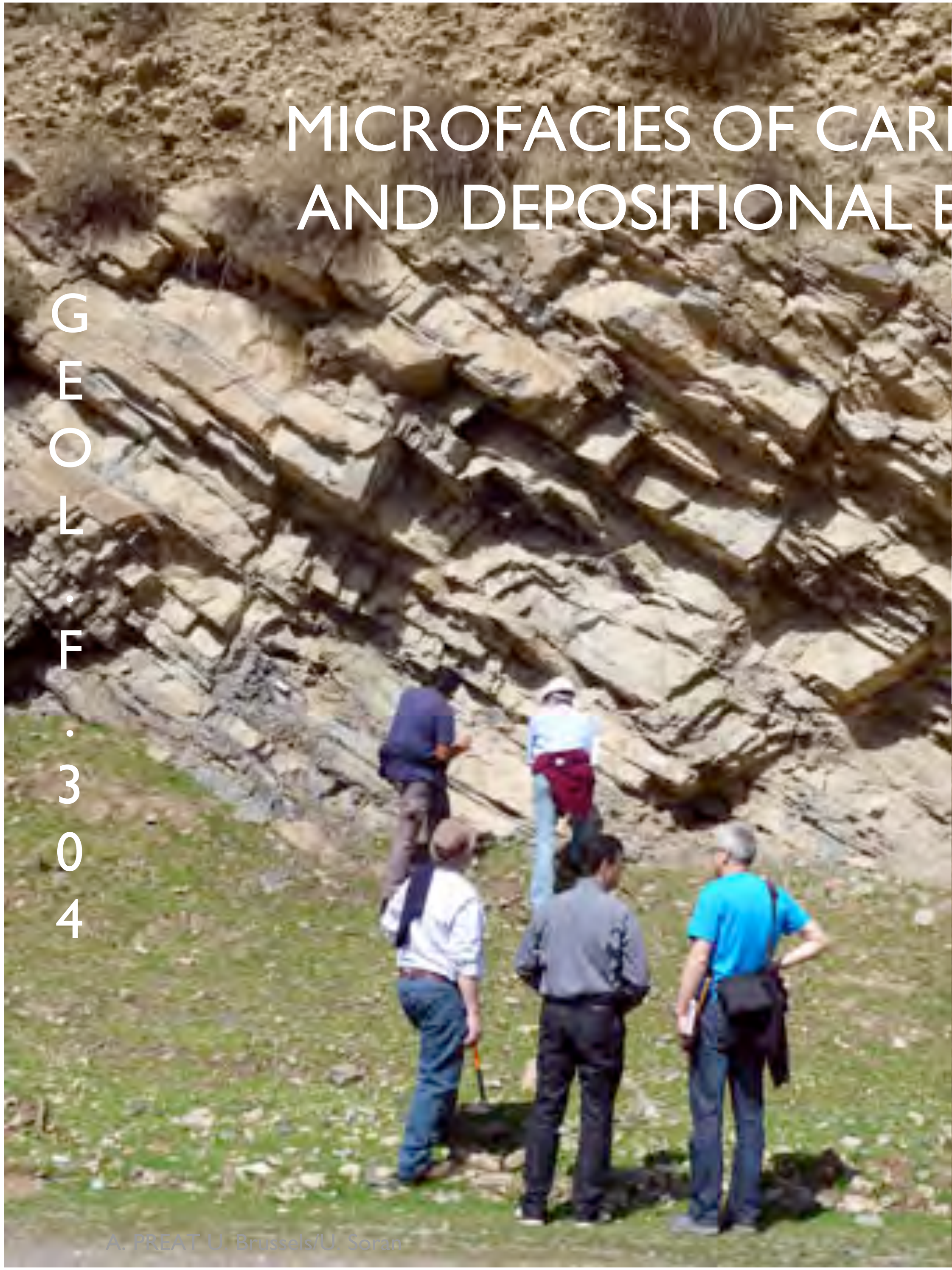
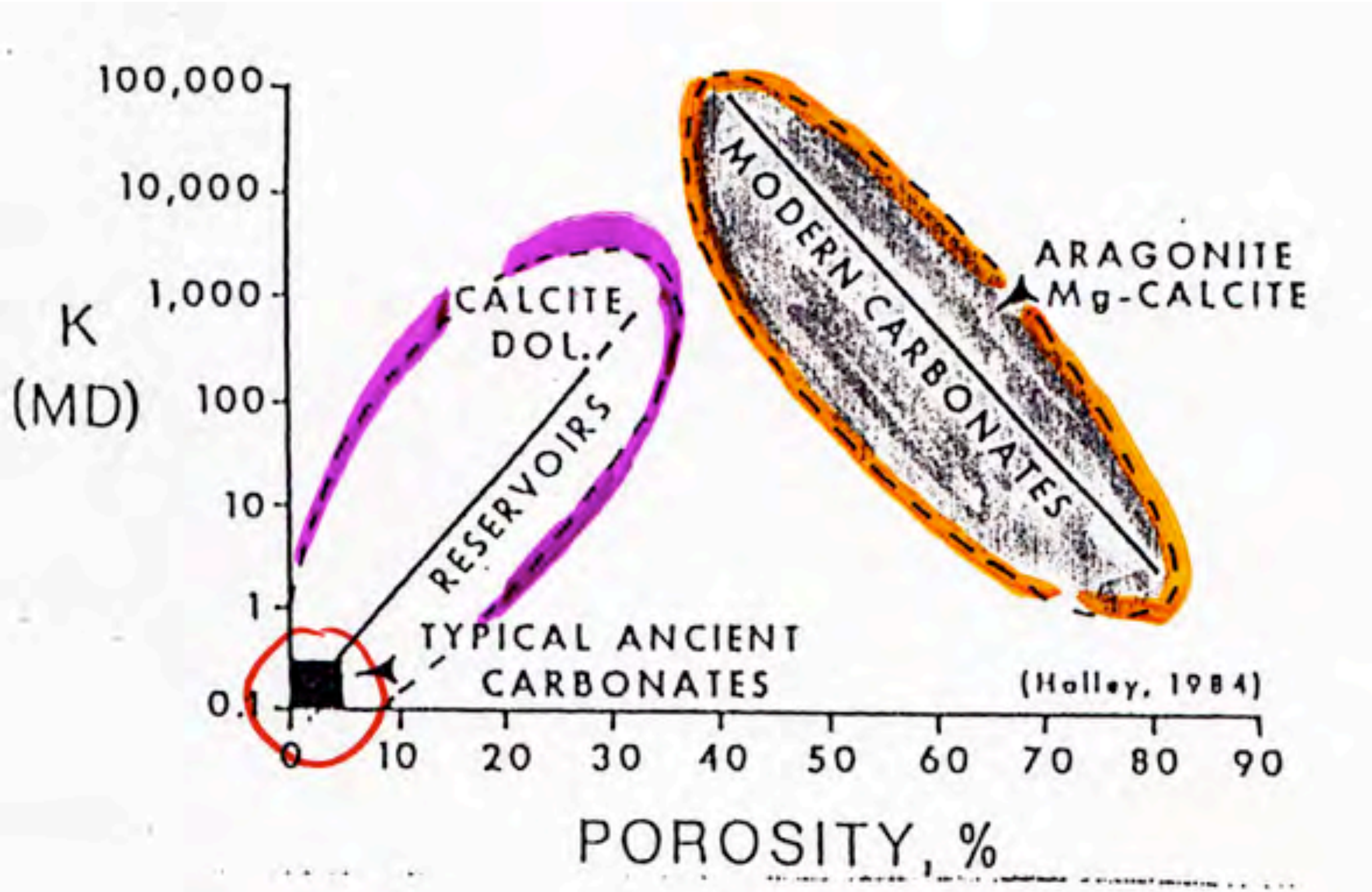
MICROFACIES OF CARBONATE ROCKS AND DEPOSITIONAL ENVIRONMENTS

GEOL.F.304



Prof. Alain Préat
Free University of Brussels

WHAT IS A 'NORMAL' LIMESTONE?

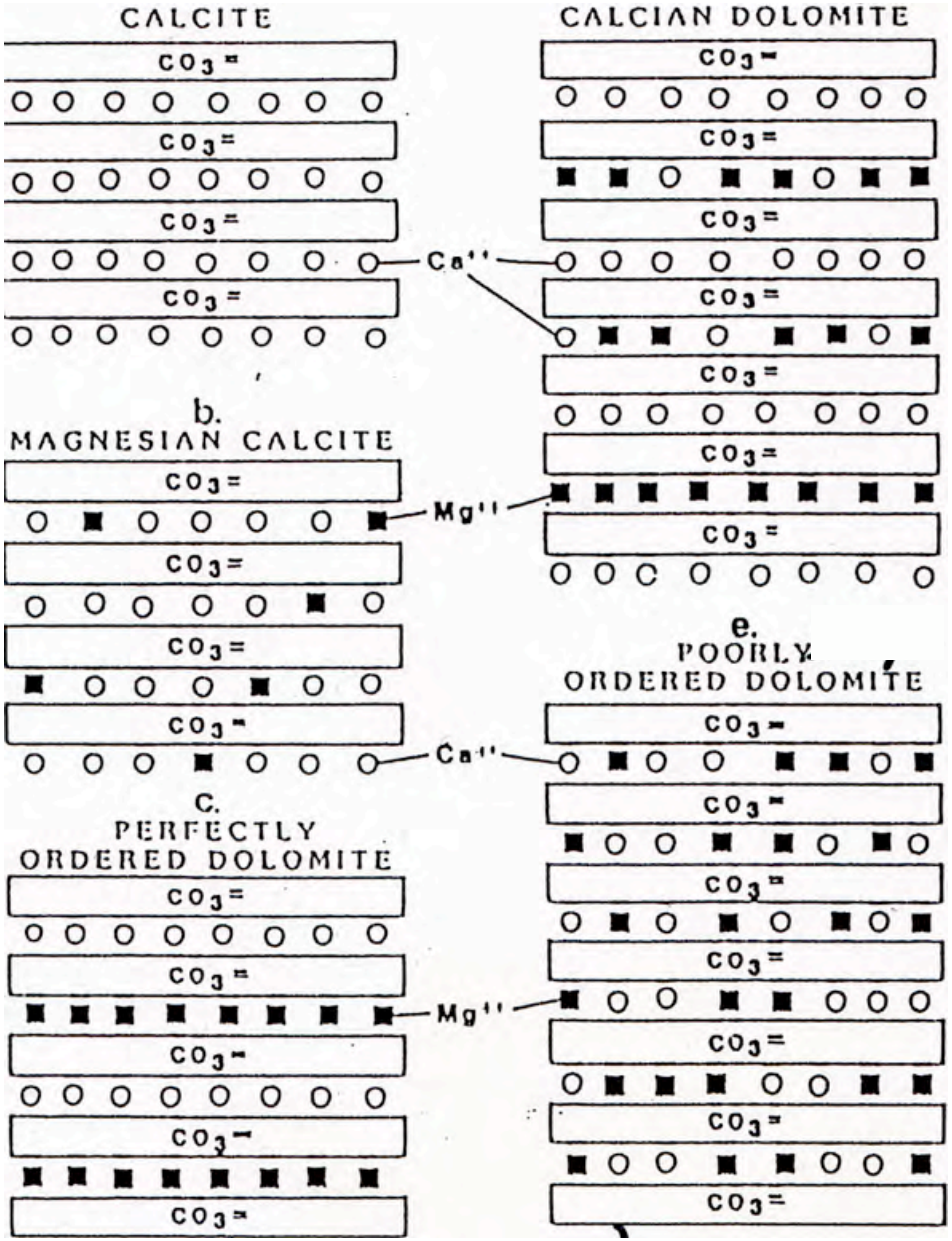


COMMON CARBONATE MINERALS

LMC

HMC
if >4
mole%
$MgCO_3$

Ca:Mg 1:1
HT>300°C



protodolomite

$Ca_{55}Mg_{45}(CO_3)_2$

primary
or
penecontemporaneous
1-2 µm

DIAGENESIS (…)

ARAGONITE + HMC ➔ LMC +(DOLOMITE)

dissolution, neomorphism, cementation (…)

COMMON CARBONATE MINERALS

	System	Mol % $MgCO_3$	Stability
Calcite $CaCO_3$ Low-Mg calcite (LMC)	trigonal	<4	stable
Mg-calcite $CaCO_3$ High-Mg calcite (HMC)	trigonal	>4 to ~30 Mg content correlated with water temperature	metastable
Aragonite $CaCO_3$	orthorhombic	very low	metastable, alters readily in calcite under aqueous conditions
Dolomite	trigonal $CaMg(CO_3)_2$	40 - 50	stable

Isotope signal Preservation potential	Mineralogy of components	Components Skeletal	Non-skeletal	Bulk sediments
HIGH	**Pristine aragonite**	Mollusks	Marine cements	
Good chance of preservation of carbon and oxygen isotope signals	**Pristine Low-Mg calcite fossils, grains or cements**	**Brachiopods, belemnites,** foraminifera, bivalves	Marine cements, Low-Mg calcite ooids	Pelagic sediments, particularly coccolith oozes
Phosphatic fossils	**Conodonts, fish teeth**			
MODERATE Carbon isotope signals may be preserved, oxygen isotope signals are commonly altered	**Secondary calcites** (stabilized in relatively closed systems with low water/rock ratio)	Molluscs, foraminifera, corals, echinoderms, calcareous algae	Marine cements, ooids, peloids, intraclasts	Some micrites, some shallow-water carbonates, some dolomites
LOW Carbon and oxygen isotope signals very likely to have been altered	**Secondary calcites** (stabilized or cemented in relatively open systems with high water/rock ratio)	Limestones altered by near surface meteoric diagenesis of intensive cementation or recrystallization during burial; many dolomites		

Preservation potential of C and O isotopes in ancient carbonates (Marshall 1992 *in* Flügel 2004)

CARBONATES : BORN IN THE SEA

✓ Well over 90% or more of the carbonates in MODERN marine environments are BIOLOGICAL in origin, i.e. the sediments are biotically induced or controlled,

✓ Carbonate sediments originate on land and in the sea. TODAY only around 10% of marine carbonate production takes place in SHALLOW SEAS. 90% is related to the deposition of calcitic plankton in the DEEP SEAS. These proportions were very different during most parts of the PHANEROZOIC => about 70% of microfacies studies concern shallow-marine carbonates formed on the shelf and near the shelf break

✓ SEAWATER

• contains 95 chemical elements, (very) far from the saturation state

Ca => carbonates, sometimes phosphates

Ba => sulfates

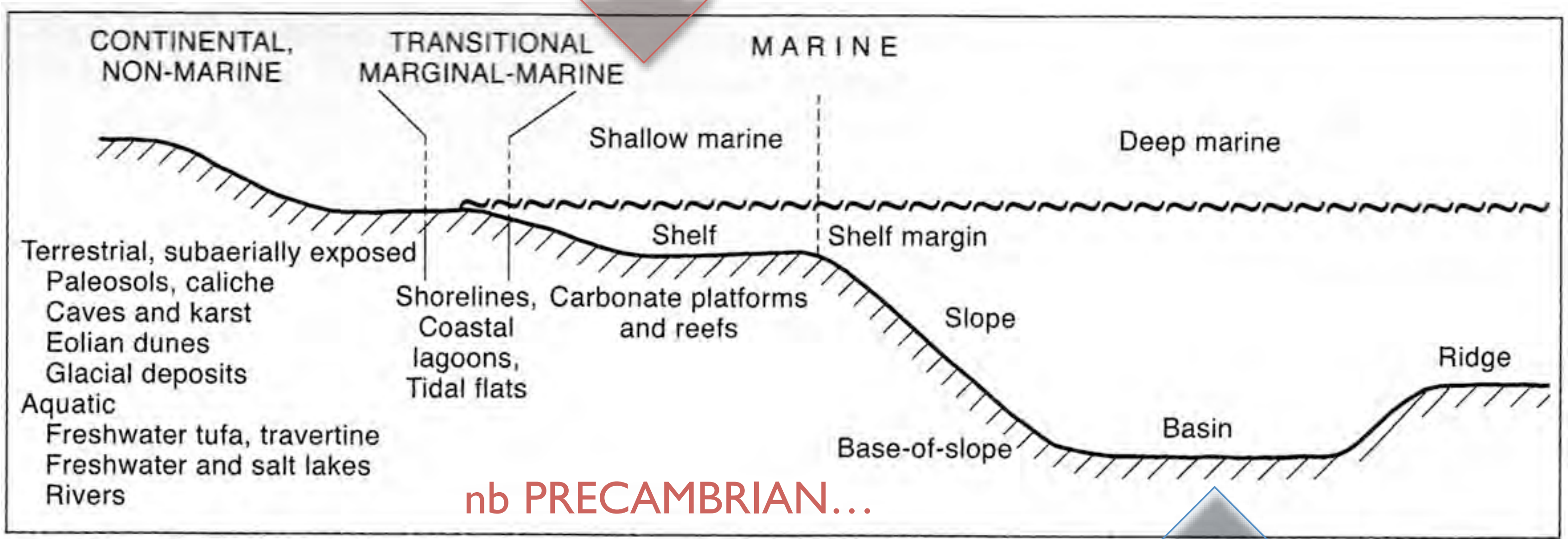
Fe and Mn => (hydr)-oxydes

Si (extracted by organisms despite undersaturation) => silica

nb: Major constituents of SW: if > 1 ppm by weight => they account for over 99% of the **salinity (=35‰)** by weight throughout most of the oceans (Cl^-, Na^+, Mg^{2+}, SO_4^{2-}, K^+ = 99.8% of the mass of the solutes in SW (Na and Cl = 86%).

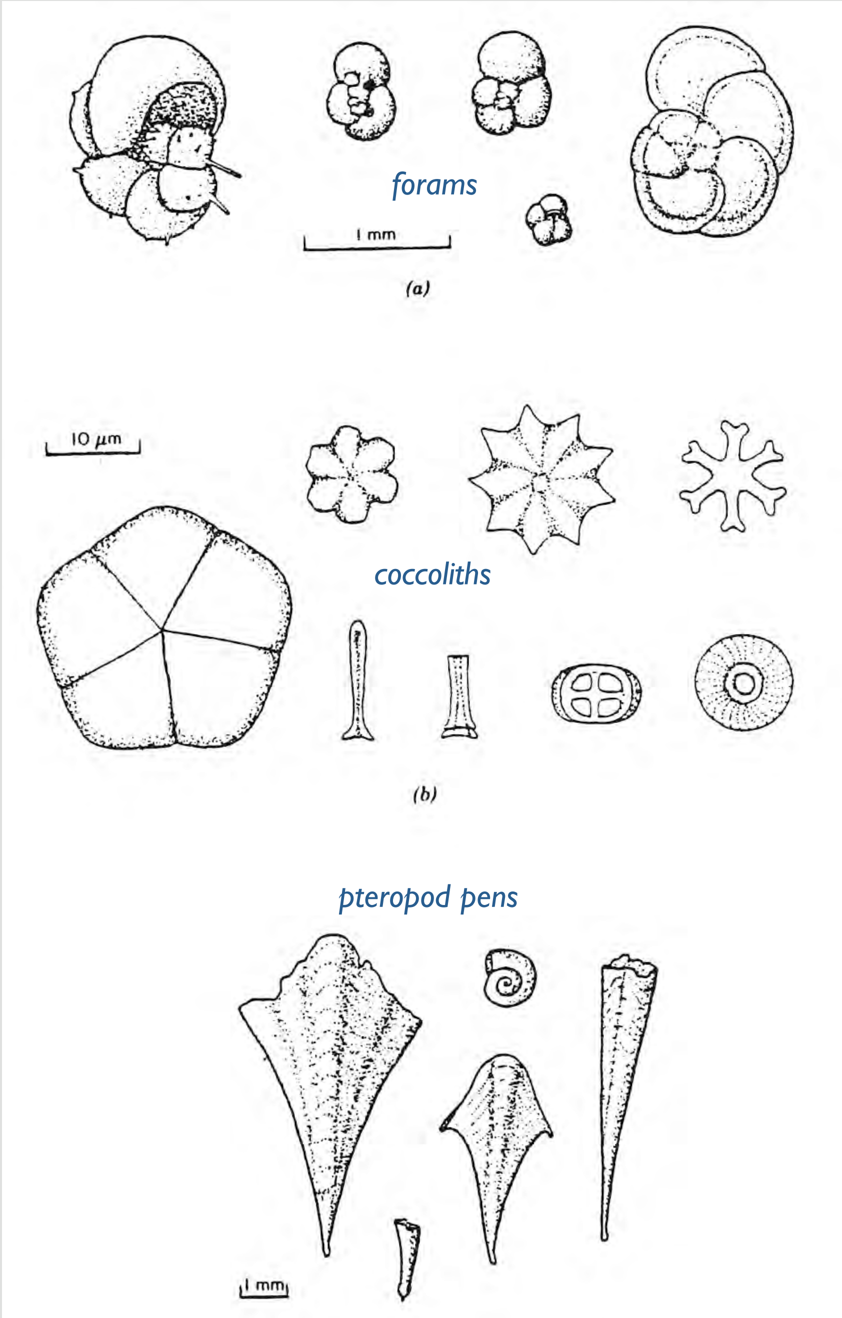
CARBONATES : BORN IN THE SEA

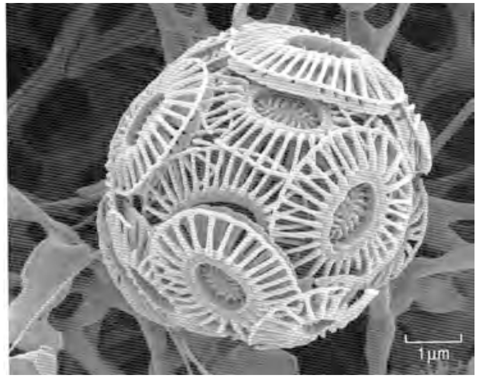
most of phanerozoic
carbonates
are shallow marine



nb PRECAMBRIAN…

most of the present day
carbonates
are pelagic



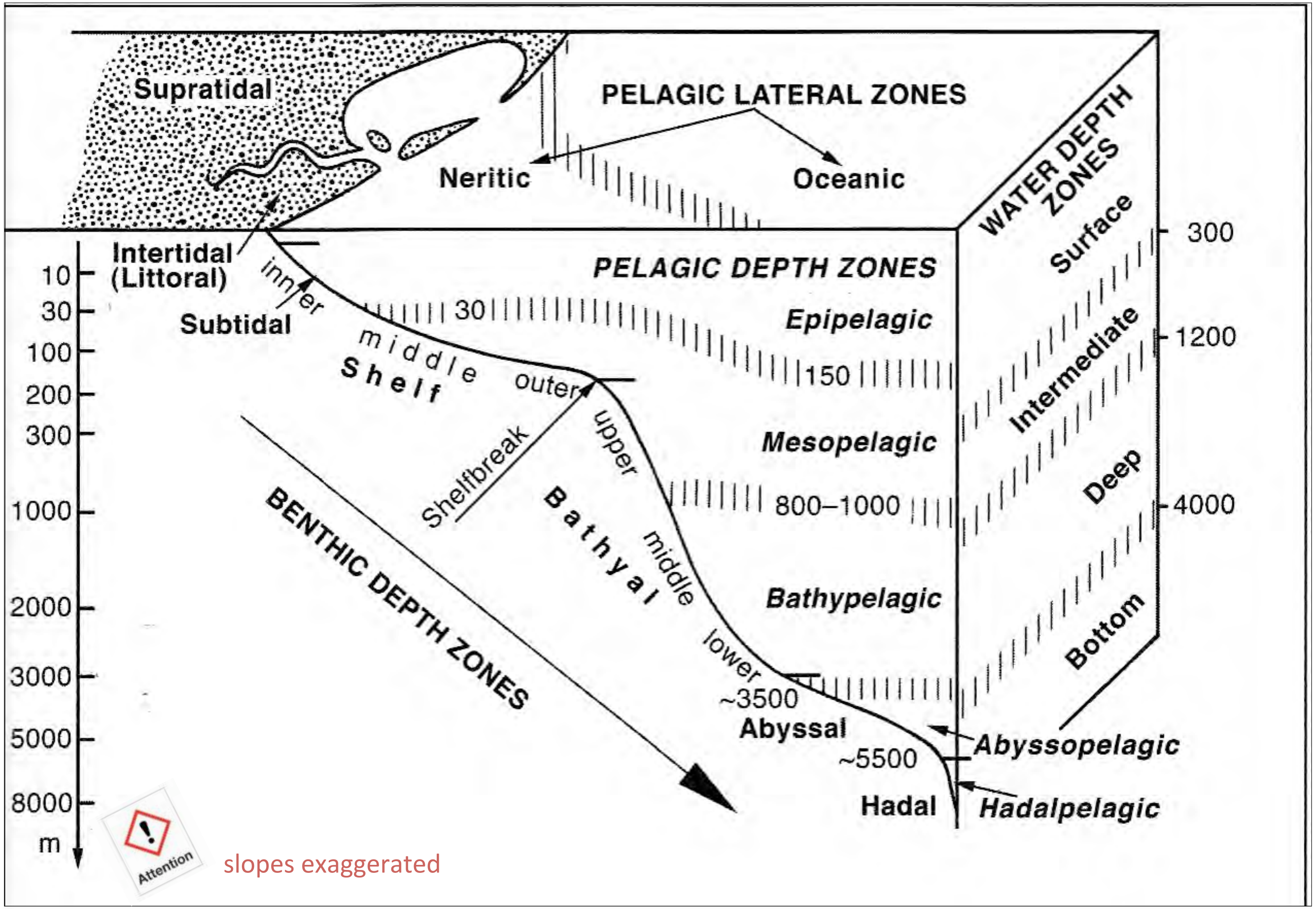


Coccosphere of the coccolithophore
Emiliana huxleyi (R James, Open U., 2005)

Calcareous remains found in the deep-sea sediments (today), Reidel 1963

most of the present day carbonates are pelagic

CARBONATES : BORN IN THE SEA
marine depositional environments

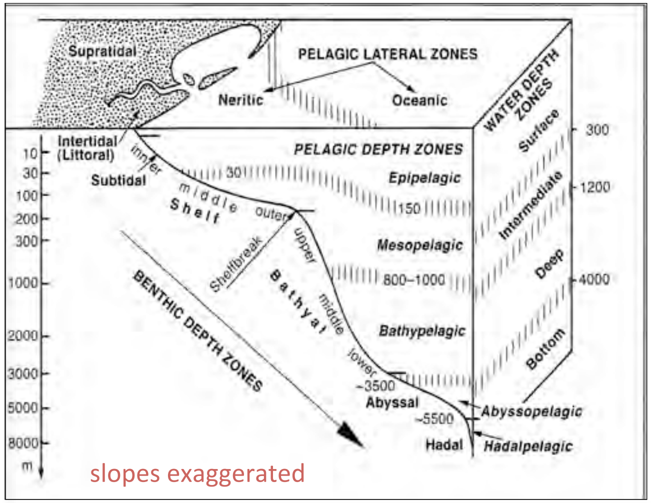


Kenneth 1982

There is no universally accepted scheme of subdivision of marine environments among biologists, oceanographers and geologists.

CARBONATES : BORN IN THE SEA
marine depositional environments

Essential critical INTERFACES that control sedimentary patterns and the distribution of the organisms are



Kenneth 1982

1 lower & upper boundaries of the TIDES (control distribution of organisms);
2 base of the photic zone (control light-depend phototrophic organisms);
3 base of the zone of wave abrasion (above which bottom currents and wave action lead to erosion and cementation);
4 base of the action of storms on the sea bottom;
5 O_2 minimum zone (strongly limiting life on the sea bottom);
6 thermocline (the layer of water that is too cold for most carbonate-producing organisms);
7 pycnocline (the layer of water where salinity is too high for most of organisms.

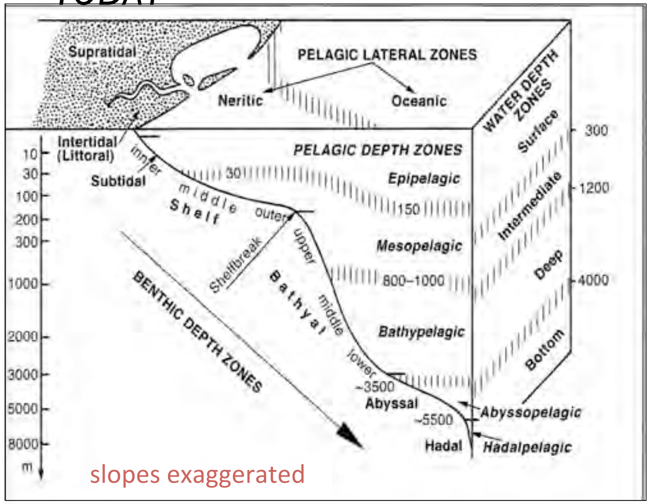
HIGH & LOW TIDES, WAVE BASE (**FWWB**) & STORM WAVE BASE (**SWB**) ARE USED **AS BASIC BOUNDARIES** IN THE CLASSIFICATION OF THE MAJOR SHALLOW-MARINE ENVIRONMENTS.

CARBONATES : BORN IN THE SEA

marine depositional environments

There is no universally accepted scheme of subdivision of marine environments among biologists, oceanographers and geologists.

TODAY



Kenneth 1982

BENTHIC (ecological) DEPTH ZONES : SIX ZONES
1 coastal sublittoral : above high tide = 'SUPRATIDAL'
2 littoral : between high & low tides = 'INTERTIDAL'
3 sublittoral : below low tide = MAJOR PART OF THE CONTINENTAL SHELF
4 bathyal= ± CONTINENTAL SLOPE
5 abyssal = ABYSSAL PLAINS
6 hadal = DEEP-SEA TRENCHES

GEOLOGISTS = SUPRATIDAL-INTERTIDAL-SUBTIDAL

PELAGIC (ecological) DEPTH ZONES : FIVE ZONES defined by the vertical distribution of floating and swimming life.
1 epipelagic: upper region of ocean to a depth of about 200m
2 mesopelagic
3 bathypelagic
4 abyssopelagic
5 hadopelagic

CARBONATES : BORN IN THE SEA
marine depositional environments

There is no universally accepted scheme of subdivision of marine environments among biologists, oceanographers and geologists.

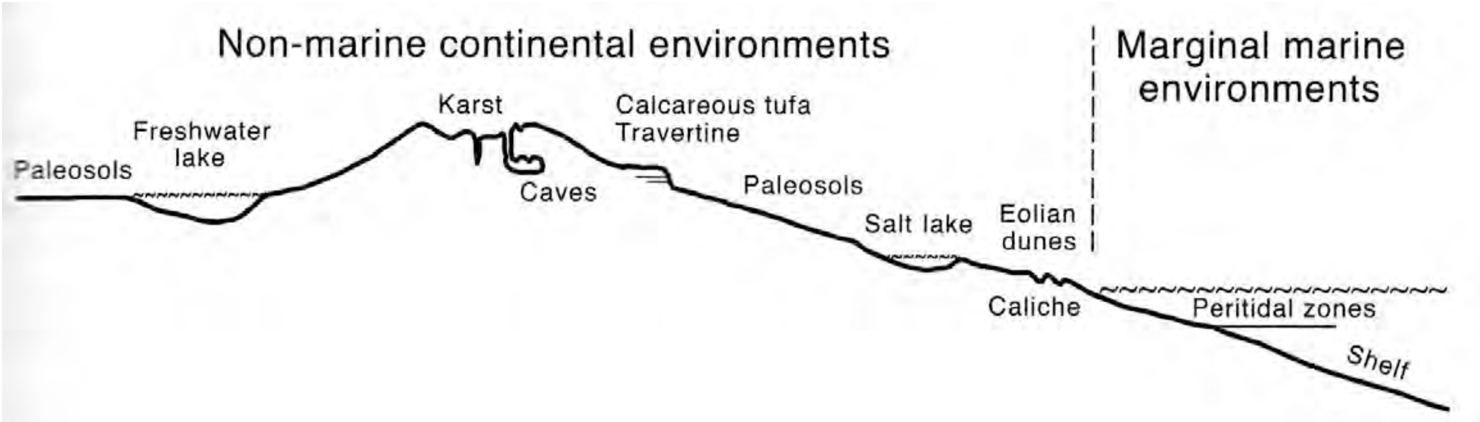
GEOLOGISTS = SUPRATIDAL-INTERTIDAL-SUBTIDAL

NERITIC ZONE : is the water that overlies the continental shelf
⇒ today generally with water depth < 200 m and covering ± 8% of the ocean floor

'OCEANIC' ZONE : refers to the water column beyond the SHELF BREAK, overlying the slope and the deep-sea bottoms, generally with water depths > 200 m and down to more than 10 000 m.

these water depths are not compatible with the situation in many ancient oceans => the term 'neritic' is often used to describe sea bottom environments below the neritic water column, or shallow-marine environments characterized by significant terrigenous influx

CARBONATES : here NOT BORN IN THE SEA
non-marine depositional environments



Non-marine carbonates originate in TERRESTRIAL and AQUATIC environments without marine influence => formed by ABIOTIC and/or BIOTIC processes
= **subaerial exposed** settings and **in submerged aquatic** settings

1. **Terrestrial subaerial exposed settings**
   - *pedogenic carbonates, paleosols, caliche/calcretes*
   - *palustrine carbonates*
   - *cave carbonates, karsts (speleothems….)*
   - *eolian carbonates => eolianites*
   - *glacial carbonates*

2. **Terrestrial aquatic settings**
   - *freshwater carbonates (travertine, calcareous tufa …)*
   - *lacustrine carbonates*
   - *fluvial carbonates*

CARBONATES : BORN IN THE SEA
MINERALOGY

- ✓ SEAWATER : Mg/Ca = 5.2
  => numerous phases coexist : ARAG, LMC, HMC, DOL
- ✓ SUBSURFACE/METEORIC WATER : Mg/Ca = 1 only LMC
- ✓ MODERN/RECENT SEDIMENTS : ARAG, LMC, HMC

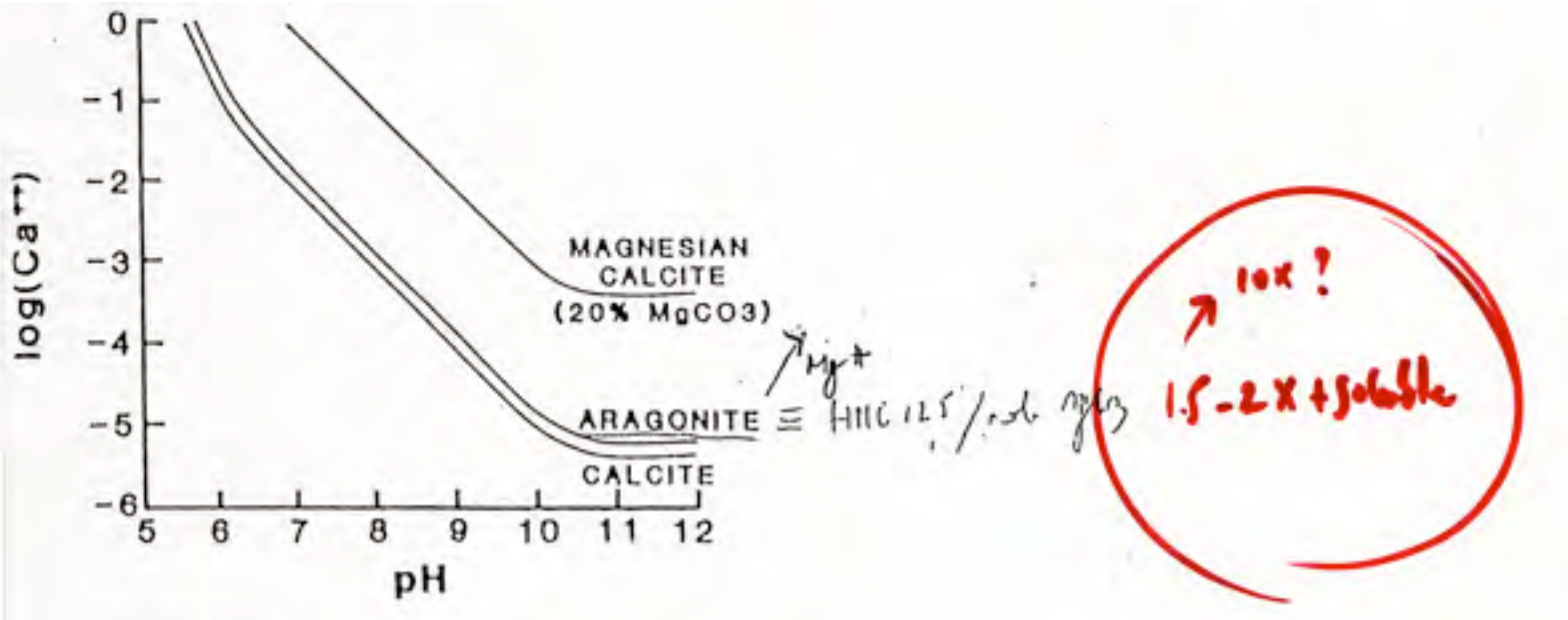
Theory/Thermodynamics : DOL first
Kinetic : ARAG and HMC due to inhibitor action of Mg
and lack of CO_3 availibility (cf. crystallography) in order to form DOL

- ✓ if Mg/Ca > 7 or = 1 => DOL [EVAPORITIC or SCHIZOHALINE]

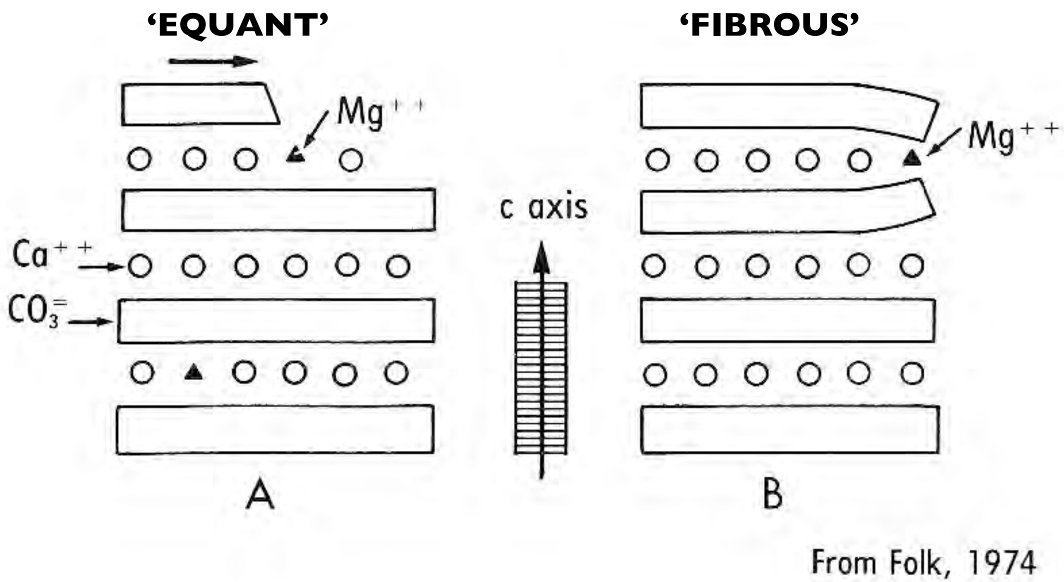
CONCLUSION: CARBONATE = KINETIC 'PROBLEM'

HT = STOECHIOMETRIC DOL Ca:Mg = 1/1 (> 300°C)
LT = 'Ca-DOL : $Ca_{55}Mg_{45}(CO_3)_2$ => XRD
[=PROTODOLOMITE, tiny crystals 1-2µm]
+ BACTERIAL-FUNGAL-induced DOL

CARBONATES : BORN IN THE SEA
MINERALOGY-DIAGENESIS



CARBONATE CRYSTALLOCHEMISTRY



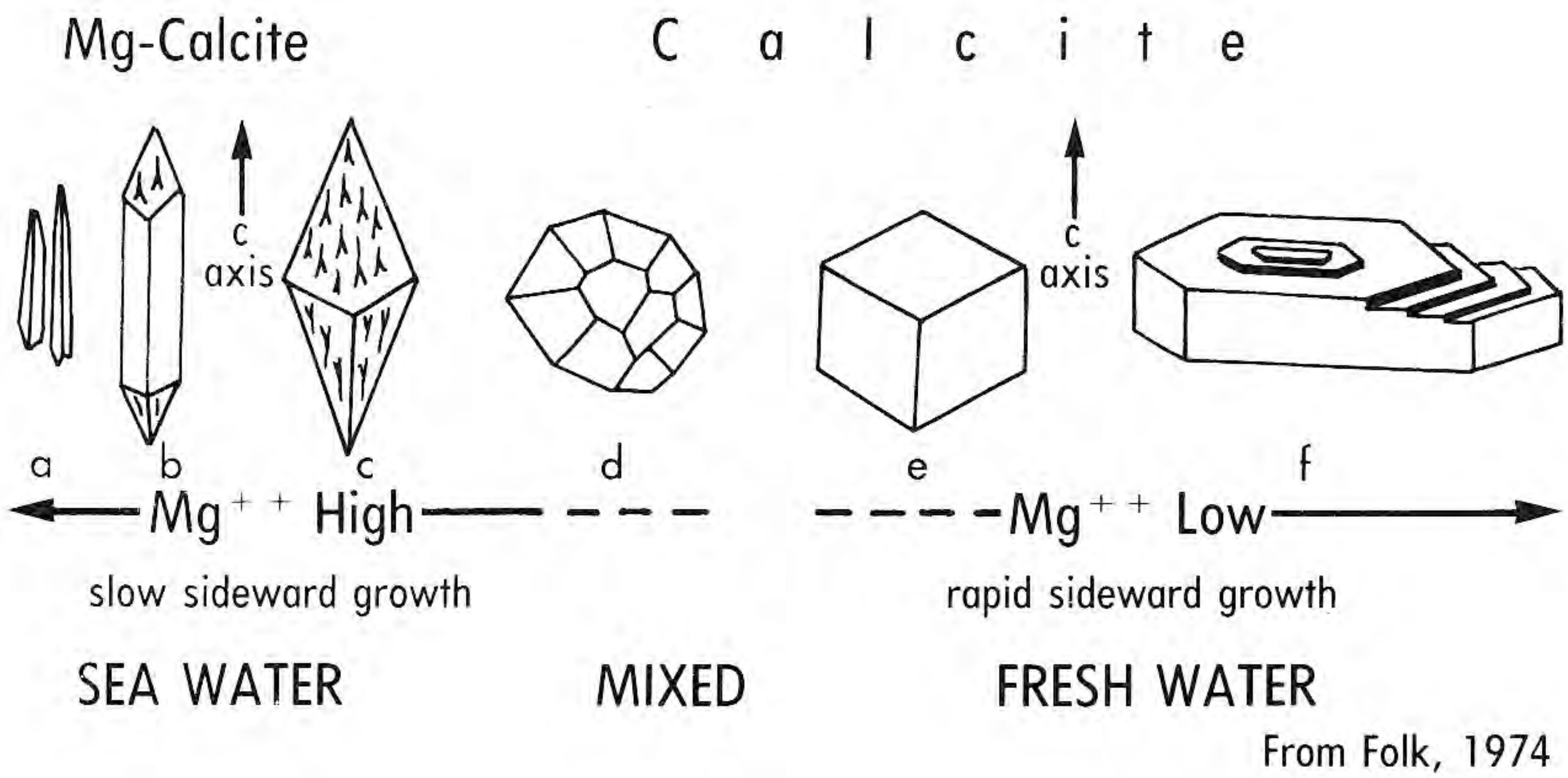
Morphology of calcite crystals as controlled by selective 'Mg-poisoining'.
A If a Mg ion is added to the end of growing crsytal it can be easily overstepped by the next succeeding CO_3 layer without harm to the crystal growth.
B If the small Mg ion is added to the side of the crsytal, the adjacent CO_3 sheets are distorted to ccomodte it in the lattice, hampering further sideward growth => growth of small, fibrous crystals.

CARBONATE CRYSTALLOCHEMISTRY

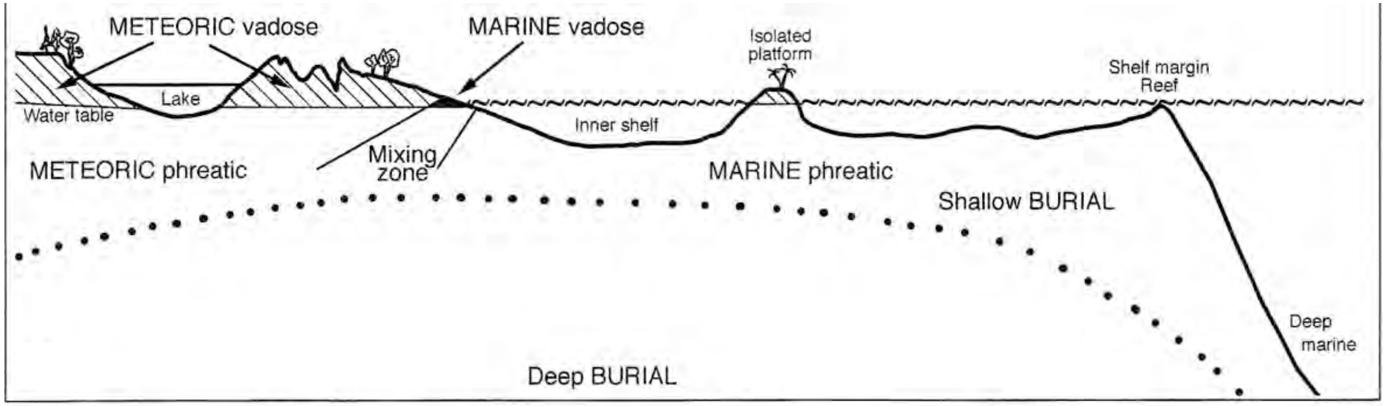
1960' Calcite crystal growth habit as a function of Mg/Ca ratio

nb : 1990' availability CO_3^{2-} ….

'FIBROUS'	'EQUANT'



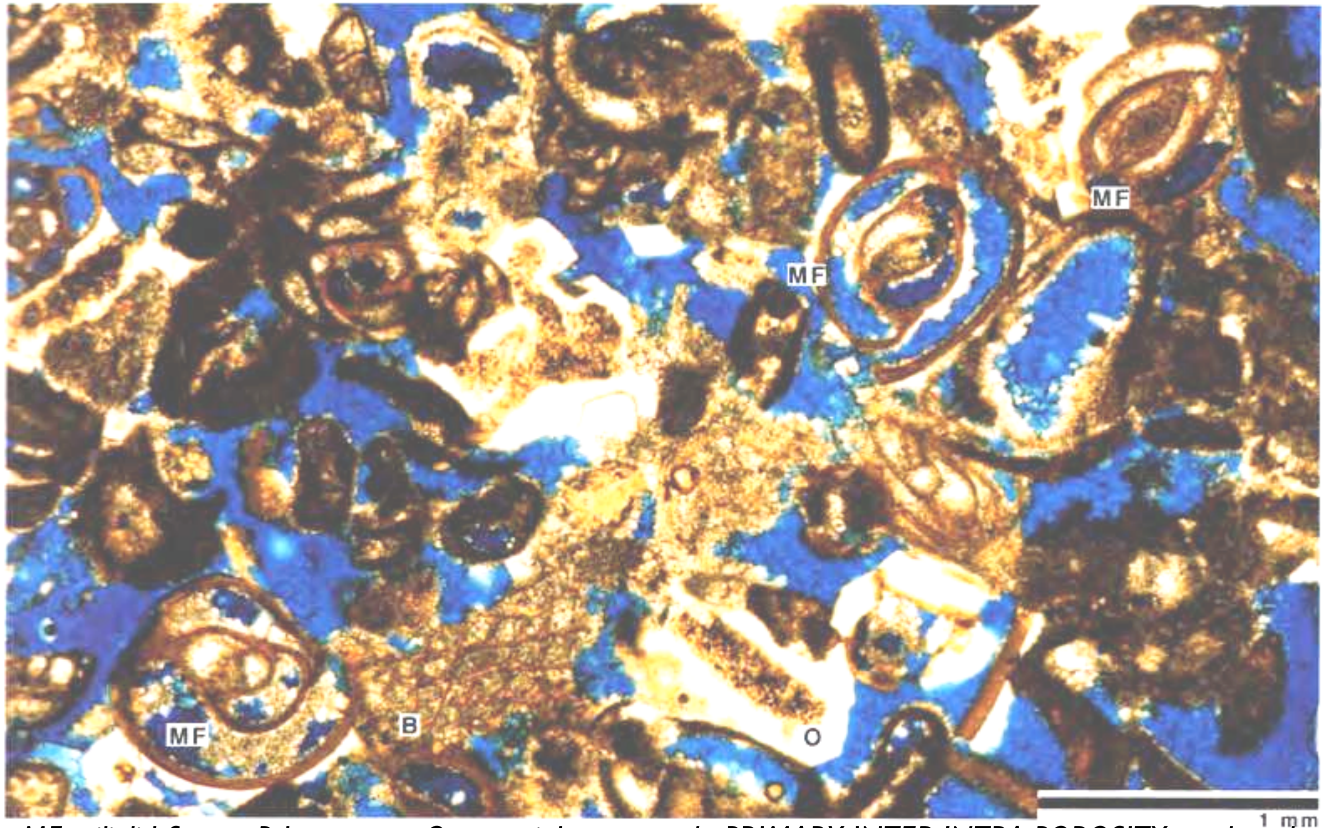
CARBONATES : BORN IN THE SEA
MINERALOGY-DIAGENESIS



Diagenetic environment	Location	Pore Filling	Processes	~ Time needed
Meteoric vadose environment	Above water table, between land surface and meteoric phreatic zone	Pores filled with freshwater and/ or air	*Solution zone* (soil): Extensive solution; removal of aragonite; formation of vugs. *Precipitation zone* (near surface): Minor cementation	10^3 - 10^5 years
Meteoric phreatic environment	Below water table, may tend downwards 100s of meters	Pores filled with freshwater	*Solution zone* (e.g. sinkholes, caves): Solution; formation of molds and/or vugs. *Active zone* (upper part of meteoric phreatic environment): Dissolution of aragonite and Mg-calcite; rapid and diverse cementation; precipitation of calcite; creation of molds and vugs. *Stagnant zone* (deeper part and in arid climates): Little cementation; stabilization of aragonite and Mg-calcite	10^3 -10^5 up to 10^6 - 10^7 years
Marine phreatic environment	On the shallow or deep sea floor or just below	Pores filled with marine water	*Shallow-marine environment:* Waters oversaturated with respect to $CaCO_3$; rapid cementation by aragonite and Mg-calcite; diverse cement types. *Deep-marine and cold-water environments:* Waters undersaturated with respect to $CaCO_3$; strong dissolution of aragonite and calcite at two dissolution levels	10^1 - 10^4 years
Burial environment	Subsurface beneath reach of surface-related processes, down to realm of low-grade metamorphism. May tend downwards 1000s of meters	Pores filled with brines of varying salinity, from brackish to highly saline	*Shallow burial* (first few meters fo tens of meters) and *deeper burial* (sediment overburden of hundreds to thousands of meters): Physical compaction; chemical compaction (pressure solution); cementation; porosity reduction	10^6 -10^8 years

in Flügel 2004

CARBONATES : BORN IN THE SEA
MINERALOGY-DIAGENESIS



in Flügel 2004

MF miliolid foram, B bryozoans, O syntaxial overgrowth. PRIMARY INTER-INTRA POROSITY partly reduced (dogtooth and granular cements within forams and echinoderm overgrowths)

‘**DISSOLUTION SEQUENCE’**

HMC => LMC (Mg🡻) or DOL (Mg🡹)

then ARAG => MOLDS or LMC,

finally ‘LMC’

Memoir 1

1962

CLASSIFICATION

OF a symposium

CARBONATE ROCKS

A Symposium arranged by the Research Committee of The American Association of Petroleum Geologists

Including papers presented orally under joint auspices of the Association and the Society of Economic Paleontologists and Mineralogists, at Denver, Colorado, April 27, 1961.

Edited by WILLIAM E. HAM

Published by The American Association of Petroleum Geologists, Tulsa, Oklahoma, U.S.A. 1962

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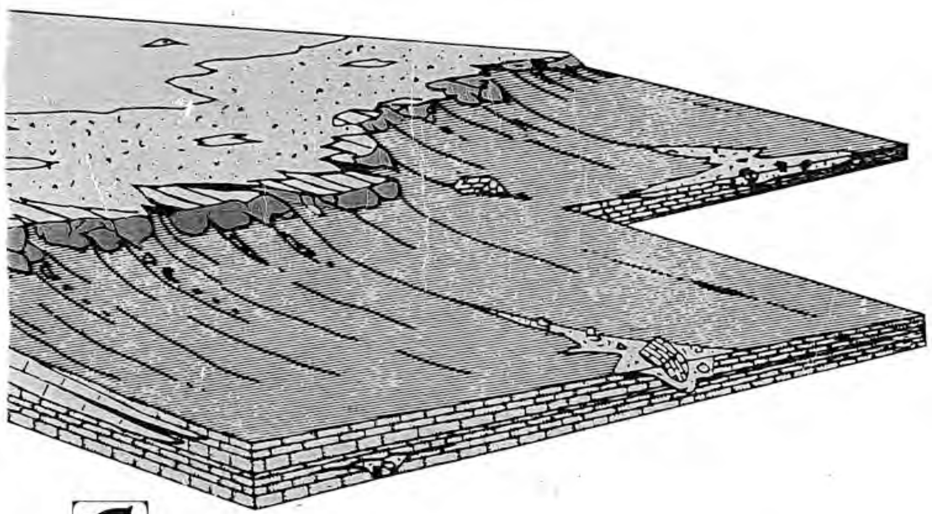
James Lee Wilson

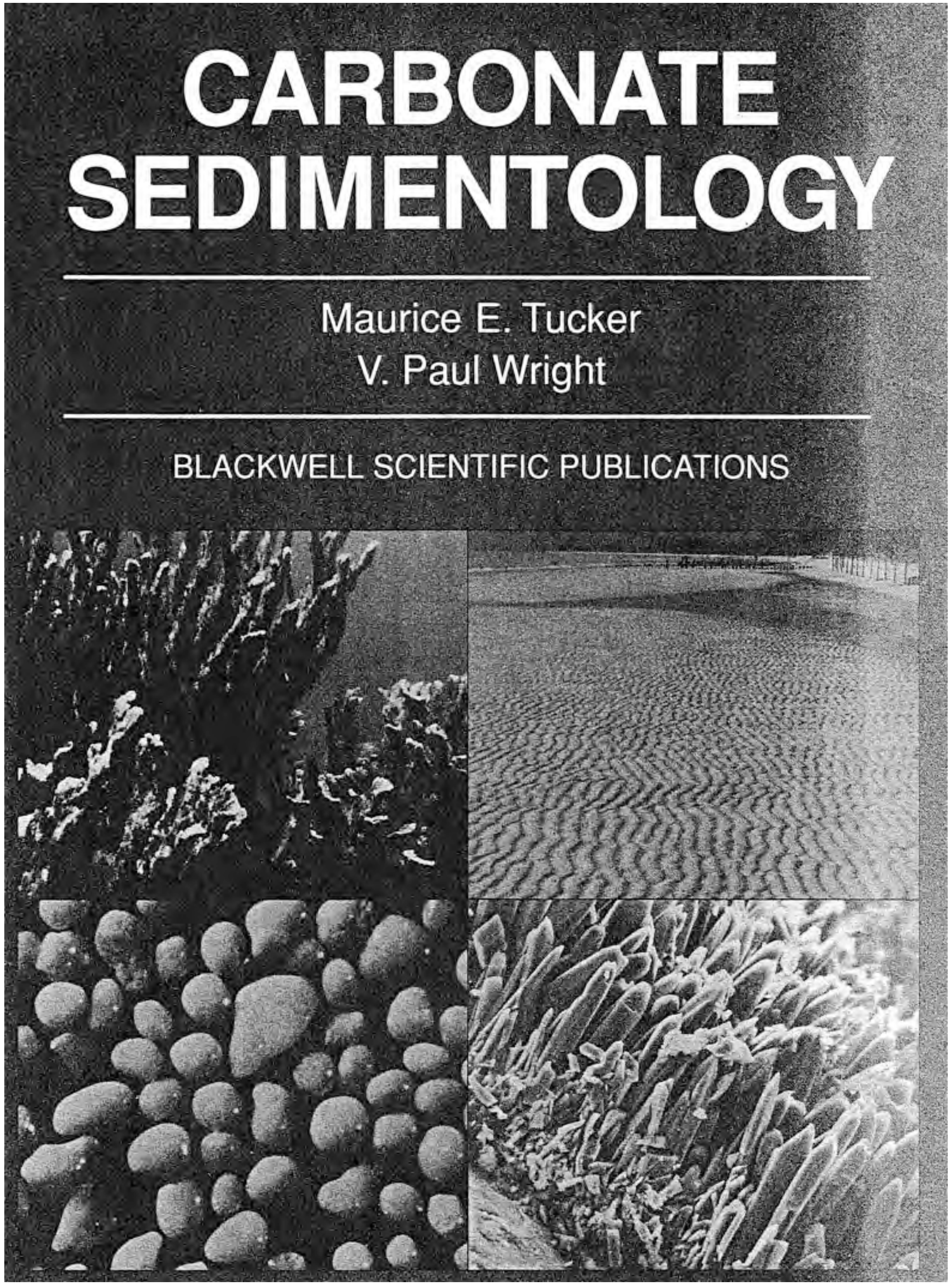
Carbonate Facies in Geologic History

1975

First synthesis



Springer-Verlag New York Heidelberg Berlin



1990

…. with
SEM
Geochemistry
Recent studies
….

= > abundant textbooks….

CLASSIFICATION OF CARBONATES
a long story ….

≈ 1900 GRABAU : 'calcirudite', 'calcarenite', 'calcilutite'
1949 PETITJOHN : limestones = allochthonous, autochthonous, bioherms, biostromes

1959-1962 FOLK first (practical) petrographic classification
based on 'textural maturity' deriving from previous studies in the siliclastics!
=> allochems (= allochthonous carbonate grains) = depositional energy
=> spar
=> micrite

1962 … AA**P**G Memoir#1
=> DUNHAM : **nature of grain support**
=> PLUMLEY et al. : energy index $I_{1,2,3}$ …. $V_{1,2,3}$

1971 EMBRY & KLOVAN BC**P**G Memoir#19 'coarse-grained **'reefal'** rocks

CLASSIFICATION OF POROSITIES (CARBONATES)

1970 CHOQUETTE & PRAY AAPG 54, 207-250
1995 LUCIA AAPG 63, 279-300

TODAY

GLOBAL APPROACHES

- Academic
- Environmental

APPLIED APPROACHES

- Source rocks
- Reservoir rocks
- Seal rocks

….

CLASSIFICATION OF CARBONATES

a long story ….

one of the most popular

VOLUMETRIC ALLOCHEM COMPOSITION			>10% Allochems ALLOCHEMICAL ROCKS (I AND II)		<10% Allochems MICROCRYSTALLINE ROCKS (III)			UNDISTURBED BIOHERM ROCKS (IV)
			Sparry calcite cement > Microcrystalline ooze Matrix	Microcrystalline Ooze Matrix > Sparry Calcite Cement	1-10% Allochems		<1% Allochems	
			SPARRY ALLOCHEMICAL ROCKS (I)	MICROCRYSTALLINE ALLOCHEMICAL ROCKS (II)				
>25% Intraclasts (i)			Intrasparrudite (Ii:Lr) Intrasparite (Ii:La)	Intramicrudite (IIi:Lr) Intramicrite (IIi:La)	Most Abundant Allochem	Intraclasts: Intraclast-bearing Micrite (IIIi:Lr or La)	Micrite (IIIm:L); if disturbed, Dismicrite (IIImX:L); if primary dolomite, Dolomicrite (IIIm:D)	Biolithite (IV:L)
<25% Intraclasts	>25% Oolites (o)		Oosparrudite (Io:Lr) Oosparite (Io:La)	Oomicrudite (IIo:Lr) Oomicrite (IIo:La)		Oolites: oolite-bearing Micrite (IIIo:Lr or La)		
	<25% Oolites; Volume Ratio of Fossils to Pellets	>3:1 (b)	Biosparrudite (Ib:Lr) Biosparite (Ib:La)	Biomicrudite (IIb:Lr) Biomicrite (IIb:La)		Fossils: Fossiliferous Micrite (IIIb: Lr, La, or L1)		
		3:1-1:3 (bp)	Biopelsparite (Ibp:La)	Biopelmicrite (IIbp:La)		Pellets: Pelletiferous Micrite (IIIp:La)		
		<1:3 (p)	Pelsparite (Ip:La)	Pelmicrite (IIp:La)				

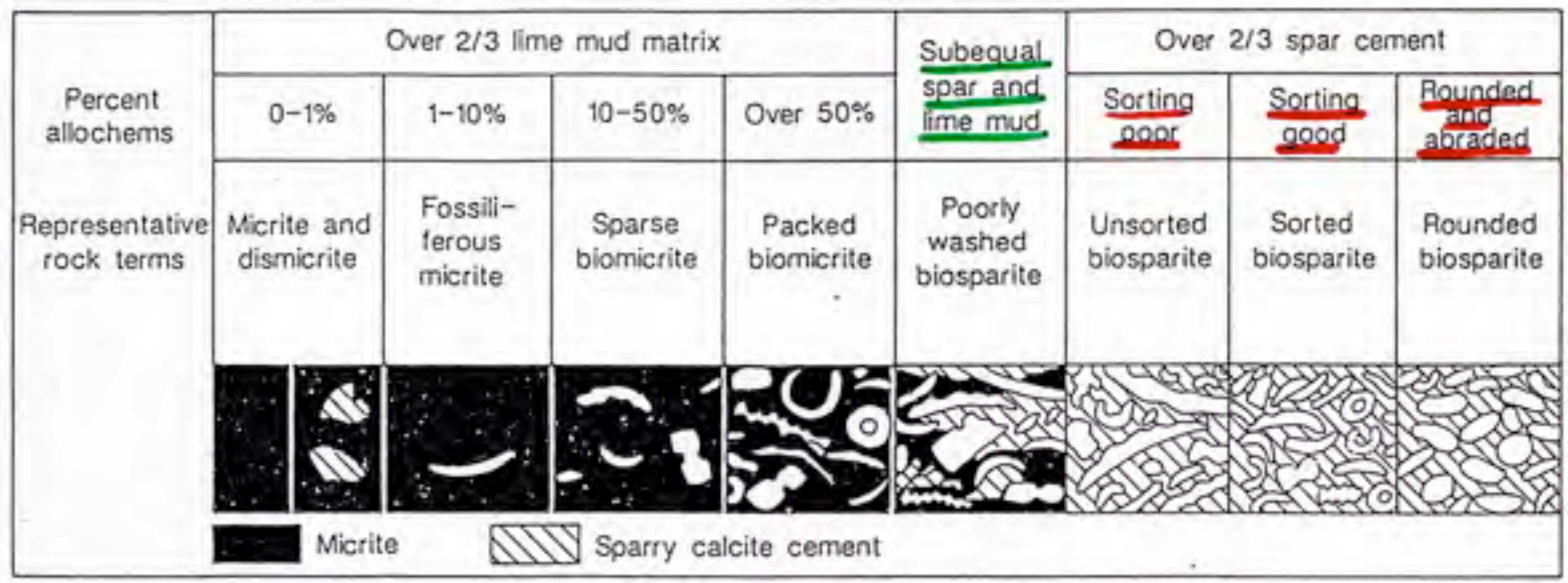
Fol (1959), as modified by Folk (1962).

This classification is compositional as well as textural (for non-reef carbonates)

The basic philosophy is that carbonate rocks are similar to siliciclastic rocks in their mode of deposition, because their textures are both controlled largely by the water energy

⇒ intraclasts and oolites > < micrite ‘**WRONG IN MOST CASES…..**’

CLASSIFICATION OF CARBONATES
a long story ….



	Over 2/3 lime mud matrix				Subequal spar and lime mud	Over 2/3 spar cement		
Percent allochems	0–1%	1–10%	10–50%	Over 50%		Sorting poor	Sorting good	Rounded and abraded
Representative rock terms	Micrite and dismicrite	Fossili-ferous micrite	Sparse biomicrite	Packed biomicrite	Poorly washed biosparite	Unsorted biosparite	Sorted biosparite	Rounded biosparite

Concept and textural spectrum of the Folk classification (1959, 1962).
Increasing maturity from left to right.

High water energy hinders deposition of fine-grained material (**'micrite, matrix'**) and favors the sedimentation of winnowed sands with large amounts of pore space that is later filled with sparry calcite **(cement, sparite**).
The most important environmental break is between limestones with a lime-mud matrix and those with calcite cement, because this should reflect the point where water energy becomes turbulent enough to wash out (winnow) the lime mud, keep it in suspension and carry it into lower energy zones.

CLASSIFICATION OF CARBONATES
a long story ….

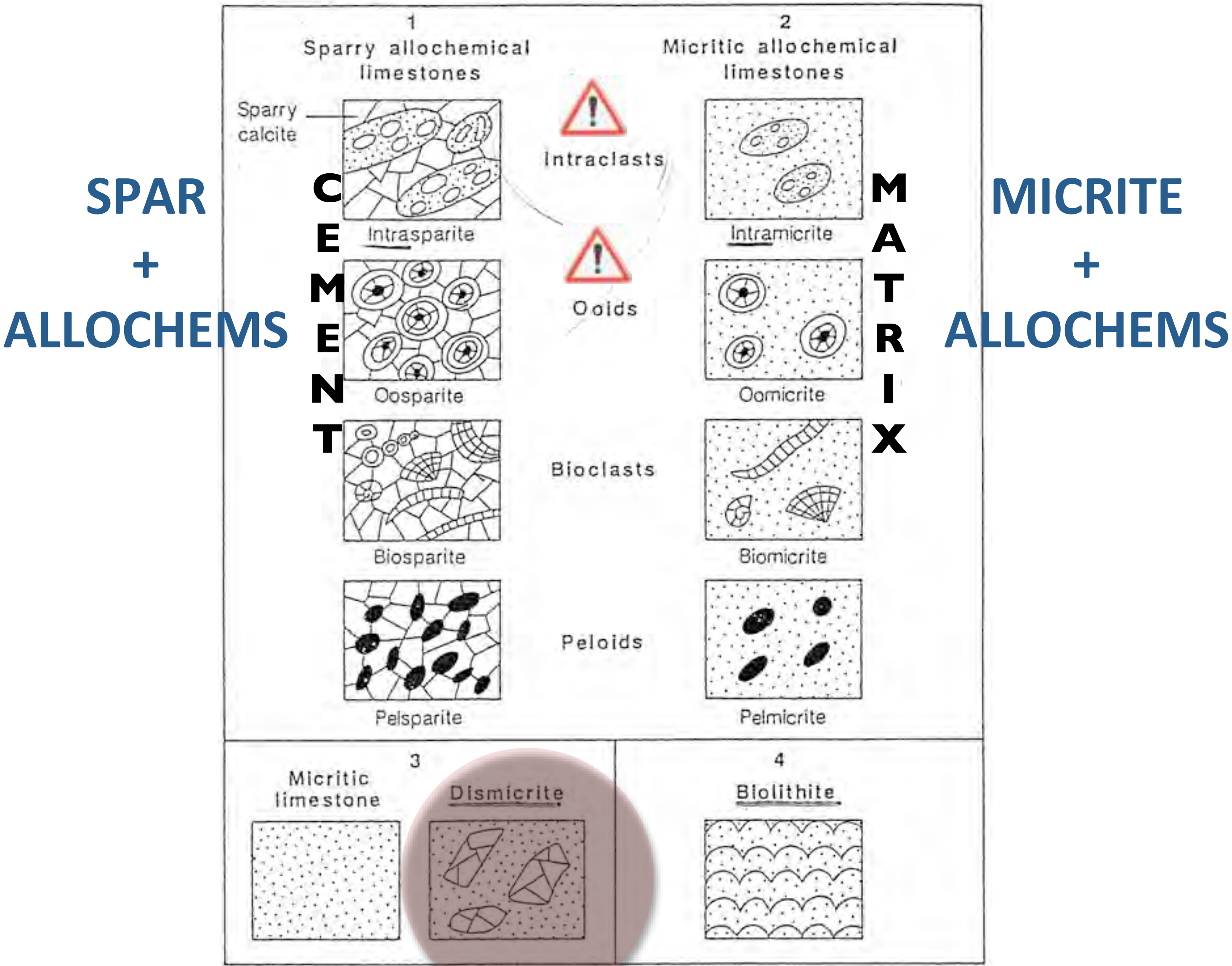
	Over 2/3 Lime Mud Matrix				Subequal	Over 2/3 Spar Cement		
Percent Allochems	0 - 1 %	1 - 10 %	10 - 50 %	over 50%	Spar and Lime Mud	Sorting poor	Sorting good	Rounded and abraded
Representative Rock Terms	Micrite	Fossil-iferous Micrite	Sparse Biomicrite	Packed Biomicrite	Poorly washed Biosparite	Unsorted Biosparite	Sorted Biosparite	Rounded Biosparite
								
1959 Terminology	Micrite	Fossil-iferous Micrite	Biomicrite			Biosparite		
Terrigenous Analogues	Claystone		Sandy Claystone	Clayey or Immature Sandstone		Submature Sandstone	Mature Sandstone	Supermature Sandstone

Lime Mud Matrix   Sparry Calcite Matrix

Concept and textural spectrum of the Folk classification with terrigenous analogues.

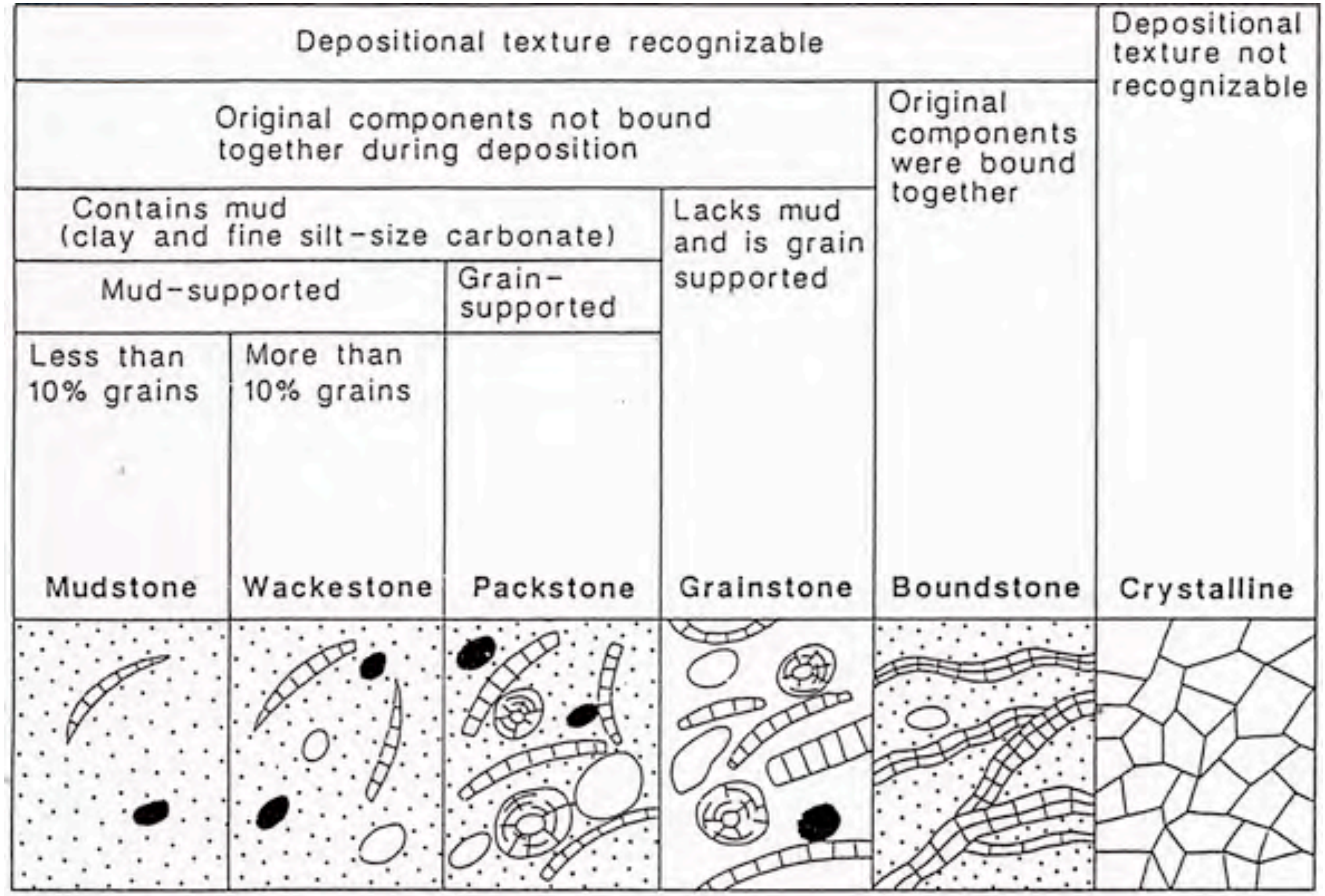
Terrigenous					
Matrix-supported				Grain-supported	
Sand: < 10%	10-25%	> 25%			
	sandy MUDSTONE	WACKE	SUBWACKE	ARENITE	
			SANDSTONE		

CLASSIFICATION OF CARBONATES
a long story ….



Concept and textural spectrum of the Folk classification (1959, 1962).

CLASSIFICATION OF CARBONATES
a long story ….

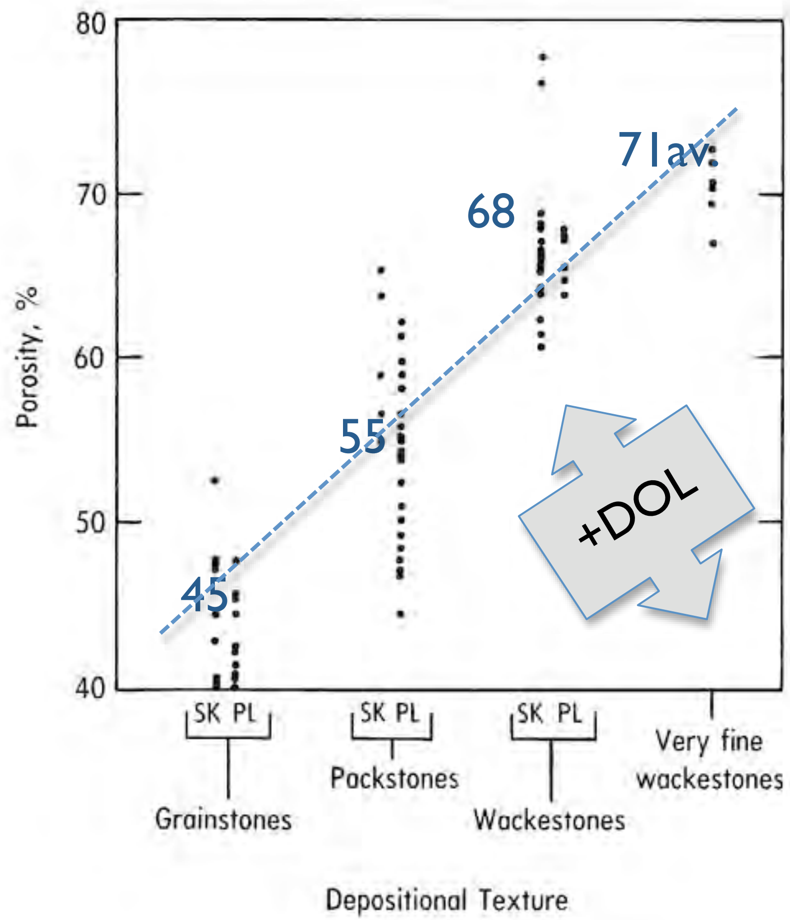


DUNHAM (1962) : THE MOST WIDELY USED CLASSIFICATION

It can equally well be applied in the field, in investigation of cores and in laboratory studies (thin sections).

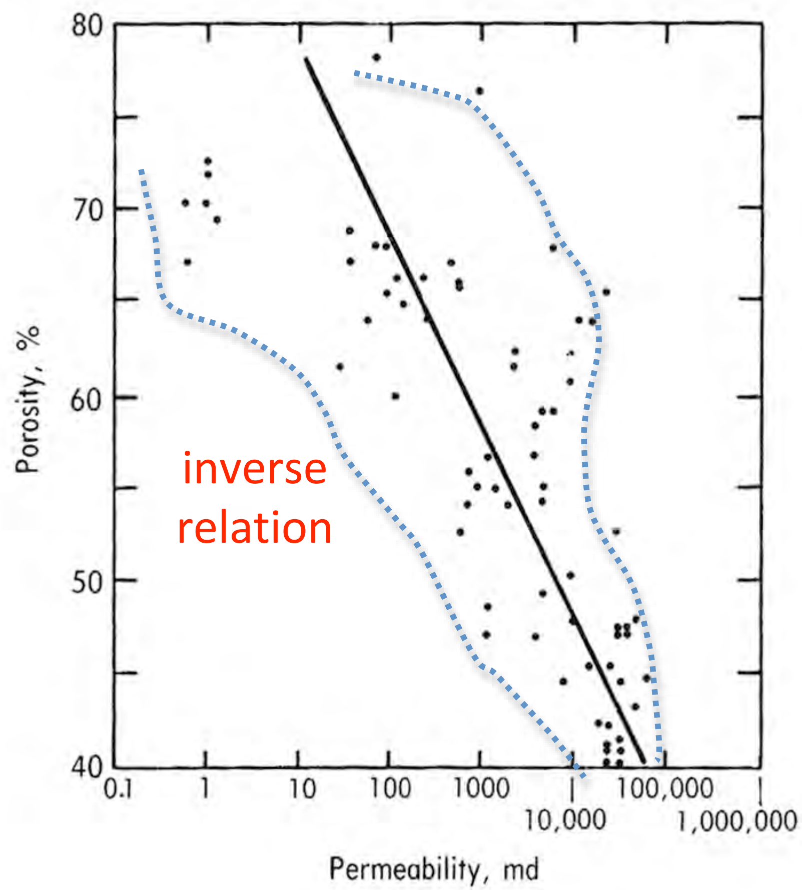
It is necessary to determine what constituents occur (grain categories, matrix, cement types) AND whether the constituent grains are grain- or mud-supported.

CARBONATES (ΦI) + ΦII
CLASTICS ΦI + (ΦII)



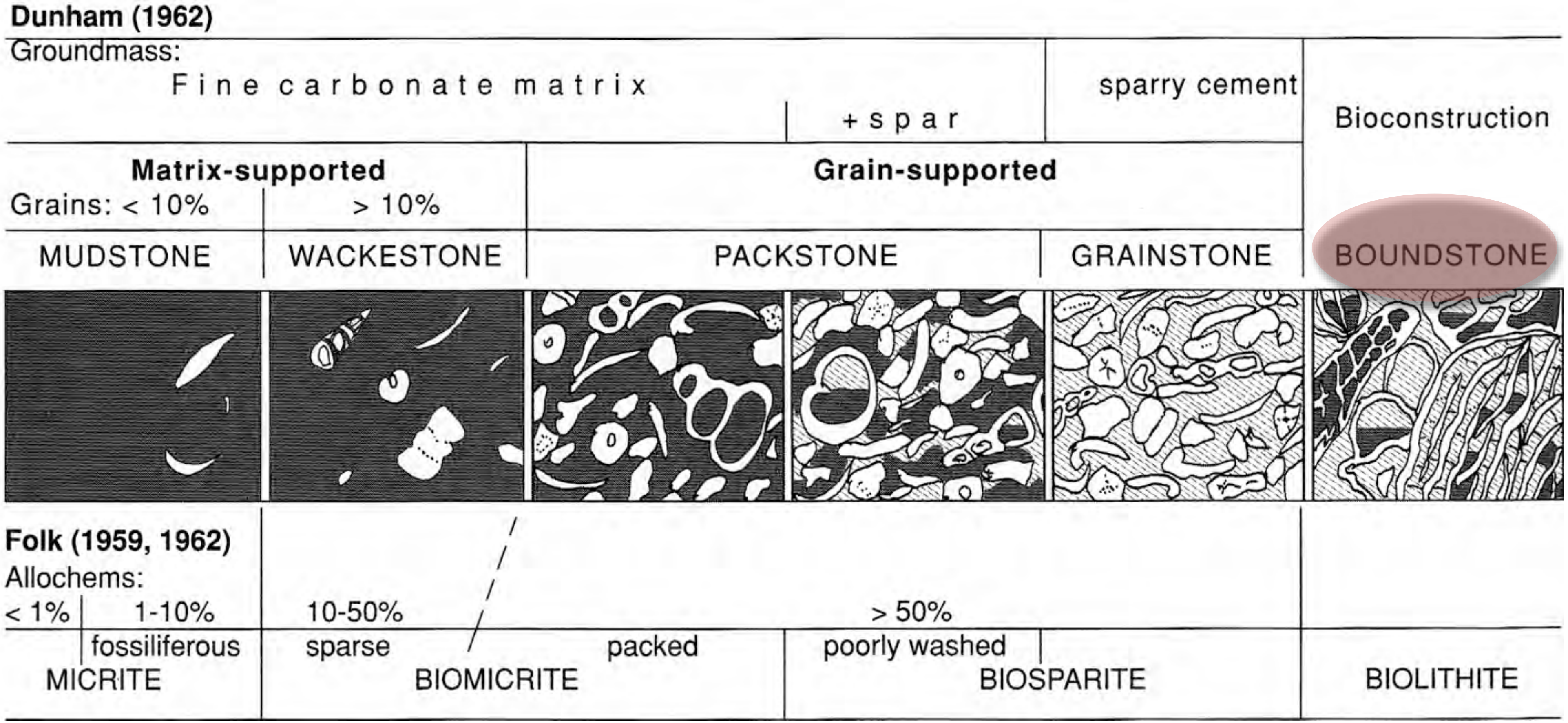
Primary depositional porosity in various Holocene carbonate sediment textural types (Enos & Sawatsky 1981)

CARBONATES ΦII≠K
CLASTICS ΦI //K



Porosity-permeability plot of Holocene carbonates (Enos & Sawatsky 1981)

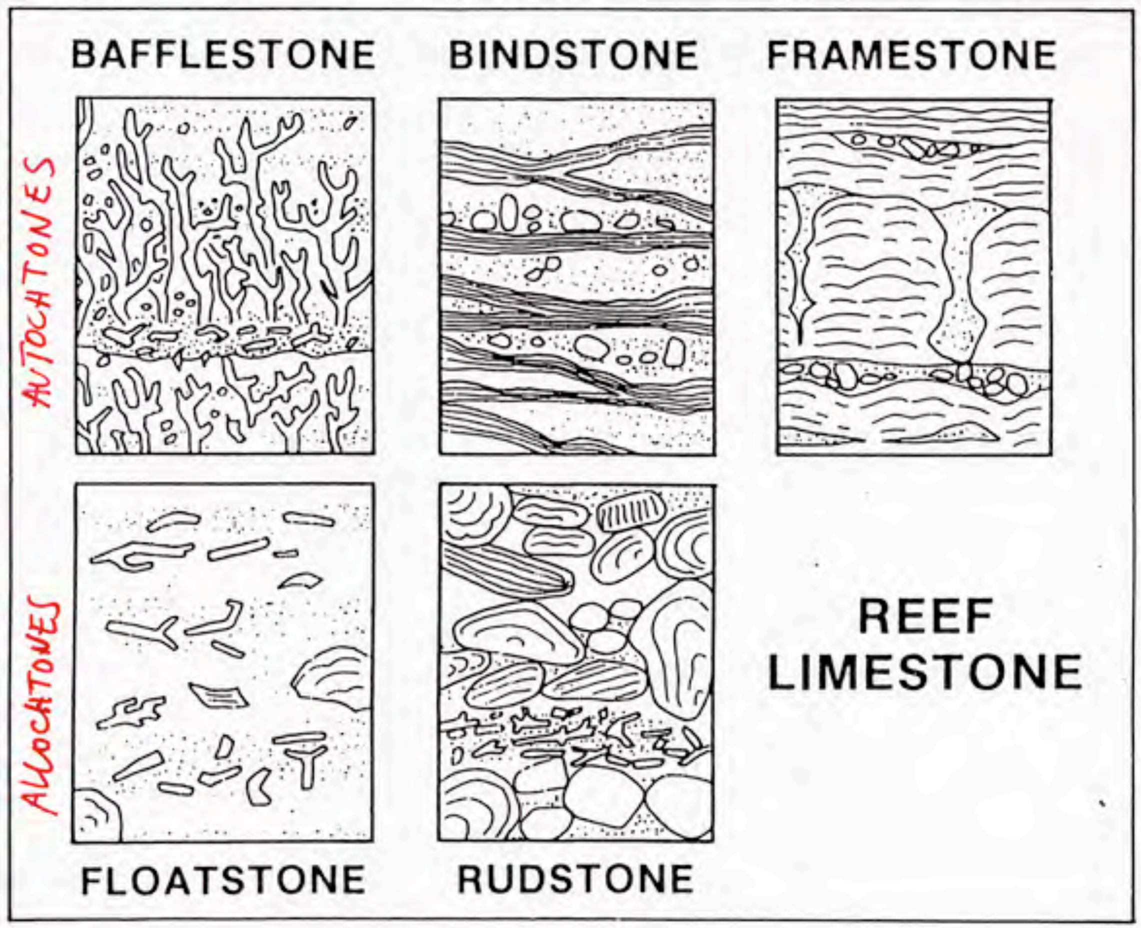
CLASSIFICATION OF CARBONATES
a long story ….



The DUNHAM classification stresses the DEPOSITIONAL fabric.
The FOLK classification tries to evaluate HYDRODYNAMIC conditions.
Both classifications consider the dominant groundmass types.

CLASSIFICATION OF CARBONATES
a long story ….

EMBRY & KLOVAN 1971 : AUTO/ALLOCHTHONOUS REEF LIMESTONES



EMBRY & KLOVAN specify **HOW** the organisms contribute to rock-building processes
=> significance of reef builders for the buildup of reefs

CLASSIFICATION OF CARBONATES
a long story ….

EMBRY & KLOVAN 1971 : AUTO/ALLOCHTHONOUS REEF LIMESTONES

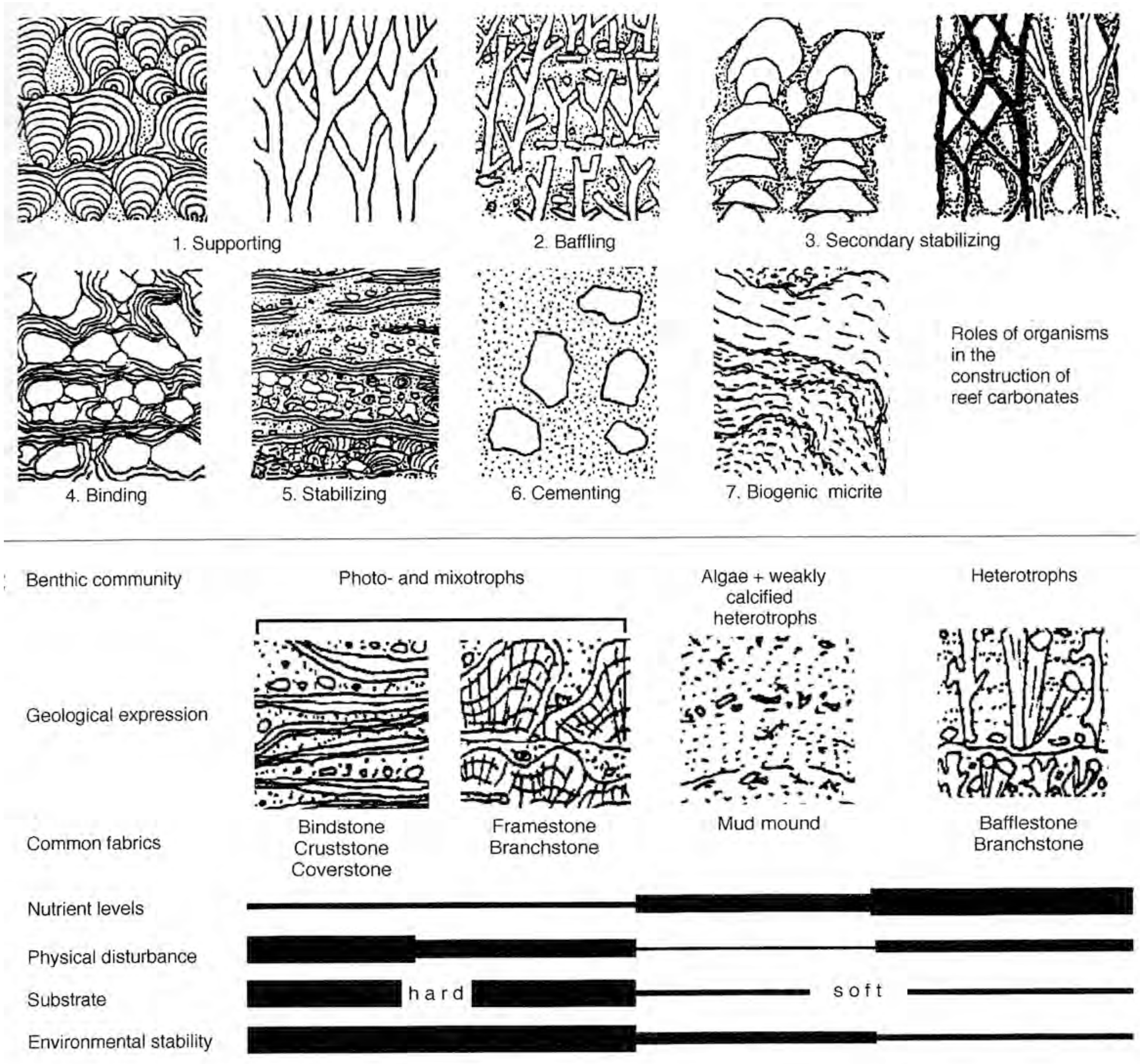
DUNHAM 1962

Original components not bound together during deposition				Original components were bound together during deposition			Original components not bound together during deposition	
Generally *smaller* grains (arenite and silt size)							More than 10 percent *larger* grains (rudite size)	
Contains mud (micrite matrix)		Lacks mud (sparite matrix)		Organisms act as sediment bafflers (e.g., dendroid corals)	Organisms act as sediment binders (e.g., algal mats)	Organisms act as frame-builders (e.g., intergrown reef corals)	Contains mud (micrite matrix)	Lacks mud (sparite matrix)
Less than 10 percent grains	More than 10 percent grains							
Mud-supported		Grain-supported		Boundstone			Matrix-supported	Grain-supported
Mudstone	Wackestone	Packstone	Grainstone	Bafflestone	Bindstone	Framestone	Floatstone	Rudstone

CLASSIFICATION OF CARBONATES
a long story ….

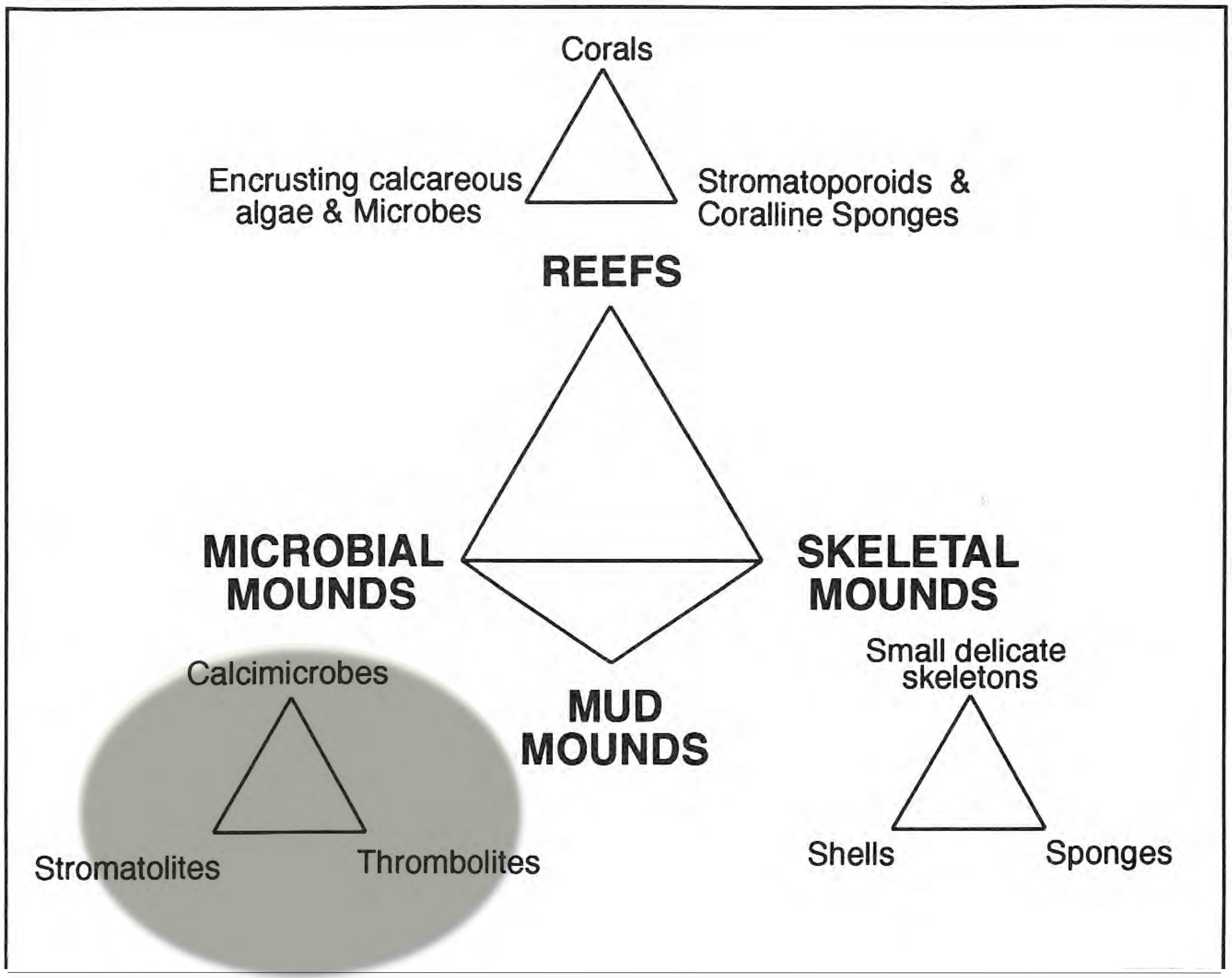
Role of organisms in the construction of reef carbonates

Dependence of reef rock types on environmental constraints of benthic communities



in Flügel 2004

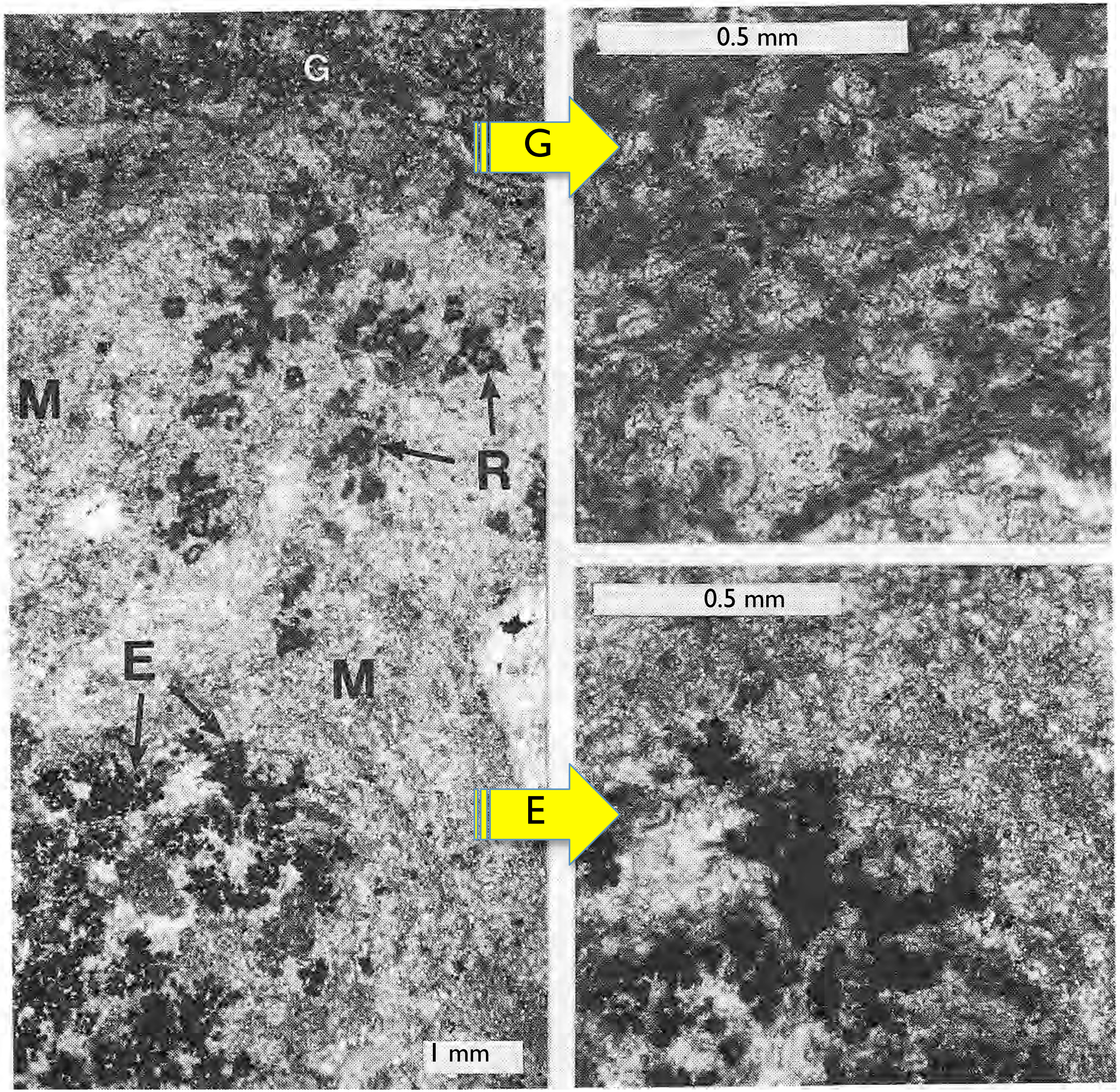
Conceptual classification of reefs and mounds including (‘**microbialites**’)



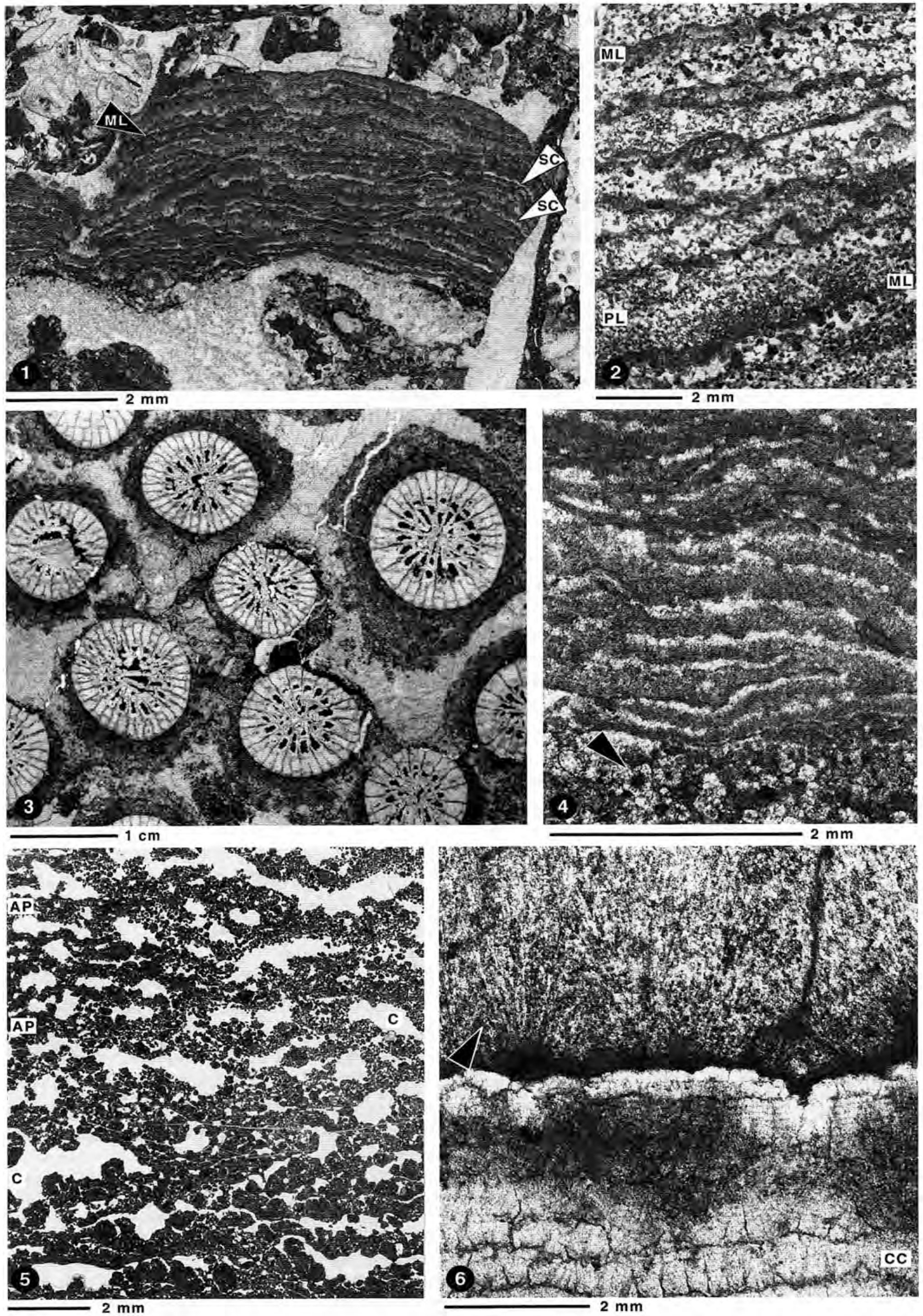
Bourque 1992

CACLIMICROBE BOUNDSTONE

Girvanella (G)
Epiphyton (E)
Renalcis (R)
?microbial spar
and microspar (M)
boundstone
Cambrian, Canada,
Bourque 1992



Flügel2004



Skeletal stromatolite crust growing on a colonial reef coral. The crust consist of a **spongiostromate** micritic layer (ML) separated by porostromate cyanobacteria filled with sparry calcite (SC).
Late Triassic, Austria

Laminated fine-grained agglutinated stromatolite (trapping/binding the sediment)
Thicker peloid layers (PL- and thinner ones (ML)
Late Triassic, Austria

Microbial crusts around and between rugosa corals
⇒ stabilization and preservation of reef structures
⇒black spots between septa and calices = asphaltic pyrobitumen (thermic effects, burial).
Frasnian, Germany

'Spongiostromate' stromatolitic crust covering the wall of a cryptic reef cavity.
Late Triassic, Austria

Agglutinated microbialite (amalgamated peloids AP) leaving space for spar-filled cavities (C) forming a 'laminoid fenestral fabric'
Late Triassic, Slovenia

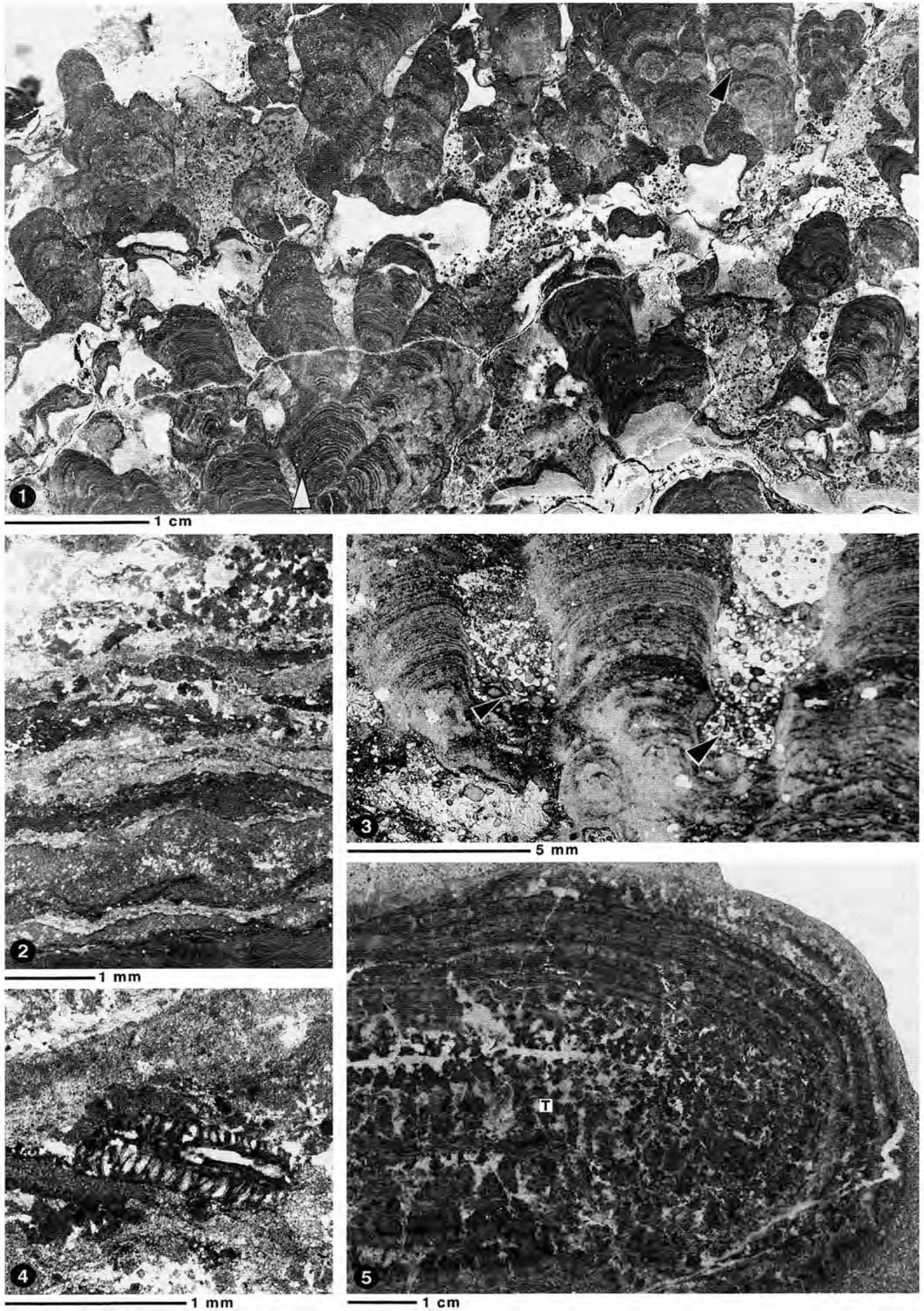
Tufa stromatolite (cement/algal bindstone)
Alternation of thick layer of bladed elongate calcite cement (CC) and layers of radiating bundles of algal threads (arrow).
Schizohaline near-coastal environment.
Tertiary, Egypt

Flügel2004

Lacustrine columnar stromatolite.
Could be up to several meters thick.
The columns are laminated and
larger columns consist of
small-sized stromatolite
(black arrow).
Early Permian, Germany

Irregularly laminated mudstone
and peloid mudstone with
syngenetically deformed
layers. Marine environment
Early Permian, Germany

Marine green and red algae
in lacustrine sediments
Early Permian, Germany



Stromatolite boundstone
with infillings of
micro-oncoids (arrows)
(high-energy shoreline/
nearshore environments)
Early Permian, Germany

Lacustrine oncoid with
thrombolite (T) micro-
structure = coccoid and
filamentous microbes
Early Permian, Germany

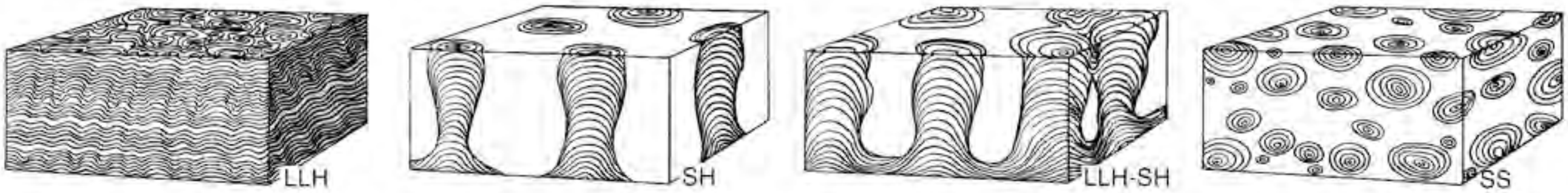
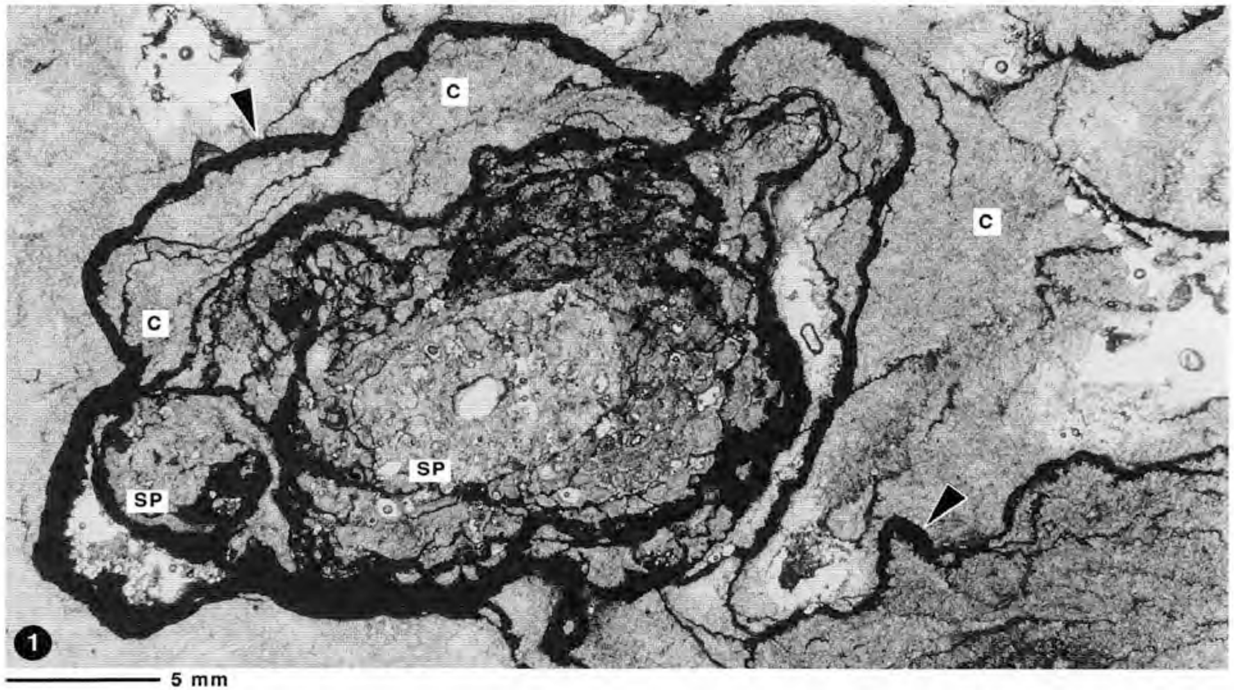


Fig. 9.3. *Stromatolite classification* after Logan et al. (1964). The classification is based on basic geometric forms expressed by the vertical and lateral arrangement of hemispheroids. Stromatolite growth forms as well as the shape of the lamination is described by symbols and formulas. These symbols can be used in the field and in the laboratory to describe thin sections and polished sections. **LLH**: **L**aterally **L**inked **H**emispheroids with laminae whose domes are either **C**losely packed or **S**paced somewhat apart (subtypes **LLH-C** and **LLH-S**). **SH**: **S**tacked **H**emispheroids forming columns that are separated by sediment. The domes of the laminae have either a **C**onstant diameter or **V**arious widths (subtypes **SH-C** and **SH-V**). **SS**: **S**pheroidal **S**tructures around a nucleus (corresponding to oncoids). Subtypes are **SS-C** (characterized by a **C**oncentric structure; normal oncoid), **SS-R** (laminae **R**andomly overlapping), and **SS-I** (**I**nverted; laminae facing each other as concentric hemispheres), see Fig. 4/15. Mixed geometric forms can be indicated by a linear combination of symbols, e.g. LLH-SH. The relations of growth forms and microstructure is expressed by a fraction, whereby the numerator describes the macrostructure seen in the field and in hand specimens, and the denominator the microstructure seen on a smaller scale as in thin sections.

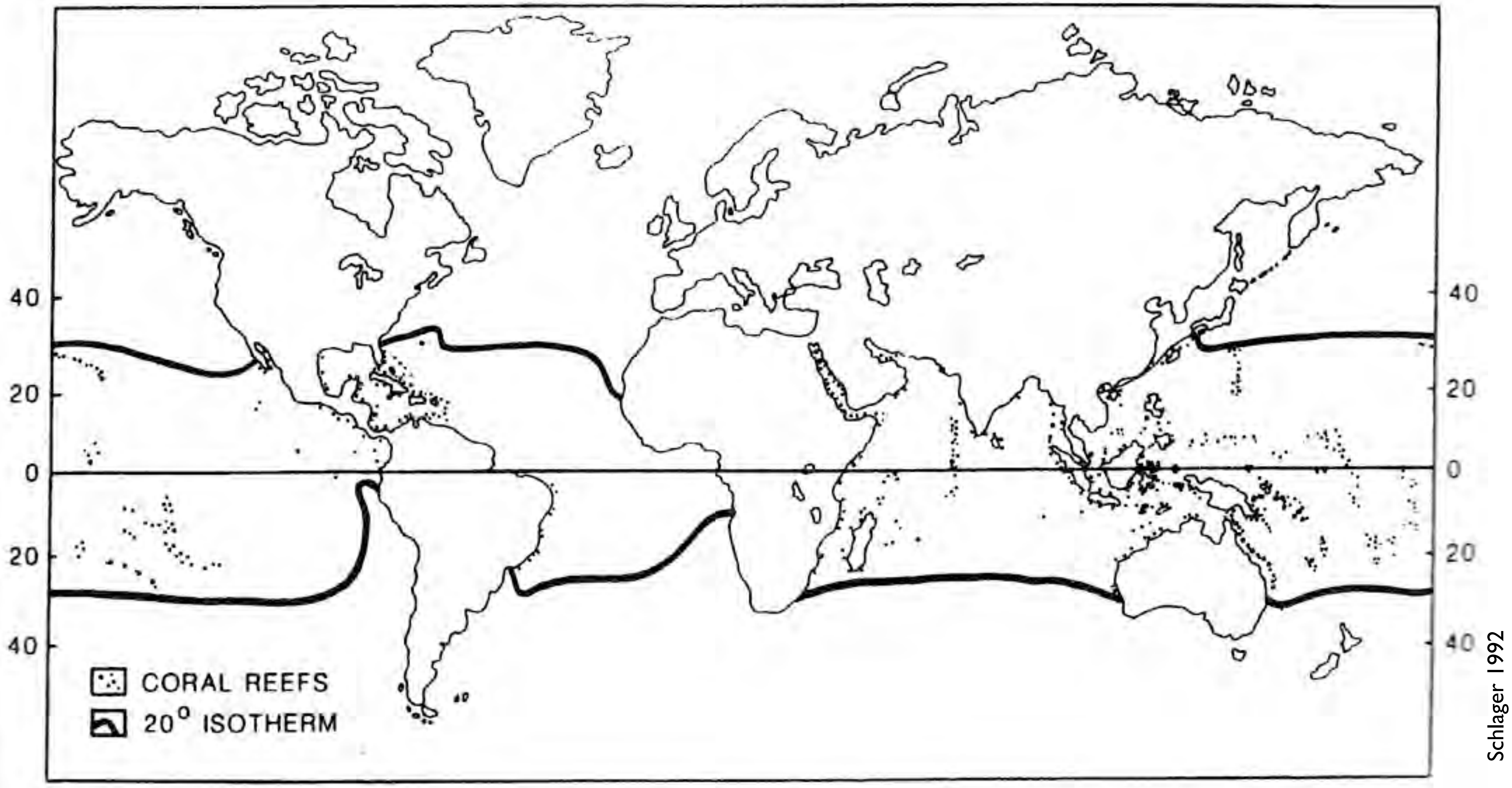
Flügel 2004

Pisoid rudstone
Arrows point to vadose cements
Carlsbad Cavern, New Mexico, USA



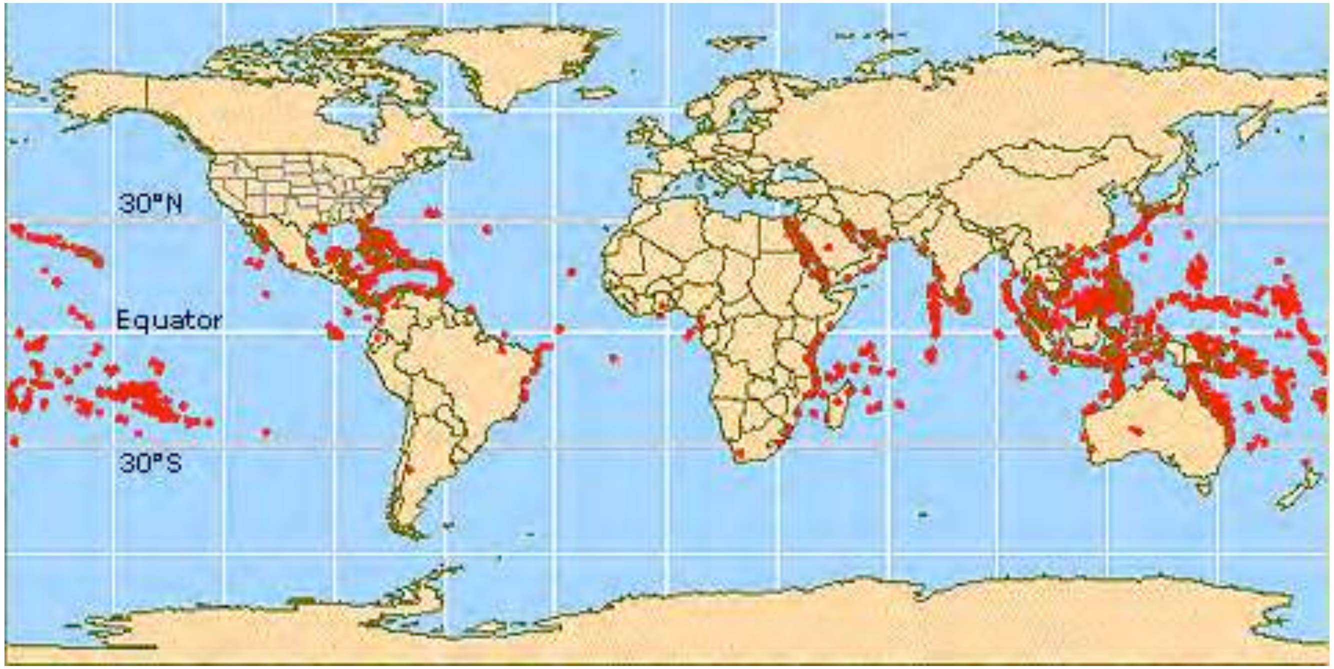
'Cementstone'
submarine, originally aragonitic
radial-fibrous cement (C)
formed synchronously with biogenic
crusts (red algae) (arrows)
growing on sponges (SP) as well
on cements.
Late Permian, Upper Capitan Limestone, USA

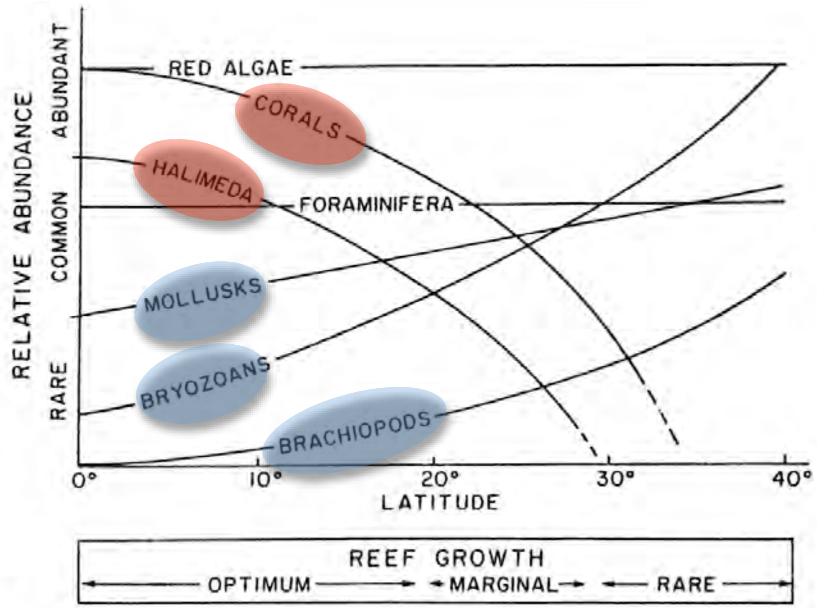
MODERN CORAL REEFAL CARBONATES



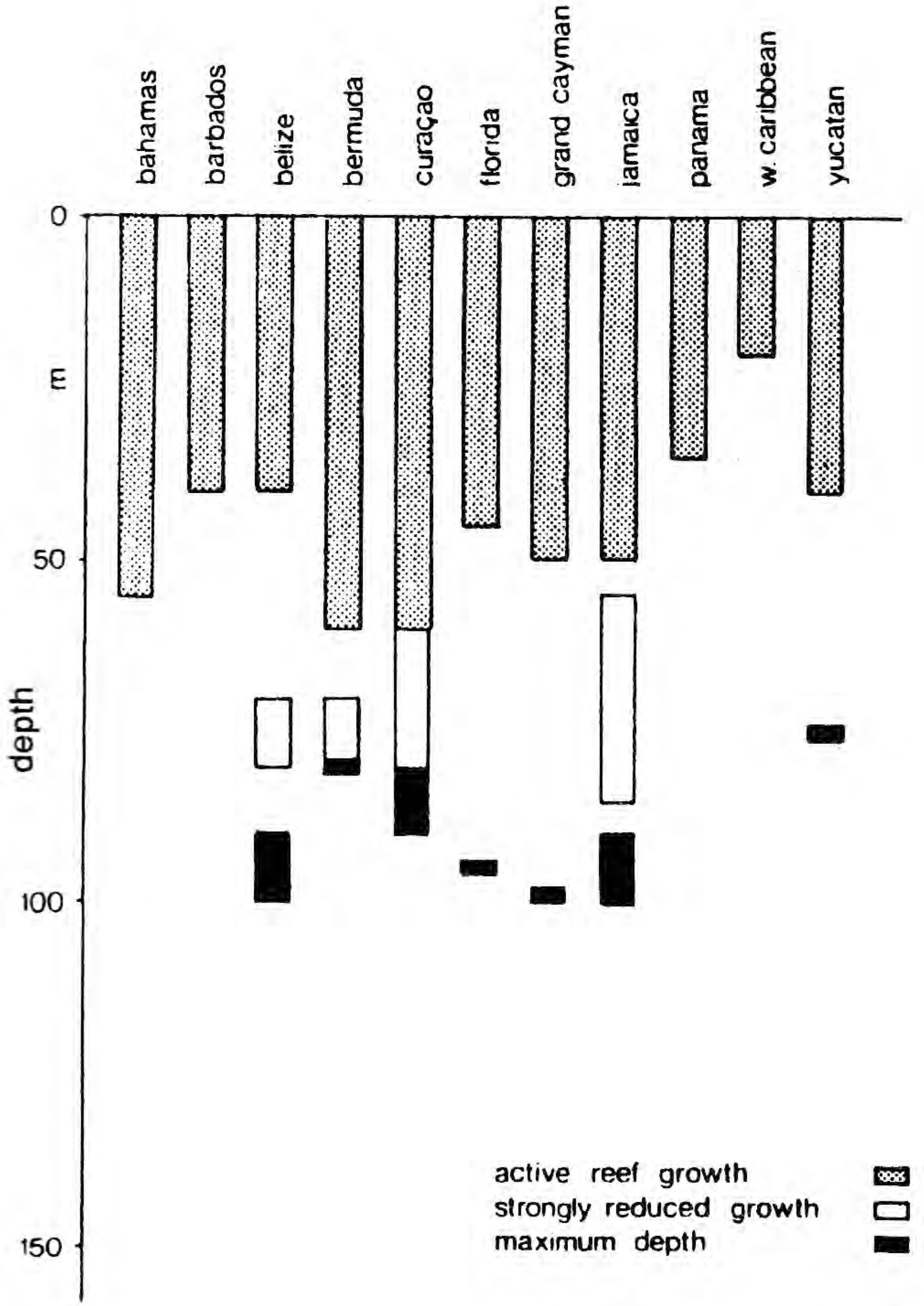
Distribution of recent coral reefs is limited in the north and south by **minimum** winter temperatures

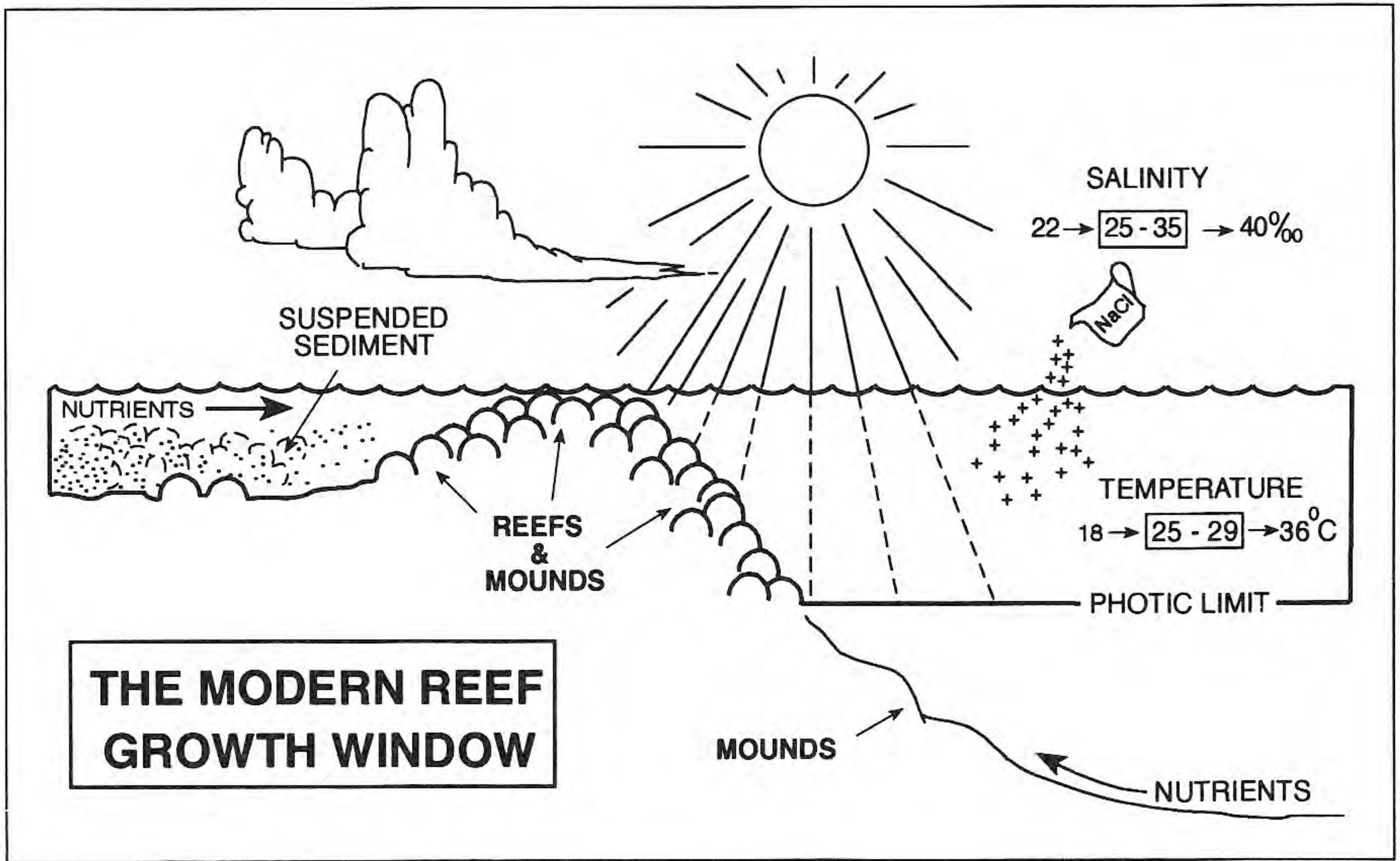
MODERN CORAL REEFAL CARBONATES



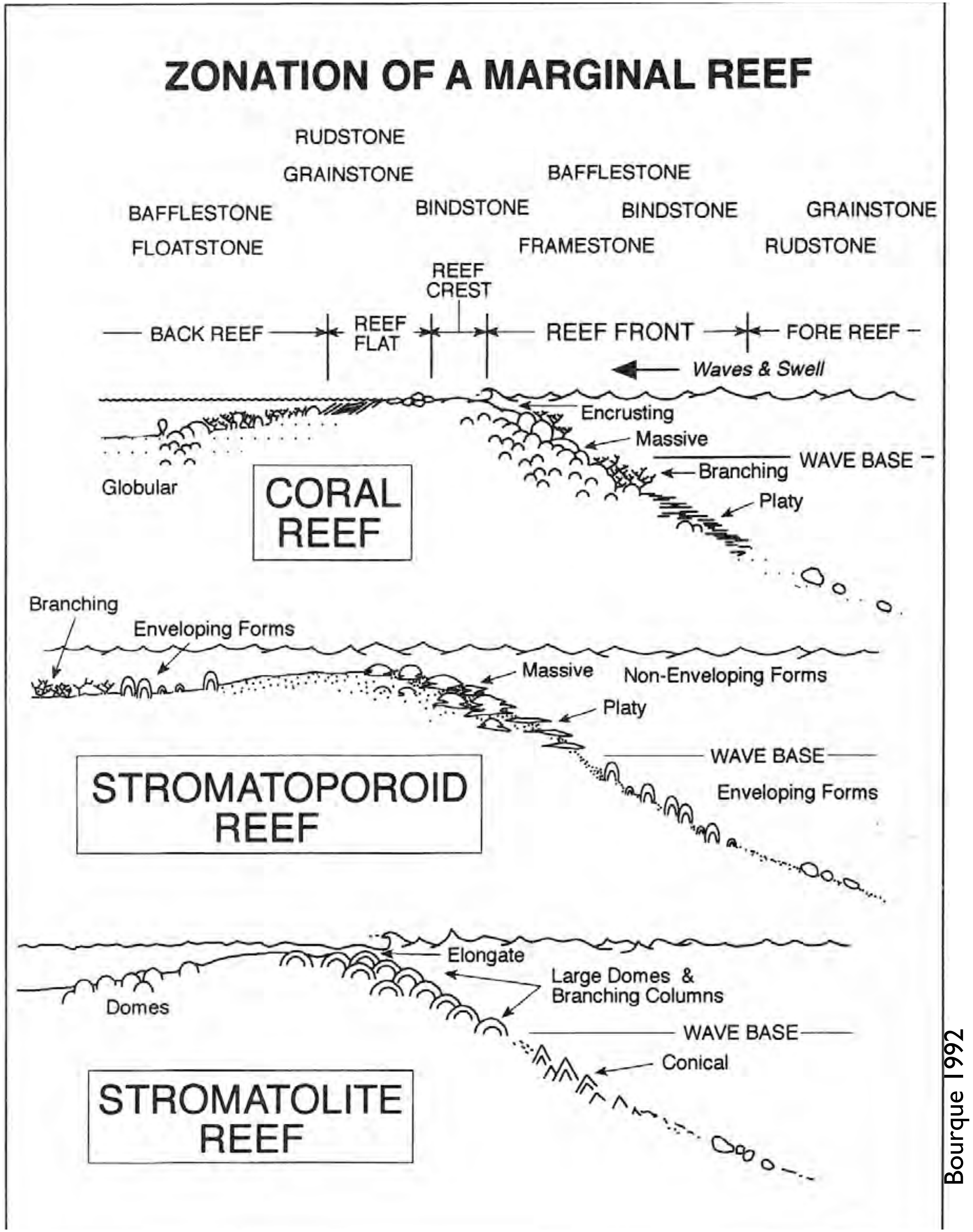


Schlager 1992


bahamas
barbados
belize
bermuda
curaçao
florida
grand cayman
jamaica
panama
w. caribbean
yucatan
0
50
100
150
depth m
active reef growth
strongly reduced growth
maximum depth



Bourque 1992

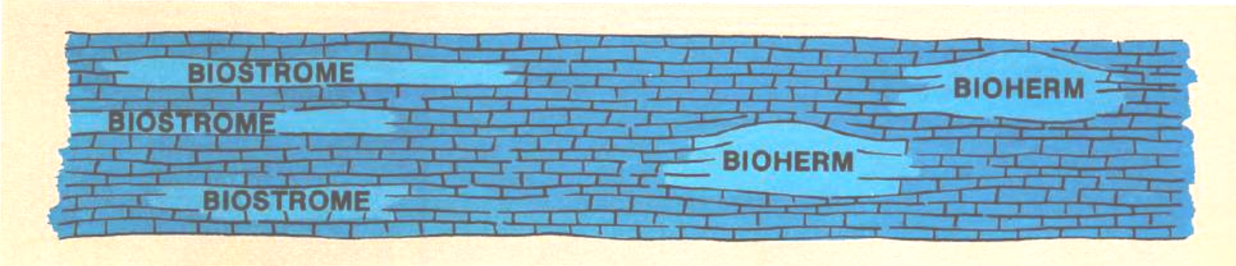


ZONATION OF A MARGINAL REEF
RUDSTONE
GRAINSTONE
BAFFLESTONE
FLOATSTONE
BINDSTONE
BAFFLESTONE
BINDSTONE
FRAMESTONE
GRAINSTONE
RUDSTONE
REEF CREST
BACK REEF
REEF FLAT
REEF FRONT
FORE REEF
Waves & Swell
Encrusting
Massive
WAVE BASE
Branching
Platy
Globular
CORAL REEF
Branching
Enveloping Forms
Massive
Non-Enveloping Forms
Platy
WAVE BASE
Enveloping Forms
STROMATOPOROID REEF
Elongate
Large Domes & Branching Columns
Domes
WAVE BASE
Conical
STROMATOLITE REEF
Bourque 1992

REEFAL CARBONATES
also a long story ….

L. = lenght
T. = thickness

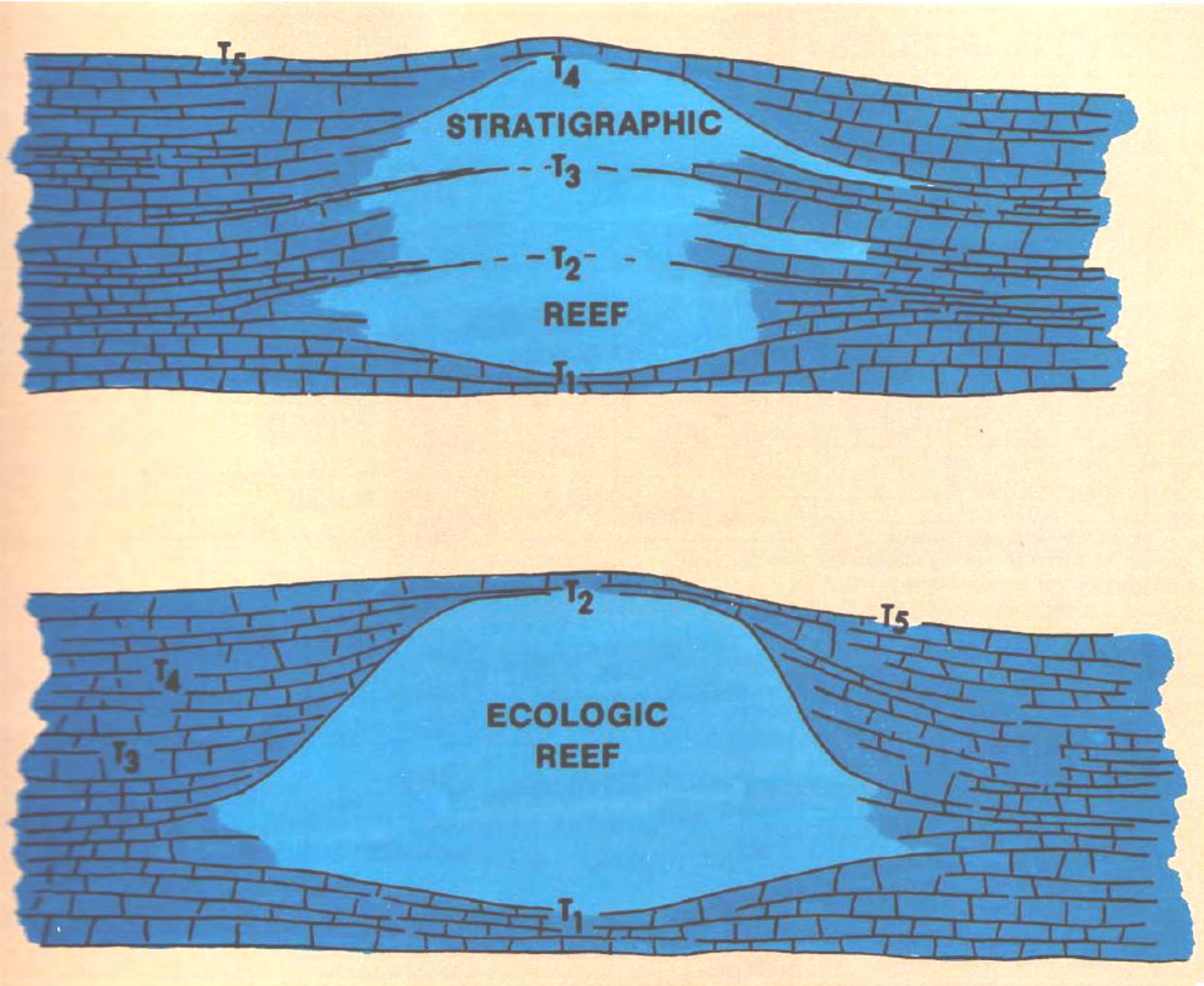
bedded unit
L. 100m'-100'km
Th. m-10'm



lens-like body
L./Th.
=
same magnitude

= several superimposed
bioherms with
little relied above
the surrounding
sea floor

= rigid, wave-resistant
topographic structure
generally formed
during one specific
period of tile



James 1983

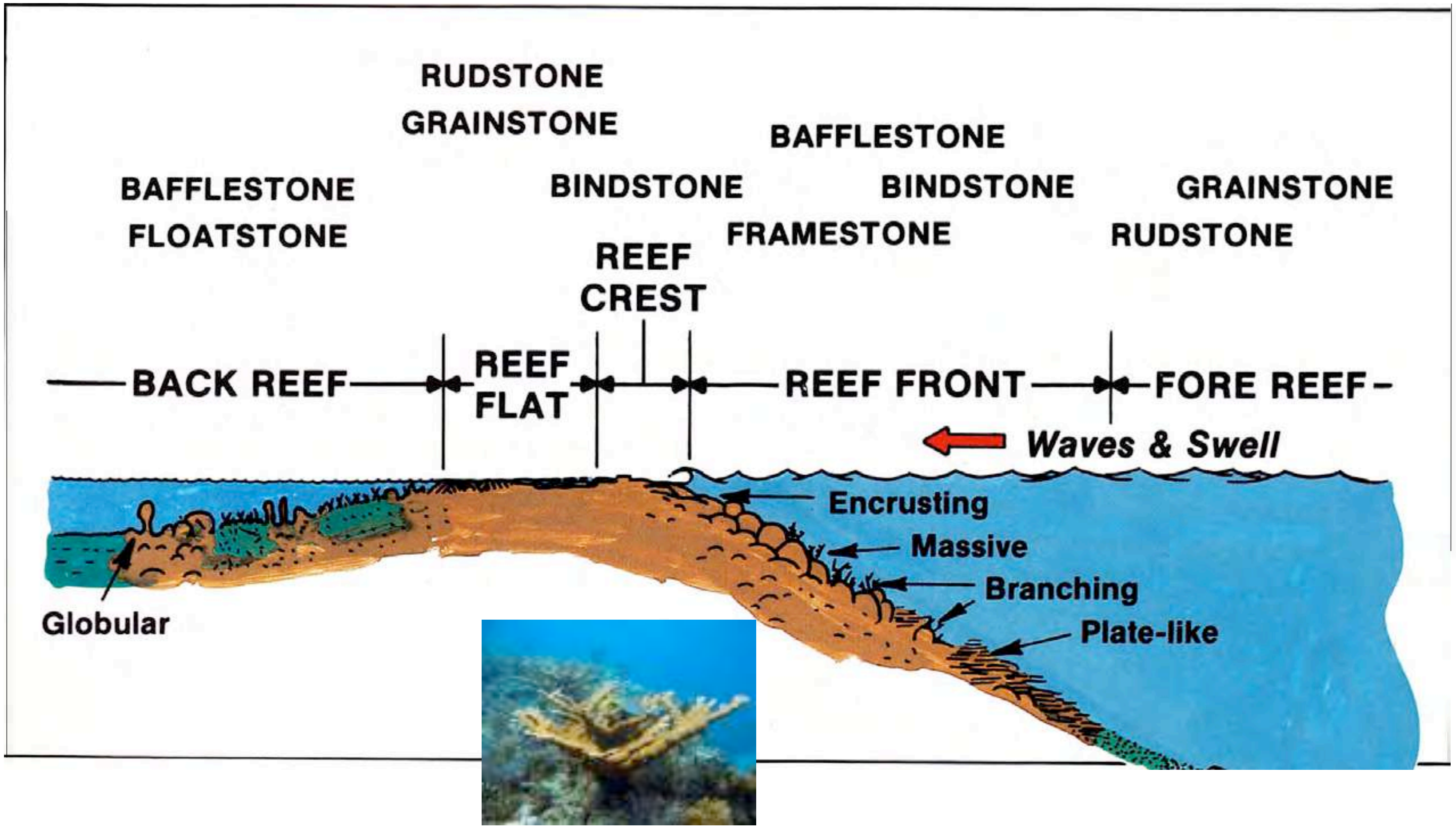
REEFAL CARBONATES
also a long story ….

GROWTH FORM AND ENVIRONMENT OF REEF BUILDING SKELETAL METAZOA

GROWTH FORM		ENVIRONMENT	
		Wave Energy	Sedimentation
	Delicate, branching	low	high
	Thin, delicate, plate-like	low	low
	Globular, bulbous, columnar	moderate	high
	Robust, dendroid, branching	mod-high	moderate
	Hemispherical, domal irregular, massive	mod-high	low
	Encrusting	intense	low
	Tabular	moderate	low

James 1983

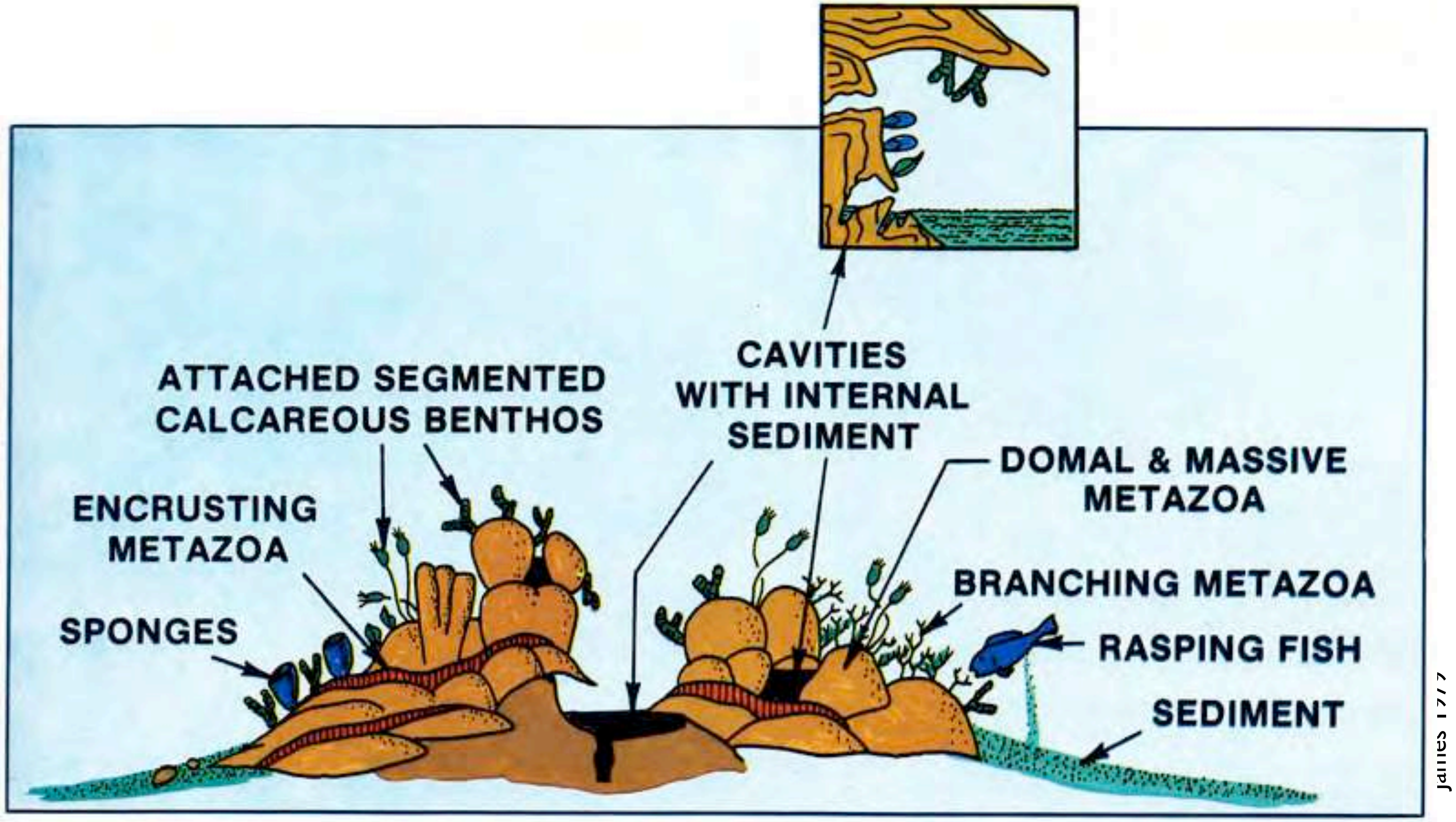
REEFAL CARBONATES
also a long story ….



James 1983

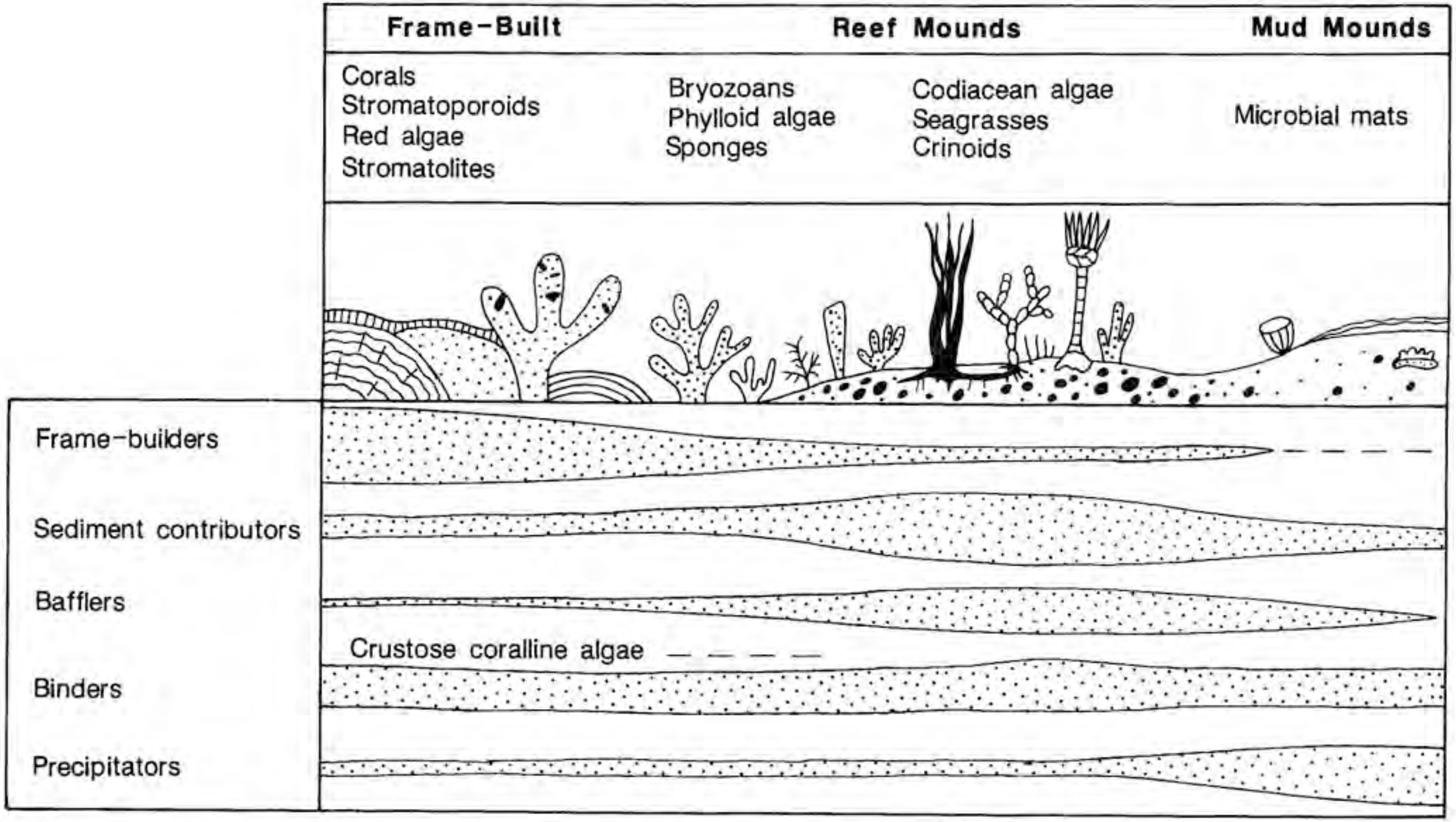
Cross-section through a zoned marginal reef. In many MODERN reefs, the reef crest is occuped by the massive *Acropora palmata.*

REEFAL CARBONATES
also a long story ….



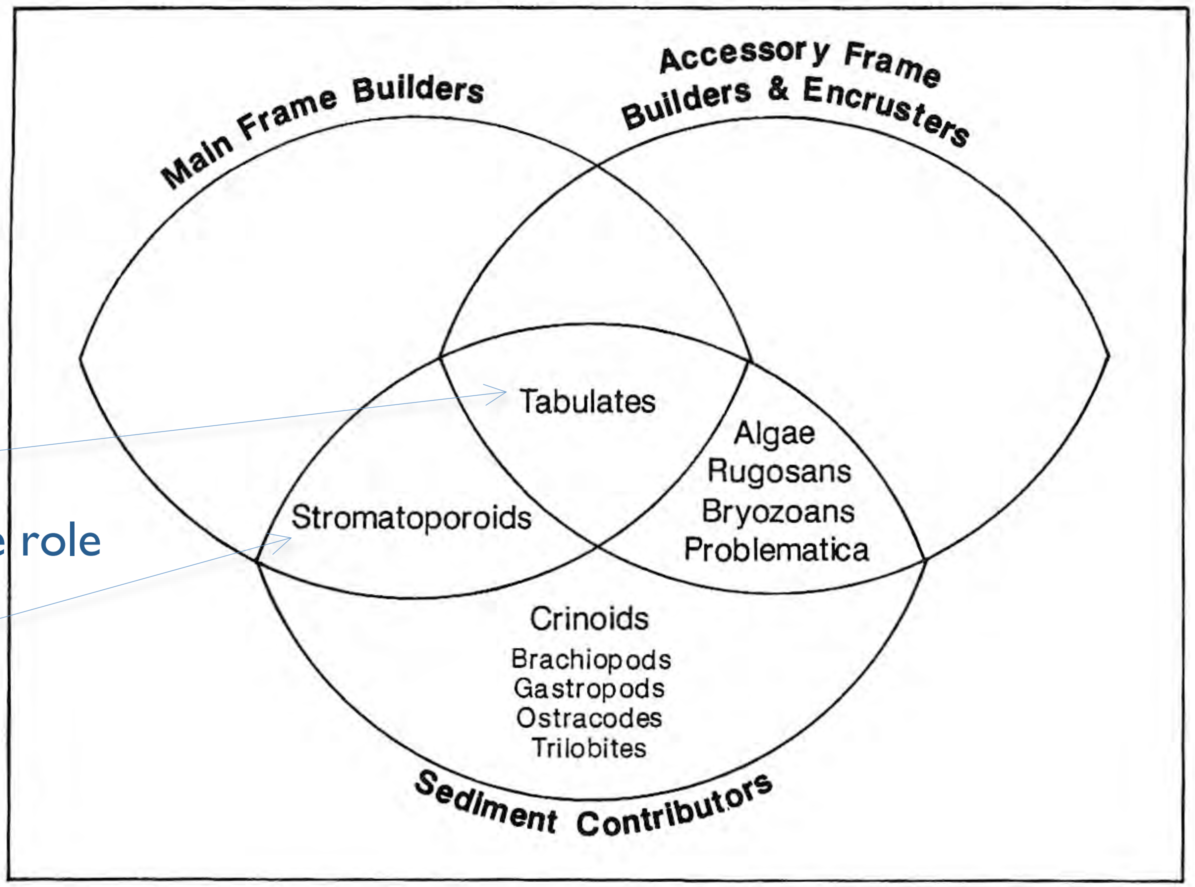
A reef is a mosaic of organisms/sediments, with very abundant **BIO**erosion and PHYSICAL erosion (waves, currents, storms). The reef is a mixture of 'altered' parts and in place 'autochthonous' organisms

Reef types and role of the various organisms involved.
Stromatolites can act as frame-builders while microbial mats
acts as ballflers, binders and precipitators (*in* Tucker & Wright 1990)



Principal **sedimentological** roles of **calcified** organims in Silurian of Europe (Riding, 1981)

More than one role



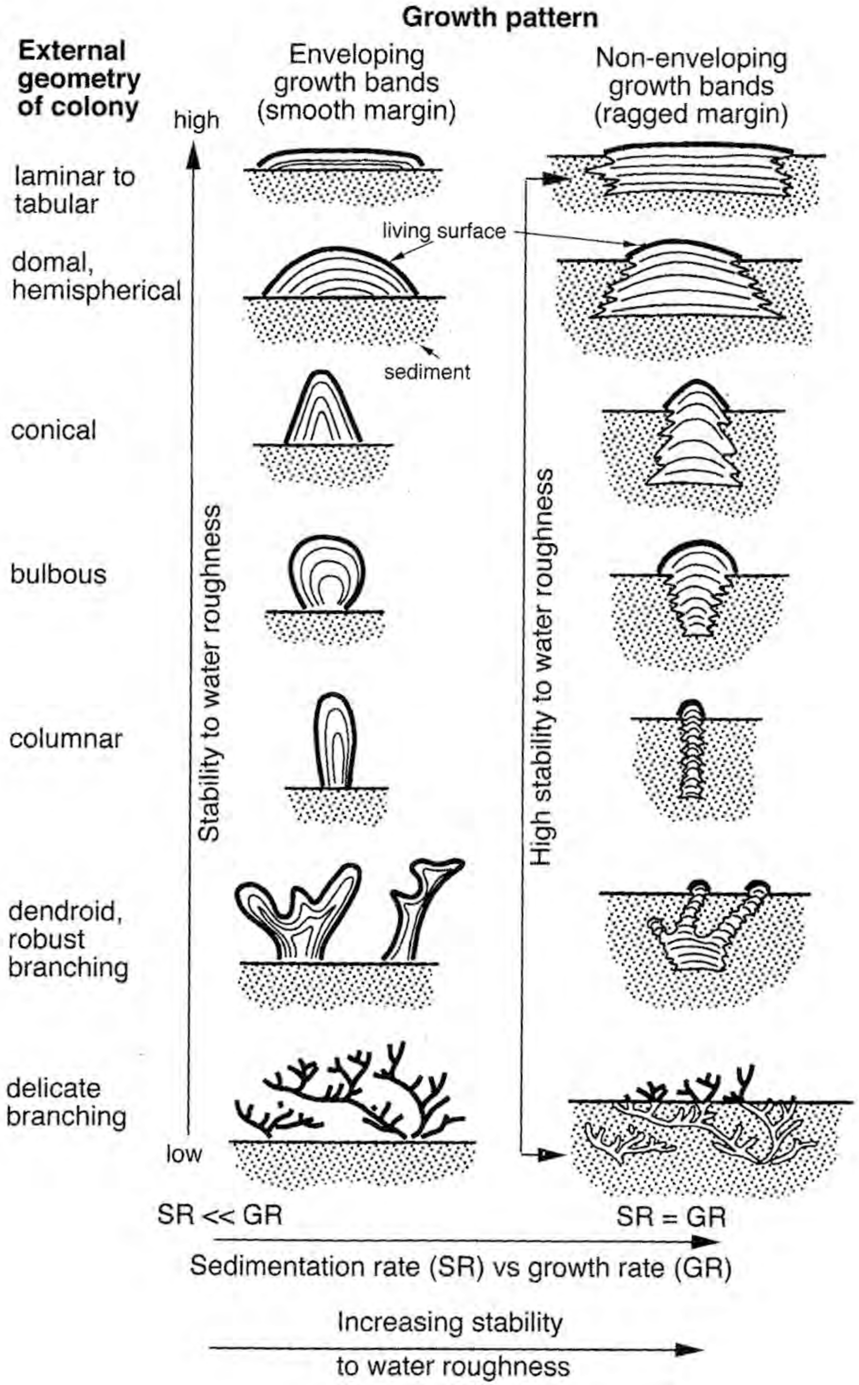
Red algae (solenoporaceans) were abundant in these reefs, but **unlike** crustose coralline algae in modern-day reefs, they were **not able to encrust** and acted as accessory frame-builders. <u>The encrusting role was filled by *problematica* and stromatolites</u>.

Controls on growth froms and growth patterns of colonial reef builders

⇒ water energy

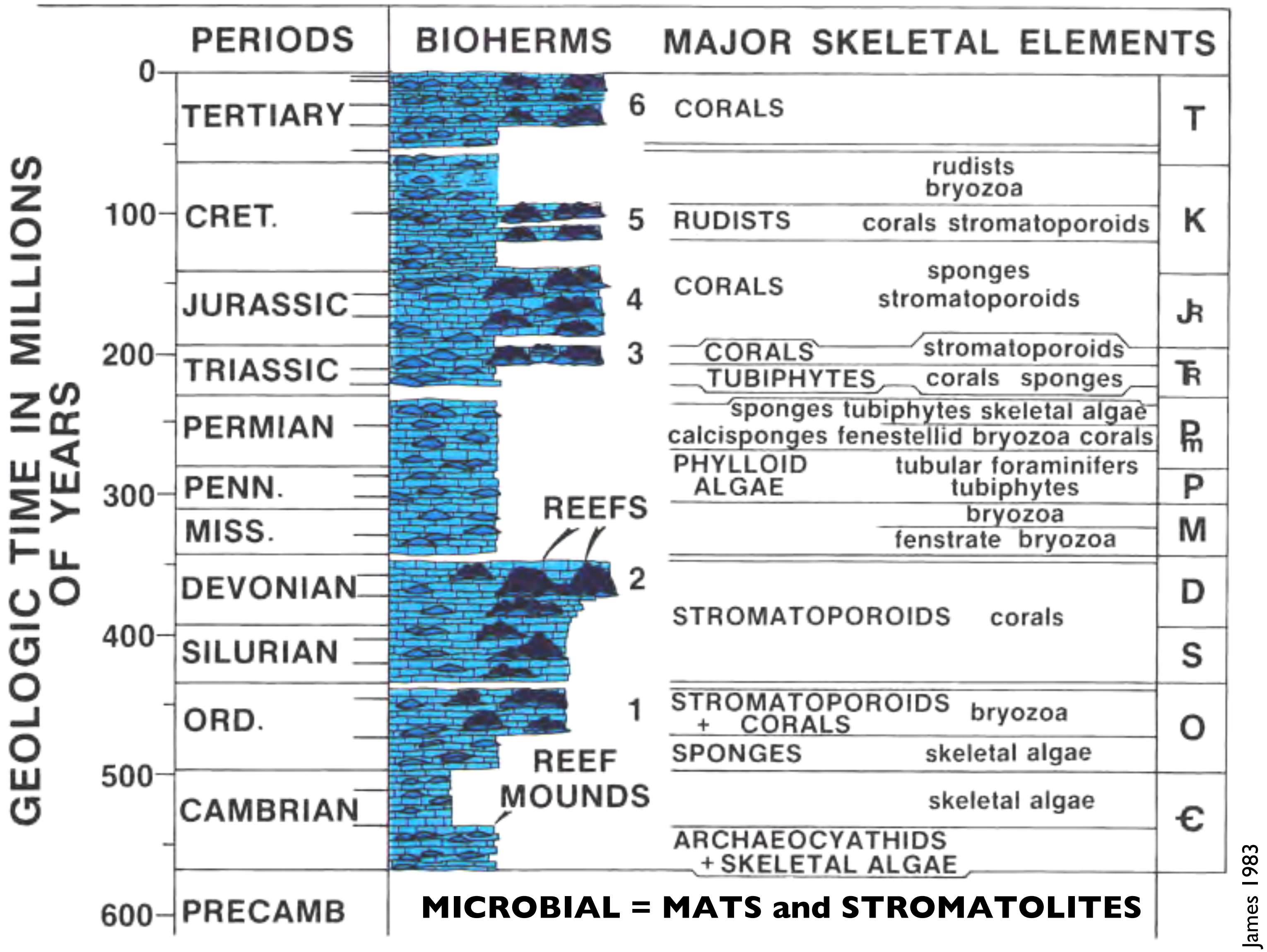
⇒ relative rate of sedimentation

(James & Bourque 1992)



REEFAL CARBONATES
also a long story ….

nb *Tubiphytes* : microfossil of unknown systematic position = 'encruster'



Stromatolites, SIc, Neoproterozoic Congo-Brazza *Préat 2012*

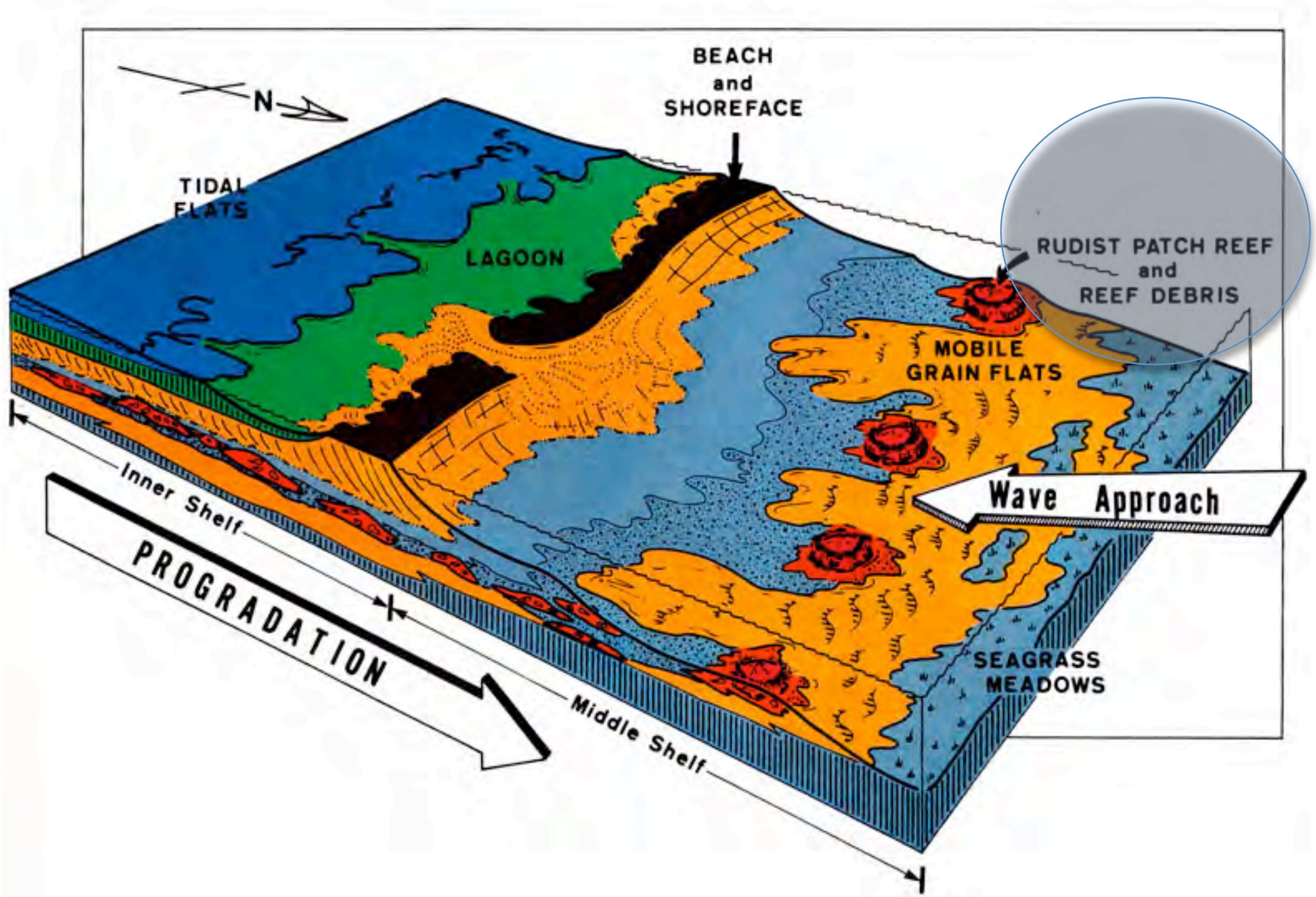
Stromatolites
SIIIc, Neoproterozoic
Congo-Brazza
Préat 2012

LLH-Stromatolites and microbial mats (partially silicified)

Sc3, Neoproterozoic, Nyanga basin, Gabon

Préat 2006

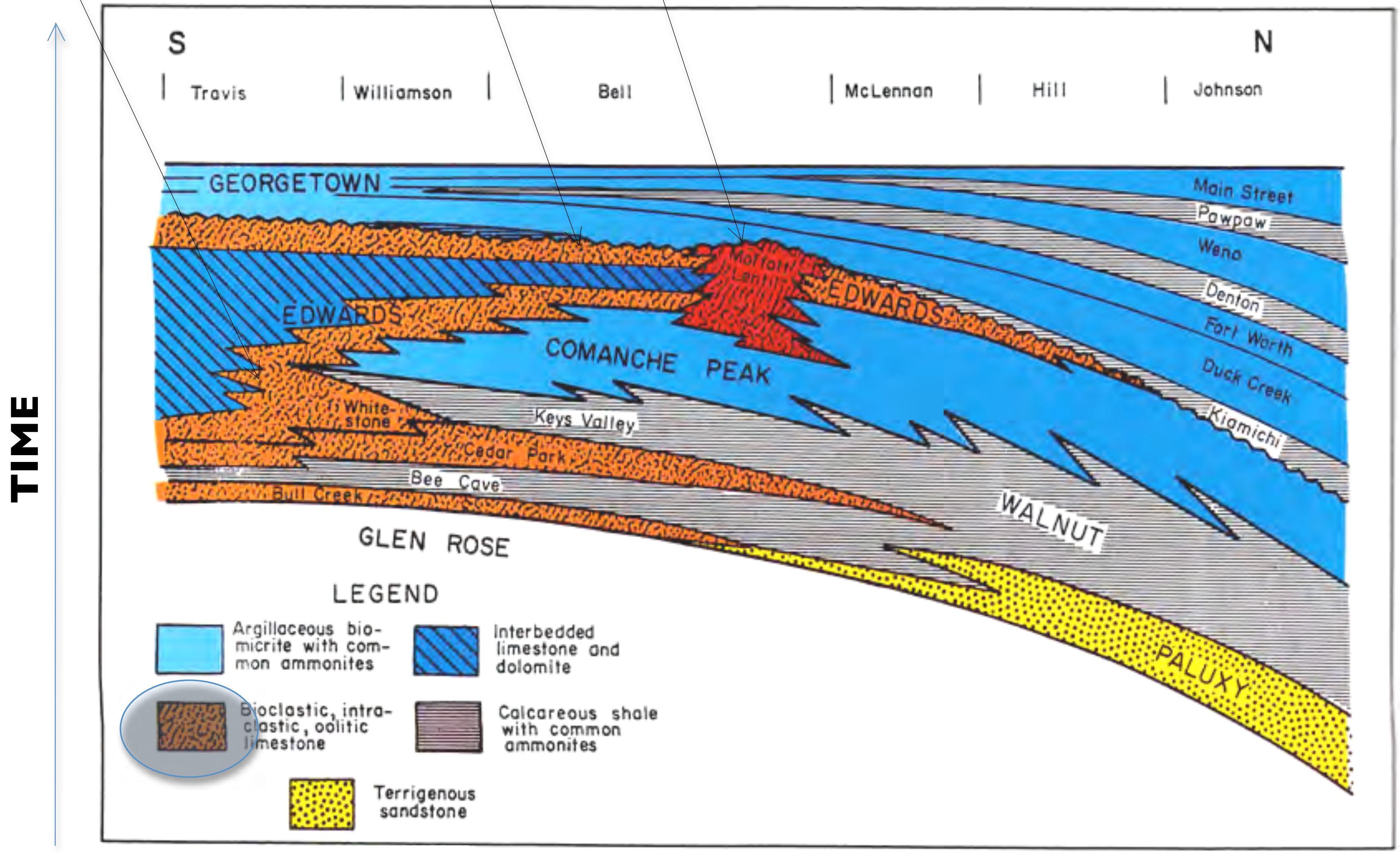
Present-day stromatolite (and fish nursery) in Shark Bay, Australia



Depositional model of the Edward Limestone, Texas, Cretaceous (Kerr 1977)

Rudist Patch-Reef

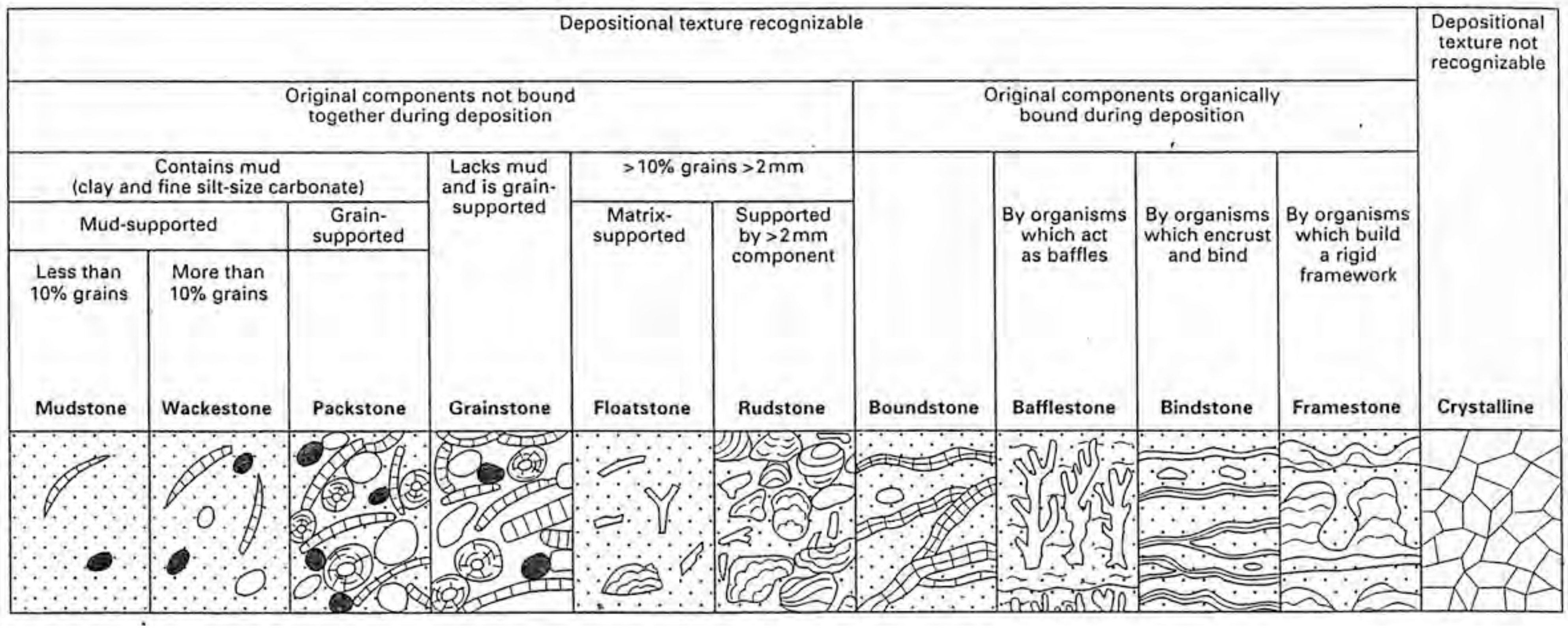
reworked patch-reef and mixing with other grains



Cross section along the ‘Edwards’ Limestone, Texas, Cretaceous (Rose1972).
Upward shoaling facies in a northerly direction.

CLASSIFICATION OF CARBONATES
a long story ….

Expanded classification (Dunham 1962, Embry & Klovan 1971)



CLASSIFICATION OF CARBONATES : SYNTHESIS
Dunham 1962 , Embry & Klovan 1971, Wright 1992

CLASSIFICATION OF LIMESTONES (DUNHAM 1962)

DEPOSITION TEXTURE RECOGNIZABLE					DEPOSITIONAL TEXTURE NOT RECOGNIZABLE
Original components not bound together during deposition				Original components were bound together during deposition as shown by intergrown or lamination contrary to gravity, sediment-floored cavities that are roofed over by organic or questionable organic matter and are too large to be interstices	CRYSTALLINE CARBONATE (Subdivide according classification designed to bear on physical texture or diagenesis)
Contains mud (particles of clay and fine silt size)			Lacks mud and is grain-supported		
Mud-supported		Grain-supported			
less the 10% grains	more than 10% grains				
MUDSTONE	WACKESTONE	PACKSTONE	GRAINSTONE	BOUNDSTONE	

EXPANDED CLASSIFICATION (EMBRY and KLOVAN 1971)

ALLOCHTHONOUS LIMESTONE ORIGINAL COMPONENTS NOT ORGANICALLY ORIGINAL BOUND DURING DEPOSITION						AUTOCHTHONOUS LIMESTONE COMPONENTS ORGANICALLY BOUND DURING DEPOSITION		
Less than 10% > 2 mm components contains lime mud (< 0.03 mm)			no lime mud	Greater than 10% > 2 mm components		by organisms which		
Mud supported		Grain-supported		Matrix-supported	> 2 mm component supported	build a rigid framework	encrust and bind	act as bafflers
less than 10% grains (> 0.03 mm and < 2 mm)	greater than 10% grains							
						BOUNDSTONE		
MUDSTONE	WACKESTONE	PACKSTONE	GRAINSTONE	FLOATSTONE	RUDSTONE	FRAMESTONE	BINDSTONE	BAFFLESTONE

REVISED CLASSIFICATION (WRIGHT 1992)

DEPOSITIONAL				BIOLOGICAL			DIAGENETIC			
Mixed supported clay and silt grains)		Grain-supported		In situ organisms			Non-obliterative			Obliterative
< 10% grains	> 10% grains grains	with matrix	no matrix	rigid organisms dominant	encrusting binding organisms	organisms acted to baffle	main component in cement	many grain contacts micro-stylolites	most grain ascontacts are micro-stylolites	crystals > 10 μm
CALCI-MUDSTONE	WACKE-STONE	PACK-STONE	GRAIN-STONE	FRAME-STONE	BOUND-STONE	BAFFLE-STONE	CEMENT-STONE	CONDENSED GRAINSTONE	FITTED GRAINSTONE	SPARSTONE
	FLOATSTONE	RUDSTONE								Crystals < 10 μm MICRO-SPARSTONE
	Grains > 2 mm									

Flügel 2004

Limestone Type According to Energy Index	Limestone Sub-Types	Mineralogy	Texture: Size	Texture: Sorting	Texture: Roundness	Fossil Abundance and Complexity	Characteristic Fossils[1] Fossil Associations Fossil Preservation
QUIET I Deposition in quiet water	I₁	Calcite Clay (15 to 50%) Detrital quartz (<5%)	Microcrystalline carbonate (<0.06 mm) or any size fossil fragments in a microcrystalline carbonate matrix (matrix <50%)	Matrix—good Fossils—poor	Original fossil shapes; angular fragments if broken	Barren to moderately fossiliferous Simple assemblages	Crinoids; echinoids; bryozoans (fragile branching types); solitary corals; ostracodes; thin-shelled brachiopods, pelecypods, and gastropods; Foraminifera; sponge spicules; tubular, encrusting, and sediment-binding algae; fecal pellets of bottom scavengers. Common fossil associations are crinoid-bryozoa assemblages, bivalve shell assemblages, Foraminifera assemblages (predominantly planktonic). Many fossils are whole and unbroken and are not mechanically abraded. Any fragmentation of fossil material probably is due to disarticulation upon death, to predatory (boring, opening, and breaking) activity and scavenger activity, or to solution.
	I₂	Calcite (predominant) Clay (<15%) Detrital quartz (<5%)					
	I₃		Any size fossil fragments in microcrystalline matrix (matrix <50%)	Matrix—good Fossils—moderate to good		Moderately to abundantly fossiliferous Simple assemblages (coquinoid limestone)	
INTERMITTENTLY AGITATED II Deposition alternately in agitated water and in quiet water	II₁	Calcite (predominant) Clay (<25%) Detrital quartz (<50%)	Microcrystalline matrix (>50%). Micrograined to medium-grained clastic carbonate and terrigenous material	Matrix—good Clastic material—poor to good	Clastic carbonate material subangular to rounded. Roundness of terrigenous clastics is principally a function of size. Oölites may be present	Barren to moderately fossiliferous. Moderately simple assemblages	Characteristic fossils and fossil associations are similar to Type I limestones. Fossil materials are more fragmental than those in Type I limestones and also may be more or less rounded by wave action. Scattered fragments of fossils from rougher water environments may be present.
	II₂		Microcrystalline matrix (>50%). Coarse- to very coarse-grained clastic carbonate and terrigenous material				
	II₃		Interbedded microcrystalline carbonate and any size clastic. Microscale rhythmic bedding	Sorting good within individual lamina		Barren to moderately fossiliferous. Moderately complex assemblages	
SLIGHTLY AGITATED III Deposition in slightly agitated water	III₁	Calcite (predominant) Detrital quartz (up to 50%)	Micrograined clastic carbonate (<0.06 mm) predominates	Matrix—good Clastic material—moderate to good	Clastic material subrounded to well rounded. Fine-grained oölites may be present	Barren to sparsely fossiliferous Simple assemblages	Echinoderm, bryozoan, and bivalve shell debris; Foraminifera; encrusting algae. Common fossil associations are Foraminifera-abraded bivalve shell fragment assemblages. Fossil materials comminuted from larger fossil structures are well abraded by wave and current action.
	III₂		Very fine-grained clastic carbonate (0.06 to 0.125 mm) predominates			Barren to moderately fossiliferous Simple assemblages	
	III₃		Fine-grained clastic carbonate (0.125 to 0.25 mm) predominates	Matrix—poor Clastic material—moderate to good		Barren to abundantly fossiliferous Simple to moderately complex assemblages	
MODERATELY AGITATED IV Deposition in moderately agitated water	IV₁	Calcite (predominant) Detrital quartz (up to 50%)	Medium-grained clastic carbonate (0.25 to 0.5 mm) predominates	Matrix—poor Clastic material—moderate to good	Clastic material subrounded to well rounded. Oölites may be present	Moderately to abundantly fossiliferous Simple to moderately complex assemblages	Crinoids, echinoids, bryozoans, brachiopod and pelecypod shell fragments, colonial coral fragments, stromatoporoid fragments (Silurian and Devonian predominantly); tubular algal fragments, colonial algal fragments (rare), encrusting algae. Common fossil associations are similar to associations of Types I, II, and III, or they are mixtures of these associations. Fossil materials are generally broken and abraded.
	IV₂		Coarse-grained clastic carbonate (0.5 to 1.0 mm) predominates				
	IV₃		Very coarse-grained clastic carbonate (1.0 to 2.0 mm) predominates			Moderately to abunantly fossiliferous Moderately complex to complex assemblages	

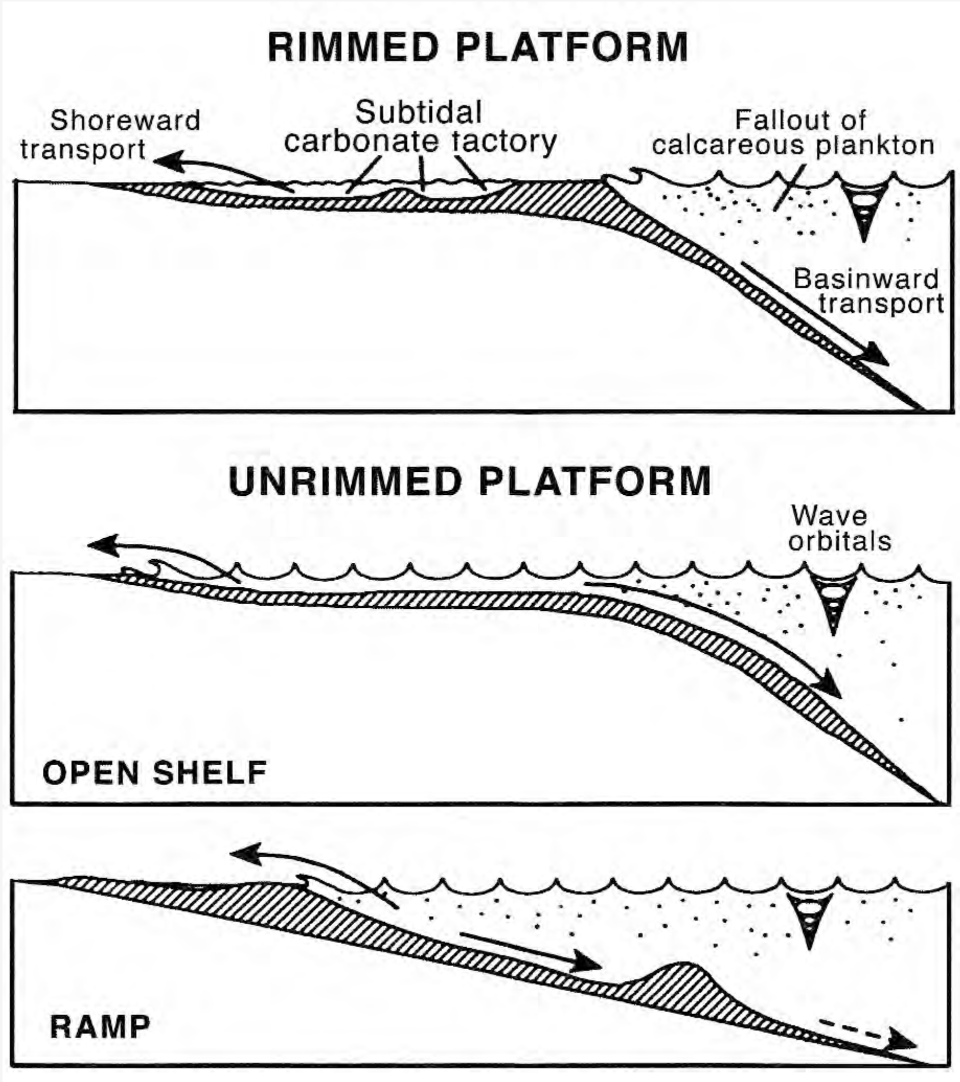
Limestone Type According to Energy Index	Limestone Sub-Types	Mineralogy	Texture: Size	Texture: Sorting	Texture: Roundness	Fossil Abundance and Complexity	Characteristic Fossils[1] Fossil Associations Fossil Preservation
STRONGLY AGITATED V Deposition and growth in strongly agitated water	V₁	Calcite (predominant) Clay (<5%) Detrital quartz (<25%)	Gravel-size clastic carbonate (rock fragments and fossil material >2.0 mm) predominates	Matrix—poor Clastic material—poor to moderate	Clastic material subrounded to well rounded. Pisolites may be present	Sparsely to moderately fossiliferous Complex assemblages	Crinoids; echinoids; encrusting bryozoans; thick-shelled brachiopods, pelecypods, and gastropods; colonial coral fragments; stromatoporoid fragments (Silurian and Devonian predominantly); colonial algal fragments; rudistid fragments (Cretaceous predominantly). Fossil associations are similar to Type IV associations. Fossil materials are generally broken and abraded.
	V₂		Gravel-size conglomeratic or brecciated carbonate (>2.0 mm) Tectonic breccias excluded	Matrix—poor Clastic material—poor	Clastic material angular to well rounded	Barren to sparsely fossiliferous Complex assemblages	
	V₃	Calcite	Not applicable	Not applicable	Not applicable	Abundantly fossiliferous Simple assemblages (fossil colonial growth in place)	Colonial corals, stromatoporoids, colonial algae (principally the Rhodophyta or red algae and some genera of the Cyanophyta or blue-green algae).

CARBONATE SYSTEMS/MODELS

Ramps and platforms differ in their geometry, depositional depths and distribution patterns of facies zones. They are controlled by variations in biogenic production as well as by fluctuations in both sea level and in accomodation and sedimentation rates. Microfacies reflect short-term environmental changes and high sea-level fluctuations as well as long-term patterns in the formation of carbonate buildups.

'**Carbonate factories**' are subtidal areas characterized by high carbonate production by predominantly benthic organisms

⇒ max near the PF margin and behind the margin in **RIMMED PF**



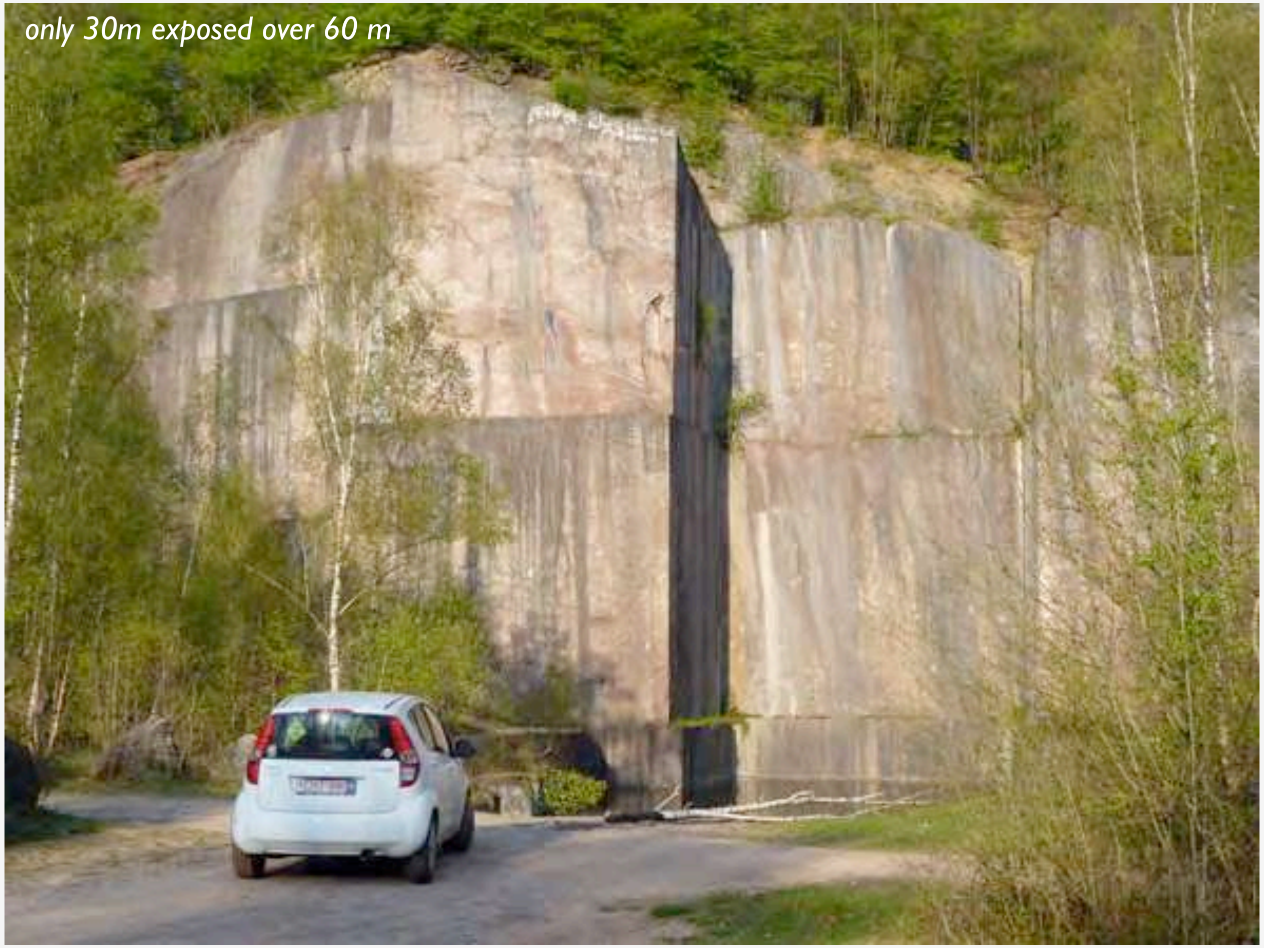
James & Kendall 1992

Rimmed/unrimmed PF are common in tropical and subtropical sunlit waters, **today** ±30°N and S of the equator, and the carbonate factory is primarily controlled by high water T (favoring phototroph carbonate –secreting organisms

⇒ over the entire extension of the **RAMP**

Ramps are common in cool-water zones, extending polward from the limit of the tropical factory to polar latitudes.
Heterotroph organisms are dominant.

Schlager 2000 differentiated a third carbonate factory **= MUD MOUNDS**
characterized by the in situ production of biotically induced and abiotic carbonate mud



Example : Red Mud Mounds/Bioherms, F2ij (Frasnian), Belgium
In situ production by **IRON-BACTERIA**

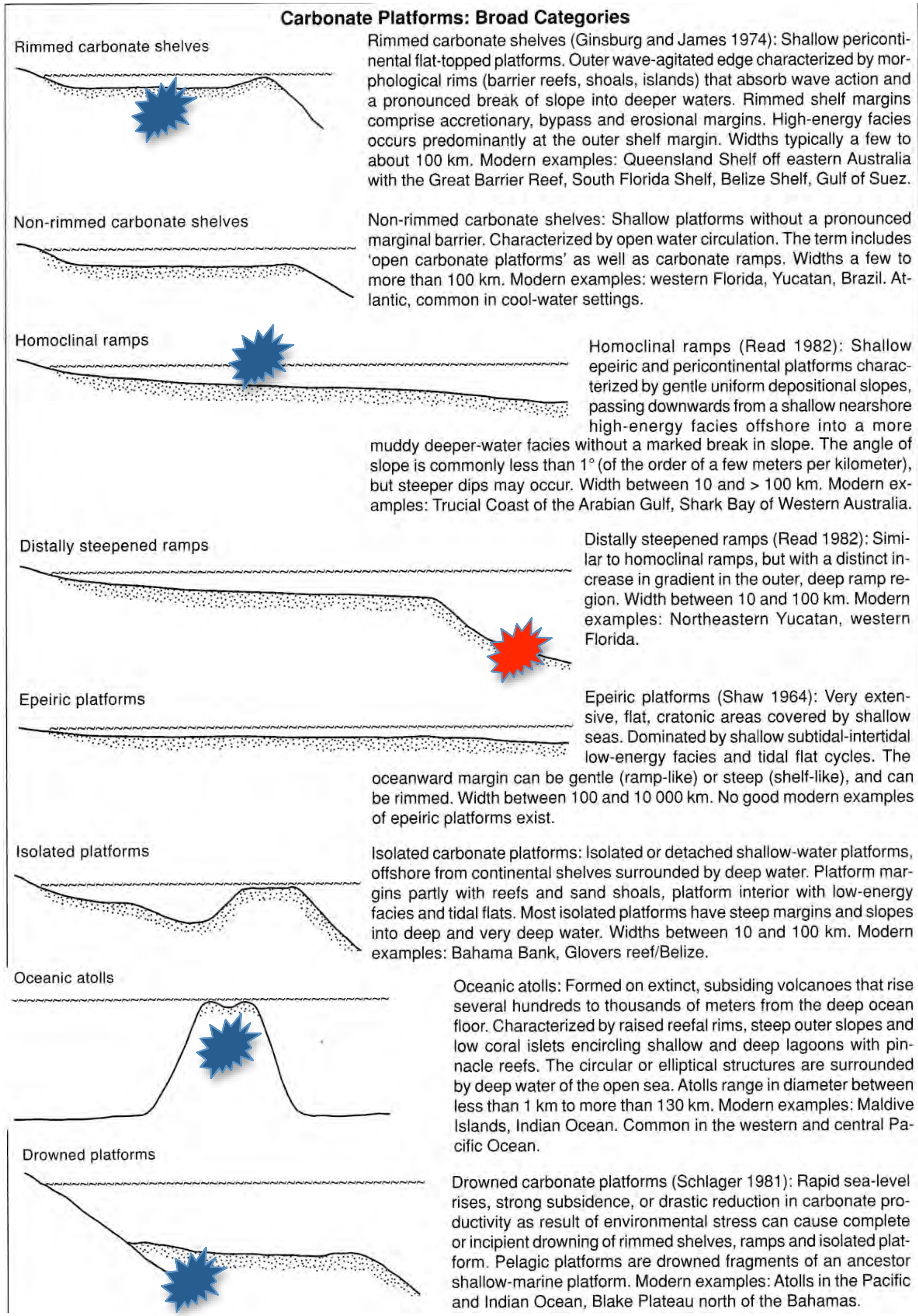
CARBONATE SYSTEMS/MODELS

		Latitudinal range	Sea-water temperature	Sub-division	Latitudinal range	Sea-water temperature	
NON-TROPICAL Carbonates Heterozoan	**POLAR CARBONATES**	>50° N and S	**Cold water** <5 -10 °C (mean) -1.5 to16 °C (range)	polar	>60° N and S (to >70° N)	>5 °C	Beyond the Arctic Circle: Central Greenland Sea, Barents Sea, Ross Sea, Antarctica
				subpolar	>50° to <60° N and S	5 - 10 °C	Arctic eastern Canada, Northern Norway, Western Canadian Shelf Northwestern Europe
	TEMPERATE CARBONATES	30° - 50° (60°) N and S	**Cool water** ~10 -18 °C (mean)	cool-temperate	30° to 50° N and S	5 - 10 °C	Southern Australia, Tasmania, New Zealand
			>10 to 25 °C (range)	warm - temperate	25° to > 30° N 25° to 30° S	10 - 18 °C	Mediterranean Sea, Off North Africa, Southwestern Australia
TROPICAL Carbonates Photozoan	**TROPICAL CARBONATES**	30°N to 30°S	**Warm water** 18 to >22 °C (mean)	subtropical		18 - 22 °C	Bahama, Florida, Bermuda, Persian Gulf, Shark Bay
			18 to 30 °C (range)	tropical		>22 °C	Great Barrier Reef, Indian Ocean, Pacific

Latitudinal distribution and critical sea-water temperature of **MODERN** tropical carbonates, temperate and polar carbonate settings. Cool-water carbonate can also form in tropical regions, where cold currents reduce sea-water temperatures (off the east of S America, off the west coast of Africa and southern Asia) (from Flügel, 2004).

EXAMPLE

'TROPICAL' DEVONIAN IN BELGIUM AND (N FRANCE)



Carbonate Platforms: Broad Categories

Rimmed carbonate shelves

Rimmed carbonate shelves (Ginsburg and James 1974): Shallow pericontinental flat-topped platforms. Outer wave-agitated edge characterized by morphological rims (barrier reefs, shoals, islands) that absorb wave action and a pronounced break of slope into deeper waters. Rimmed shelf margins comprise accretionary, bypass and erosional margins. High-energy facies occurs predominantly at the outer shelf margin. Widths typically a few to about 100 km. Modern examples: Queensland Shelf off eastern Australia with the Great Barrier Reef, South Florida Shelf, Belize Shelf, Gulf of Suez.

Non-rimmed carbonate shelves

Non-rimmed carbonate shelves: Shallow platforms without a pronounced marginal barrier. Characterized by open water circulation. The term includes 'open carbonate platforms' as well as carbonate ramps. Widths a few to more than 100 km. Modern examples: western Florida, Yucatan, Brazil. Atlantic, common in cool-water settings.

Homoclinal ramps

Homoclinal ramps (Read 1982): Shallow epeiric and pericontinental platforms characterized by gentle uniform depositional slopes, passing downwards from a shallow nearshore high-energy facies offshore into a more muddy deeper-water facies without a marked break in slope. The angle of slope is commonly less than 1° (of the order of a few meters per kilometer), but steeper dips may occur. Width between 10 and > 100 km. Modern examples: Trucial Coast of the Arabian Gulf, Shark Bay of Western Australia.

Distally steepened ramps

Distally steepened ramps (Read 1982): Similar to homoclinal ramps, but with a distinct increase in gradient in the outer, deep ramp region. Width between 10 and 100 km. Modern examples: Northeastern Yucatan, western Florida.

Epeiric platforms

Epeiric platforms (Shaw 1964): Very extensive, flat, cratonic areas covered by shallow seas. Dominated by shallow subtidal-intertidal low-energy facies and tidal flat cycles. The oceanward margin can be gentle (ramp-like) or steep (shelf-like), and can be rimmed. Width between 100 and 10 000 km. No good modern examples of epeiric platforms exist.

Isolated platforms

Isolated carbonate platforms: Isolated or detached shallow-water platforms, offshore from continental shelves surrounded by deep water. Platform margins partly with reefs and sand shoals, platform interior with low-energy facies and tidal flats. Most isolated platforms have steep margins and slopes into deep and very deep water. Widths between 10 and 100 km. Modern examples: Bahama Bank, Glovers reef/Belize.

Oceanic atolls

Oceanic atolls: Formed on extinct, subsiding volcanoes that rise several hundreds to thousands of meters from the deep ocean floor. Characterized by raised reefal rims, steep outer slopes and low coral islets encircling shallow and deep lagoons with pinnacle reefs. The circular or elliptical structures are surrounded by deep water of the open sea. Atolls range in diameter between less than 1 km to more than 130 km. Modern examples: Maldive Islands, Indian Ocean. Common in the western and central Pacific Ocean.

Drowned platforms

Drowned carbonate platforms (Schlager 1981): Rapid sea-level rises, strong subsidence, or drastic reduction in carbonate productivity as result of environmental stress can cause complete or incipient drowning of rimmed shelves, ramps and isolated platform. Pelagic platforms are drowned fragments of an ancestor shallow-marine platform. Modern examples: Atolls in the Pacific and Indian Ocean, Blake Plateau north of the Bahamas.

in Flügel 2004

Givetian, Frasnian, Belgium

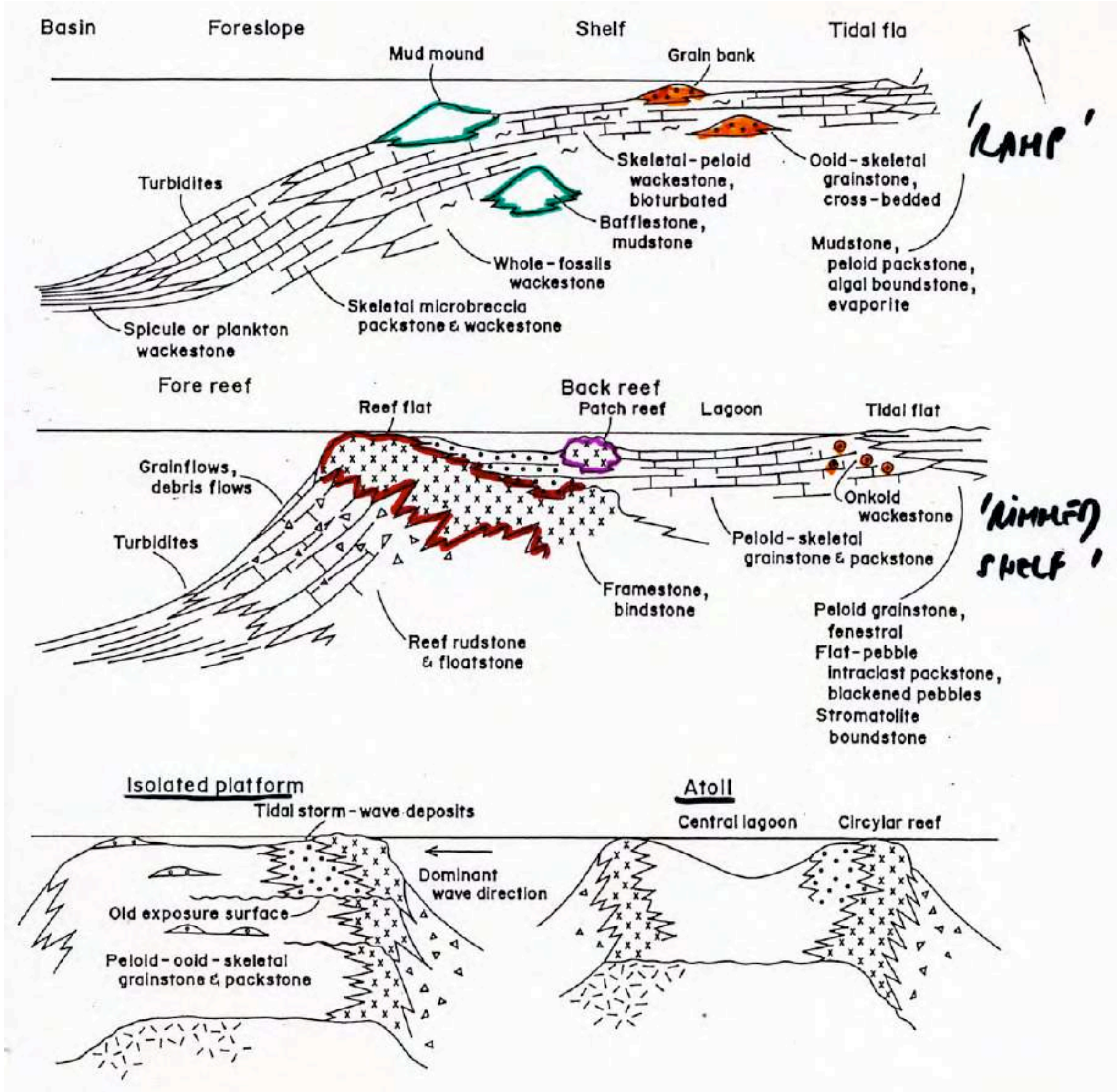
Eifelian, Belgium

Red Mud Mounds Frasnian, Belgium

Frasnian, Belgium (locally)

Lower Frasnian, Belgium

CARBONATE SYSTEMS/MODELS



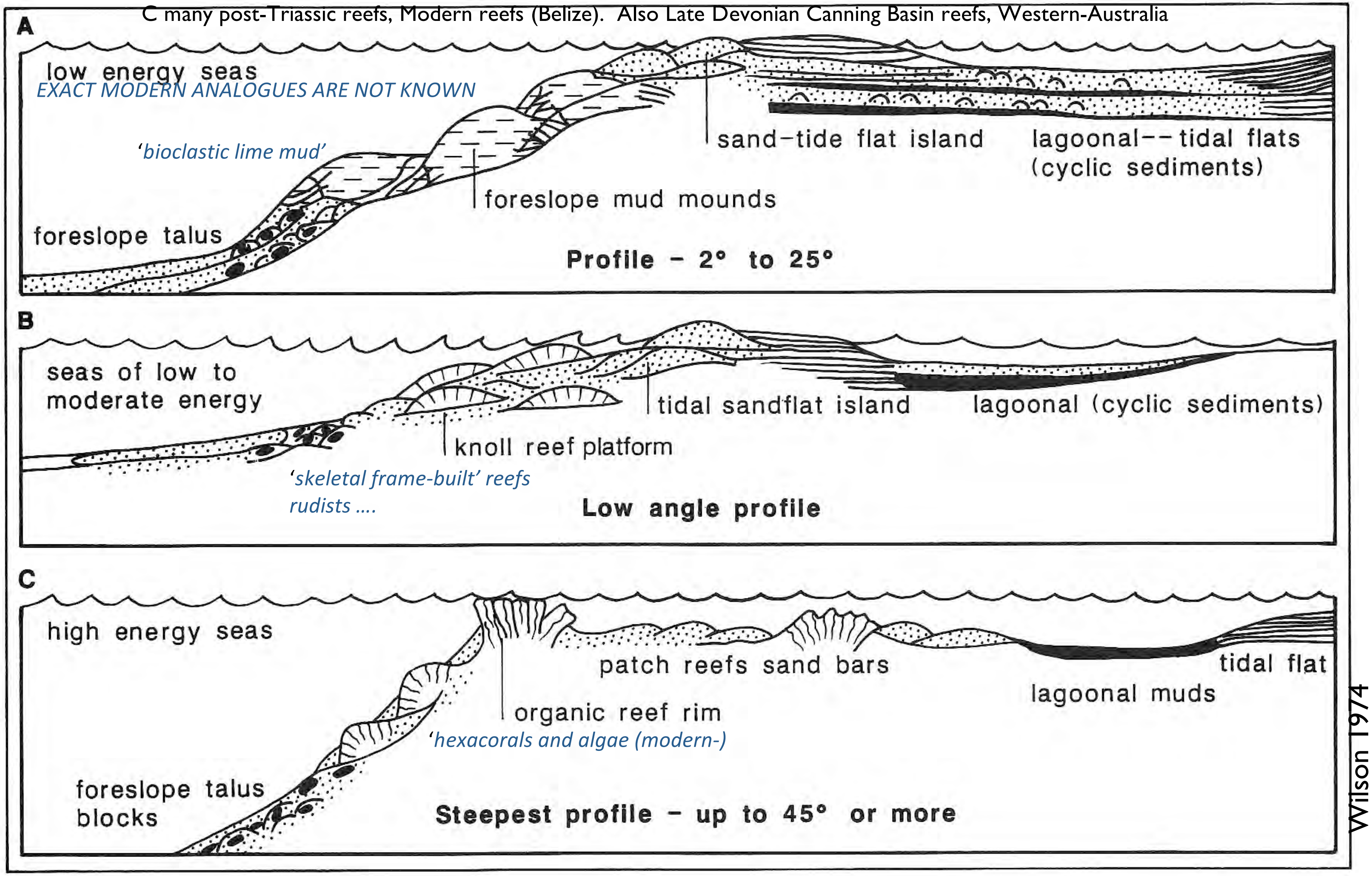
Three types of carbonate shelf margins

A downslope lime-mud accumulation **B** knoll reef ramp or platform **C** organic reef

A Capitan Fm, Permian Reef West texas/New Mexico…+ Waulsortian mounds of Europe (BELGIUM) and N-Amarica…

B Rudist reefs Middle Cretaceous S-Texas, MIDDLE EAST, M-U Dev Canada, Modern Bermuda platform …

C many post-Triassic reefs, Modern reefs (Belize). Also Late Devonian Canning Basin reefs, Western-Australia



CARBONATE SYSTEMS/MODELS
lateral classification of carbonate shelves….

Carbonate shelves

Inner shelf: Near-coast tide-dominated zone including peritidal and shallow subtidal environments varying and restricted salinity; sluggish circulation; biota low-diverse.

Mid-shelf: Extended shallow subtidal zone between the near-shore area and the shelf break; below fair-weather wave-base, but above storm-wave base; mud-dominated but with grainy storm sediments; water depths between a few tens of meters and 100 to 200 m; normal marine, but different conditions in local restricted areas; biota high-diverse.

Outer shelf: Rimmed shelves: A narrow zone near the shelf break, with shoals and reefs. Non-rimmed shelves: A wide zone below normal storm-wave base which may be affected by intruding ocean currents.

Carbonate ramps

Inner ramp: Between upper shoreface (beach or lagoonal shoreline) and fair-weather wave base; seafloor more or less constantly affected by wave agitation; includes shoreline deposits, sand-shoals, and back-barrier peritidal sediments.

Mid-ramp: Between fair-weather wave base and storm-wave base. The bottom is frequently reworked by storm waves and swells. Sediment composition and textures reflect proximal-distal trends.

Outer ramp: Below normal storm-wave base, down to the basin plain. Mud-dominated, but with few storm beds. In deeper zones, restricted bottom conditions may develop.

Wilson & Jordan 1983, Burchette & Wright 1992

CARBONATE SYSTEMS/MODELS
glossary of 'reefal' terms….

Bioherm: Mound or lens-shaped reefal buildup.

Biostrome: Tabular rock body, usually a single bed of similar composition. Laterally extended, dense growth of skeletal organisms. No depositional relief. A rigid framework may or may not be present.

Buildup: A carbonate rock mass that is thicker than laterally equivalent strata, and probably stood above the sea floor during some or all of its depositional history. The term is often very loosely used for reefs, banks or thick massive limestone structures.

Ecologic reef: An ancient reef interpreted as having been built by organisms into a rigid, wave resistant, topographic high on the sea floor (Dunham 1970).

Framework reef: Built by organisms forming a rigid calcareous frame.

Microbial mound: Biogenic mounds, formed by the action of microbes which initiate carbonate precipitation, and bind and trap sediment (James and Bourque 1992).

Mound: A rounded hill-like structure. In the context of reef studies used for counterparts of framework reefs. See microbial mounds, skeletal mounds and mud mounds.

Mud mound: Mud-dominated carbonate buildups (Wilson 1975). Organisms are minor constituents. Syndepositional relief.

Reef: Laterally confined biogenic structures, developing due to the growth or activity of sessile benthic organisms and exhibiting topographic relief. This broad definition covers framework reefs, reef mounds, mud mounds as well as biostromes (Flügel and Kiessling 2002).

Reef mound: Lenticular carbonate bodies consisting of bioclastic mud with minor accounts of organic binding (James 1980). Skeletal organisms are common, but there is no evidence for a prominent in situ skeletal framework. Lime mud/carbonate cement and skeletal organisms are about equally important. Syndepositional relief.

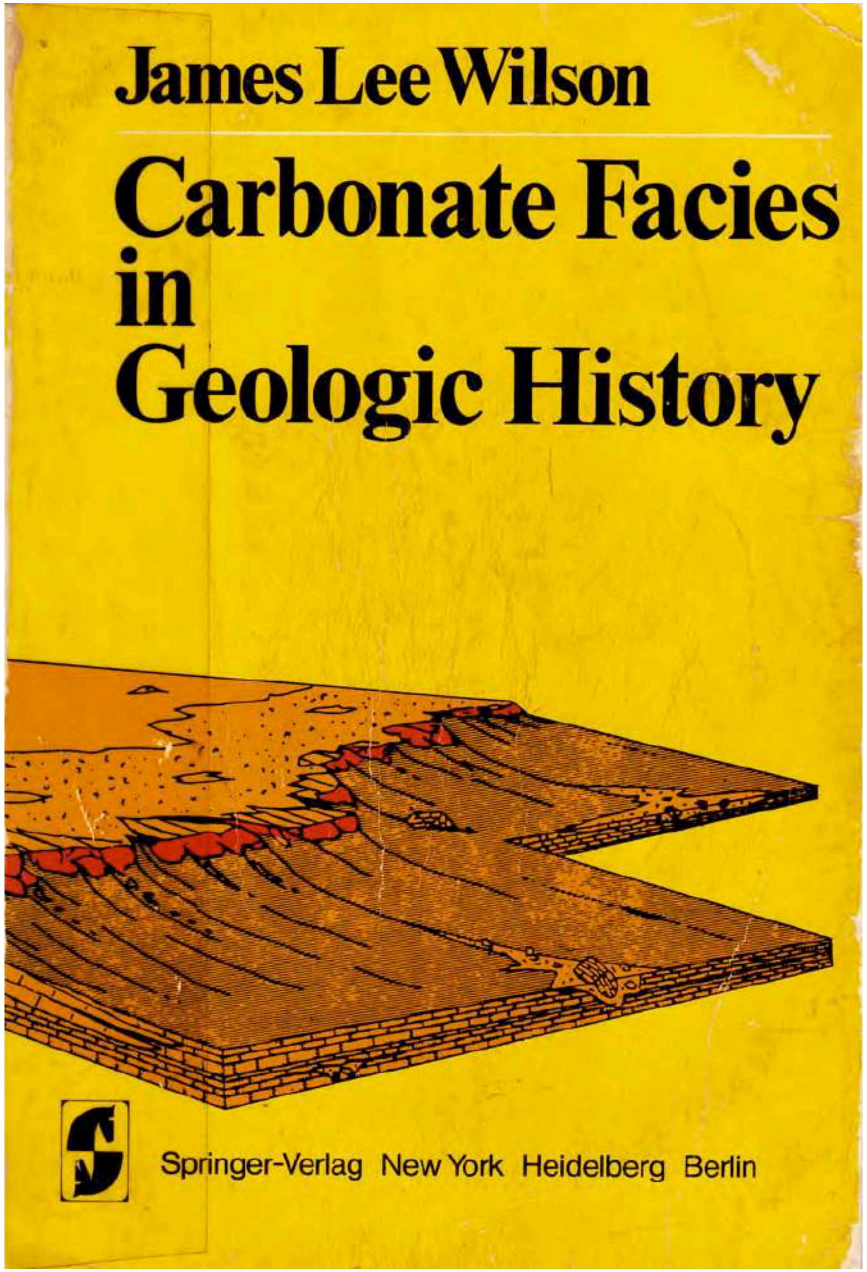
Skeletal mound: Biogenic mounds made of small delicate skeletal or encrusting organisms that are thought to baffle, trap, bind and stabilize lime mud (James and Bourque 1992).

Skeletal reef: Corresponds to framework reefs with organisms, forming a rigid calcareous framework.

Stratigraphic reef: A thick, laterally restricted mass of carbonate rock, without genetic connotations (Dunham 1970).

in Flügel 2004

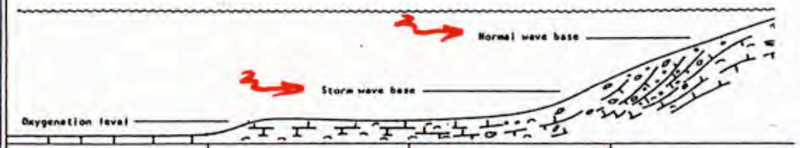
1975
First Synthesis

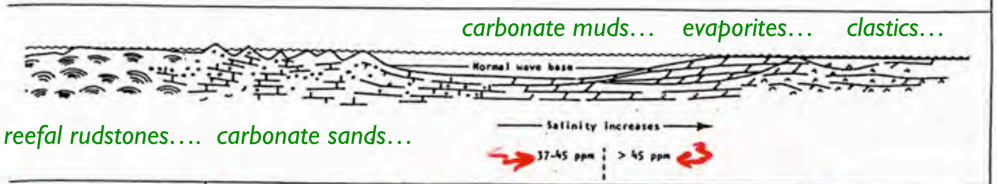


STANDARD FACIES MODEL –WILSON 1975

of a rimmed tropical platform along a **strongly** generalized shore-to-basin transect

9 FACIES BELTS and 24 SMF Standard Microfacies Types



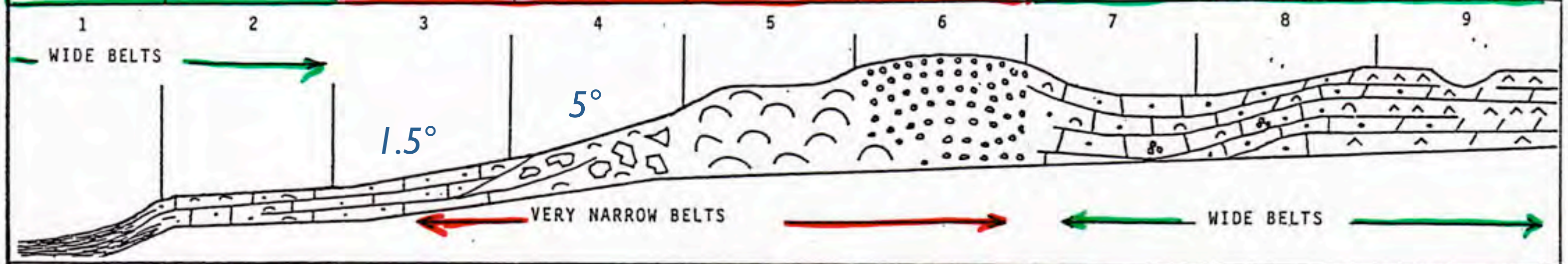


Scaled cross section									
Diagrammatic cross section									
Facies number	1	2	3	4	5	6	7	8	9
Facies	*Basin* (euxinic or evaporitic) a) Fine clastics b) Carbonates c) Evaporites spiculite radiolarian shales	*Open shelf* (undaform) Open marine neritic a) Carbonates b) Shale microbioclastic calcisiltites	*Toe of slope carbonates* radiolarian pelagic micrites	*Foreslope* a) Bedded fine grain sediments with slumps b) Foreset debris and lime sands c) Lime mud masses debris/slumps	*Organic (ecologic) reef* a) Boundstone mass b) Crust on accumulation of organic debris and lime mud; bindstone c) Bafflestone	*Sands on edge of platform* a) Shoal lime sands b) Islands with dune sands	*Open platform* (normal marine, limited fauna) a) Lime sand bodies b) Wackestone-mudstone areas, bioherms c) Areas of clastics	*Restricted platforms* a) Bioclastic wackestone, lagoons and bays b) Litho-bioclastic sands in tidal channels c) Lime mud-tide flats d) Fine clastic units	*Platform evaporites* a) Nodular anhydrite and dolomite on salt flats b) Laminated evaporite in ponds
Lithology	Dark shale or silt, thin limestones (starved basin); evaporite fill with salt	Very fossiliferous limestone interbedded with marls; well segregated beds	Fine grain limestone; cherty in some cases	Variable, depending on water energy upslope; sedimentary breccias and lime sands	Massive limestone-dolomite	Calcarenitic-oolitic lime sand or dolomite	Variable carbonates and clastics	Generally dolomite and dolomitic limestone	Irregularly laminated dolomite and anhydrite, may grade to red beds
Color	Dark brown, black, red	Gray, green, red, brown	Dark to light	Dark to light	Light	Light	Dark to light	Light	Red, yellow, brown
Grain type and depositional texture	Lime mudstones; fine calcisiltites	Bioclastic and whole fossil wackestones; some calcisiltites	Mostly lime mudstone with some calcisiltites	Lime silt and bioclastic wackestone-packestone; lithoclasts of varying sizes	Boundstones and pockets of grainstone; packstone	Grainstones well sorted; rounded	Great variety of textures; grainstone to mudstone	Clotted, pelleted mudstone and grainstone; laminated mudstone; coarse lithoclastic wackestone in channels	
Bedding and sedimentary structures	Very even mm lamination; rhythmic bedding; ripple cross lamination	Thoroughly burrowed; thin to medium; wavy to nodular beds; bedding surfaces show diastems	Lamination may be minor; often massive beds; lenses of graded sediment; lithoclasts and exotic blocks. Rhythmic beds	Slump in soft sediments; foreset bedding; slope bioherms; exotic blocks	Massive organic structure or open framework with roofed cavities; Lamination contrary to gravity	Medium to large scale crossbedding; festoons common	Burrowing traces very prominent	Birdseye, stromatolites, mm lamination, graded bedding, dolomite crusts on flats. Cross-bedded sand in channels	Anhydrite after gypsum; nodular, rosettes, chickenwire, and blades; irregular lamination; carbonate caliche
Terrigenous clastics admixed or interbedded	Quartz silt and shale; fine grain silstone; cherty	Quartz silt, siltstone, and shale; well segregated beds	Some shales, silt, and fine grained siltstone	Some shales, silt, and fine grained siltstone	None	Only some quartz sand admixed	Clastics and carbonates in well segregated beds	Clastics and carbonates in well segregated beds	Windblown, land derived admixtures; clastics may be important units
Biota	Exclusively nektonic-pelagic fauna preserved in local abundance on bedding planes	Very diverse shelly fauna preserving both infauna and epifauna	Bioclastic detritus derived principally from upslope	Colonies of whole fossil organisms and bioclastic debris	Major frame building colonies with ramose forms in pockets; in situ communities dwelling in certain niches	Worn and abraided coquinas of forms living at or on slope; few indigenous organisms	Open marine fauna lacking (e. g. echinoderms, cephalopods, brachiopods); mollusca, sponges, forams, algae abundant; patch reefs present	Very limited fauna, mainly gastropods, algae, certain foraminifera (e. g. miliolids) and ostracods	Almost no indigenous fauna, except for stromatolitic algae

Facies Belts = changes of sedimentology and biology across shore-to-basin transects
SMF derived from **local** MF types looking at joint palaeontology and/or sedimentology

STANDARD FACIES MODEL –WILSON 1975

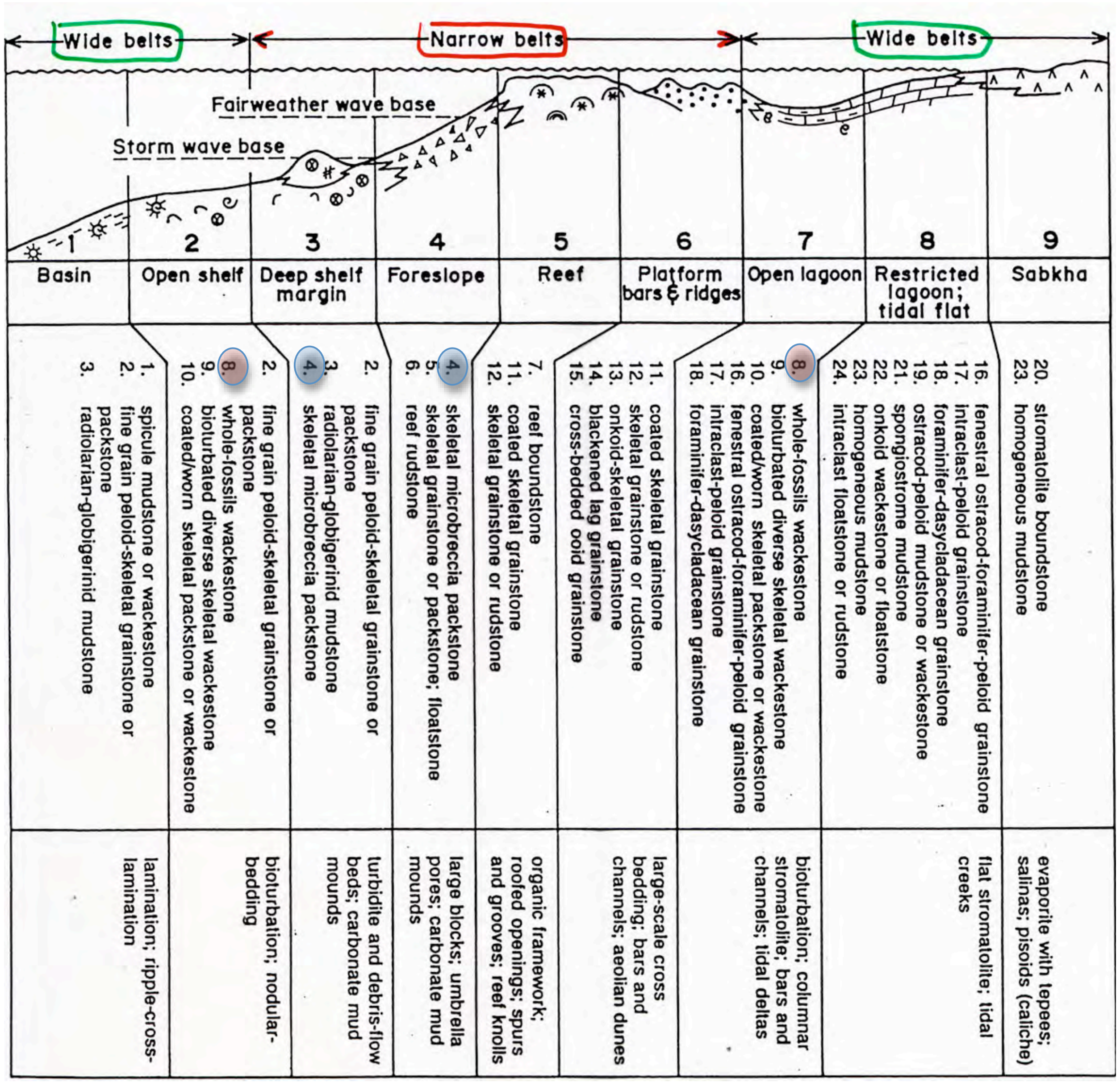
of a rimmed tropical platform along a **strongly** generalized shore-to-basin transect



	BASIN	OPEN SEA SHELF	DEEP SHELF MARGIN	FORESLOPE	ORGANIC BUILD UP	WINNOWED EDGE SANDS	SHELF LAGOON OPEN CIRCULATION	RESTRICTED CIRCULATION SHELF AND TIDAL FLATS	EVAPORITES ON SABKHAS-SALINAS
FACIES PROFILE	1	2	3	4	5	6	7	8	9
2ND ORDER SEDIMENTARY BODIES			DEBRIS FLOWS AND TURBIDITES IN FINE LAMINATE STRATA. MOUNDS ON TOE OF SLOPE.	GIANT TALUS BLOCKS. INFILLED LARGE CAVITIES. DOWNSLOPE MOUNDS.	DOWNSLOPE MOUNDS. REEF KNOLLS. BOUNDSTONE PATCHES. FRINGING AND BARRIER FRAME-WORK REEF. SPUR AND GROOVE.	ISLANDS, DUNES, BARRIER BARS, PASSES AND CHANNELS.	TIDAL DELTAS. LAGOONAL PONDS. TYPICAL SHELF MOUNDS. COLUMNAR ALGAL MATS. CHANNELS AND TIDAL BARS OF LIME SAND.	TIDAL FLATS. CHANNELS NATURAL LEVEES. PONDS. ALGAL MAT BELTS.	ANHYDRITE DOMES. TEPEE STRUCTURES. LAMINATED CRUSTS OF GYPSUM. SALINAS (EVAPORATIVE PONDS) SABKHAS (EVAPORATIVE FLATS)
STANDARD MICROFACIES	1 SPICULITE 2 MICROBIO-CLASTIC CALCISILT 3 PELAGIC MICRITE RADIOLARITE SHALE	2 MICROBIOCLASTIC CALCISILT 8 WHOLE SHELLS IN MICRITE 9 BIOCLASTIC WACKESTONE 10 COATED GRAINS IN MICRITE	2 MICROBIOCLASTIC CALCISILT 3 PELAGIC MICRITE 4 BIOCLASTIC-LITHOCLASTIC MICROBRECCIA	4 BIOCLASTIC LITHOCLASTIC MICROBRECCIA. LITHOCLASTIC CONGLOMERATE. 5 BIOCLASTIC GRAINSTONE-PACKSTONE. FLOATSTONE. 6 REEF RUDSTONE.	7 BOUNDSTONE 11 COATED, WORN, BIOCLASTIC GRAINSTONE. 12 COQUINA (SHELL HASH)	11 COATED, WORN BIOCLASTIC GRAINSTONE 12 COQUINA (SHELL HASH) 13 ONKOIDAL BIOCLASTIC GRAINSTONE 14 LAG BRECCIA 15 OOLITE	8 WHOLE SHELLS IN MICRITE 9 BIOCLASTIC WACKESTONE 10 COATED GRAINS IN MICRITE 16 PELSPARITE 17 GRAPESTONE ONKOIDS IN MICRITE 18 FORAM, DASYCLADACEAN GRAINSTONE	16, 17, 18 19 FENESTRAL PELOIDAL LAMINATE MICRITE 24 RUDSTONE IN CHANNELS 21 SPONGIOSTROME MICRITE 23 NON LAMINATE PURE MICRITE 22 ONKOIDAL MICRITE	20 STROMATOLITIC MICRITE. 23 NON LAMINATE, PURE MICRITE NODULAR-PEARL ENTEROLITHIC ANHYDRITE. SELENITE BLADES IN MICRITE.
	no O_2	*no O_2*	*(O_2)*	*O_2*	*O_2*	*O_2*	*O_2*	*(O_2)*	*O_2(O_2)*
	below WB below PhZ 100'-1000'm [30-100'm in cratonic basin]	*below FW WB 'near' SWB "near' PhZ 200-300m*	*below WB 'near' SWB "near' PhZ 200-300m*	*reworking chaotic*	*some meters [to 100'm for mud mounds]*	*some meters with subaerial exposure above FWWB in PhZ*	*above FWWB in PhZ 'm-10'm*	*above FWWB in PhZ 'm-10'm*	*ARID or HUMID*

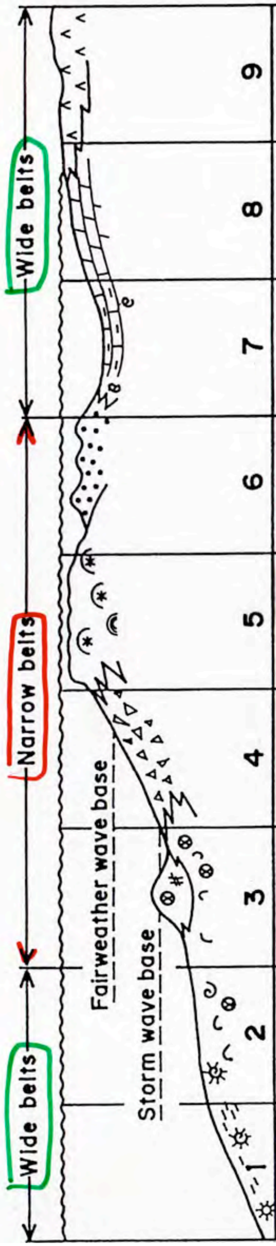
STANDARD FACIES MODEL –WILSON 1975

of a rimmed tropical platform along a **strongly** generalized shore-to-basin transect



STANDARD FACIES MODEL –WILSON 1975

of a rimmed tropical platform along a **strongly** generalized shore-to-basin



9	Sabkha	20. stromatolite boundstone 23. homogeneous mudstone	evaporite with tepees; salinas; pisoids (caliche)
8	Restricted lagoon; tidal flat	16. fenestral ostracod-foraminifer-peloid grainstone 17. intraclast-peloid grainstone 18. foraminifer-dasycladacean grainstone 19. ostracod-peloid mudstone or wackestone 21. spongiostrome mudstone 22. onkoid wackestone or floatstone 23. homogeneous mudstone 24. intraclast floatstone or rudstone	flat stromatolite; tidal creeks
7	Open lagoon	8. whole-fossils wackestone 9. bioturbated diverse skeletal wackestone 10. coated/worn skeletal packstone or wackestone 16. fenestral ostracod-foraminifer-peloid grainstone 17. intraclast-peloid grainstone 18. foraminifer-dasycladacean grainstone	bioturbation; columnar stromatolite; bars and channels; tidal deltas
6	Platform bars & ridges	11. coated skeletal grainstone 12. skeletal grainstone or rudstone 13. onkoid-skeletal grainstone 14. blackened lag grainstone 15. cross-bedded ooid grainstone	large-scale cross bedding; bars and channels; aeolian dunes
5	Reef	7. reef boundstone 11. coated skeletal grainstone 12. skeletal grainstone or rudstone	organic framework; roofed openings; spurs and grooves; reef knolls
4	Foreslope	4. skeletal microbreccia packstone 5. skeletal grainstone or packstone; floatstone 6. reef rudstone	large blocks; umbrella pores; carbonate mud mounds
3	Deep shelf margin	2. fine grain peloid-skeletal grainstone or packstone 3. radiolarian-globigerinid mudstone 4. skeletal microbreccia packstone	turbidite and debris-flow beds; carbonate mud mounds
2	Open shelf	2. fine grain peloid-skeletal grainstone or packstone 8. whole-fossils wackestone 9. bioturbated diverse skeletal wackestone 10. coated/worn skeletal packstone or wackestone	bioturbation; nodular-bedding
1	Basin	1. spicule mudstone or wackestone 2. fine grain peloid-skeletal grainstone or packstone 3. radiolarian-globigerinid mudstone	lamination; ripple-cross-lamination

STANDARD FACIES MODEL –WILSON 1975

of a rimmed tropical platform along a **strongly** generalized shore-to-basin

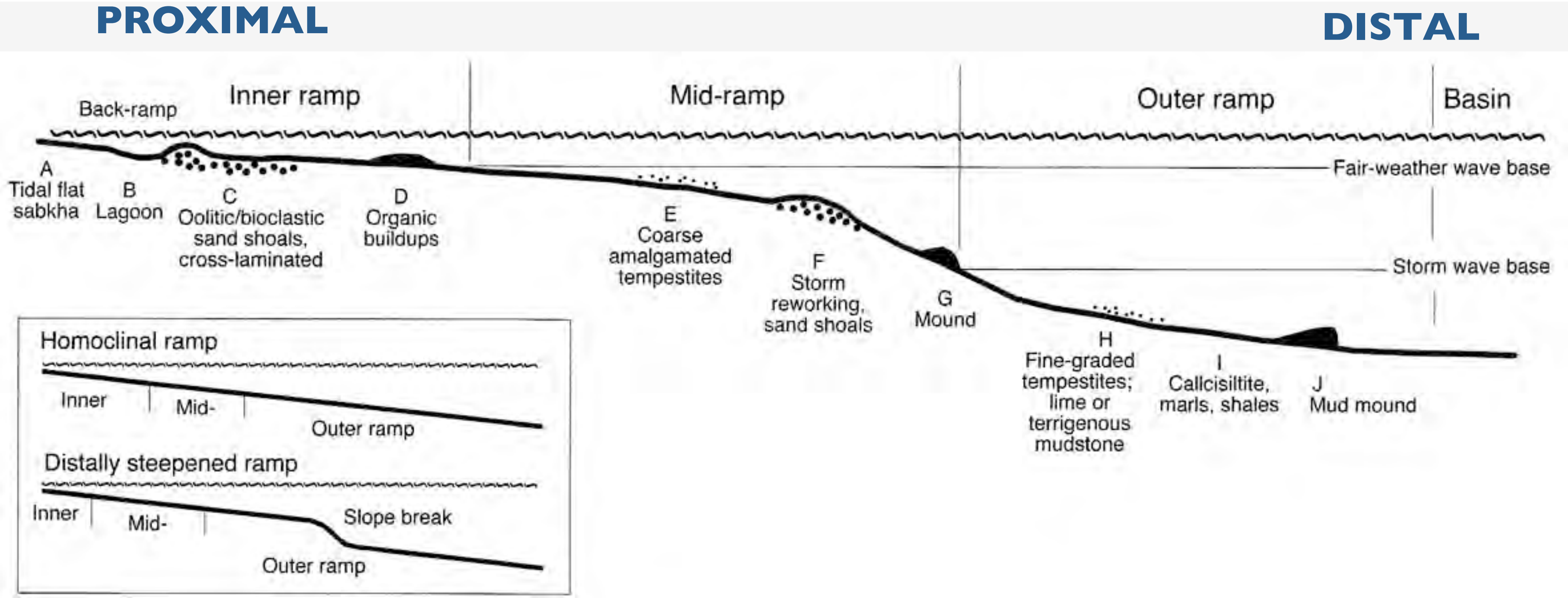
The Wilson FACIES BELTS are limited to tropical platforms and do **NOT** consider platforms in **COOL-WATER** settings that often correspond better to non-rimmed platforms or ramps.

The Wilson model contains more Facies Belts (or 'Zones') than can normally be found on one platform => rimmed platforms usually exhibit a reduced number of Facies Belts, and often a different lateral arrangement of Facies Belts.

The WILSON MODEL was the first one established in the carbonate research….
It developed a static approach and a broad generalization of the carbonate settings
⇒ the model is just a snapshot illuminating potential depositional patterns and their lateral relationships….

=> **TODAY**: **dynamic models** describe the development of (micro)facies belts/ zones during time taking account into variations in water depth related to sea-level fluctuations, accomodation space and biogenic production…

THE CARBONATE RAMP MODEL – AHR1973
and many others authors



Burchette & Wright 1992

A carbonate ramp is a gently dipping sedimentary surface on the sea floor.
The FACIES BELTS are controlled primarily by **ENERGY LEVELS** (FWWB & SWB), variations in ramp topography and material transport by storms, waves and tides.
The depositional slope is usually **less than 1°** (a few m/km).

THE CARBONATE RAMP MODEL – AHR1973

Carbonate ramps can develop during the drowning of shelves and during the early stages of platform formation. Often they evolve into rimmed platforms.

Inner ramp

The inner ramp comprises the euphotic zone between the upper shoreface (beach or lagoonal shoreline) and the fair-weather wave base.The sea floor is almost constantly affected by wave action. The zone is dominated by sand shoals or organic barriers and shoreface deposits. The shallow inner ramp may consist of (1) a beach barrier-tidal delta complex with lagoons and tidal flats behind (back-ramp), or (2) fringing sand banks and shoal complexes with intertidal and supratidal flats, but no lagoons behind, or (3) a strandplain of linear beach ridges with depressions.

Characteristic sediments are carbonate lime sand bodies formed in agitated, shallow subtidal shoreface areas above the fair-weather wave base. The sands consist predominantly of ooids or various skeletal grains, usually foraminifera, calcareous algae, or mollusks. Peloids may be common in places. Storms contribute to the formation of extended sheet-like sand bodies and sand beaches that may grade into eolian dunes. Offshore storm surges transport shoreface sands to deeper, outer ramp settings. Organic buildups in inner-ramp environments are biostromes and small patch reefs characterized by low-diversity biota (e.g. corals, rudists, oysters). Frequent limestone types are grainstones and packstones.

Back-ramp sediments originate in peritidal settings similar to those of inner platforms (comprising mudstones, bindstones and wackestones), and in restricted lagoonal areas (mudstones, wackestones, packstones).

Mid-ramp

The mid-ramp is the zone between fair-weather wave base and the storm wave base. Water depths reach some tens of meters. The bottom sediment is frequently reworked by storm waves and swells. The sediments reflect varying degrees of storm influence depending on the water depth and bottom relief. Intraclast and breccia beds may be common.

Thick oolitic and bioclastic sand shoals are common. Storm-related features are graded packstone, grainstone beds, hummocky cross-stratification, and tempestite couplets. Skeletal grains exhibit signs of transport.

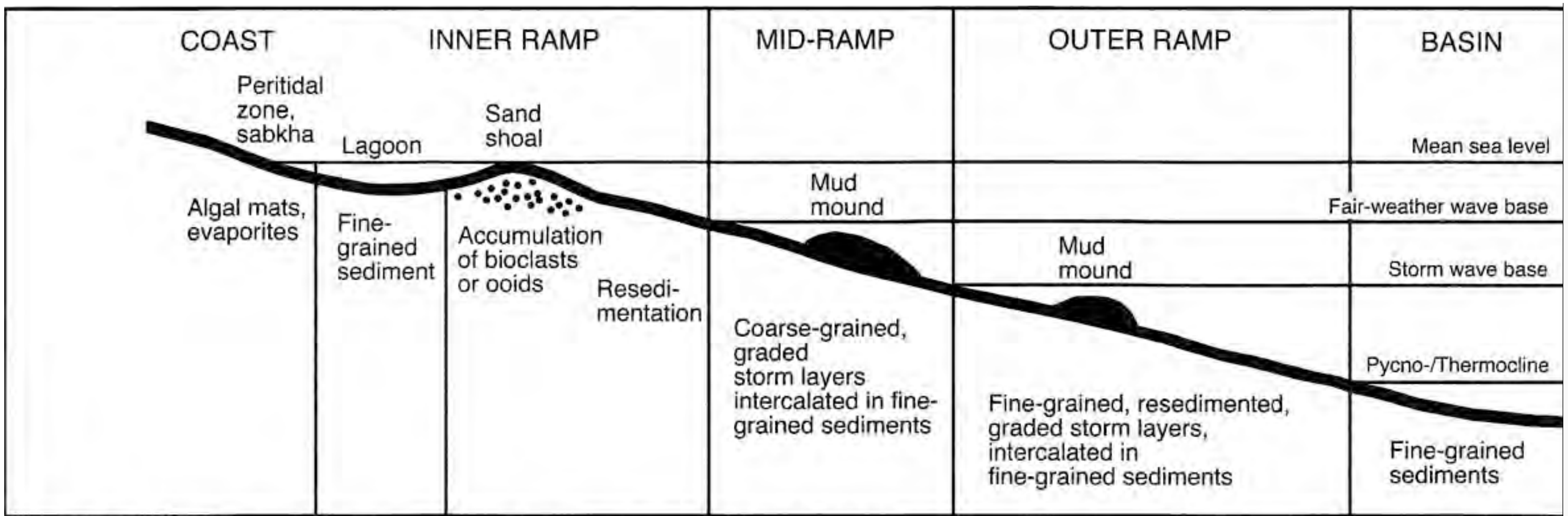
Fair-weather phases are represented by burrowed sediments dominated by lime mud or terrigenous mud forming lime mudstones and marls. Much of the fine-grained sediment might be caused by lateral sediment transport in offshore zones or by transport from the shoreline to mid- and outer ramp areas. Mid-ramp deposits are often thicker than coeval inner ramp deposits. Organic buildups are represented by pinnacle reefs and mounds.

Outer ramp

The outer ramp is the zone below normal storm wave base. Water depths vary between tens of meters and several hundreds of meters. The zone is characterized by low-energy allochthonous and autochthonous carbonates, and hemipelagic sedimentation. Little evidence of direct storm reworking exists, but various storm-related deposits (e.g. graded distal tempestite beds) may occur. Common lithofacies types are bedded, fine-grained limestones (argillaceous lime mudstone and wackestone) associated and interbedded with marl or shale beds. Calcisiltite matrix is abundant. Biota comprise normal marine diverse benthos, sometimes associated with plankton and nekton. Benthic organisms include foraminifera, sponges, bryozoans, brachiopods, mollusks, and echinoderms. Algae may be represented by red algae. Burrows are common. In deeper outer ramp settings restricted bottom conditions may develop. Common organic buildups are mud mounds.

The *slope break of distally steepened ramps* is usually located in a position around the mid- or outer ramp boundary or within the outer ramp. Deposition of slope-derived material may dominate proximal to the break.

THE CARBONATE RAMP MODEL – AHR1973

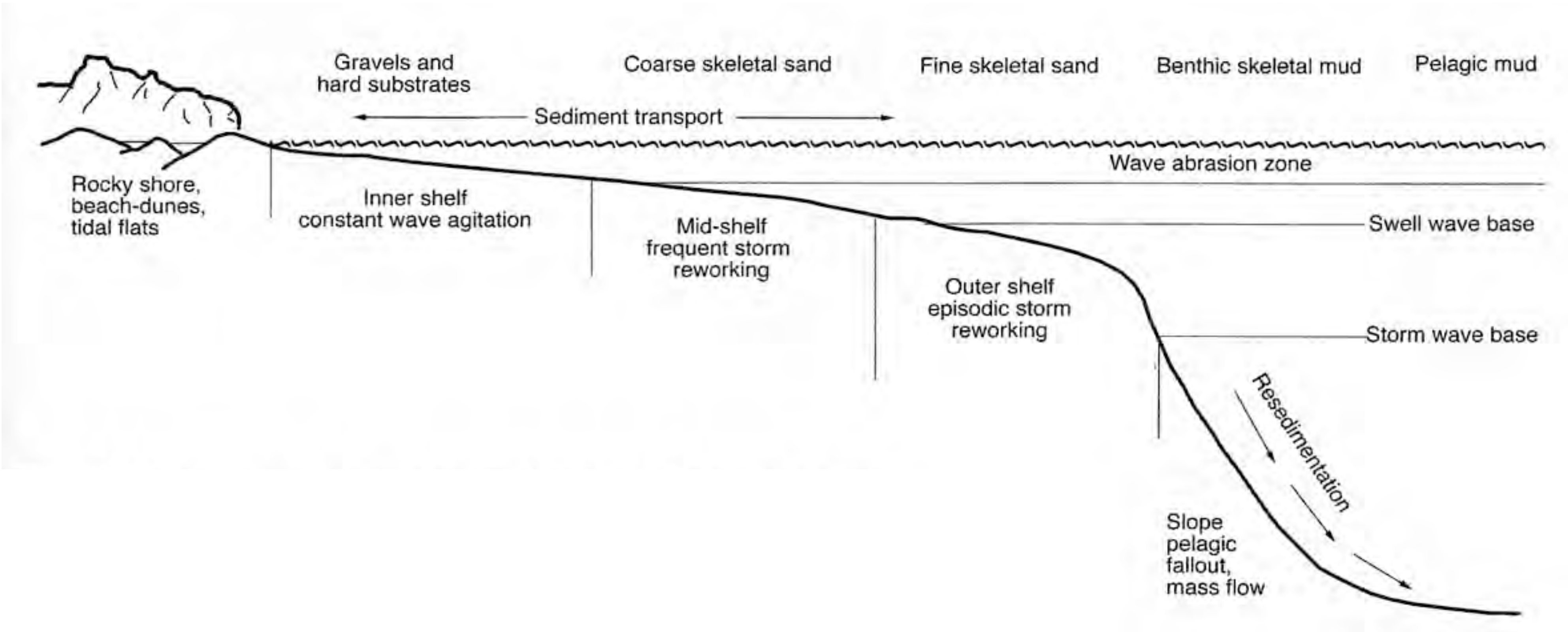


Depositional water energy	Low and high	Low	High	Low	Low and high	Low	Low
Sedimentary structures	Lamination	Irregular bedding, bioturbation	Cross-bedding		Hummocky cross-stratification	Bioturbation, lamination	Lamination
Prevailing carbonate texture in limestones	Mudstones, bindstones, grainstones	Wacke-stones, mudstones	Grain-stones	Wacke-stones, packstones	Wackestones and resedimented grain/packstones, mudstones		Mudstones, bindstones, grainstones

Generalized subdivisions of carbonate ramps (*in* Flügel 2004)

Widths and lengths of ancient carbonate ramps vary within a wide range
Max. width <10km to 800km (most values <200km, generally <10 to ±20km)
Lengths: 10-1600km (if behind 1000km = '**epeiric** ramp'). Most values <500km (10-200km)

NON-RIMMED SHELVES AND PLATFORMS –JAMES 1997
cool-water (temperate) shelf



Base of wave abrasion ranges from 30 m to 70 m
Swell base may reach 120 m
Storm wave base about 250 m

NON-RIMMED SHELVES AND PLATFORMS –JAMES 1997
cool-water (temperate) shelf

Criteria used in the subdivision of a non-rimmed carbonate cool-water shelf

Inner shelf

Depositional processes: Constant wave agitation. Particle abrasion and bioerosion. Winnowing.

Sediment: Zone of sediment movement and active sediment production. Gravels, lithoclastic sands and hard substrates. Subaqueous dunes. Shaved shelf areas.

Biota: Coralline red algae, benthic foraminifera, bryozoans, sponges, bivalves, gastropods, serpulids, echinoids. Deposition of epibionts from high-energy kelp forests and low-energy sea grass.

Mid-shelf

Depositional processes: Frequent storm reworking. Particle abrasion. Sediment transport to outer and inner shelf areas results in sediment-free areas. Bioerosion and burrowing common.

Sediment: Zone of active sediment production. Thin sediment veneer over lithified bedrock. Coarse bioclastic sand. Rippled sands, subaqueous dunes.

Biota: Coralline red algae, mollusks, benthic and planktonic foraminifera, bryozoans, brachiopods, sponges, barnacles, echinoids.

Outer shelf

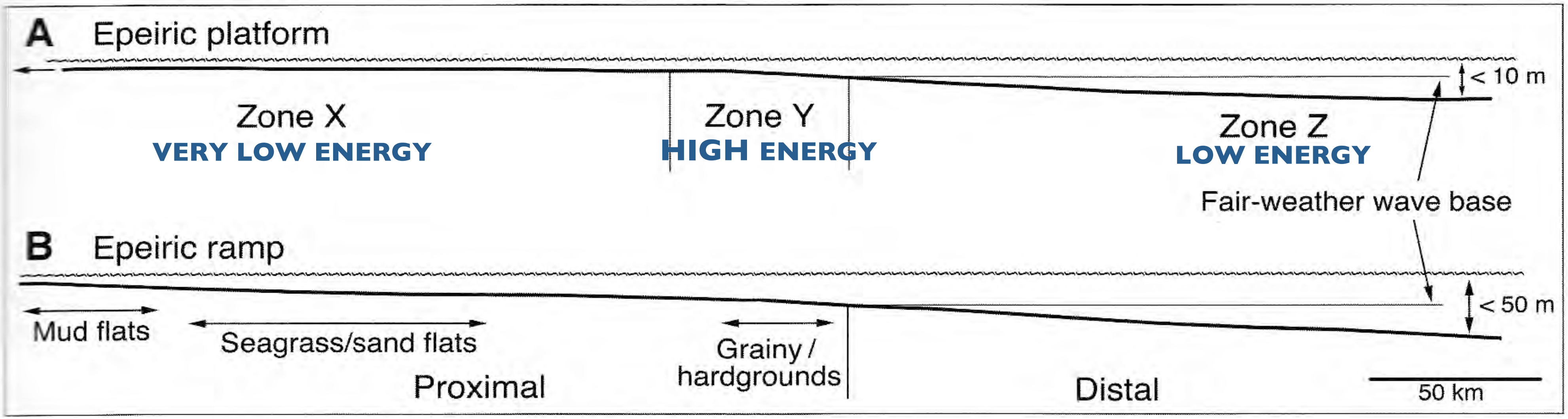
Depositional processes: Sea bottom reworked by episodic storms. Suspension settling. Bioerosion and burrowing common.

Sediment: Zone of carbonate production and accumulation. Fine bioclastic sands. In deeper parts mud (consisting of a mixture of calcitic plankton and skeletal fragments, siliceous sponge spicules, and clay). Burrowed sediments and storm beds.

Biota: Bryozoans, sponges, mollusks, brachiopods, benthic and planktonic foraminifera.

EPEIRIC PLATFORM MODEL – IRWIN 1965

During the Phanerozoic epeiric seas covered **extensive** areas of the cratons
⇒ very shallow, low-energy seas extended for 100' to 1000' km.
Epeiric seas first flooded the margins and later the interior of tectonically stable cratons.
Modern epeiric seas are rare. Examples of warm-water epeiric seas are the Sunda Sea and the Java Sea, cool-water examples are the Baltic Sea, the North Sea and the Hudson Bay.



A. Irwin model B. Lukasik et al 2000 model differing in the nature of the slope and the extent of the basin.
nb : Lukasik et al model is from temperate TERTIARY carbonates from the Murray Basin in Australia.

Characteristics : clear-water sedimentation, extremely low slope angle and regionally extended low-energy conditions and distinct salinity gradient. The inner platform consists of subtidal to intertidal mudflats with widths of tens of 100km, and water depths generally < 10m.

THE ESSO MODEL –FRASNIAN/FAMENNIAN, W CANADA