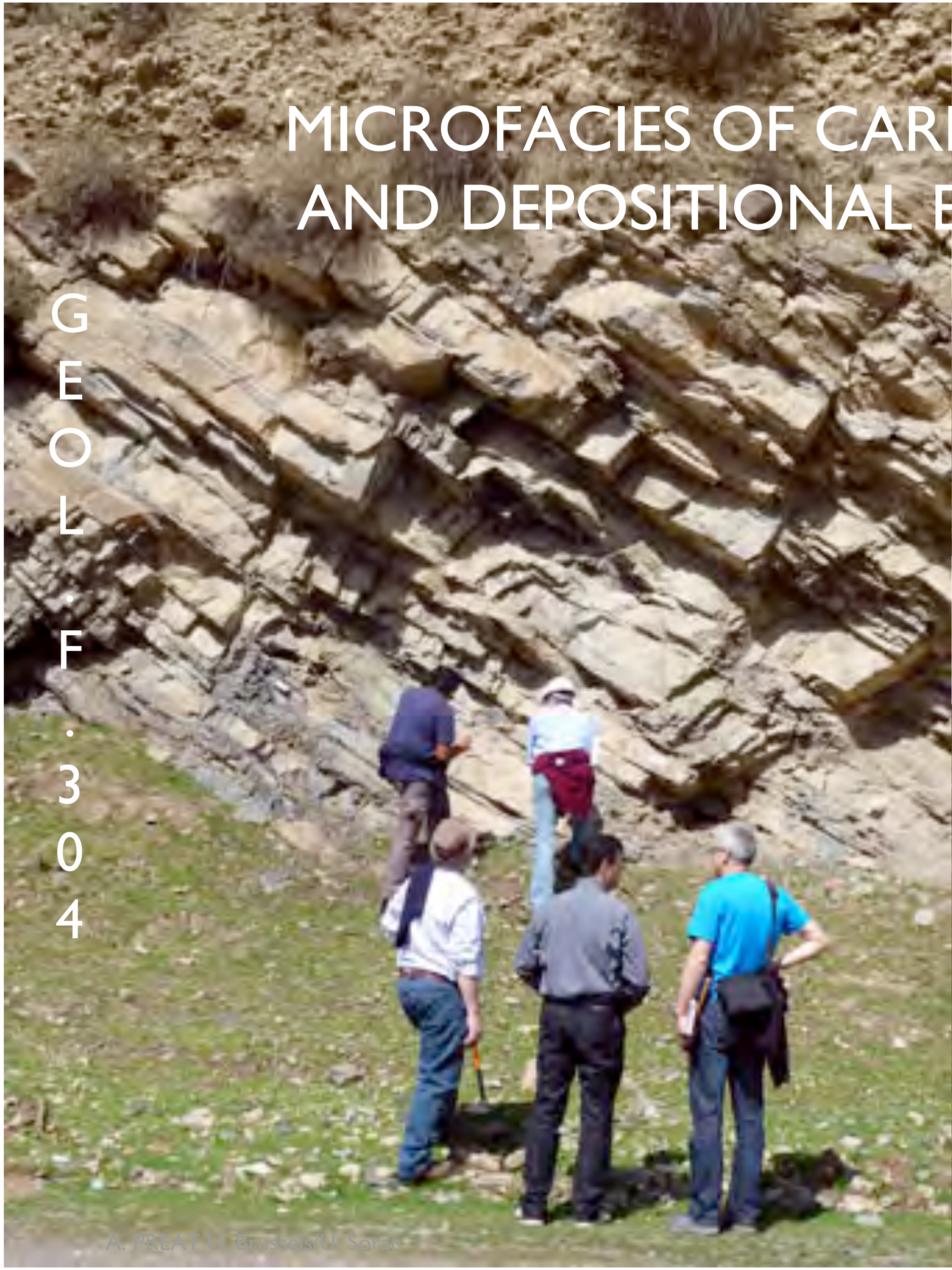
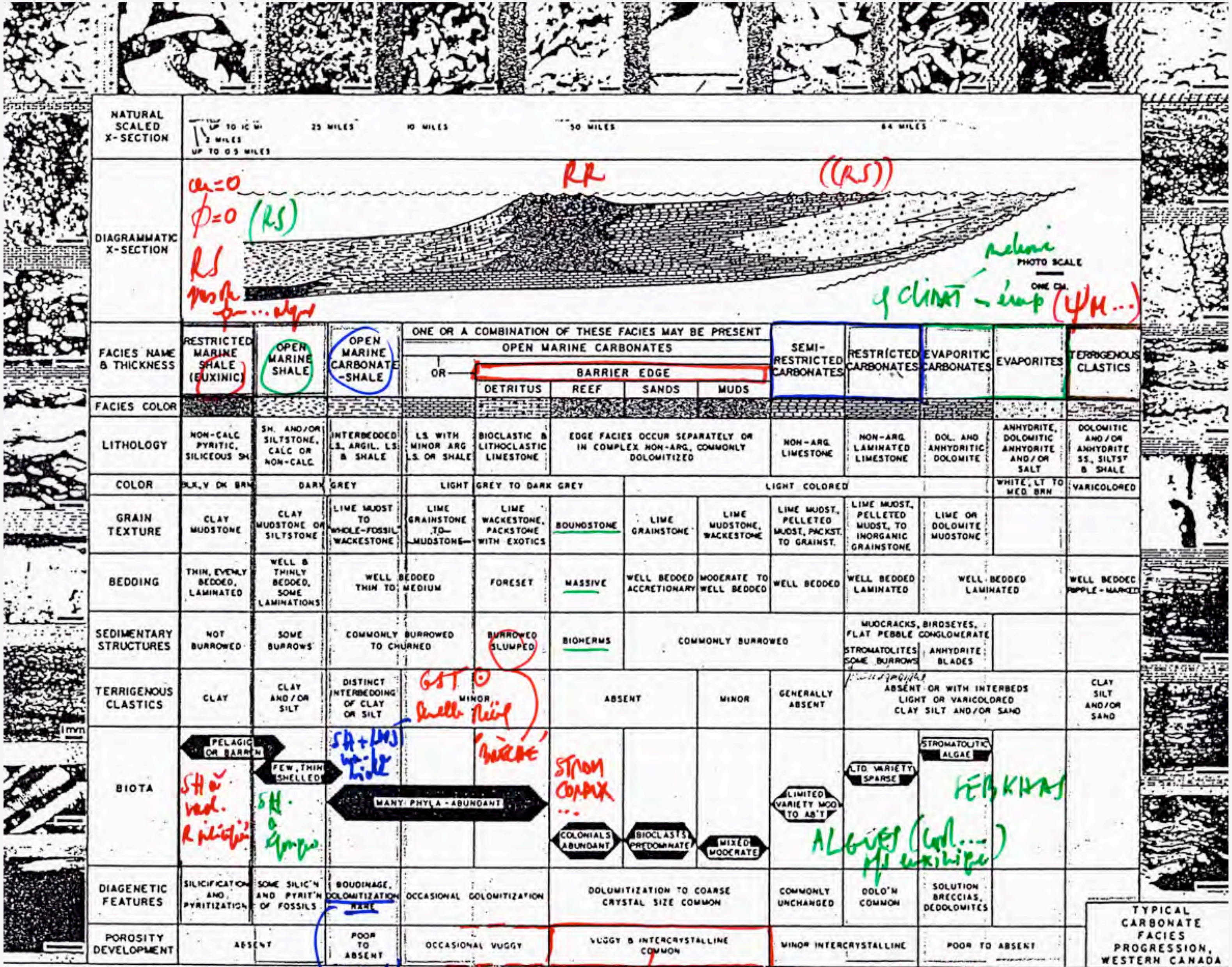
MICROFACIES OF CARBONATE ROCKS AND DEPOSITIONAL ENVIRONMENTS

GEOL-F-304



Prof. Alain Préat
Free University of Brussels

THE ESSO MODEL –FRASNIAN/FAMENNIAN, W CANADA



NATURAL SCALED X-SECTION	UP TO 10 MI / 2 MILES / UP TO 0.5 MILES		25 MILES	10 MILES			50 MILES				64 MILES		
DIAGRAMMATIC X-SECTION													
FACIES NAME & THICKNESS	RESTRICTED MARINE SHALE (EUXINIC)	OPEN MARINE SHALE	OPEN MARINE CARBONATE-SHALE	ONE OR A COMBINATION OF THESE FACIES MAY BE PRESENT — OPEN MARINE CARBONATES — OR	BARRIER EDGE — DETRITUS	BARRIER EDGE — REEF	BARRIER EDGE — SANDS	BARRIER EDGE — MUDS	SEMI-RESTRICTED CARBONATES	RESTRICTED CARBONATES	EVAPORITIC CARBONATES	EVAPORITES	TERRIGENOUS CLASTICS
FACIES COLOR													
LITHOLOGY	NON-CALC PYRITIC, SILICEOUS SH	SH. AND/OR SILTSTONE, CALC OR NON-CALC	INTERBEDDED LS, ARGIL. LS & SHALE	LS WITH MINOR ARG LS OR SHALE	BIOCLASTIC & LITHOCLASTIC LIMESTONE	EDGE FACIES OCCUR SEPARATELY OR IN COMPLEX NON-ARG, COMMONLY DOLOMITIZED			NON-ARG LIMESTONE	NON-ARG LAMINATED LIMESTONE	DOL. AND ANHYDRITIC DOLOMITE	ANHYDRITE, DOLOMITIC ANHYDRITE AND/OR SALT	DOLOMITIC AND/OR ANHYDRITE SS., SILTST & SHALE
COLOR	BLK, V DK BRN	DARK GREY		LIGHT GREY TO DARK GREY			LIGHT COLORED					WHITE, LT TO MED BRN	VARICOLORED
GRAIN TEXTURE	CLAY MUDSTONE	CLAY MUDSTONE OR SILTSTONE	LIME MUDST TO WHOLE-FOSSIL WACKESTONE	LIME GRAINSTONE TO MUDSTONE	LIME WACKESTONE, PACKSTONE WITH EXOTICS	BOUNDSTONE	LIME GRAINSTONE	LIME MUDSTONE, WACKESTONE	LIME MUDST., PELLETED MUDST., PACKST. TO GRAINST.	LIME MUDST., PELLETED MUDST., TO INORGANIC GRAINSTONE	LIME OR DOLOMITE MUDSTONE		
BEDDING	THIN, EVENLY BEDDED, LAMINATED	WELL & THINLY BEDDED, SOME LAMINATIONS	WELL BEDDED THIN TO MEDIUM		FORESET	MASSIVE	WELL BEDDED ACCRETIONARY	MODERATE TO WELL BEDDED	WELL BEDDED	WELL BEDDED LAMINATED	WELL BEDDED LAMINATED		WELL BEDDED RIPPLE-MARKED
SEDIMENTARY STRUCTURES	NOT BURROWED	SOME BURROWS	COMMONLY BURROWED TO CHURNED		BURROWED SLUMPED	BIOHERMS	COMMONLY BURROWED			MUDCRACKS, BIRDSEYES, FLAT PEBBLE CONGLOMERATE — STROMATOLITES SOME BURROWS	ANHYDRITE BLADES		
TERRIGENOUS CLASTICS	CLAY	CLAY AND/OR SILT	DISTINCT INTERBEDDING OF CLAY OR SILT	MINOR		ABSENT		MINOR	GENERALLY ABSENT	ABSENT OR WITH INTERBEDS LIGHT OR VARICOLORED CLAY SILT AND/OR SAND			CLAY SILT AND/OR SAND
BIOTA	PELAGIC OR BARREN	FEW, THIN SHELLED	MANY PHYLA - ABUNDANT			COLONIALS ABUNDANT	BIOCLASTS PREDOMINATE	MIXED MODERATE	LIMITED VARIETY MOD TO AB'T	LTD. VARIETY SPARSE	STROMATOLITIC ALGAE		
DIAGENETIC FEATURES	SILICIFICATION AND PYRITIZATION	SOME SILIC'N AND PYRIT'N OF FOSSILS	BOUDINAGE, DOLOMITIZATION RARE	OCCASIONAL DOLOMITIZATION		DOLOMITIZATION TO COARSE CRYSTAL SIZE COMMON			COMMONLY UNCHANGED	DOLO'N COMMON	SOLUTION BRECCIAS, DEDOLOMITES		
POROSITY DEVELOPMENT	ABSENT		POOR TO ABSENT	OCCASIONAL VUGGY		VUGGY & INTERCRYSTALLINE COMMON			MINOR INTERCRYSTALLINE		POOR TO ABSENT		

TYPICAL CARBONATE FACIES PROGRESSION, WESTERN CANADA

THE ESSO MODEL –FRASNIAN/FAMENNIAN, W CANADA

1. EUXINIC RESTRICTED ENVIRONMENT
Radiolarian shales, silicified algae
No porosity => no reservoir rocks
Source rocks if anoxia (for example no bioturbation)

2. OPEN MARINE ENVIRONMENT
Shales with sponges, few shells
Potential source rocks

3. OPEN MARINE ENVIRONMENT
Carbonate shales, wackestones-packstones with bryozoans, forams, mollusks, algae
If dolomitization (rare) => potential porosity (10% or more)

4. REEFAL COMPLEX
4.1. REEFAL SOLE = substratum stabilized by cements and/or organisms
4.2. REEFAL BRECCIA = detritus. Fore-reef with detritus removed by storms
+ slumps if 'steep' slope
4.3. REEFS with stromatoporoids, tabulata and algae = BIOHERMS
High porosities increasing with dolomitization => important reservoir rocks
4.4. SANDS = fine- medium-grained (reefal) bioclasts, important dolomitization => reservoir rocks
4.5. MUDS = back-reef area, very fine-grained (reefal) altered (rounded, abraded) bioclasts.
Strong dolomitization but low permeability.

THE ESSO MODEL –FRASNIAN/FAMENNIAN, W CANADA

5. SEMI-RESTRICTED ENVIRONMENT

Marine water (= salty) STILL present in the lagoon

⇒ two types of lagoon

(i)hypersaturated-hypersaline : along the land area, with aridity => EVAPORITES

(ii)subsaturated-brackish with meteoric water inputs => HUMID CLIMATE

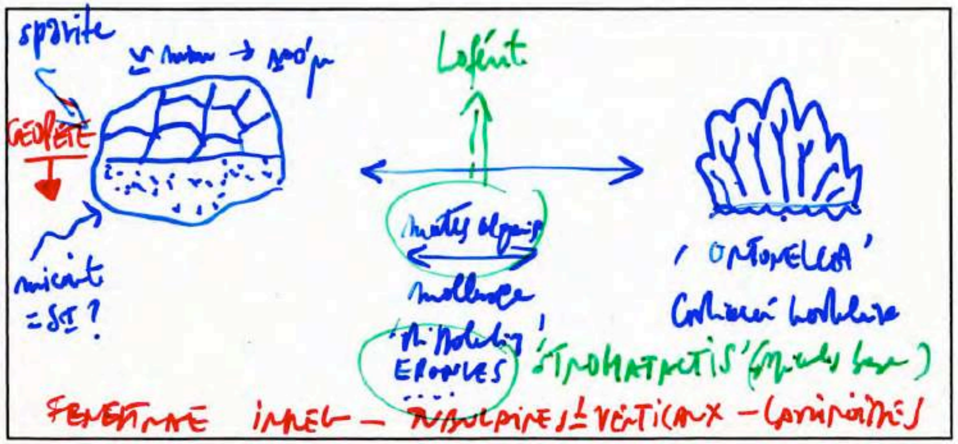
nb pellets: very abundant

6. RESTRICTED ENVIRONMENT (sometimes euxinic => source rocks)

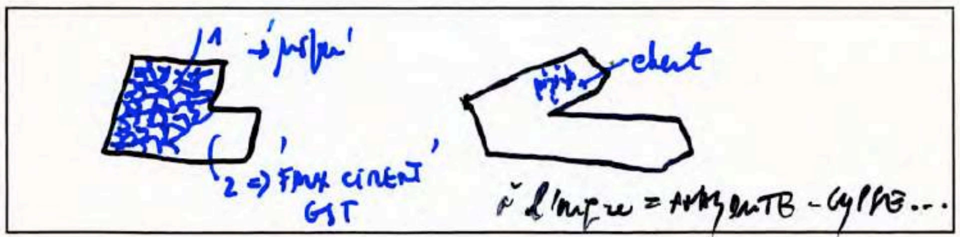
Cyanobacteria and algae, ostracods, gastropods … and production of 'true' pellets

Potential strong dolomitization with consequent intercrystalline porosities => reservoir rocks

No clastics excepted aeolian (dust)…



formation pseudomorphes (sulfates)



wackestones => loferites/dismicrites

BIRDSEYES/FENESTRAE

wackestones => packstones-'FALSE' grainstones

THE ESSO MODEL –FRASNIAN/FAMENNIAN, W CANADA

7 and 8. CARBONATES/EVAPORITES AND EVAPORITES

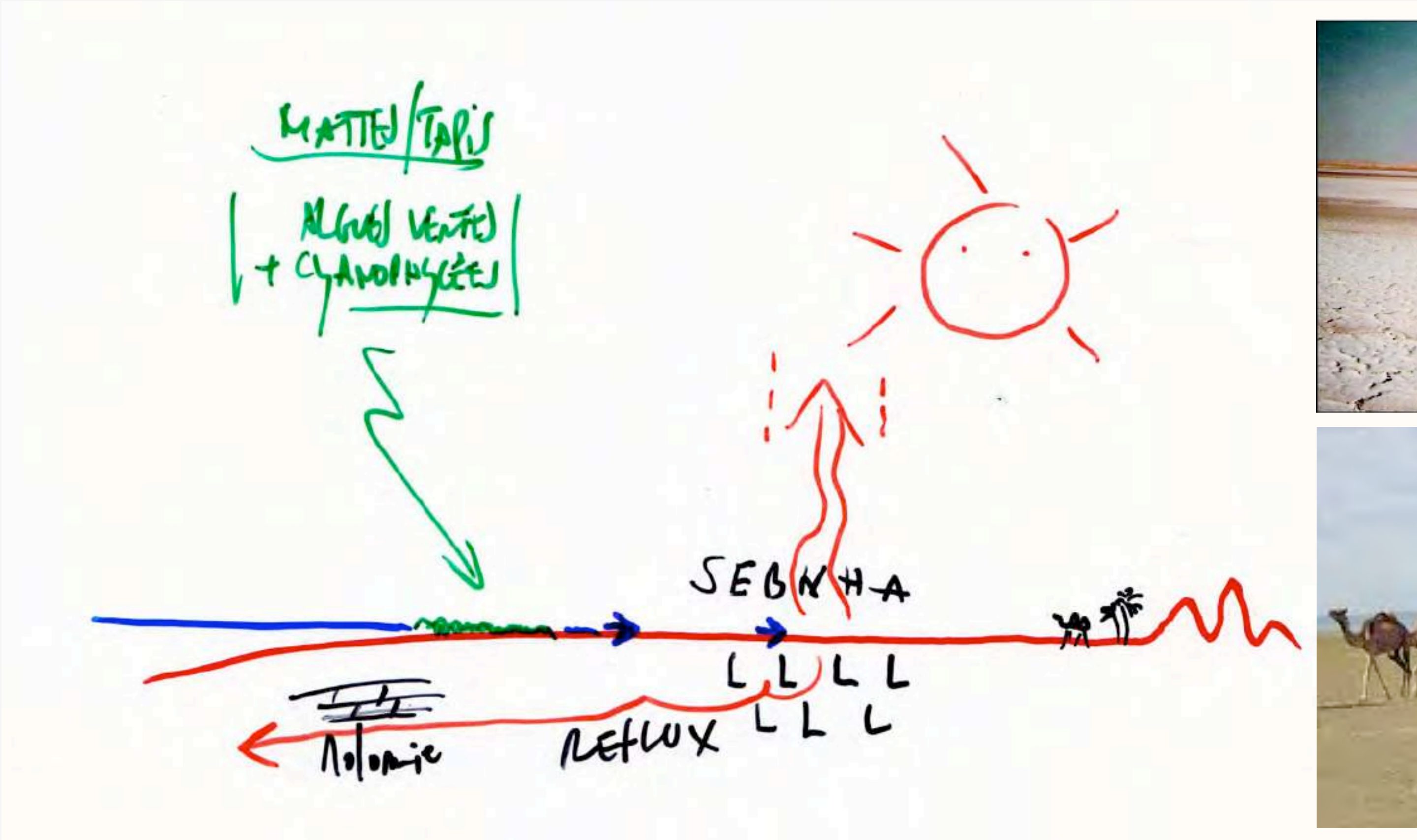
STROMATOLITES, CYANOBACTERIA, ?FUNGI

Breccia = 'COLLAPSE BRECCIA'

Heavy dolomitization (wiping original petrofabtrics) and dedolomitization or (re)calcitization = creation and destruction of porosities => potential source/reservoir/seal rocks

Sometimes: 'metamorphic aspect of the rock (limestone)

This Facies Belts (7 & 8) are typical of SEBKHA (cf Persian Gulf) environments



Water is slightly saturated with 10cm-heigh with microbial mats. During annual high tides or storms, the sea invades the sebkha and stays one month leading to evaporitic precipitation. Reflux dolomitic brines escape downward…

THE ESSO MODEL –FRASNIAN/FAMENNIAN, W CANADA

7 and 8. CARBONATES/EVAPORITES AND EVAPORITES

BEAR IN MIND

(i)capillar evaporites (sebkha) < > basinal evaporites ('Schmälz' evaporites)

(ii)EVAPORITES ARE A DIAGENETIC PRODUCT, NOT A TRUE SEDIMENT
= '*intrasediment precipitates*'

(iii) Evaporites are chemical sediments precipitated from brines in a wide range of depositional settings (> 40 minerals, most comon = gypsum, anhydrite, halite sylvite, polyhalite ….

- = rocks formed by precipitation of salts from aqueous **solutions as water is removed** and ionic species become **more concentrated** => good indicators of paleoclimate and of chemistry of ancient water sea waters, lake waters and other surface waters
- they may be major sources of solutes for deep-circulating hydrothermal brines ans sedimentary basinal sediments => association with ore deposits and oil fields

= > subaqueous accumulations of surface–nucleated crystals
= > subaqueous bottom precipitates or crusts
= > diagnenetically emplaced intrasediment precipitates
= > clastic accumulations of eavporite particles

- after formation evaporites are subject to many early diagenetic processes
  => alteration (weak to total) the original mineralogy and sediment fabric
  => complete removal by dissolution
  => induce sedimentary processes : slumps, collapse, tepees, diapirs … deformations ….

THE ESSO MODEL –FRASNIAN/FAMENNIAN, W CANADA

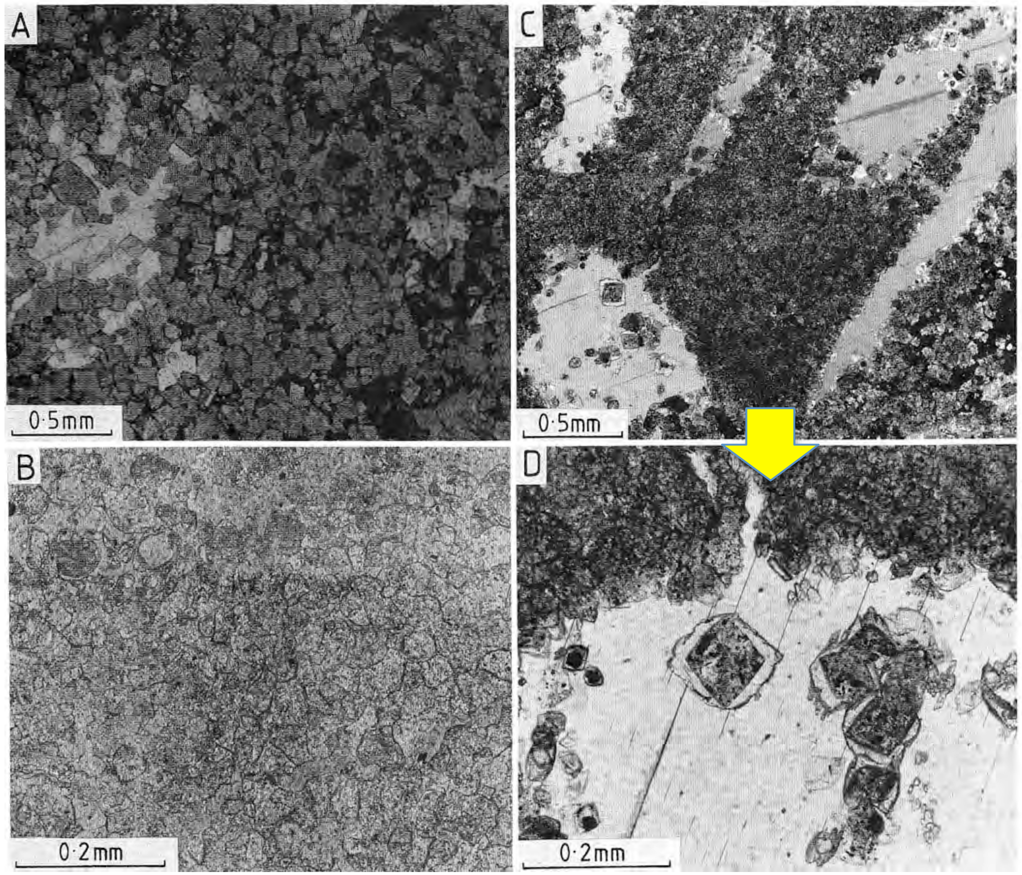
7 and 8. CARBONATES/EVAPORITES AND EVAPORITES

BEAR IN MIND

(i)DOLOMITES ARE PENECONTEMPORANEOUS (SEBKHA)
(ii)DOLOMITES CAN BE SCHIZOHALINE (METEORIC MIXING)
(iii)DOLOMITES CAN BE RELATED TO BURIAL (HT)
(iv)DOLOMITES CAN BE RELATED TO MARINE ENVIRONMENTS

…

Idiotopic
= euhedral rhombs
after= patchy poikilotopic
anhydrite (white)
after = oil emplacement (dark)



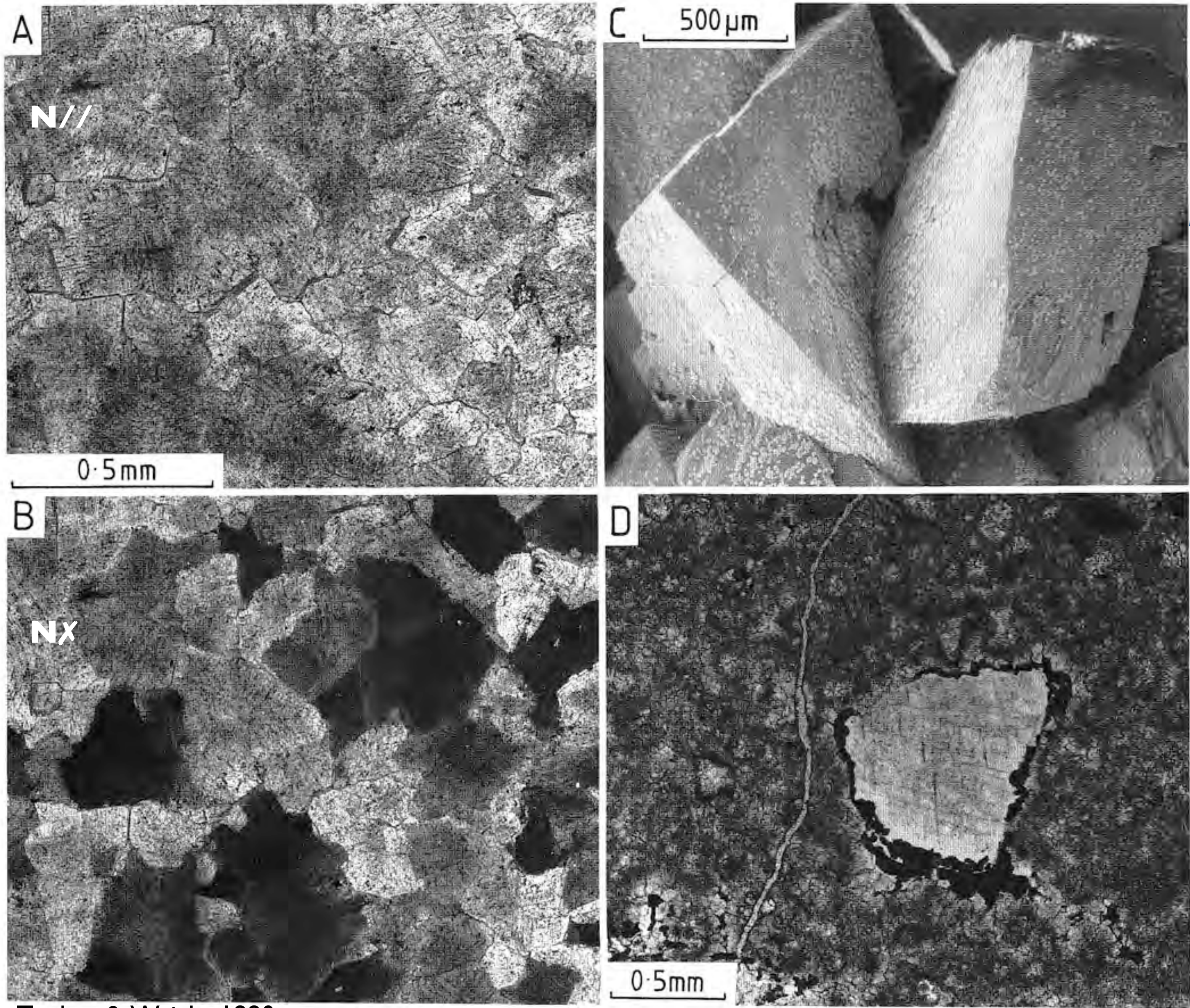
Fine xenotopic dolomite crystals
with poikilotopic gypsum
with cloudy rhombs (**D**)
in a nummulite, Eocene,
Tunisia

Xenotopic mosaic
of anhedral dolomite crystals
A, B Jurassic, Arkansas

Tucker & Wright 1990

7 and 8. CARBONATES/EVAPORITES AND EVAPORITES
DOLOMITES

Baroque or saddle dolomite with a xenotopic texture *Gully Oolite, Lower Carboniferous, South Wales*



SEM, *curved crystal faces, Lower Carboniferous, NW UK*

Baroque dol *in an algal gst with bitumen, Late PCm, Morocco*

Tucker & Wright 1990

BAROQUE-SADDLE DOLOMITE, CRETACEOUS, IRAK

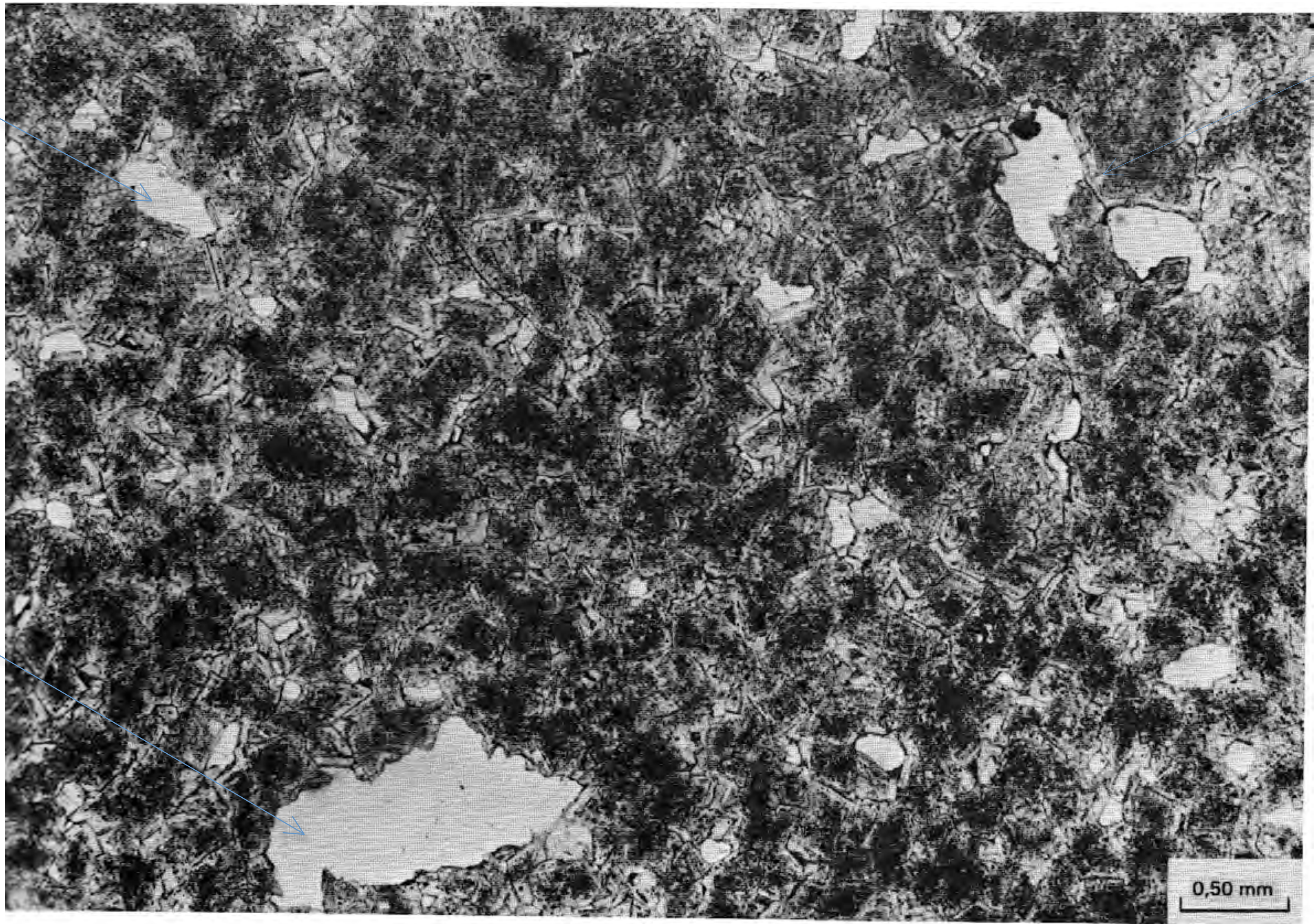
Préat 2011

7 and 8. CARBONATES/EVAPORITES AND EVAPORITES

DOLOMITES

Φ

micritic 'relicts
=
former
mud-supported
facies

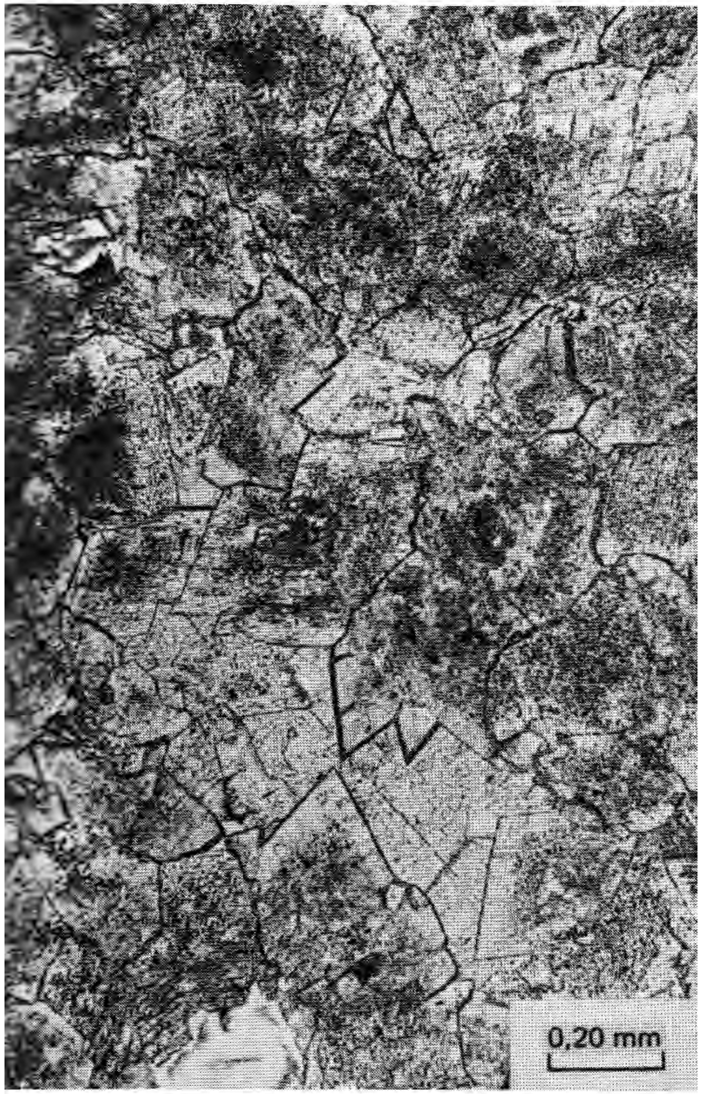


Poronecrosis by dolomitization and growth of hypidiotopic dolomite rhombs,
Shelf deposit from the Upper Cretaceous, SW France (Elf Aquitaine, 1975)

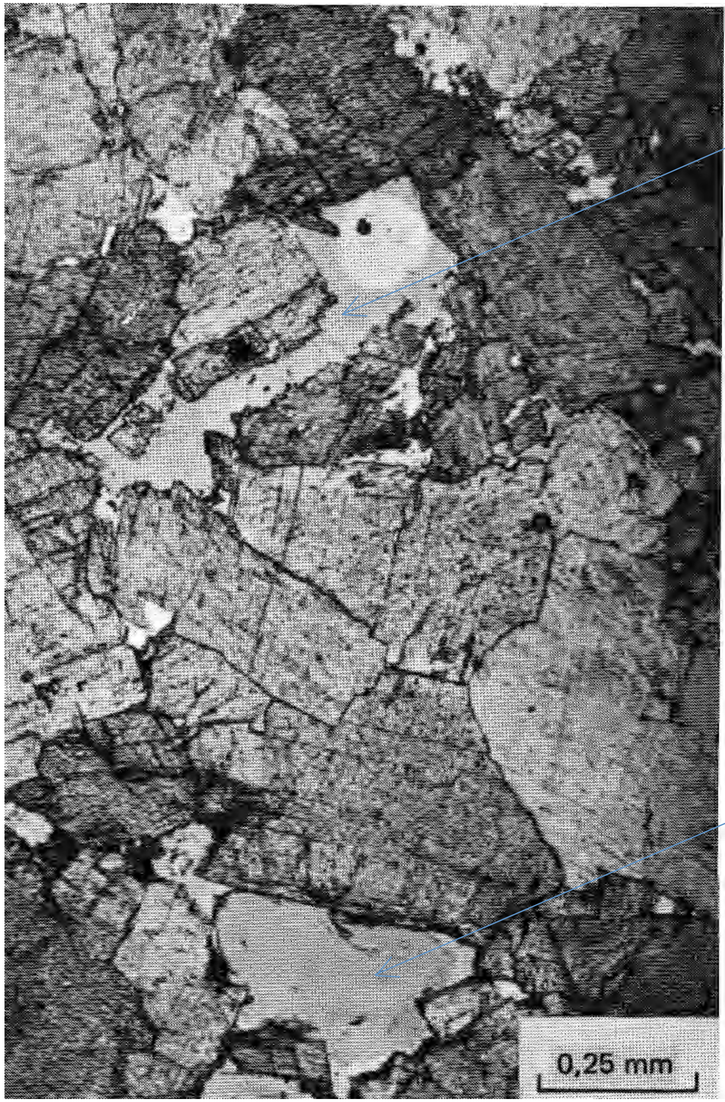
7 and 8. CARBONATES/EVAPORITES AND EVAPORITES

DOLOMITES

micritic ‘relicts
=
former
‘grains’



***Complete** poronecrosis by plane boundaries of hypidiotopic rhombs in a high energy level, Jurassic, SE, France, Elf Aquitaine 1975*



Φ

Φ

***Porosity development** due to local solution of a plane boundary dolomite , Elf Aquitaine 1975*

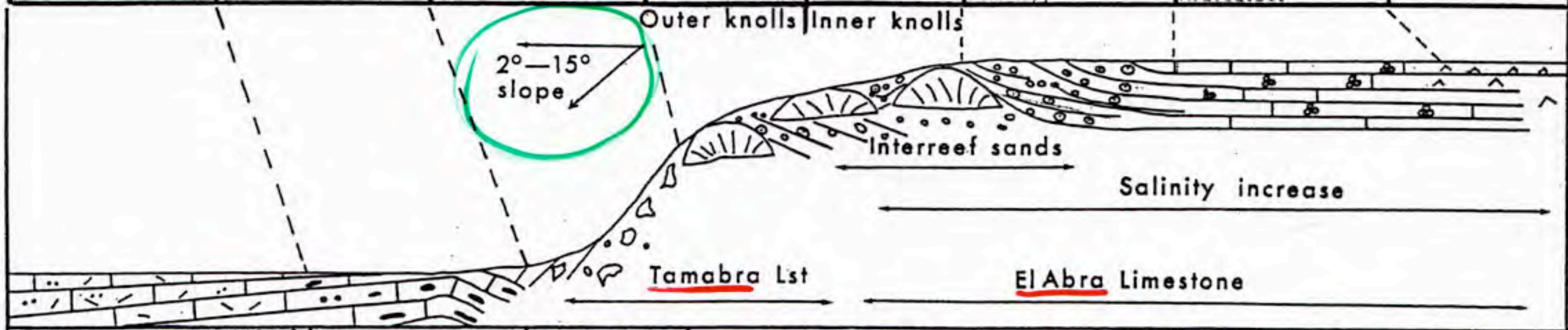
THE ESSO MODEL –FRASNIAN/FAMENNIAN, W CANADA

9. CLASTICS/TERRIGENOUS
= 'CONTINENTAL' SANDSTONES….
with or without evaporation => evaporites + true continental evaporites (chotts, lakes….)


Chott El-Jérid, South Tunisia, width 120 km

'MIDDLE' CRETACEOUS MODEL

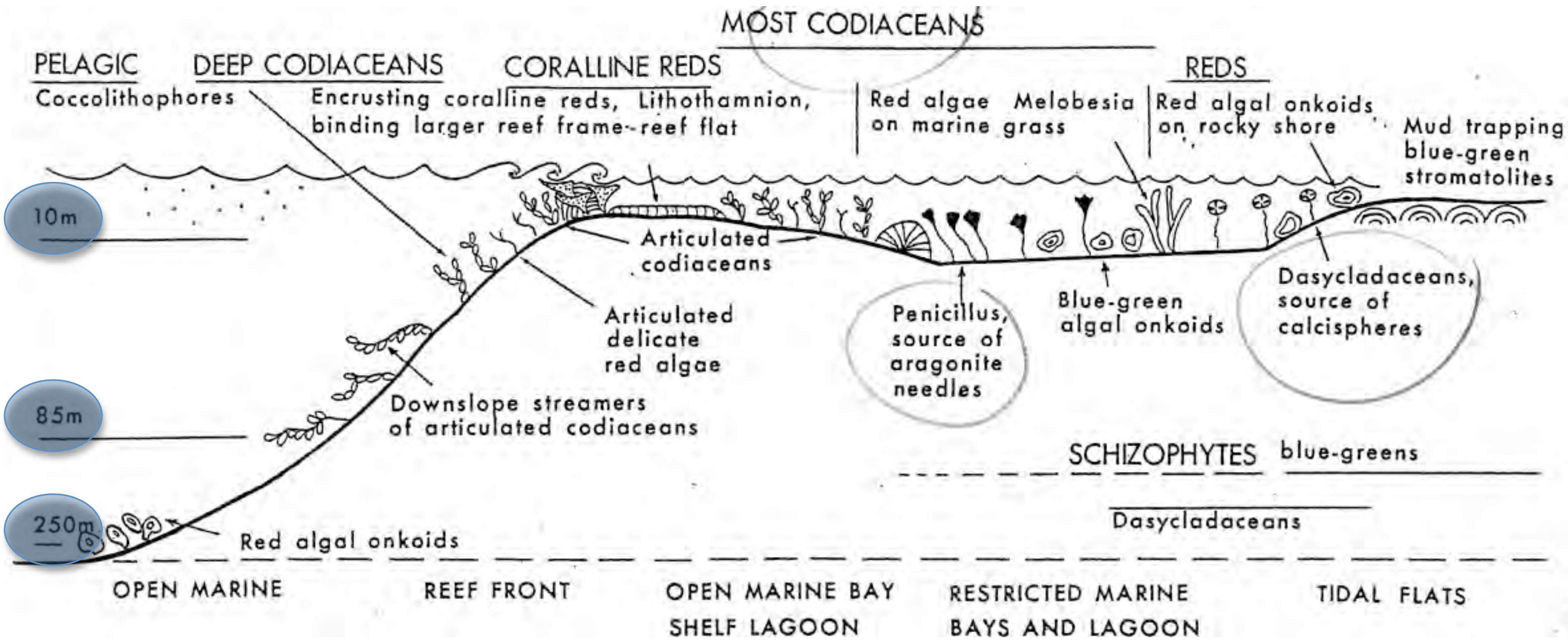
	FACIES 1	FACIES 3	FACIES 4	FACIES 5a 5b		FACIES 6	FACIES 8	FACIES 9
MICROFACIES	LIGHT TO DARK. LAMINATE TO HOMOGENEOUS, PELAGIC MICRITE, FINELY CALCARENITIC IN PLACES.	DARK MICROBIOCLASTIC AND PELAGIC MICRITE THICK TO THIN RHYTHMIC BEDDING. DARK CHERT NODULES. SLUMP STRUCTURES.	COARSE LITHOCLASTIC-BIOCLASTIC, BOULDERS IMBEDDED IN MICRITE.	MICRITE RUDIST KNOLLS WITH CREAMY, SHELLY, THICK-BEDDED LIMESTONE. ← OVERLAPPING		OOLITIC-BIOCLASTIC GRAINSTONE FACIES →	LIGHT COLORED MICRITE, THIN TO MEDIUM BEDS. MINOR CYCLES OF MILIOLID GRAINSTONE; BIOTURBATED WACKESTONE TO LAMINATED FENESTRAL MICRITE DOLOMITE CRUSTS	ANHYDRITE FACIES WITHIN GOLDEN LANE BANK.
BIOTA	PLANKTONIC MICROFOSSILS: AMMONITES, GLOBIGERINIDS, TINTINNIDS.	PLANKTONIC MICROFOSSILS: AMMONITES, GLOBIGERINIDS, TINTINNIDS, MICROPELOIDS.	MIXED BIOTA, MAINLY DEBRIS FROM UPSLOPE, (5A)	CAPRINIDS, RADIOLITIDS, COLONIAL CORALS, STROMATOPOROIDS, ENCRUSTING ALGAE, PHOLAD (BORING CLAMS), DICTYOCONUS (BENTHONIC FORAM).	CAPRINIDS DOMINATE, TOUCASIA ON MOUND TOPS, CHONDRODONTA AT TOP. NERINEA. (LARGE FORAMS), MILIOLIDS.	CAPRINID DEBRIS SAUVEGESIA (RAD.) NERINEA PARKERIA (STROM.) SOLENOPORA (RED ALGA) CODIACEAN DASYCLADACEAN MILIOLIDS, (LARGE FORAMS).	RESTRICTED BIOTA, ALGAL STROMATOLITES. BIOSTROMES OF REQUIENIA & TOUCASIA. GRYPHAEA WHEN MARLY, DASYCLADACEANS, DICYCLINA, MILIOLIDS.	ESSENTIALLY NO BIOTA EXCEPT MILIOLIDS.



EXTENT				
BATHYAL-TAMAULIPAS FACIES many km wide	TOE OF SLOPE TAMAULIPAS 2km wide	FOREREEF CLASTICS 2km wide	SHELF MARGIN KNOLLS AND PATCH REEFS few km wide	INNER BANK 100km across

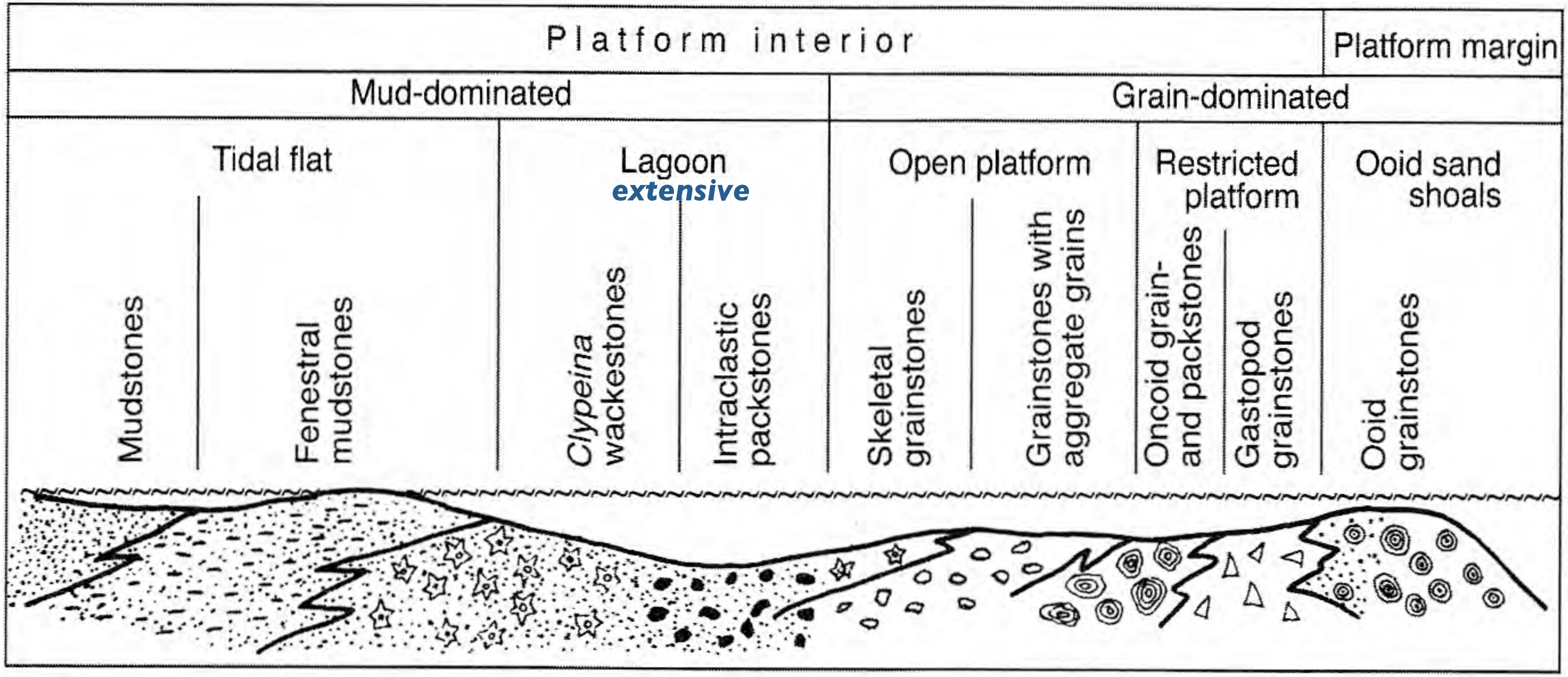
Idealized middle Cretaceous facies across large offshore banks in central Mexico. Biofacies from Bonet 1952, Griffith et al 1969.

MODERN ALGAL DISTRIBUTION



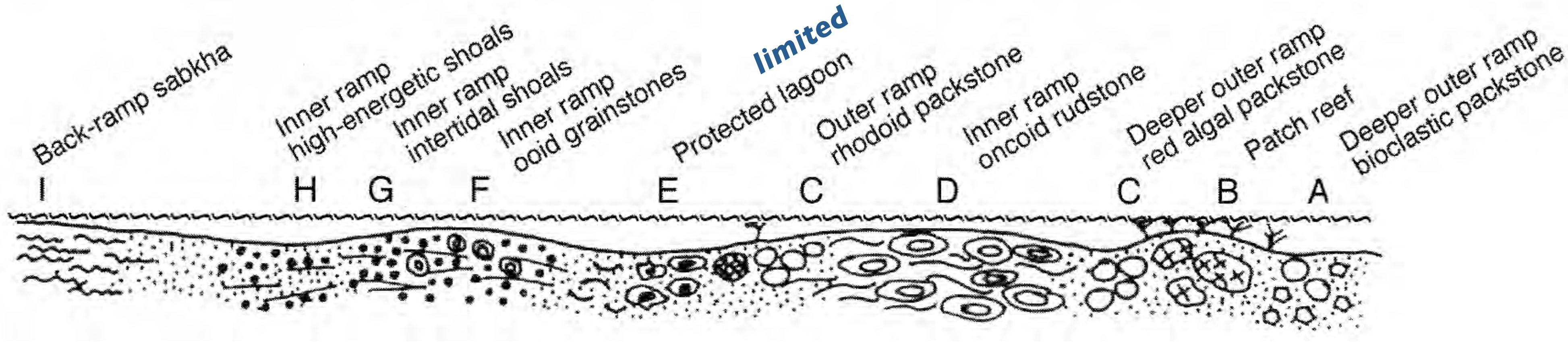
Ecology of calcareous marine algae, depositional environments along an idealized profile of a carbonate shelf margin.

JURASSIC BAHAMIAN-TYPE PLATFORM



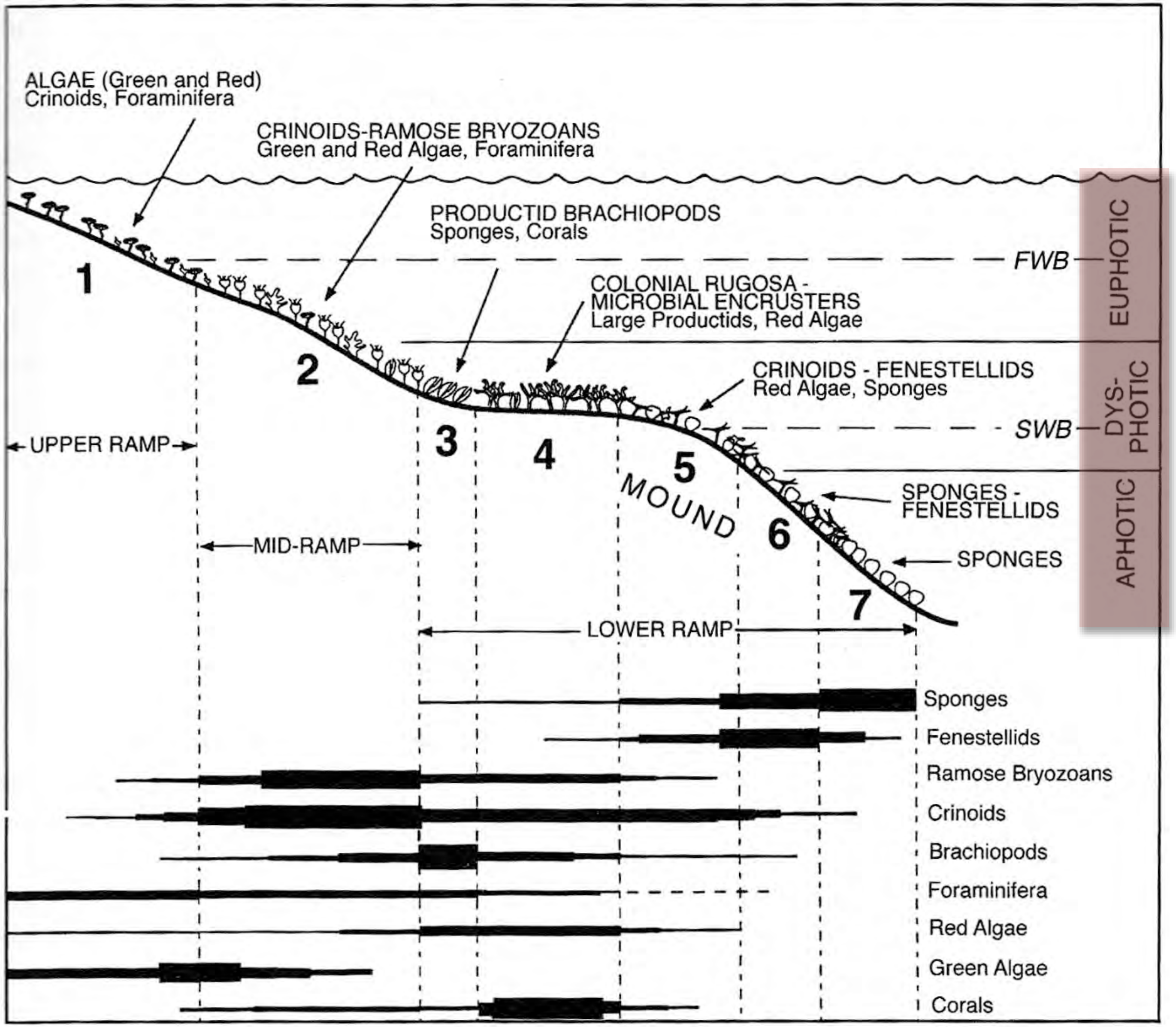
General microfacies succession of the Late Jurassic, Sulzfuh **platform**, Swiss-Austrian boundary, Flügel 1979. Not to scale.

MESOZOIC CARBONATE RAMP, GERMANY



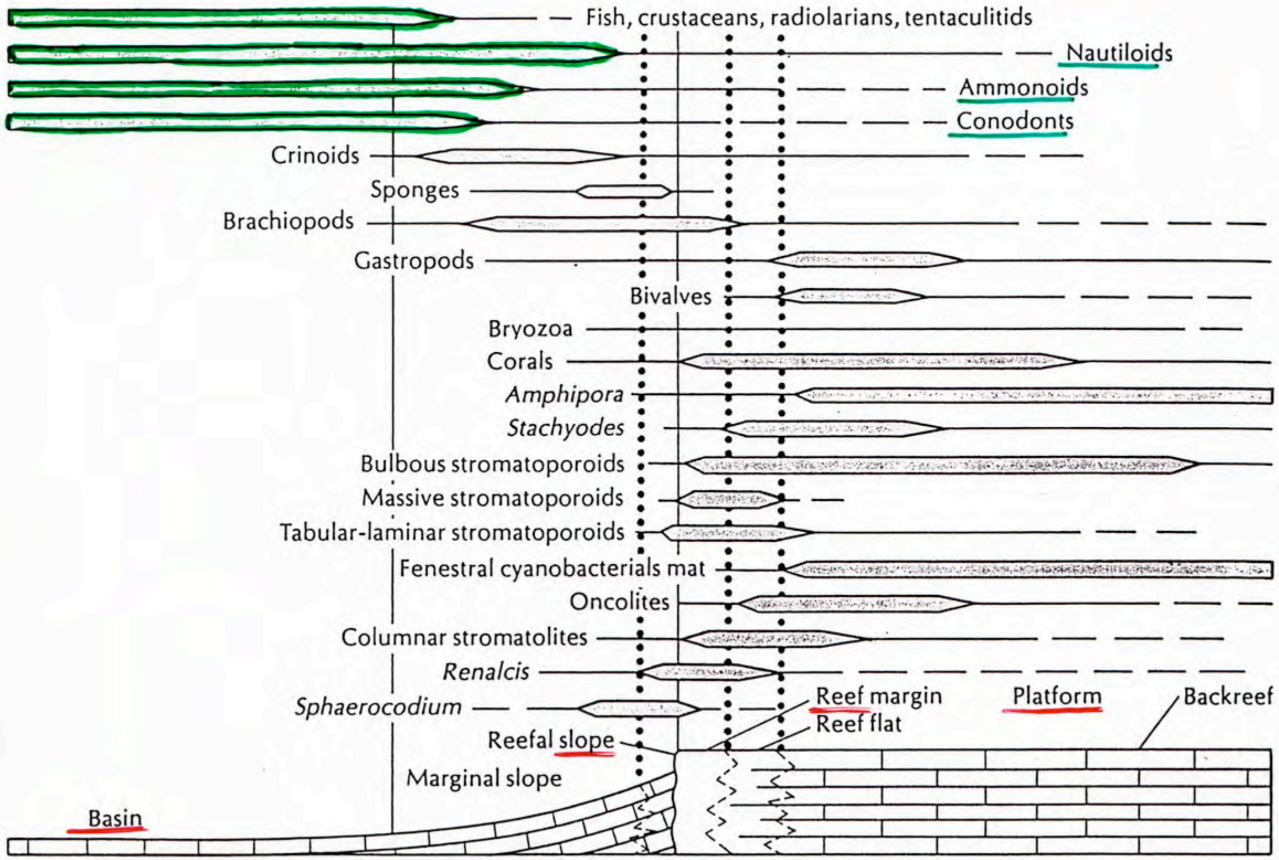
Generalized facies distribution of a Late Jurassic/Early Cretaceous carbonate **ramp** based on data from the subsurface of southern Bavaria, Germany (*in* Flügel 2004).

VISEAN CARBONATE RAMP, ALGERIA



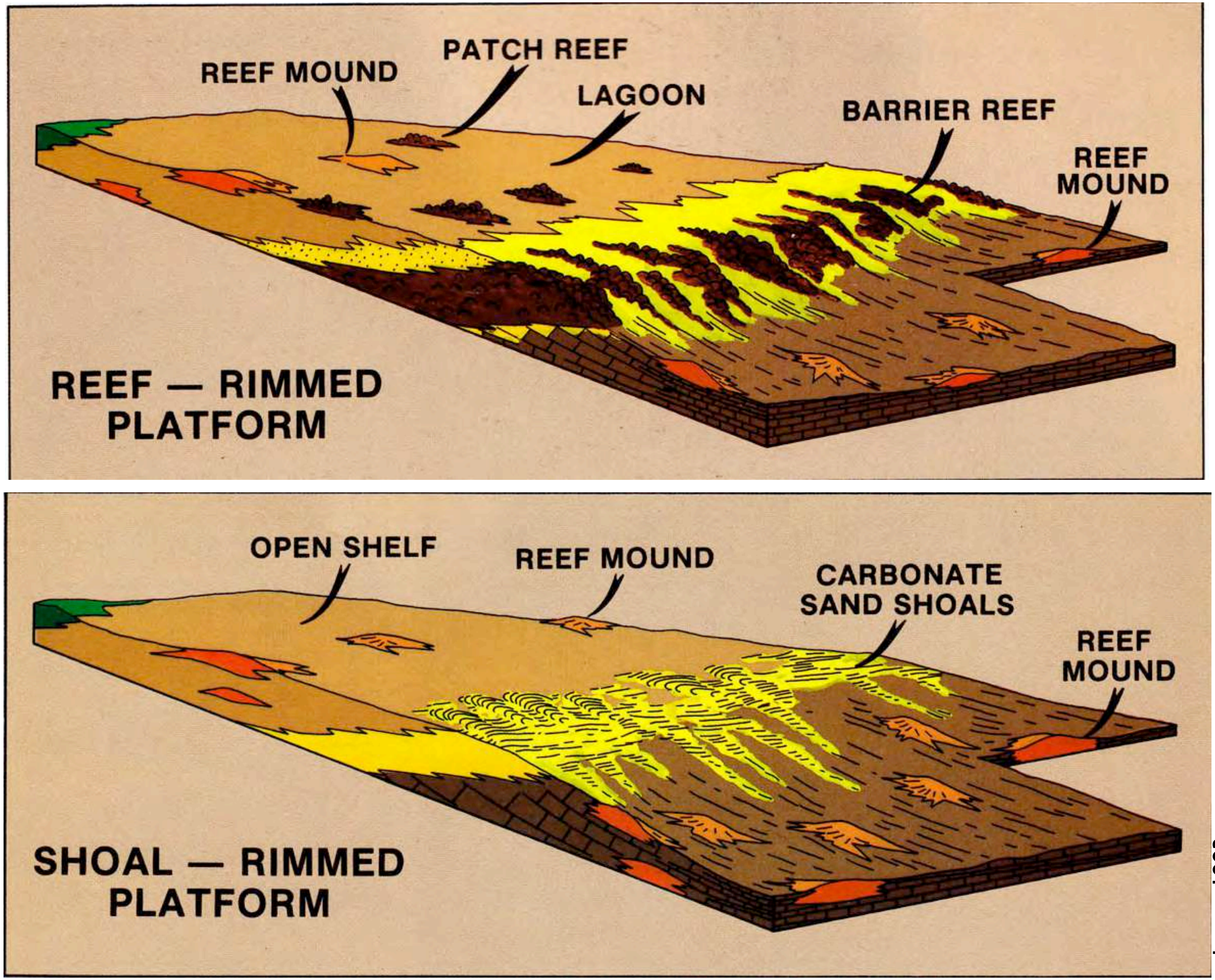
Depth zonation along a Late Viséan **ramp** profile in the Béchar basin, Western Algeria, Madi et al. 1996.

DEVONIAN CARBONATE PLATFORM, CANNING BASIN



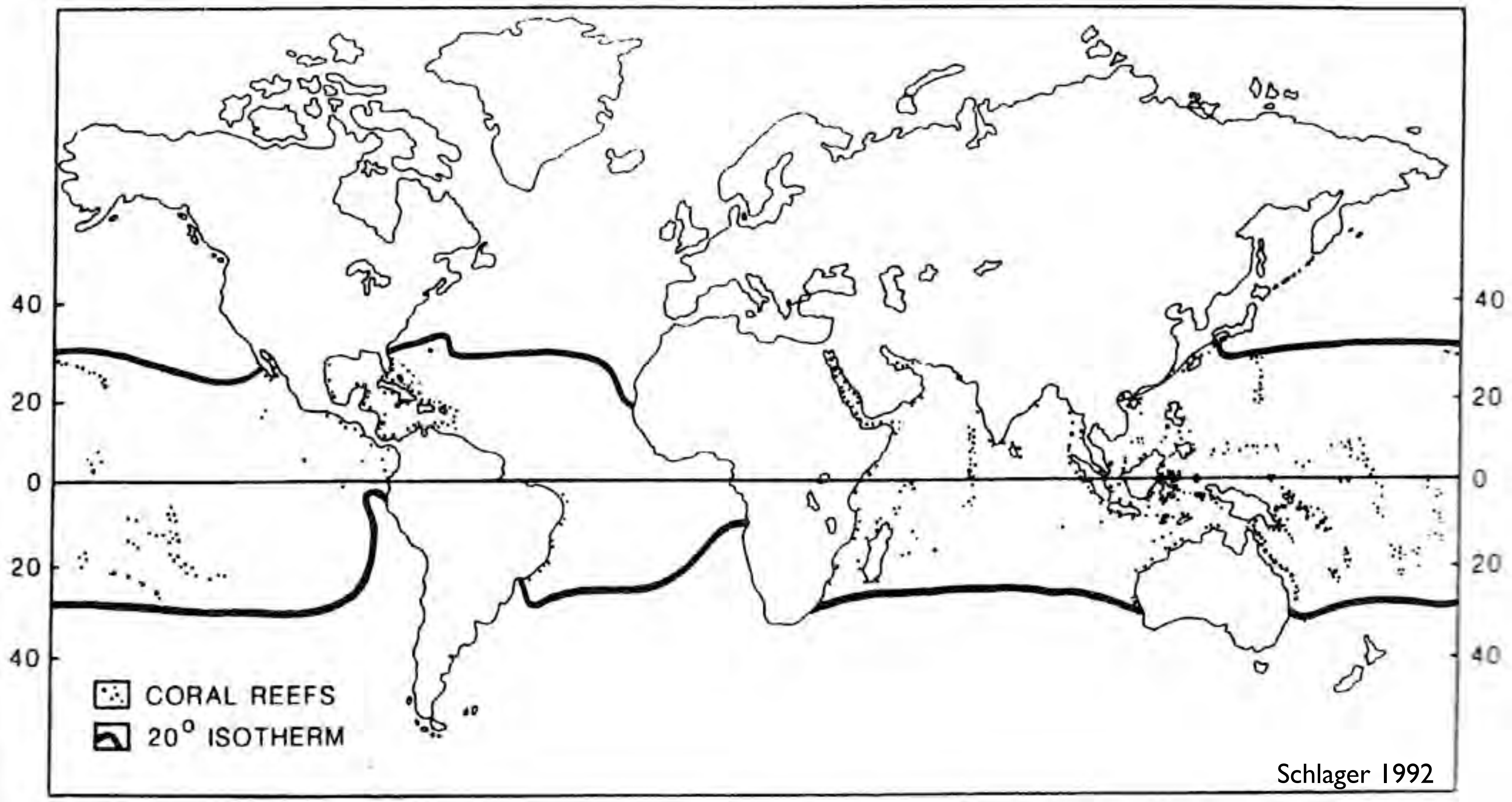
Ecological zonation of Frasnian (Late Devonian) organisms in the Canning Basin reef complex. The basinal fauna is predominantly free-swimming or floating organisms, such as fish, cephalopods, conodonts, crustaceans, radiolarians, and tentaculitids. The marginal slope is dominated by animals with the ability to anchor to the substrate, such as crinoids, sponges, and brachiopods. The reef crest is made of wave-resistant colonial organisms that build the reef framework, such as corals, massive and laminar stromatoporoids, and algae. The backreef contains organisms that prefer the sheltered conditions and can tolerate elevated temperatures and salinities and occasional desiccation, such as gastropods, bivalves, corals, bulbous stromatoporoids, and stromatolites. (Modified from Playford, 1980, *Amer. Assoc. Petrol. Geol. Bull*. 64:814–840; by permission of the American Association of Petroleum Geologists, Tulsa, Okla.)

REEFAL *vs* SHOAL RIMMED PLATFORMS



James 1983

MODERN CARBONATES : GEOGRAPHIC DISTRIBUTION
mainly in warm seawater …



1. **MATRIX**
2. **CEMENT**
3. **GRAINS**

PETROGRAPHY OF CARBONATES
1. MATRIX = MICRITE

Matrix or 'groundmass' : interstitial material between grains
= **MICRITE** (microcrystalline calcite) or small-sized crystals (1-4 µm) developing a crypto- to microcrystalline crystal texture. Firstly defined by Folk (1959).

- Micrite is the fine-grained matrix of carbonate rocks and the fine-grained constituents of carbonate grains,
- Need the use of SEM to be described in details, observable with a petrographic microscope, not visible with a binocular microscope or a hand-lens,
- **Synonyms** are lime *mud, lime ooze, lime mudstone, calcimudstone, calcilutite*
- Microfacies thin section are ± 30µm thick => micrite appears black or dark under the microscope.

- **Recent SEM studies** => MINIMICRITE (< 1µm), PSEUDOMICRITE, BLOCKY MICRITE …

PETROGRAPHY OF CARBONATES
I. MATRIX = MICRITE

Origin : **today** fine-grained carbonate muds originate in non-marine environments (e.g. pedogenic and lacustrine) AND marine environments (shallow marine inter- and subtidal settings, e.g. tidal channels, algal mats, lagoons, platforms, reefs) and deep-marine ocean floors.
⇒ ***in marine and non-marine sites, in warm and cold waters***

Many hypotheses starting with Sorby (1879) explain the origin of micrite

(i)in place formation triggered by biochemical and physicochemical factors
(ii)post-mortem disintegration of calcareous algae
(iii)physical or biological abrasion of skeletal material
(iv)accumulation of pelagic calcareous plankton
(v)result of diagenetic processes including cementation and recrystallization

\+ several ***genetically*** terms
- Automicrite = 'autochthonous' micrite (in place formation of fine-grained LMC/ARAG on the sea floor or within the sediment by physico-chemical, microbial, photosynthetic and biochemical processes
- Allomicrite = 'allochthonous' micrite (derived from various carbonate grains…)

I. MATRIX = MICRITE

Origin

Mud-producing processes operating in modern carbonate environments that were operating in the formation of ancient carbonates are **mainly** related to the metabolic activity of bacteria, cyanobacteria (microbial mats) and algae.

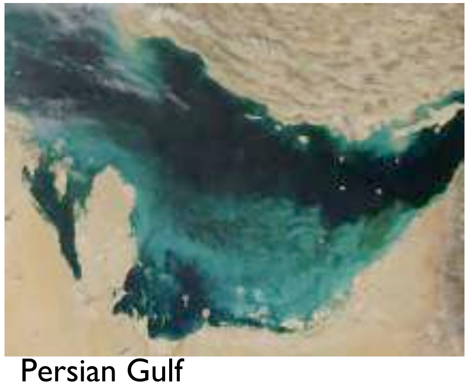
The three main processes (Modern and Ancient including Precambrian) are

AUTOMICRITE

(i) Terrigenous : today = insignificant. **Only** LMC/DOL fluvial in Persian Gulf (Zagros Mts, Iran) and eolian inputs (Irak)

(ii) Precipitation directly from seawater (Cloud 1962) = 'WHITINGS' i.e. floating patches of lime mud (ARAG) = physicochemical process? caused by biologically induced carbonate precipitation due to pH, CO_2 …variations in shallow-water areas and lakes.
Also with high salinity and high temperature. Trucial Coast, Bahamas, Dead Sea

Increase of micrite during Early Proterozoic = ? result of blooms of cyanobacteria in phosphate-rich oceans.



Persian Gulf

Bahamas

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PETROGRAPHY OF CARBONATES
I. MATRIX = MICRITE

The three main processes (Modern and Ancient including Precambrian) are

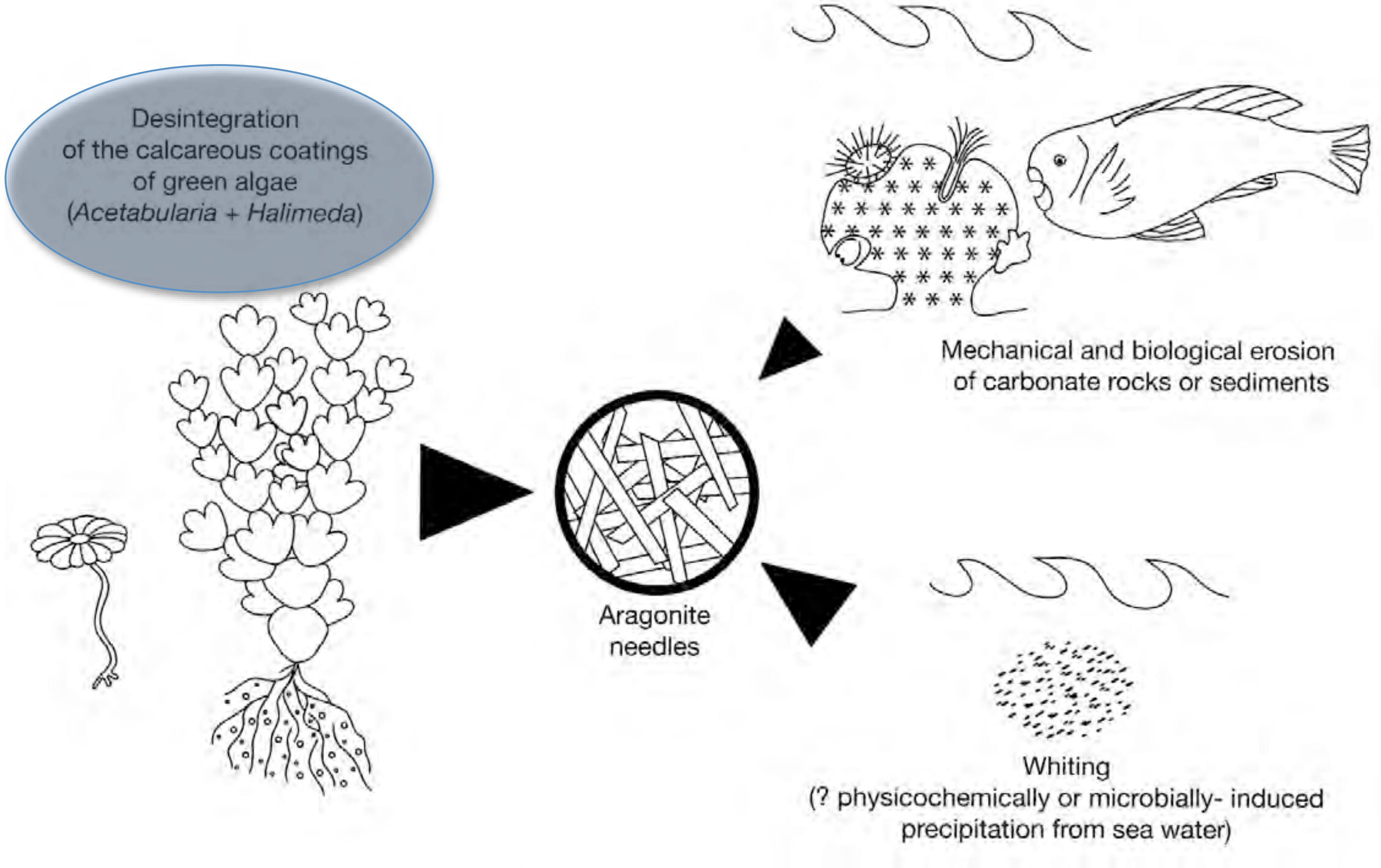
(iii) Disintegration of benthic calcareous algae *(the 'Halimeda model'*)

Disintegration of the skeletons of modern calcareous algae => sand-to clay-sized particles. The **ultrastructure** of the green algae is **aragonite needles**, they are set free after decomposition of the organic matter.

Morphologically similar needles are abundant in carbonate muds in the Great Bahama Bank, Florida Bay as well as in Pacific lagoons (West Indies….).

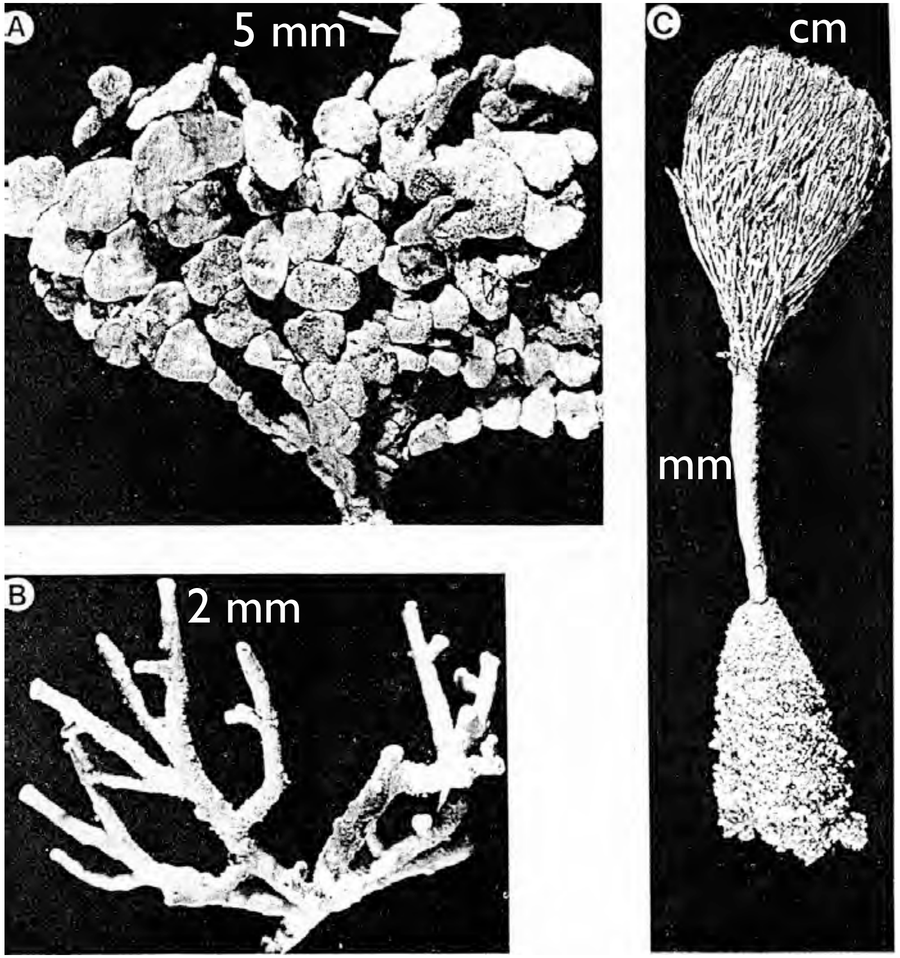
Halimeda : udoteacean green alga

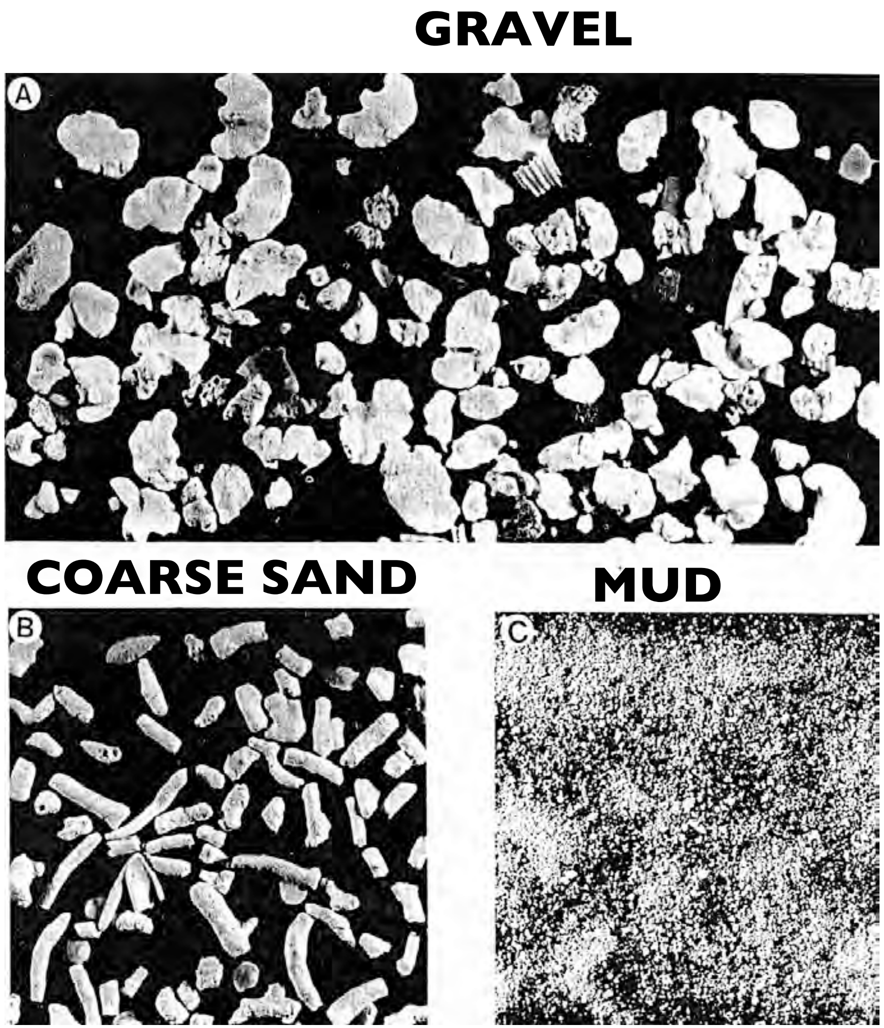
CARBONATE FACTORY : ORIGIN OF CALCAREOUS MUD



Granier 2012

PETROGRAPHY OF CARBONATES
I. MATRIX = MICRITE





A *Halimeda* B *Goniolithon* (red alga) C *Penicillus* (Dasycladaceae)
Florida Bay, Purser 1980.

PETROGRAPHY OF CARBONATES
1. MATRIX = MICRITE

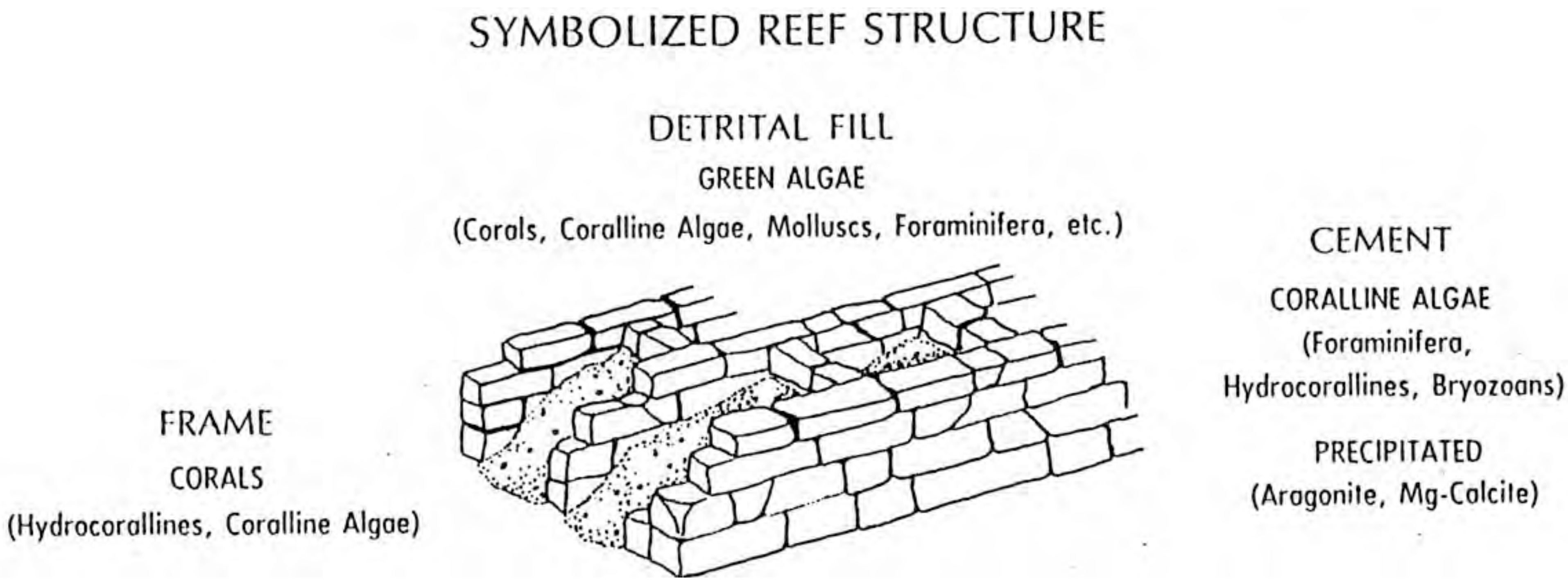
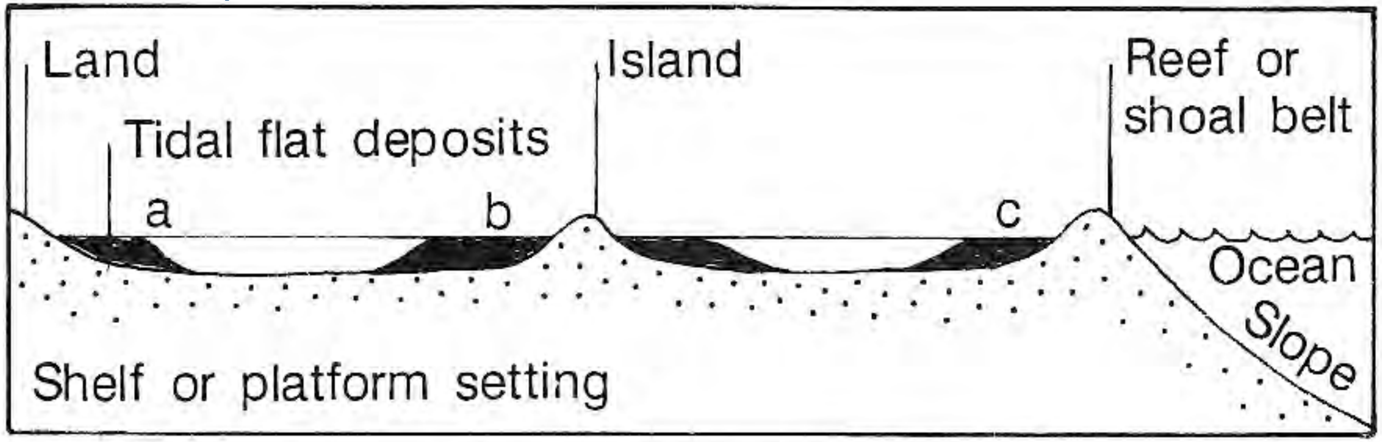


Diagram showing symbolized reef structure emphasizing interaction between frame, detrital fill and cement. Ginsburg & Lowenstam 1958.

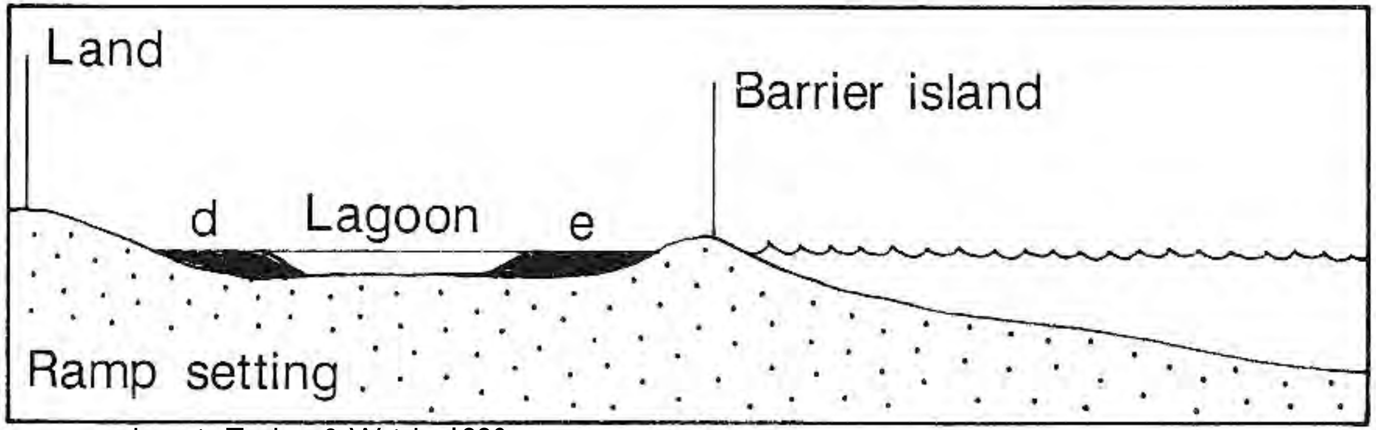
PETROGRAPHY OF CARBONATES
I. MATRIX = MICRITE

TIDAL FLAT DEPOSITION

a. Florida Bay   b. Shelf islands of Belize   c. Shelf islands of Belize

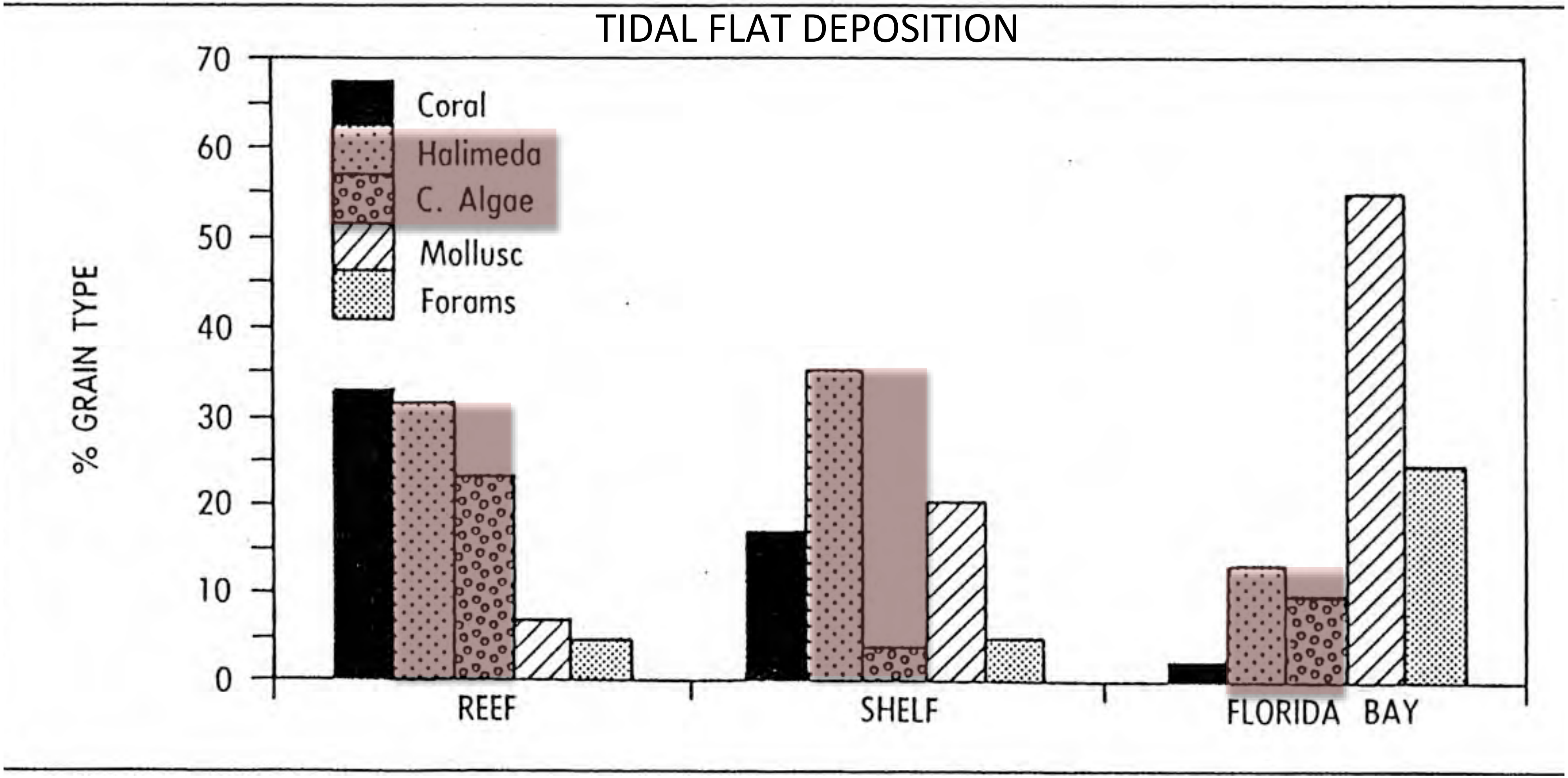


d. and e. Trucial Coast of Arabian Gulf



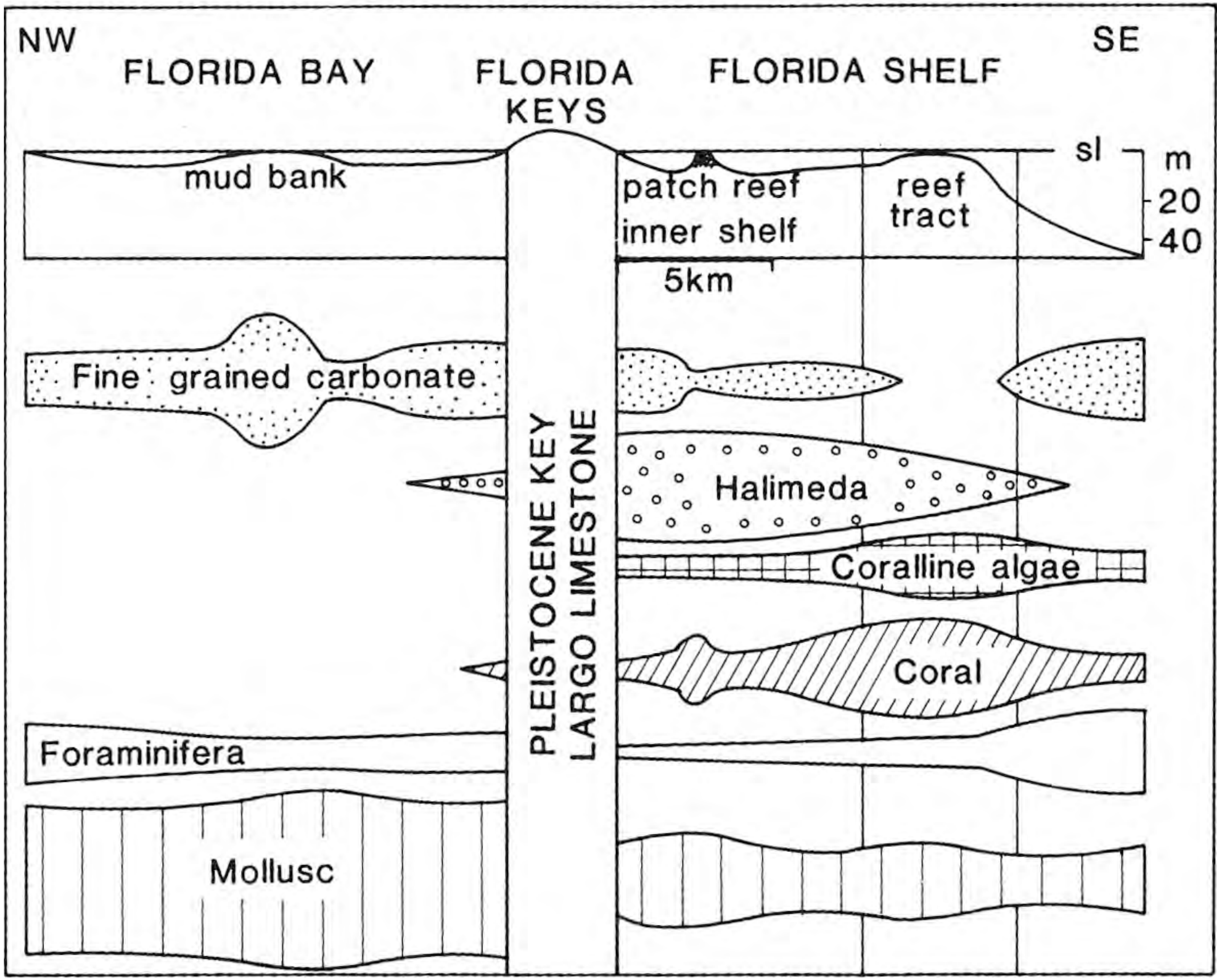
many authors *in* Tucker & Wright 1990

PETROGRAPHY OF CARBONATES
I. MATRIX = MICRITE



Percentage of major grain types in the dominant depositional environments **of South Florida**.
Thibodeaux 1977.

Distribution of sediment grain size and type across the Florida Shelf and Florida Bay

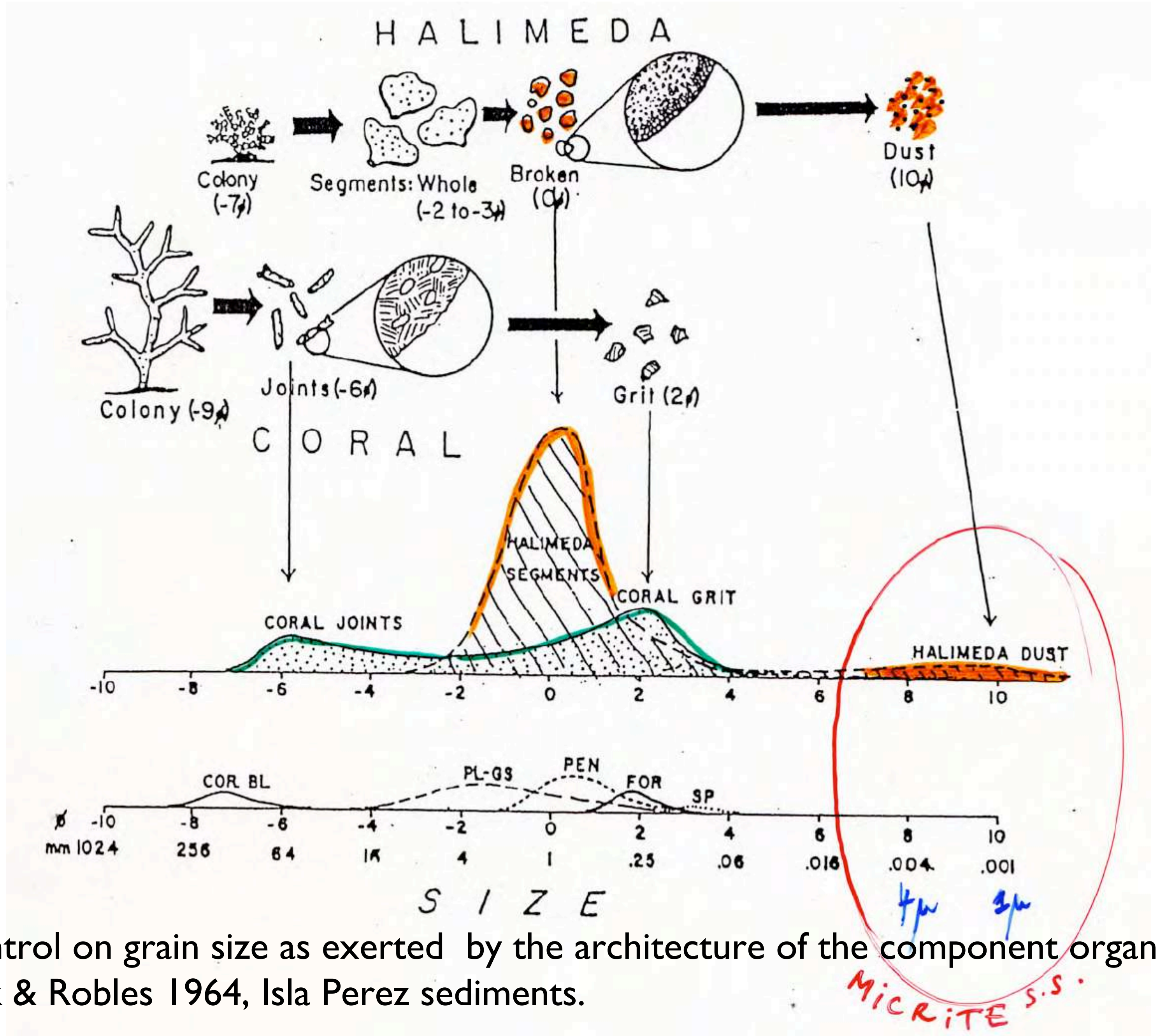


Ginsburg 1956 *in* Tucker & Wright 1990

The carbonate sediments of the Florida Shelf are almost entirely BIOGENIC

= > **<u>much of the lime mud is probably of codiacean algal origin</u>**

PETROGRAPHY OF CARBONATES
I. MATRIX = MICRITE



Control on grain size as exerted by the architecture of the component organisms
Folk & Robles 1964, Isla Perez sediments.

PETROGRAPHY OF CARBONATES

I. MATRIX = MICRITE

Carbonate sediments, Persian Gulf

Emerged intertidal channel

Algal laminae (organic matter/black carbonate/white)

subspherical nanograins 0.1-0.5 µm

White lamina Needles

Black lamina Nanograins on rods

Loreau 1982

PETROGRAPHY OF CARBONATES
I. MATRIX = MICRITE

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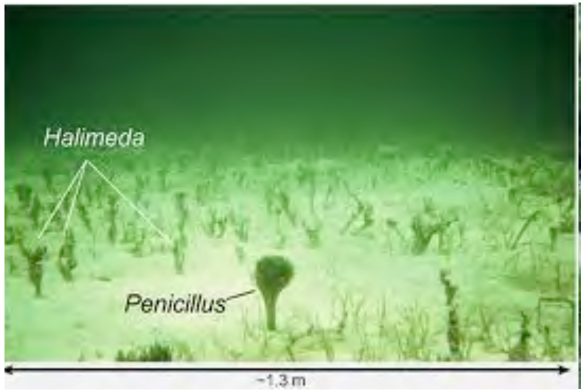
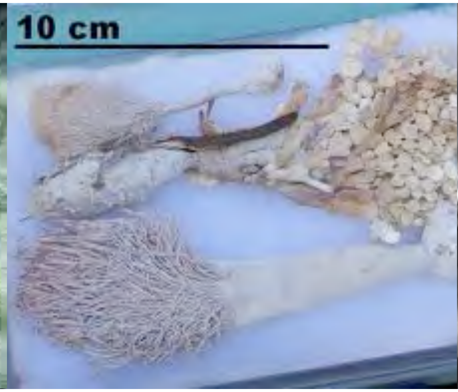
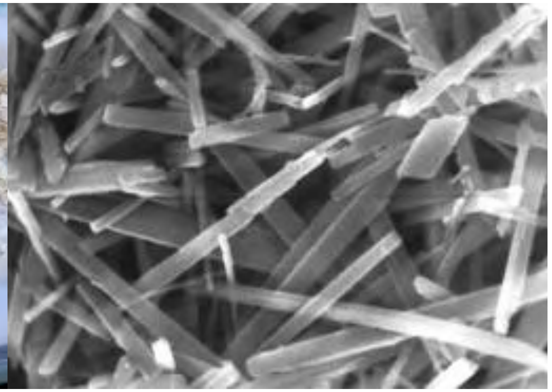
AMONG
the three main processes (Modern and Ancient including Precambrian)
=
(iii) Disintegration of benthic calcareous algae (the 'Halimeda model')

The algal origin of the needles is supported by
• comparable stable isotope data of muds and algal needles
• SEM photomicrographs between the aragonitic needles from muds and algae
….

Halimeda and *Penicillus* green algae





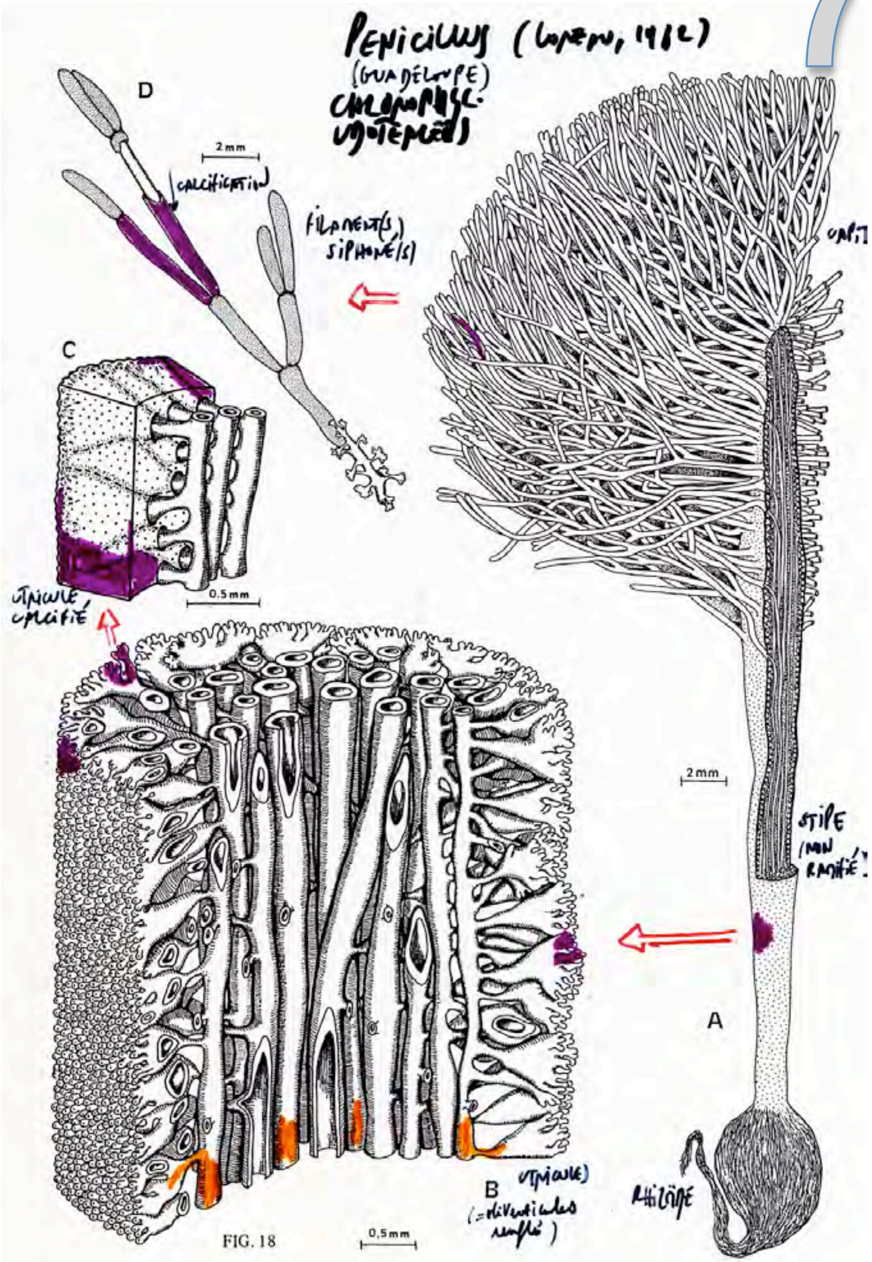
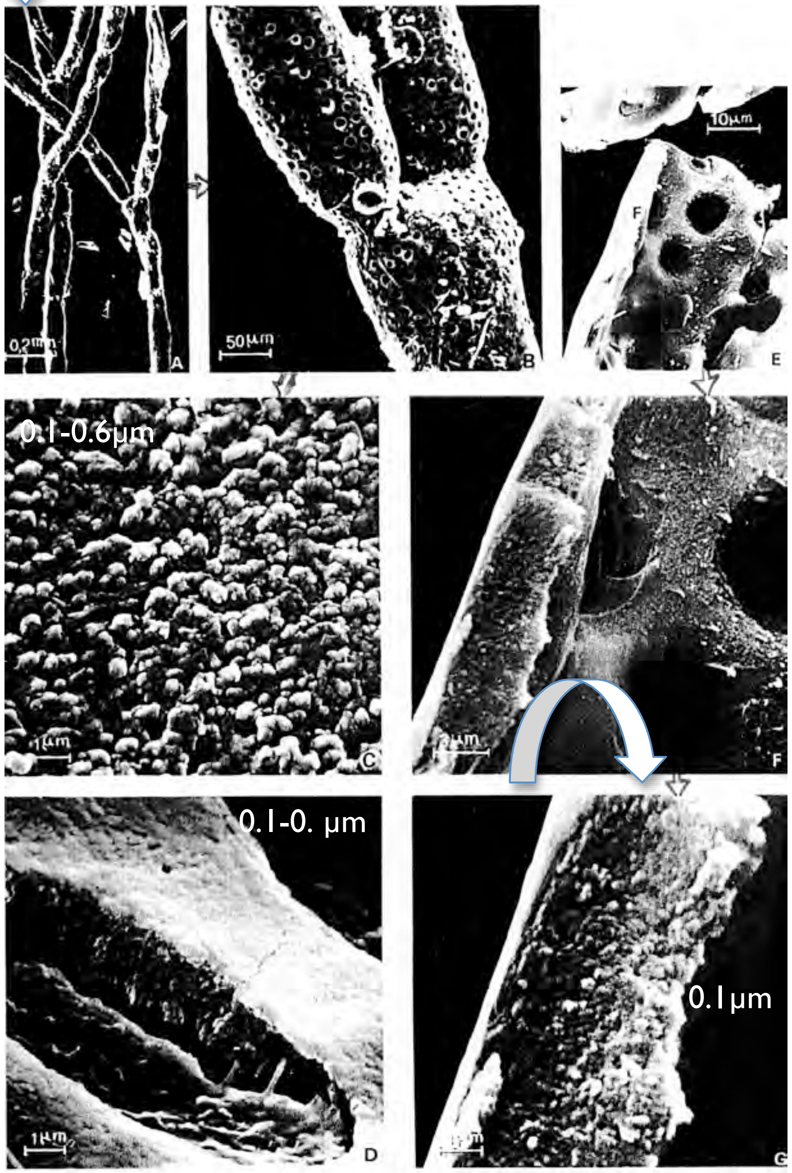


FIG. 18

filaments

NANOGRAINS 0.1-0.5µm
ARAGONITE

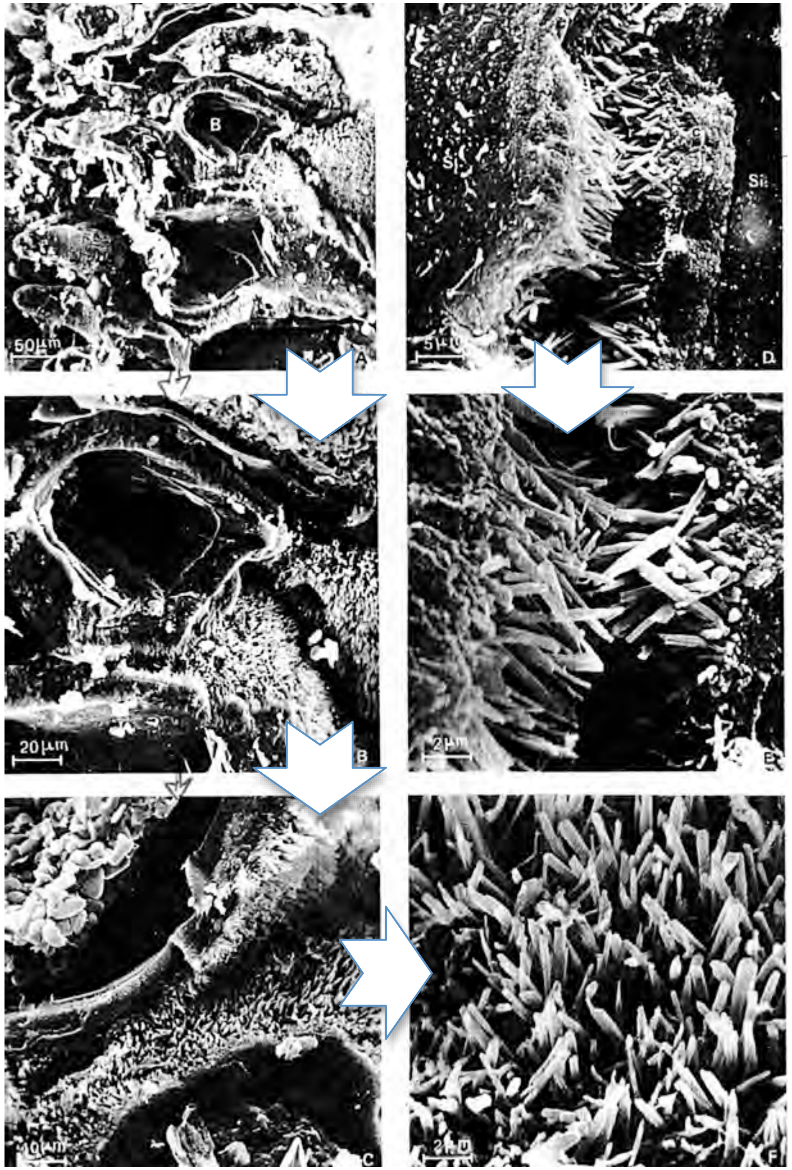


Guadeloupe, West Indies, Loreau 1982

UTRICLE : 30-40% = ARAG needles 1-5µm x 0.5µm

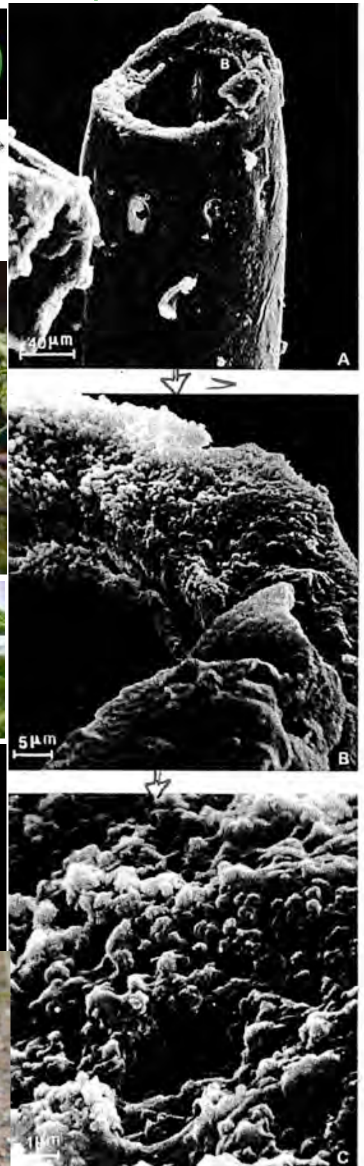
packed NANOGRAINS 0.1-0.2µm

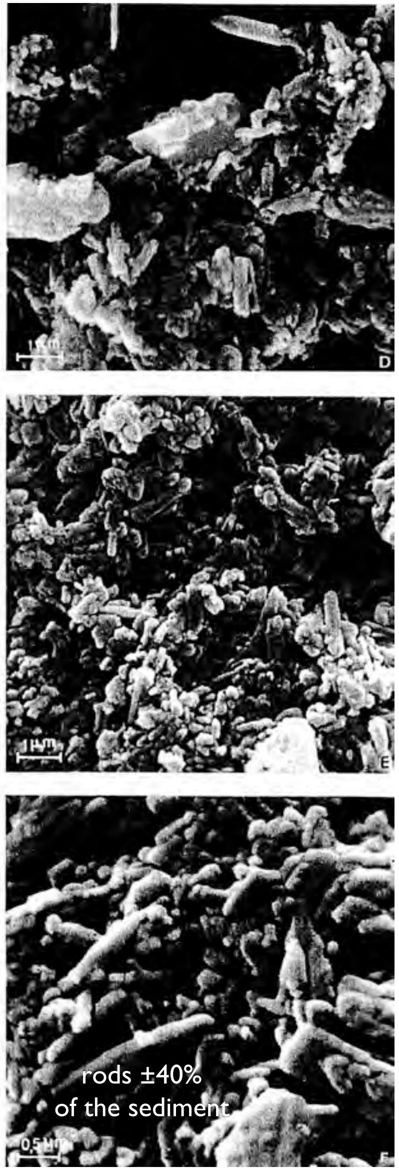
MUD ARAG nanograins 0.1-2µm



Penicillus sp., Florida Bay, USA, Loreau 1982

Acetabularia sp.



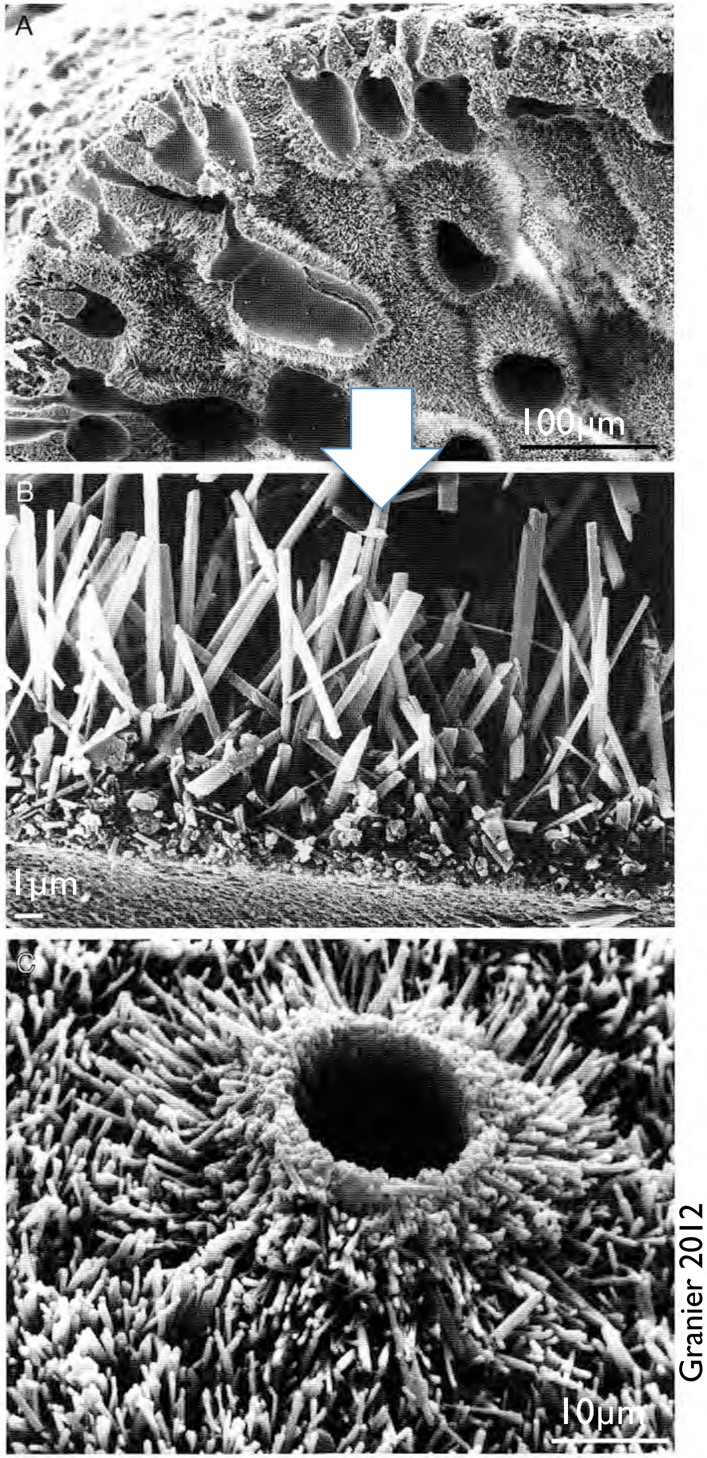


MUD, Florida Bay

Calcification in
Halimeda praeopuntia
Oligocene, France

ARAGONITIC NEEDLES

Calcification in
Neomeris arenularia
Eocene, France



SEDIMENT-MUD, ABU DHABI = needles+pellets+forams

nanograins

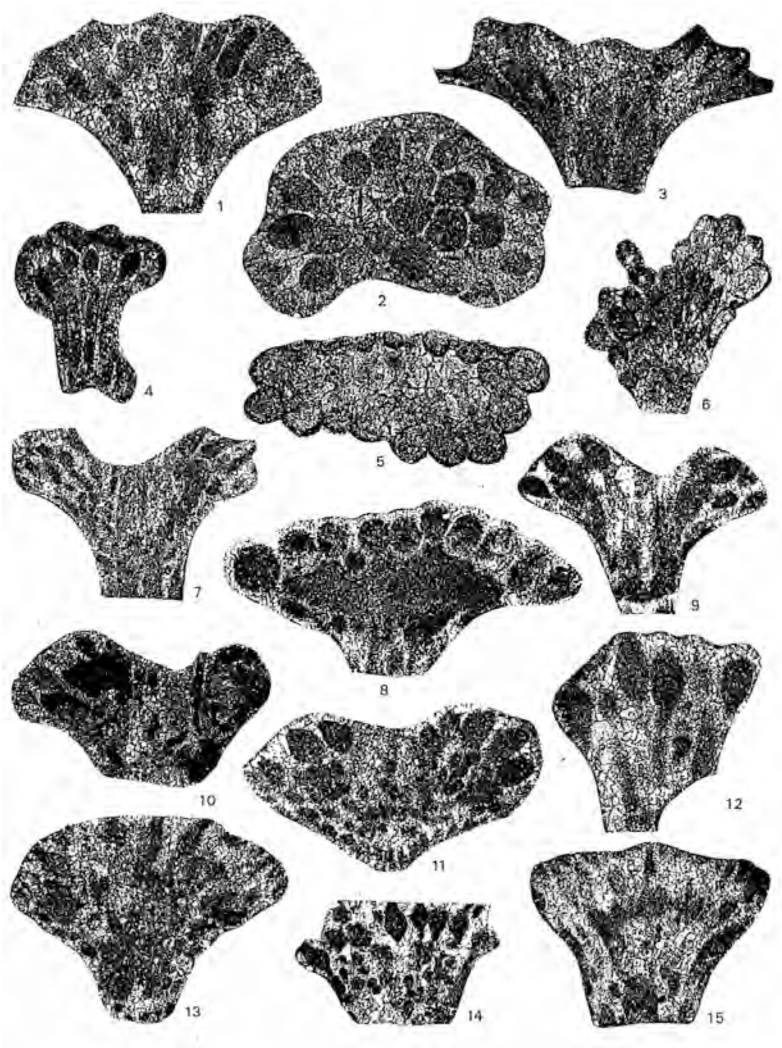
depth -12m
with bioclasts

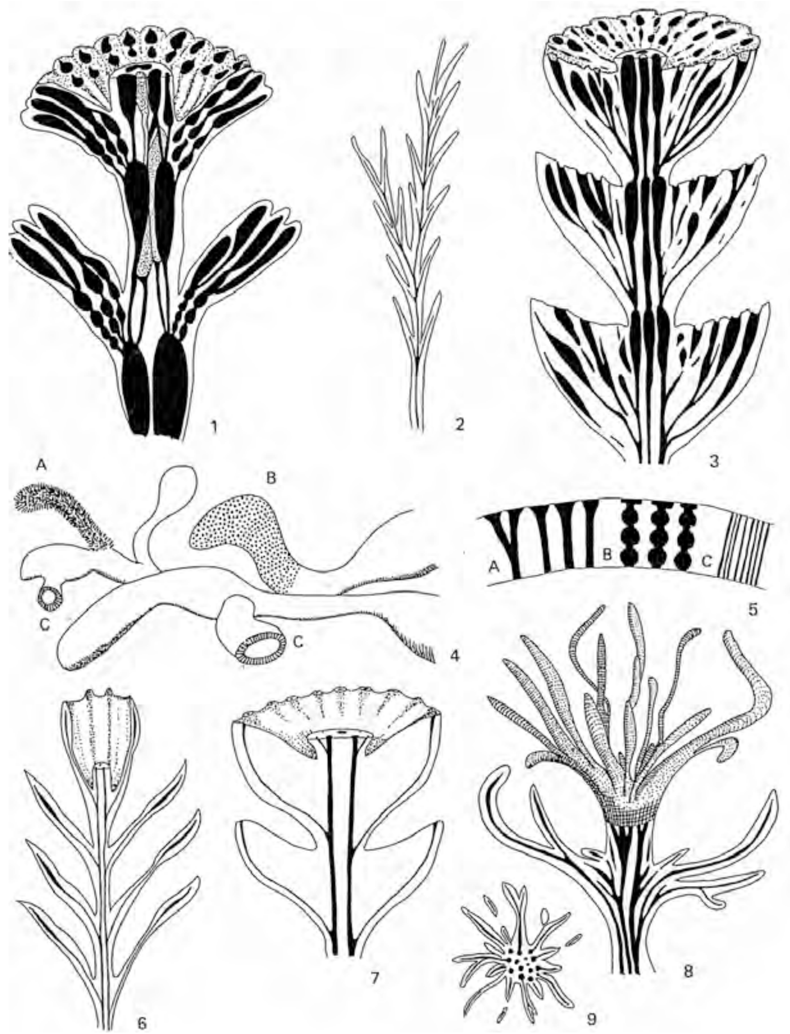
depth -55m

anhedral needles
LMC 0.2x1µm

WHAT ABOUT THE GEOLOGICAL RECORD?

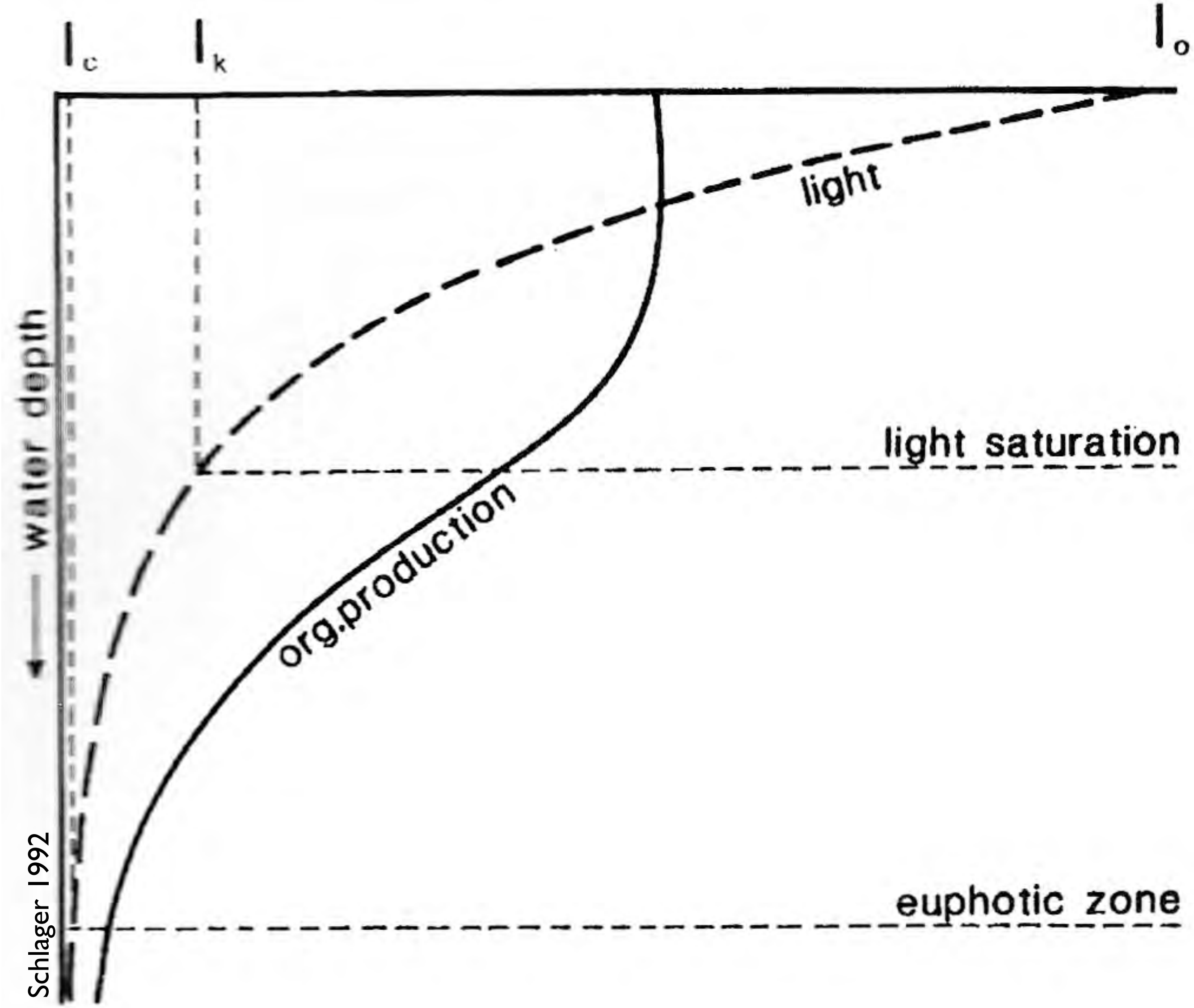
size of algal-clasts < 1mm





Eifelian (Middle Devonian, Belgium), Mamet & Préat 1985

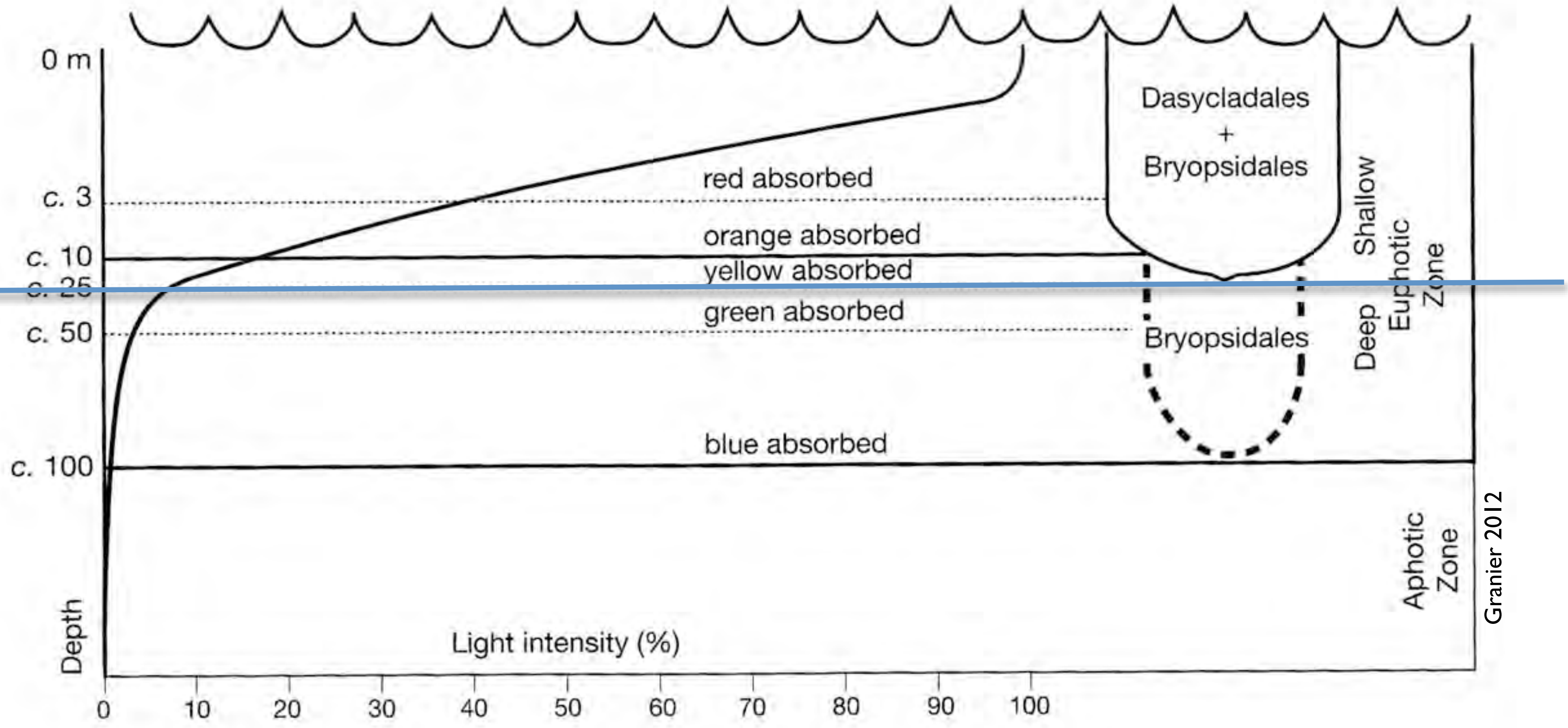
ORGANIC PRODUCTION – EUPHOTIC ZONE



Light displays a simple exponential decrease with water depth.
The curve of organic production is related to light intensity
⇒ **production shows a shallow zone of light saturation, where light is not a growth-limiting factor, followed by rapid decrease of organic growth with water depth.**

WHAT ABOUT THE DEPTH OF CALCIFICATION?

= S H A L L O W …



Photosynthesis (the curve) decreases exponentially with depth as a function of the intensity of light. But calcification is not necessarily a correlate of this process…

60% of the sunlight is absorbed in the first 3m, 80% at about 10m and 99% at about 100m.

The depth at which **most** of the cyan/blue rays have been absorbed is the lower limit of the **EUPHOTIC ZONE (-25m, here**. It can be deeper (=> -140m).

PETROGRAPHY OF CARBONATES

I. MATRIX = MICRITE

Finally

micrite *sensu stricto* <4 μm

Sedimentology : < 62μm = ‘mud’

FOLK 1959: MICROSPAR 5-15μm => 40μm

others AUTHORS : ‘MACROSPAR’’, ‘PSEUDOSPAR’

Recently 1996-1998 : ‘Minimicrite’ < 1μm, ‘Pseudomicrite’, ‘blocky micrite’

Origin

BATHURST 1958 = aggrading recrystallization (or ‘neomorphism’)

≠

MUNNECKE & SAMTLEBER 1996, REID & MACINTYRE 1998

= cementation (without neomorphism, without dissolution)

SEM observation

Loreau 1982 … = disintegration of green (and brown) algae (today)

Micritic Bahamian muds

Halimeda flakes : $50 g/m^2/yr$

Penicillus needles : $30 g/m^2/yr$

Padina (brown alga) : $240 g/m^2/yr$

…

Padina sp.

PETROGRAPHY OF CARBONATES

I. MATRIX = MICRITE

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MICROSPAR : fine-grained LMC matrix with uniformly sized subhedral-euhedral calcite crystals ranging from 5 to more than 20 µm in diameter (FOLK 1959)

⇒ 'mosaic-like' microstructure,

⇒ equant grain shapes and boundaries,

⇒ pits within the crystals (= former ARAG needles…),

⇒ impurities of clay and organic matter between the crystals,

⇒ sometimes a patchy distribution within the micrite,

⇒ association of microsparitic limestones with shaly interbeds

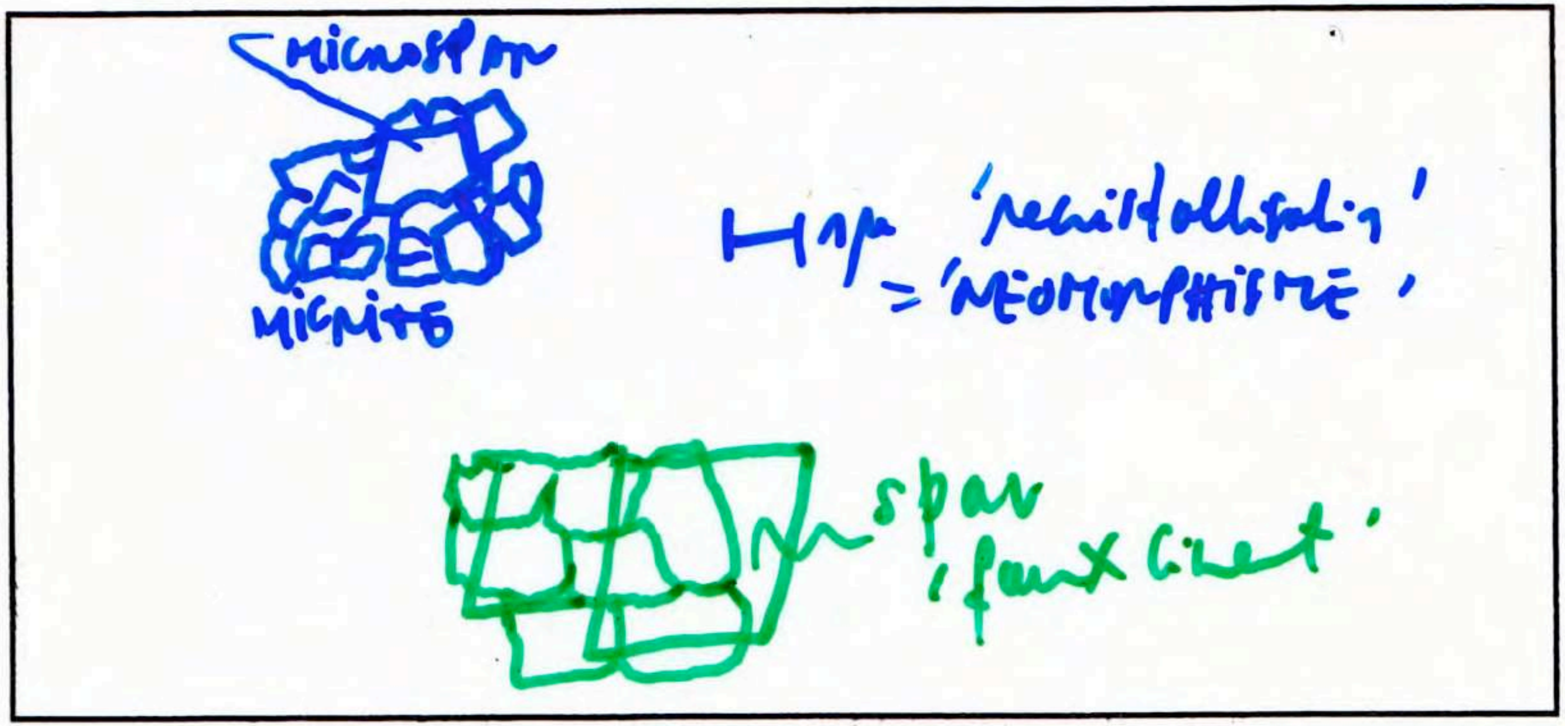
Origin: several processes (with evidence of meteoric diagenesis)

- recrystallization (aggrading neomorphism, Folk 1965) …
- one-step neomorphic process of cementation and replacement (calcitization) of aragonite-dominated precursors (with infiltration of meteoric water…) Munnecke & Samtleben 1995 …
- neomorphic growth from deep surface fluids …. Brand & Veizer 1981….
- recrystallization of silt-sized carbonate grains… Duringer & Vecsei 1998…

PETROGRAPHY OF CARBONATES

I. MATRIX = MICRITE

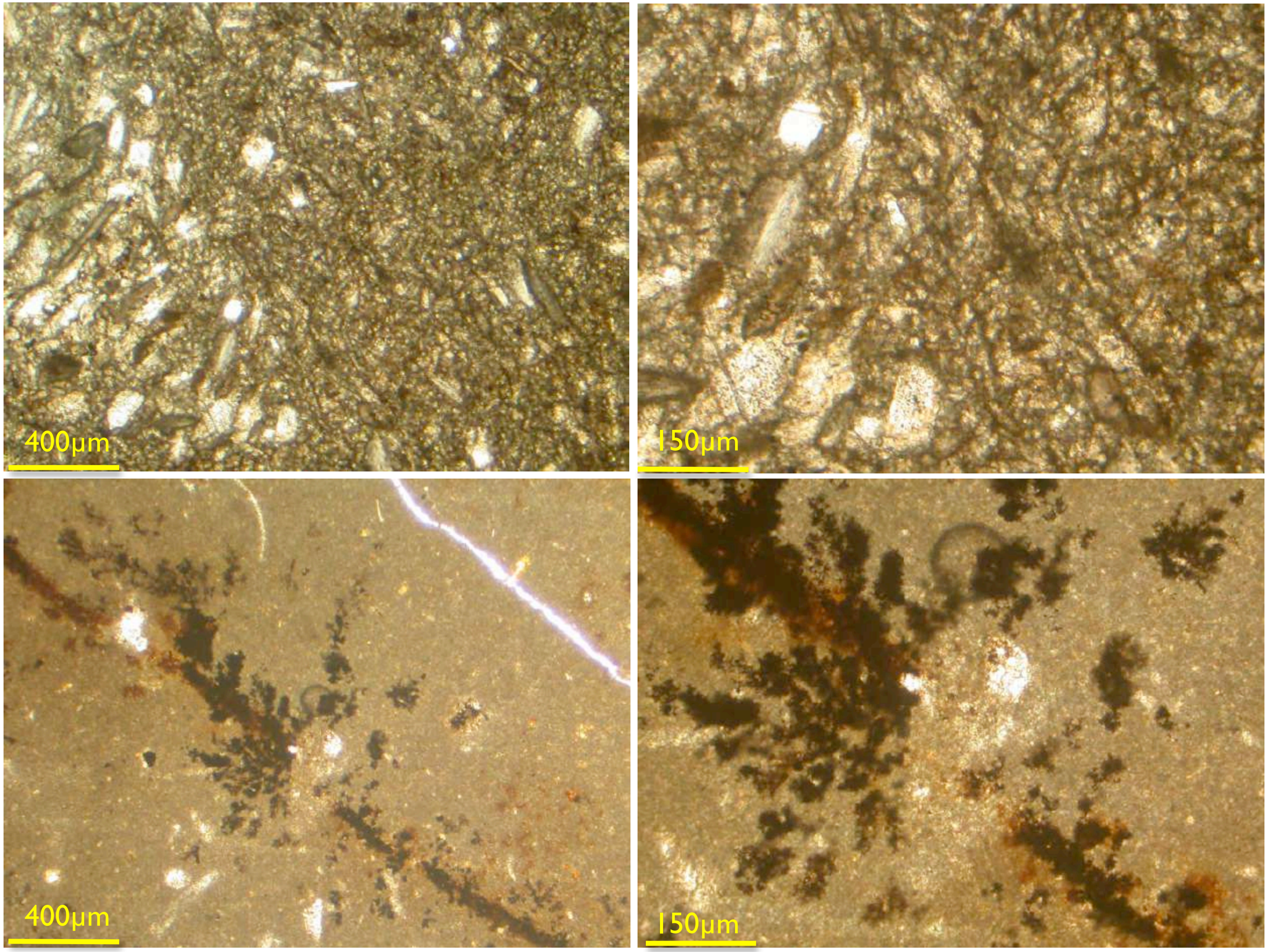
wackestone or packstone => ‘FALSE’ GRAINSTONE



‘microsparite’ is often ‘greyish’, light passes through the ‘microspar’ that contains abundant ‘micritic’ inclusions….

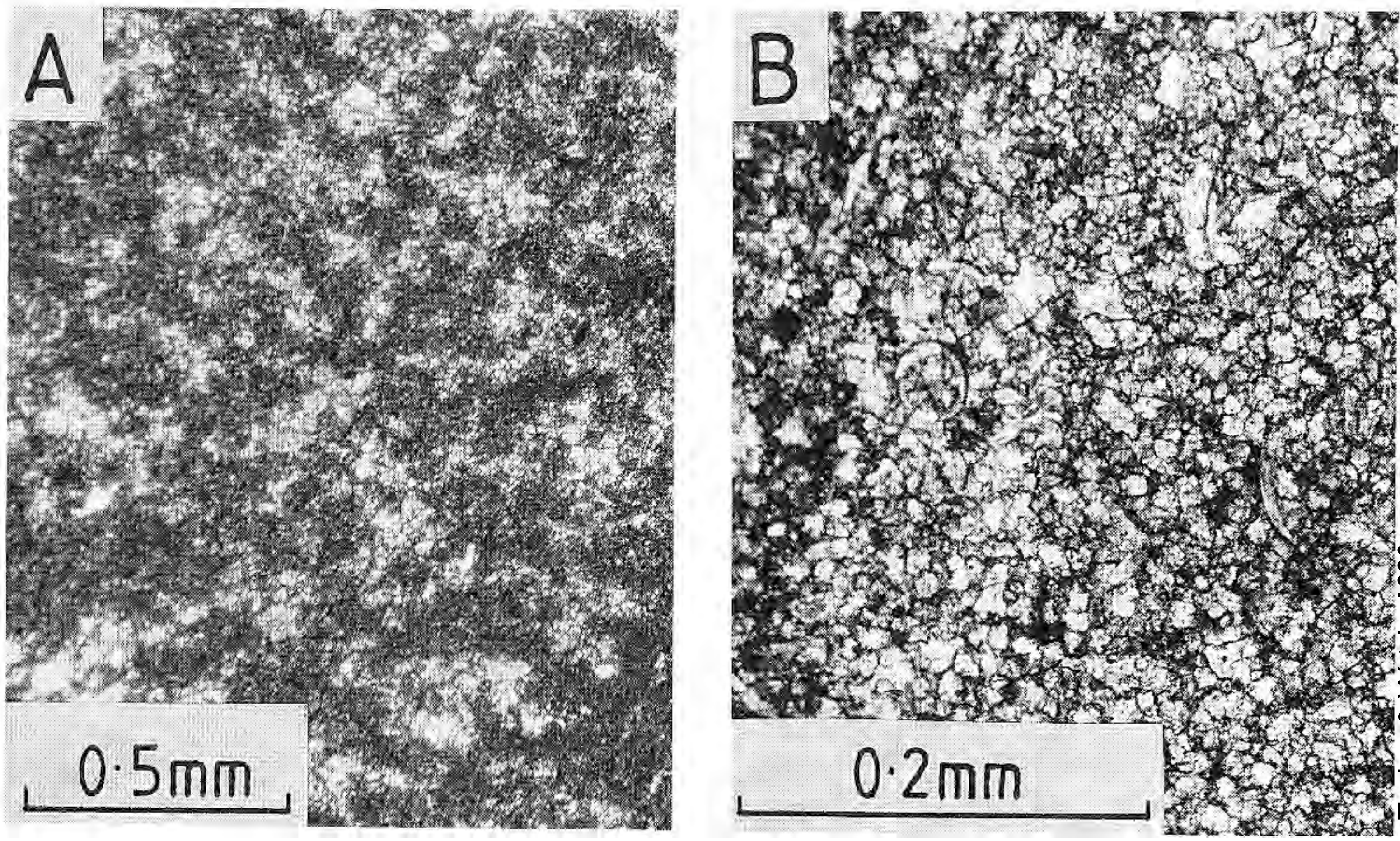
nb dolomite and sulphate reflux => ‘microsparitization’

Very coarse-sized neomorphic microspar, open shelf, Givetian/Frasnian boundary
Nismes section, Belgium, Casier & Préat 2009



Neomorphic microspar = aggrading neomorphism

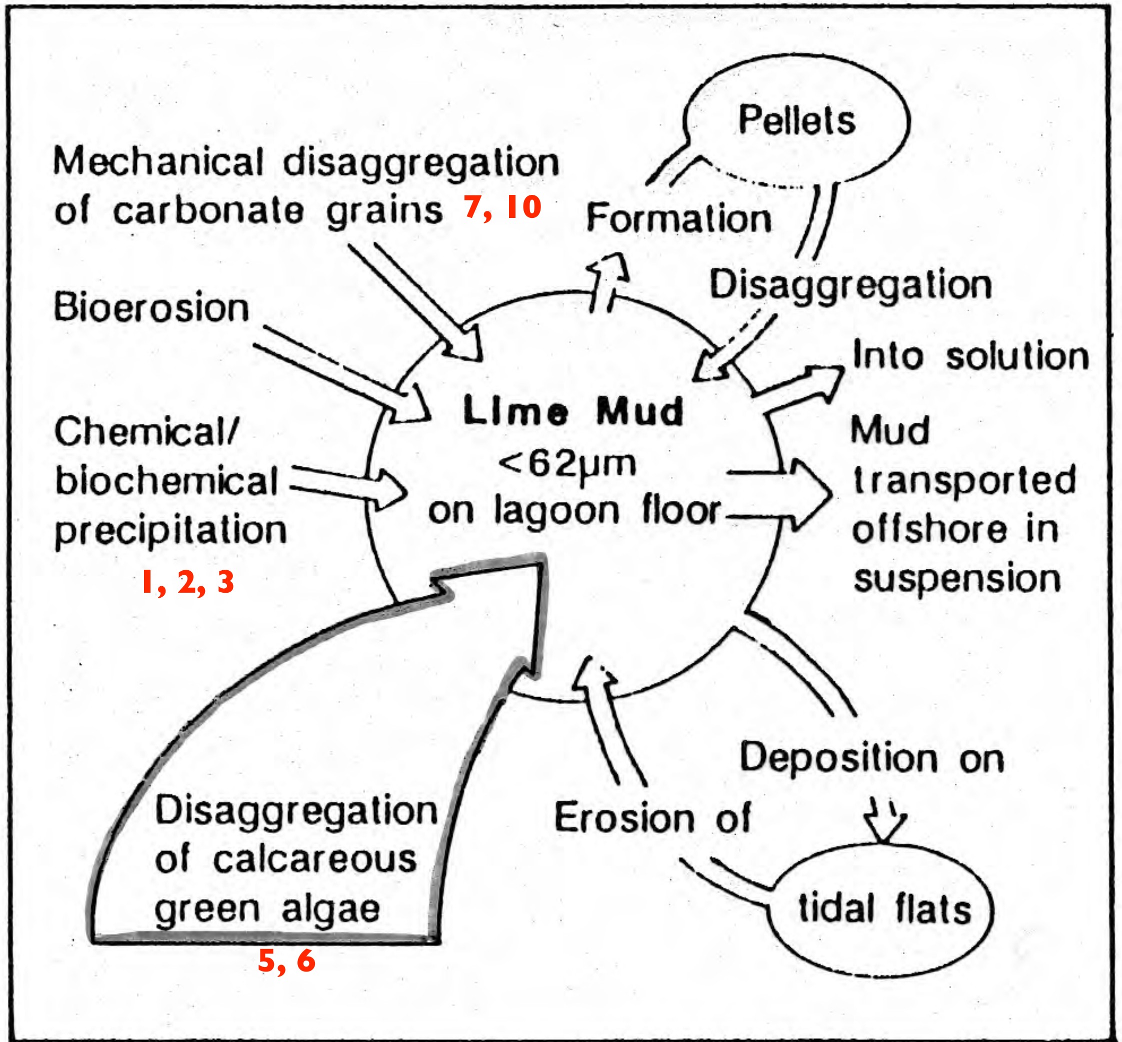
A patches of microspar in a micritic pelagic limestone, Devonian, Germany
B coarse microspar mosaic of equant crsytals with floating skeletal debris, Carboniferous, UK



Tucker & Wright 1990

POLYGENIC CARBONATE MUD PRODUCTION IN A SHALLOW MARINE PLATFORM ENVIRONMENT

Bight of Abaco
semi-closed lagoon
depth 7m
T 20°-30°C
Salinity 34-39%
Carbonates
=
ARAG+HMC
(muds and sands)



Lime mud budget for the Bight of Abaco, Little Bahama Bank.
Neumann & Land 1975, Tucker 1981. Red figures from Flügel 2004 (next slide).

TERMINOLOGY AND GENETIC MODES OF ORIGIN OF CARBONATE MUDS AND MUDDY LIMESTONES (Flügel 2004)

		Processes
Automicrite (autochthonous micrite) formed in place at the seabottom or within the sediment	Abiogenic ('inorganic')	**1** Physicochemical precipitation triggered by salinity and water temperature fluctuations
	Biologically induced	**2** Carbonate precipitation mediated by organic matrices (Ca-binding organic macromolecules), causing organomineralization and formation of *organomicrite*
	Biologically induced / Biologically controlled	**3** Metabolic processes of heterotroph and chemolithotroph bacteria and other microbes causing microenvironmental changes which induce carbonate precipitation
	Biologically controlled	**4** Metabolic processes of phototrophic cyanobacteria and algae causing carbonate precipitation
Allomicrite (allochthonous micrite), deposition of disintegrated skeletal material and of fine erosional detritus	Disintegration of predominantly benthic biota	**5** Disintegration of benthic calcareous algae into sub-microscopic fragments (*Halimeda* model)
		6 Disintegration of epibionts living on seagrass and macro-algae
		7 Disintegration of invertebrate skeletons
		8 Bioerosion causing detrital abrasion and microborings causing 'micritization'
	Disintegration of pelagic biota	**9** Accumulation of calcareous plankton (foraminifera; cocco-lithophorids and other nannofossils causing *'nannomicrites'*)
	Erosion and abrasion	**10** Mechanical erosion of limestones, e.g. at coasts
Pseudomicrite Diagenetic 'micrite'	Diagenesis	**11** Micro- and cryptocrystalline carbonate cements
		12 Recrystallization and 'grain diminution' (replacement of former larger crystals by tiny crystals)

A	
Extremely Coarsely Crystalline	>4mm
Very Coarsely Crystalline	1-4mm
Coarsely Crystalline	1-250µm
Medium Crystalline	62-250µm
Finely Crystalline	16-62µm
Very Finely Crystalline	16-4µm
Aphanocrystalline or Cryptocrystalline	1-4µm

Terminology for crystal sizes in limestones and dolomites
(A) Folk 1962 (B) Friedman 1965

B	
Micron-sized	0-10µm
Decimicron-sized	10-100µm
Centimicron-sized	100-1000µm
Millimetre-sized	1-10mm
Centimetre-sized	10-100mm

PETROGRAPHY OF CARBONATES

1. MATRIX

2. CEMENT

3. GRAINS

PETROGRAPHY OF CARBONATES

2. CEMENT = pore-filling process

Mineralogy LMC (often called ‘spar’ or ‘sparite’), HMC, ARAG, (DOL)
(less common: ankerite, siderite, quartz, anhydrite, gypsum, halite)

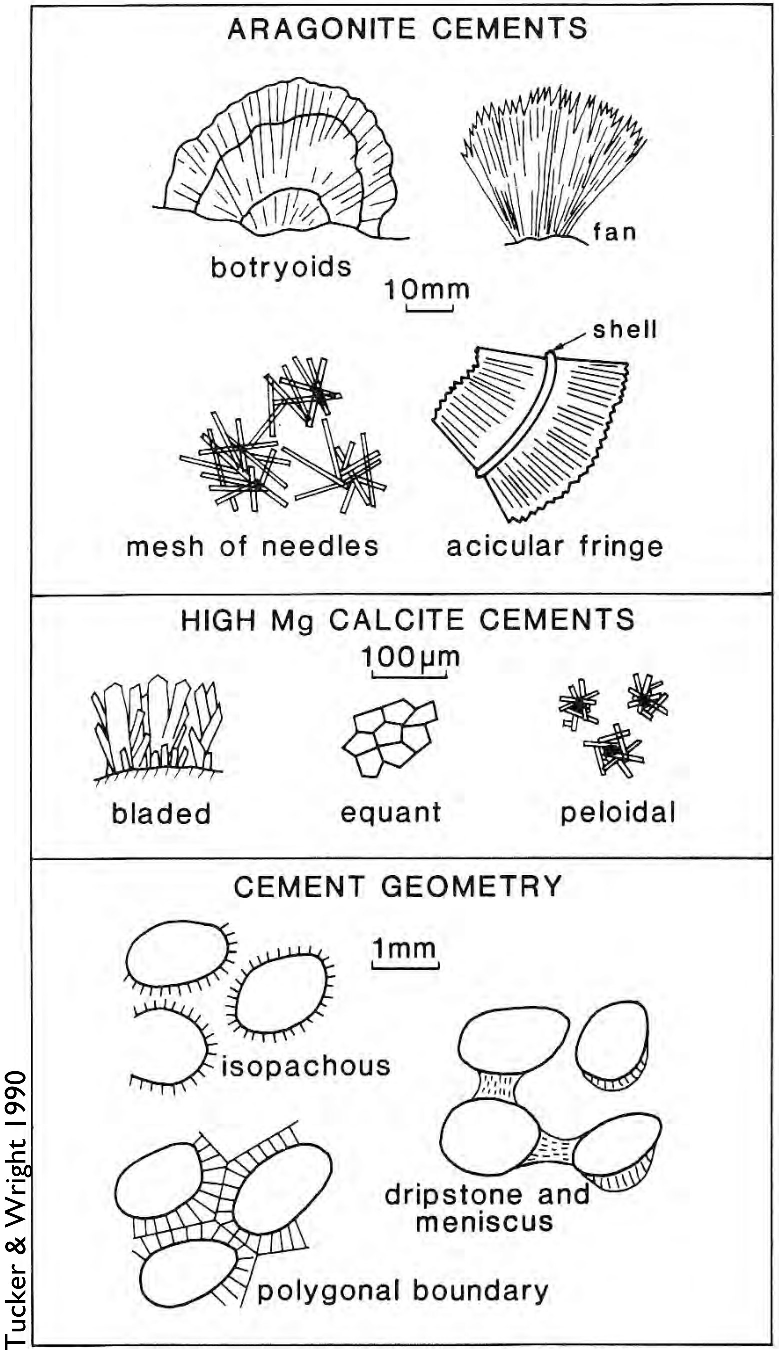
Petrography

- often clear and clean appearance (≠micrite), with well-defined, sometimes straight crystal boundaries,
- sharp contact between spar and particles,
- spar between grains does not penetrate into or cut across grains,
- presence of two or more generations of spar,
- straight crystal edges and frequent triple junction with 180° angles (=enfacial junctions),
- long axes of crystals often normal to grain surfaces,
- increasing crystal size away from grain surface (drusic filling).

Size 10’-100’µm up to mm

Timing Early (synsedimentary) to late or very late (burial)

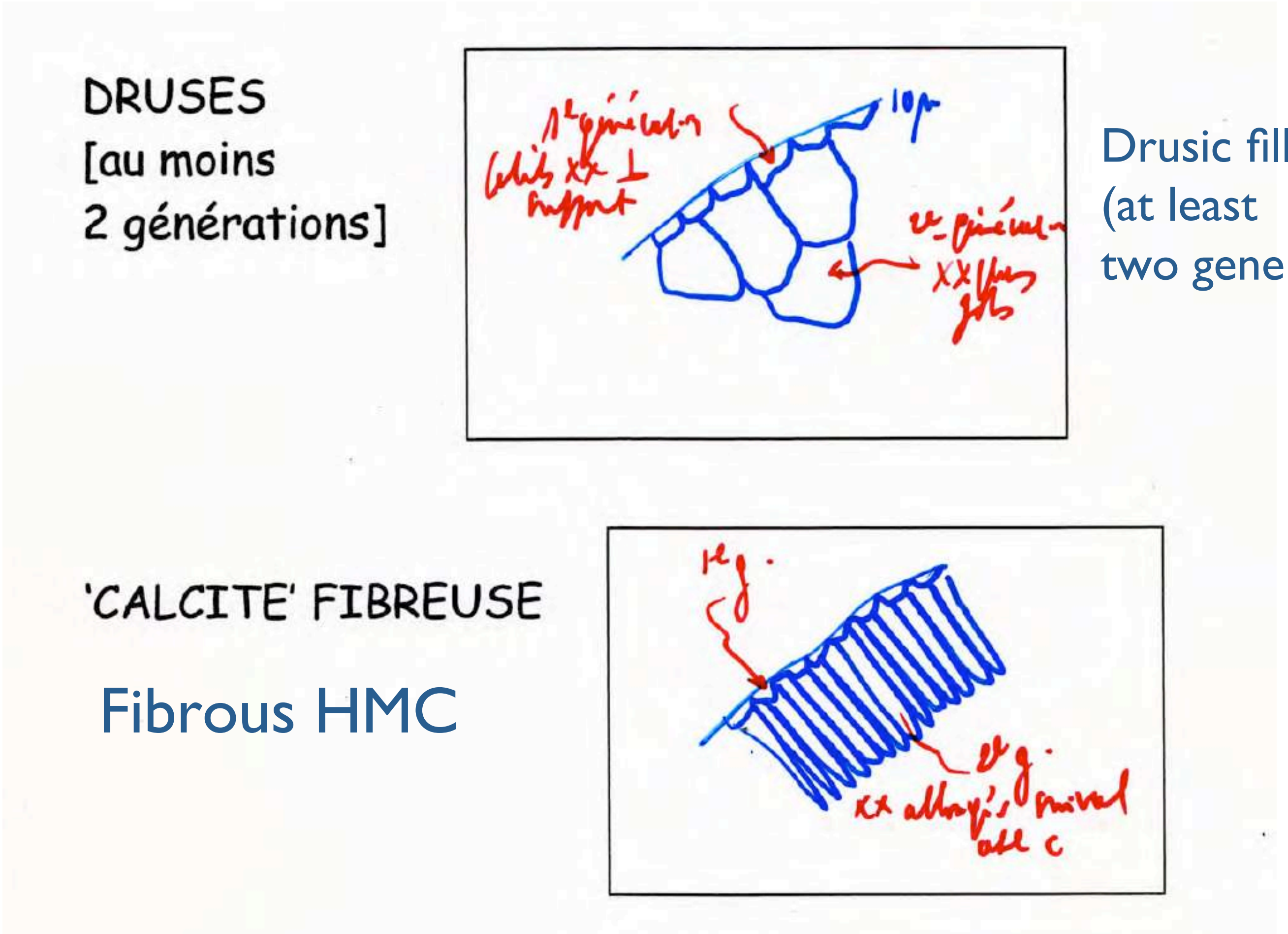
Modern marine cements and their geometries



Tucker & Wright 1990

PETROGRAPHY OF CARBONATES

2. CEMENT = pore-filling process



Drusic filling
(at least
two generations)

Fibrous HMC

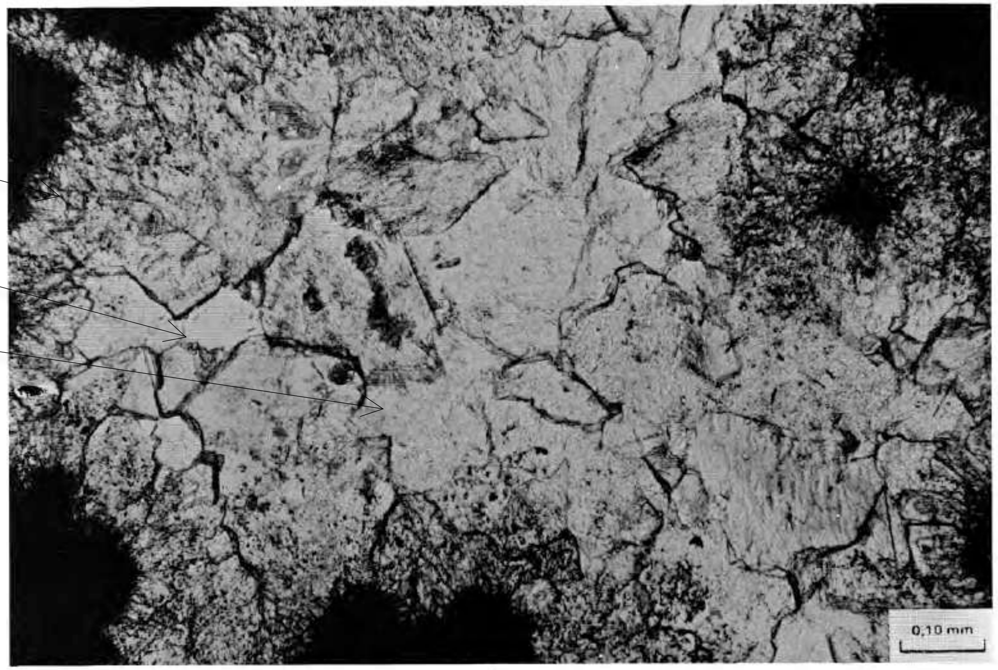
Cementation of carbonates is favoured by high pH and higher T
(Quartz or chert by low pH and low T)

DRUSY FILLING

I. fibrous

2. granular

3. coarse granular



1

Drusy calcite making up an irregular 'pore space'
Elf Aquitaine, 1975

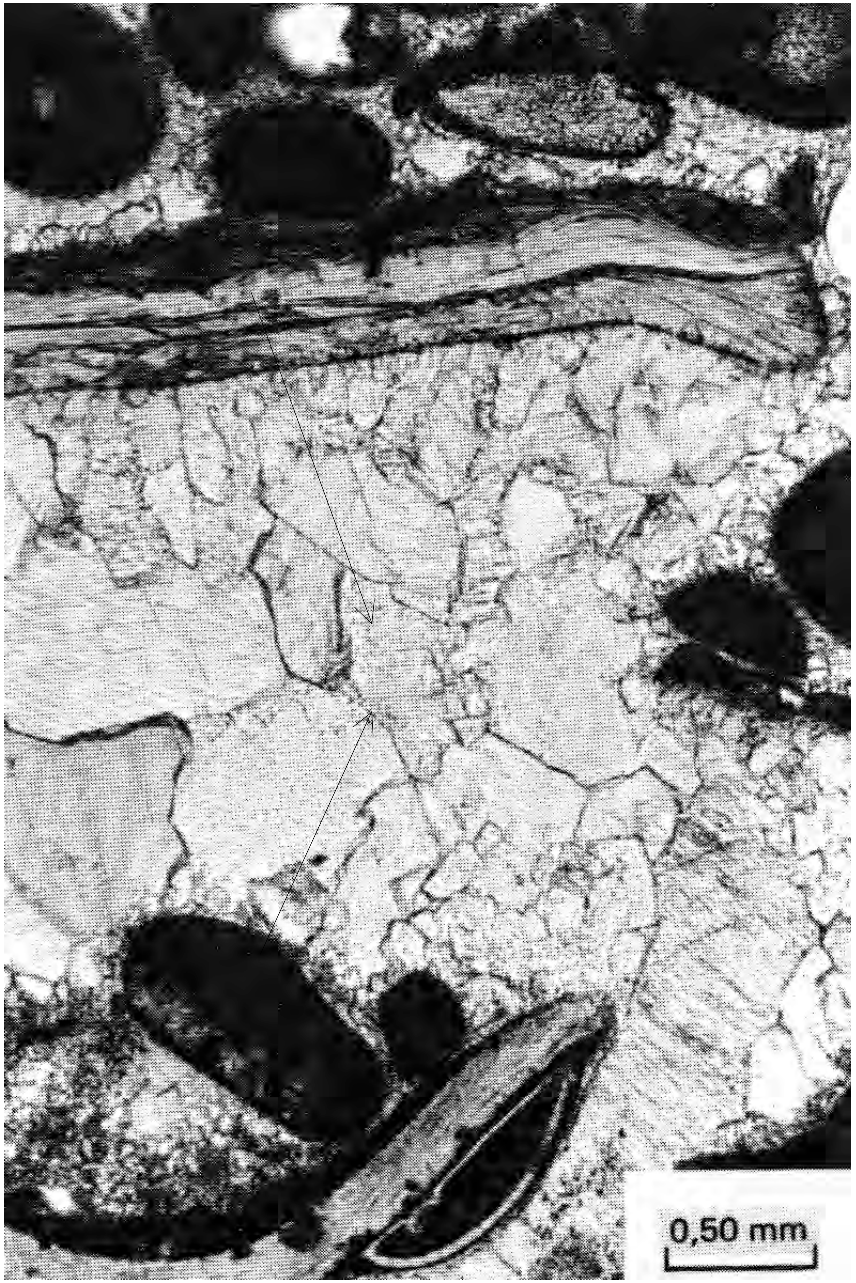
I

2

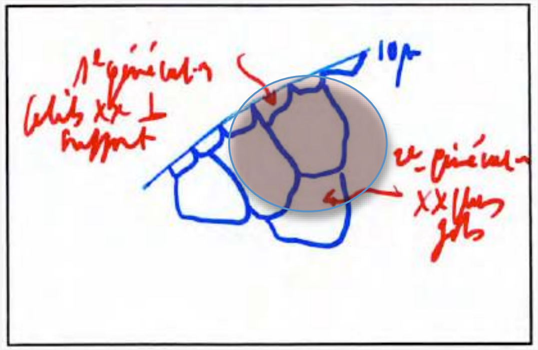
I

DRUSY FILLING

Intergranular porosity closed by a **drusy** mosaic calitic cementation in a bioclastic grainstone. *Shoal, Jurassic, Parsi Basin, Elf Aquitaine, 1975*



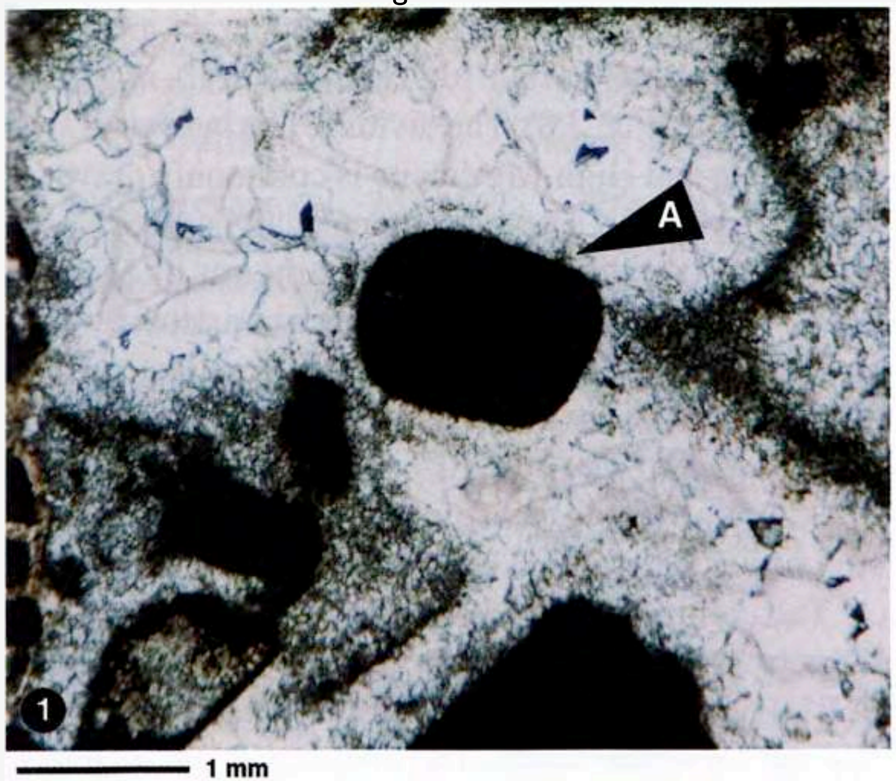
PETROGRAPHY OF CARBONATES
2. CEMENT = pore-filling process



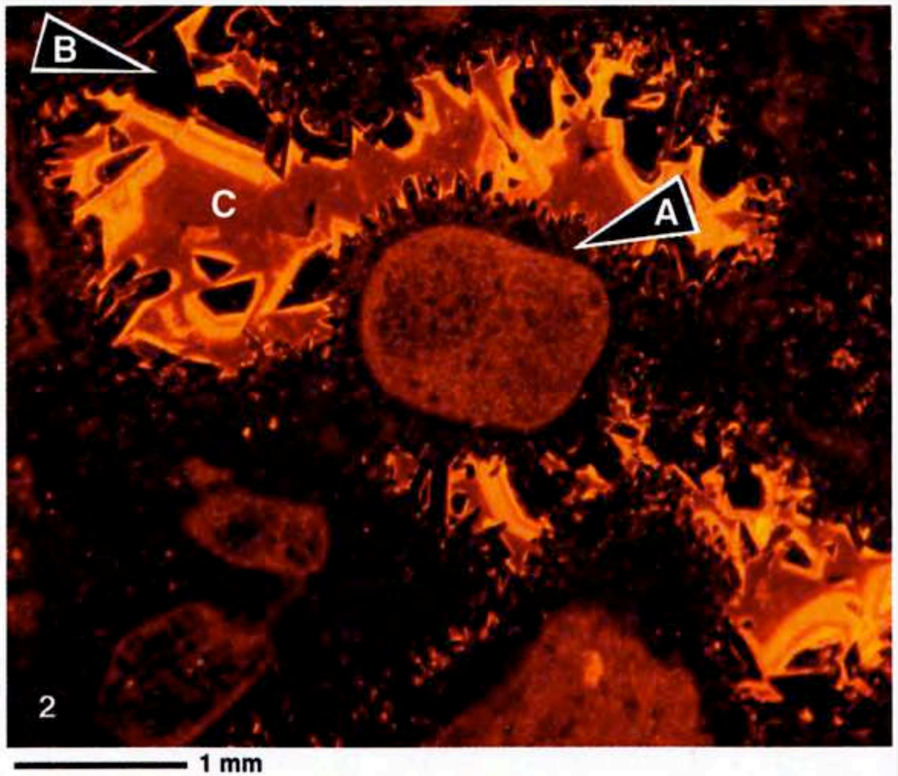
Cathodoluminescence microscopy (CL) = too see more…
(A) **NL** radial fibrous cement => (B) **NL** dogtooth cement
⇒(C) banded yellow to brown **L** burial coarse mosaic calcspar filling the remaining pore space. No **D** (DULL) cement.

Early Jurassic, carbonate platform, Morocco. Blomeier & Reijmer 1999 *in* Flügel 2004

Transmitted light



CL



2. CEMENT = pore-filling process

Cathodoluminescence 'facies'

• used to interpret diagenetic environments => 'geological events'
• erosional or truncated phases, if any, are visible
• combined with geochemical data (stable isotopes, trace and minor elements)
• also used in clastic sequences

• very useful to improve the knowledge of the quality of hydrocarbon reservoirs (= evolution of porosity-cementation PHASES during time)

Abundant literature and a lot of books….!

PETROGRAPHY OF CARBONATES

2. CEMENT = pore-filling process

Fibrous/Acicular cements : very common in modern reefs

⇒ **ARAGONITE : acicular crystals** forming isopachous fringes, needle meshwork, bothroid and micron-sized equant crystals (micrite)

- **acicular** = needle-like crsyals 10 μm across x 100 μm long [up to 500 μm]. In some cases the crystals are in optical continuity with crystals of the substrate (mollusks),
- needle meshwork and micritic aragonite cements : silt-sized internal sediment in intra-, interskeletal cavities
- **bothroidal** = up to 1cm in diameter, isolated or coalescent mamelons = fans of elongated euhedral fibres, commonly twinned giving a 'pseudohexagonal' shape.

= > **HMC** : **acicular-bladed** isopachous fringes, equant crystals micrite and peloids.

- **bladed** = common in many reefs with crsytals 20-100 μm long and < 10 μm wide. Gradual increase in width along their length and obtuse pyramid termination. They form fringes sometimes with several generations of cement or tight clusters or bundles. **Palisade** structure when all crytsals parallel,
- **micritic HMC** is common = 2-8 μm rhombs with curved faces, forming coating dup to 20 μm or more around grains or in intraskeletal cavities,

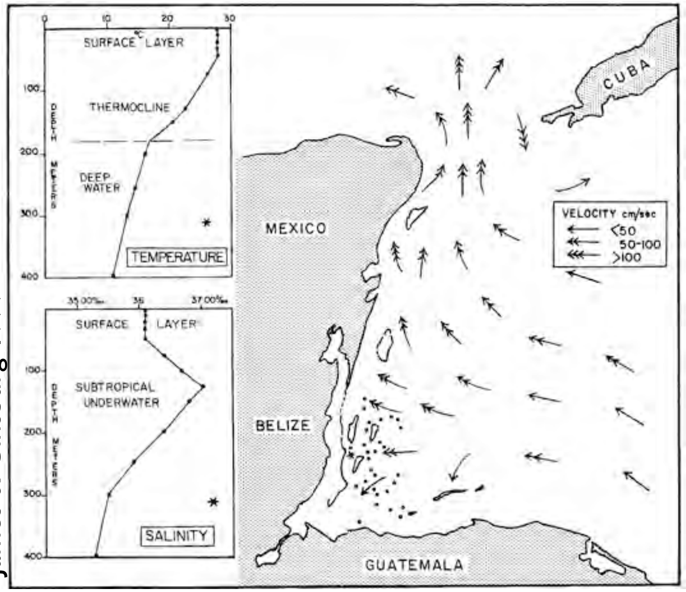
- **equant 'block' coarser HMC** : = last void-void filling marine cement after aciculr aragonite
  not to be confused with 'sparry' equant LMC = meteoric and burial environments
- **peloid** = (sub)spherical, 40 μm in diameter [20-60 μm], controverial origin? (microbial or not …) in inter- and intraskeletal cavities, can form crusts on corals….

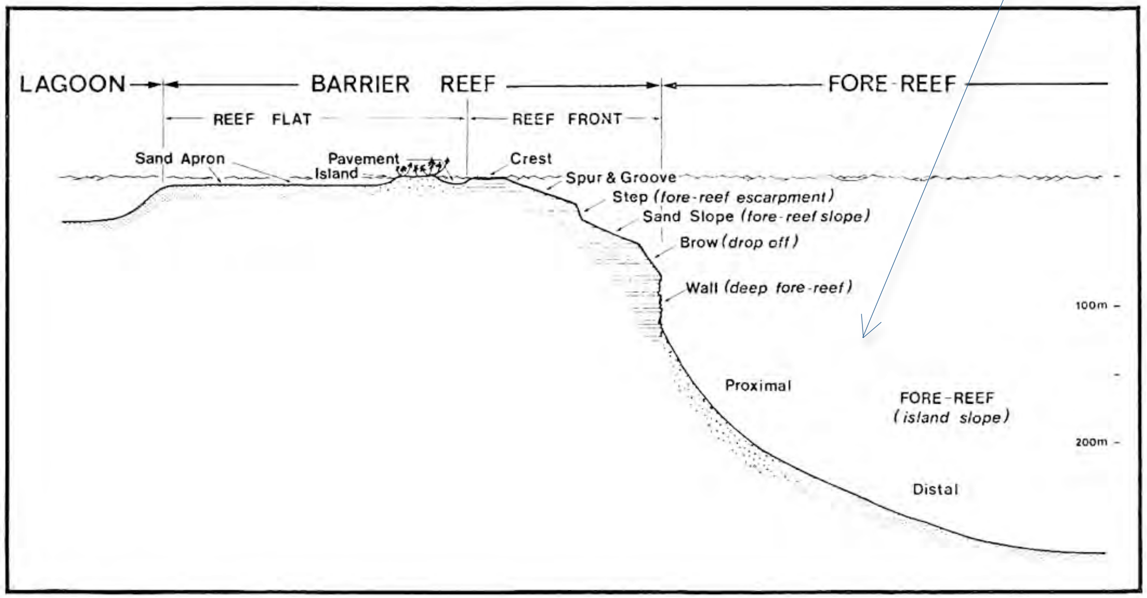
PETROGRAPHY OF CARBONATES
2. CEMENT = pore-filling process

reef-derived talus and sediment

Belize : subtropical modern carbonate rimmed platform
Reef barrier extending some 250 km form the Yucatan Peninsula to the Gulf of Honduras
Seaward the barrier reef there are three isolated platforms….

James & Ginsburg 1979





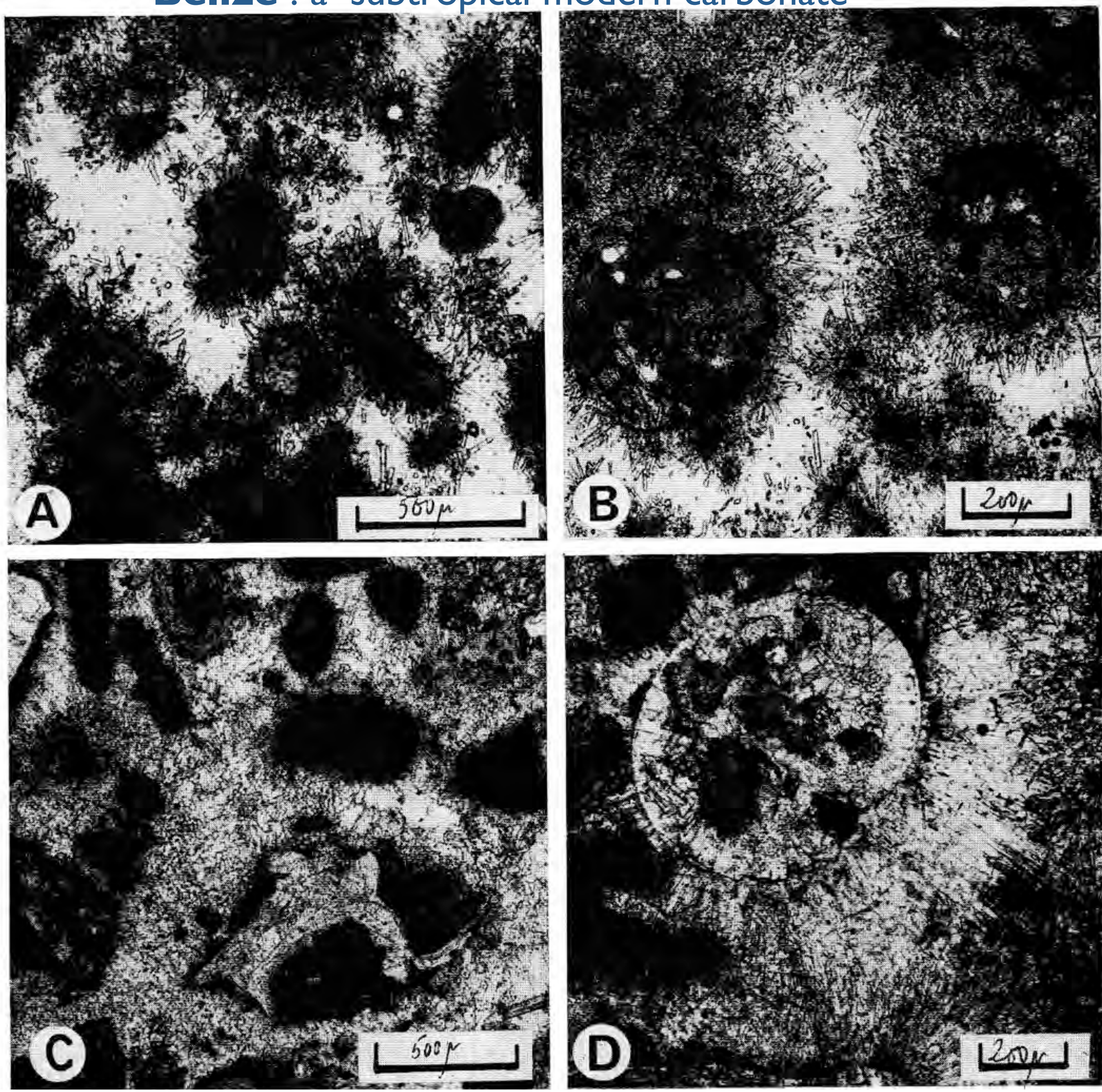
The lower limit of coral and calcareous green algae **growth** = ± 80m

2. CEMENT = pore-filling process

Belize : a subtropical modern carbonate

Aragonite cement
between widely spaced
grains => poor cementation
= needles of various shapes
in all directions
Depth -110m

Aragonite
cement
= needles
Depth -100m



James & Ginsburg 1979

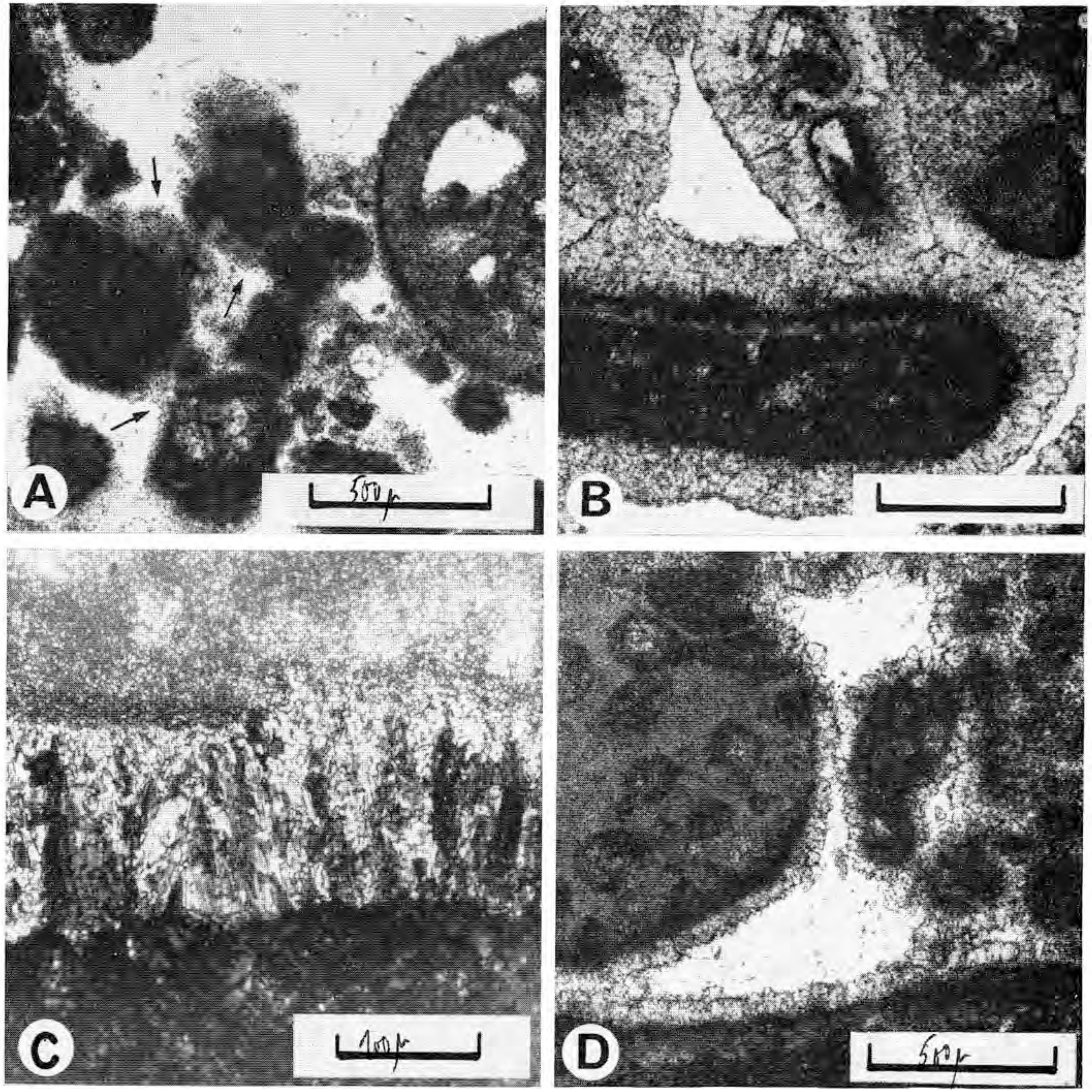
Well-cemented grainstone
by a mesh of aragonite
needles
Depth -110m

Aragonite cement
in optical
continuity on a
gastropod shell
Depth -88m

PETROGRAPHY OF CARBONATES

2. CEMENT = pore-filling process

Belize : a subtropical modern carbonate



HMC cement in a medium-grained sand. Early stage in development of micritic rinds (arrows)
Depth -110m

Isopachous rinds of bladed HMC in a *Halimeda*, red algal, foram grainstone
Depth -110m

Bundles of elongate HMC crsytals filling intergranular porosity in a skeletal grainstone
Depth -110m

'Palisade' or stubby`` HMC in a m/c grainstone
Depth -110m

James & Ginsburg 1979

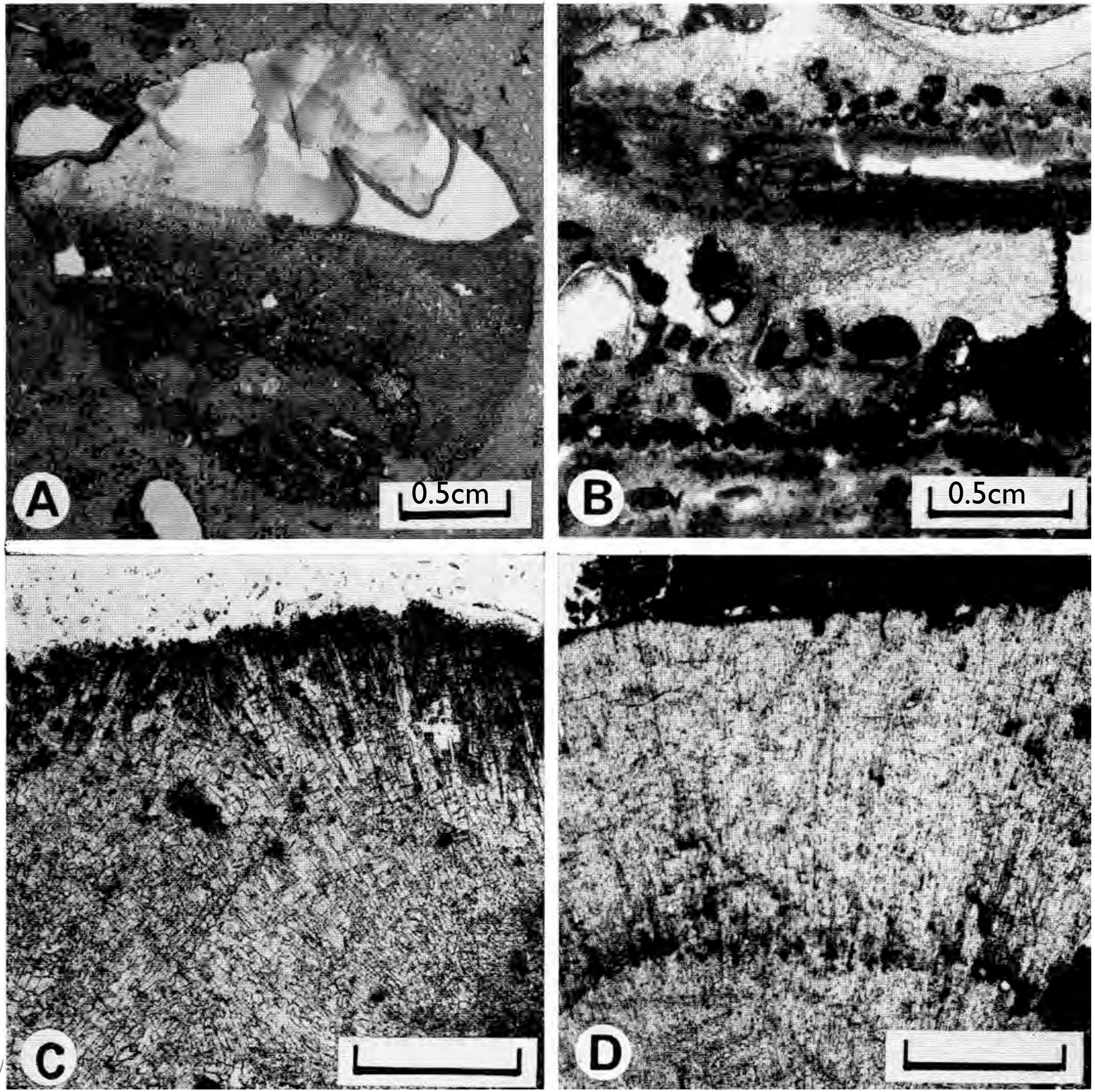
PETROGRAPHY OF CARBONATES

2. CEMENT = pore-filling process

Belize : a subtropical modern carbonate

Botryoidal aragonite filling a cavity in a coral (*Porites*). The cavity, a boring of a mussel (*Lihtophaga*), was partially filled with sand and mud.
Bothroidal aragonite is succeeded by a rind of HMC bladed spar
Depth -110m

Mesh of aragonite needles (left) in a cavity
Depth -110m



James & Ginsburg 1979

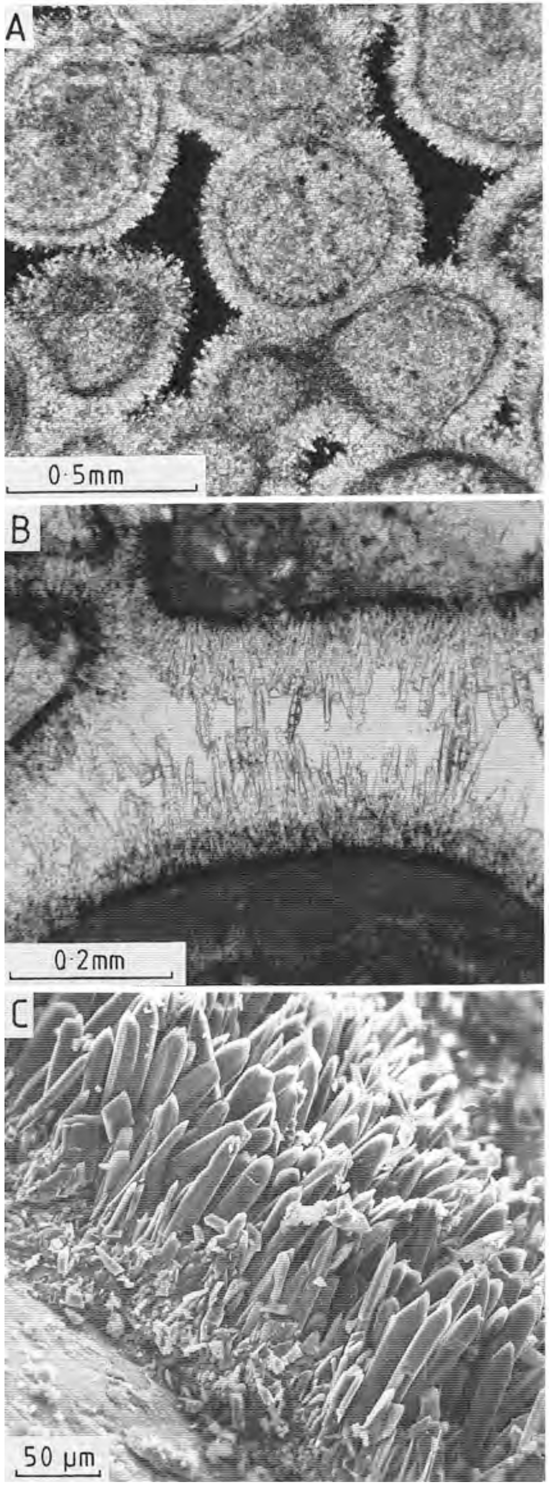
Aragonite spherulite in a large intergranular pore

needles (left)
Depth -110m

Close-up in a botryoidal aragonite with very abundant small needles
Depth -110m

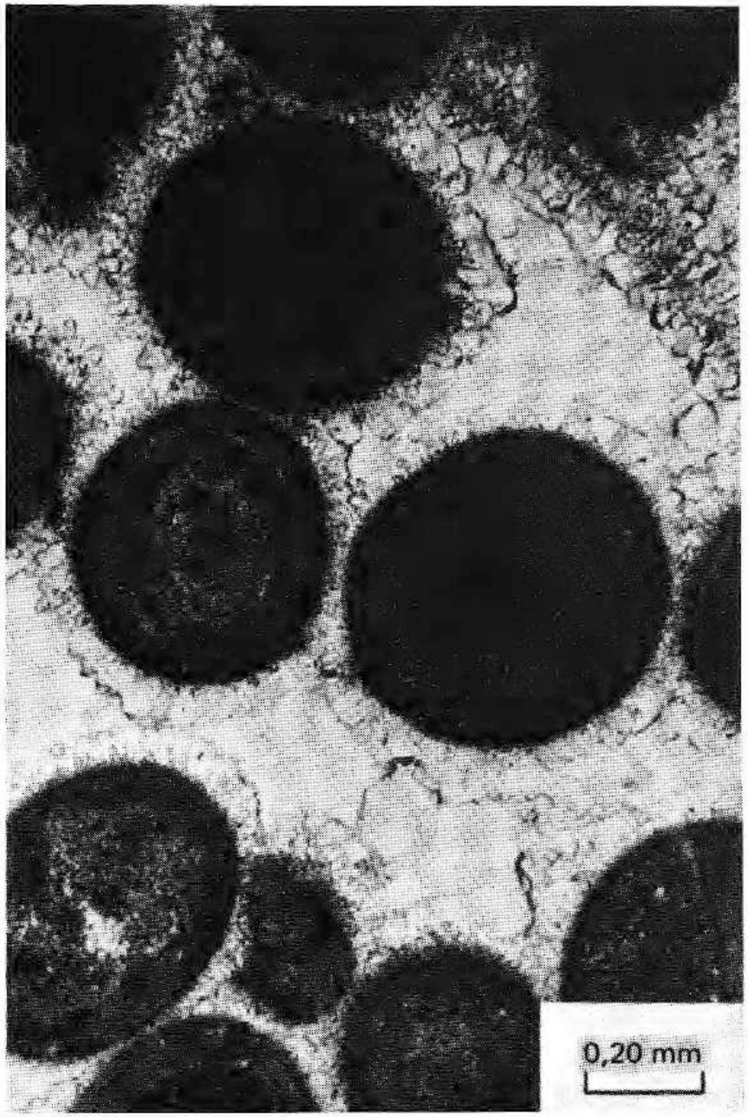
<u>Cemented lime sands</u>.
A.Ooids cemented by isopachous fringe of acicular aragonite Shallow subtidal, **Bahamas**
B. Coral (upper) and calcareous algal grains cemented by thin, dark layer of micritic HMC and then acicular aragonite. **Great Barrier Reef** area, Australia.
C. Aragonite needles growing on micrite upon the grain (bottom left). **Great Barrier Reef** area, Australia.

in Tucker & Wright 1990.

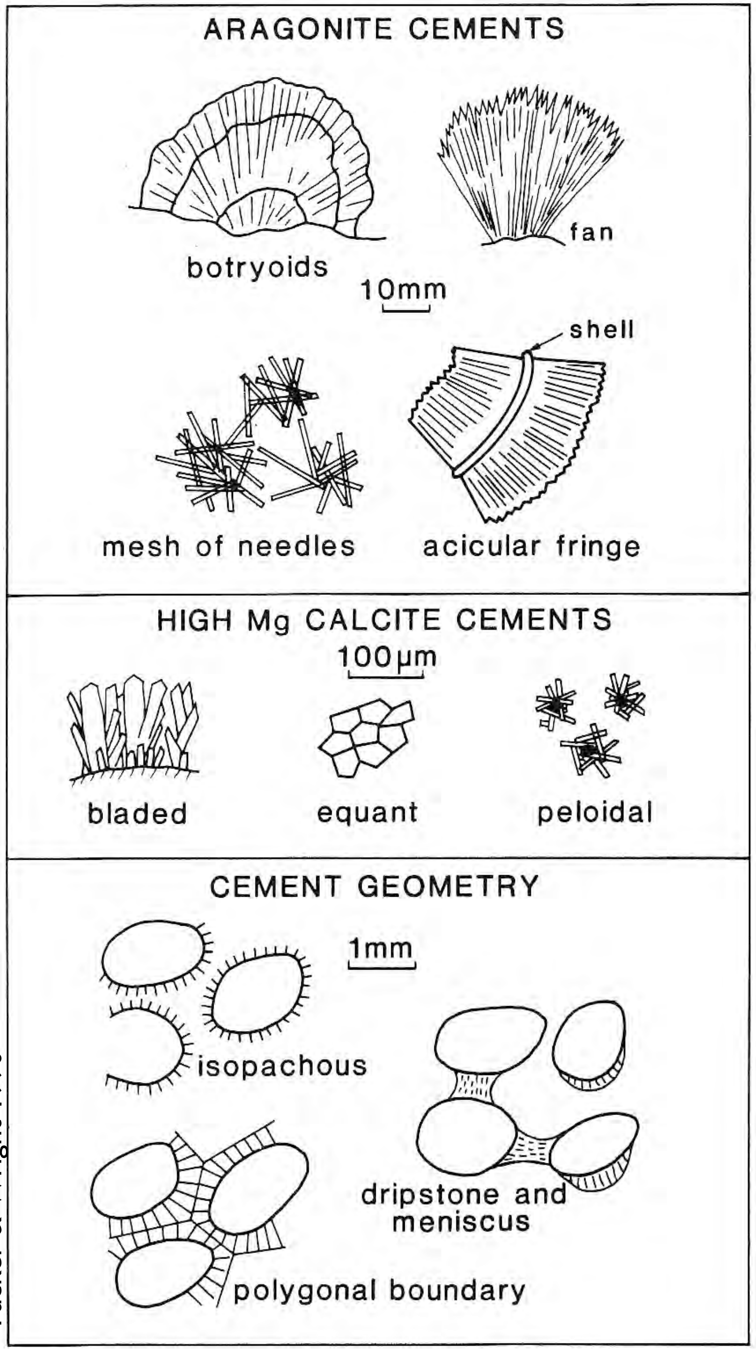


PETROGRAPHY OF CARBONATES
2. CEMENT = pore-filling process

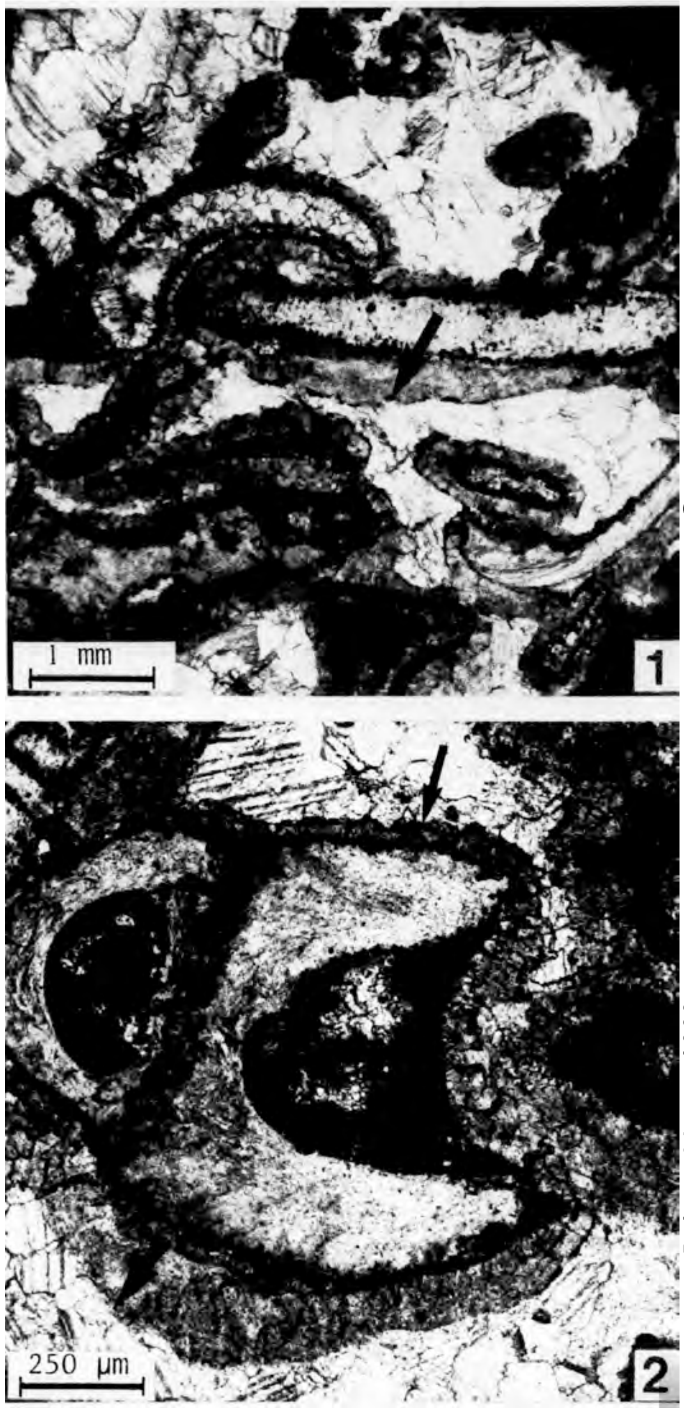
Intergranular porosity partially
closed by an isopachous rim of bladed LMC
in a shoal of grainstone deposit.
Beachrock?, Jurassic, Paris Basin
Elf Aquitaine, 1975.



Modern marine cements and their geometries



Tucker & Wright 1990



Préat & Mamet 1989

Vadose pendant cements in a Givetian grainstone
=
Beach-rock
Resteigne,
Lower Givetian
Belgium

PETROGRAPHY OF CARBONATES
2. CEMENT = pore-filling process

Granular cement : probably the most abundant in the geologic record
= EQUANT CEMENT

- ± equidimensional pore-filling small LMC crystals,
- common in interparticle pores, generally without distinct substrate control
- formed in meteoric-vadose, meteoric-phreatic and burial environments
- also from recrystallization of pre-exiting cements

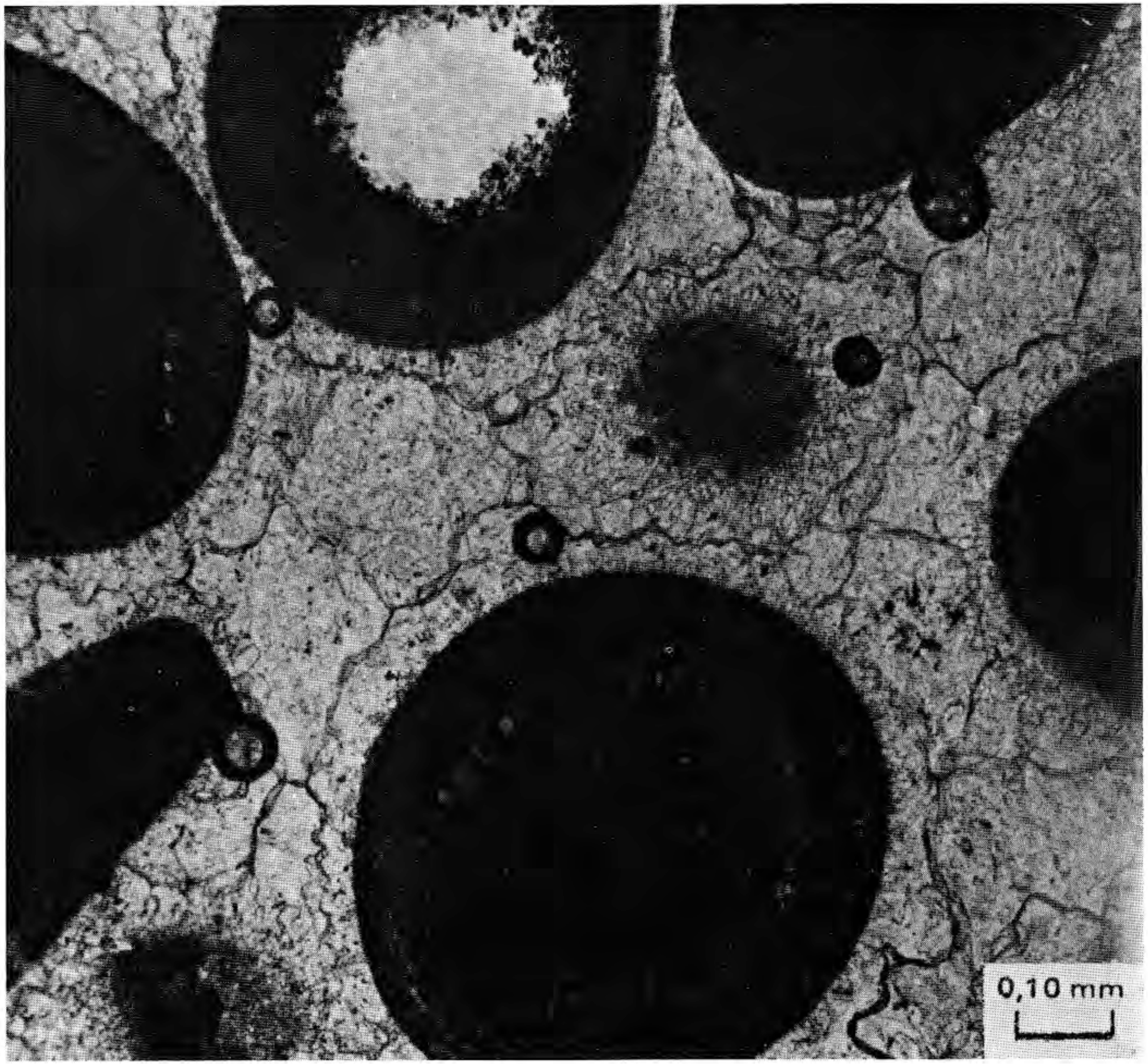
- GEOPETAL STRUCTURE
  A 'roof' formed by a shell or in a cavity… may prevent complete infilling by mud
  = > the resulting upper part of the void is later infilled by drusy or granular cement, permitting the determination of the original stratigraphic deposition or the up direction in a slide (for example along a reefal flank or slope..)

PETROGRAPHY OF CARBONATES

2. CEMENT = pore-filling process

GRANULAR CEMENT

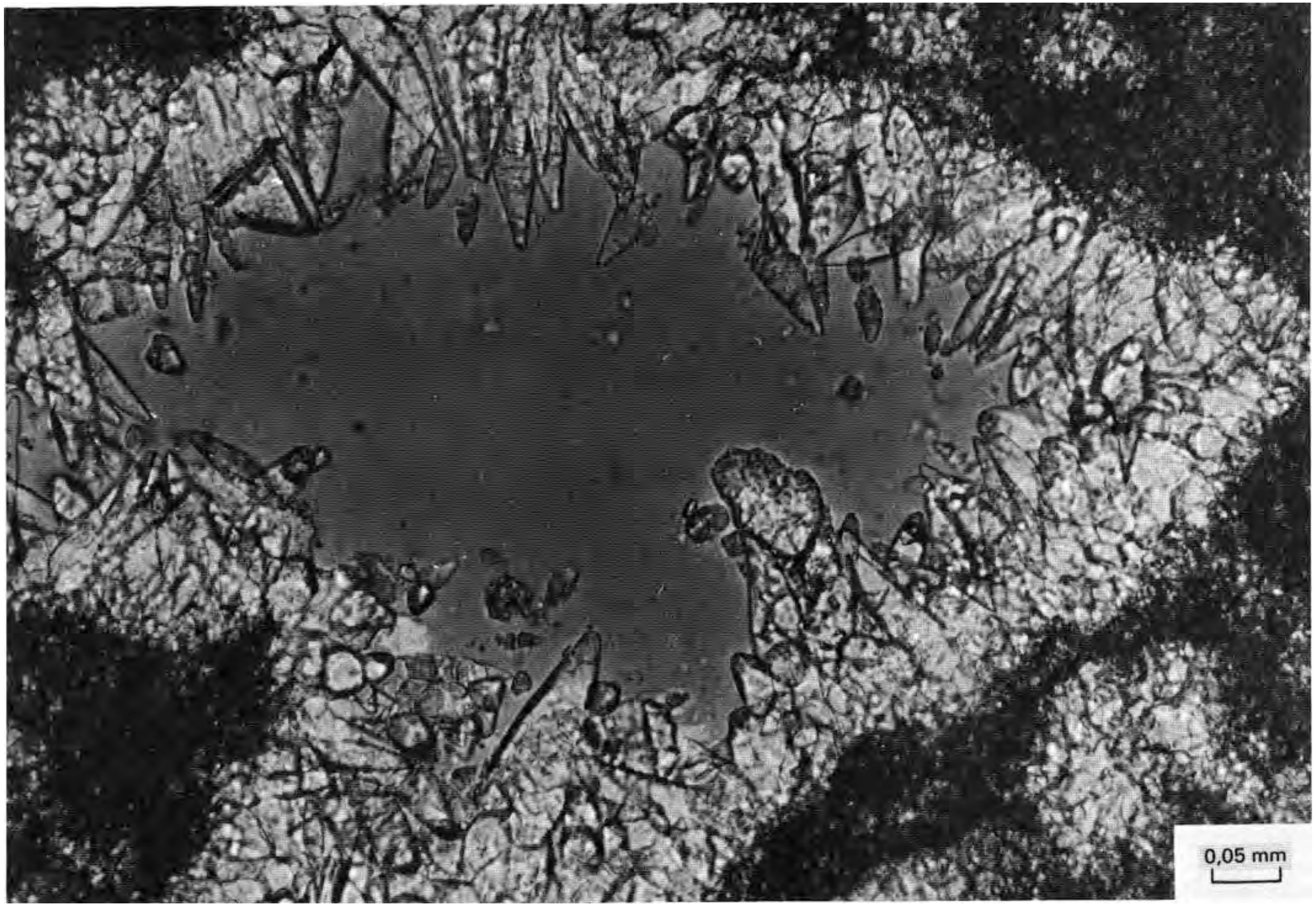
Granular cement
surrounding ooids
Elf Aquitaine, 1975



2. CEMENT = pore-filling process

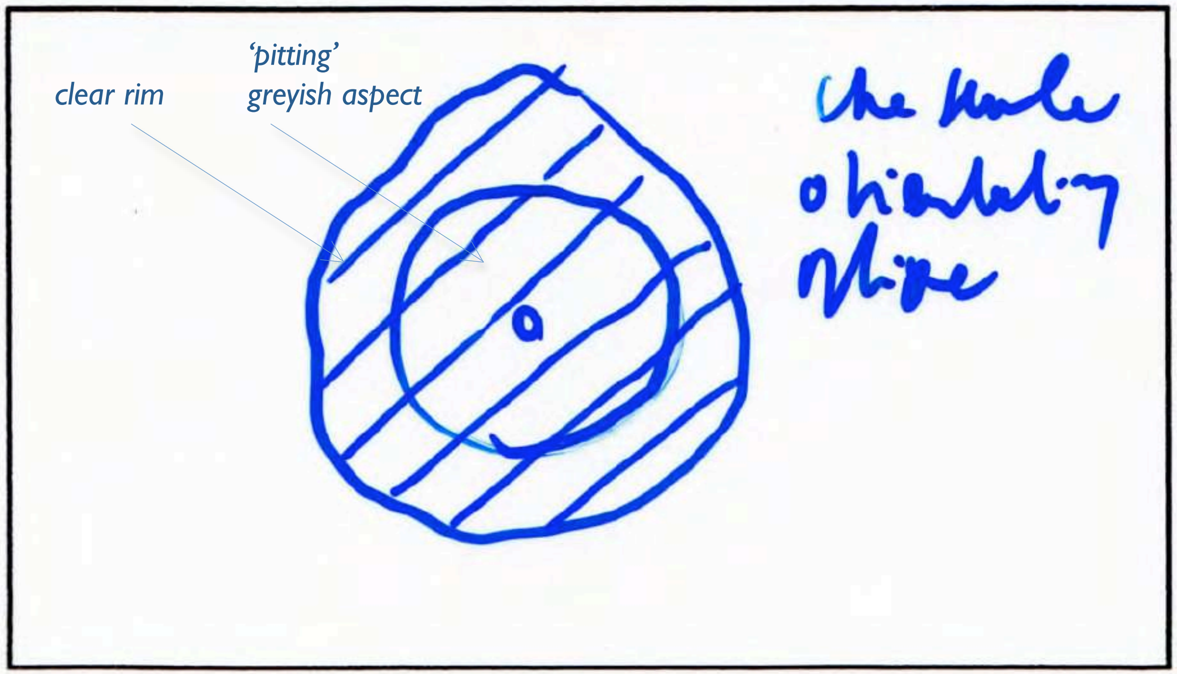
'DOG-TOOTH' CEMENT

'Dog-tooth' cement occluding partially a vuggy porosity.
Mio-Pliocene, Pacific
Elf Aquitaine, 1975



2. CEMENT = pore-filling process

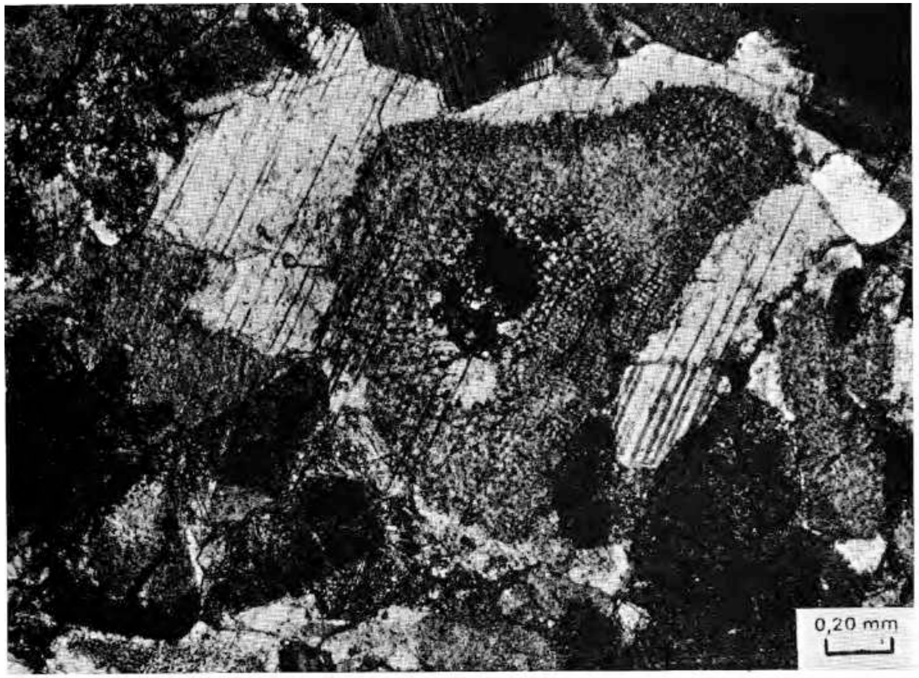
Echinoderm overgrowth rim cement or syntaxial cement

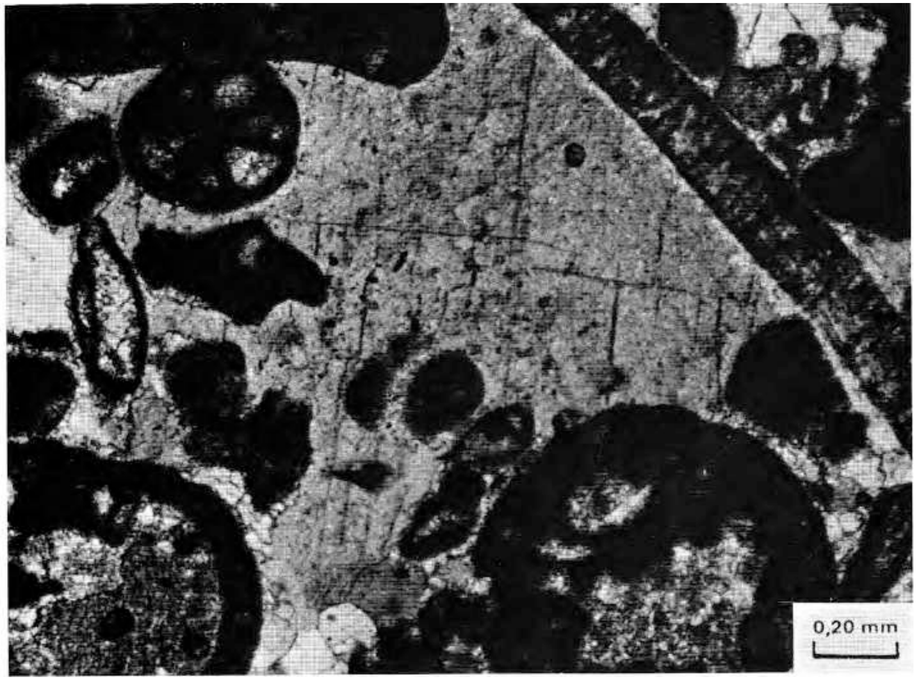


Overgrowth of clear rim cements in optical continuity with large monocrystalline host grains (e.g. crinoid ossicles, echinoid plates) is common in wkst-pkst-**gst**

PETROGRAPHY OF CARBONATES
2. CEMENT = pore-filling process

Syntaxial calcite, growing in optical continuity with echinoderm debris (Elf Aquitaine, 1975)





Poikilitic ('granular') calcite including bioclasts
(Elf Aquitaine, 1975)

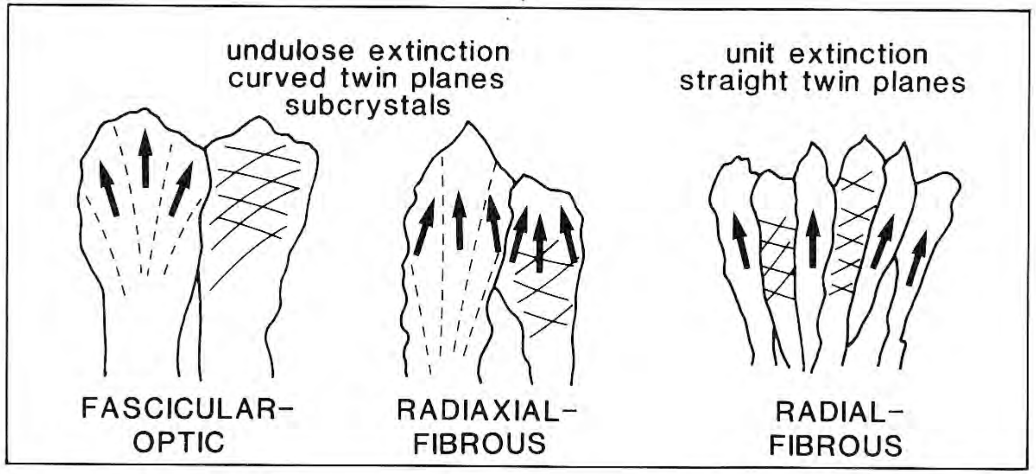
RFC = RADIAXIAL FIBROUS CALCITE
FOFC FASCICULAR-OPTIC FIBROUS CALCITE

Common ancient marine cement

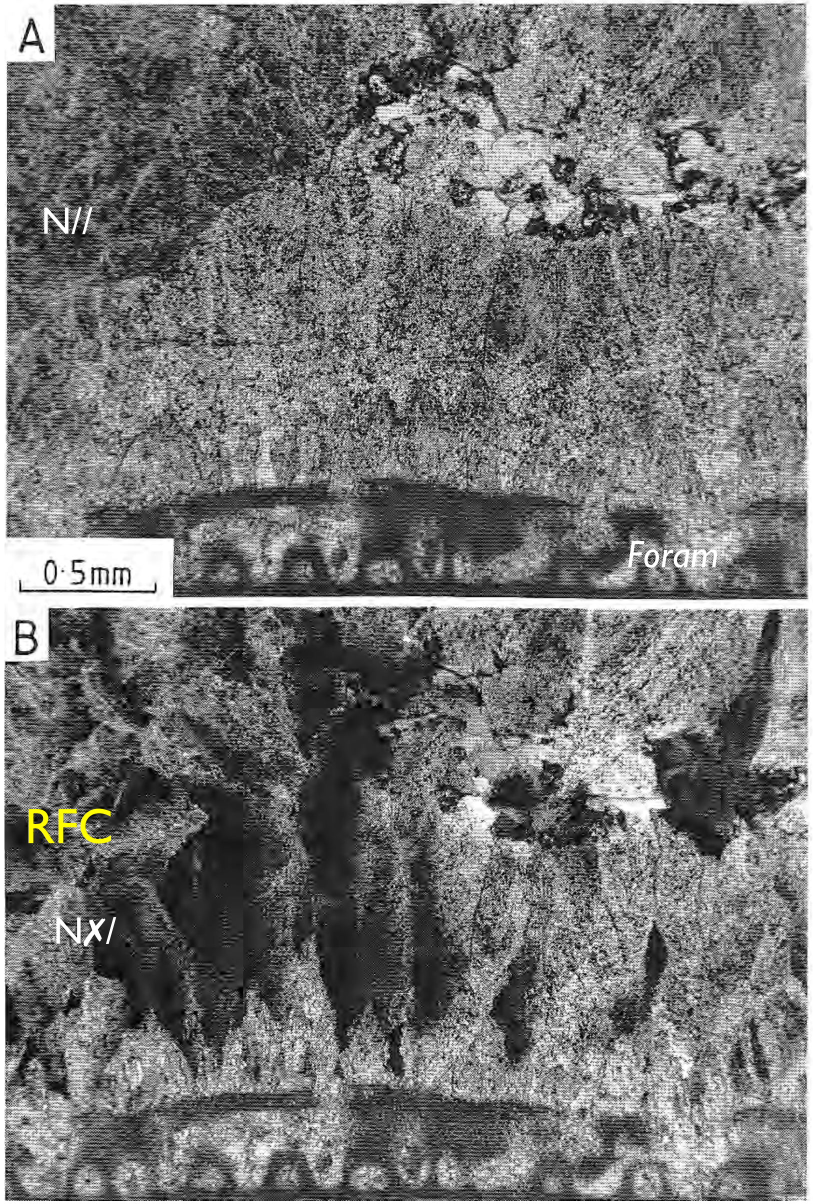
- **abundant in Paleozoic reefs and mud mounds**
- fibrous calcite crystals extinguishing with straight twin planes and slightly intercrystalline boundaries … each crystal has unit extinction but is part of a larger structure of swinging extinction

ORIGIN? controversial since ***there is NO modern equivalent***

- ? replacement of an acicular precursor
- probably primary origin from seawater…. of particular chemical composition….
- probably original **calcite** composition (?LMC or? HMC)….



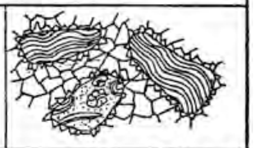
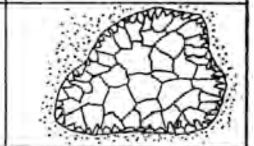
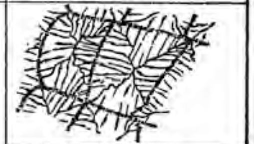
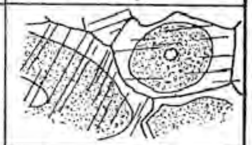
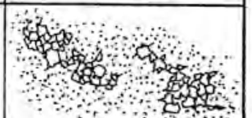
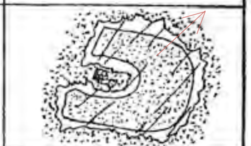
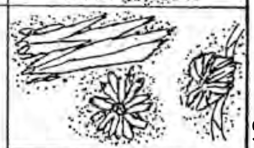
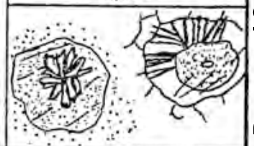
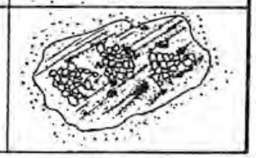
Undulose extinction due to divergent (=FOFC) or convergent (RFC) fast vibration (black arrows) direction (optic axes)



Permian, Capitan Reef, Texas *in* Tucker & Wright 1990

2. CEMENT = pore-filling process

calcite neoformation

PROCESS	FABRIC	
CEMENTATION AND CAVITY FILLING	GRANULAR CEMENT very common	
	DRUSY MOSAIC at least 2 generations	
	DRUSY FIBROUS CALCITE reefs, cavities….	
	SYNTAXIAL CEMENT RIM optical continuity	
GRAIN GROWTH	COARSE MOSAIC + microspar => 'false' cement	 10-20-30µm
	SYNTAXIAL REPLACEMENT RIM replace also the matrix	
	REPLACEMENT FIBROUS CALCITE	
GRAIN DIMINUTION RARE		
	GRANULAR MOSAIC	

Orme & Brown 1963

PETROGRAPHY OF CARBONATES

2. CEMENT = pore-filling process

Control of carbonate cementation

• cementation occurs at or near the sediment/water interface and requires an enormous input of $CaCO_3$ and an efficient fluid flow mechanism,
• the source of $CaCO_3$ in the marine realm = seawater,
in meteoric and burial environments = the solution of the sediment itself.

• precipitation of cements and dissolution are controlled by

. composition of pore fluids,
. flow rate => energy and rate of sedimentation (shallow-marine environments and reefs),
. primary porosity ad permeability,
. number of ions => oversaturation *vs* undersaturation,
. salinity and Mg/Ca ratio **=> Mg/Ca LOW = equant LMC , Mg/Ca HIGH = fibrous, acicular, 'micritic' HMC (+ARAG**)
. mineralogy of the substrates (important in reefs and sands),
. rate of precipitation,
. organic matter within and on grains => organic-rich poor waters prevent carbonate precipitation event from supersaturated waters => 'oil' in reservoir rock,s
. microbial mediation.

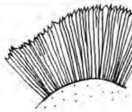
• timing of precipitation of carbonate cements
(i) oversaturation of a pore fluid within a pore space
(ii) nucleation, controlled by the mineralogy of the substrate => growth rates will control crystal morphology
(iii) crystal growth depends on the presence of sufficient Ca ions => cf porosity and permeability

PETROGRAPHY OF CARBONATES

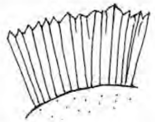
2. CEMENT = pore-filling process

Cement types

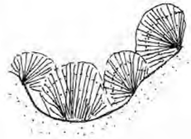
in Flügel 2004



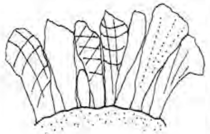
Acicular: Needle-like crystals, growing normal to the substrate. Crystals elongated parallel to the c-axis, exhibiting straight extinction. Terminations are pointed or chisel-shaped, twinning is common. Width < 10 μm, length about 100 μm and more. Often forming isopachous crusts. Predominantly aragonite, but also Mg-calcite. Marine phreatic. Pl. 31/2, Pl. 34/1.



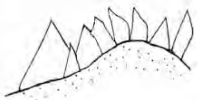
Fibrous: Fibrous crystals, growing normal to the substrate. Crystals show a significant length elongation, usually parallel to the c-axis. Crystal shape is needle-like or columnar (length to width ratio > 6:1, width > 10 μm). Size commonly fine to medium crystalline. Often forming isopachous crusts; common in inter- and intraparticle pores. Aragonite or High-Mg calcite. Mostly marine-phreatic, but also meteoric-vadose and marine-vadose (columnar crystal shape). Syn.: Radial fibrous. Pl. 2/4, Pl. 31/1-2, Pl. 32/1-4, Pl. 50/6.



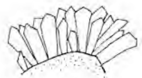
Botryoidal: Pore-filling cement made of individual and coalescent mamelons exhibiting discontinuous horizons, e.g. dust lines ranging in size from tens of microns to several centimeters. The cement consists of individual and compound fans, which in turn are composed of elongated euhedral fibers with a characteristic sweeping extinction in cross-polarized light. Aragonite. Usually marine (common in cavities of reefs and steep seaward slopes), but also known from burial environments. Syn.: Spherulitic. Pl. 145/1-3.



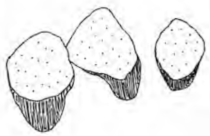
Radiaxial fibrous: Large, often cloudy and turbid, inclusion-rich calcite crystals with undulose extinction. Size medium to coarse crystalline. Sometimes extending several millimeters in length, usually about 30 to 300 μm. Crystal length/width ratio 1:3 to 1:10. Crystals show a pattern of subcrystal units. Within each subcrystal that diverges away from the substrate an opposing pattern of distally-convergent optic axes occurs, caused by a curvature of cleavage and twin lamellae. Undulose extinction of subcrystals or subcrystal units are used in distinguishing three radiaxial subtypes (see text). Often forming isopachous crusts. Phreatic-marine and burial. Pl. 27/2, Pl. 34/2; Fig. 7.9.



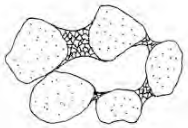
Dog tooth: Sharply pointed acute calcite crystals of elongated scalenohedral or rhombohedral form, growing normal and subnormal to the substrate (grain surfaces, atop earlier cements). Crystals are a few tens to a few hundred micrometers long and have acute and sometimes blunted terminations. Often meteoric and shallow-burial but also marine-phreatic and hydrothermal. Syn.: Bladed scalenohedral cement, bladed prismatic calcite cement, dentate cement, scalenohedral calcite cement. Pl. 2/3, Pl. 31/5-6, Pl. 34/8.



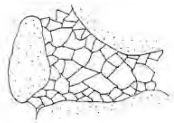
Bladed: Crystals that are not equidimensional and not fibrous. They correspond to elongate crystals somewhat wider than fibrous crystals (length/width ratio between 1.5:1 to 6:1) and exhibiting broad flattened and pyramid-like terminations. Crystal size up to 10 μm in width and between less than 20 and more than 100 μm in length. Crystals increase in width along their length. Commonly forming thin isopachous fringes on grains. Usually High-Mg calcite but also aragonite. Marine-phreatic (abundant in shallow-marine settings) and marine-vadose. Pl. 33/1, 3, 5, 8; Pl, 34/7.



Dripstone: Pendant cement characterized by distinct thickening of cement crusts beneath grains or under the roofs of intergranular and solution voids. The cement forms on droplets beneath grains after the bulk of the mobile water has drained out of the pores, leaving a thicker water film at the lower surface of the grains. Forms typically gravitational, beard-like patterns. Predominantly calcite. Formed below the zone of capillarity and above the water table within the meteoric-vadose zone (often associated with meniscus cement), but also in the meteoric-phreatic and sporadically in marine-vadose diagenetic environments (e.g. inter- and supratidal, and beachrocks: aragonitic dripstone cement). Syn.: Gravitational cement, microstalactitic cement, microstalactitic druse cement, stalactitic cement. Pl. 34/6, Pl. 126/1.



Meniscus: Calcite cement precipitated in meniscus style at or near grain-to-grain contacts in pores containing both air and water. Exhibits a curved surface below grains. Resulting intergranular pores have a rounded appearance due to the meniscus effect. Characteristically formed in the meteoric-vadose zone but may also occur in the phreatic-meteoric and the vadose-marine environment (beachrock). Pl. 14/1, Pl. 32/5-6, Pl. 33/4, Pl. 126/1.

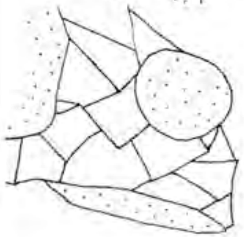


Drusy: Void-filling and pore-lining cement in intergranular and intraskeletal pores, molds and fractures, characterized by equant to elongated, anhedral to subhedral non-ferroan calcite crystals. Size usually >10 μm. Size increases toward the center of the void. Displays a characteristic fabric (see Fig. 7.12). Near-surface meteoric as well as burial environments. Syn.: Drusy calcite spar mosaic, drusy equant calcite mosaic. Pl. 10/2.

PETROGRAPHY OF CARBONATES
2. CEMENT = pore-filling process

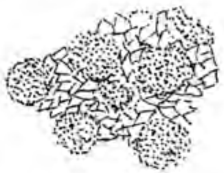
Cement types *in* Flügel 2004

Granular: Calcite cement consisting of relatively equidimensional pore-filling small crystals. Common in interparticle pores, generally without distinct substrate control. Formed in meteoric-vadose, meteoric-phreatic and burial environments. Can also originate from recrystallization of pre-existing cements. Pl. 10/2.

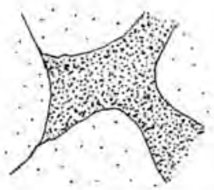


Blocky: Calcite cement consisting of medium to coarse-grained crystals without a preferred orientation. Characterized by variously sized crystals (tens of microns to several millimeters), often showing distinct crystal boundaries. Xenotopic and hypidiotopic crystal fabrics common. High-Mg calcite or Low-Mg calcite. Typically in meteoric (meteoric phreatic and vadose) and burial environments; rare in marine hardgrounds and reefs. Precipitated after the dissolution of aragonite cements or grains or as late diagenetic cement filling remaining pore space. Blocky textures can also originate from recrystallization of pre-existing cements. Pl. 20/1, Pl. 28/2, Pl. 34/1.

Syntaxial calcite overgrowth cement: Substrate-controlled overgrowth around a host grain made by a single crystal (usually High-Mg calcitic echinoderm fragments). Overgrowth often in crystallographic lattice continuity with the host grain. Echinoderm overgrowth is often zoned. Color differences between the skeletal grain and the overgrowth cement can be conspicuous. Overgrowth cements from near-surface marine, vadose-marine and meteoric-phreatic environments are inclusion-rich and cloudy, in contrast to clear overgrowth from deep burial environments Syn.: Grain overgrowth cement, syntaxial echinoderm cement, syntaxial cement rim, syntaxial overgrowth rim cement. Pl. 31/3-4, Pl. 34/3-4, Pl.144/5; Fig. 7.10.



Peloidal microcrystalline cement: Characterized by a peloidal (or pelleted) fabric composed of tiny peloids (size <100 μm) within a microcrystalline calcite matrix. The peloids consist of micrite-sized crystals bearing a radiating halo. Shallow-marine. Common in modern and ancient reefs. Possible interpretations: Chemical and/or microbially induced precipitation (Sect. 4.2.2). Pl. 8/5.



Microcrystalline or micrite cement: Micron-sized curved rhombic crystals. Forms thin coatings around grains, lines intraskeletal pores, fills pores completely or constructs bridges between grains (contributing to meniscus cement). Mg-calcite. Micritic cement fringes should be distinguished from micrite envelopes (Sect. 4.2.3). Often associated with peloidal cements. Pl. 31/3-4, Pl. 32/1-4, Pl. 33/2.

2. CEMENT = pore-filling process

Control of carbonate cementation in major settings

• Platform carbonates

. rapid sedimentation,
. variable pore waters ranging in salinity from freshwater and brackish to marine and hypersaline,
. fine-to coarse grained sediments often associated with evaporites,
. metastable and stable carbonate minerals,
. variable diagenetic and compaction potential,
. possibility of the influx of meteoric water,
. carbonate source for cement initially provided by meteoric dissolution, later pressure solution,
. decreasing porosity with depth and overburden, but strongly varying with pore water flux rates and different compaction intensities depending from different sedimentary fabrics.

• Basinal carbonates

. slow sedimentation,
. initially marine pore waters,
. fine-grained sediments often associated with clay and organic matter,
. stable carbonate minerals,
. low diagenetic and compaction potential,
. no possibility of influx of meteoric water,
. carbonate source for cementation provided by pressure solution,
. exponential decrease of porosity-permeability with depth and overburden.

PETROGRAPHY OF CARBONATES
2. CEMENT = pore-filling process

Control of carbonate cementation in major settings

• Very deep burial diagenesis (6000-9000 m, T 210°C, hydrostatic p 2.5 kbar)

. grainstones exhibit twinning and cleavage of LMC,
. mechanical displacement along cleavage planes occurs within single echinoderm crystals,
. twin lamellae appear more narrowly set than in shallow burial,
. multiple displacement of differently oriented twin lamellae is common,
. bent twinning lamellae and diminution within echinoderm single crystal.

. wackestones and packstones do not display thin-section criteria (protected effect by micrite),
. the size of micrite crystals is enlarged up to 30μm,
. the texture resembles that of fine-grained marbles (with patchy extinction).
compaction intensities depending from different sedimentary fabrics.

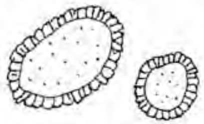
PETROGRAPHY OF CARBONATES

2. CEMENT = pore-filling process

Cement fabrics, *in* Flügel *2004*

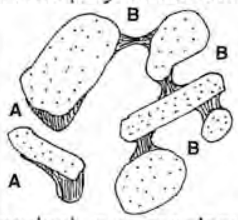
Cement rims around grains (symmetrical cements)

Isopachous: Characterized by single or multiple cement rims growing with equal thickness around grains. The cement rim may consist of fibrous, bladed, or microcrystalline crystals. Thickness of the rim within the range of tens of microns to several millimeters. Common in marine-phreatic and marine-vadose environments.



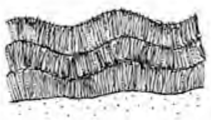
Circumgranular: Characterized by a cement rim around grains, consisting of equidimensional crystals forming the first generation of pore-lining cements. The rim is commonly thinner than isopachous cement rims. Meteoric phreatic environment.

Cement rims restricted to the underside of grains and void roofs (asymmetrical cements)



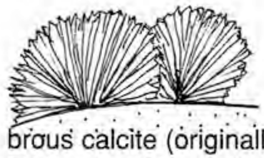
Gravitational: Pendant beard-like cements (A) beneath grains. Often associated with bridging cements (B, meniscus cement) which connect adjacent grains. Gravitational and bridging cements (crossing pores and connecting grains), e.g. meniscus cement and microcrystalline cement, are irregularly distributed and absent in many pores. Meteoric-vadose, meteoric-phreatic and marine-vadose environments.

Large cement structures exhibiting geometrical patterns



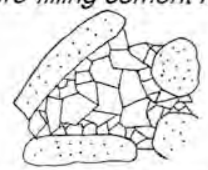
Crusts: Millimeter- to centimeter thick crusts consisting of calcite cements (fibrous, radiaxial fibrous, microcrystalline) growing on extended substrates (e.g. pore walls, hardgrounds, shells). Cement crusts may consist of one or more growth zones and may display internal differentiations (e.g. alternating crusts formed by fibrous or radiaxial cements and festooned cellular crusts). Marine and meteoric environments. Chevron crusts, characterized by V- and inverted V-shape patterns, may sometimes be caused by neomorphic processes.

Splays: Fan-like structure consisting of fibrous outward spreading calcite crystals. The structures may occur isolated or within marine cement crusts.



Botryoids: Complex structures consisting of various dome-shaped hemispheres built by radiating fibrous calcite (originally aragonite) crystals and crystal fans. Formed on free surfaces as well as in marine cavities.

Pore-filling cement mosaics

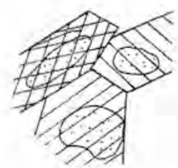


Drusy mosaic: Characterized by pore-filling calcite crystals increasing in size toward the center of interparticle pores or voids. Crystals with compromise boundaries (plane intercrystalline boundaries generated by two crystals growing alongside each other). Burial and near-surface meteoric environments.

Equant mosaic: Characterized by small pore-filling calcite crystals of approximately equal size. Subhedral and anhedral crystals with well-developed boundary faces.

Granular mosaic: Characterized by small pore-filling calcite crystals without a preferred orientation and no substrate control. Meteoric-vadose, meteoric-phreatic and burial environments.

Overgrowth



Syntaxial echinoderm overgrowth: Fabric characterized by the dominance of syntaxial calcite cement, formed as overgrowth usually on echinoderm skeletal grains within the sediment. In many places in optical continuity with a substrate of the same mineralogy. Vadose, meteoric-phreatic, and burial environments.

PETROGRAPHY OF CARBONATES
2. CEMENT = pore-filling process

RECRYSTALLIZATION vs CEMENTATION

° not many generations ≠ drusic with 2 or > 2 generations,
° homogeneous ≠ heterogeneous,
° often inside or in the border of the grain or crystals ≠ straight contacts,
° clay, organic matter between crystals ≠ no clay or organic matter (=inhibitor),
° small-sized < 500µm ≠ coarse-sized, several 100'µm up to mm, sometimes cm,
° often micritic relics => 'greyish' ≠ translucid = 'clear sparite'.

PETROGRAPHY OF CARBONATES

1. MATRIX

2. CEMENT

3. GRAINS