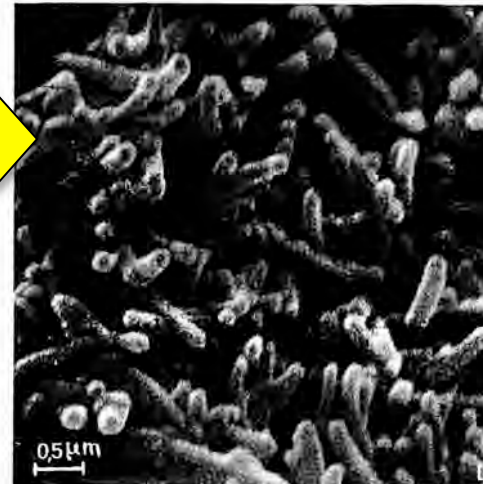
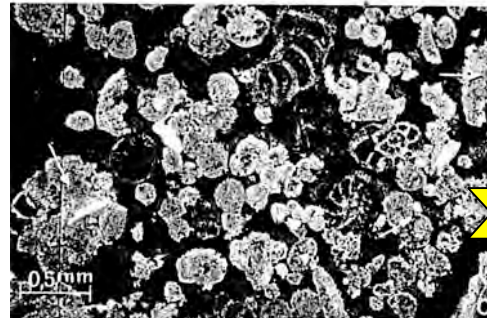
ABU DHABI Loreau 1982

Intertidal fecal pellet



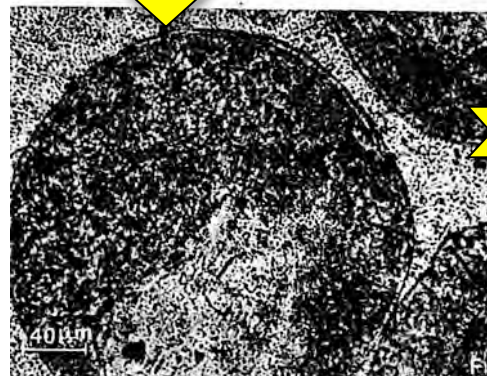
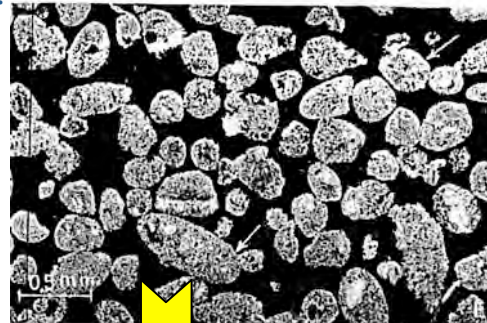
nanostructure

anhedral-subhedral
rods



surface of a fecal pellet

loose anhedral rods
0.1-0.3 μm x 1-2 μm



surface of oolite layer

packed rods

loose rods

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.6 PELLETS and PELOIDS

micron-mm sized ±STRUCTURELESS SUBROUNDED micritic grains

✓ ANCIENT PELOID LIMESTONES

- account for 1000' km³ of lagoonal, shelf, bank, reef-core (and mud mound) deposits
- fine-grained peloidal limestones => shallow, low-energy, restricted marine environments
=> if higher energy = => they can be allochthonous (transported to shallower or deeper environments)

✓ COMMON FABRICS IN PELOIDAL LIMESTONES

- USUALLY INTERPRETED AS PRODUCTS OF MICROBially OR BIOLOGICALLY INDUCED CARBONATE PRODUCTION

= micritic clotted fabric

= sparry peloidal fabric

= thrombolitic peloidal fabrics

= biocemenstones

Micritic clotted fabric (Pl. 10/1)

Texture: Densely spaced, variably sized globular and irregular peloids forming amalgamated clots; commonly within a microspar, micrite or spar matrix.

Origin: (a) Recrystallization of carbonate mud and peloidal micrite (Cayeux 1935; Bathurst 1970; Leeder 1982), (b) diagenetic alteration of soft-pellet grainstones to wackestones (Bathurst 1970) (c) diagenetic amalgamation of precipitated peloids (Reid 1987), (c) diagenetic alteration of soft-bodied organisms (Bourque 1984), (d) diagenetically modified algal debris (Coniglio and James 1985), (e) products of in situ calcified mats of benthic coccoid cyanobacteria (Kazmierczak et al. 1996), and (f) grazing and decay of algal mats (Pratt 1982).

Occurrence: Common in tidal laminated carbonates, in mud mounds, and reefs (Sun and Wright 1983; Neuweiler 1993) as exemplified by Triassic reefs, where about 75% of the reef core framework can consist of precipitated peloids occurring in cavities, intraskeletal voids and organic crusts (Reid 1987).

Sparry peloidal fabric (Pl. 8/5)

Texture: Abundant, very small peloids formed in situ and consisting of a microcrystalline core surrounded by a dentate crystal rim (Type 9: Fig. 4/11). The peloids are part of submarine carbonate cements.

Origin: Chemical or biochemical precipitation (type 9, Fig. 4/11).

Occurrence: Common in intra- and interskeletal voids of reef rocks similar to clotted fabrics, associated with internal sediments and carbonate cements and within crusts associated with corals and sponges.

Thrombolitic peloidal fabrics (Pl. 50/5)

Texture: Non-laminated structure. Abundant peloids of irregular shape and size, some retaining filamentous structures. Common calcite 'spherulites' (peloids) consisting of radially-oriented, non-ferroan calcite, typically 12–20 µm in diameter with a cloudy micrite core, 1–10 µm in diameter.

Origin: (a) In-situ precipitation. The formation of in-situ spherulites within the sediment is controlled by supersaturation of CaCO₃ in solution and a site for nucleation. Supersaturation of CaCO₃ is caused by (a) the release of CO₂ and NH₄ on the decay of organic matter and (b) bacterial sulphate reduction. Bacteria can form spherulites in aerobic, anaerobic, agitated and non-agitated laboratory conditions, but experimental precipitation of spherulites without the presence of bacteria points to the possibility that spherulitic textures also can form as a by-product of decayed organic matter. Spherulites in stromatolites have been interpreted as calcified cyanobacteria. (b) Allochthonous grains. Deposition of small allochthonous fecal pellets and algal peloids within cavities (James et al. 1976) or formation of pellets by cryptic filter feeders (e.g. clionids: Land and Moore 1980). These interpretations are supported by the fact that peloids can settle at the base of cavities.

Occurrence: Thrombolitic fabrics occur in lacustrine limestones (Pl. 131/5) and beachrocks, and are common in laminated tidal and subtidal carbonates (stromatolites) as well as in subtidal shelf carbonates, mud mounds and non-skeletal microbialite reef frameworks (particularly in the Carboniferous and Permian, Jurassic and Cretaceous).

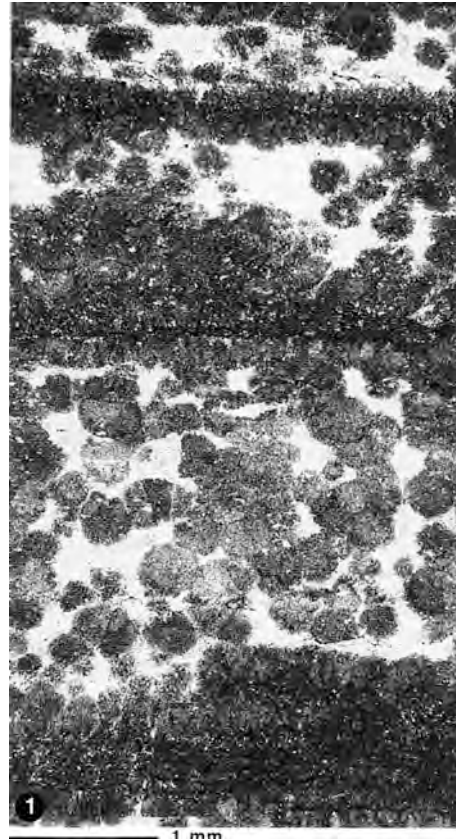
Biocementstones (Tsien 1981) - Sect. 8.2

Texture: Fine-grained micritic limestones consisting of peloids, delicate small and/or poorly calcified organisms contained within abundant, localized carbonate cement.

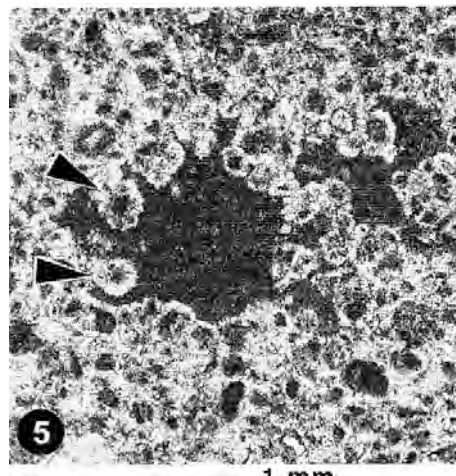
Origin: Fabric, formed by free-living microorganisms (cyanobacteria, algae, sulfur-reducing and sulfate-reducing bacteria) and small encrusting benthic invertebrates, which trap and build carbonate mud from bottom waters, resulting in the formation of small micritic 'protipeloids' (Tsien 1985). Amalgamation of the peloids leads to the formation of peloidal automicrite. A large part of the limestones is formed by biologically induced carbonate cements.

Occurrence: Reef frameworks, specifically in the Permian and Triassic (Webb 1996).

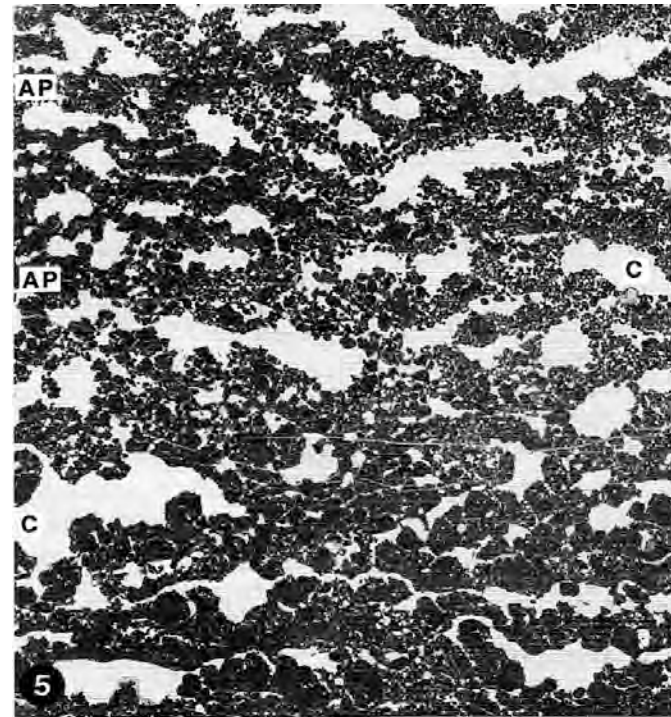
Clotted fabric
 Microbial peloids
in situ within algal-
 cyanobacterial mats
 Late Permian (Zechstein)
 Germany



Sparry peloidal fabric
 'Black/white' peloids
In situ cavity-fill precipitates
 or laminated crust,
 microbial mediation
 Middle Permian, Slovenia



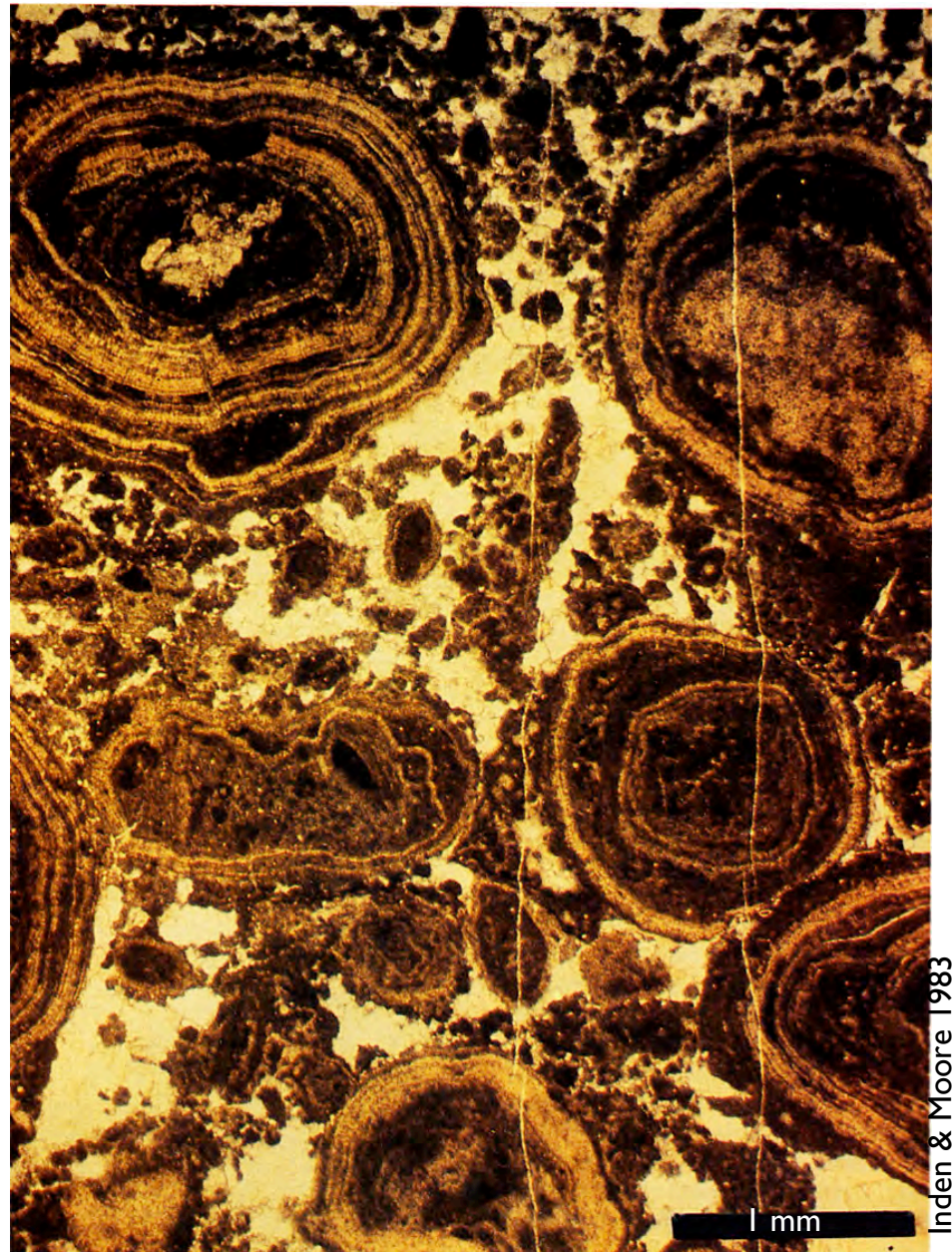
Flügel 2004



**Thrombolite fabric
 or
 Laminoid fenestral
 fabric**
 Microbial peloids
 Agglutinated microbialite
 Late Triassic, Slovenia
 AP amalgamated peloids
 c cavity



**Lacustrine oncolite
 with thrombolite
 structure (T)**
 with a clotted
 structure
 clots =? coccoid and
 filamentous microbes
 Early Permian, Germany



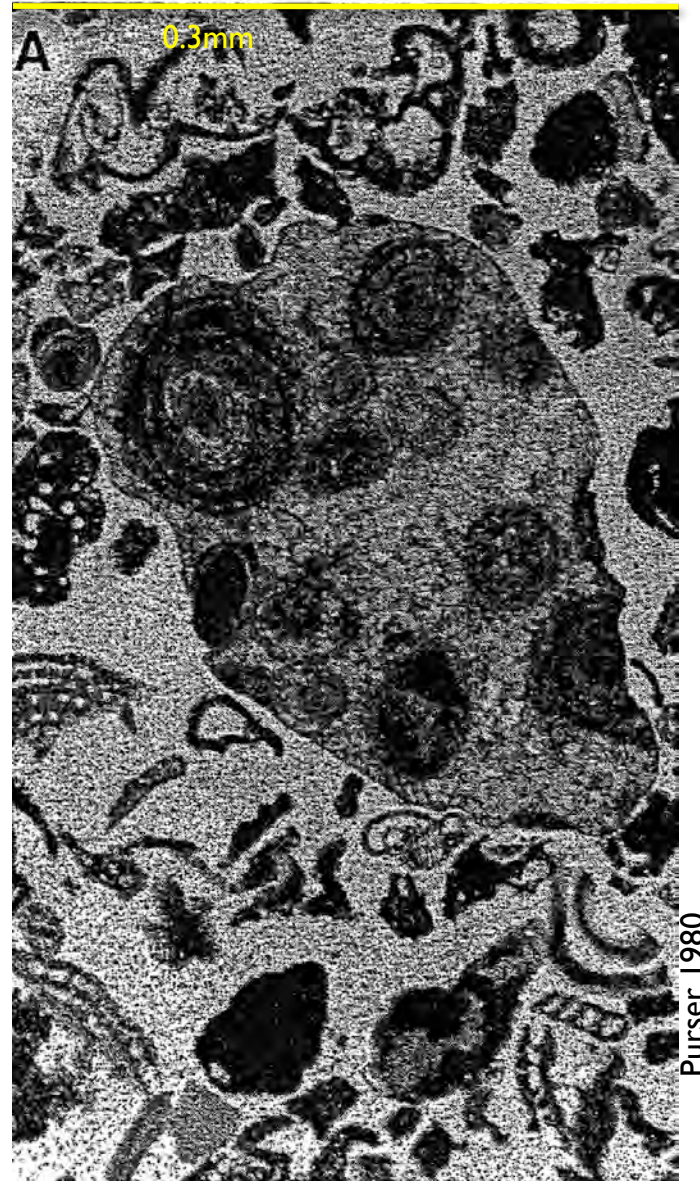
Mission Canyon Formation, Williston Basin, Mississippian
Regressive sequence with well-sorted and rounded pisoid-oid-pellet grainstone.
Irregular fibrous laminae of pisoids indicates deposition in a hypersaline environment (near a beach)

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.7 INTRACLASTS-MICROBRECCIAS

Carbonate **FRAGMENT** of lithified or semi-lithified sediment derived from the erosion of nearby **pencontemporaneous** sediment > < **EXTRACLASTS**

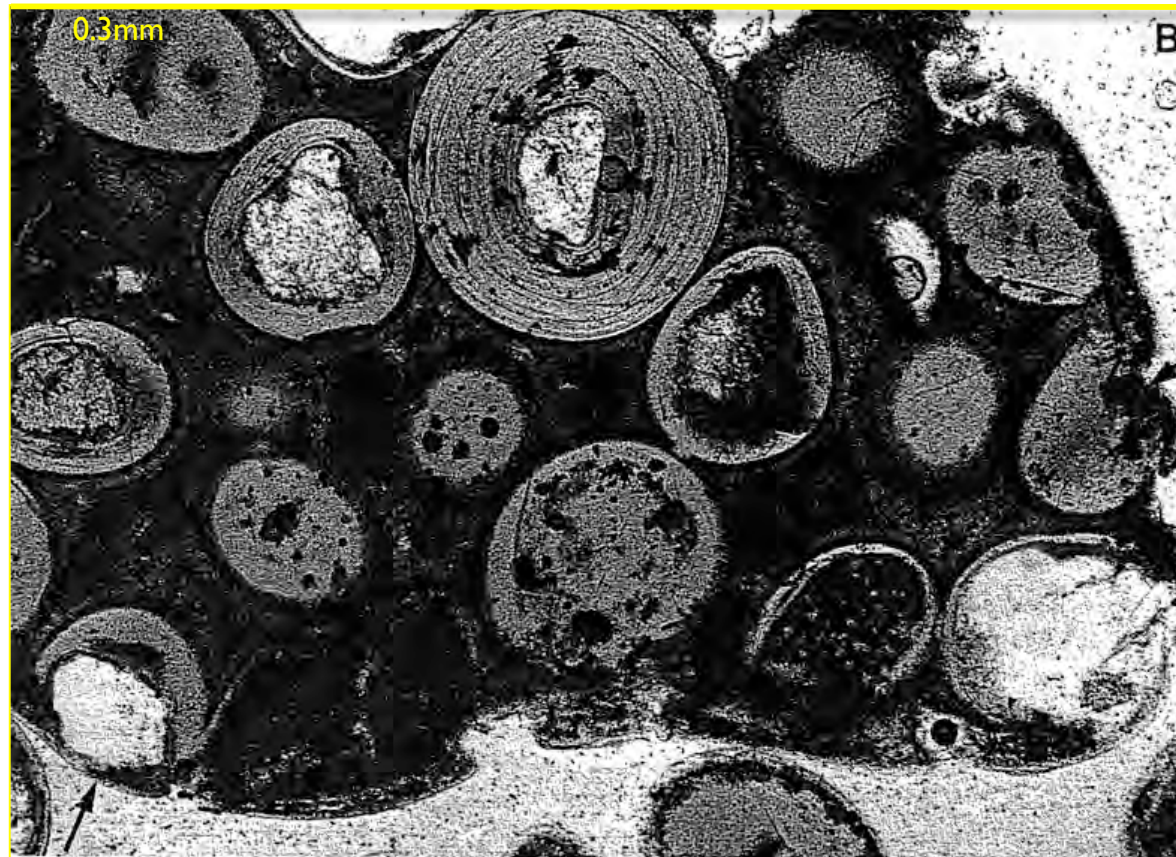
Pleistocene, Bahamas
oolite **intraclast**
*the intraclast does
not come from the sediment itself*



PETROGRAPHY OF CARBONATES

3. GRAINS = 3.7 INTRACLASTS-MICROBRECCIAS

Carbonate **FRAGMENT** of lithified or semi-lithified sediment derived from the erosion of nearby **pencontemporaneous** sediment > < **EXTRACLASTS**



Recent, Persian Gulf
oolite **intraclast** with truncated oolite (arrow)
the intraclast come from the sediment itself

Purser 1980

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.7 INTRACLASTS-MICROBRECCIAS

Carbonate **FRAGMENT** of lithified or semi-lithified sediment derived from the erosion of nearby penecontemporaneous sediment > < **EXTRACLASTS**

✓ GENESIS



- currents (e.g. storms), **desiccation muds**, local sliding, burrowing and grazing activities of organisms, redeposition, and diagenetic changes in volume during dehydration, compaction or leaching...
 - differential dolomitization leads to 'false' intraclasts i.e. 'residual',
 - early lithification surfaces (hardground) in shallow water series AND condensed series = 'hiatus concretions'
- 'TRUE' INTRACLASTS => HIGH ENERGY => basin analysis (e.g. sea level drop, uplift....)
- common in shallow-marine environment (waves, tides, storms)
 - => also 'rip-up clasts' in inter- and supratidal environments where scouring undermines lithified mud beds
- commonly associated with cross-bedded channels
- intraclasts + extracasts = **lithoclasts** : in practice somewhat tricky... to distinguish...



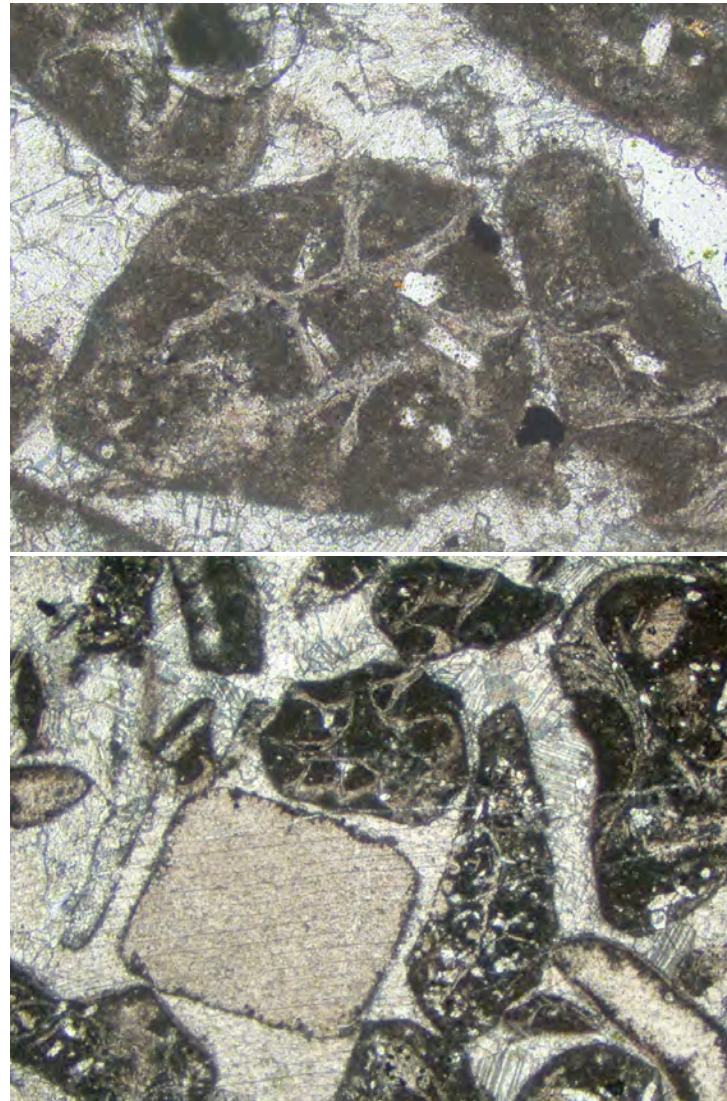
- ### ✓ A PARTICULAR CASE : collapse breccia
- not true intraclasts ... = mud flakes breccias formed by desiccation, dehydration and cementation/sparitization in evaporative settings.
= FLAT-PEBBLE or EDGE-WISE BRECCIAS/CONGLOMERATES (no energy!)

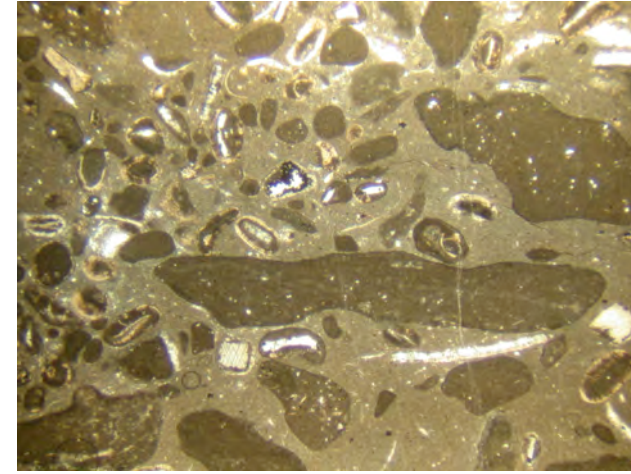
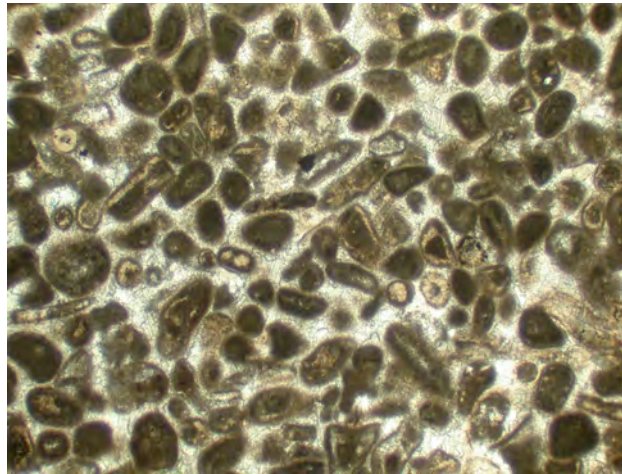
PETROGRAPHY OF CARBONATES

3. **GRAINS = 3.7 INTRACLASTS-MICROBRECCIAS**

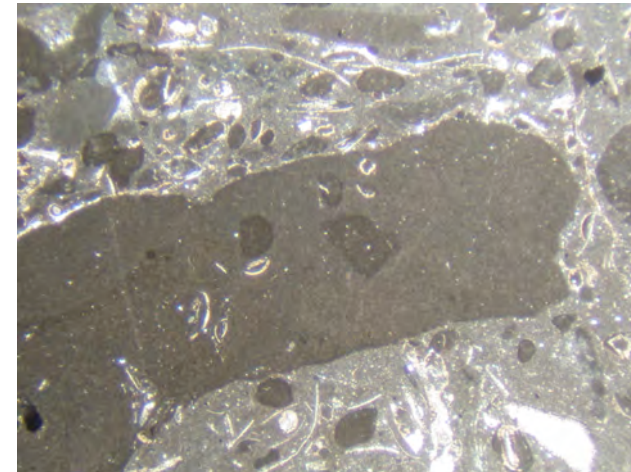
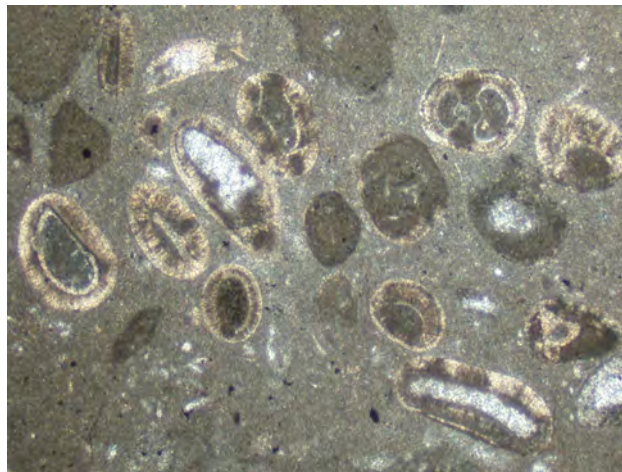
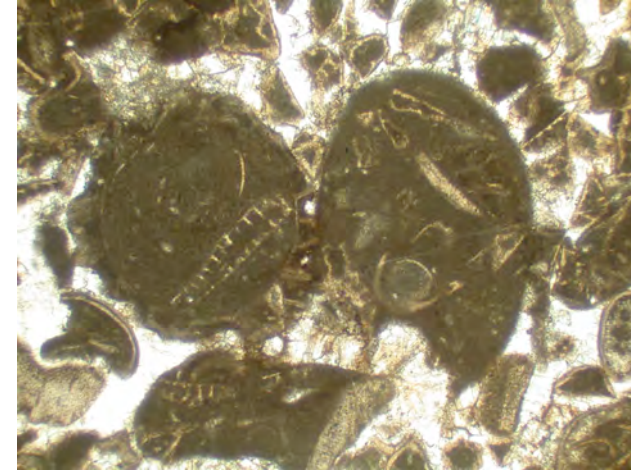
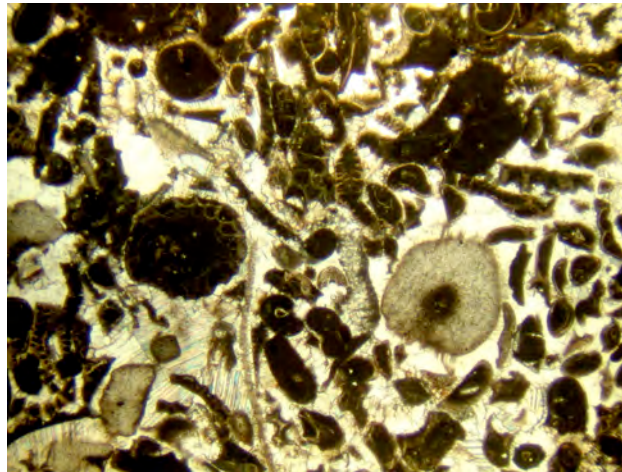
Carbonate **FRAGMENT** of lithified or semi-lithified sediment derived from the erosion of nearby penecontemporaneous sediment > < **EXTRACLASTS**

Grainstone with bryozoans and bioclastic packstone subrounded and subangular intraclasts. Syntaxial cement around the echinodermal plate and micritized bioclasts. Open marine setting (mid-ramp). Storm reworking in *Middle Devonian, Belgium, Pr  at.*



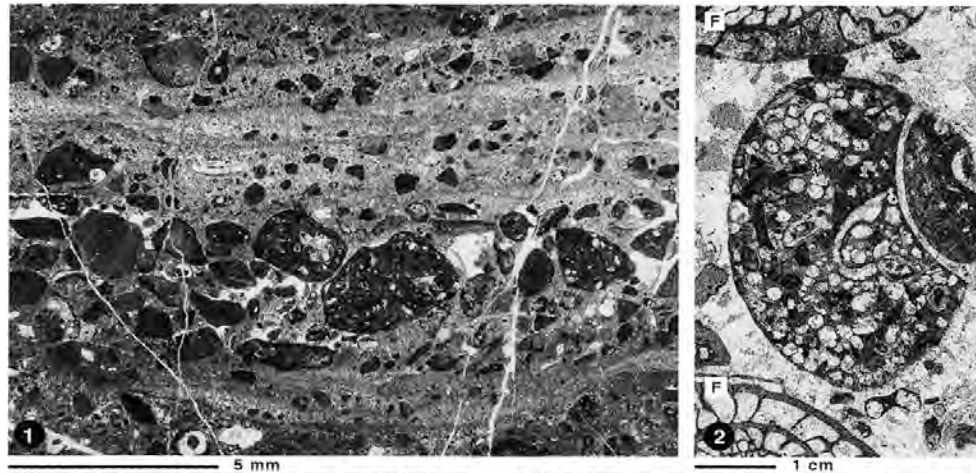


Grainstone and packstone.
Well-sorted ooids in a
shoal and intraclast-ooid
in a fore-shoal area.
Open marine facies,
Mid-ramp setting.
*Middle Devonian, Belgium,
Préat.*



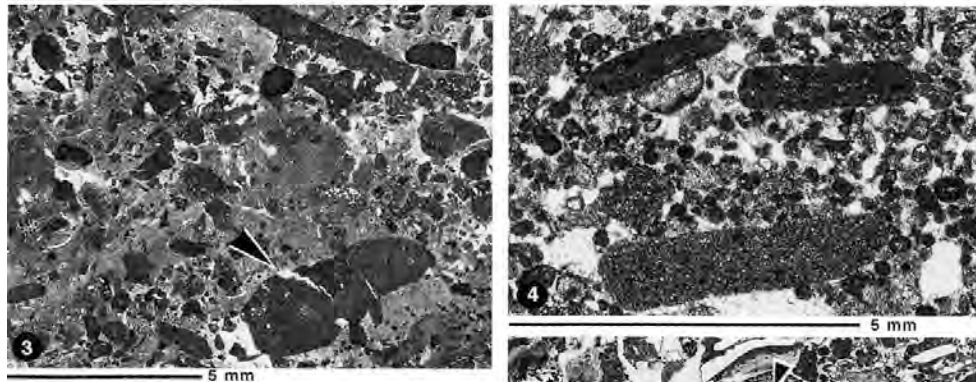
Flügel 2004

Intraclasts reworked by storms
and deposited in floatstone-
rudstone layers.
Early Tertiary, Austria



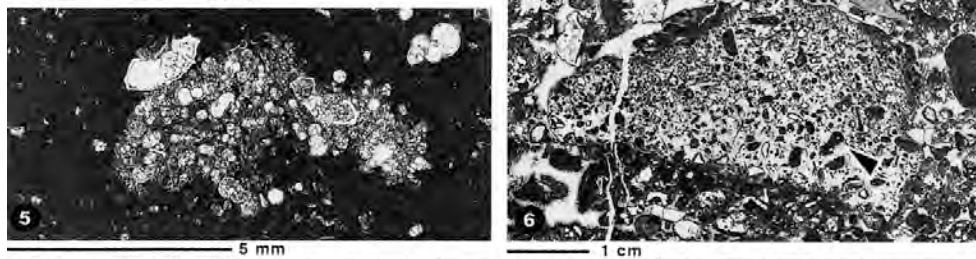
Well-rounded **extraclast**
with algal spores and shells.
Truncation of the gastropod
at the boundary of extraclast.
Fusulinid (F) foram in the
host rock.
Early Permian, Austria.

Poorly-sorted **intraclast** wackestone
Strong reworking of semi-
lithified sediment (size, shape and
orientation. Dark clasts =
'black pebbles' with rootlets (arrow.)
Late Jurassic, Switzerland



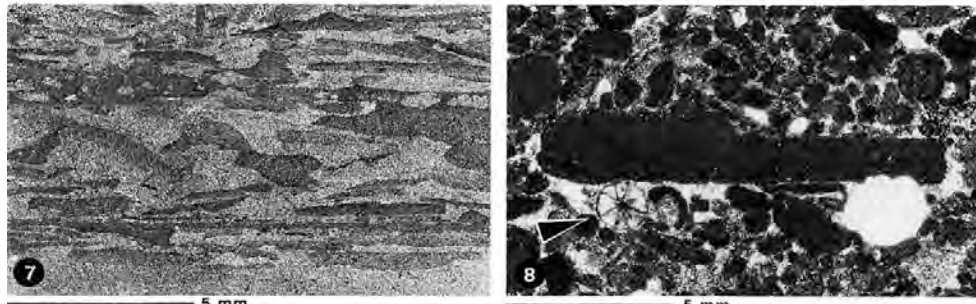
Siltstone **extraclast**
(storm-derived).
Early Carboniferous, Poland.

Accumulation of planktonic forams
in a **clast** in pelagic wackestone
containing the same forams.
Late Cretaceous, Tunisia



Fine-grained peloidal
grainstone **intraclast**
adjacent to a reef zone.
Late Jurassic, Germany

Tidal **intraclasts** formed
as lag deposit in tidal channels.
Late Jurassic, Germany

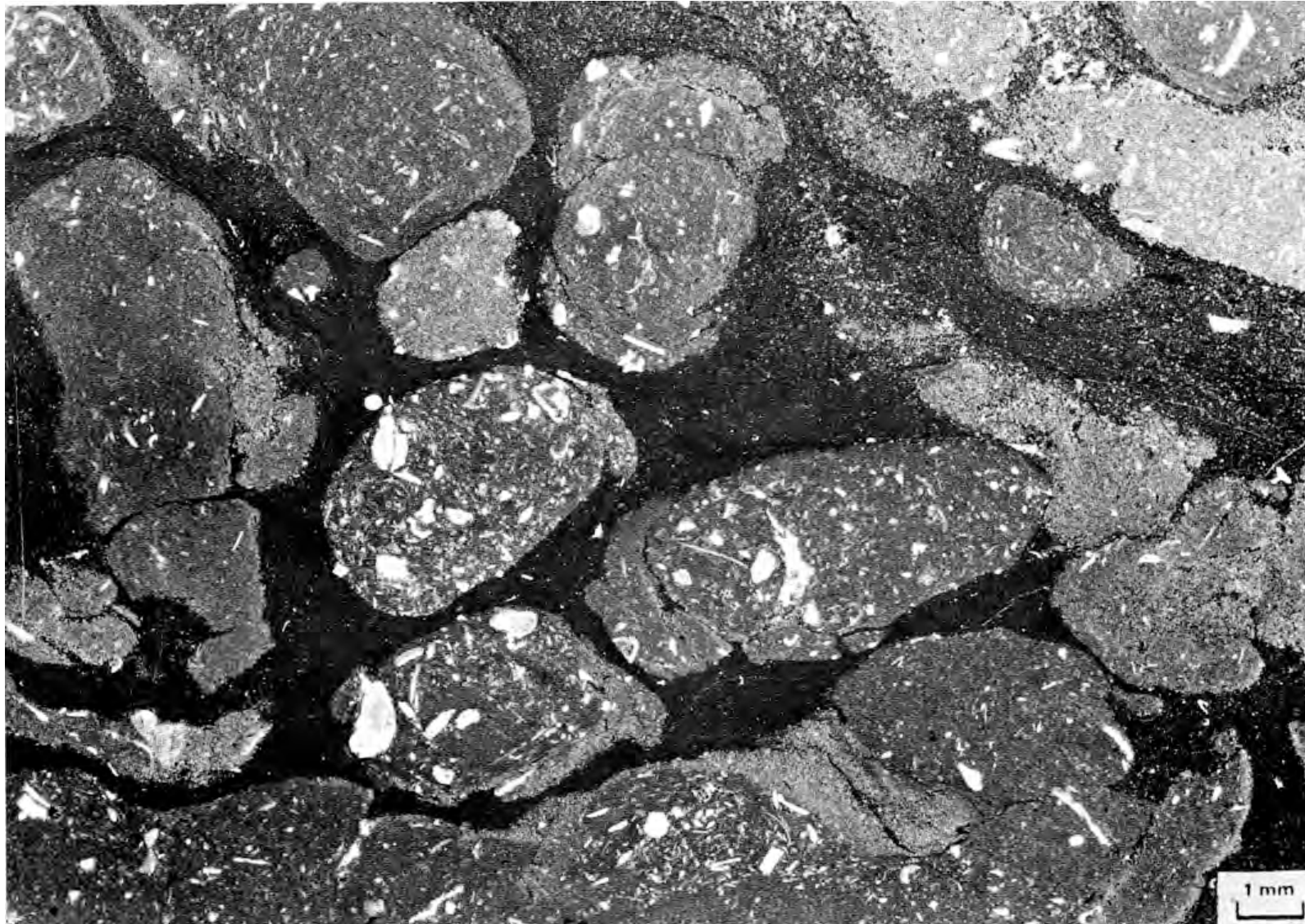


Precambrian **intraclasts**
together with ooids.
Montana, USA.

PETROGRAPHY OF CARBONATES

3. **GRAINS = 3.7 INTRACLASTS-MICROBRECCIAS**

Carbonate **FRAGMENT** of lithified or semi-lithified sediment derived from the erosion of nearby penecontemporaneous sediment > < **EXTRACLASTS**



Intraclasts in an argillaceous matrix, *Elf Aquitaine 1973*

PETROGRAPHY OF CARBONATES

3. GRAINS = 3.7 INTRACLASTS-MICROBRECCIAS

Carbonate FRAGMENT of lithified or semi-lithified sediment derived from the erosion of nearby penecontemporaneous sediment > < EXTRACLASTS

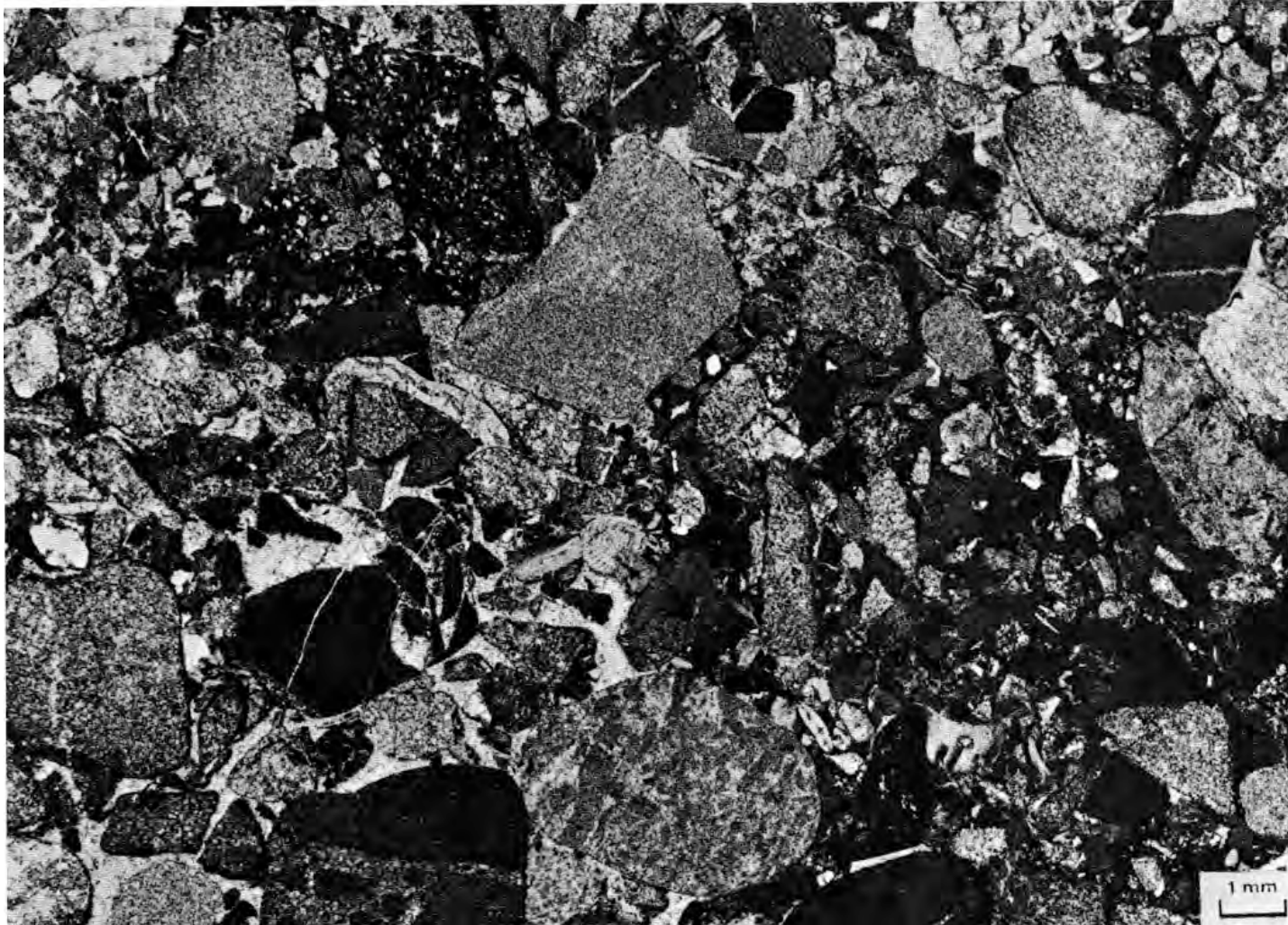
✓ INTRACLASTS vs EXTRACLASTS

- intraclasts => fragments weakly consolidated ==> soft or lobate outlines ≠ extraclasts round or angular
 - fossils and other grains are truncated within the extraclast at the extraclast boundary
 - extraclasts should contain stratigraphically 'older' fossil than the matrix
 - many extraclasts exhibit criteria pointing to recrystallization, dolomitization, tectonic deformation prior to deposition of clasts
-
- extraclasts originate from the drainage of rivers in near-coastal regions, rock-fall at coasts, deposition of erosional material by debris and turbidity flows, also by eolian transport.

PETROGRAPHY OF CARBONATES

3. **GRAINS = 3.7 INTRACLASTS-MICROBRECCIAS**

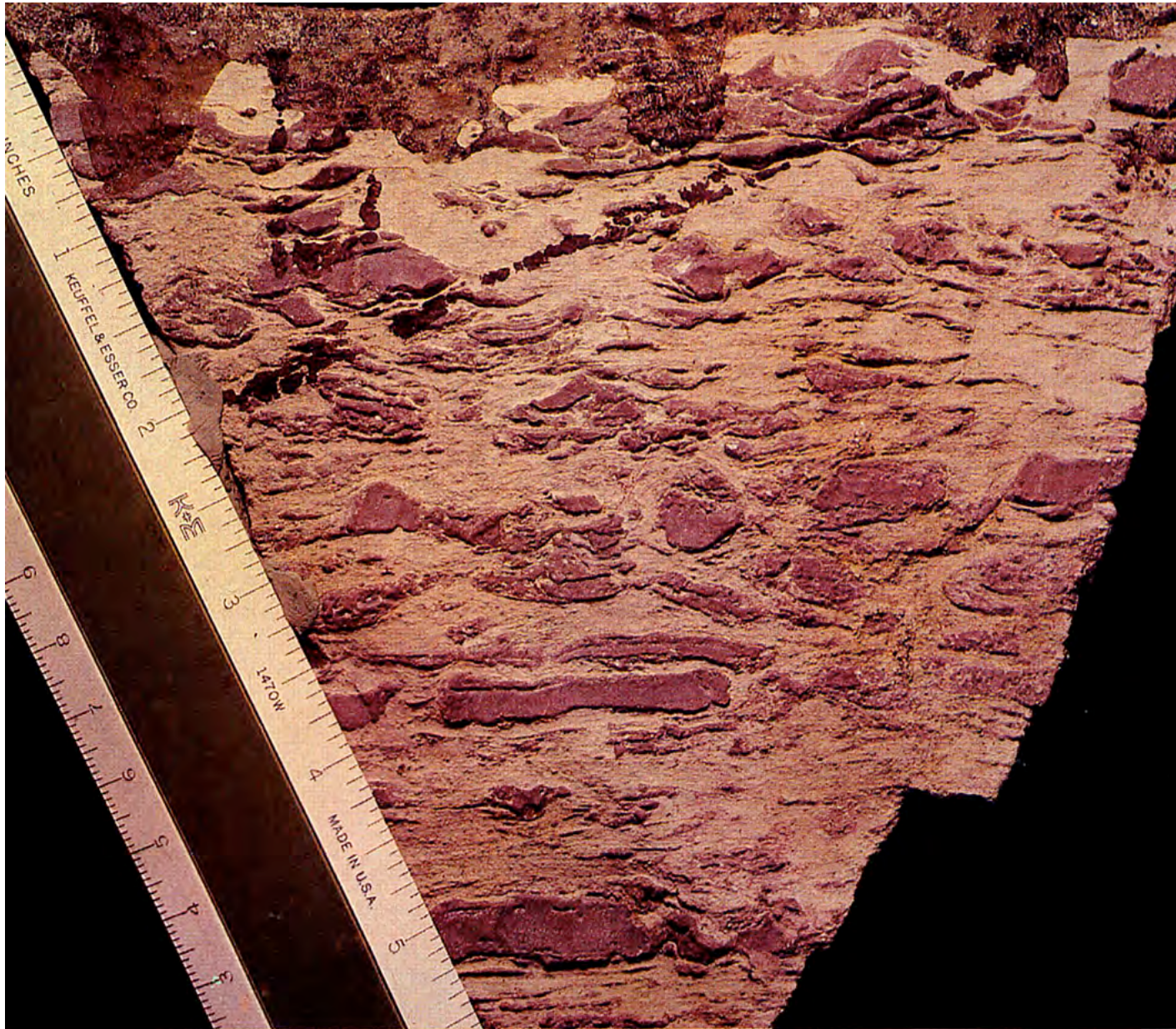
Carbonate **FRAGMENT** of lithified or semi-lithified sediment derived from the erosion of nearby penecontemporaneous sediment > < **EXTRACLASTS**



Extraclasts (=lithoclasts s.s.), generally angular = ‘breccia’ with diversified fragments (micritic, dolomicrosparitic, argillaceous-sandy) with extremely reduced micritic to microsparitic cement, *Elf Aquitaine 1973*

NOT TRUE INTRACLASTS...!

Limestone lenses = rounded mudcrack polygons that escaped early dolomitization in a tidal flat setting. Ordovician, Maryland, Shinn 1983.



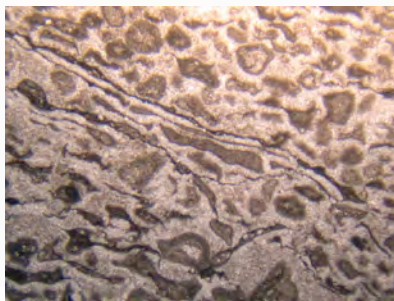
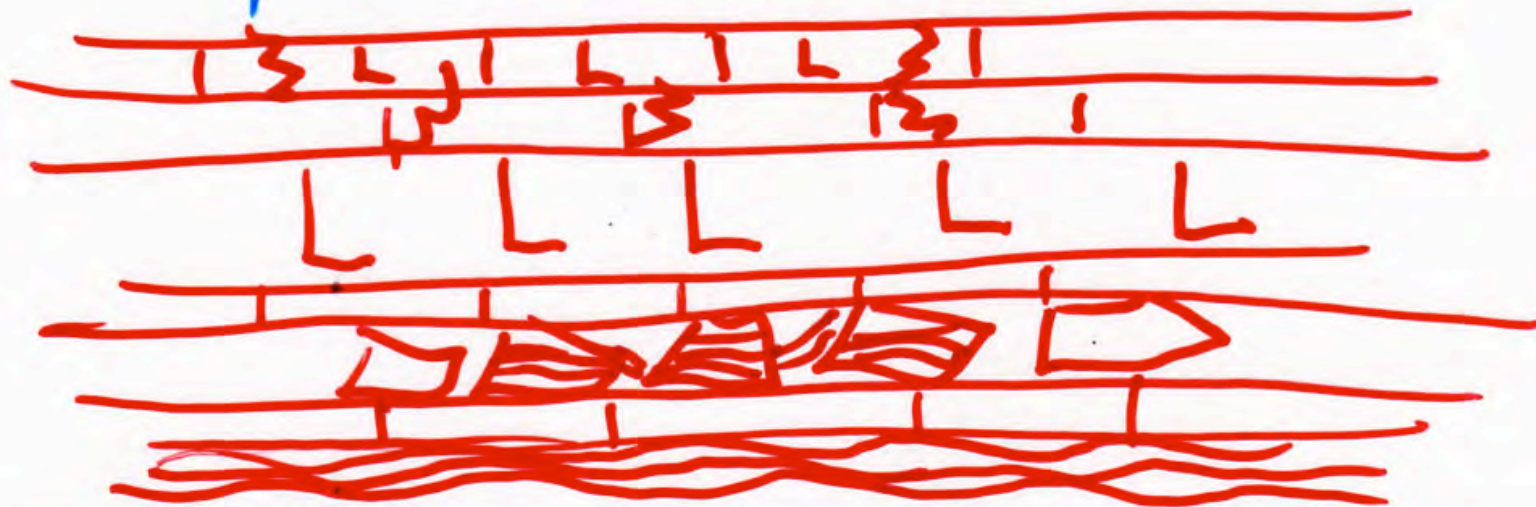
TRUE INTRACLASTS...!

= **FLAT PEBBLES** from a cyclical tidal flat sequence in a bioclastic (hash) basal channel deposit. Cambro-Ordovician. Shinn 1983.



GREAT LATERAL EXTENSION : 10'-100' km

grande extension latérale 10'-100'-km



mm



mm

Néoprotérozoïque Congo-Brazza, Préat 2012

PETROGRAPHY OF CARBONATES

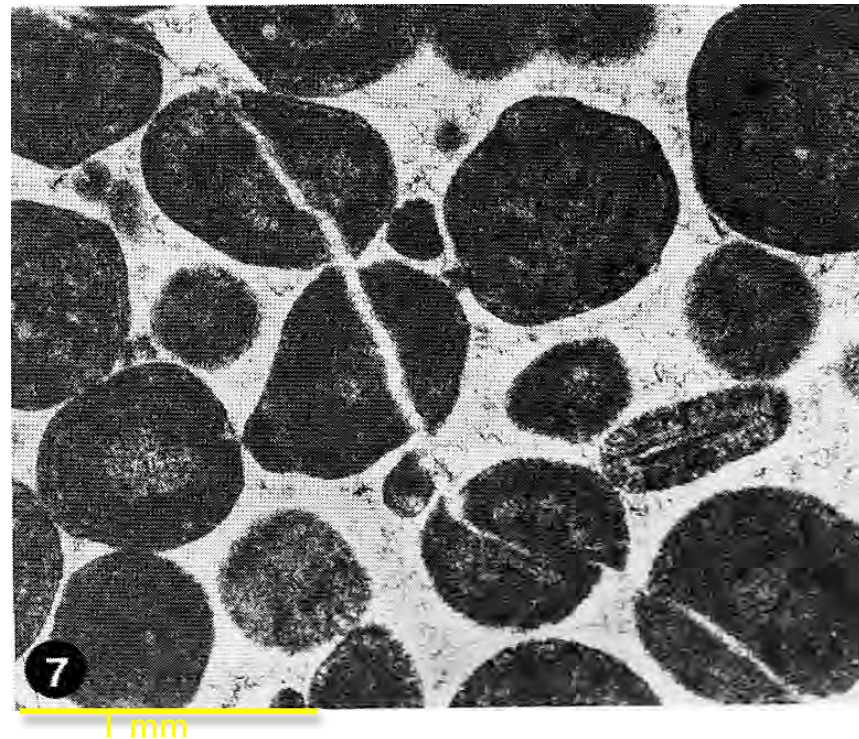
3. GRAINS = 3.8 MICRITIZED GRAINS

GRAINS EXHIBITING MICRITIC ENVELOPES

GENESIS

The margins of the grains or the total volume of grains are **replaced** by crypto- or micro-crystalline micrite (= MICRITIZATION PROCESS) as a result of microborers and microbes.

Micritized ooids in an ooid grainstone. The irregular shape of some ooids results from biogenic encrustations, indicating only weak reworking of the grains.
Circumgranular LMC cements, due to meteoric-phreatic overprint.
Late Jurassic, Switzerland
(Flügel 2004)



TOTAL REPLACEMENT

PETROGRAPHY OF CARBONATES

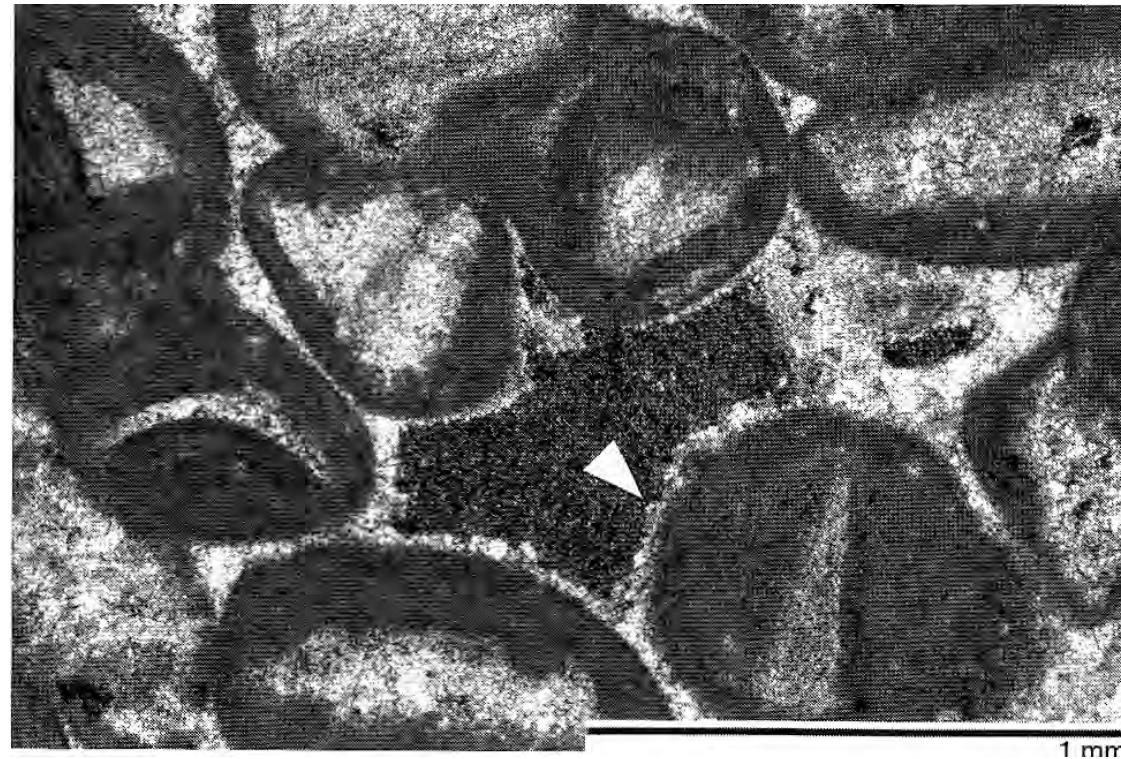
3. GRAINS = 3.8 MICRITIZED GRAINS

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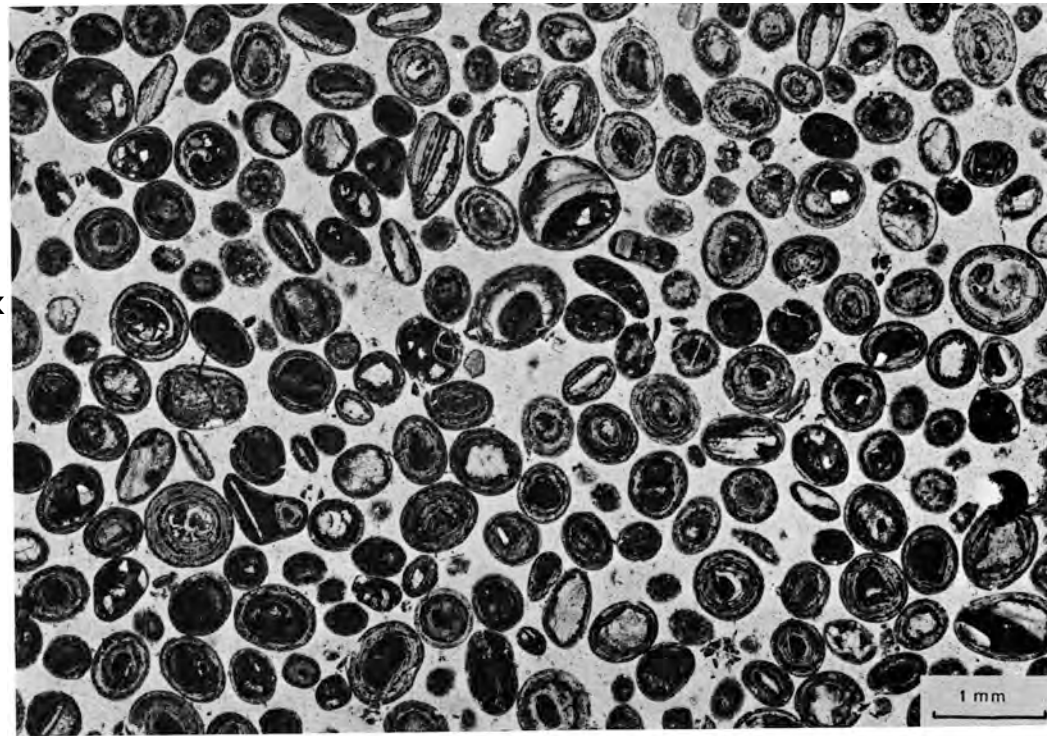
Partly micritized bioclasts
from a platform-marginal shoal.
adjacent to a grapestone facies.
Jurassic, Iran
(Fürsich et al 2003 in Flügel 2004)



PARTIAL
REPLACEMENT

Well developed concentric structure in ooids, apart a few specimen with a reduced cortex (= proto-ooids).

Elf Aquitaine, 1975

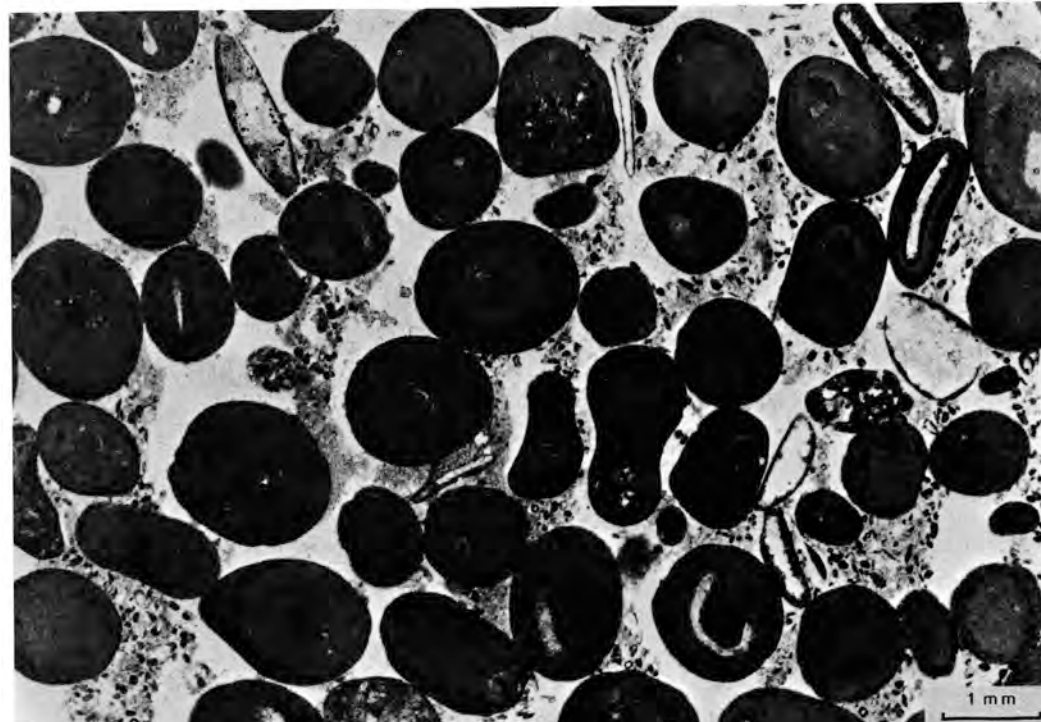


1

Micritized ooids.

Notice how the differences in the form of the nucleus influence the general form of the ooid.

Elf Aquitaine, 1975



PETROGRAPHY OF CARBONATES

3. GRAINS = 3.8 MICRITIZED GRAINS

GRAINS EXHIBITING MICRITIC ENVELOPES

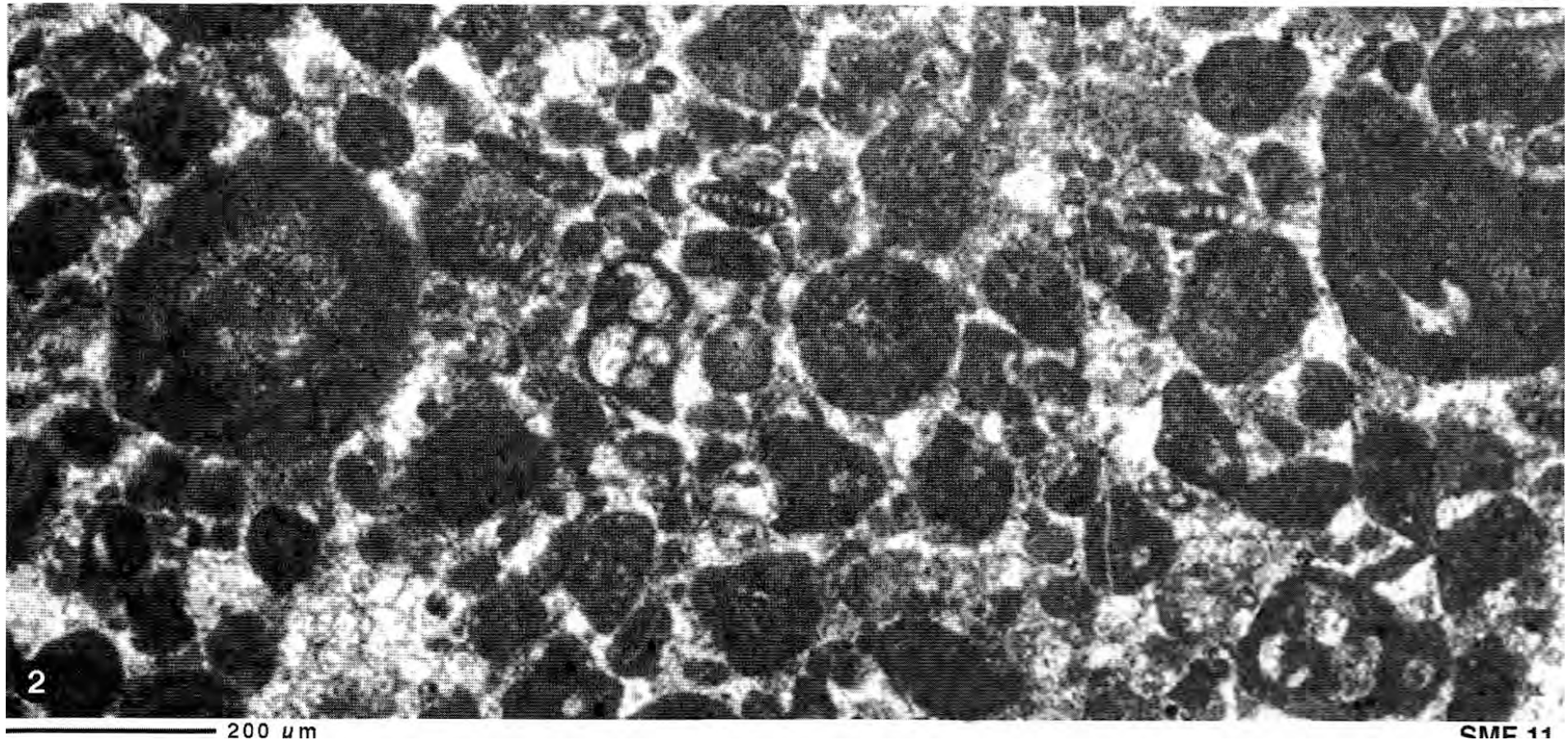
✓ GENESIS AND OCCURENCES

- MICRITIZATION processes are controlled by biological and chemical factors and take place in shallow- and deep-marine as well as in terrestrial and lacustrine environments
 - => described in great detail on aragonite skeletal grains from the Bahamas and the Persian
 - => on HMC skeletal grains from Florida and Belize
 - = = > loosening the surface, abrading and rounding carbonate grains, completely destroying the original structures
- persistent micritization => formation of carbonate mud (micrite)
- 'MICRITE ENVELOPE' (Bathurst 1964) : thin a few μm -500 μm , laminated coating of very fine micrite around carbonate grains (particularly skeletal grains and ooids) => modern envelope = aragonite
- micritized grains = 'mud coated grains'

PETROGRAPHY OF CARBONATES

3. **GRAINS = 3.8 MICRITIZED GRAINS**

GRAINS EXHIBITING MICRITIC ENVELOPES



Coated bioclastic grainstone : strongly micritized skeletal grains associated with small-sized benthic foraminifera. Isolated Bahamian-type carbonate platform, Middle Jurassic, Monte Kumeta, Sicily (in Flügel 2004).

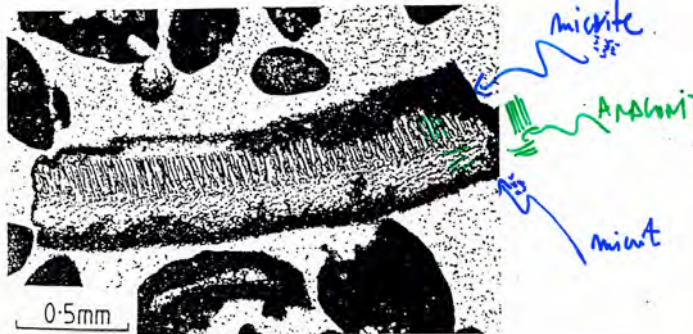
PETROGRAPHY OF CARBONATES

3. GRAINS = 3.8 MICRITIZED GRAINS

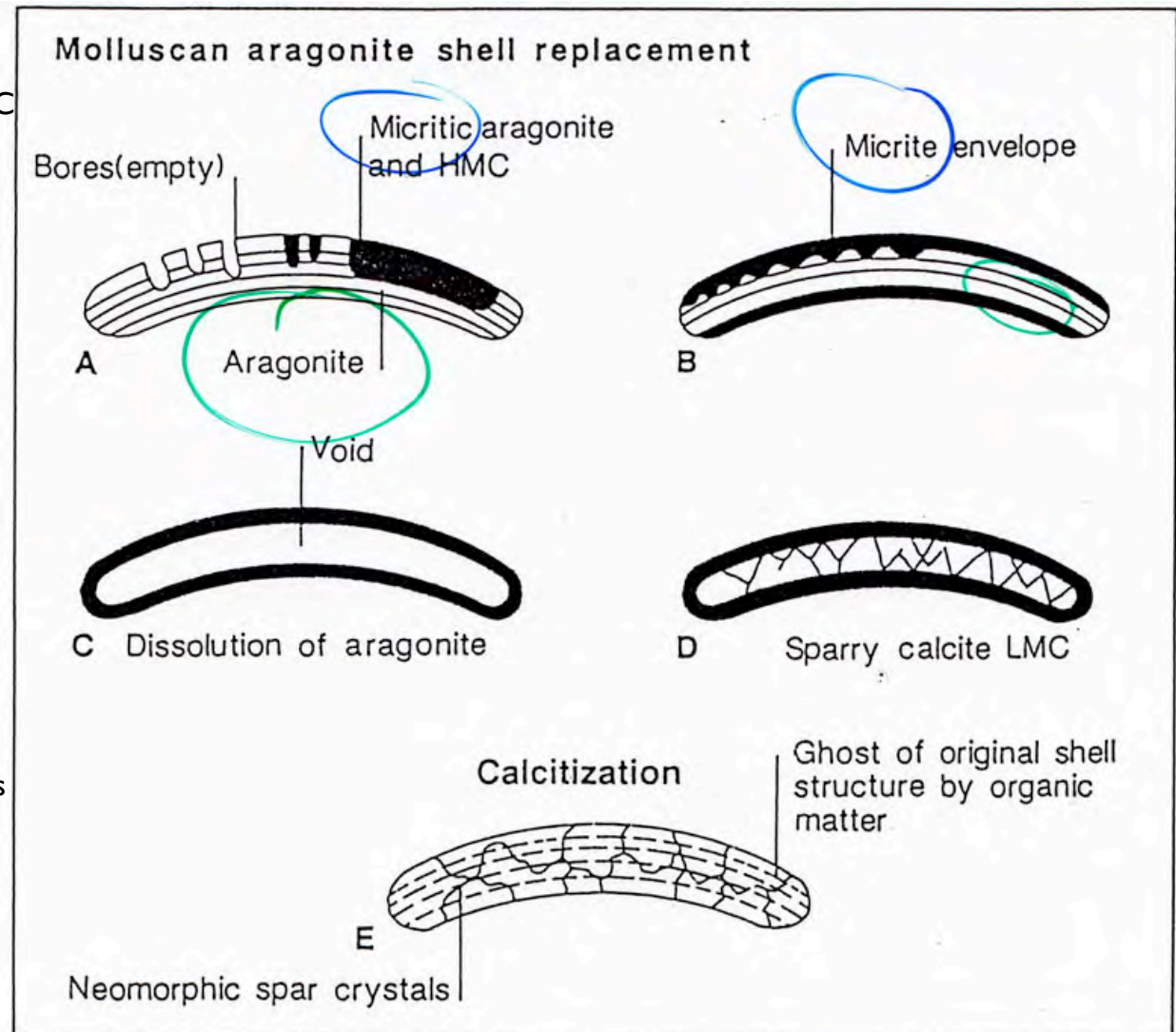
GRAINS EXHIBITING MICRITIC ENVELOPES

Dissolution of skeletal aragonite is a widespread diagenetic process. Most aragonite shells undergo **complete** dissolution and passive mould filling HMC

The shell shape is preserved in limestone because they are defined by micrite envelopes



Skeletal debris lying on the sea floor is attacked by endolithic (boring) microorganisms (algae, cyanobacteria, fungi) => the individual microborings become filled with micritic cement when vacated = = > rim or envelope



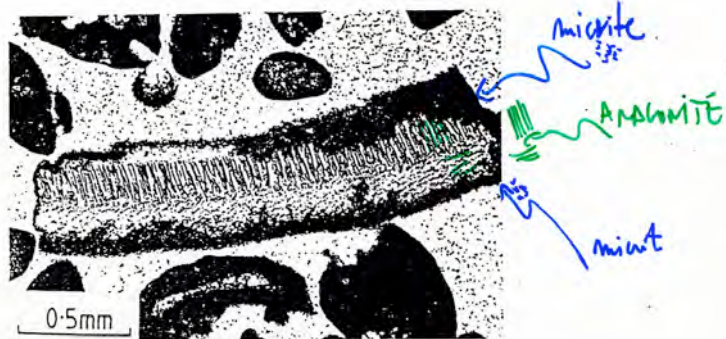
PETROGRAPHY OF CARBONATES

3. GRAINS = 3.8 MICRITIZED GRAINS

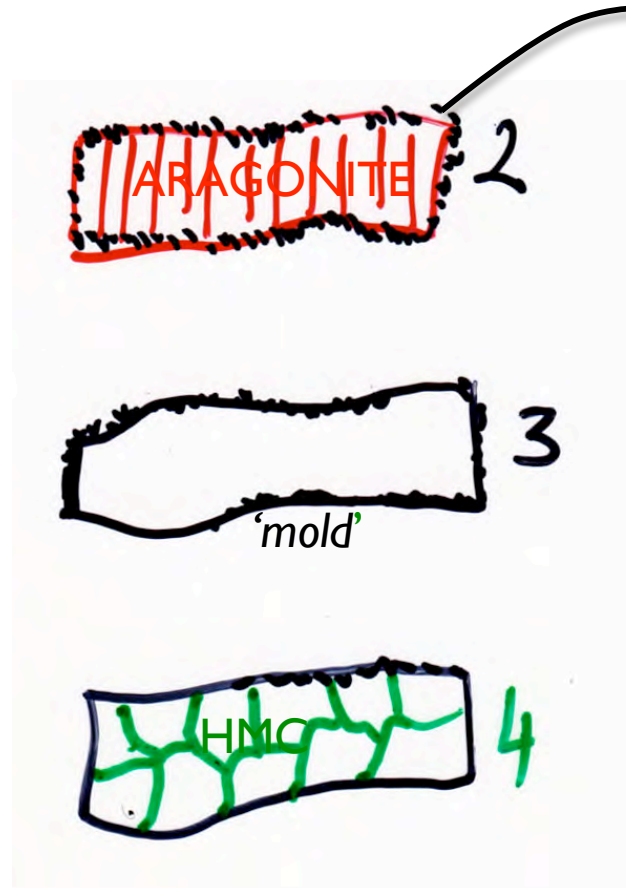
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1 Bivalve, or algal fragment or ooid....

2 Microbial micritization (also sponges)

3 exondation, dissolution arag preservation envelope

4 LMC

2-3-4 shallow nearshore facies salinity waters



confusion with lumps....

PERSIAN GULF

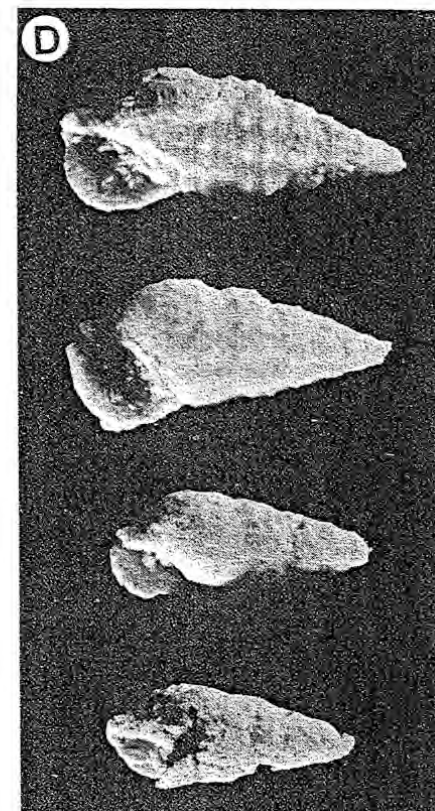
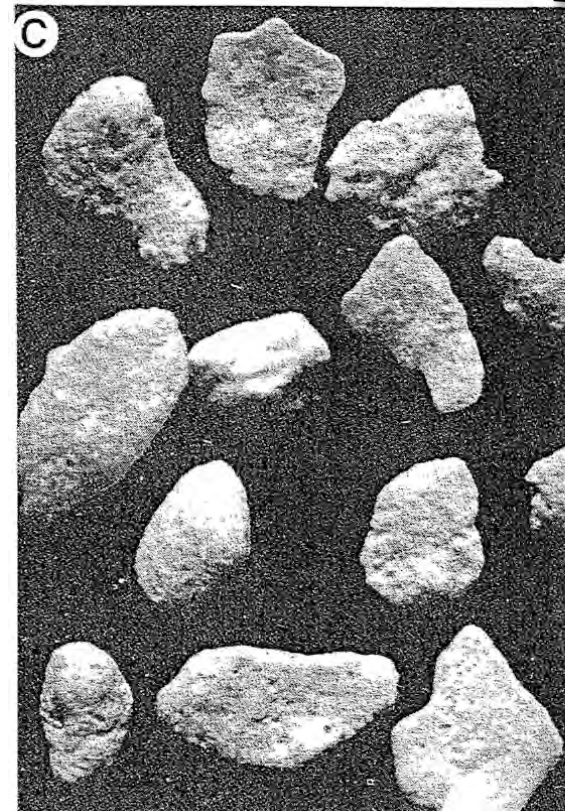
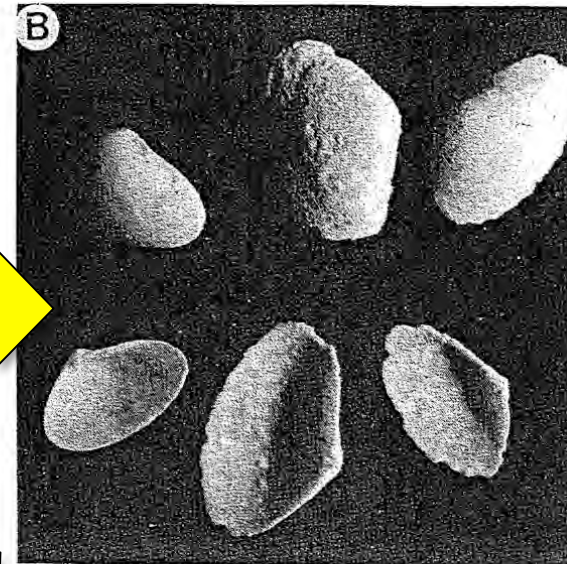
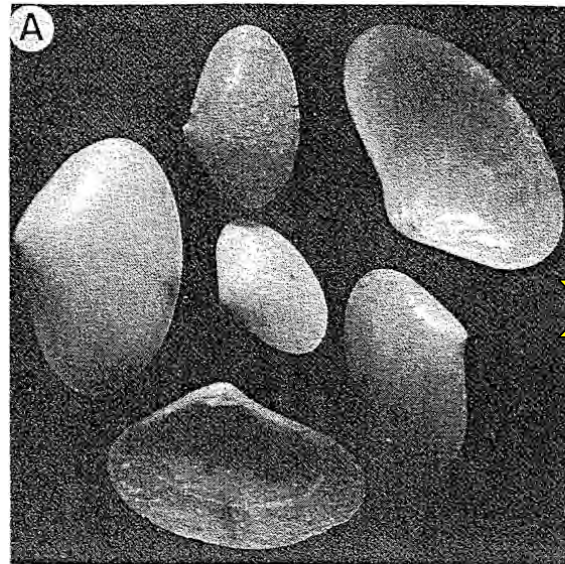
Purser 1980

Bivalve (*Ervillea*) A-C

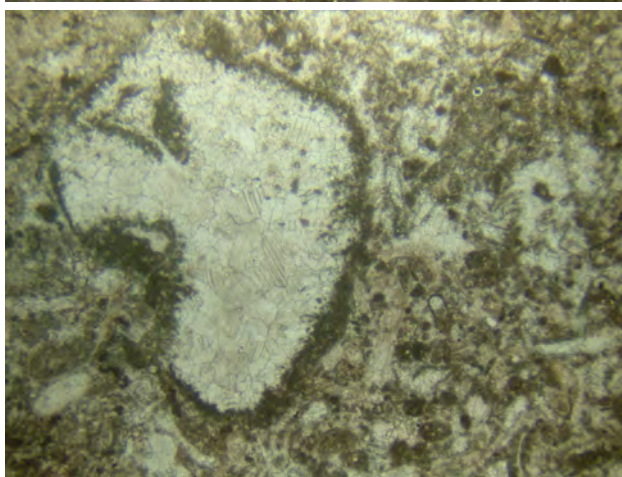
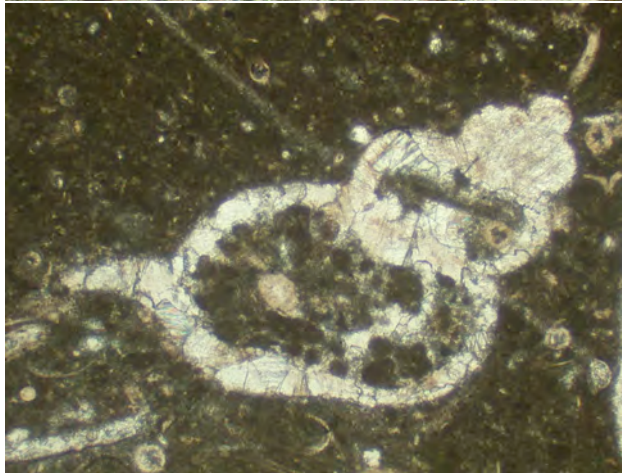
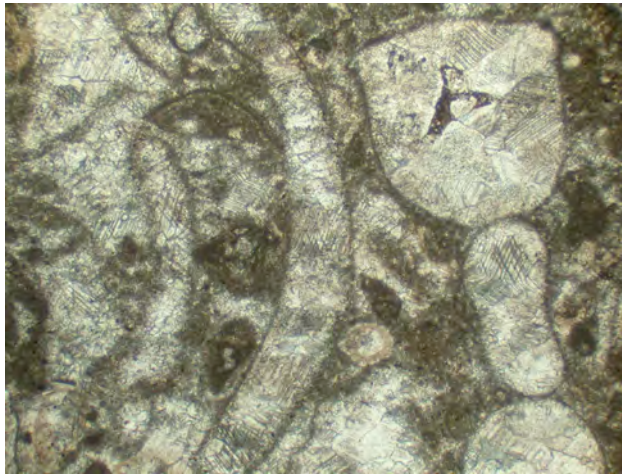
A. well preserved, non micritized,
B. chalky surface, worn, micritized,
C. strongly micritized

D. Gastropod (*Cerithium*)

increased micritization from top
to bottom



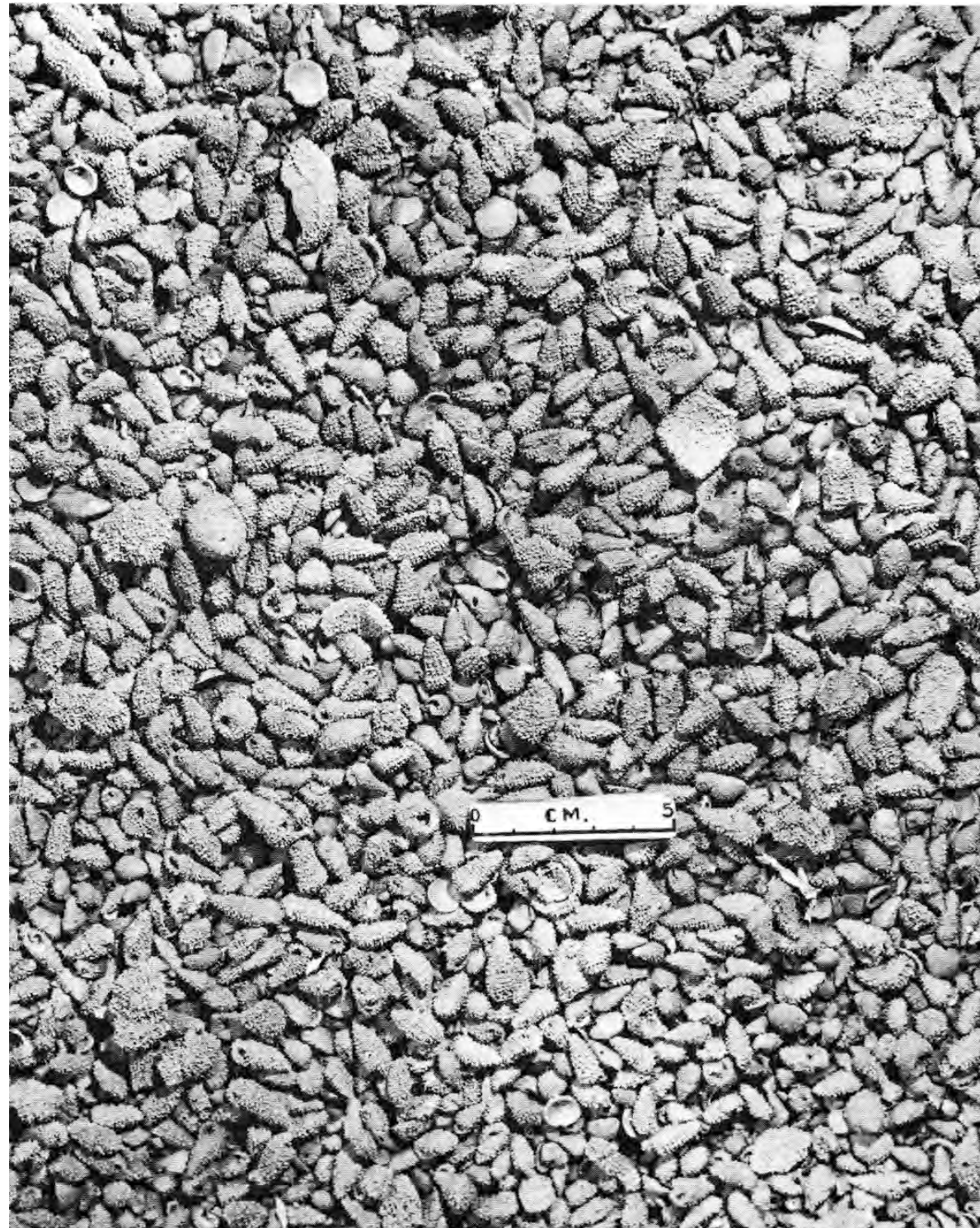
Molluskan packstone.
Organisms : micritized, dissolved,
filled with LMC.
Middle Devonian, Belgium, Pr  at



Natural accumulation
of cerithiid gastropods
each encrusted with
aragonite.

In shallow depression
in the higher part of
the supratidal zone.

Persian Gulf,
Purser & Loreau 1973



PETROGRAPHY OF CARBONATES

1. MATRIX

2. CEMENT

3. GRAINS

**A carbonate grain tells a story \neq A clastic grain
('highly sensitive' > < 'inert')**

4 . FABRICS