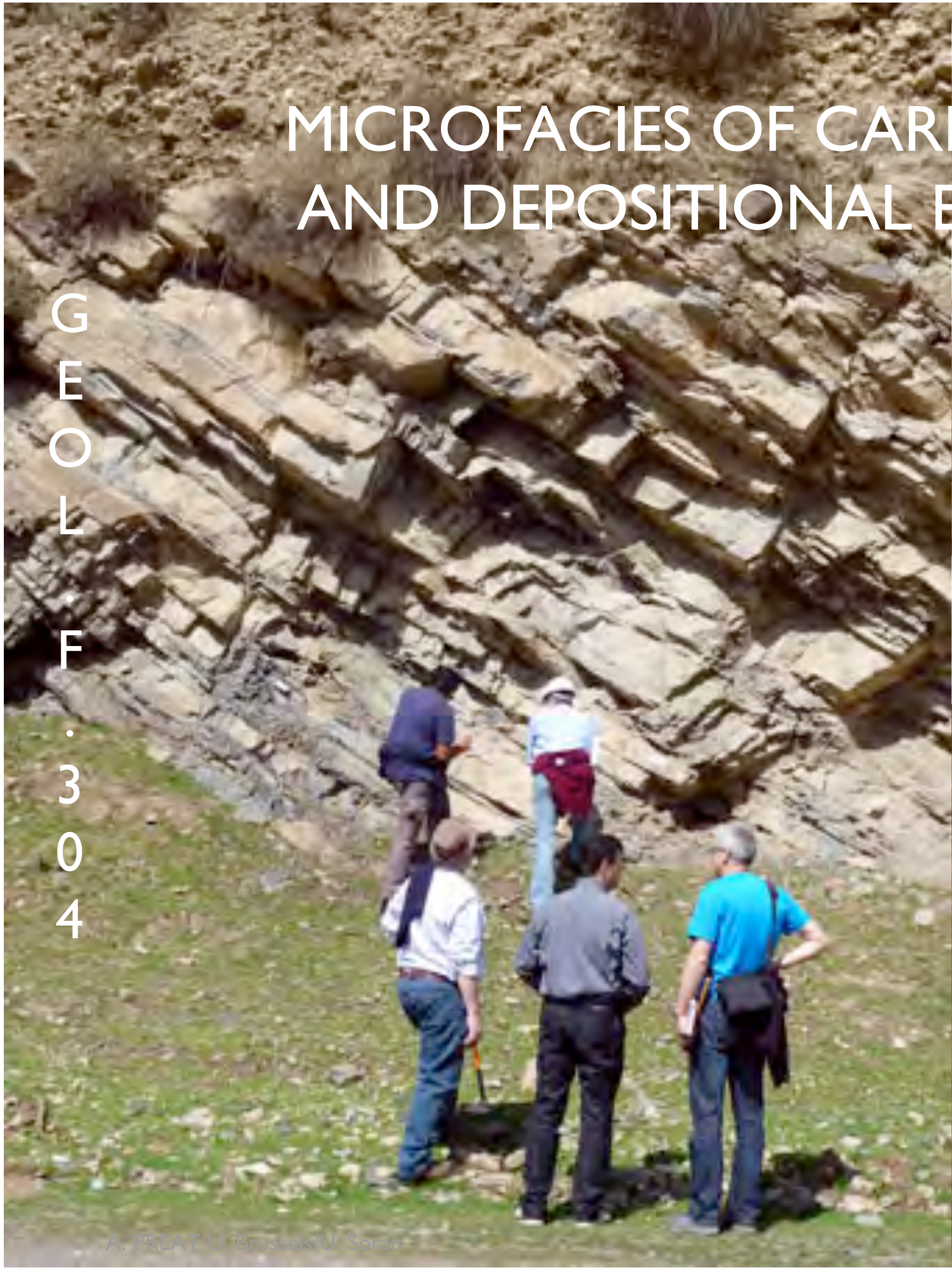
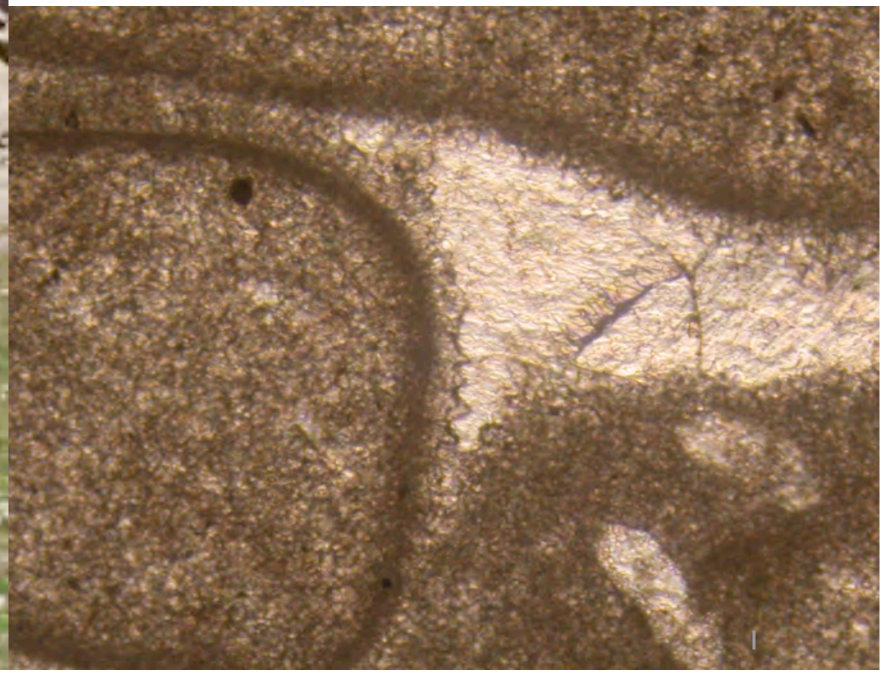
MICROFACIES OF CARBONATE ROCKS AND DEPOSITIONAL ENVIRONMENTS

GEOL.F.304



Prof. Alain Préat
Free University of Brussels



PETROGRAPHY OF CARBONATES

1. MATRIX

2. CEMENT

3. GRAINS

A carbonate grain tells a story ≠ A clastic grain
('highly sensitive' > < 'inert')

4 . FABRICS

THE TERM **FABRIC** INCLUDES TEXTURAL AS WELL AS STRUCTURAL CRITERIA

- Most fabrics reflect depositional controls or early diagenetic processes, they are sometimes related to postdepositional features,
- Fabrics are ‘constructed’ by rock constituents (matrix, cement and grain types).

PETROGRAPHY OF CARBONATES
4. DEPOSITIONAL AND DIAGENETIC FABRICS
4.1. BIRDSEYES, FENESTRAL and STROMATACTIS FABRICS

✓ = **OPEN-SPACE STRUCTURES**

- non-genetic term for sedimentary and **diagenetic voids** (mainly in mudstones, packstones, bindstones) filled with calcite
- sizes : mm-cm (sometimes >)
- **BIRDSEYES** : **isolated** bubble-like vugs (1-3mm in diameter) or as planar isolated vugs 1-3mm high x a few mm in width forming 'fenestral fabric' (birdseyes are important constituents of fenestral fabrics)
  => often associated with microbial and algal/microbial mats, from Precambrian to Recent,
  => <u>supratidal, sometimes upper intertidal settings,</u>
  => origin : direct or indirect organic interactions (e.g. gas bubbles due to decaying organisms) and/or inorganic (desiccation, shrinkage pores, air inclusions, leaching of anhydrite …),
  - small tubular 'vertical' birdseyes = ? root tubes or burrows in subtidal settings.
  - **FENESTRAL FABRIC :** open cavities or completely or partially filled by surface-derived internal sediment, diagenetic internal sediment (e.g. crystal silt) or cements
    => **fenestrae** <u>have no apparent support in the framework of primary grains composing the sediment</u> they are '<u>fabric-selective</u>' ≠ from growth-framework pores or from solution voids,
    => TERMINOLOGY : fenestrae are concordant to stratification, cross-bedded, or irregularly distributed,
    = = > classification : **LAMINOID/TUBULAR/SPHERICAL/IRREGULAR** fenestrae.

PETROGRAPHY OF CARBONATES

4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.1. BIRDSEYES, FENESTRAL and STROMATACTIS FABRICS

• **FENESTRAL FABRIC**

LAMINOID FENESTRAE : elongate horizontal fenestrae within fine-grained or grain-supported sediment
⇒ wetting and drying of carbonate mud in supratidal settings
⇒ drying out of the surface of cyanobacterial mats with wrinkling, lifting and separation from the adjacent sediment
⇒ degassing of decaying organic material connected with compaction of subspherical gas bubbles
⇒ **common in intertidal to supratidal** settings,

TUBULAR FENESTRAE in modern **intertidal and shallow-subtidal** environments = burrows, root holes, upward escape of gas bubbles biogenically produced in the sediment,

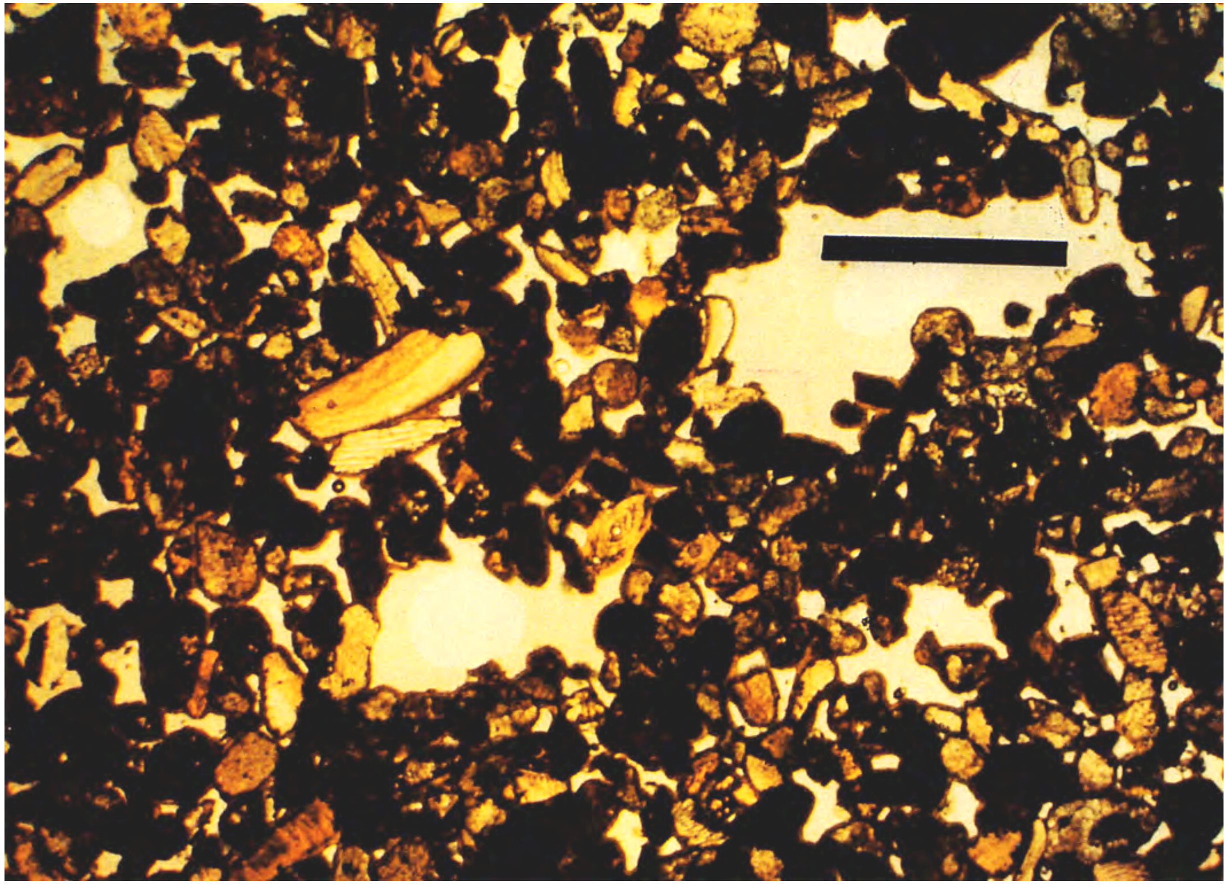
SPHERICAL-SUBSPHERICAL FENESTRAE produced by air and gas bubbles trapped during the deposition of the sediment or generated by post decay of organic matter. Air bubbles can be transported witihin sediment by rising groundwater
⇒ **KEYSTONE VUGS** : mm-cm (sub)spherical open fenestrae, the vugs are larger than ordinary birdseyes and produced by trapping of air-bubbles during storm deposition in the swash zone on beaches or in the sheetwash zone on tidal flats or playas.

IRREGULAR FENESTRAE : formed by desiccation, soft-sediment deformation, gas bubbles, evaporite molds, burrows, burial of pustular cyanobacterial mats, dewatering of gel-like carbonate muds, replacement of grains.

4. DEPOSITIONAL AND DIAGENETIC FABRICS

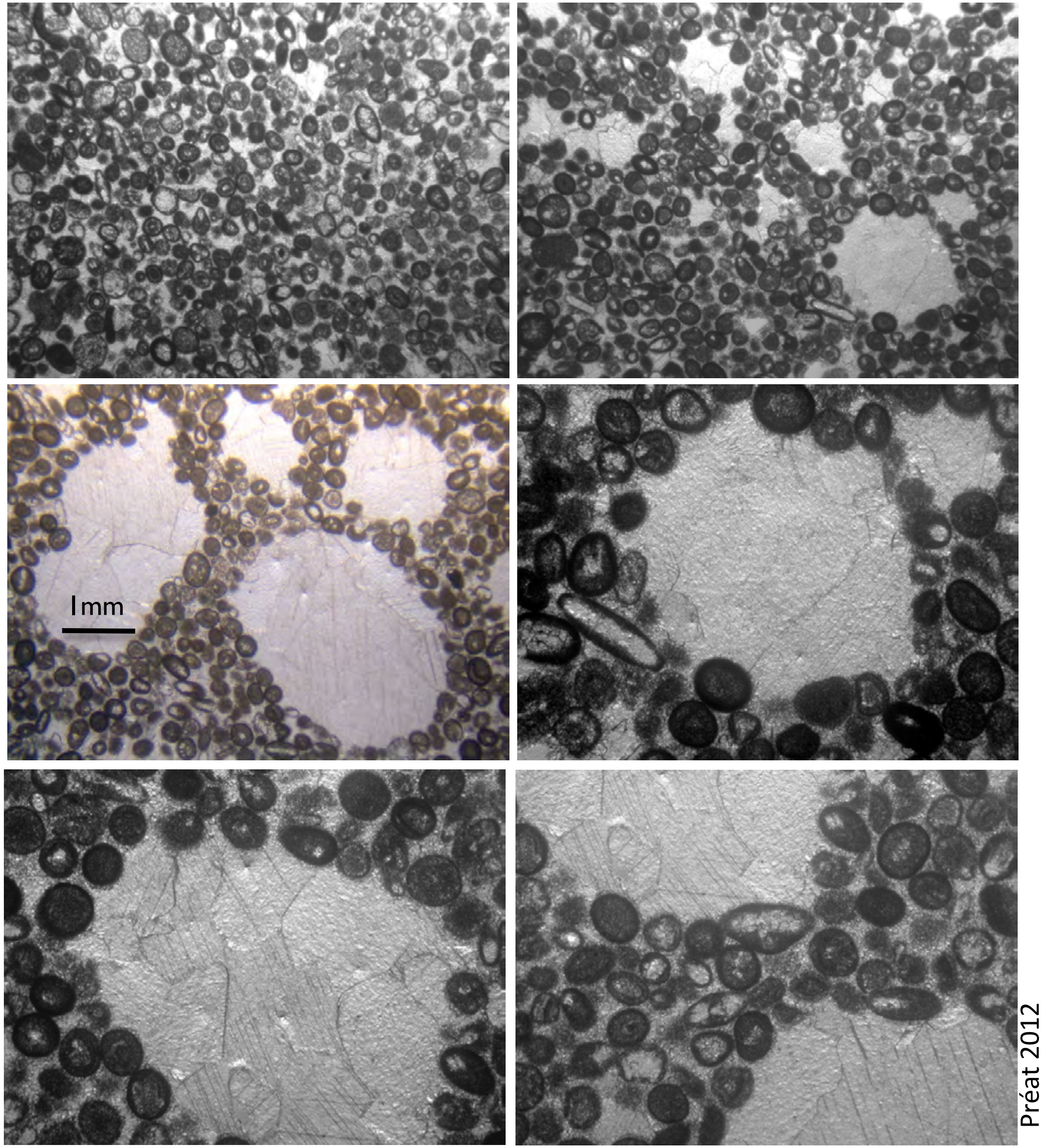
4.1. BIRDSEYES, FENESTRAL and STROMATACTIS FABRICS

Seaward dipping slabs of Recent beach-rock cemented foreshore sediment, Grand Cayman Island, British West Indies, Inden & Moore 1983.



Large ovoid keystone vugs in Recent carbonate beachrock. Scale equals 1.0 mm, Inden & Moore 1983.

KEYSTONE VUGS, NEOPROTEROZOIC CONGO-BRAZZAVILLE



PETROGRAPHY OF CARBONATES

4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.1. BIRDSEYES, FENESTRAL and STROMATACTIS FABRICS

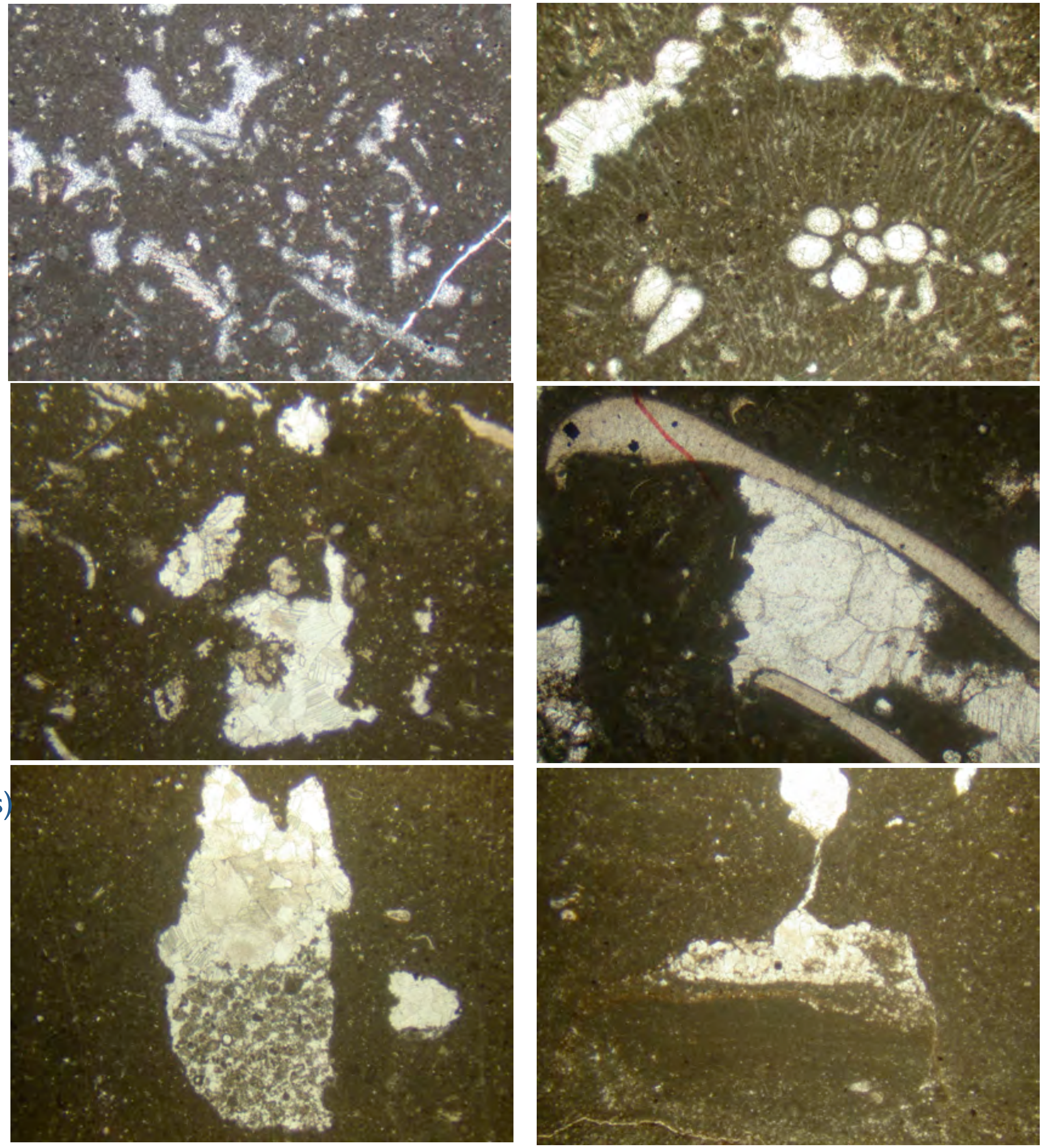
Irregular fenestrae and birdseyes in lagoonal wakestones, *Givetian carbonate platform, Belgium, Préat 2008*

From left to right and top to bottom

Sponge spicules

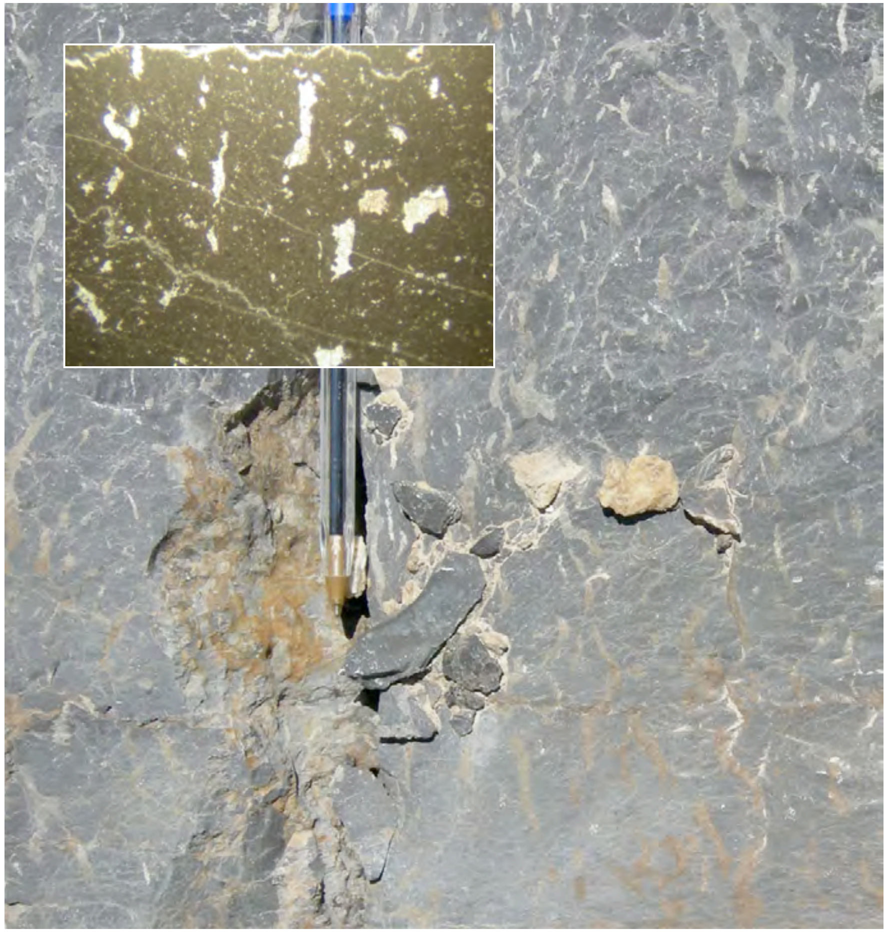
- Ortonella *cyanobacterial nodule*
- *Small coral (obstacle)*
- *Irregular fenestrae*
- *Umbrella effect between two Leperdicopid ostracods*
- *Peloidal geopetal filling*
- *Laminar mud filling*

nb scale : ±0.5mm (picture widths)



4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.1. BIRDSEYES, FENESTRAL and STROMATACTIS FABRICS



Tubular fenestrae from roots in intertidal environment, carbonate platform, Middle Devonian (Givetian) Flohimont old quarry, France, Préat 2010.

PETROGRAPHY OF CARBONATES

4. DEPOSITIONAL AND DIAGENETIC FABRICS

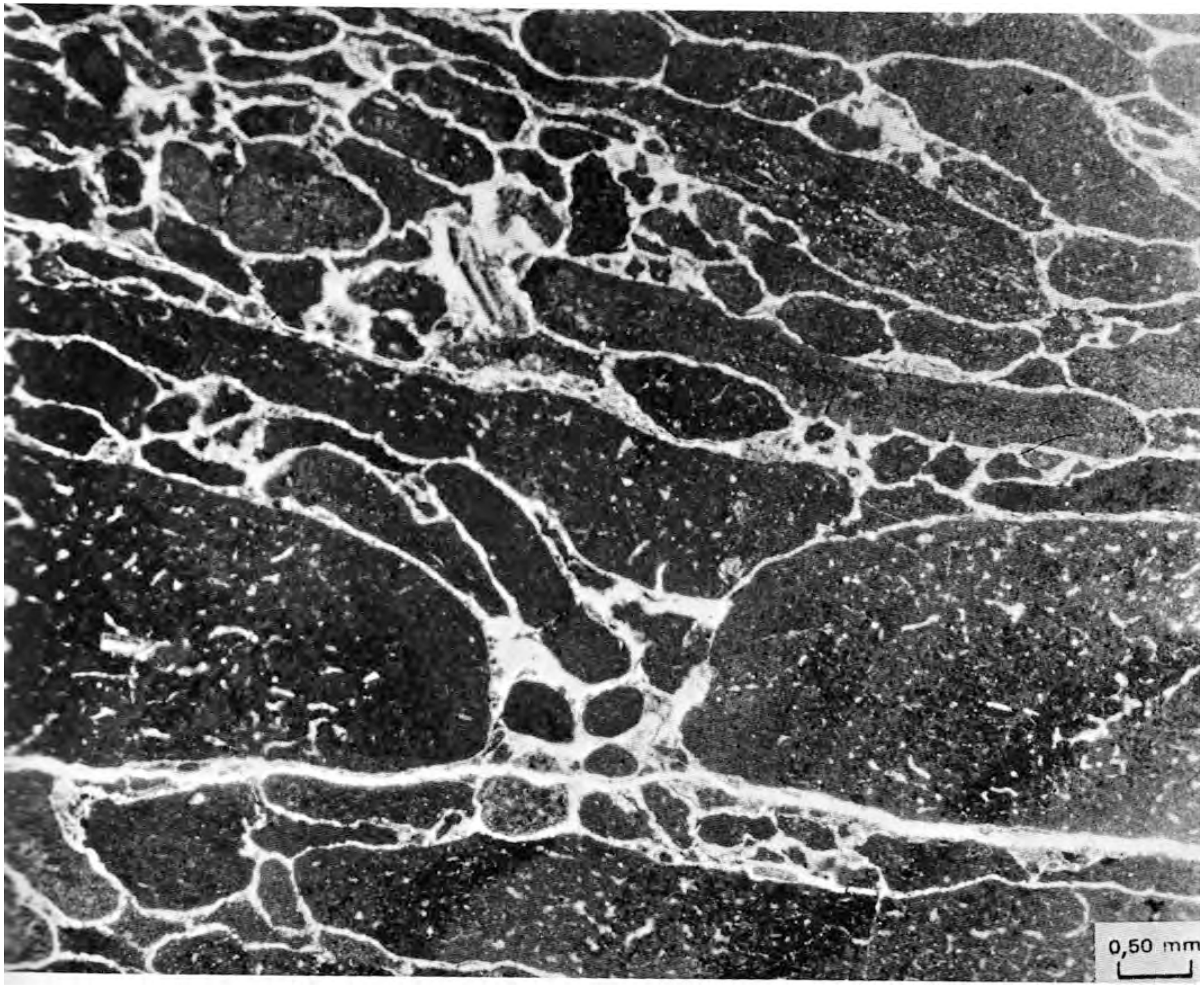
4.1. BIRDSEYES, FENESTRAL and STROMATACTIS FABRICS

'Tubular fenestrae' from roots in supratidal-paleosoil environment, carbonate platform, Upper Devonian, (Frasnian), Tailfer, old quarry, Belgium, Préat 2009.

4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.1. BIRDSEYES, FENESTRAL and STROMATACTIS FABRICS

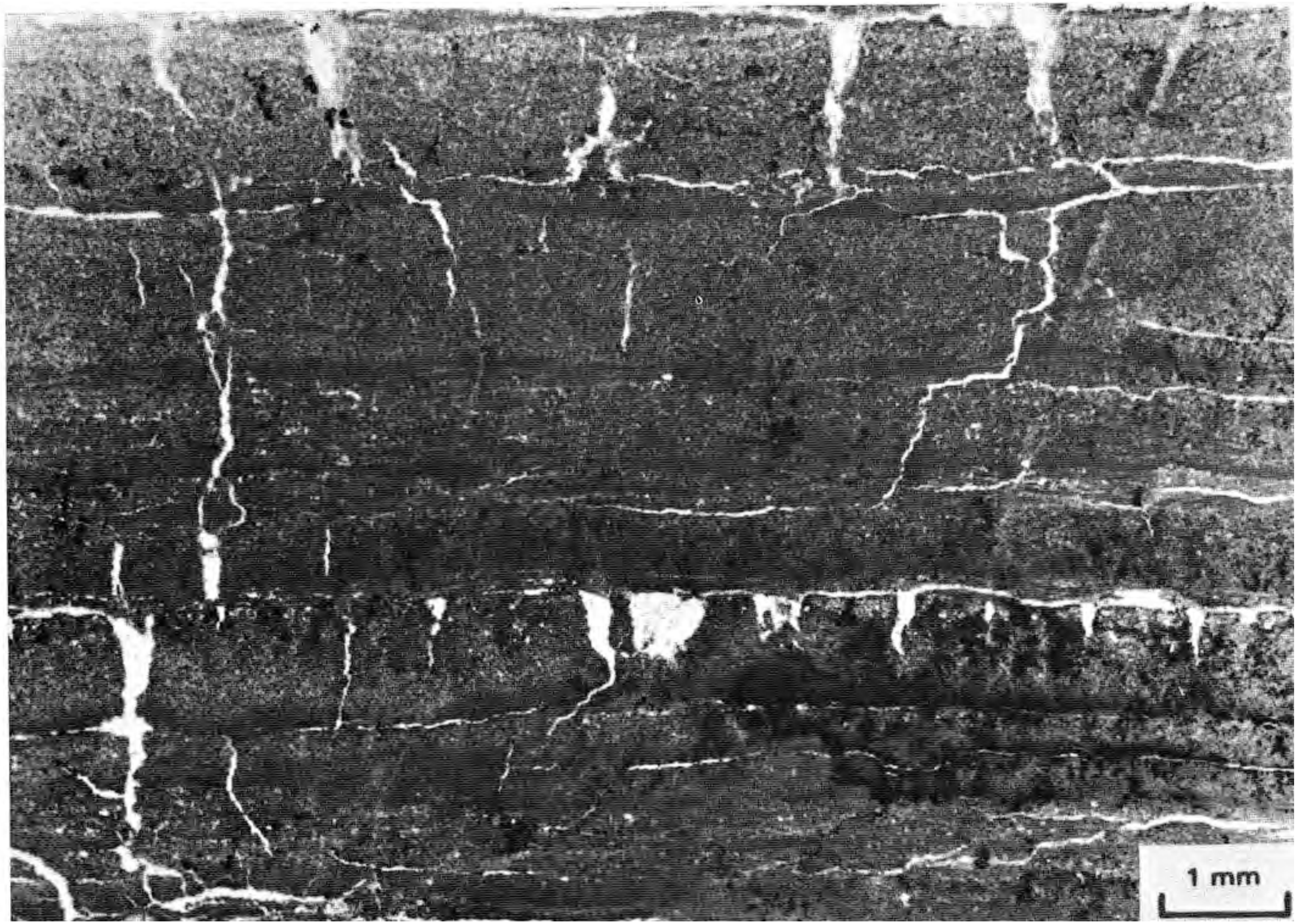
Monogenic desiccation breccia with subangular to subrounded micrite ‘clasts’ or ‘chips’.
NO ENERGY!
Elf Aquitaine, 1975

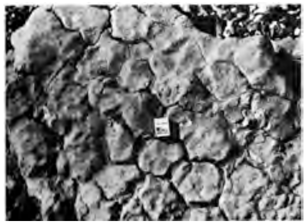


4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.1. BIRDSEYES, FENESTRAL and STROMATACTIS FABRICS

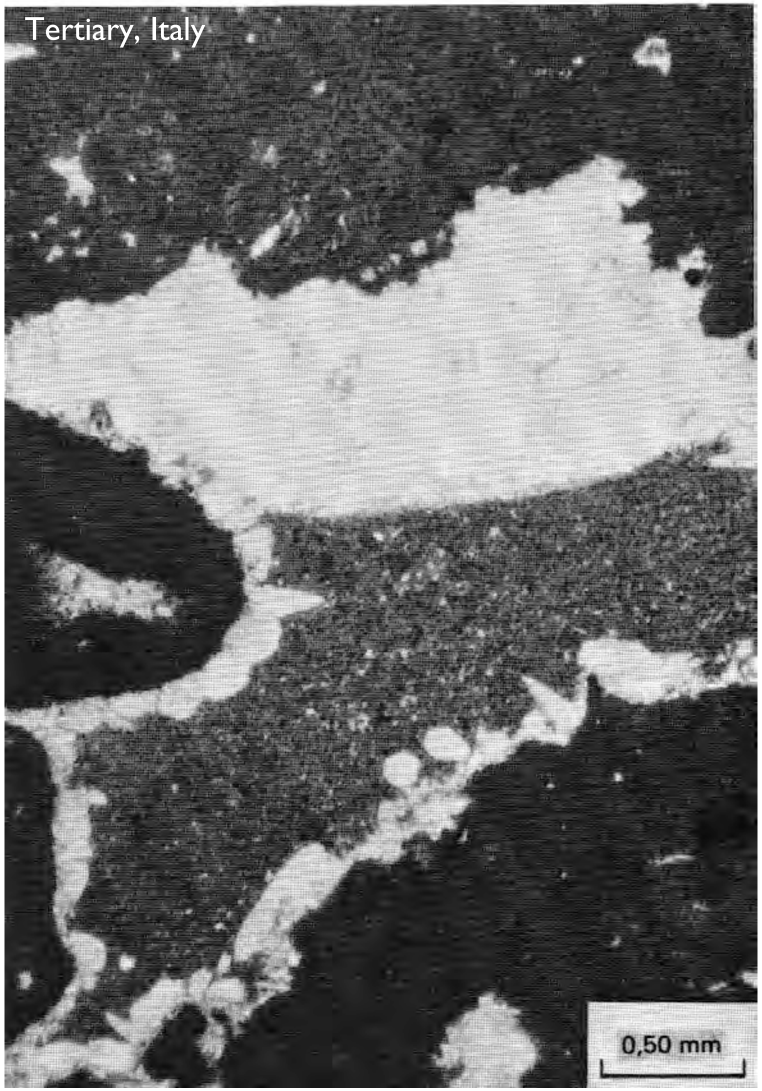
Desiccation pores with calcitic filling.
NO ENERGY!
Elf Aquitaine, 1975



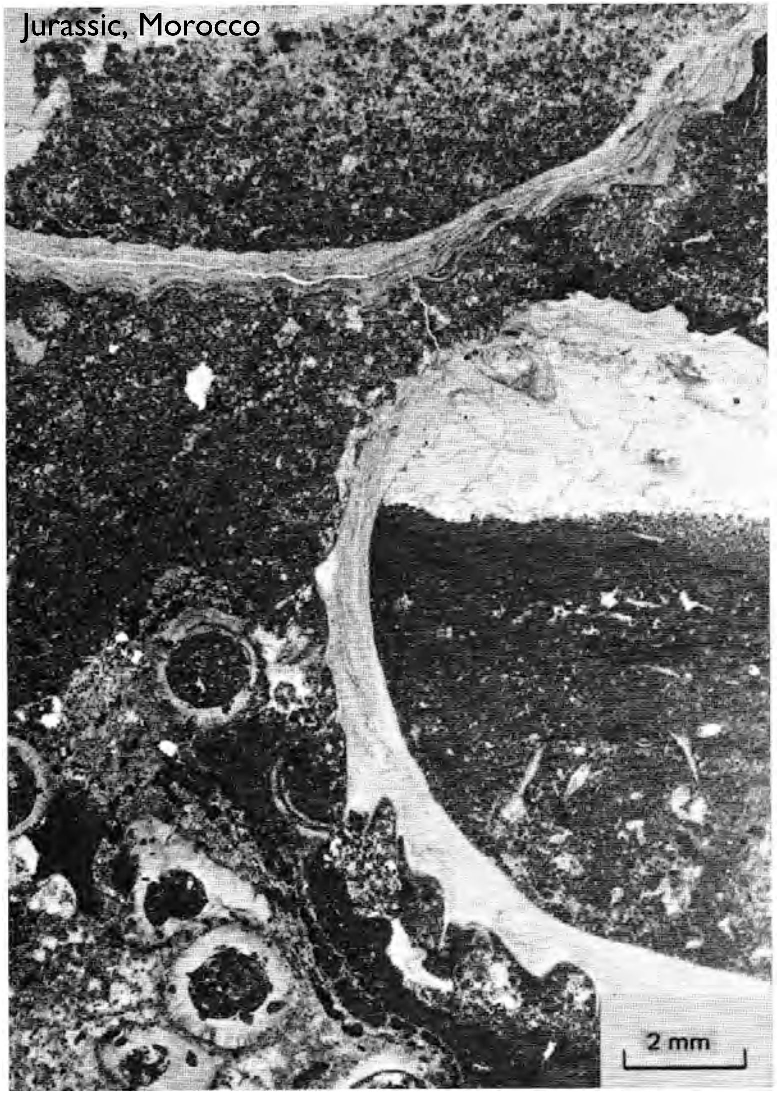


Desiccation cracks
with argillaceous filling carving polygonal figures (Elf Aquitaine, 1975)

GEOPETAL STRUCTURES

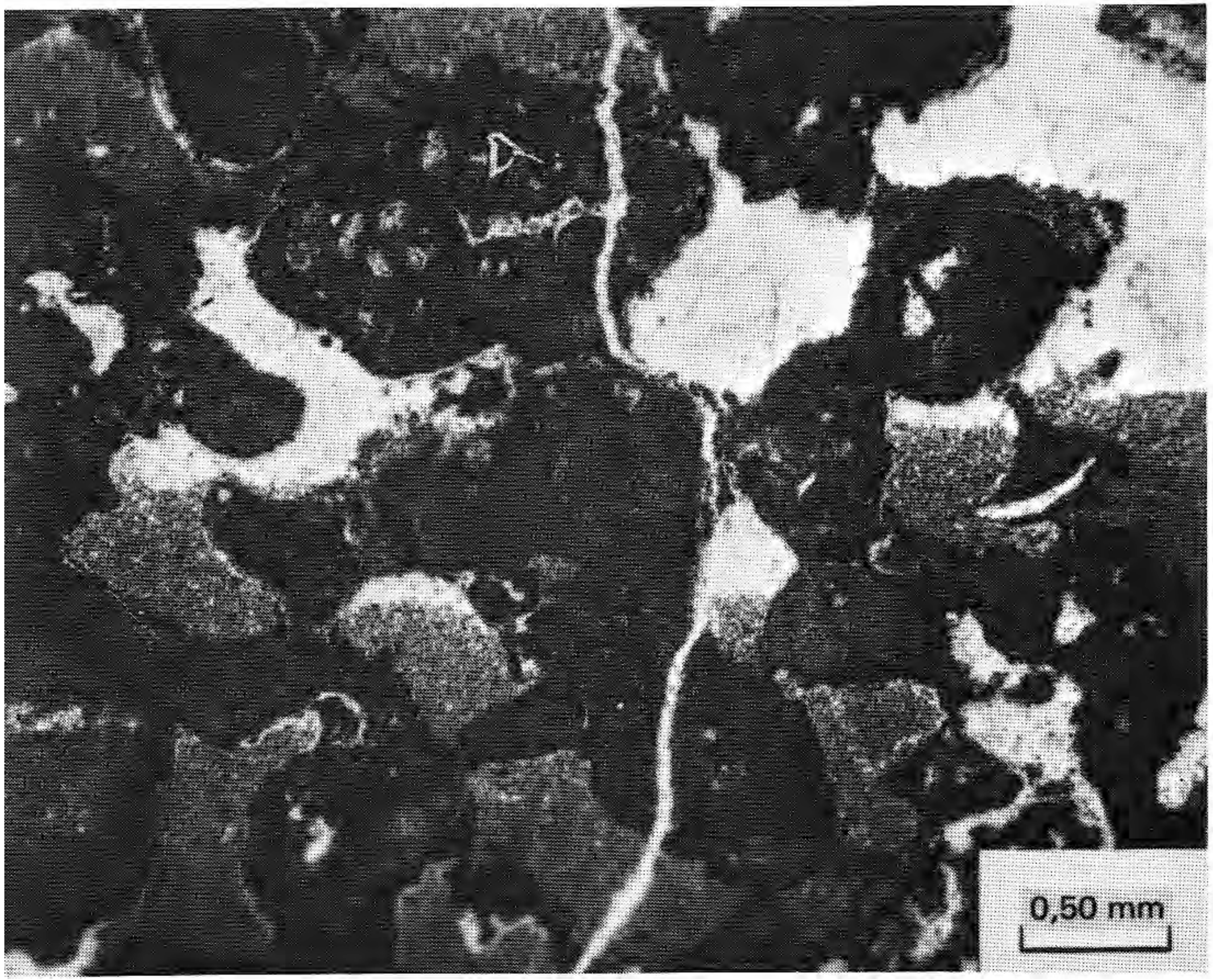


Internal sediment (vadose silt?) filling a vug.
First 'dog-tooth' calcite cementation, then internal silty sediment and finally drusy calcite (Elf Aquitaine, 1975)



Internal sediment (microbioclastic lime mud) filling a brachiopod shell, then drusy calcite (Elf Aquitaine, 1975)

GEOPETAL STRUCTURES



Burrowed microbial bindstone with' vadose' geopetal infillings.
Dogger, Paris Basin, France (Elf Aquitaine, 1975)

PETROGRAPHY OF CARBONATES

4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.1. BIRDSEYES, FENESTRAL and STROMATACTIS FABRICS

STROMATACTIS FABRIC : elongated cavities with irregular tops and flat bases, first defined in Belgium in Frasnian and Early Carboniferous carbonate mounds (Dupont 1881, 1993),
= > spar-filled (sometimes mud-filled) body/cavity embedded in carbonate mudstones,
= > centripetal cementation of cavities by fibrous and radiaxial cements.

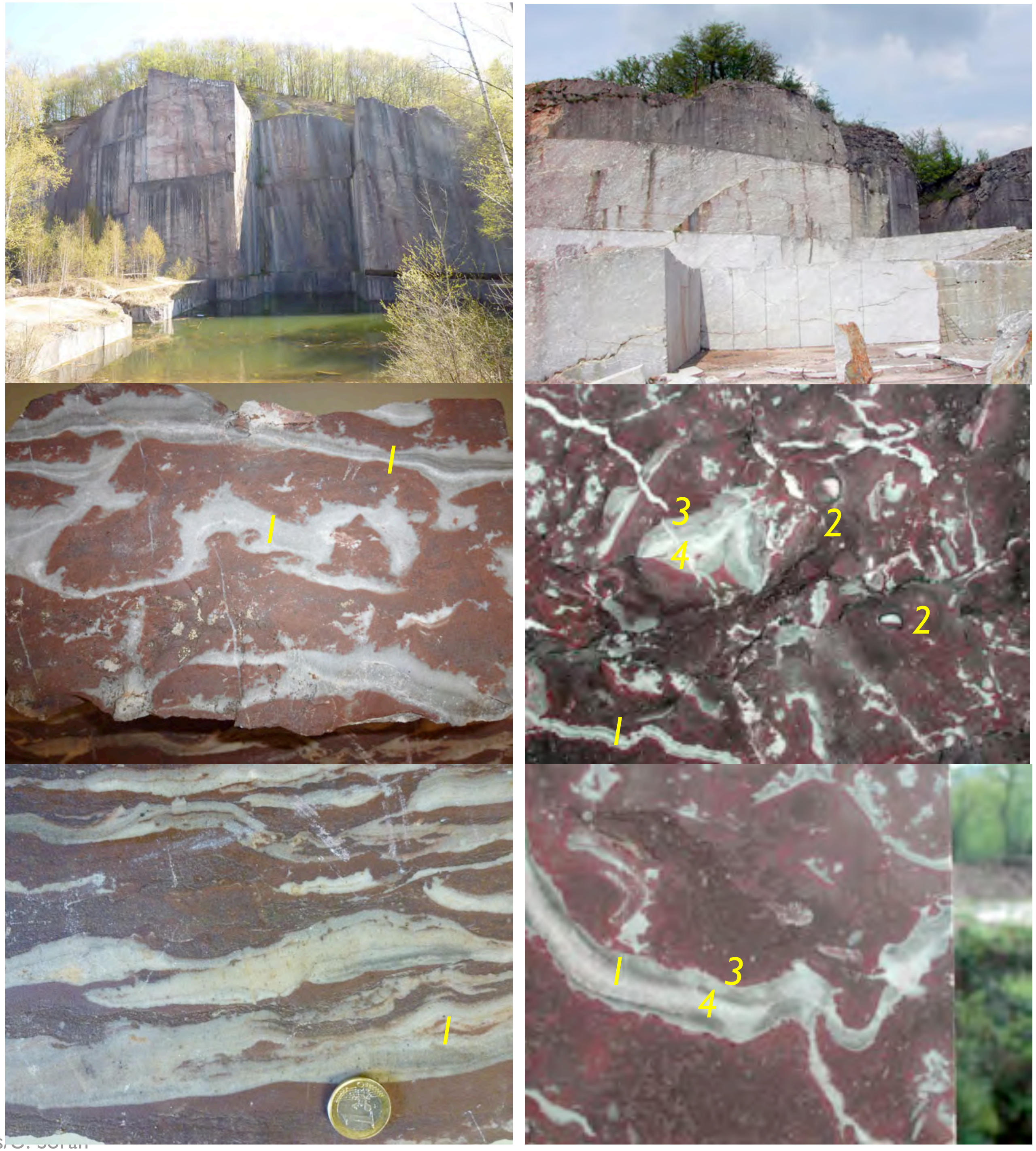
= > abundant litterature …. controversial.

Today : the '*stromatactis*' structures resulted from cementation of synsedimentary shelter cavities or cavities formed by the collapse of mud underneath a rigid object (coral, stromatoporoid, bryozoans …) acting as an umbrella during water escape and mud compaction.

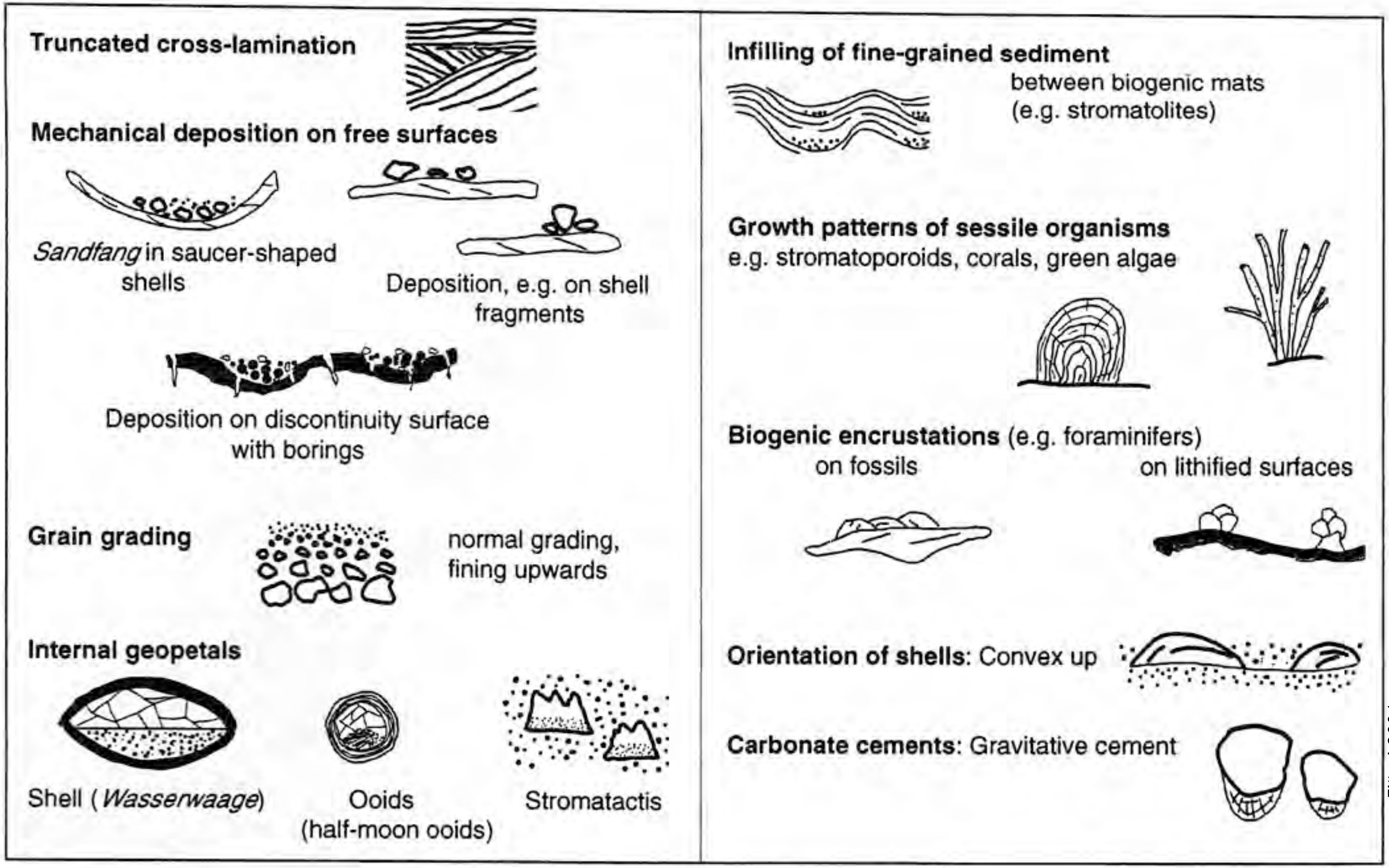
Internal sediments of the *stromatactis* = fine-grained micrite, sometimes with microfossils, peloidal micrite or laminated silt-sized sediment.
Cements of the *stromatactis* = radiaxial, fibrous and granular calcite,
=> early synsedimentary origin a few cm-dm below the depositional surface.

Red mud mounds
Frasnian, Belgium,
Préat.
Height 30m

Sromatactis,
Corals ***1***
= Phillipsastrea
Geopetal cavities ***2***
Fibrous and granular cements (LMC) ***3-4***



Common geopetal fabrics in thin sections of limestones



Flügel 2004

PETROGRAPHY OF CARBONATES

4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.1. BIRDSEYES, FENESTRAL and STROMATACTIS FABRIC

+ ZEBRA FABRIC? (QUITE COMMON)

controversial => many hypotheses

ZEBRA

- layered 'stromatactis' structures (peritidal, Trias , Austria)
- ancient beachrocks in Paleozoic
- sheet cracks
- lithified crusts
- superposed microbial mats
- soft sediment dilation and deformation with slumping
- gas clathrate hydrates

…

…

•late diagenesis?

Flügel 2004

Stromatactis in peloid wackestone
Uppermost slope close to
microbial sponge reef
….
Late Jurassic, Poland

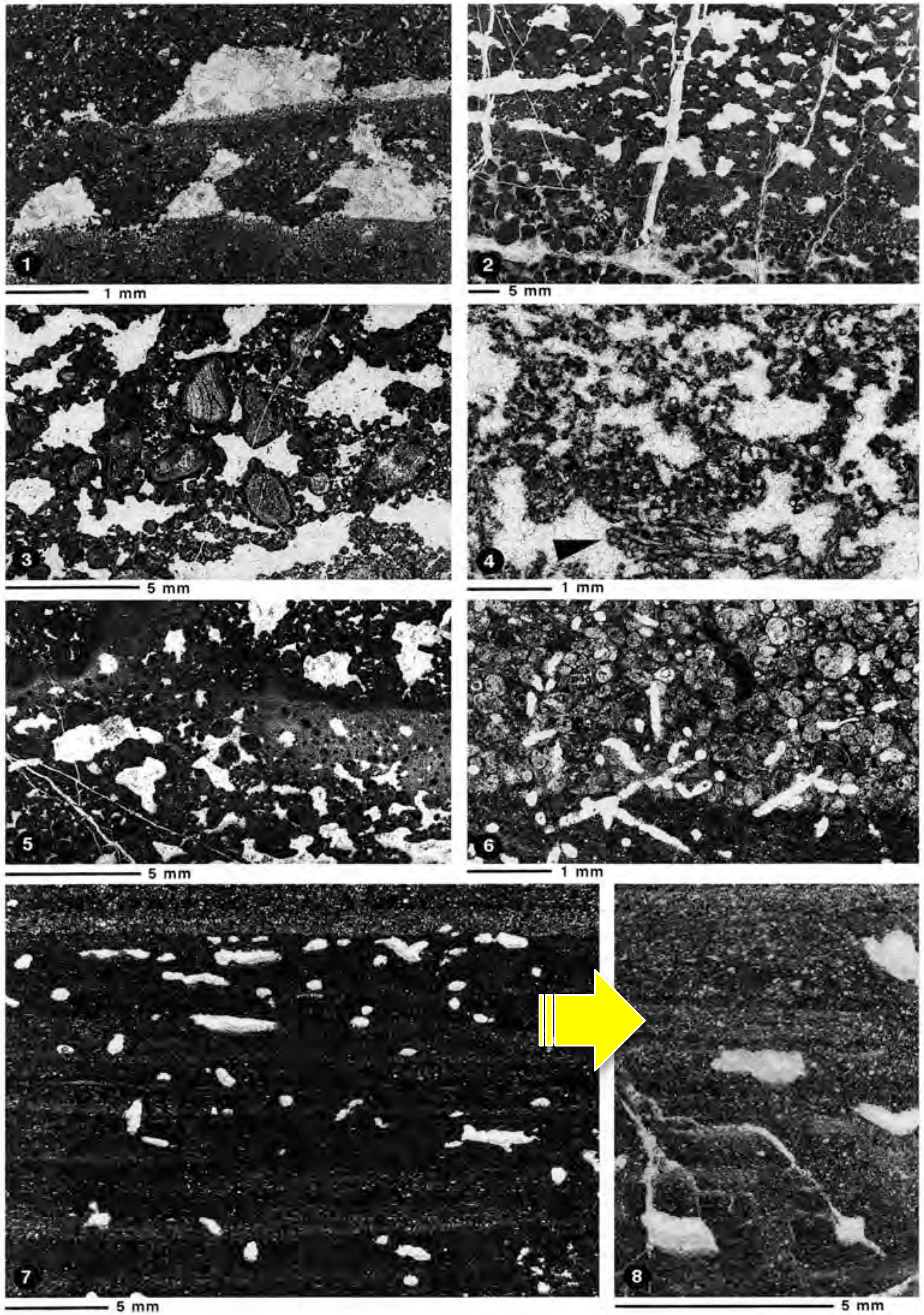
Laminoid fenestral fabric
= laterally elongated open
spaces within pisoid layers
Supratidal environment
Late Triassic, Hungary

Laminoid fenestral fabric
in bindstone with reworked
pisoids.
Intertidal/supratidal environment
Inner platform
Early Jurassic, Greece

Fenestral fabric within
cyanobacterial mats
(arrow = filaments).
Peritidal environment
Early Carboniferous, Poland

Fenestral fabric with
pisoids and black pebbles.
Supratidal environment
Inner platform
Early Jurassic, Greece

Not birdseyes!
= open bifurcated voids from
plant roots and rootlets within
Recent caliche,
Bahamas

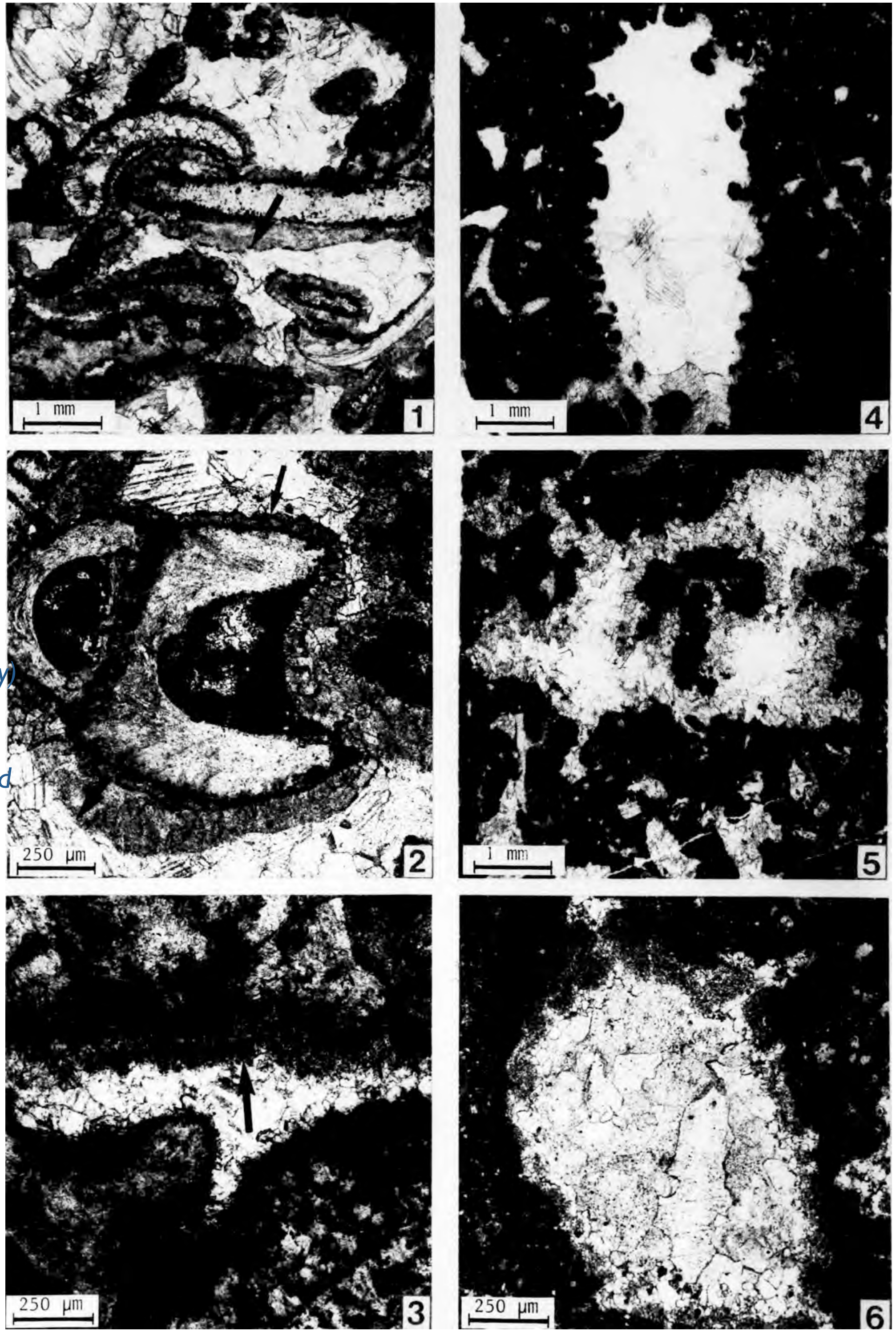


Birdseyes in peritidal laminated
dolomudstone
=
Lagoonal intertidal environment
Late Triassic, Austria

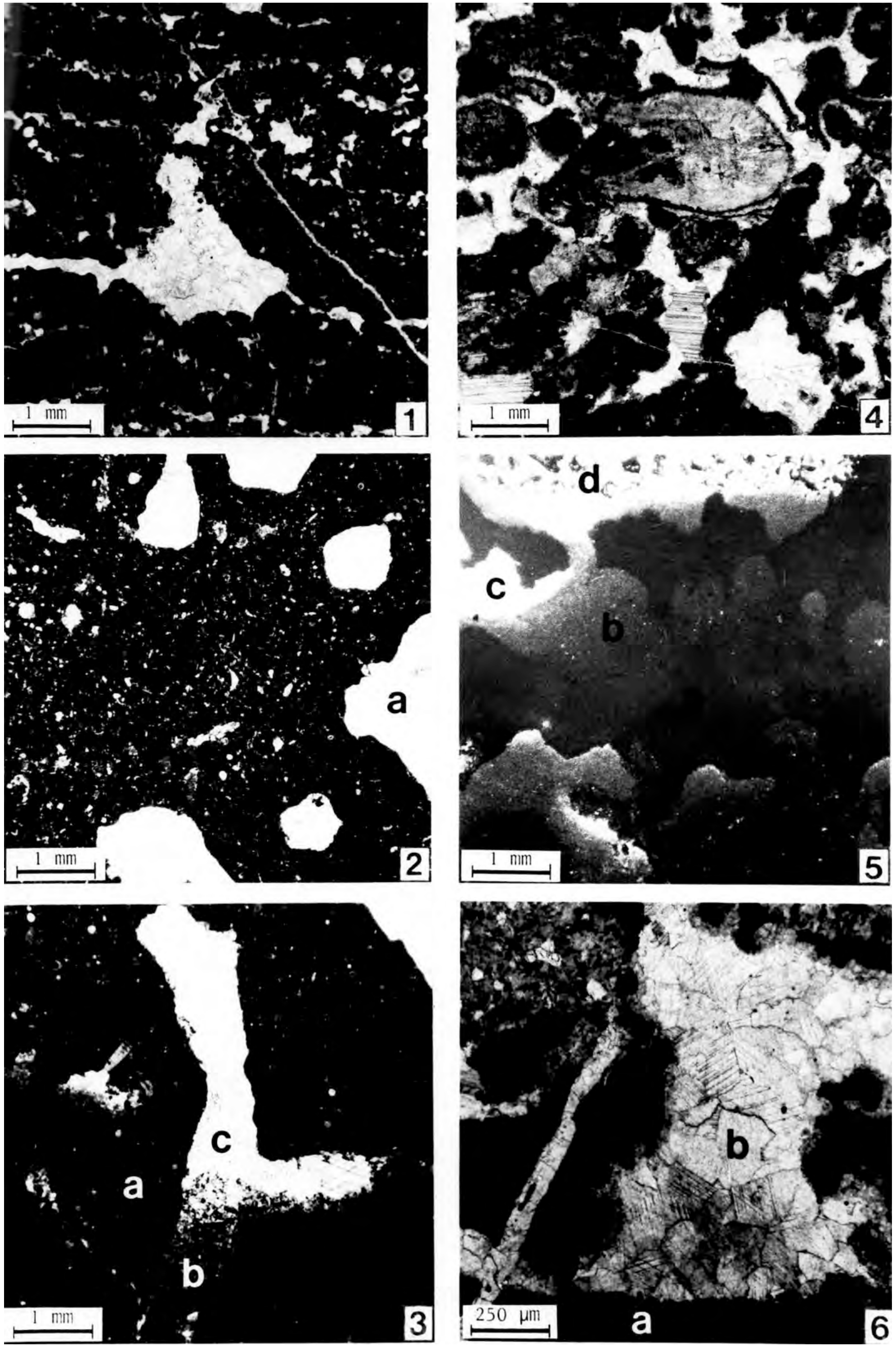
Close-up of picture 7.
showing sediment infilling
in the birdseyes.
Bahamas

Birdseyes in a loferite passing laterally to an inertidal/supratidal marine vadose beachrock with pendant fibrous cements.
Subaerial Lagoonal environment
Inner platform
Early Givetian, Belgium (Resteigne quarry)
Préat & Mamet 1989

Slightly bladed calcite and coarse-grained spar suggest a freshwater influence.



Loferite (1), birdseyes (2) related to gas bubbles, infilled burrow (3) in a semi -lithified sediment, and fenestral floatstones (4-5-6)with dissolved partially infilled cavities. Coral (Tabulata) fragment in (4) and mutiphase geopetal infillings (5).
Lagoonal restricted environment
Inner platform
Early Givetian, Belgium (Resteigne quarry)
Préat 1984



4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.1. BIRDSEYES, FENESTRAL and STROMATACTIS FABRICS

TO CONCLUDE

• Birdseyes and laminoid-fenestral fabric **=** shallow near-coast supratidal and upper intertidal environments
= > birdseyes are not exclusively marine = => lacustrine, eolianite
• Abundant stromatactis structures => deeper subtidal environments

• **Diagenesis and reservoir potential**
Primary fenestral porosity may be high up to 65% and permeability in birdseyes limestones can be increased significantly by dolomitization (through intercrystalline porosity).

PETROGRAPHY OF CARBONATES

4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.2. NODULAR FABRICS : generally MUD-SUPPORTED

= BEDDED NODULAR LIMESTONES : cm-dm sized often 'rounded' nodules floating within usually micritic matrix = > compositions of the nodules, shapes, boundaries, sizes

• nodules are generally rounded or subrounded,

=> if angular or subangular => probable reworking or redeposition

• boundaries between nodules and matrix : inconspicuous or distinct,

=> if distinct => often a dark clay-rich seam at the boundary

• ISOLATED NODULES with black Fe and Mn coatings = often represent 'hardground clasts'

• nodule size (largest diameter) and orientation => information of possible transport (e.g. along a slope relief)

ORIGIN

• **diagenetic, sedimentary and tectonic** processes

diagenetic => solution processes , cementation and nodule growth within the sediment

sedimentary => transport and redeposition

tectonic => shear processes in limestone/clay alternations

• **processes leading to nodule formation**

solution => relicts of intensive submarine dissolution of carbonate at the sea bottom, and/or different solubility of clay-rich sediments during late diagenesis (cf. pressure solution)

cementation => microbial, decay of organic matter, selective lithification …..

mechanical processes => early diagenetic, tectonic ('boudinage') …

PALEOENVIRONMENT most occur in deeper-marine setting (e.g. Jurassic Ammonitco Rosso, Italy, Sicily) but some are formed in shallow subtidal settings in connection with burrowing

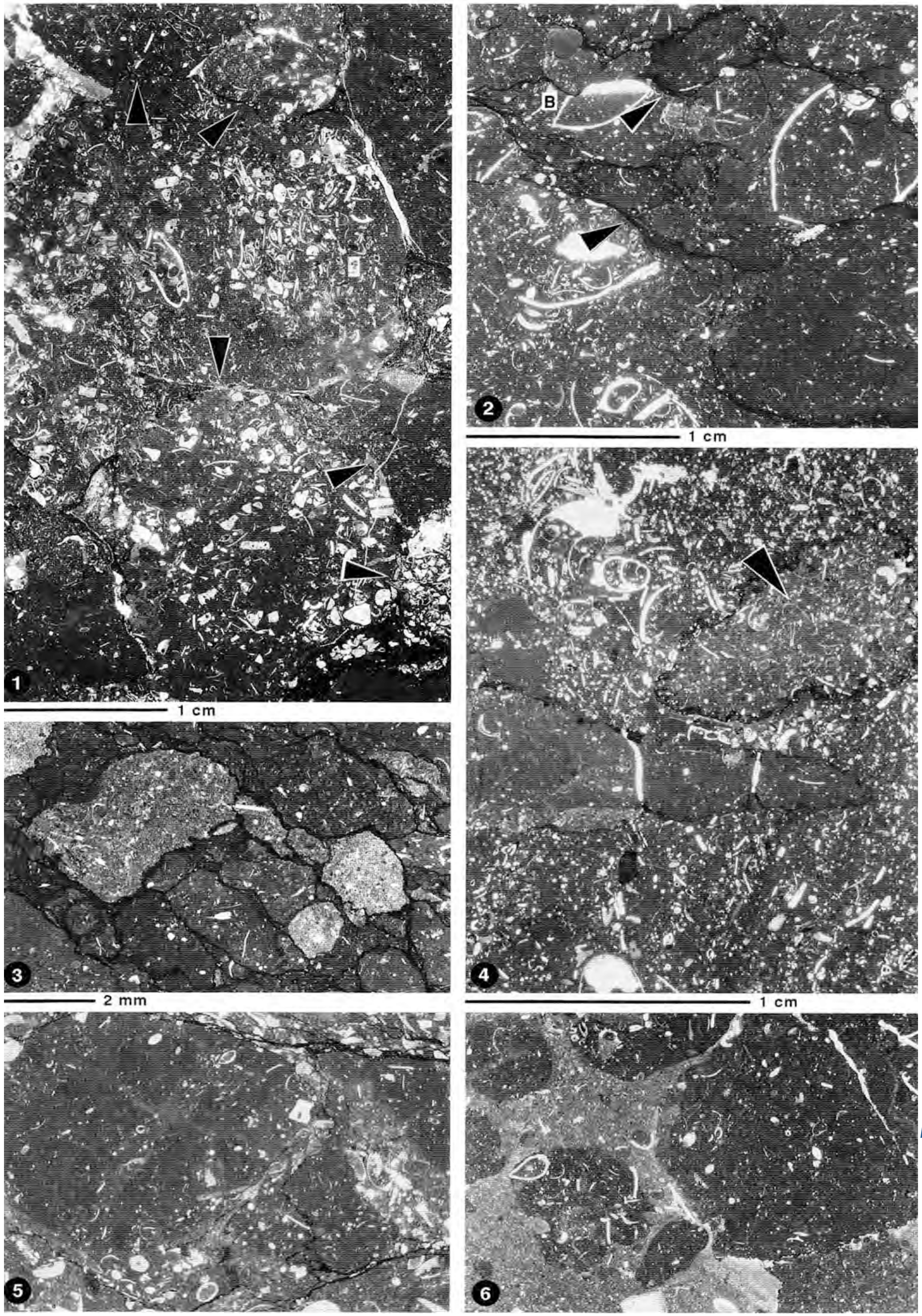
TIME FORMATION is long as indicated by the common occurrence of condensed faunas representing several biozones.

Flügel 2004

Red nodular limestone
Initial stage of nodule formation
(local partial cementation of the mud).
Indistinct boundaries (arrows)
between the nodules.
Bioclasts =echinoderms and brachiopods
Early Jurassic, Adnet Limestone,
Austria

Nodular fabric
Pronounced pressure solution..
Early Jurassic, Adnet Limestone,
Austria

***In situ* Nodule formation**
Partial cementation.
Early Jurassic, Adnet Limestone,
Austria



Nodular limestone
Boundaries marked
by dark clay seams
(arrows)
= incipient
pressure solution.
Bivalves and brachiopods
Early Jurassic, Adnet Limestone
Austria

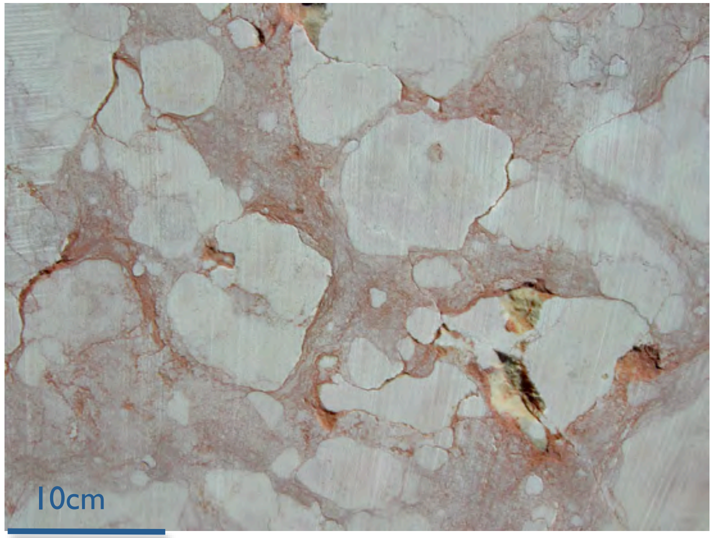
Nodular fabric
in a red crinoid-shell
wackestone
Nodules are
redeposited hardground
intraclasts.
Early Jurassic, Adnet Limestone
Austria

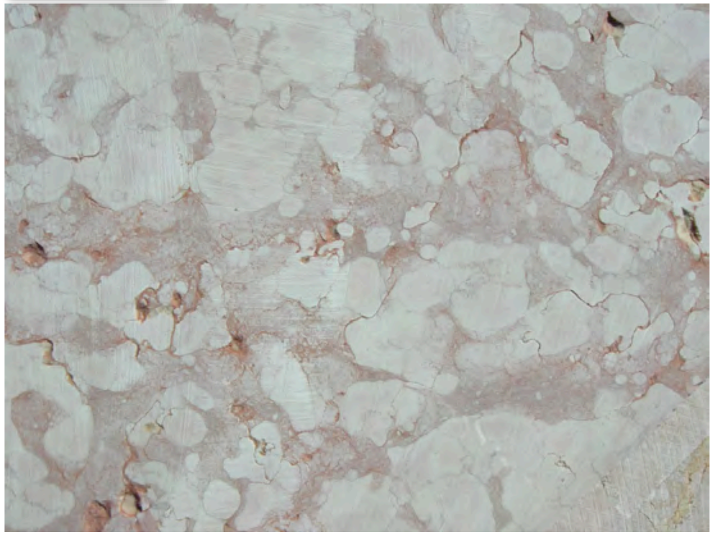
Typical Nodular
limestone
Early Jurassic, Adnet Limestone
Austria

4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.2. NODULAR FABRICS : generally MUD-SUPPORTED

Typical nodular fabric in the Jurassic Ammonitico Rosso of Sicily, *Préat, 2007*

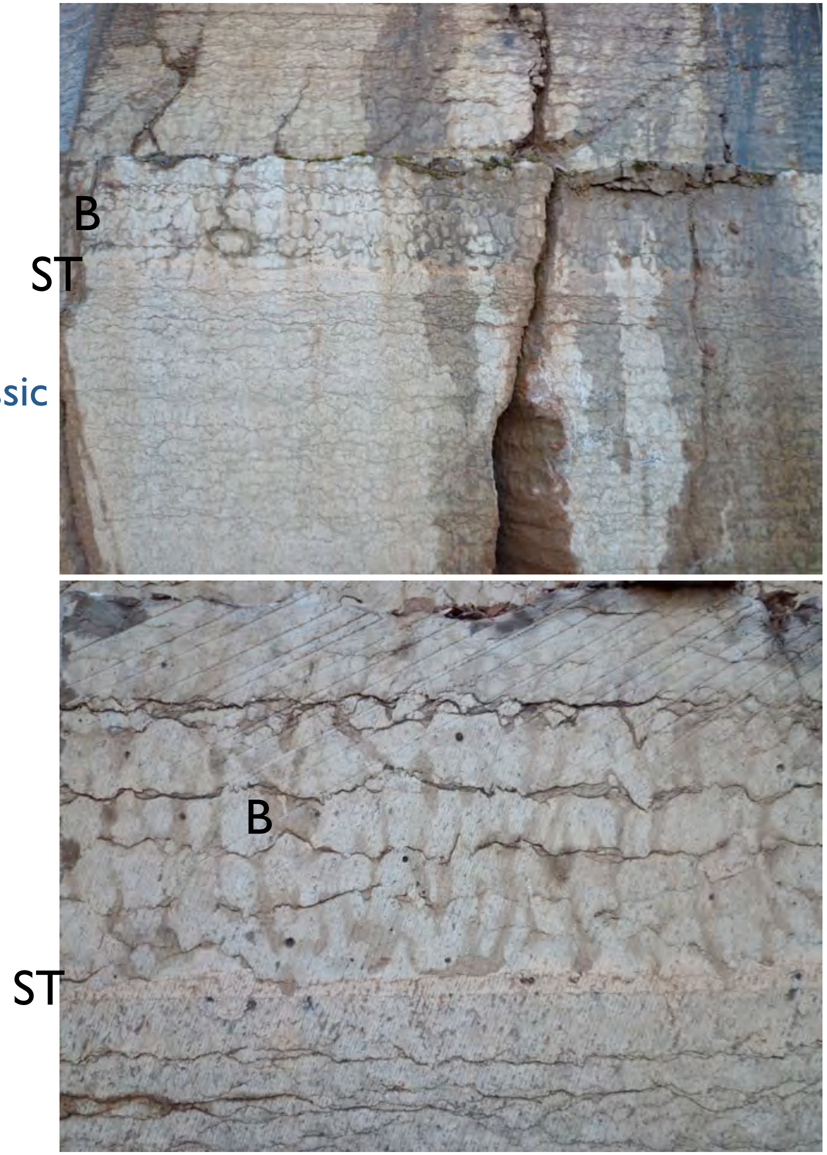




4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.2. NODULAR FABRICS : generally MUD-SUPPORTED

Typical nodular fabric in the Jurassic Ammonitico Rosso of N Italy,
Pressure solution, burrows (B)
and stromatolites (ST)
Préat, 2007
(section 2m-thick, upper picture)



PETROGRAPHY OF CARBONATES

4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.3. HARDGROUND and NEPTUNIAN DIKES

= **Hardgrounds :** cm-sized discontinuous surfaces of synsedimentary lithification, having existed as hardened sea floor prior to the deposition of the overlying sediment

⇒ combination of NON-DEPOSITION or LOW SEDIMENTATION RATES and CONDENSATION

⇒They result of the submarine cementation by aragonite and HMC directly from seawater circulating through the upper most few cm-10'cm of a porous sandy sea bottom

= = > they are common but not confined to deeper-marine settings

• **Mineralization** : uppermost layers may be mineralized => crusts or impregnations

=> shelf hardgrounds = GLAUCONITE, Ca-PHOSPHATE, Fe (hydro-oxides)

=> pelagic hardgrounds = same with addition of Mn-oxides

• Strong microbial control on the formation of laminated Fe-Mn crusts.

• Abundant encrusters : calcareous algae, foraminifera, bryozoans, corals, serpulids, some brachiopods ….

• Abundant borings, mainly buy bivalves, sponges, algae and fungi

• Abundant burrowing

=> borings and burrowing give paleoecological information about environmental condition and substrate conditions

• Abundant clasts of cemented limestones (lithoclasts)

….

+ **HIATUS CONCRETIONS** : multiple phases of deposition, burial, excavation

…

TIME FORMATION is long as indicated by the common occurrence of condensed faunas representing several biozones.

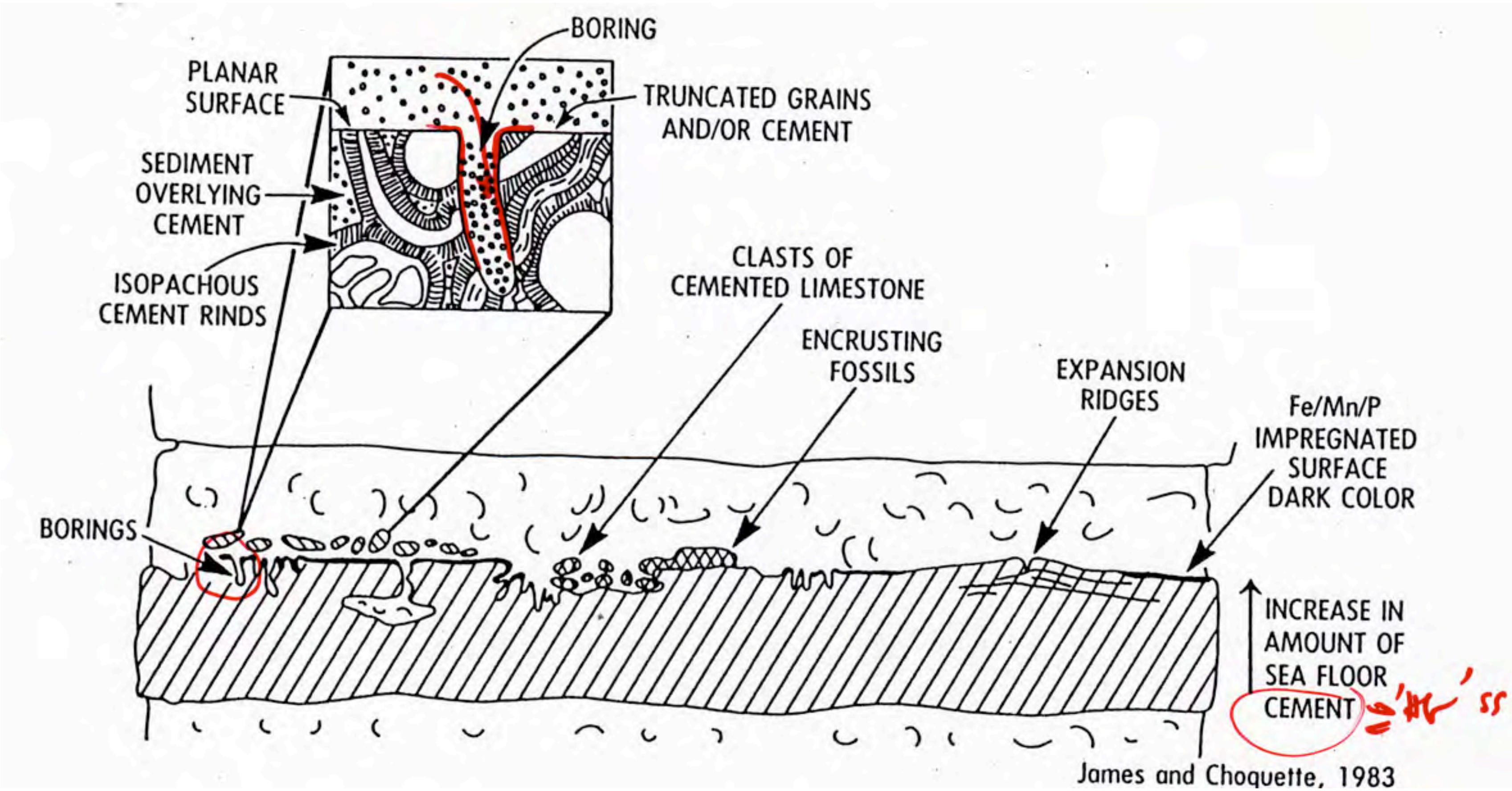
PETROGRAPHY OF CARBONATES

4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.3. HARDGROUND and NEPTUNIAN DIKES

HARDGROUND IN DEEP WATER

(e.g. Ammonitico Rosso)



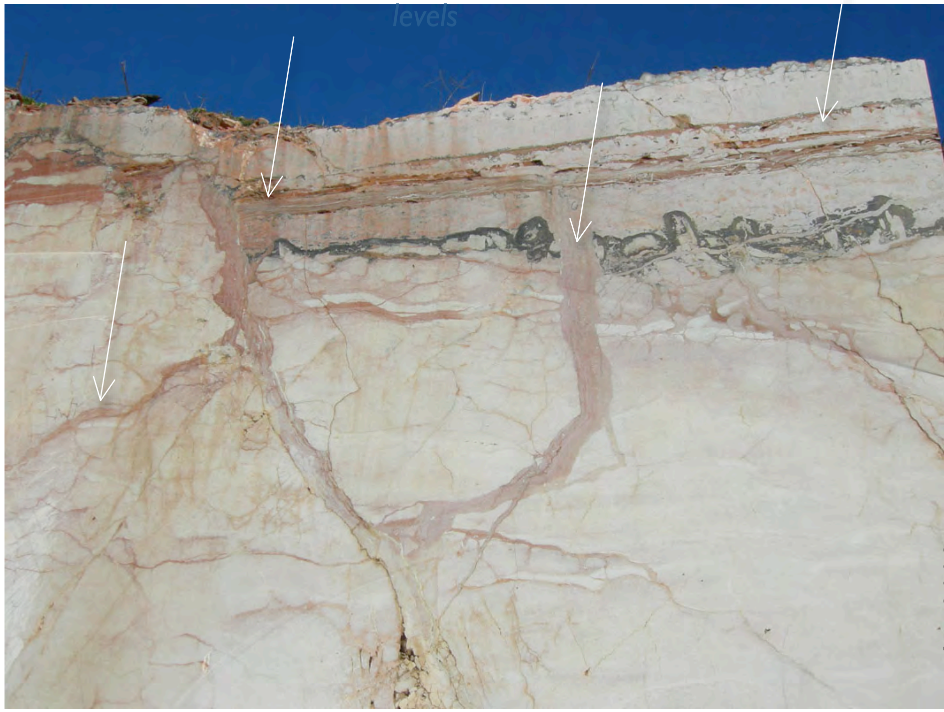
PETROGRAPHY OF CARBONATES

4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.3. HARDGROUND and NEPTUNIAN DIKES

HARDGROUND IN DEEP WATER

Ammonitico Rosso, Sicily



HG+NEPTUNIAN DIKES, Mn-coatings and Mn-stromatolites
Strong dissolution and HIATUS

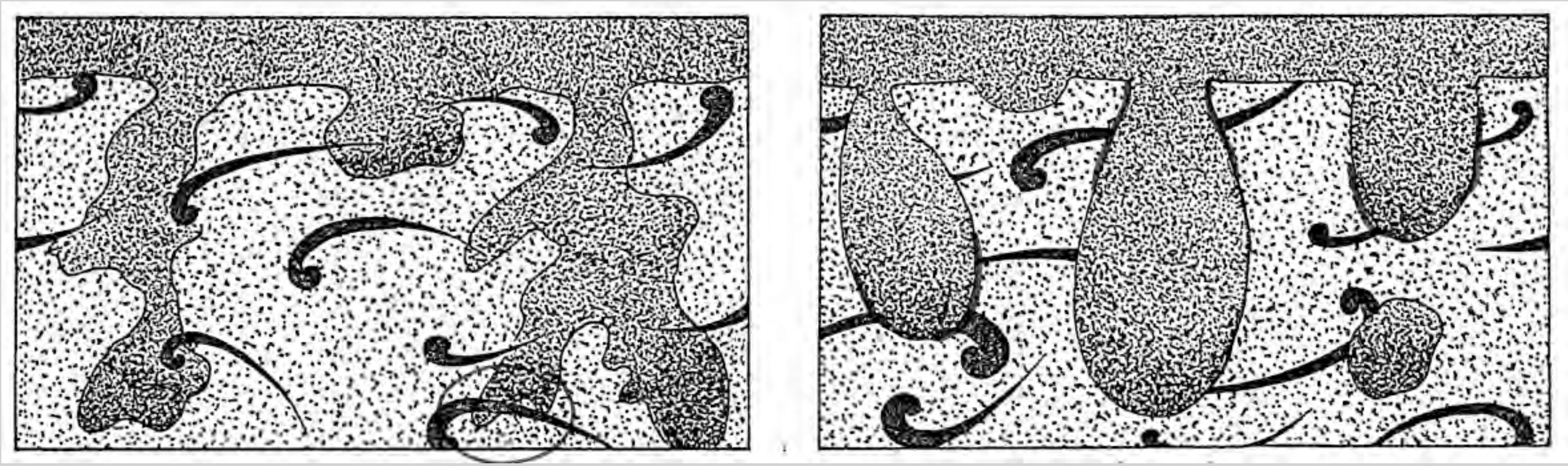
Préat 2008

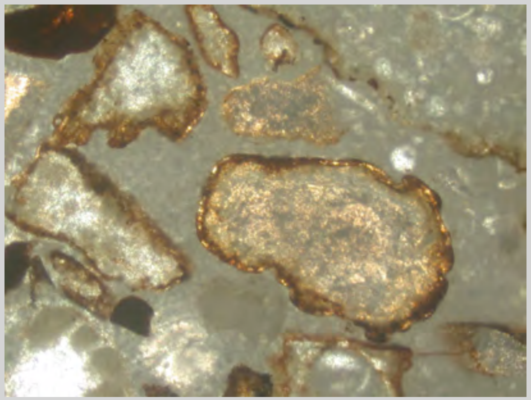
VERY VERY strong dissolution and HIATUS

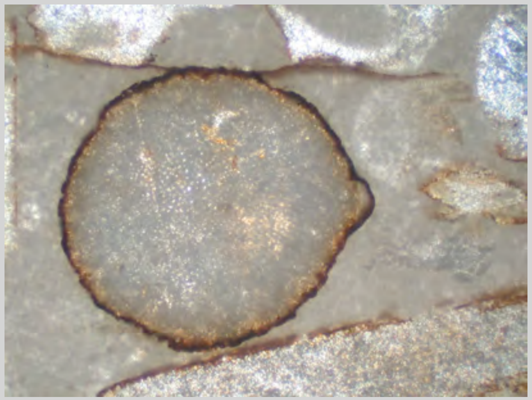
Dissolved crinoidal limestone as 'pinnacles' in the Ammonitico Rosso

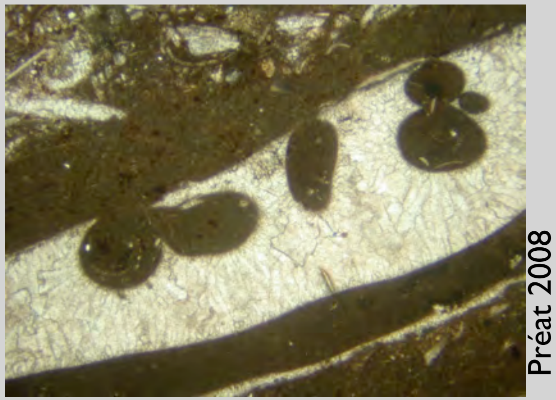
PETROGRAPHY OF CARBONATES
4. DEPOSITIONAL AND DIAGENETIC FABRICS

ALSO BIOTURBATION *vs* PERFORATION









4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.3. HARDGROUND and NEPTUNIAN DIKES

= **Neptunian Dikes:** infilling of submarine sediment in fissures and cavities of rocks exposed on the sea floor.
⇒ fissure walls are commonly subparallel, planar or irregularly undulated
⇒ they cut the host rocks obliquely or vertically across bedding planes, or parallel to the bedding
⇒ width : a few cm to several meters
=> they may be several hundreds of meters up and can be followed horizontally a few 10'cm up to several 100'm

• **Where :** submarine and subaerial
=> submarine = common in platform carbonates, particularly at platform margins
=> slope and basinal settings

• **How :** various processes
• differential compaction, , rapid extensional tectonic activities, high hydrostatic pressure
=> injection of sediments into voids and fissures
• hydrothermal effects related to thermochemical effects
• opening of fissures in platform carbonates during rifting phases and infilling of pelagic sediment during and/or after drowning of platforms are common from the Mesozoic of the Alpine-Mediterranean region
• on tilted fault blocks = Ammonitico Rosso of Italy and Sicily
• on flanks of red mud mounds = Frasnian of Belgium with neptunian dikes rich in crinoids.

• **Age** deduced form micro- and macrofossils in the fissure infillings
=> continuous or interrupted sedimentation over very long time spans
…

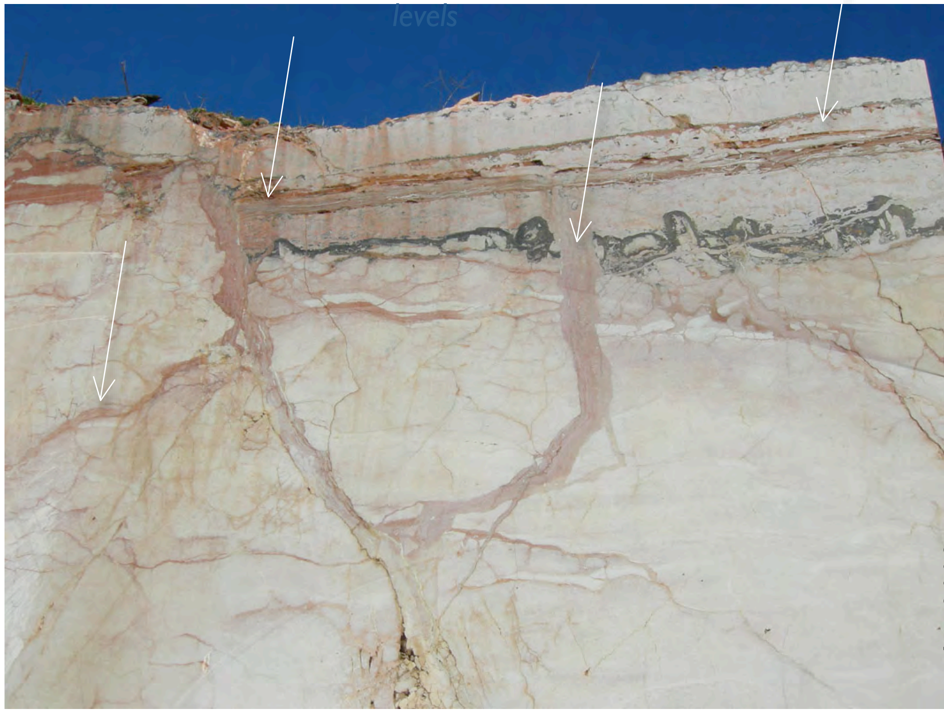
PETROGRAPHY OF CARBONATES

4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.3. HARDGROUND and NEPTUNIAN DIKES

HARDGROUND IN DEEP WATER

Ammonitico Rosso, Sicily



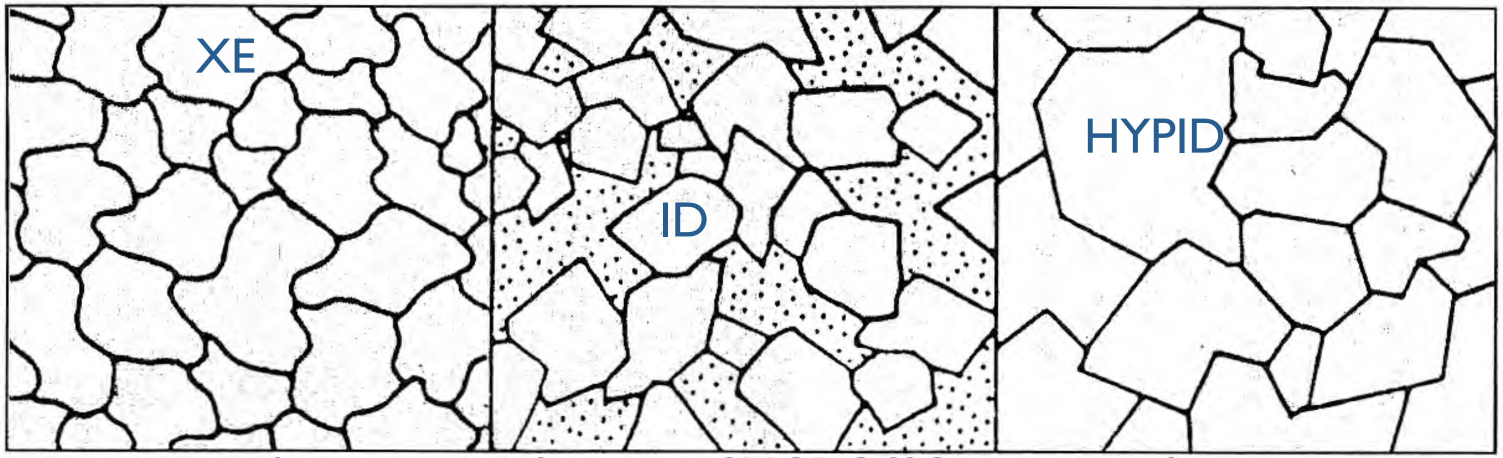
4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.4. DOLOMITE and EVAPORITE FABRICS : early to late diagenesis

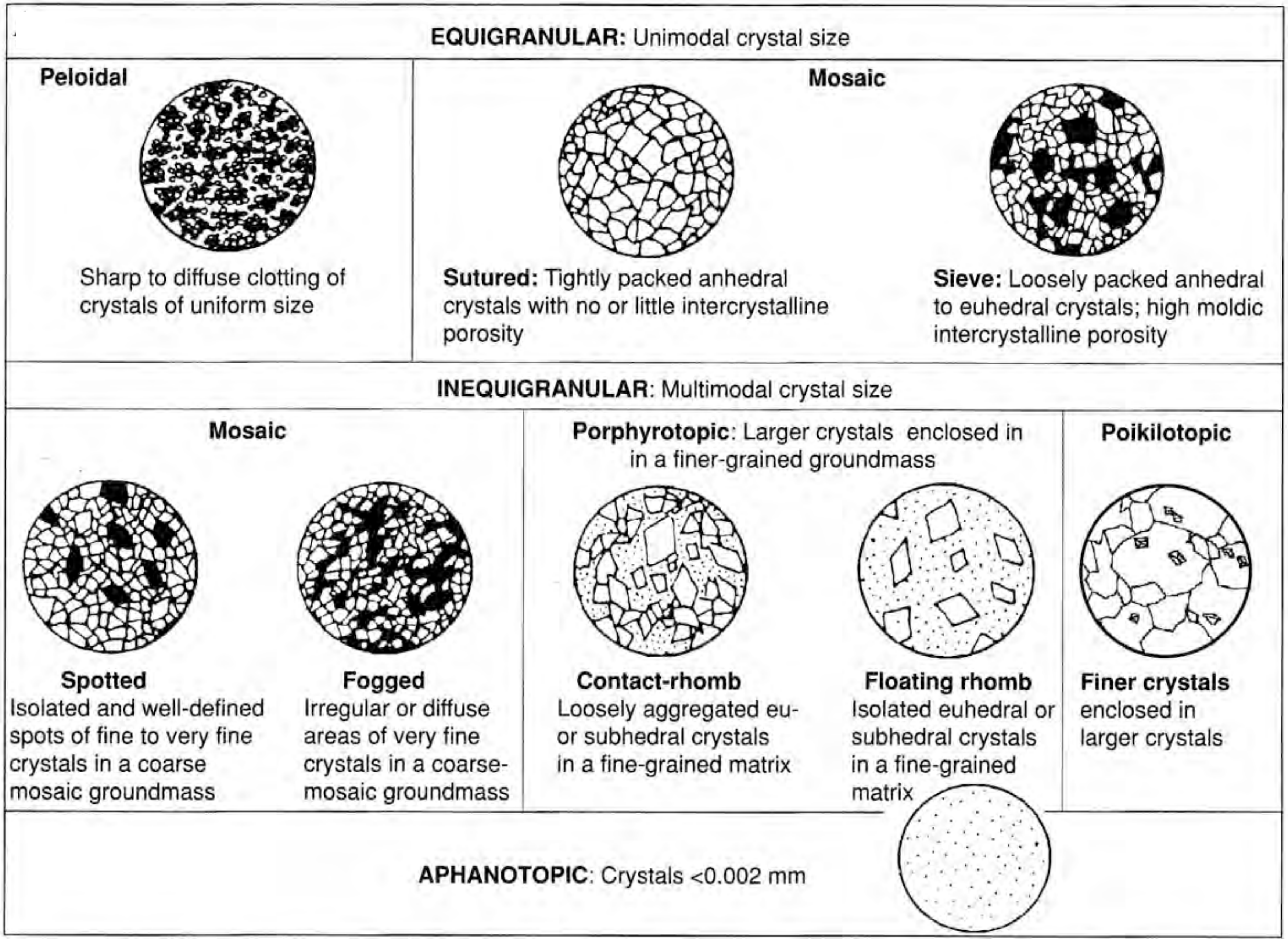
Dolomite fabrics : crystal shapes, types of distribution (uniform or not), zonations or not, scattered rhombs or 'mosaic' texture…

⇒ ***common dolomite*** : idiotopic (euhedral), hypidiotopic (subhedral), xenotopic (anhedral) => 'SUCROSIC'
⇒ ***saddle dolomite = 'baroque dolomite'*** : larger sizes (mm, >mm), deep burial or hydrothermal
⇒ ***dedolomite*** : early or late diagenetic replacement of dolomite by calcite

• Basic terminology in describing dolomite rocks = Friedman 1965, expanded by numerous authors….
TODAY: we use the Sibley & Gregg 1987 practical classification considering crystal size, growth effects expressed by planar or non-planar textures, and the degree of dolomitization of the grains, matrix and voids
=> dolomitization of grains = unreplaced/in molds/partially replaced/replaced
=> matrix dolomitization = unreplaced/partially replaced/replaced
=> void-fillings = unreplaced/partially replaced/replaced by dolomite



non-planar planar-e +SUCROSIC planar-s



Classification of dolomite fabrics, from Friedman 1965; Randazzo & Zachos 1983 *in* Flügel 2004.
Size classes used are 0.256-0.126mm (prefix micro), < 0.002 mm (aphanotopic).

4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.4. DOLOMITE and EVAPORITE FABRICS : early to late diagenesis

Dolomitization Models

⇒ ***'primary' dolomites*** : very rare, saline lakes and lagoons
⇒ ***evaporitive dolomite*** : supratidal, sebkha (the Persian Gulf, the Bahamas)
= microcrsytalline (1-5 µm) and non stoechiometric, formed by hypersaline brines derived from intense evaporation
⇒ ***seepage-reflux*** : Mg-rich hypersaline fluids (related to supratidal gypsum precipitation) permeate the underlying carbonate sediments
⇒ ***evaporation-drawdown*** dolomitization intertidal and subtidal facies, as a response of sea-level changes
⇒ ***alkaline lakes*** ephemeral lakes in South Australia behind a modern beach barrier

⇒ ***shizohaline dolomite :*** mixing freshwater (meteoric) and seawater = 'Dorag model'

⇒ ***seawater dolomite*** : needs an efficient mechanisms for pumping the water trough the carbonate sediments
= tidal pumping oceanic tides, oceanic currents, thermal convection (through a volcanic basement)

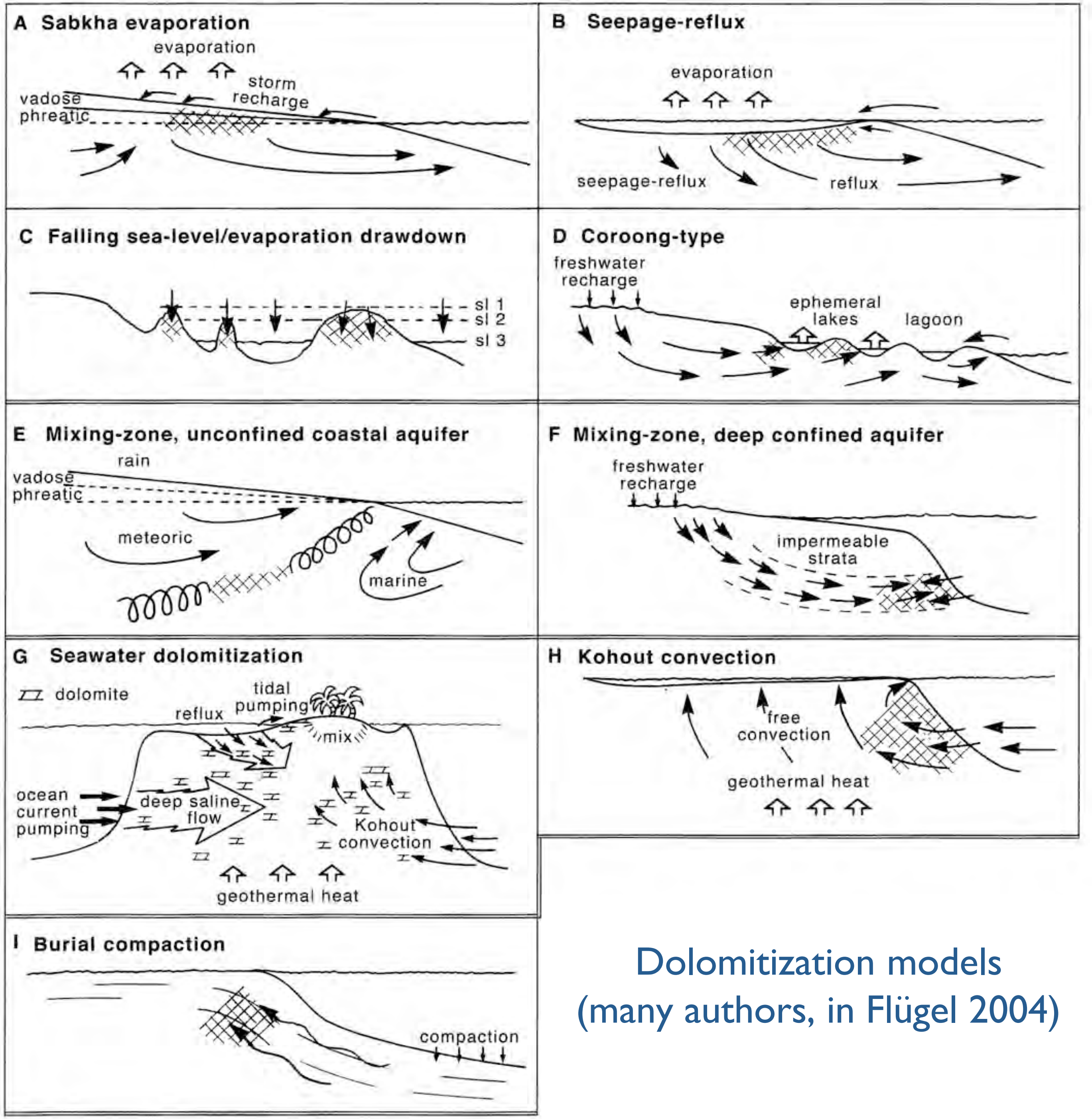
⇒ ***convection model*** : large-scale and prolonged circulation of seawater into carbonate platform margins
= horizontal density gradient between cold marine waters adjacent to carbonate platforms and geothermally heated groundwaters within the platform Kohout convection

⇒ ***subsurface burial dolomite :*** T° and Mg coming form the compactional dewatering of basinal mudrocks and expulsion of Mg-fluids from porewater during the transformation of clay minerals (smectite to illite).
Other Mg-sources are pressure solution and possible metamorphic and hydrothermal fluids.
Criteria : coarse crystals, saddle dolomite, Fe-content, specific isotopes values.
Often: only the matrix is dolomitized = 'matrix dolomite'

Dolomitization Models

⇒ ***dedolomite*** under the influence of meteoric water => potential secondary porosity
can be early OR late diagenetic
==> useful to recognize subaerial exposure and unconformities
dedolomitization => calcitization

⇒ ***saddle dolomite or 'baroque' dolomite*** : coarse, milky-white or brown dolomite crystals (mm or >mm) with curved saddle-like crystal faces due to rotating c-axes. Fluids inclusions are abundant.
= => it occurs in moldic and vuggy pores, often in sulfate-bearing carbonate host-rocks associated with hydrocarbons and epigenetic sulfides (MVT ore deposits)
= deep burial or hydrothermal conditions from high-saline brines and under high T°or as a by-product of thermochemical sulfate reduction.



Dolomitization models
(many authors, in Flügel 2004)

4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.4. DOLOMITE and EVAPORITE FABRICS : early to late diagenesis

High salinites => Evaporite formation

- common in arid/semi-arid shallow-marine environments => evaporite-carbonate shorelines, lagoons
- may also form during dry seasons in more humide areas, but are redissolved during the wet seasons

= association with peritidal carbonates => SABKHAS

⇒ the most common evaporite minerals are gypsum, anhydrite and halite (Trucial Coast of the Arabian Gulf = broad supratidal zone or 'sabkha')

⇒ waters are supplied to the sabkha

= = > by flood recharge during storms

= = > by capillarity evaporation

= = > evaporitive pumping (upward flow of groundwater replace waters lost by capillary evaporation (the source of this groundwater is continental in the Trucial Gulf Coast sabkhas)

Fabrics

- very different, various…

⇒ interbedded lime mudstones and layers with anhydrite or gypsum crystals

⇒ microfolds in fine-grained dolomites due to the dehydration of primary gypsum or hydration of anhydrite

⇒ collapse breccia

⇒ silicified or calcitized nodules formed by the replacement of anhydrite nodules

⇒ half moon ooids

⇒ pseudomorphs of evaporite minerals

⇒ palisade calcites

⇒ lenght-slow chalcedony

⇒ auhigenic idiomorphic and double-terminated euhedral crystals

⇒ authigenic euhedral feldspar

⇒ low-diversity but abundant skeletal grains = endemism

⇒ microbial mats (cyanobacterial and fungi)

4. DEPOSITIONAL AND DIAGENETIC FABRICS

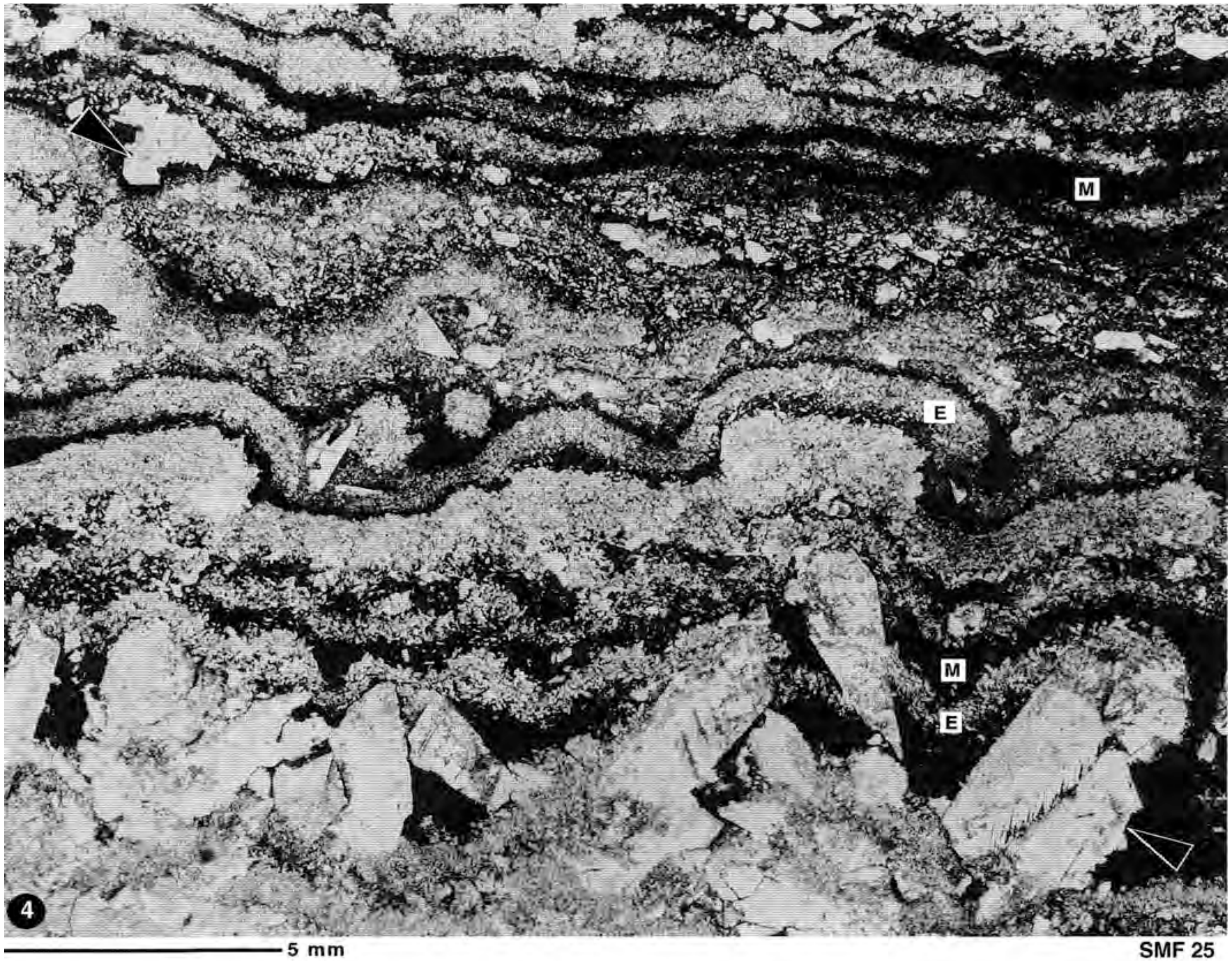
4.4. DOLOMITE and EVAPORITE FABRICS : early to late diagenesis

• very different, various…

⇒ entherolites

⇒ nodules

⇒ chicken-wire



Laminated evaporitic lime mudstone with alternating organic-rich layers (M) and evaporitic layers (E) with tiny gypsum crystals. Some layers with early diagentic entherolitic folds showing antiform buckles. Deformation is related to growth of large gypsum crystals (arrow).

Deep evaporitic lacustrine basin, Eocene, Mormoiran Basin, France, in *Flügel 2004*

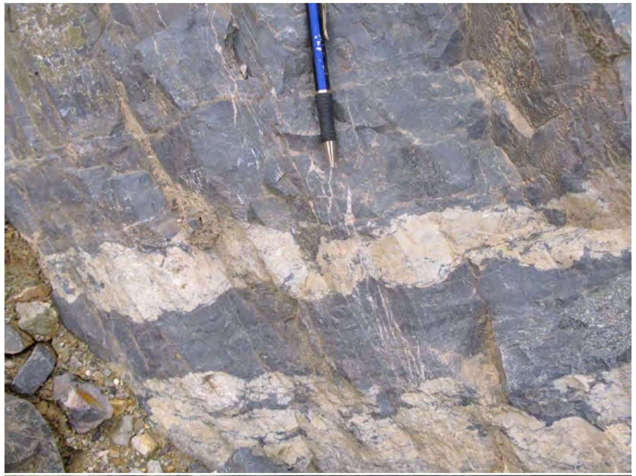
4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.4. DOLOMITE and EVAPORITE FABRICS : early to late diagenesis

Collapse roof of a cavern, karstification-dissolution Upper Miocene reef limetone

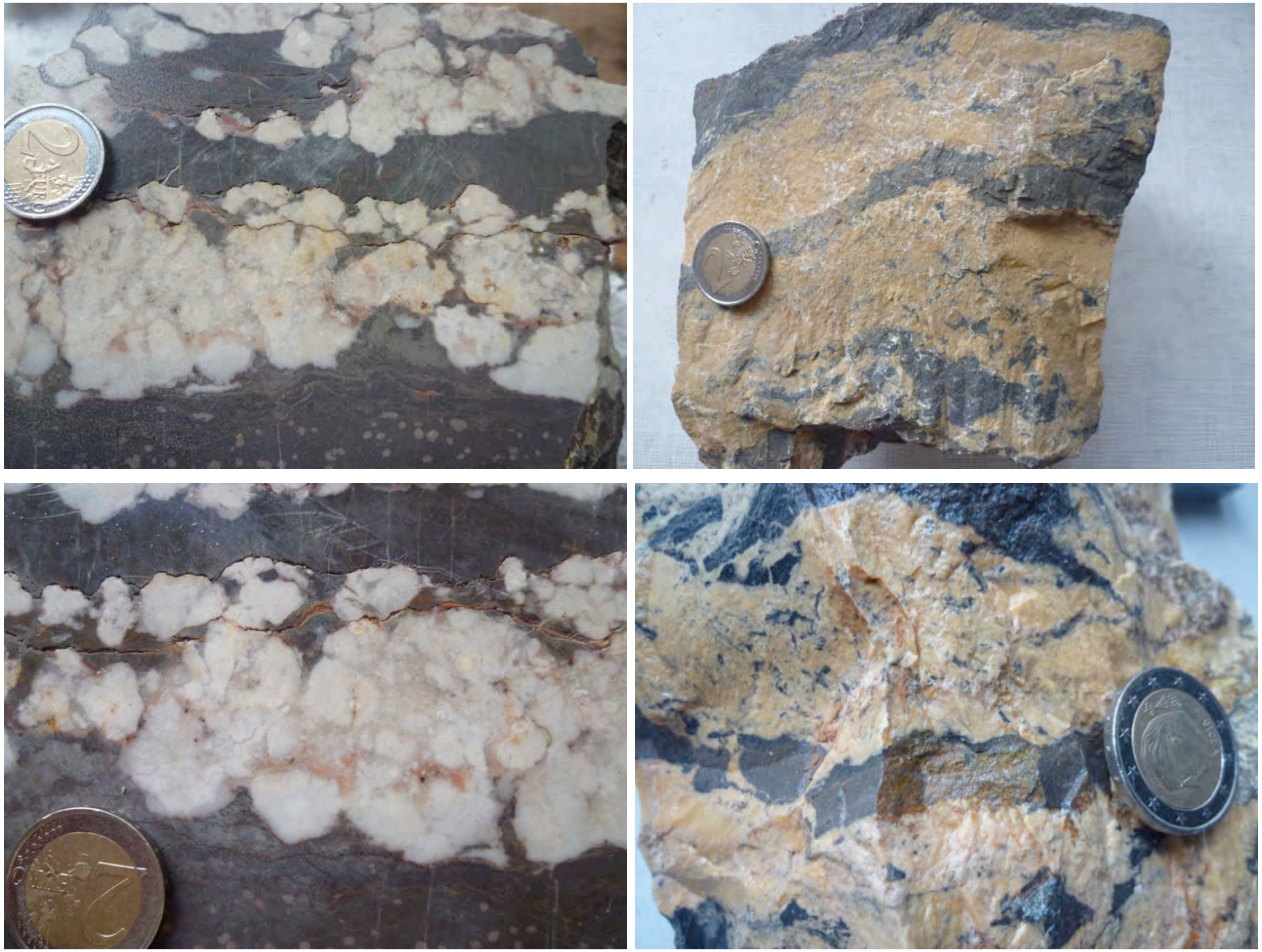
Entherolites and sliding of an evaporitic series, Midldle Viséan, Avesnes-sur-Helpe, France.

Mamet & Préat 2005



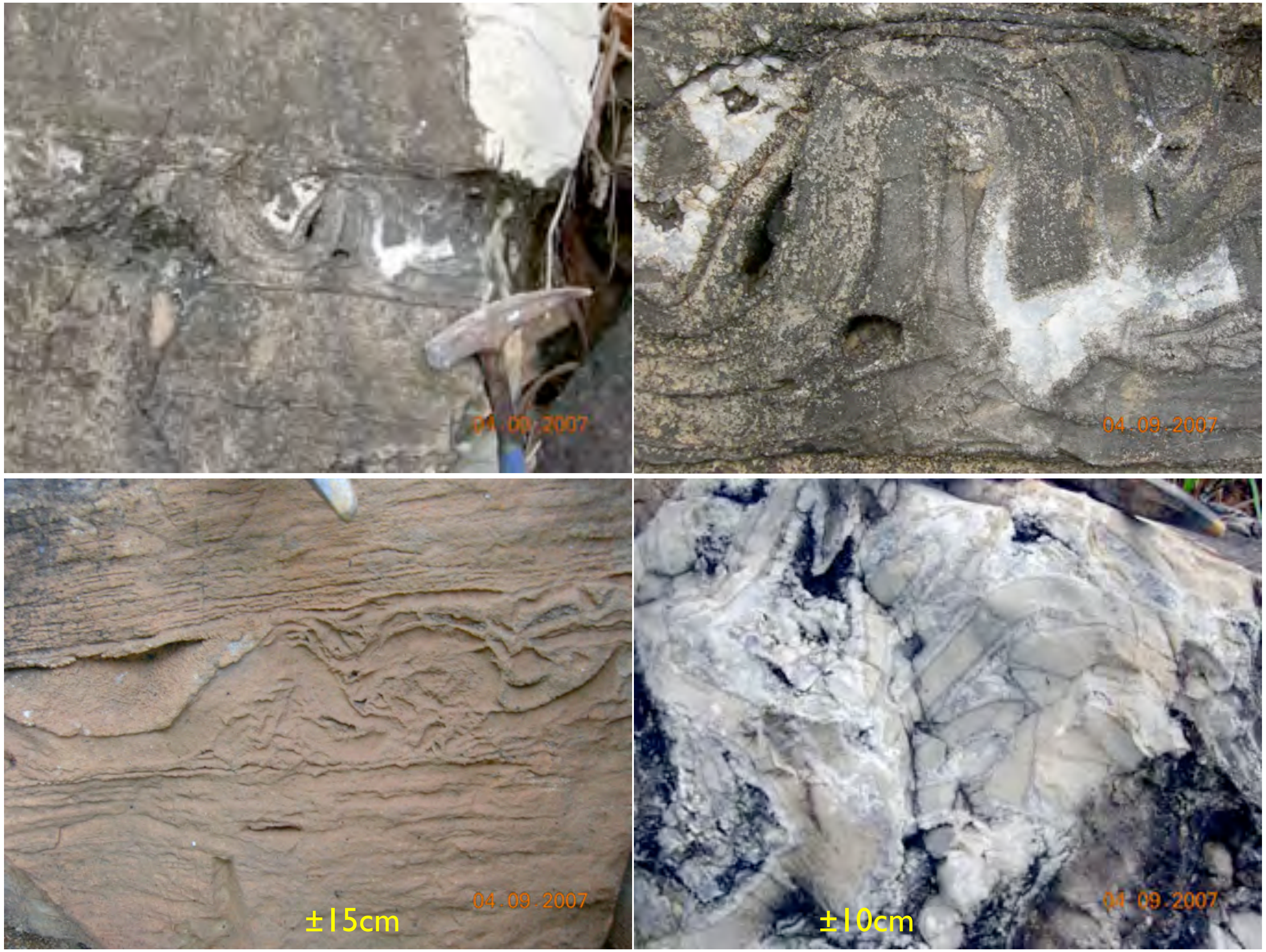
Entherolites and collapse breccia in an evaporitic series, Midldle Viséan, Avesnes-sur-Helpe, France.

Mamet & Préat 2005



Folding, Tepee and Collapse breccia, Paleoproterozoic, Gabon

Préat et al 2011

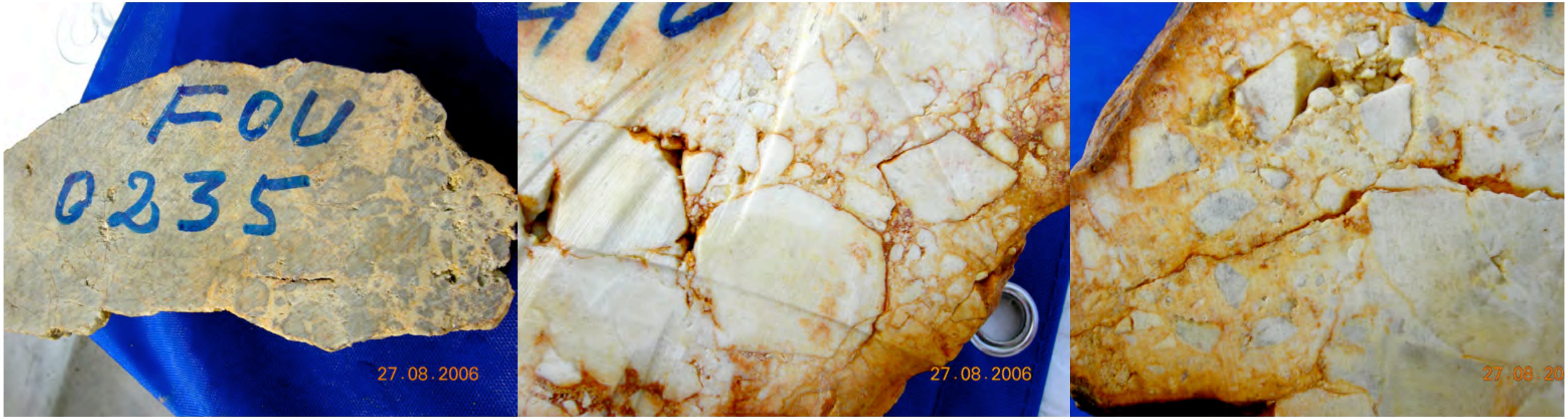


Folding and collapse breccia, Paleoproterozoic, Gabon

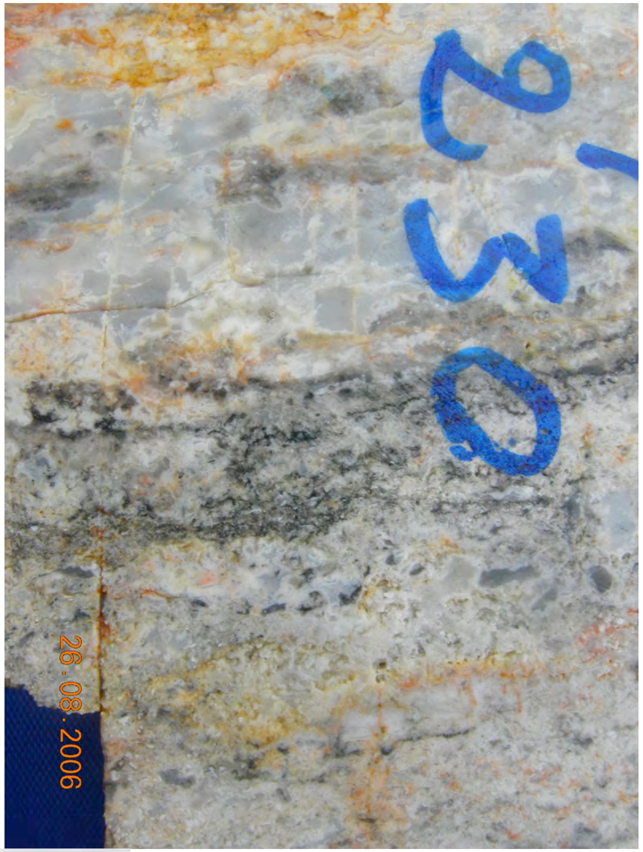
Préat et al 2011

Collapse breccia, Neoproterozoic, Gabon

Préat et al 2010



Evaporites (E)
from a laminar
dolostone (D)
Neoproterozoic,
Gabon
Préat et al. 2010



E

D

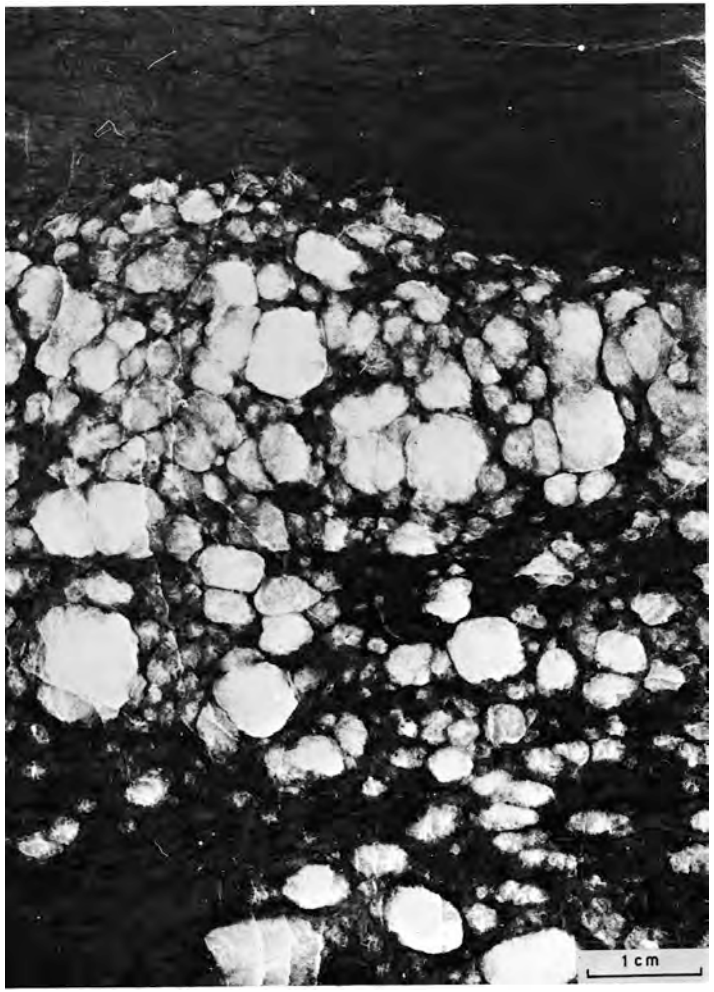
Silicification of
evaoporite
Neoproterozoic,
Gabon
Préat et al. 2010

Evaporites

Chicken wire structure

Irregular anhydrite masses distributed in dolmicrite

Elf Aquitaine, 1975

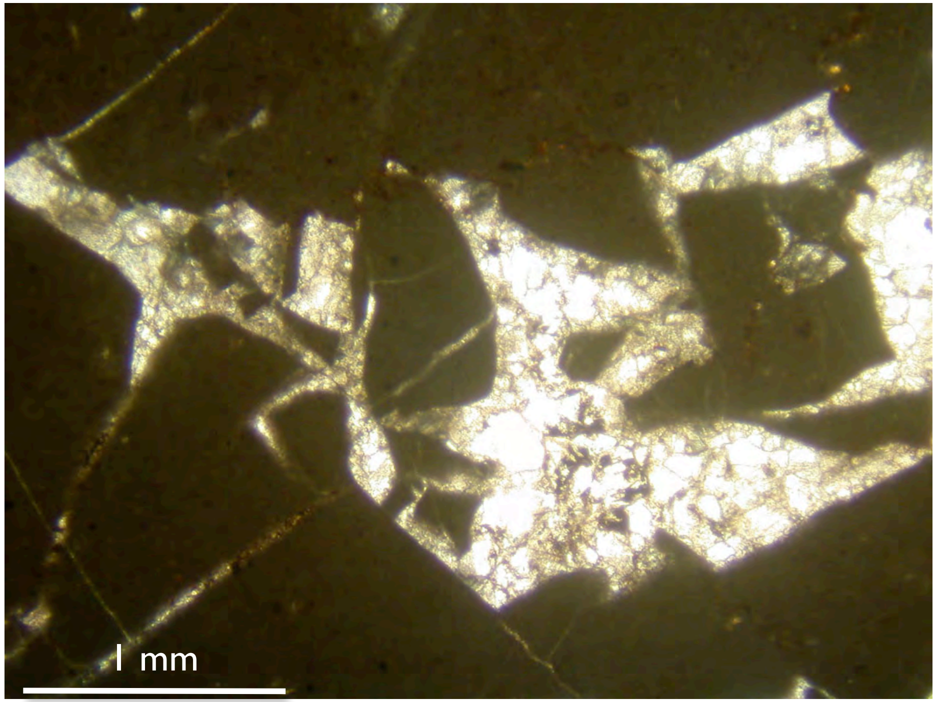


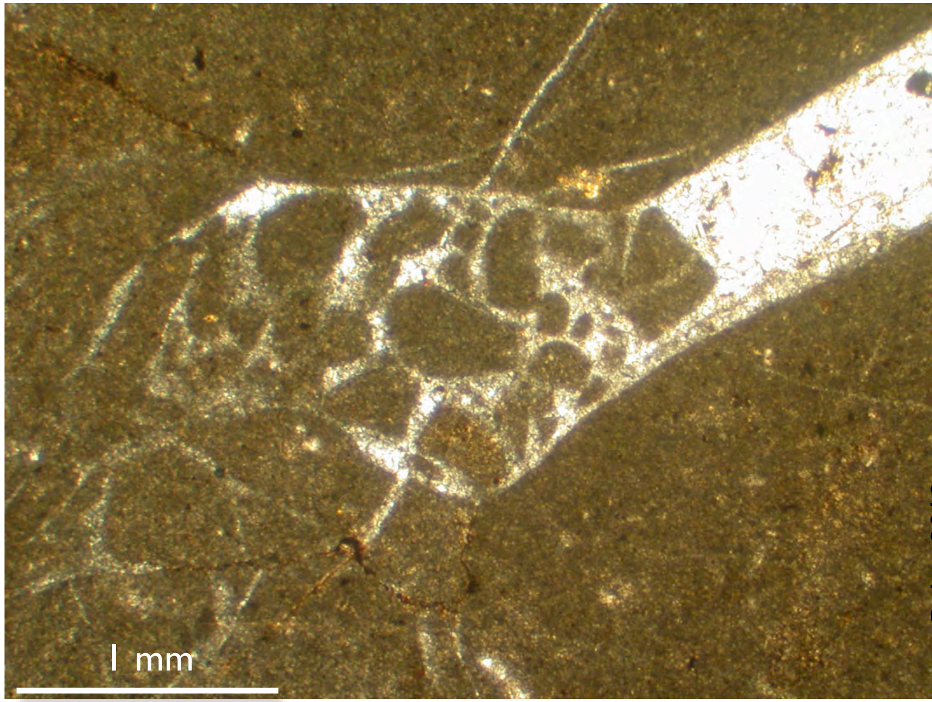
4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.4. DOLOMITE and EVAPORITE FABRICS : early to late diagenesis

Collapse breccia of fine crystalline dolostone blocks cemented by yellow sphalerite.
Late diagenetic, Mascot-Jefferson City District, USA, Kyle 1983.

Pseudomorphs after sulfates and collapse breccia
Late Givetian, Nismes section, Belgium





Préat, 2010

Main type of carbonate breccias (multiple processes) Flügel 2004

Depositional breccias (resulting from the deposition of eroded carbonate material)	**Mass-flow breccia:** Breccia originating from the downslope transport of shallow-marine and (re-slope sediments moving under the force of gravity. Includes breccias formed by slumps and slides, debris flows, grain flows, and turbidity flows.
	Submarine rockfall breccia: Mass-flow breccia formed by the accumulation of coarse, angular rock fragments derived by falling from a cliff, escarpment or steep rocky slope.
	Peritidal and shallow-marine breccia: Breccia formed by synsedimentary deposition of eroded peritidal, shallow subtidal as well as subaerial carbonates, often related to storm events. Deposition takes place in inter- and supratidal settings, and at the beach.
	Forereef breccia: Breccia deposited on the seaward slope of high-energy reefs. Consisting of eroded reef material and remains of organisms living in the reef or on the foreslope.
Non-depositional breccias (resulting from in-place dissolution)	**Caliche breccia**: Breccia formed by in-situ brecciation in arid and semiarid climates, controlled by soil-forming processes, and connected with extensive weathering, erosion, solution and shrinkage.
	Solution-evaporite-collapse breccia: Breccia formed by collapse of beds subsequent to the removal of soluble material within some beds (e.g. evaporites).
Tectonic breccias (resulting from internal dislocation of carbonate rocks)	**Fissure fill breccia**: Breccia formed within submarine neptunian dikes or subaerial fissure infills and karst fissures.
	Internal breccia: Breccia formed by rupture and fracturing of carbonates near the depositional surface. These breccias are products of dilation of slightly lithified limestones caused by tectonics (e.g. hydraulic fracturing, earthquakes). Internal breccias occur in platform and slope carbonates which were brecciated shortly after deposition and before final lithification.
	Shear breccia: Breccia caused by brittle deformation associated with thrust and sliding displacement.
Diagenetic breccias (resulting from early diagenetic processes)	**Pseudobreccia:** Mottled limestones and dolomites with breccia-like textures caused by patchy recrystallization and cementation, possibly controlled by the distribution of organic compounds.
	Stylobreccia: Breccia in which fragments are bound by stylolites. Caused by fracturing of carbonate rocks, accompanied by pressure solution between the fragments of the breccia.

PETROGRAPHY OF CARBONATES

4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.5. BIOTURBATION, BURROWING and BIOPERFORATION (BIOEROSION)

Burrowing and Bioturbation => sea-bottom conditions and post-sedimentary diagenetic changes

⇒ spatial arrangement and geometry of burrows, burrow density, burrow abundance and texture and fillings of burrows

= => qualitative and quantitative analyses from the field and/or thin sections

= = > function of substrate types ad conditions, oxygenation, particle flux, depositional setting, sedimentation rates

Burrows : form within soft unconsolidated sediments (muds, sands…) by the activity of animals (….)

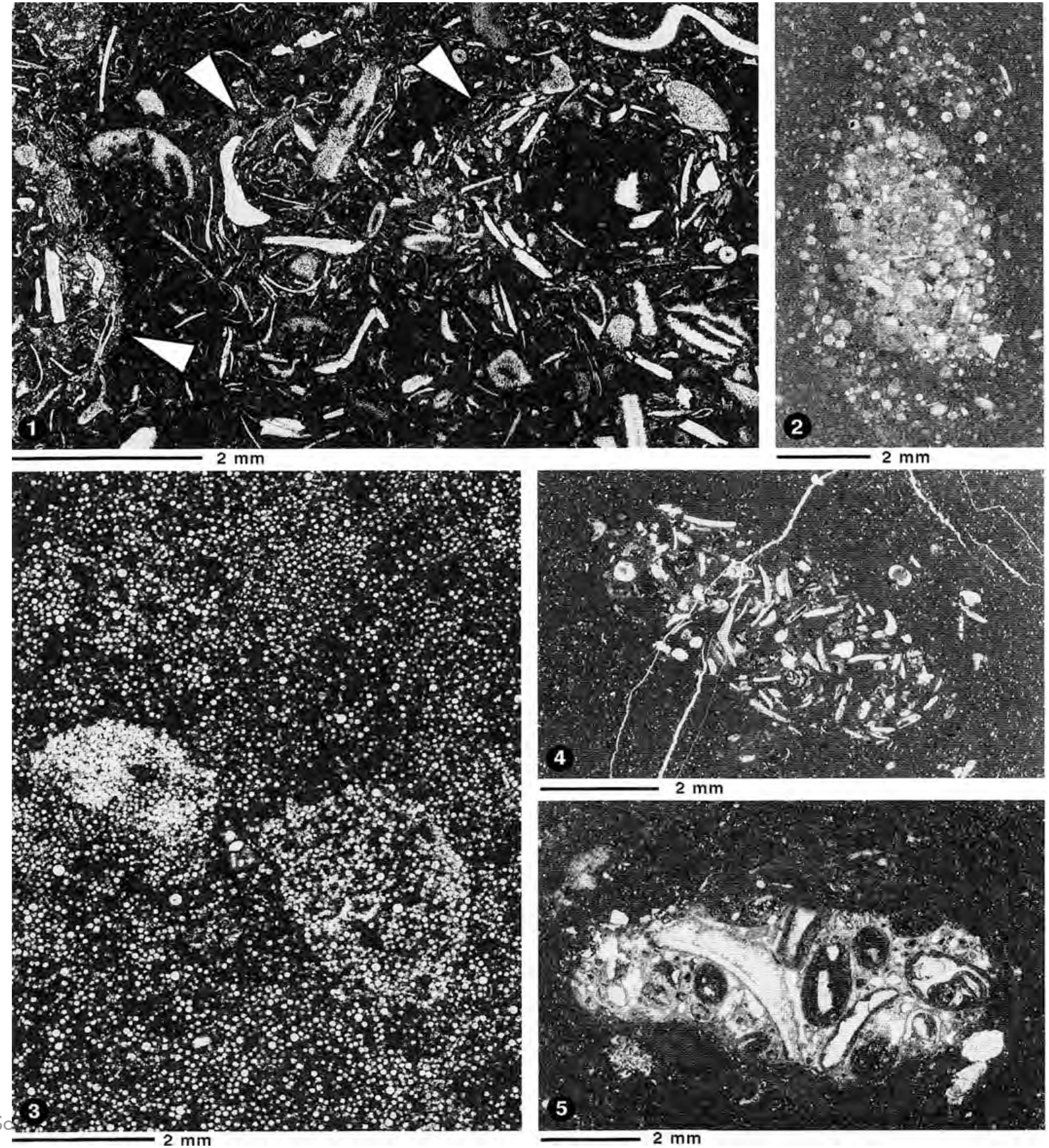
Bioturbation = 'churning and stirring of sediments by organisms => destruction of sedimentary structures (bedding, storm layers …)

….

….

Econmic significance : influence the distribution of porosity and permeability => acts on reservoir properties

Flügel 2004



Bioturbation = circular swirls (arrows) of skeletal debris (trilobites, echinoderms)
Patchy distribution of these structures and variations in packing densities of grains
Well-oxygenated subtidal mid-shelf environment
Ordovician, Sweden

Burrowed radiolarian wackestone
Bathyal environment
Late J , Alps

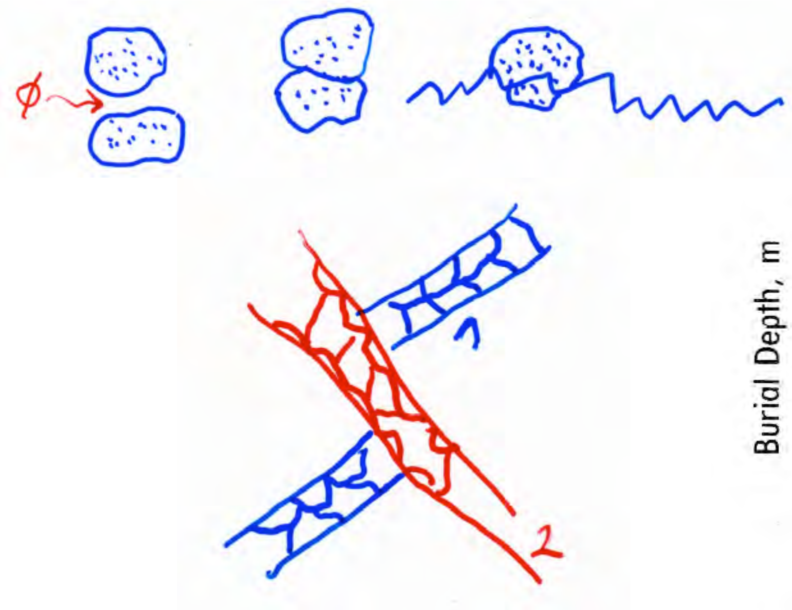
Burrowed calcisphere packstone
Late Cretaceous, Germany

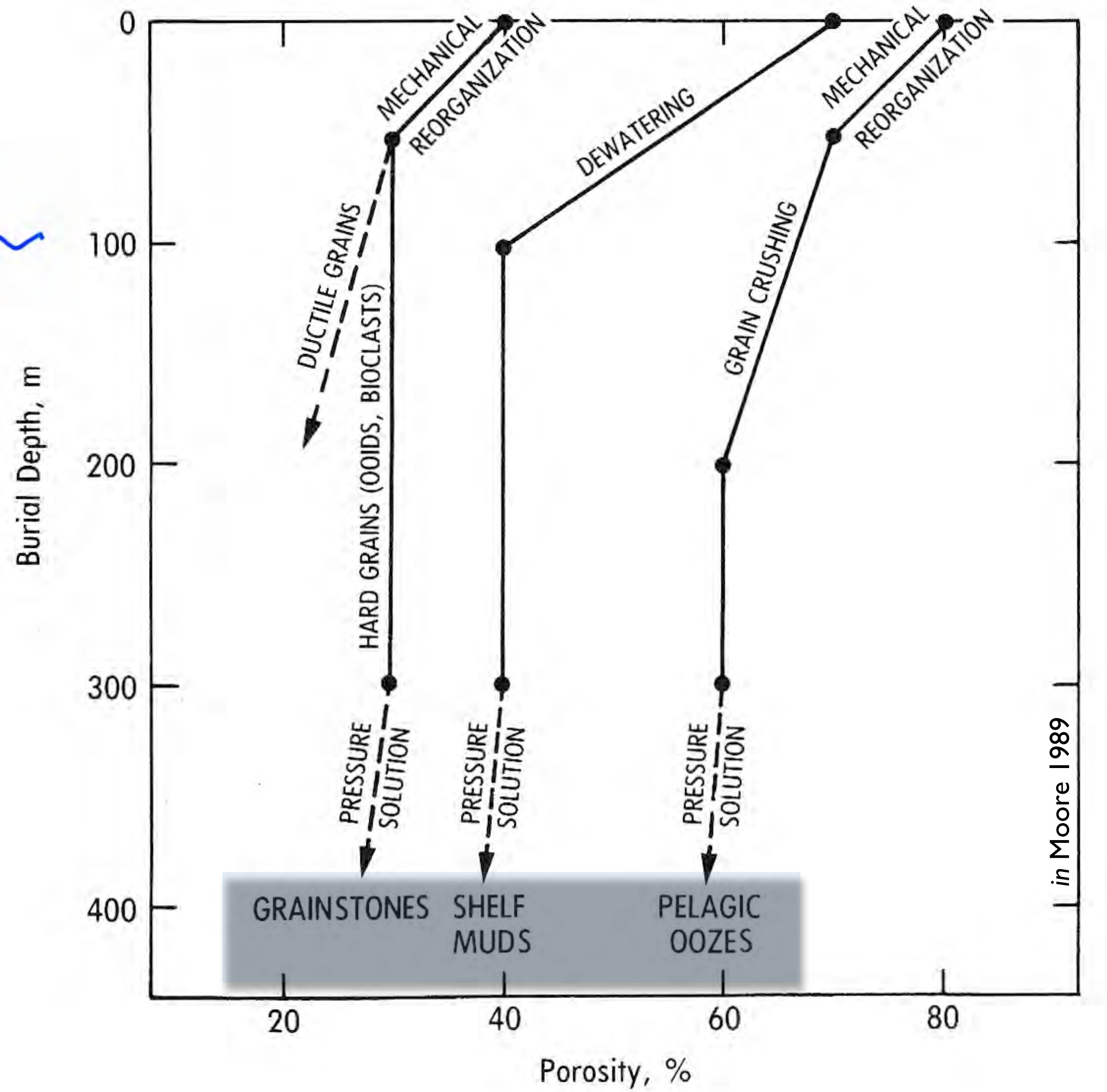
Burrow filling of benthic foram ad shell clasts
Absence compaction = firmground substrate consistency
Late J, France

Burrow within microbial crusts infilled with oncoids
….
Upper slope, *Late Trias, Italy*

4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.6. BURIAL DIAGENESIS





PETROGRAPHY OF CARBONATES

4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.6. BURIAL DIAGENESIS

Most ancient limestones have spent 10' to 100' Myr in the burial environment (the longest time…)
⇒ **cementation, compaction and pressure dissolution *vs* depth, pressure, T° and in pore-fluids salinity**
⇒ begin below the depth where sediments are affected by near-surface processes of the marine/meteoric environment
⇒**pore-fluids rates are very low : 1-10m/yr << shelf-margin reefs 2000m/day**
= => cement precipitation very slow….

Cementation : coarse calcite spar (LMC) cement enriched in Fe and Mn, poor in Sr. Fluids inclusions are common
+ coarse poikilotopic calcite (= large crystals including several grains), drusy and other equant mosaic calcite,
syntaxial calcite spar (if echinoderm fragments): zoned, clear ≠ cloudy earlier overgrowths

Physical or Mechanical Compaction: due to sediment overburden
=> reduces thickness, leads to breakage and distortion of grains = = > 'compressed fabrics'
Chemical Compaction: starts at various depths of overburden 100'-1000'm (but also 100-200m)
⇒ reduces thickness of sediment, porosity, permeability
⇒ produces STYLOLITES and PRESSURE-SOLUTION STRUCTURES (SEAMS)
<u>provides carbonate for burial cementation</u>

Minor solution porosity caused by dissolution of carbonate and calcium sulfate minerals

Burial dolomitization : anhedral (xenotopic) crystalline fabric, generally **coarse** crystals

PETROGRAPHY OF CARBONATES
4. DEPOSITIONAL AND DIAGENETIC FABRICS
4.6. BURIAL DIAGENESIS

Most ancient limestones have spent 10' to 100' Myr in the burial environment (the longest time…)
⇒ cementation, compaction and pressure dissolution *vs* depth, pressure, T° and in pore-fluids salinity

Pressure :
• hydrostatic = transmitted only through the water column, cf. sediment pore system (= fluid salinity and T°)
• lithostatic = transmitted through the rock framework
• directed pressure = tectonic stresses
⇒ the net pressure on a sedimentary particle in the subsurface is found by substracting hydrostatic p – lithostatic p
= = > particular cases with overpressuring or geopressure (rapid burial with aquacludes-evaporites, shales, even thin cemented layers (marine hardgrounds ….) => possible hydrofracturing and increase of porosity

Temperature : geothermal gradient
• increasing T => speeds chemical reactions and rate of ionic diffusion
• increasing T => decrease the solubility of carbonates due to CO_2
• increasing T => modification oxygen isotopes of subsurface calcite cements and dolomites
• oil window (organic matter) oil/gas

INCREASING BOTH P AND T => triggers a series of mineral reactions and phase
= = > release water and ions that can become involved in carbonate diagenesis processes
Conversion of gypsum to anhydrite at ±1000m (±42°C) => significant H_2O
Conversion of smectite to illite at ±2000 m (±60°c) =>significant H_2O + Mg => dolomitization

Salinity : well-know from samples of oil field waters

4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.6. BURIAL DIAGENESIS

Most ancient limestones have spent 10' to 100' Myr in the burial environment (the longest time…)
⇒ cementation, compaction and pressure dissolution *vs* depth, pressure, T° and in pore-fluids salinity

Salinity : well-know from samples of oil field waters

• most of these waters = saline water or brines : 10,000-100,000ppm dissolved salts, more saline than seawater (related to dissolved -former- evaporites and mixing with meteoric, marine and basinal fluids)

….

….

• in detail the composition of subsurface fluids is complex and varies widely within and between basins….

4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.6. BURIAL DIAGENESIS

Physical or Mechanical Compaction: due to sediment overburden, can start with a burial depth of 1m!

• dehydration, porosity reduction (of lime mud up to 80%) , reduction of sediment thickness (up to 25%)

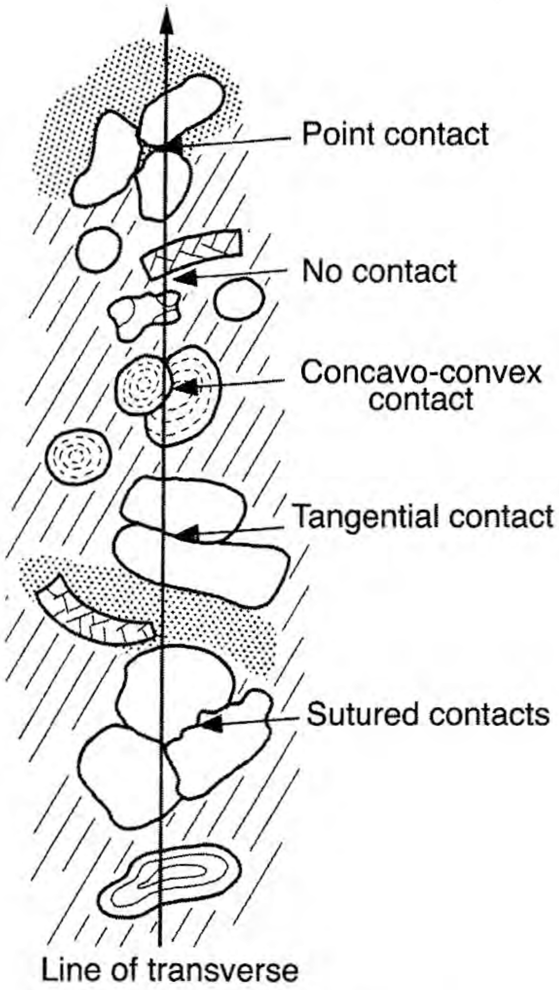
• reorientation and/or plastic deformation of grains (followed by crushing and pressure solution)

….

• **HOW TO MEASURE THE COMPACTION?**
= measuring the diameters of deformed burrows
= measuring deformed fossils with originally circular cross sections
= point counter methods ('packing density') => Packing Index
….

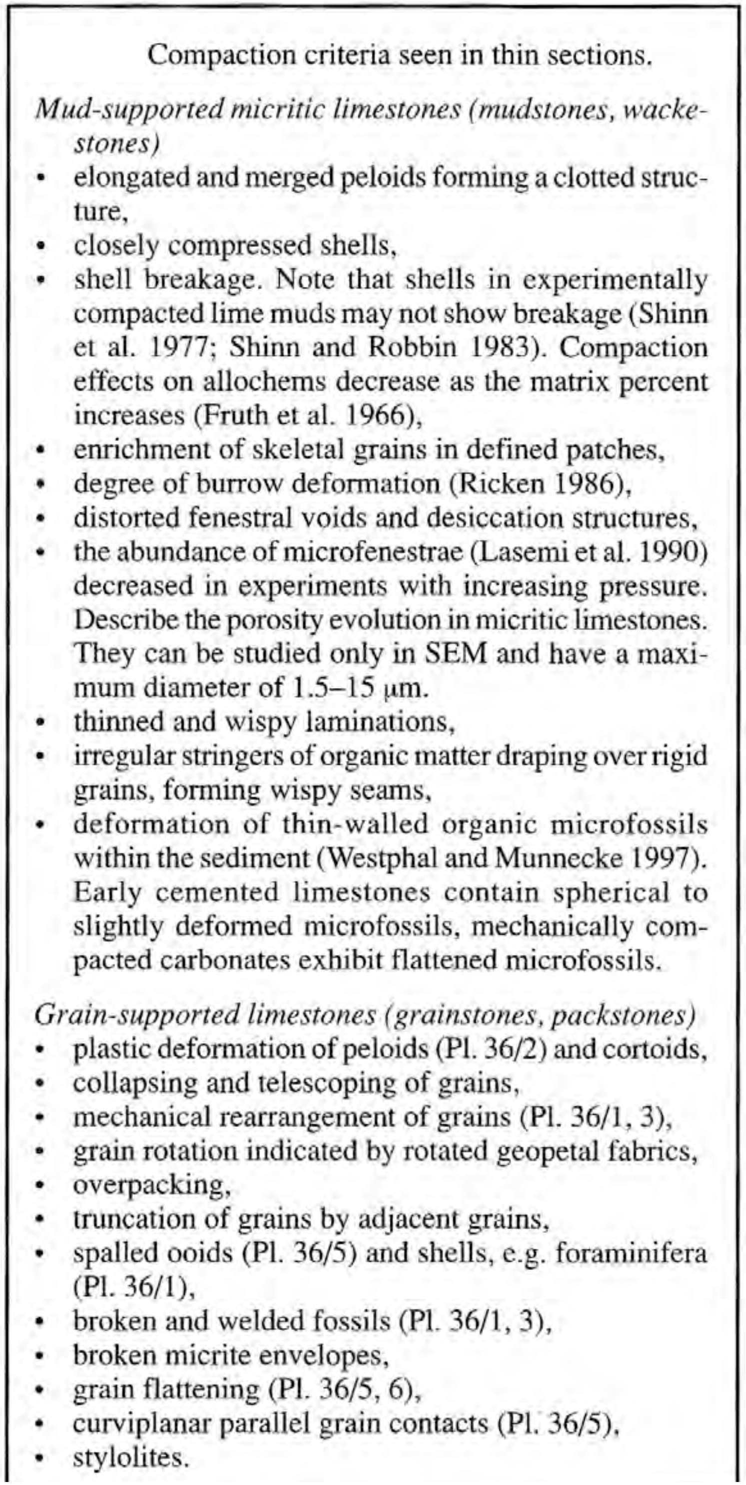
• Inhibiting factors
= preburial cementation
= preburial dolomitization
= clay content

• 'on average' grain stabilization is reached under burial conditions of 100m or < 100m
• 'on average' grain-supported carbonates may be resistant to compaction down to 700m



Grain contact types (Taylor 1950)

Quantitative measurements can be done among traverse which are vertical to the sedimentary bedding.



Compaction criteria seen in thin sections.

Mud-supported micritic limestones (mudstones, wackestones)

- elongated and merged peloids forming a clotted structure,
- closely compressed shells,
- shell breakage. Note that shells in experimentally compacted lime muds may not show breakage (Shinn et al. 1977; Shinn and Robbin 1983). Compaction effects on allochems decrease as the matrix percent increases (Fruth et al. 1966),
- enrichment of skeletal grains in defined patches,
- degree of burrow deformation (Ricken 1986),
- distorted fenestral voids and desiccation structures,
- the abundance of microfenestrae (Lasemi et al. 1990) decreased in experiments with increasing pressure. Describe the porosity evolution in micritic limestones. They can be studied only in SEM and have a maximum diameter of 1.5–15 µm.
- thinned and wispy laminations,
- irregular stringers of organic matter draping over rigid grains, forming wispy seams,
- deformation of thin-walled organic microfossils within the sediment (Westphal and Munnecke 1997). Early cemented limestones contain spherical to slightly deformed microfossils, mechanically compacted carbonates exhibit flattened microfossils.

Grain-supported limestones (grainstones, packstones)

- plastic deformation of peloids (Pl. 36/2) and cortoids,
- collapsing and telescoping of grains,
- mechanical rearrangement of grains (Pl. 36/1, 3),
- grain rotation indicated by rotated geopetal fabrics,
- overpacking,
- truncation of grains by adjacent grains,
- spalled ooids (Pl. 36/5) and shells, e.g. foraminifera (Pl. 36/1),
- broken and welded fossils (Pl. 36/1, 3),
- broken micrite envelopes,
- grain flattening (Pl. 36/5, 6),
- curviplanar parallel grain contacts (Pl. 36/5),
- stylolites.

Flügel 2004

Chemical Compaction: due to sediment overburden, e.g. load and/or tectonic stress

• pressure solution and formation of STYLOLITES and SOLUTION SEAMS (often associated with fracturing)
=> dissolution and source of porosity-occluding subsurface cements
=> **but** pressure solution may create conduits for fluids and open migration paths
FRACTURE AND PRESSURE SOLUTION ARE PRIME FACTORS FOR RESERVOIR ROCKS IN THE MIDDLE EAST

• stylolitization => bulk volume reduction = = > particular terminology has been developed (Wanless 1979).

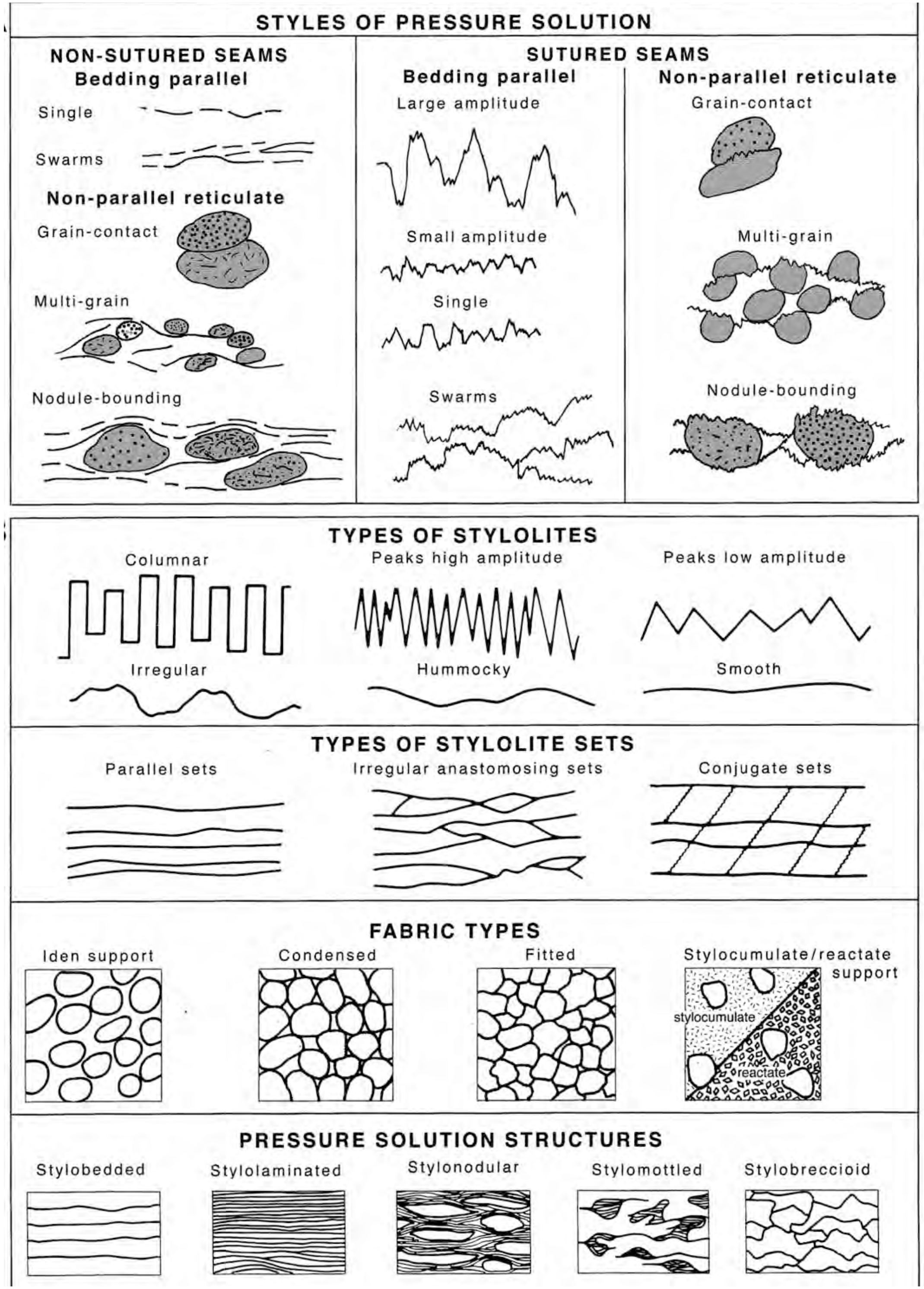
….

• chemical compaction 10' to 100'm

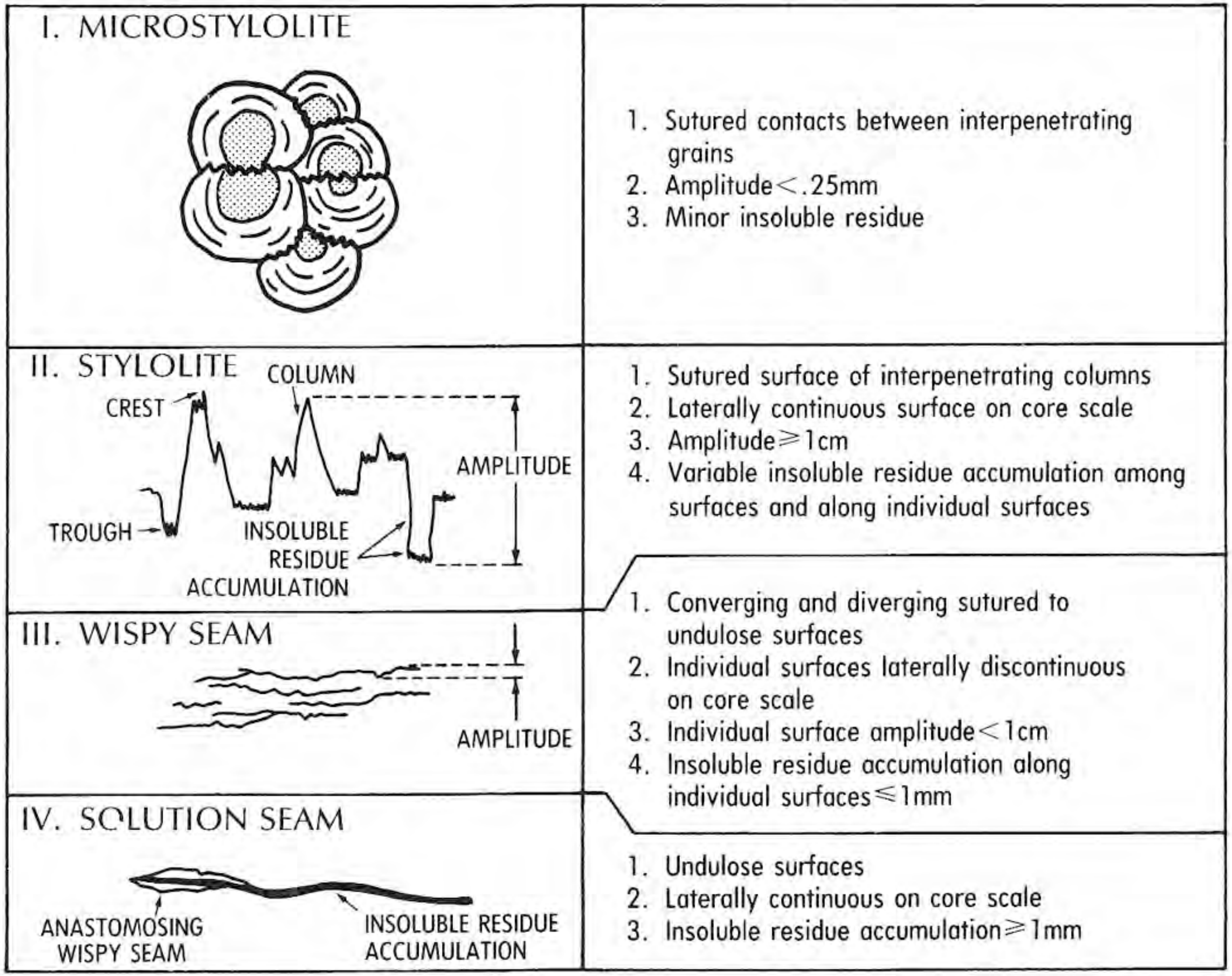
….

Most of these categories can be derived from thin-section studies

Wanless 1979
Choquette & James
….



TYPE OF PRESSURE SOLUTION FEATURES ENCOUNTERED IN THE SUBSURFACE



in Moore 1989

nb : **STYLOLITES** pressure-solution (burial >200m?, >500m)
if clays=> ‘seams’ and ‘flat’

STYLOLITES accumulation of insoluble residues
(clays, oxides, pyrite….)
HERE = oblique stylolites (tectonic superimposed)
Neoproterozoic, the Democratic Republic of Congo

VERY WELL DEVELOPED STYLOLITES, NEOPROTEROZOIC, CONGO-BRAZZAVILLE

important dissolution of coarse-grained facies

Préat 2012

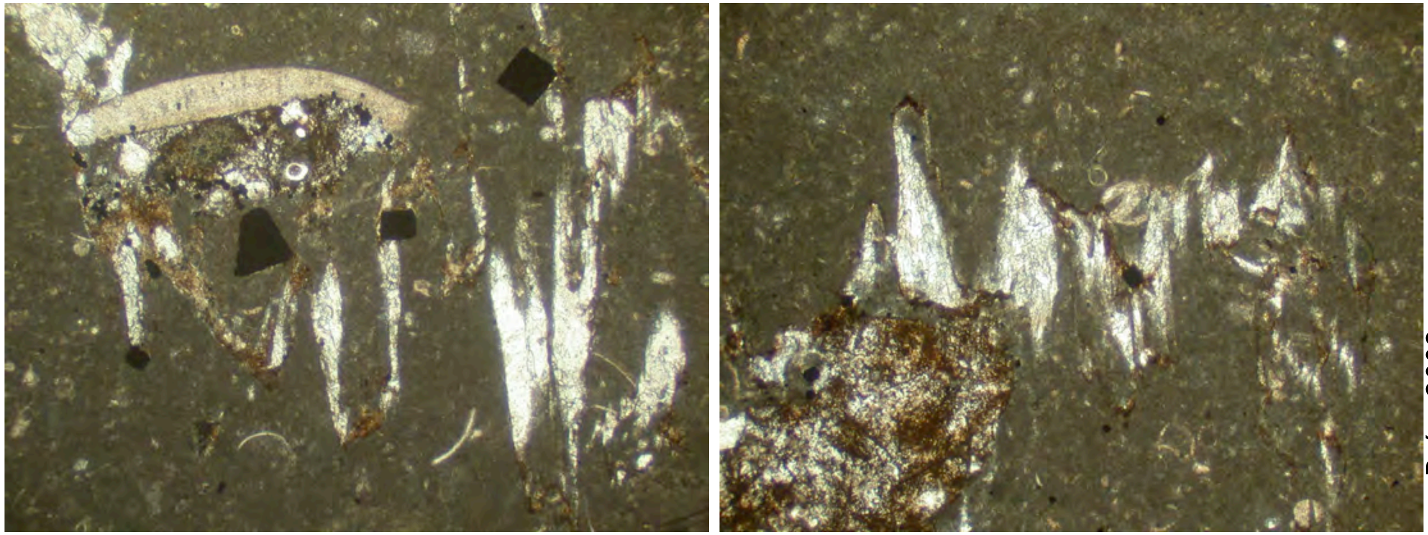
Préat 2012

important dissolution of coarse-grained facies

VERY WELL DEVELOPED STYLOLITES, NEOPROTEROZOIC, CONGO-BRAZZAVILLE

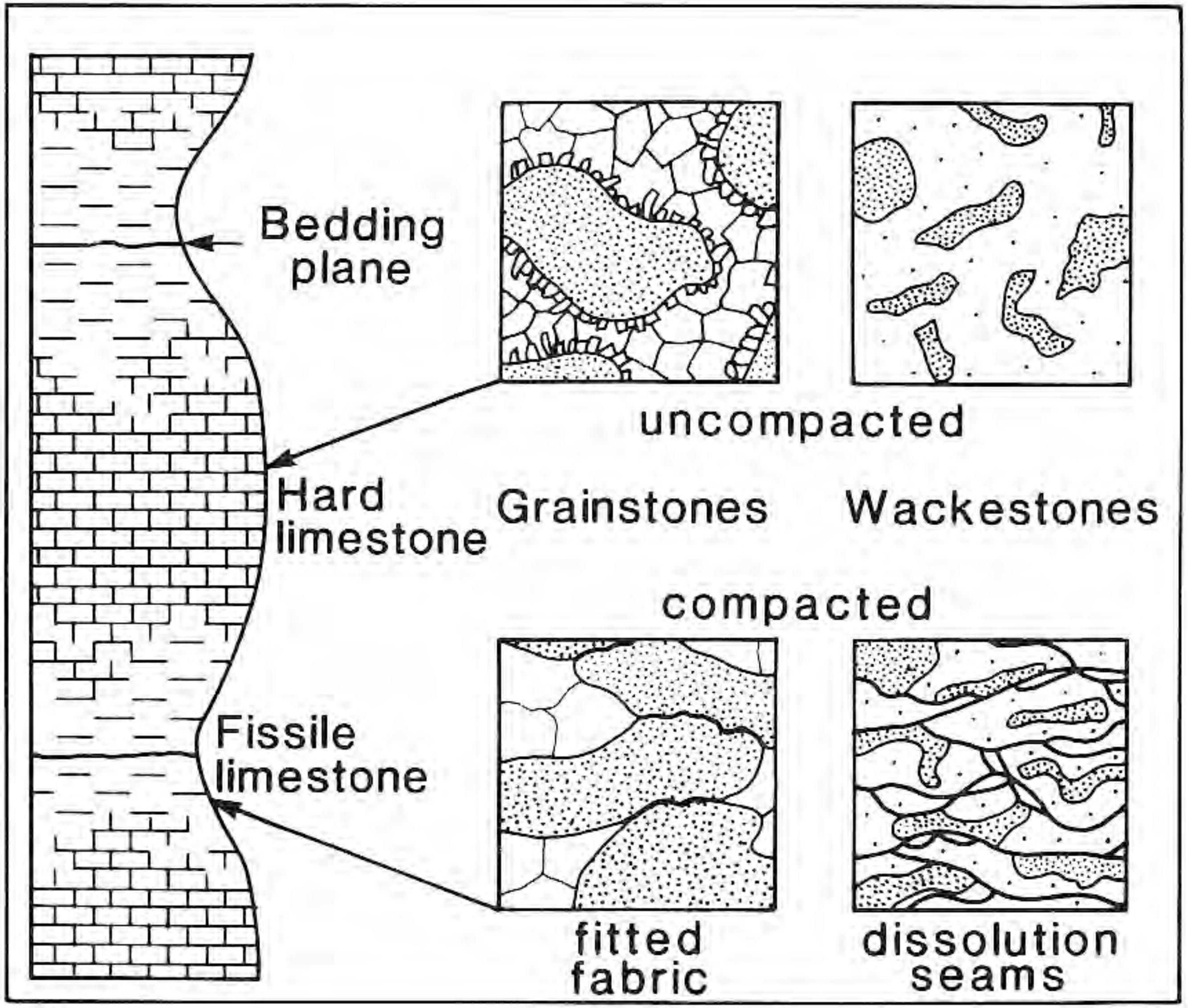
Preat 2012

Intense alteration from stylolites in a Frasnian mud mound (Lion Quarry), Belgium



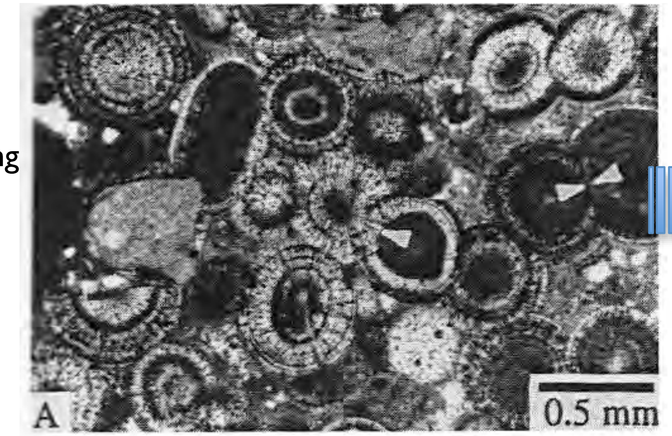
Préat 2008

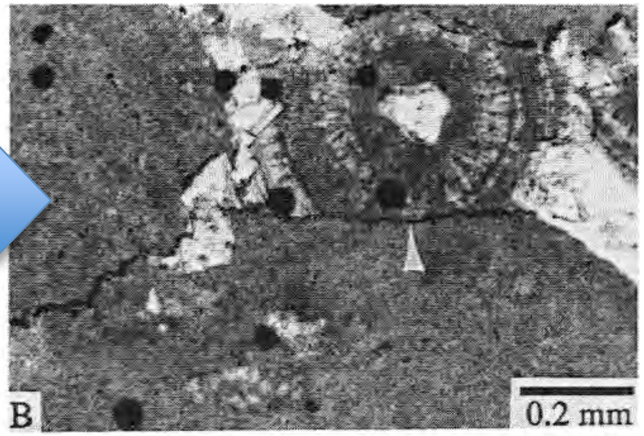
Sulfates in vertical stylolites, Late Givetian, Belgium



Uncompacted, **hard** limestones alternating with **fissile** limestones showing fitted fabrics and dissolution seams. This is the result of episodic subseafloor cementation (Ginsburg 1987 in Tucker & Wright 1990)

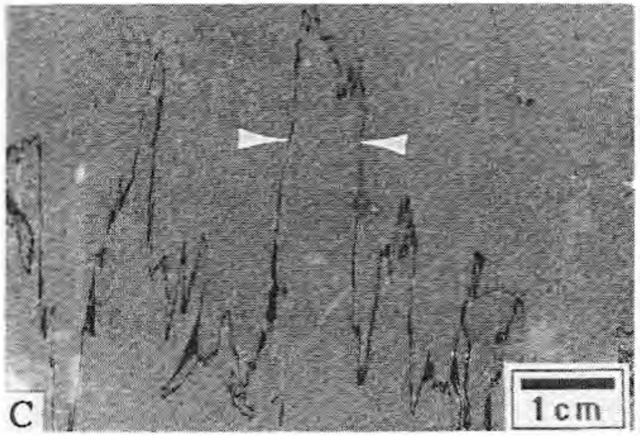
Strongly compacted ooid grainstone showing grain-to-grain pressure solution (arrows)
Jurassic, USA,
Depth 2970m



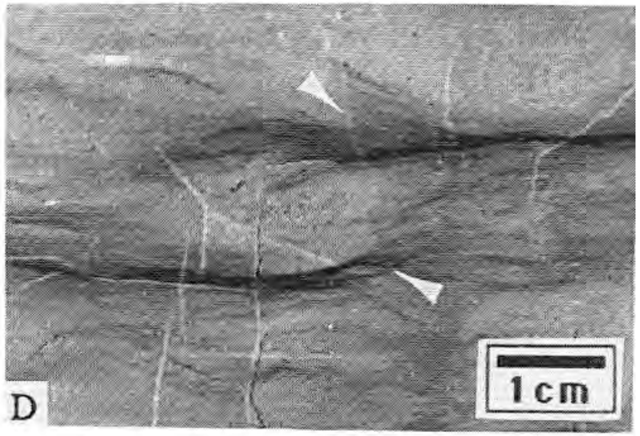


Idem
Jurassic, USA,
Depth 3325m

High amplitude stylolites (arrows)
Jurassic, USA,
Depth 4130m

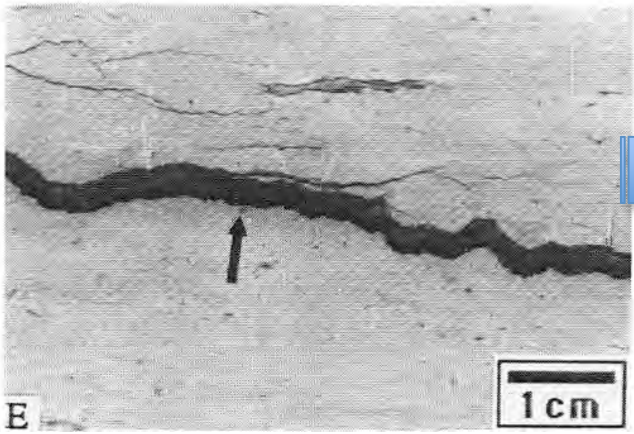


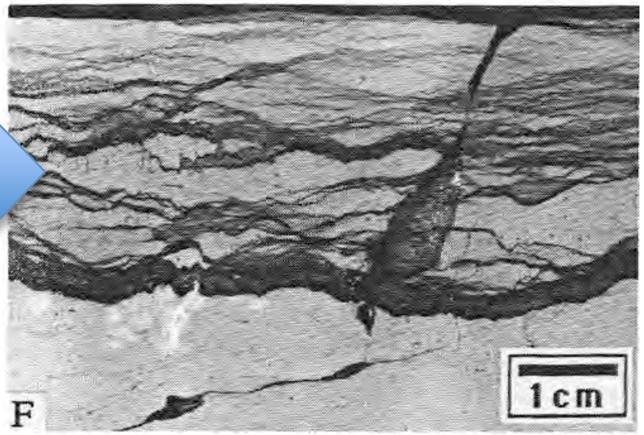
in Moore 1989



Wispy seam stylolites with 'horse tails' (arrows)
Jurassic, USA,
Depth 4164m

Solution seam with insoluble residue accumulation (arrow)
Jurassic, USA,
Depth 4147m





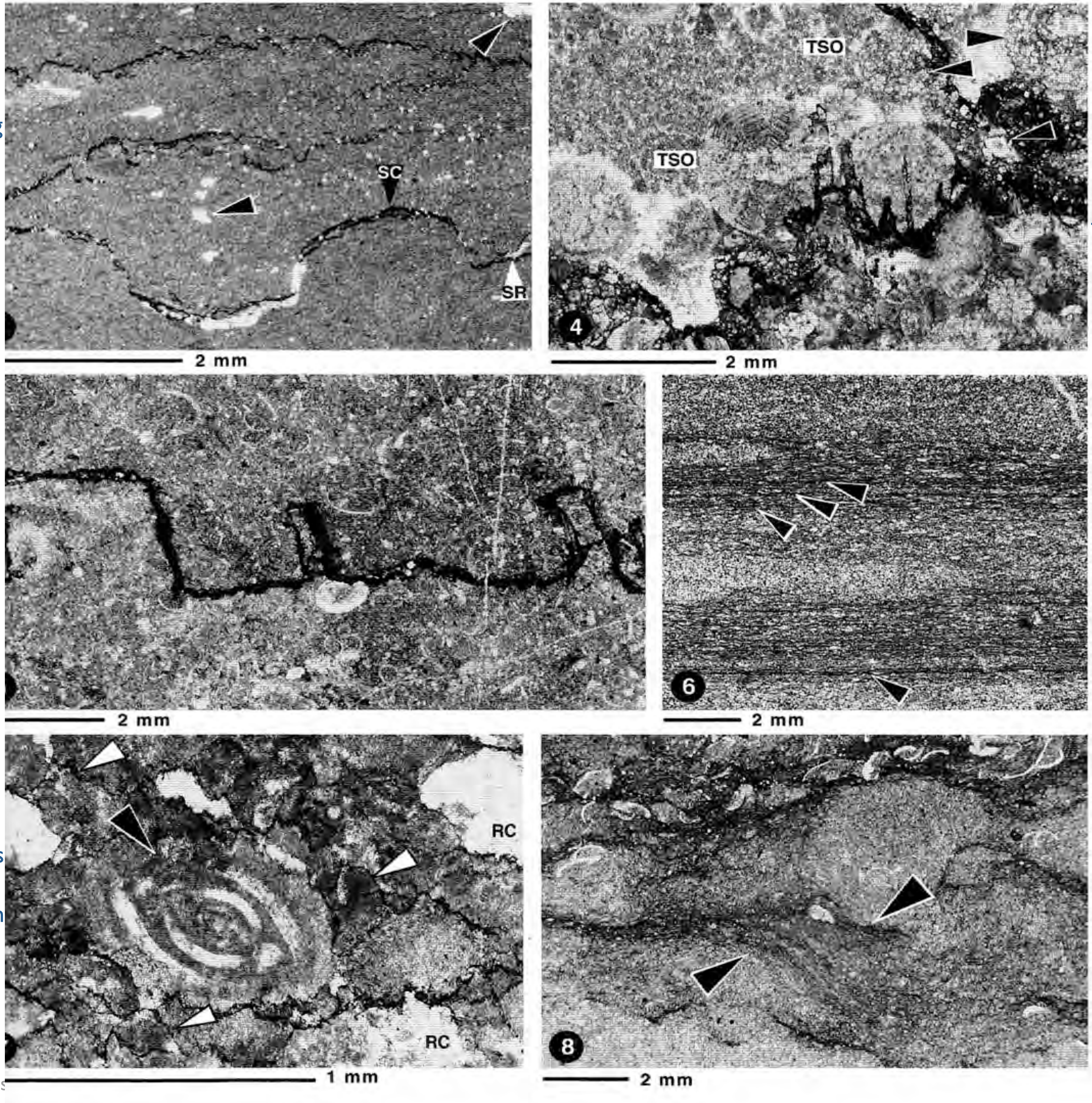
Idem
Anastomosing wispy seams
Jurassic, USA,
Depth 41564m

Flügel 2004

Bedding parallel irregular anastomosing sutured seams
SC= dark insoluble residues [stylo-cumulate]
Late Permian, Germany

Widely spaced high-amplitude columnar stylolites (with clays/pyrite) cumulate]
Silurian, Austria

Stylobreccia with) anastomosing stylolites (white arrows)
black arro =dissolution of a miliolid foram
Molasse, Germany



Pressure-solution postdates compaction
TSO: tgtially structured fractured ooids
Cambrian, Canada

Non-sutured wispy parallel sets of dissolution = stylolaminite (due to clay>10%)
Jurassic, Greece

Bedded non-sutured wispy seams parallel
Lateral splitting of seams (arrows)
Cretaceous, Egypt

PETROGRAPHY OF CARBONATES
4. DEPOSITIONAL AND DIAGENETIC FABRICS
4.7. RECRYSTALLIZED and METAMORPHIC (marbles)

Recrystallized Carbonate Rocks: partially or total destruction of depositional criteria

• depends on clay content (>2% may inhibit recrystallization) and can create '**microspar**' 10'-100'µm in diameter

• => recrystallized carbonate rocks with crystal sizes up to 10' mm (depending on T, p, fluids …..)

….

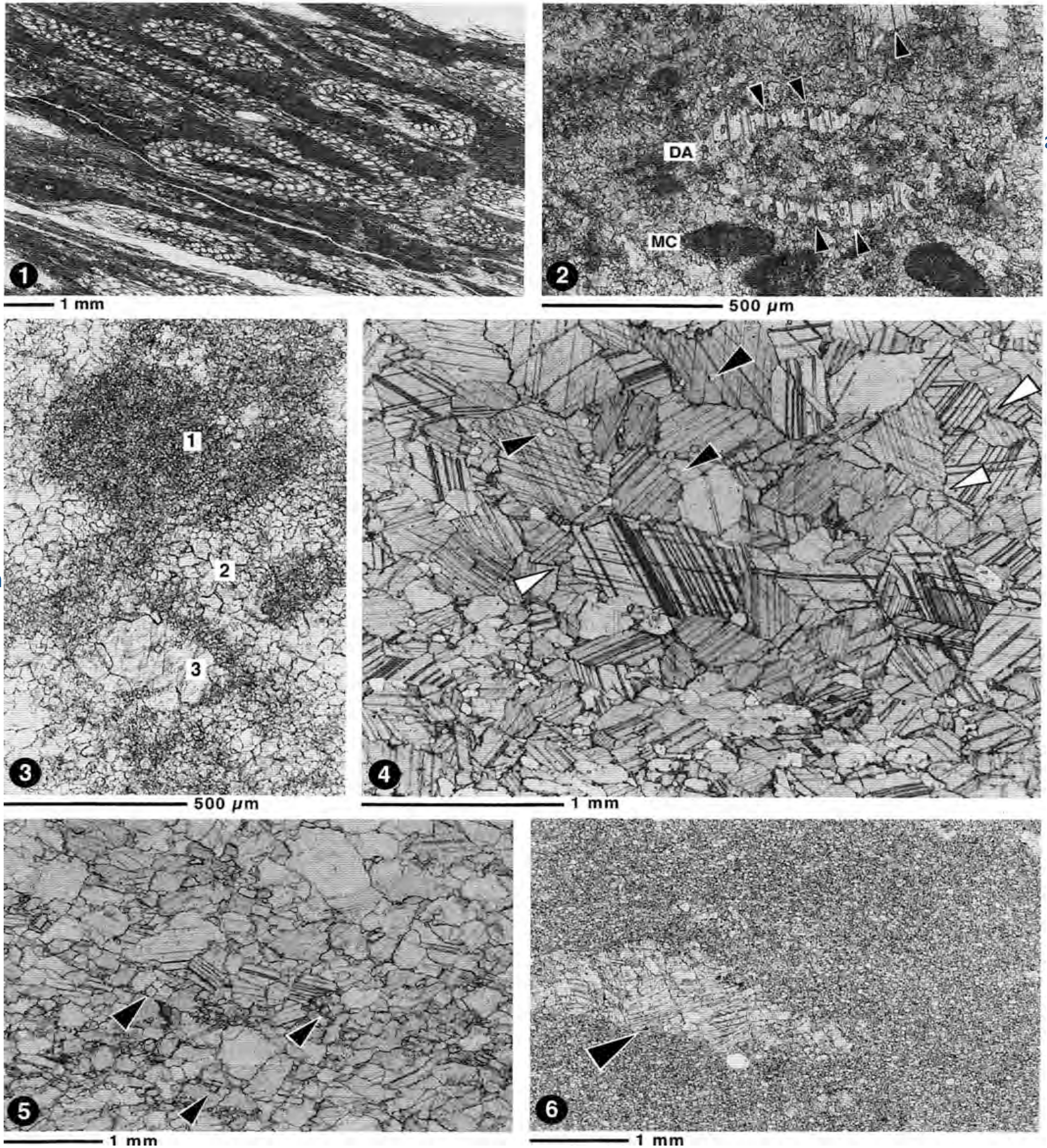
Marble fine-to coarse-grained, dynamically recrystallized calcite and/or dolomite with a **granoblastic**, crsytalline texture

….

Flügel 2004

Recrystallized lmst
with tectonically
elongated fusulinids
=
'shear process'
Permian, Hungary

Neomorphized lmst
MC primary calcitic
micite clasts
arrows = twin lamellae
developed within an
algal fragment
Carboniferous, China



Neomorphized
-Recrystallized
lmst
with tectonically
1=relicts of former
micritic grains
2= aggrading neomorhism
in intraparticles pores
3= foram? shell with
replaced central part
Carboniferous, China

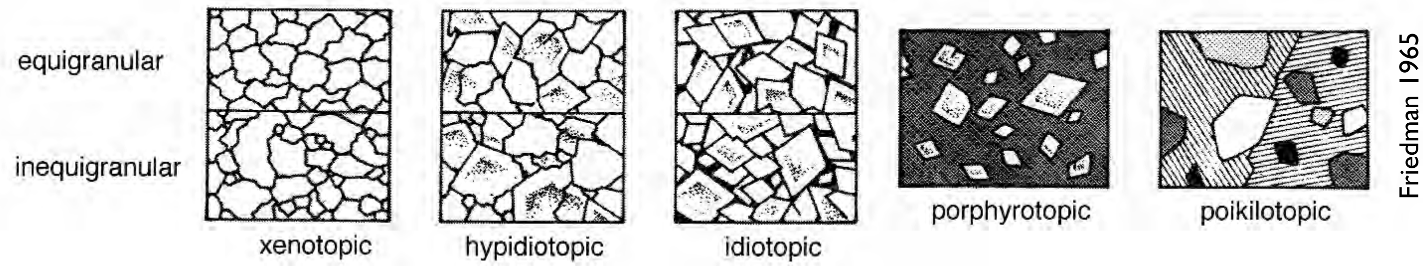
Inequigranular coarse
crystalline
calcite marble.
Xenotopic and
Poikilotopic fabric
…
Paleozoic, Austria
Roman quarry

Inequigranular xenotopic
m/c crystalline
marble
=
intensive strain
recrystallization
Carboniferous, Chine

Equigranular finely
crystalline
calcite marble.
resulting from
cataclastic granulation
…
Jurassic, Tunisia
Roman quarry

4. DEPOSITIONAL AND DIAGENETIC FABRICS

4.7. RECRYSTALLIZED and METAMORPHIC (marbles)



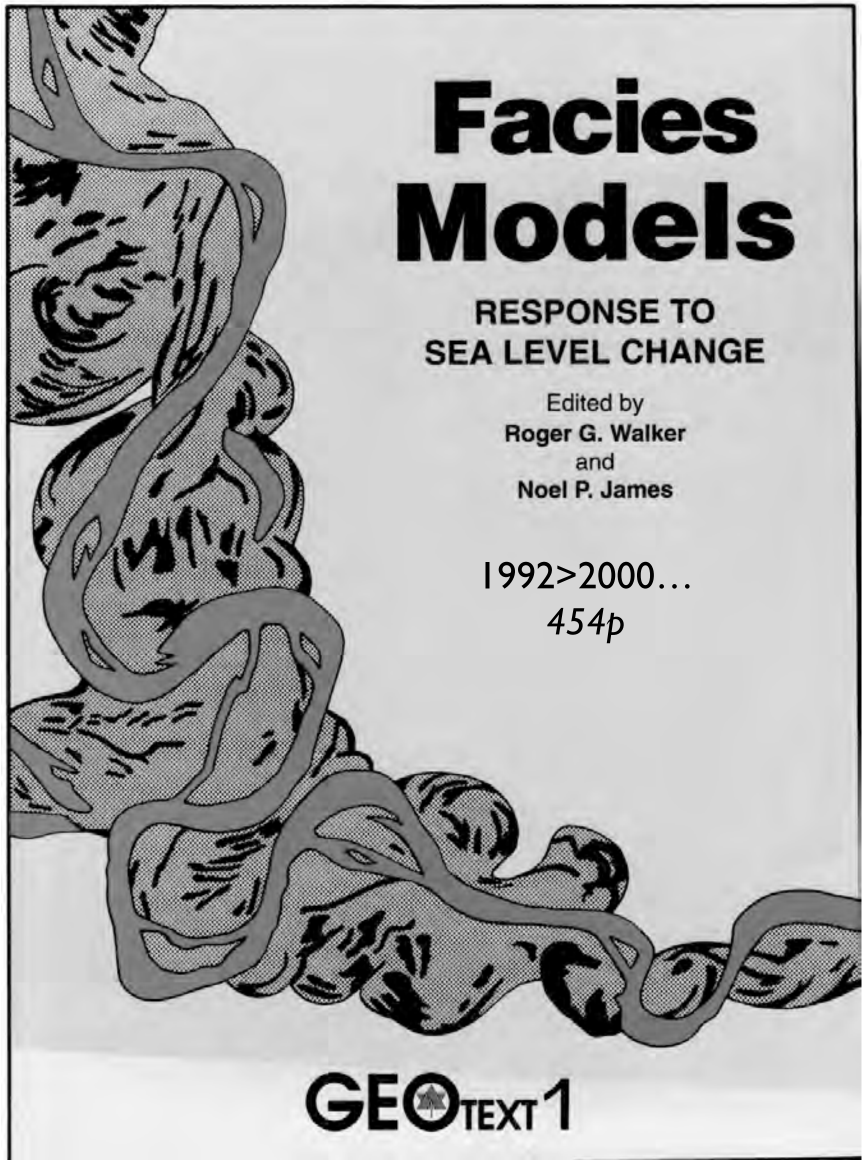
Descriptive terms for crystallization textures and fabrics after Friedman (1964). Compare Fig. 7.20. The scheme can also be used to describe calcite and dolomite marbles.

Crystallization textures: Refer to the shape of mineral crystals and the type of crystal faces at crystal boundaries. Descriptive terms are
Anhedral: Characterized by the absence of crystal facing bounding the mineral grains. Pl. 38/3.
Subhedral: Characterized by partly developed crystal faces.
Euhedral: Characterized by crystals that are bounded by crystal faces.

Crystallization fabrics: Refer to the size and mutual relations of crystals that can be differentiated into
Equigranular fabrics: Consist of crystals of approximately the same size (e.g. Pl. 38/6). Fabrics subdivided into
Xenotopic: Predominantly anhedral crystals.
Hypidiotopic: Predominantly subhedral crystals.
Idiotopic: Predominantly euhedral crystals.

Inequigranular fabrics: Consist of crystals of various sizes (e.g. Pl. 38/4, 5, 7). Fabrics are subdivided into
xenotopic
hypidiotpic
idiotopic.
Each of these inequigranular fabrics is in turn subdivided into
Porphyrotopic: Larger crystals are enclosed in a fine-grained matrix.
Poikilotopic: Crystals are of more than one size; larger crystals enclose smaller crystals of another mineral.

Flügel 2004



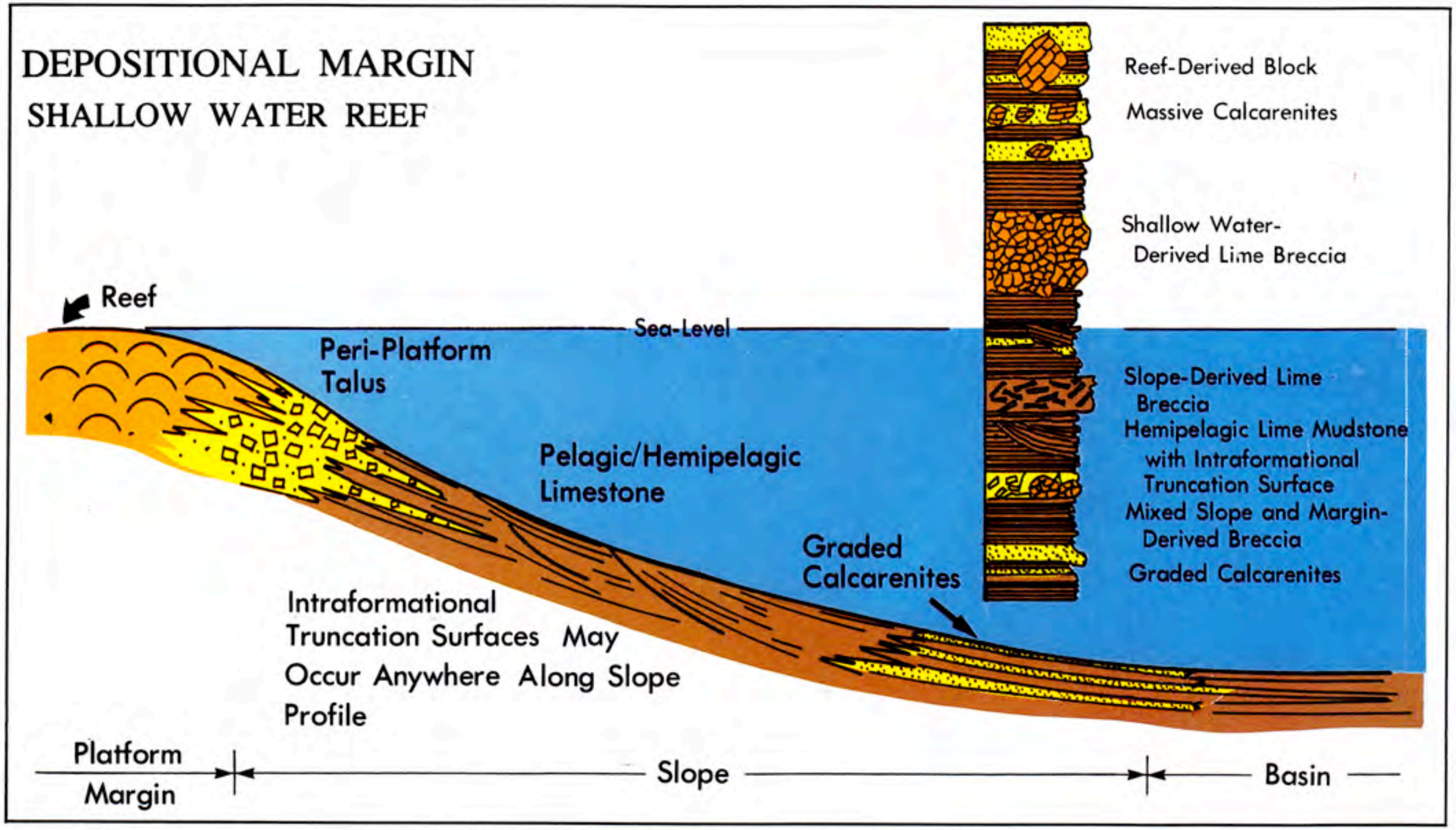
1992>2000…
454p

….. introduction….

5 Glacial Depositional Systems
6 Volcaniclastics
7 Alluvial Deposits
8 Eolian Systems
9 Deltas
10 Barriers and Estuaries
11 Tidal Systems
12 Wave- an Storm-Dominated Shallow Marine Systems
13 Turbidites and Submarine Fans
14 Carbonate and Evaporite Models
15 Platform Systems
16 Peritidal Carbonates
17 Reefs and Mounds
18 Carbonate Slopes
19 Evaporites

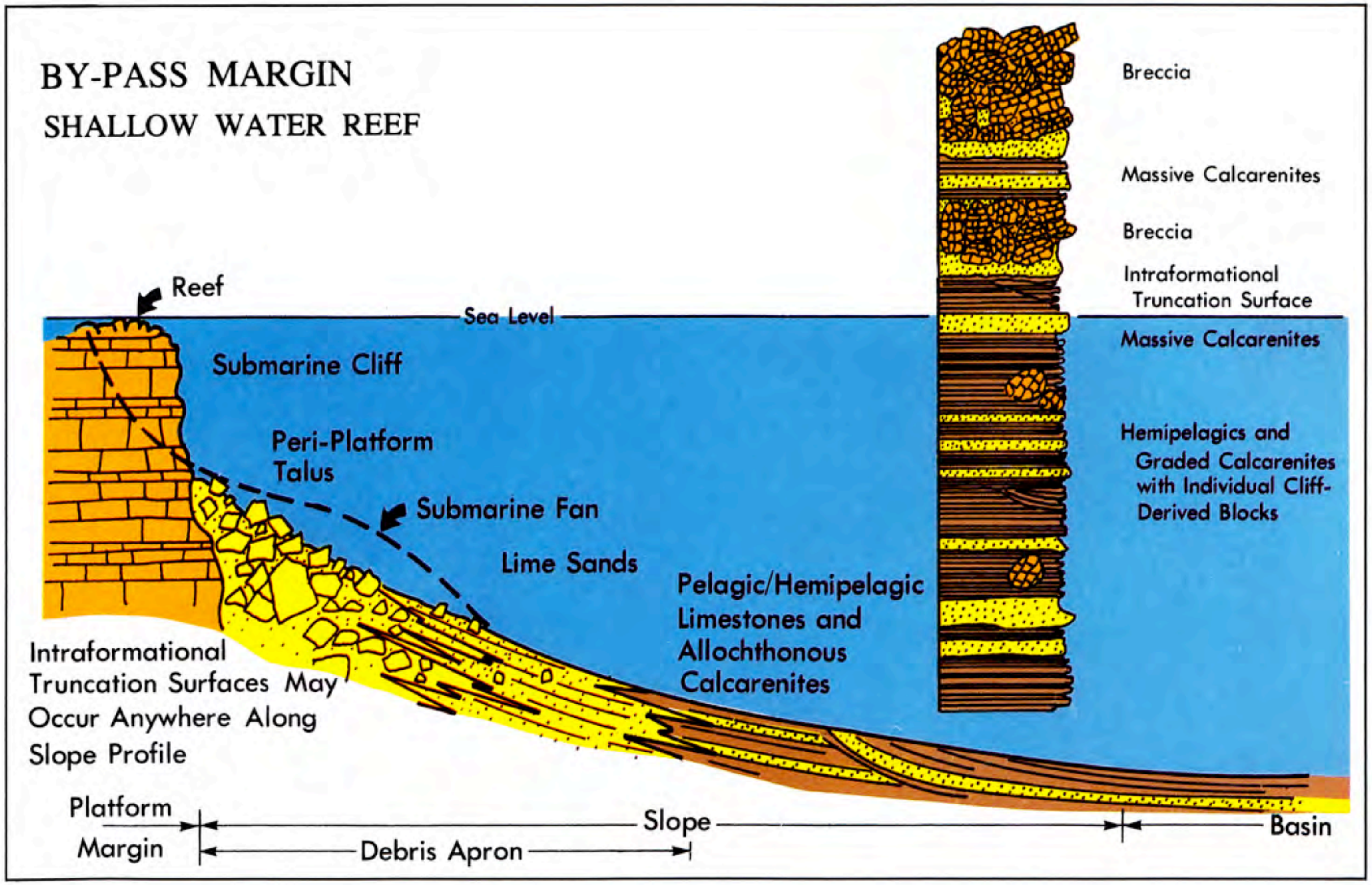
SOME EXAMPLES AMONG MANY…

FORE-REEF SLOPE MARGIN



Schematic model for a shallow-water reef, reef dominated carbonate margin with resulting hypothetical sequence of deposits from slope accretion, McIlreath & James 1978.

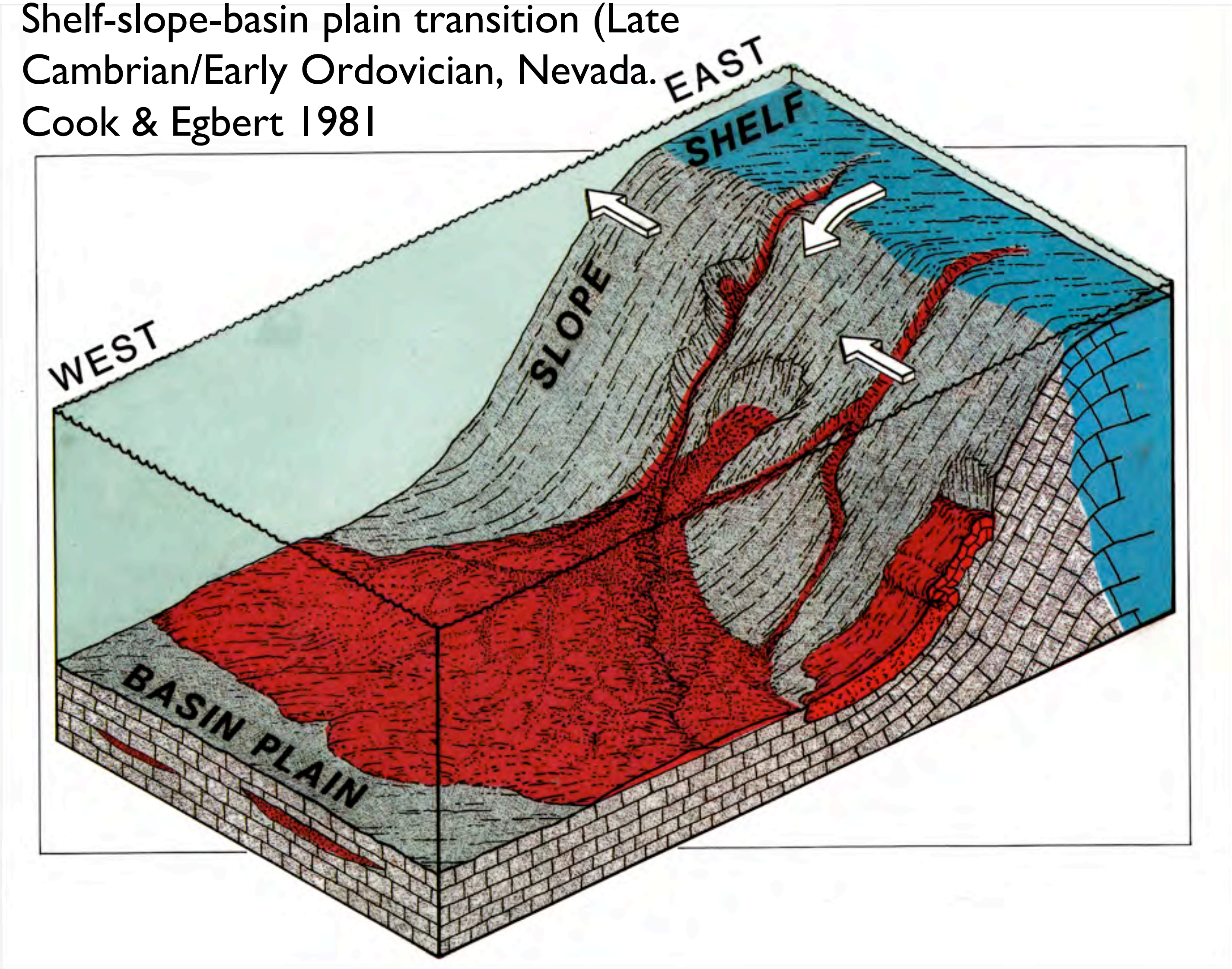
FORE-REEF SLOPE MARGIN



Schematic model for a shallow-water reef, reef dominated by-pass type of carbonate margin, McIlreath & James 1978.

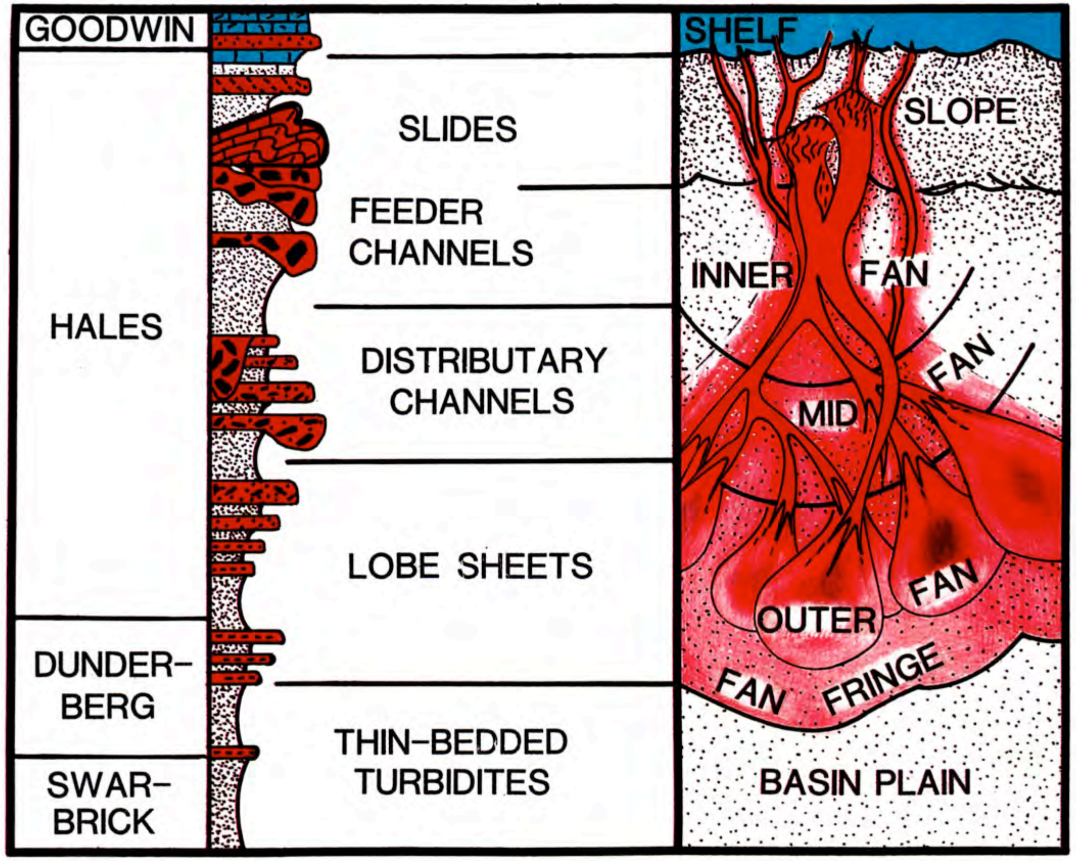
BASIN MARGIN

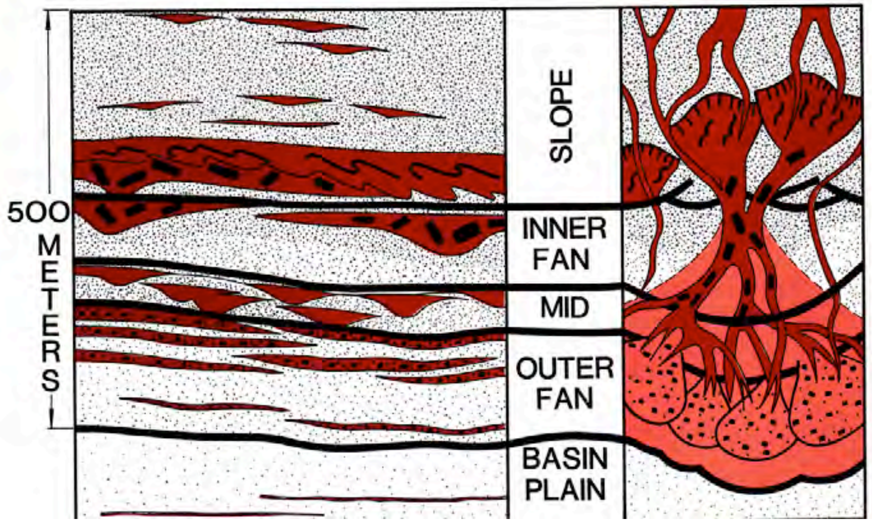
Shelf-slope-basin plain transition (Late Cambrian/Early Ordovician, Nevada. Cook & Egbert 1981



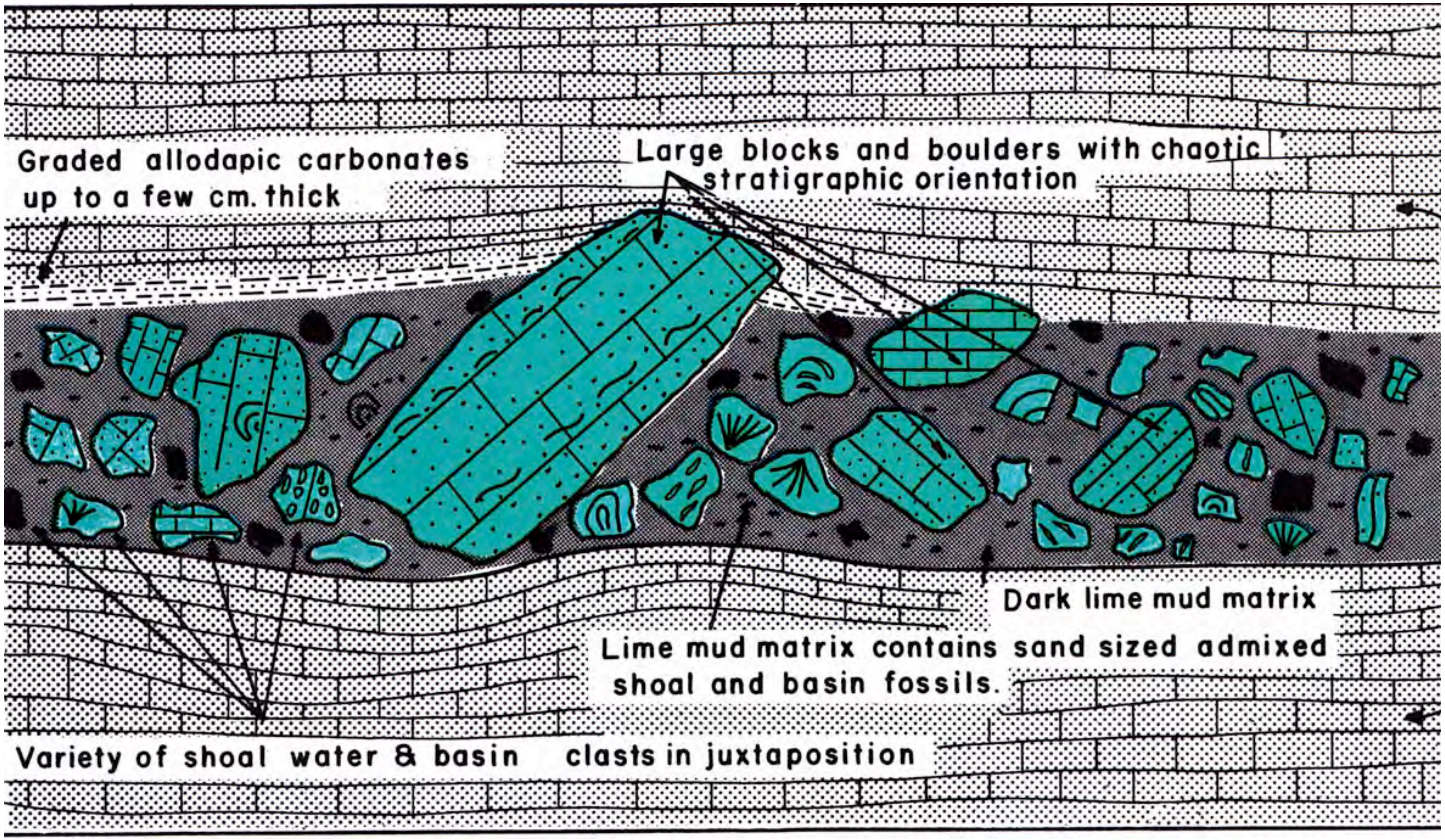
BASIN MARGIN

Submarine fan model, with sediment derived from the shelf. Cook & Egbert 1981



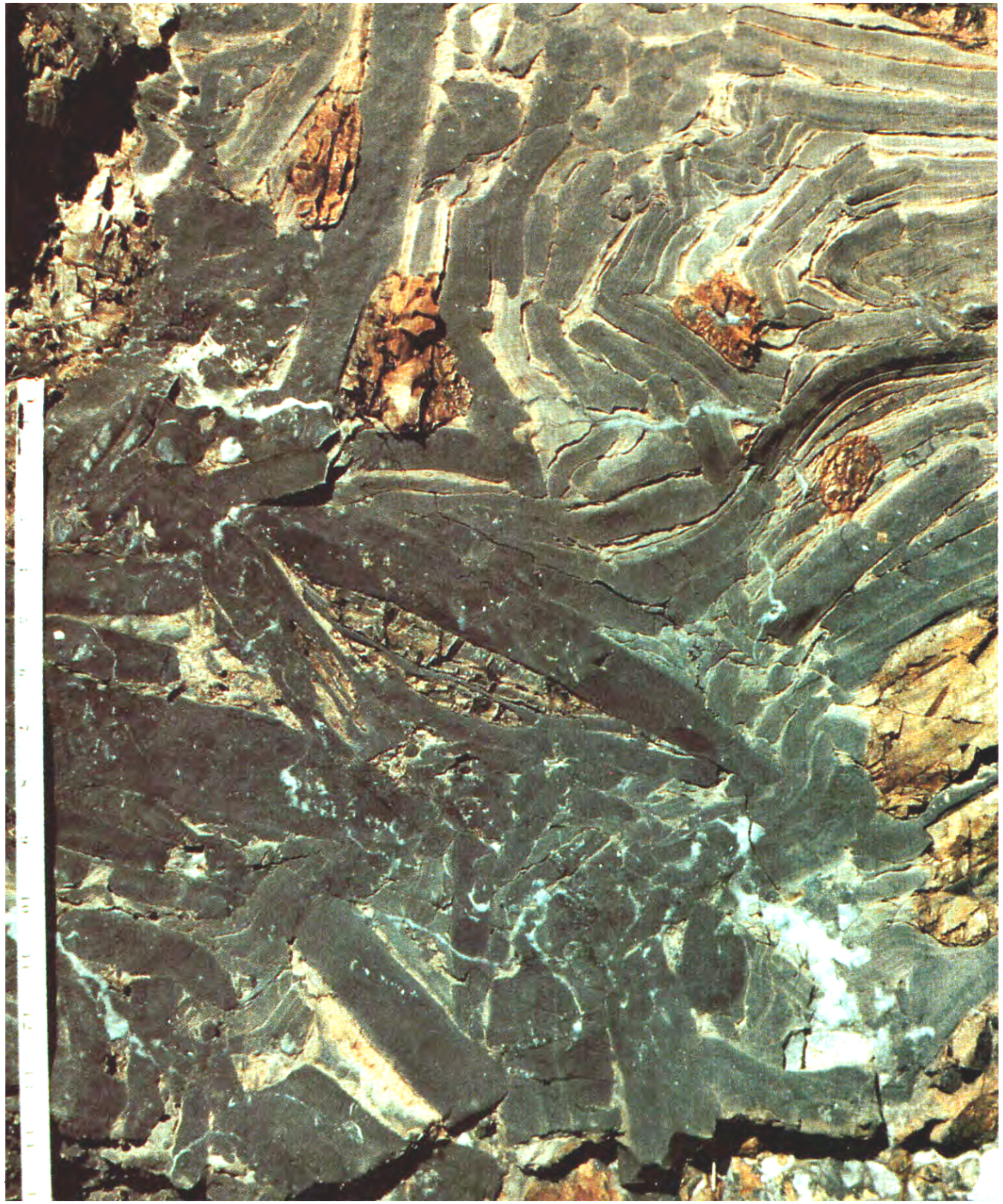


BASIN MARGIN



Upper Devonian carbonate debris flow deposits, Rocky Mountains, Alberta, Canada
Cook et al 1972.
DEBRIS BEDS ENCLOSED WITHIN A NORMAL DARK LIME BASIN FACIES

BASIN MARGIN

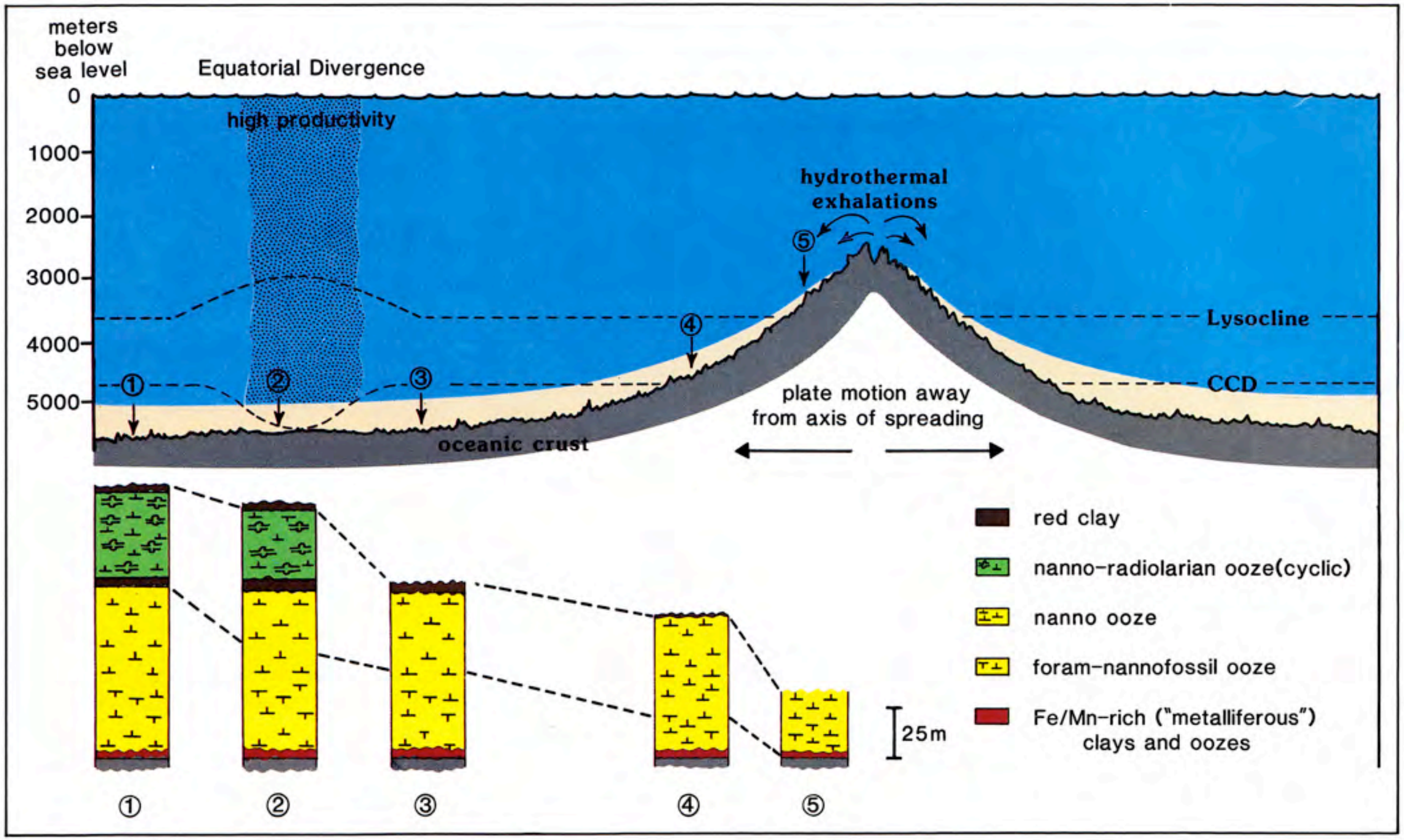


Base of 3.5-m-thick transitional slide in lower slope facies showing basal shear folds, developed in semi-consolidated sediment, breaking up into tabular clasts.
Lower Ordovician, Nevada
Cook 1979.

BASIN MARGIN

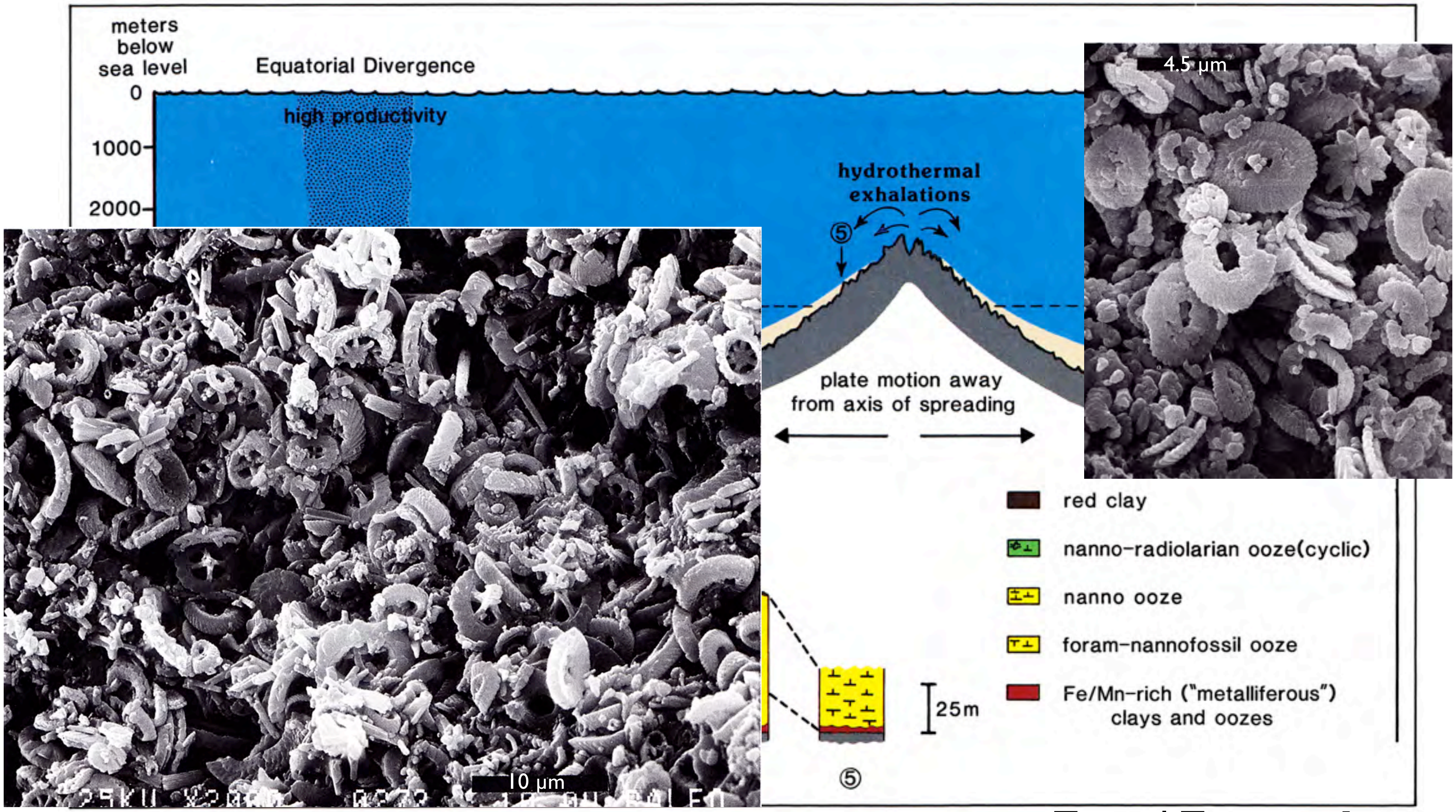
Different types of carbonate slope deposits in an (overturned) sequence.
Middle Ordovician, W Newfoundland, James 1978.

PELAGIC



Diagrammatic representation of subsidence of oceanic crust and succession of sediment facies related to changes in water depth and productivity of surface water.
Scholle et al 1983.

PELAGIC



SEM : continental **shelf** chalk
with well preserved coccoliths and rhabdoliths
(porosity 35 to 40%), Scholle et al 1983.

Typical Tertiary **deep-sea**
chalk with minor corrosion
of coccolith margins,
Scholle et al 1983.

CARBONATE DEPOSITIONAL ENVIRONMENTS

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Peter A. Scholle, Don G. Bebout, Clyde H. Moore

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Table of Contents

Table of Contents

Table of Contents