# 8. Carbonate and Evaporite Environments

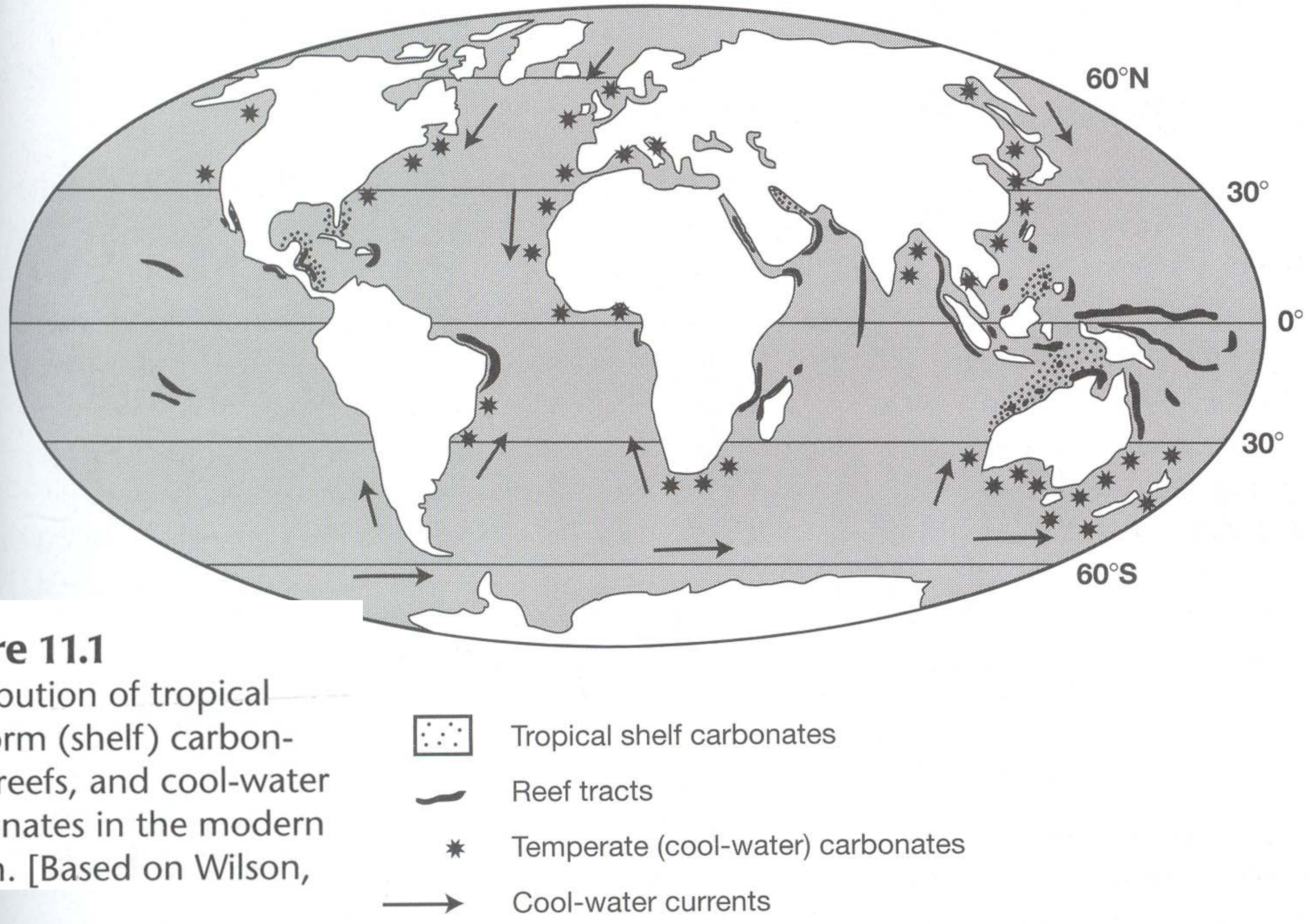



**Figure 11.1**
Distribution of tropical platform (shelf) carbonates, reefs, and cool-water carbonates in the modern ocean. [Based on Wilson,

# 8. Carbonate and Evaporite Environments

8.1 **Introduction**

8.2 **Carbonate Shelf (nonreef) Environments**

- Depositional setting
- Sedimentation processes
  - Chemical and biochemical processes
  - Physical processes
- Skeletal and sediment characteristics of carbonate deposits
- Examples of modern carbonate platforms
- Examples of ancient carbonate shelf successions
  - Isolated platforms
  - Rimmed shelves
  - Ramps
  - Epeiric platforms

8.3 **Slope/Basin Carbonates**

8.4 **Organic Reef Environments**

- Modern reefs and reef environments
  - Depositional setting
  - Reef organisms
  - Reef deposits
  - Low-energy reef facies
- Ancient Reefs
  - Reef deposits
  - Occurrence of ancient reefs

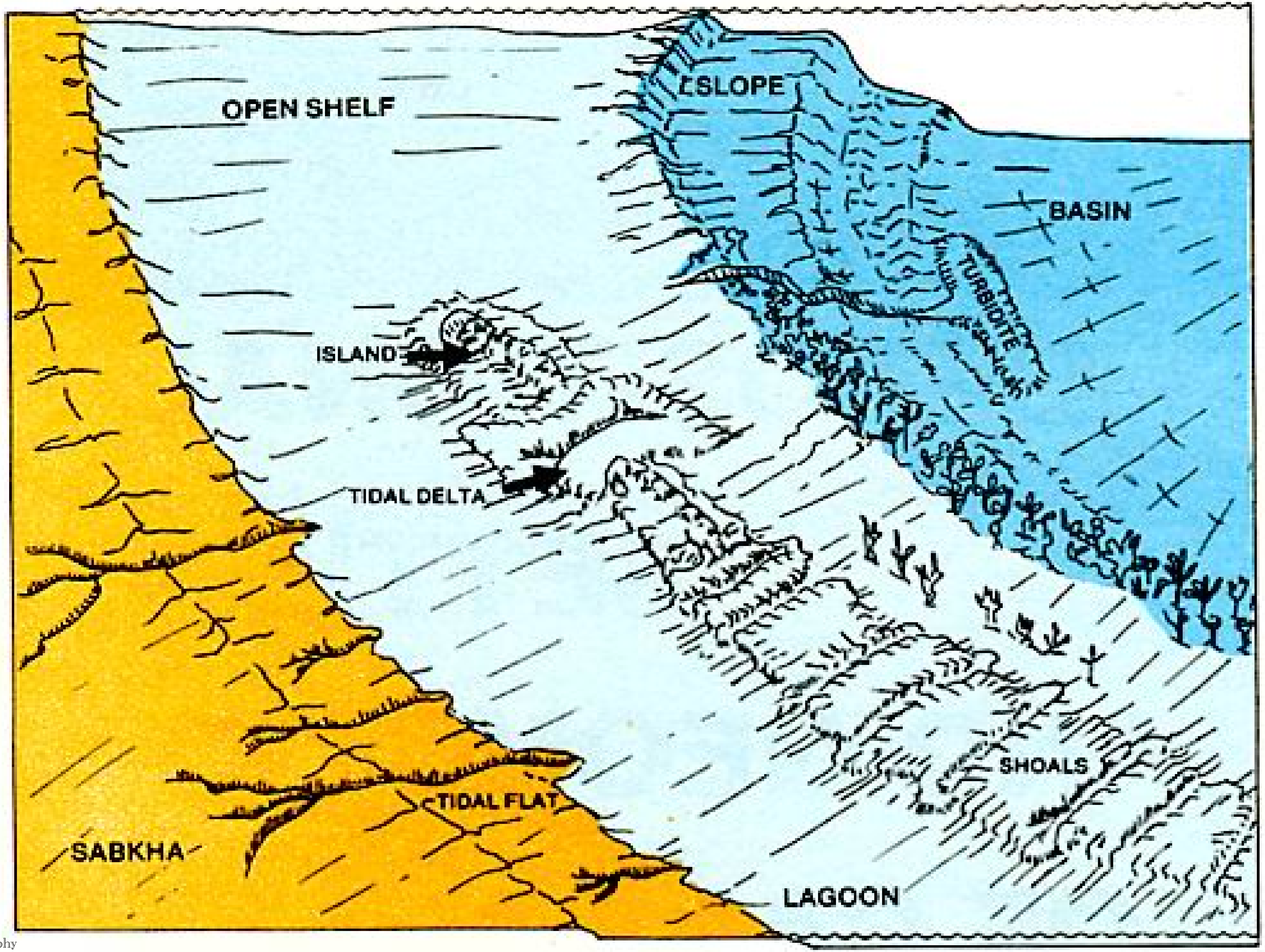
8.5 **Mixed Carbonate-Siliciclastic Systems**

8.6 **Evaporite Environments**

- Modern evaporite environment
  - Nonmarine environment
  - Shallow marine environment
  - Deep-water environment
- Ancient evaporite environment
  - Nonmarine environment
  - Marine environment

# Carbonate depositional settings

- Shelf margin
- Shelf
  - Outer more normal marine
  - Inner restricted
- Margin slope and base of slope
- Basin


SLOPE
OPEN SHELF
BASIN
TURBIDITE
ISLAND
TIDAL DELTA
SHOALS
TIDAL FLAT
SABKHA
LAGOON

# CARBONATE HIERARCHY - UNITS

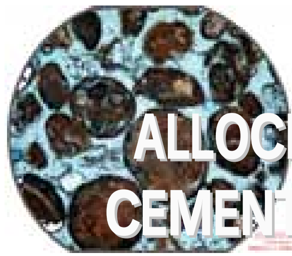
- SHELF COMPLEX **–** Mix of shelf, shelf margin & adjacent basin facies evolving in response to complete & complex cycles of changing base level & paleogeography
- MARGIN COMPLEX **–** Shelf, shelf margin & adjacent basin facies evolving in response to a cycle in changing base level
- STACKED CYCLES OF BEDS **–** Vertical character of beds from varying depositional settings
- BEDDING **–** Internal character including lithology, geometry, sedimentary structures, & fauna
- ALLOCHEMS **–** Lthological components, their cementation & diagenesis

# Hierarchy of Carbonate Shelf Architectural Elements


SHELF COMPLEX


MARGIN COMPLEX

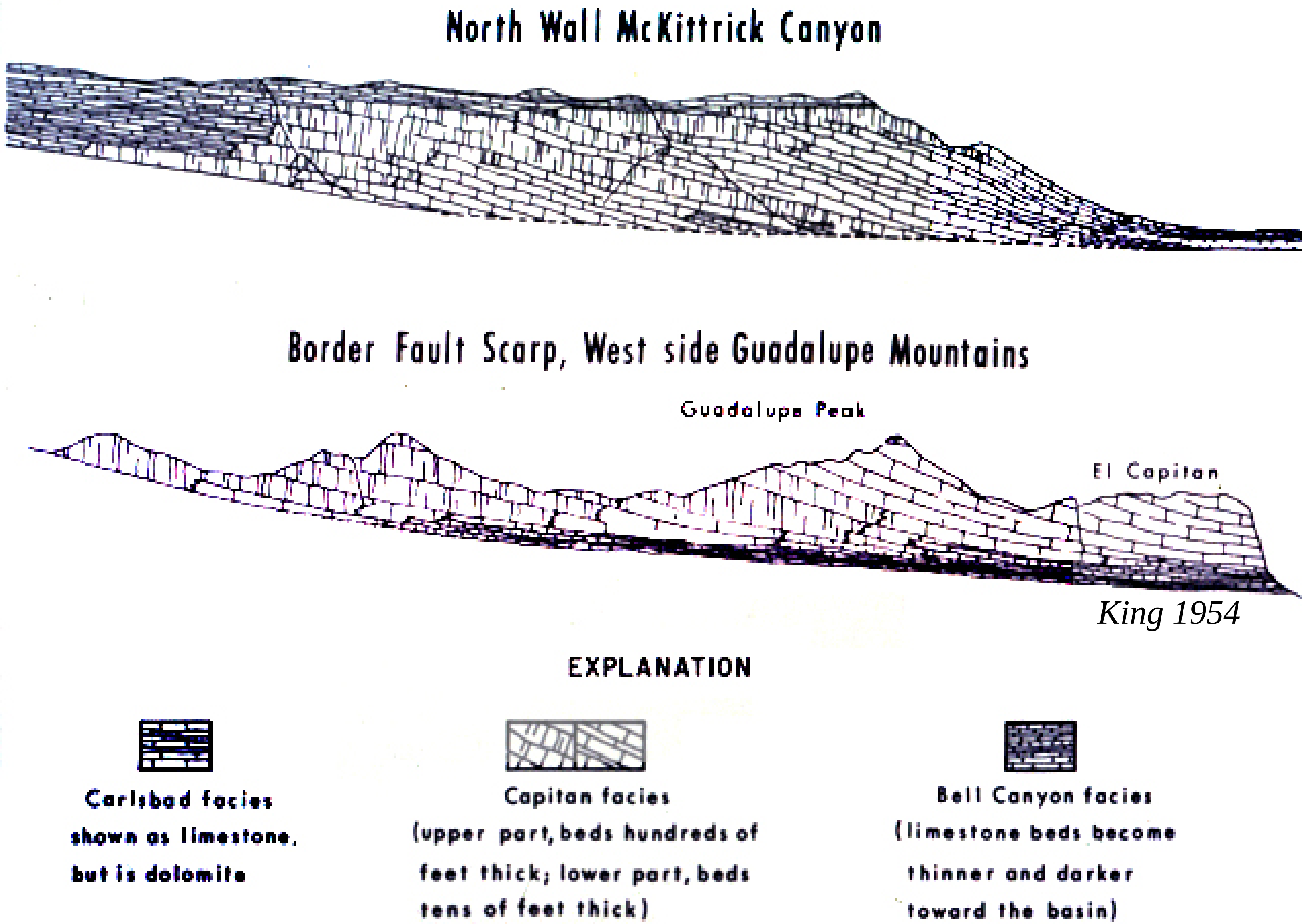




ALLOCHEMS
CEMENTATION
& DIAGENESIS

t

From C. Kendall




*King 1954*

From C. Kendall

# Major Controls on Carbonates

- Bathymetry **–** *Sunlight, temperature & sea floor slope*
- Eustatic sea level **–** *Function of climate & tectonics*
- Turbulence of water **–** *Oxygen, $CO_2$ & Clarity*
- Ocean circulation **–** *Dissolution or precipitation*
- Nutrients **–** *Clastic influx & ocean circulation*
- Climate belt **–** *Tropical, temperate or polar*
- World atmosphere **–** *Aragonite or calcite ocean*
- Tectonic setting **–** *Ocean width & plate position*
- Biologic community **–** *Beat of time* (*evolving party*)

# 8.2 Carbonate Shelf (nonreef) Environment

## Depositional setting

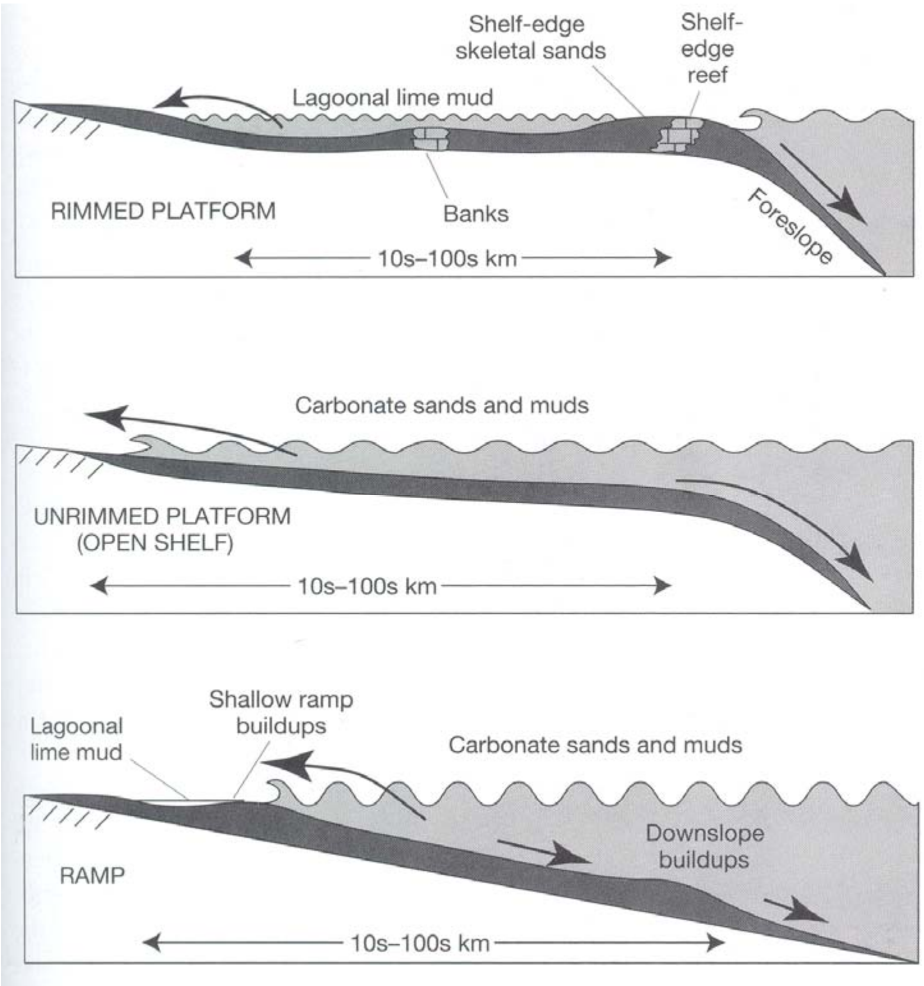
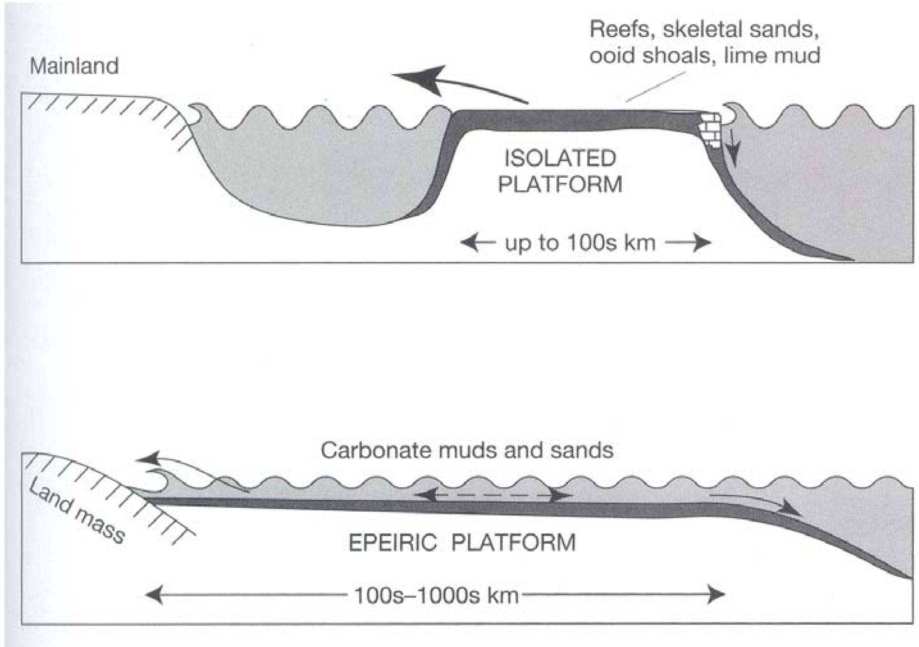



**Figure 11.2**
Schematic representation of principal kinds of carbonate platforms, shown in cross section. Arrows indicate directions of sediment movement. [Based on



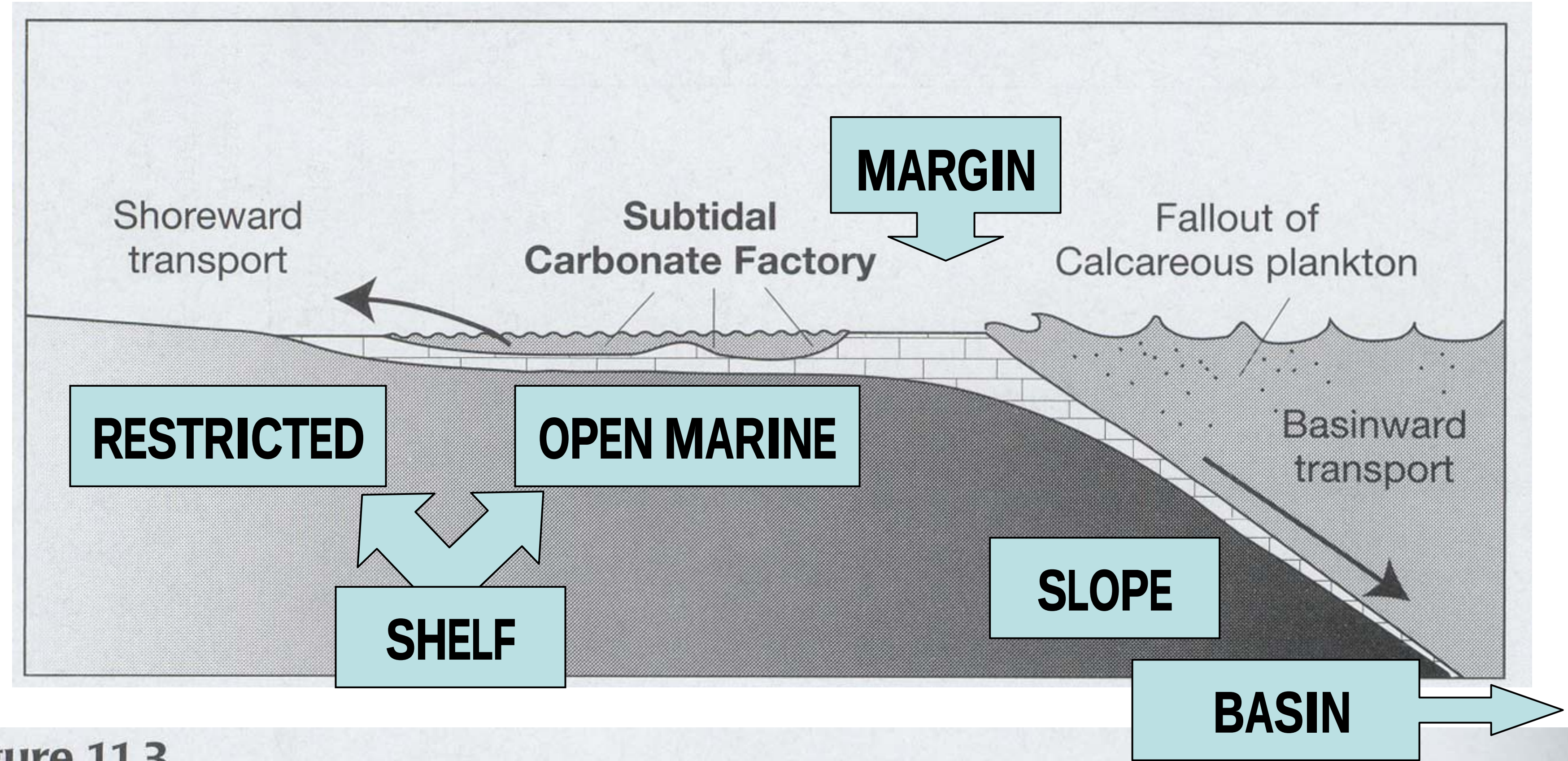



**Figure 11.3**
The main areas of marine carbonate production. Most carbonates accumulate in water less than about 30 m deep—the "subtidal carbonate factory." The example shown depicts carbonate production on a rimmed platform. Similar production takes place on the other platforms illustrated in Fig. 11.2. [After James, N. P., 1984. Introduction to carbonate fa-

**Sedimentation processes**

Physical Processes

# DOMINANT PROCESSES IN CARBONATE ENVIRONMENTS

| PHYSIOGRAPHIC AREA | | PROCESS |
|---|---|---|
| SHELF | LANDWARD EDGE | WIND-DRIVEN WAVES<br>TIDAL EXCHANGE<br>biological activity |
| SHELF | SHELF MIDDLE | WIND, WAVES, AND CURRENTS<br>SLOW TIDAL CURRENTS<br>biological activity |
| SHELF | SHELF MARGIN | TIDAL EXCHANGE<br>BIOLOGICAL ACTIVITY<br>WAVE THRUST |
| SLOPE | | GRAVITY |
| BASIN | | GRAVITY<br>DEEP-SEA CURRENTS |

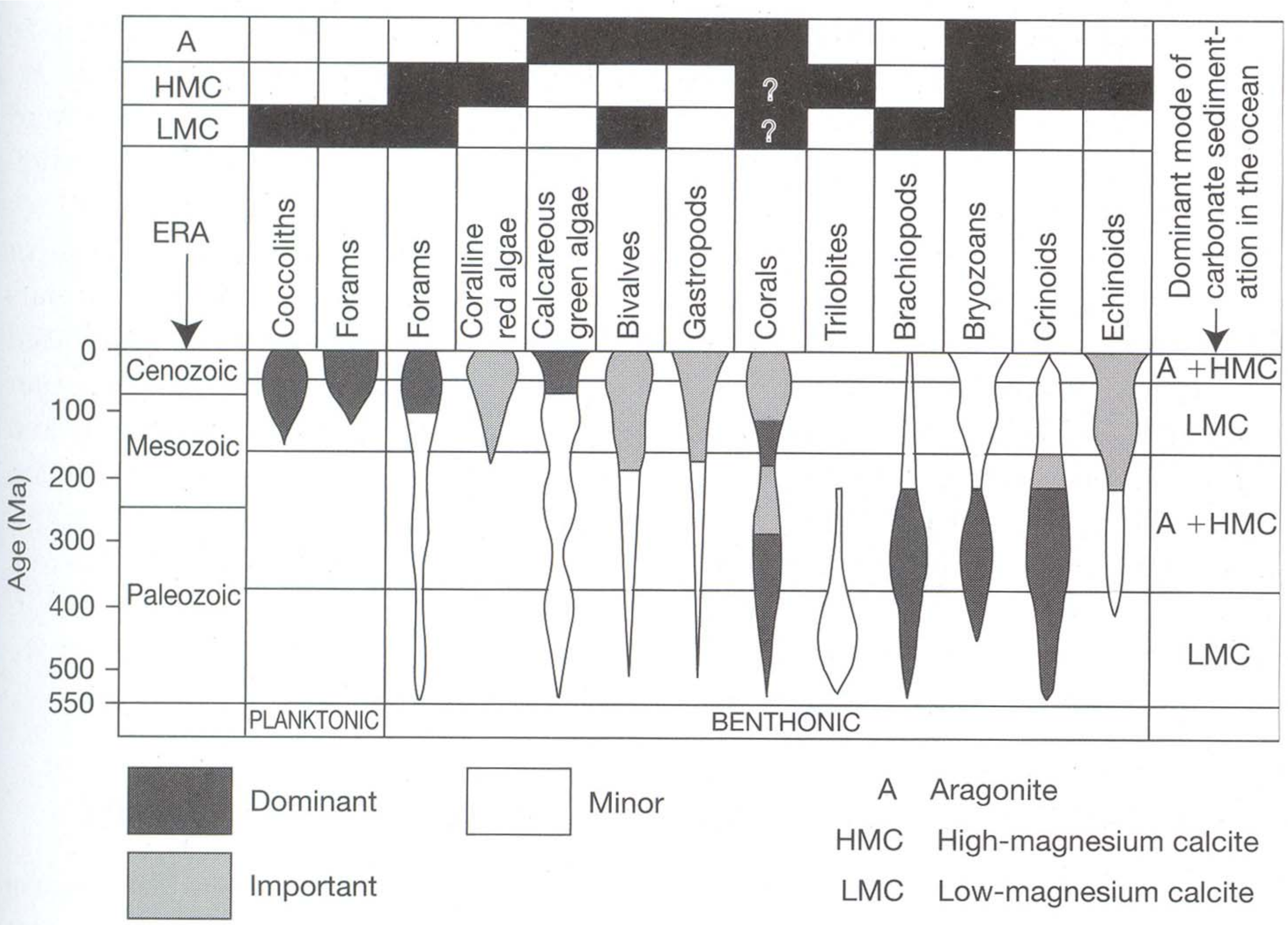



**Figure 11.4**
The relative importance through time of various calcareous marine organisms as sediment producers. This diagram also shows the skeletal mineralogy of the organisms, which, in some cases, changed as the sea chemistry changed from a "calcite sea" to an "aragonite sea" through time. Calcite seas favored precipitation of low-magnesian skeletal structures, and argonite seas favored precipitation of aragonite and high-magnesian calcite, although not all organisms responded to such changes in sea chemistry.

**Skeletal and sediment characteristics of carbonate deposits**

**Table 11.1** Modern warm- and cool-water marine organisms and their counterparts in the fossil record

| Modern, warm-water | Modern, cool-water | Ancient counterpart | Sedimentary aspect |
|---|---|---|---|
| Corals | Absent | Corals, stromatoporoids, stromatolites, coralline sponges, rudist bivalves | Large components of reefs and biogenic mounds |
| Bivalves, red algae, echinoderms | Bivalves, red algae, brachiopods, echinoderms, barnacles | Red algae, brachiopods, cephalopods, trilobites | Remain whole or break apart into several pieces to form sand- and gravel-size particles |
| Gastropods, benthic foraminifera | Gastropods, benthic foraminifera | Gastropods, benthic foraminifera | Whole skeletons that form sand- and gravel-size particles |
| Green (codiacean) and red algae | Red algae, bryozoans | Phylloid algae, crinoids and other echinoderms, bryozoans | Spontaneously disintegrate upon death to form many sand-size particles |
| Ooids, peloids | Absent | Ooids, peloids | Concentrically laminated or micritic sand-size particles |
| Planktonic foraminifera, coccoliths, pteropods | Planktonic foraminifera, coccoliths, pteropods | Planktonic foraminifera, coccoliths (post-Jurassic), styliolinoids | Medium sand-size and smaller particles in basinal deposits |
| Encrusting foraminifera, red algae, bryozoans | Encrusting foraminifera, red algae, bryozoans, serpulid worms | Red algae, renalcids, encrusting foraminifera, bryozoans | Encrust on or inside hard substrates; build up thick deposits or fall off upon death to form sand grains |
| Dasyclad green algae | Absent | Dasyclad green algae | Spontaneously disintegrate upon death to form lime mud |
| Cyanobacteria and other calcimicrobes | Cyanobacteria and other calcimicrobes | Cyanobacteria and other calcimicrobes (especially pre-Ordovician) | Trap, bind, and precipitate fine-grained sediments to form mats and stromatolites or thrombolites |

Source: James, N. P., and A. C. Kendall, 1992, Introduction to carbonate and evaporite facies models, *in* Walker, R. G., and N. P. James (eds.), Facies models—Response to sea level change: Geol. Assoc. Canada. Table 2, p. 269.

# Limestone Textures

Calcite are present in at least three forms:
1. Carbonate grains
2. Microcrystalline calcite (微晶質方解石, or micrite:微晶質灰泥,微晶石灰岩)
3. Sparry calcite (粗粒方解石)

**1. Carbonate Grains (allochems):** carbonate grains typically range in size from coarse silt (0.02 mm) to sand (up to 2 mm), but larger particles such as fossil shells also occur. They can be divided into five basic types, each characterized by distinct differences in shape, internal structure, and mode of origin:

**A.** **Carbonate Clasts (lithoclasts):** Rock fragments that were derived either by erosion of ancient limestones exposed on land (this type of grain is called **extraclasts**外積岩屑) or by erosion of partially or completely lithified carbonate sediments within a depositional basin (**intraclasts**內積岩屑). The term lithoclast is used in non-distinguishable extraclasts and intraclasts. Lithoclasts range in size from very-fine sand to gravel.

**B.** **Skeletal Particles** (bioclast, 化石): Occur as whole microfossils, whole larger fossils, or broken fragments of larger fossils. They are the most common kind of grain in carbonate rocks.

**C.** **Ooids** (鮞石): Coated carbonate grains that contain a nucleus of some kind – a shell fragment, pellet, or quartz grain – surrounded by one or more thin layers or coating (the cortex) consisting of fine calcite or aragonite crystals. Oolites (鮞狀石灰岩): Rocks that contain mainly of ooids. Grains with similar internal structures to that of ooids but larger in grain size, > 2mm, are called pisoids (for rock it is called pisolite豆石). Oncoids (藻粒體): spherical stromatolites (疊層石) that reach a size exceeding 1 to 2 cm. Oncolite: 核形石

**D.** **Peloids** (球粒): grains that are composed of microcrystalline or cryptocrystalline calcite or aragonite and that do not display distinctive internal structures. Peloids are generally of silt to fine-sand size (0.03-0.1 mm).
The most common kind of peloids are **fecal pellets** (糞球) , produced by organisms that ingest calcium carbonate muds and extrude undigested mud as pellets.

**E.** **Aggregate Grains** (rare): Irregular carbonate grains that consist of two or more carbonate fragments (pellets, ooids, fossil fragments) joined together by a carbonate-mud matrix that is generally dark colored and rich in organic matter.

# Types of carbonate grains

A. Rounded carbonate clasts cemented by sparry calcite.
B. Angular to subangular carbonate clasts in a micrite matrix.
C. Skeletal grains (B:苔蘚蟲類, Br:腕足動物, C: 海百合, F:有孔蟲) cemented with sparry calcite.
D. Normal ooids cemented with sparry calcite.
E. Radial ooids cemented with sparry calcite (white) and micrite (dark).
F. Pellets cemented with sparry calcite.

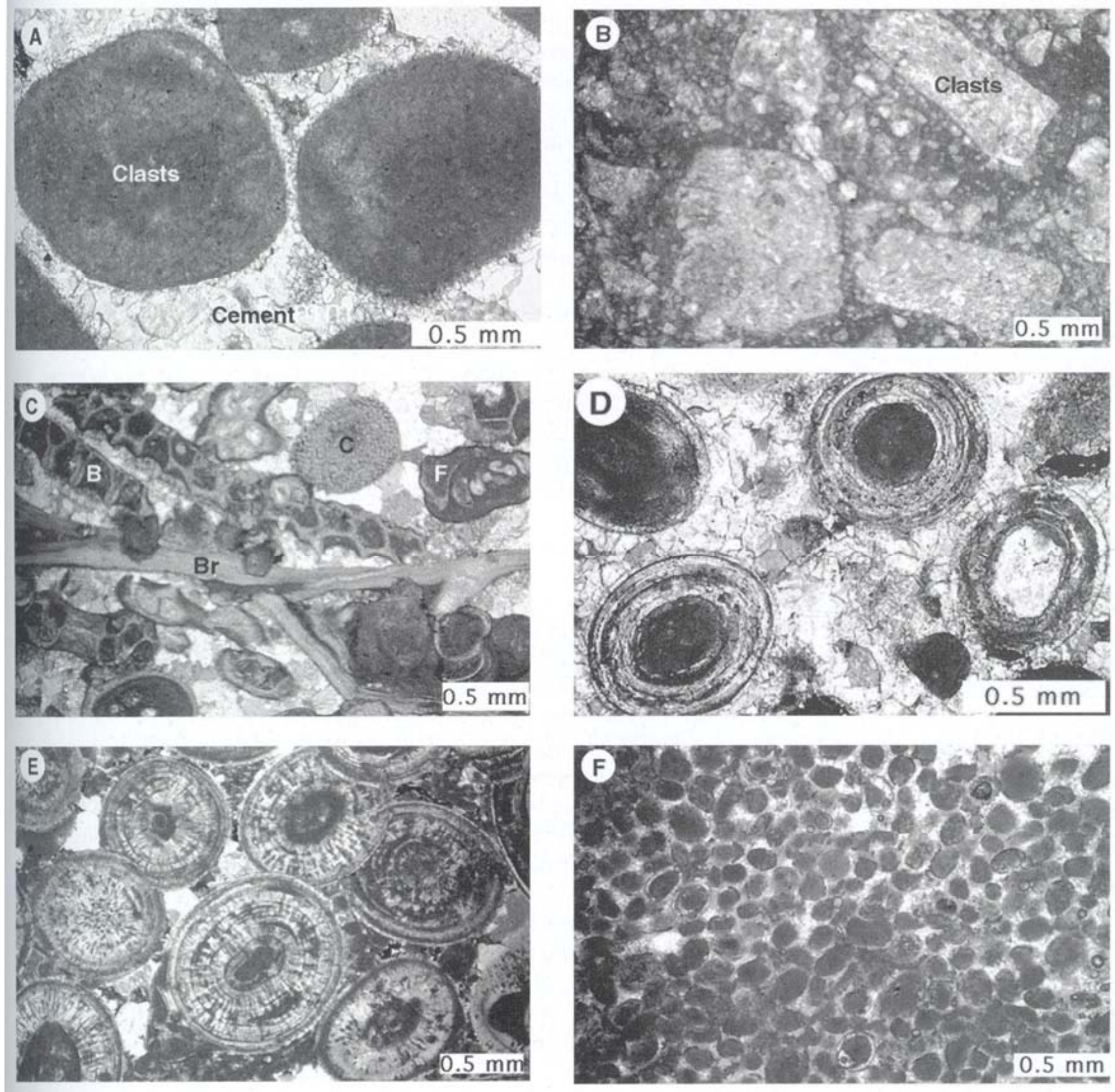
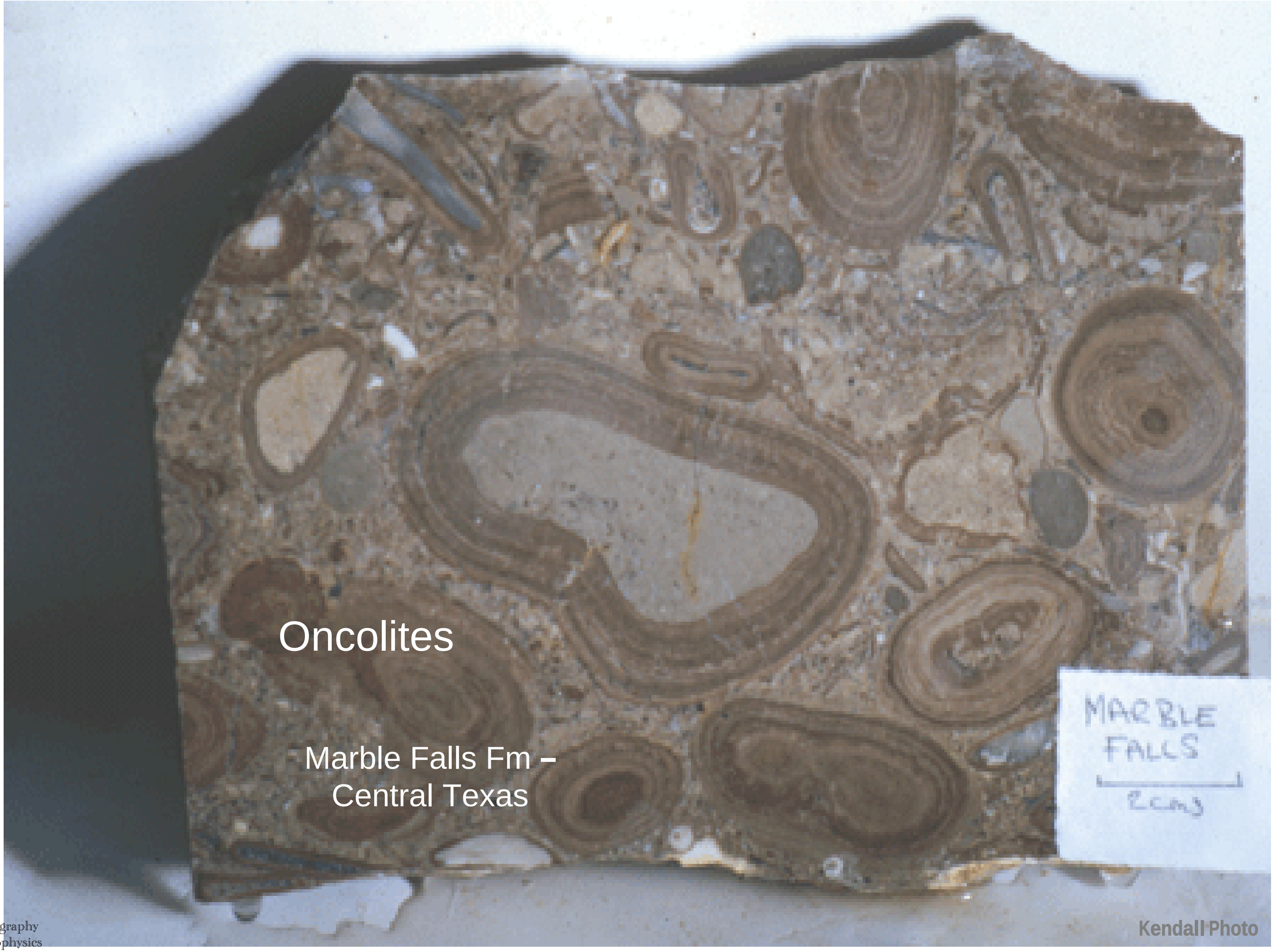



**Figure 6.1**
Fundamental kinds of carbonate grains (allochems) in limestones: A. Rounded clasts cemented with sparry calcite cement, Devonian limestone, Canada. B. Angular to subangular clasts in a micrite (dark) matrix, Calville Limestone (Permian), Nevada. C. Mixed skeletal grains (B = bryozoan, Br = brachiopod, C = crinoid, F = foraminifer) cemented with sparry calcite, Salem Formation (Mississippian), Missouri. D. Normal ooids cemented with sparry calcite (white), Miami Oolite (Pleistocene), Florida. E. Radial ooids cemented with sparry calcite (white) and micrite (dark); note relict concentric layering, Devonian limestone, Canada. F. Pellets cemented with sparry calcite, Quaternary-Pleistocene limestone, Grand Bahama Banks. Crossed nicols.

Boggs (2006) p.163


Oncolites
Marble Falls Fm –
Central Texas
MARBLE
FALLS
2cm
Kendall Photo

**2. Microcrystalline Calcite (or micrite):** Carbonate mud (or lime mud) composed of very fine size (1~5 microns, 0.001~0.005 mm) calcite crystals. Modern lime mud consists mainly of aragonite, while ancient carbonate mud consists mainly of calcite. Lime mud may contain small amounts of fine-grained detrital minerals such as clay minerals, quartz, feldspar, and organic matters. Micrite may be present as matrix among carbonate grains, or it may make up most or all of a limestone. Micrite may be formed by inorganic precipitation of aragonite, later converted to calcite, from surface water supersaturated with $CaCO_3$. Much modern carbonate mud appears to originated through organic processes. The presence of micrite indicates deposition under quiet-water conditions (analogous to siliciclastic mudrock).

Boggs (2006) p.166

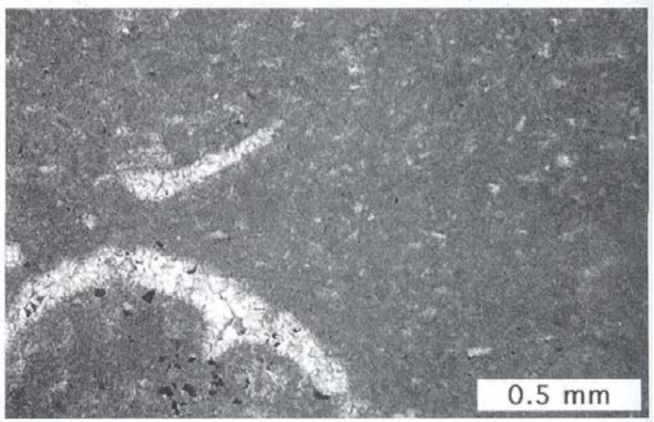



**Figure 6.3**
Micrite-rich limestone containing a few skeletal grains. Plattin Limestone (Ordovician), Missouri. Crossed nicols.

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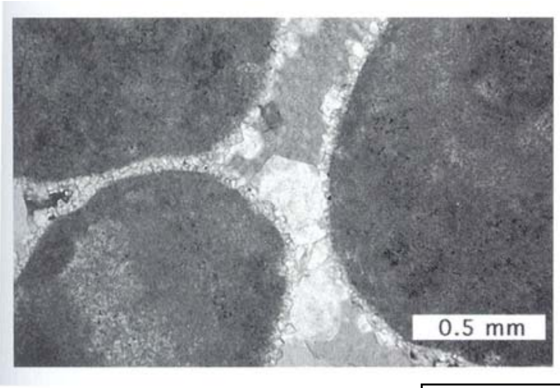
**3. Sparry Calcite:** Large crystals (on the order of 0.02~0.1 mm) of calcite that appear clear or white viewed with a hand lens or in plane light under a polarizing microscope. It is formed during diagenesis. They are distinguished from micrite by their larger size and clarity and from carbonate grains by their crystal shapes and lack of internal texture. The presence of sparry calcite cement in pore spaces indicates that grain framework voids were empty of lime mud at the time of deposition, suggesting deposition under high-energy flow condition. Sparry calcite can also form by recrystallization of primary depositional grains and micrite during diagenesis.




Boggs (2006) p.167

**Figure 6.4**
Sparry calcite cementing rounded intraclasts. Note that the cement displays drusy texture: small calcite crystals, oriented with their long dimensions perpendicular to the clast surfaces, grade outward from the margins of the clasts into larger, randomly oriented calcite crystals. Devonian limestone, Canada. Crossed nicols.

Boggs (2006) p.167

Note: Micrites form as a matrix; sparry calcites form as a cement.

# Classification of carbonate rocks

The principal parameters used in carbonate classification are the types of carbonate grains or allochems and the grain/micrite ratio. Folk (1962)'s classification is the most widely accepted one that bases on the relative abundance of three major types of constituents: (1) carbonate grains (allochems); (2) microcrystalline carbonate mud (micrite); and (3) sparry calcite cement.

## A. Classification based on dominant constituents (Folk)

**Table 6.2** Classification of carbonate rocks

Boggs (2006) p.170

| Volumetric allochem composition | Limestones, partly dolomitized limestones: >10% Allochems, Allochemical rocks — Sparry calcite cement > microcrystalline ooze matrix (Sparry allochemical rocks) | Limestones, partly dolomitized limestones: >10% Allochems, Allochemical rocks — Microcrystalline ooze matrix > sparry calcite cement (Microcrystalline allochemical rocks) | <10% Allochems, Microcrystalline rocks — 1%–10% Allochems (Most abundant allochem) | <10% Allochems, Microcrystalline rocks — <1% Allochems | Undisturbed bioherm rocks | Replacement dolomites — Allochem ghosts (Evident allochem) | Replacement dolomites — No allochem ghosts |
|---|---|---|---|---|---|---|---|
| >25% Intraclasts | Intrasparrudite<br>Intrasparite | Intramicrudite*<br>Intramicrite* | Intraclasts: intraclast-bearing micrite* | Micrite; if disturbed, dismicrite; if primary, dolomite, dolomicrite | Biolithite | Finely crystalline intraclastic dolomite, etc. | Medium crystalline dolomite |
| <25% Intraclasts; >25% Ooids | Oosparrudite<br>Oosparite | Oomicrudite*<br>Oomicrite* | Ooids: ooid-bearing micrite* | | | Coarsely crystalline oolitic dolomite, etc. | Finely crystalline dolomite |
| <25% Intraclasts; <25% Ooids; Volume ratio of fossils to pellets >3:1 | Biosparrudite<br>Biosparite | Biomicrudite<br>Biomicrite | Fossils: fossiliferous micrite | | | Aphanocrystalline biogenic dolomite, etc. | |
| <25% Intraclasts; <25% Ooids; Volume ratio of fossils to pellets 3:1–1:3 | Biopelsparite | Biopelmicrite | | | | | |
| <25% Intraclasts; <25% Ooids; Volume ratio of fossils to pellets <1:3 | Pelsparite | Pelmicrite | Pellets: pelletiferous micrite | | | Very finely crystalline pellet dolomite, etc. | etc. |

Source: Folk, R. L., 1962, Spectral subdivision of limestone types, in W. E. Ham (ed.), Classification of carbonate rocks: *Am. Assoc. Petroleum Geologists Mem.* 1. Table 1, p. 70, reprinted by permission of AAPG, Tulsa, Okla.

Note: Names and symbols in the body of the table refer to limestones. If the rock contains more than 10 percent replacement dolomite, prefix the term "dolomitized" to the rock name. The upper name in each box refers to calcirudites (median allochem size larger than 1.0 mm); the lower name refers to all rocks with median allochem size smaller than 1.0 mm. Grain size and quantity of ooze matrix, cements, or terrigenous grains are ignored.

*Designates rare rock types.

Folk’s classification scheme shown in Chinese

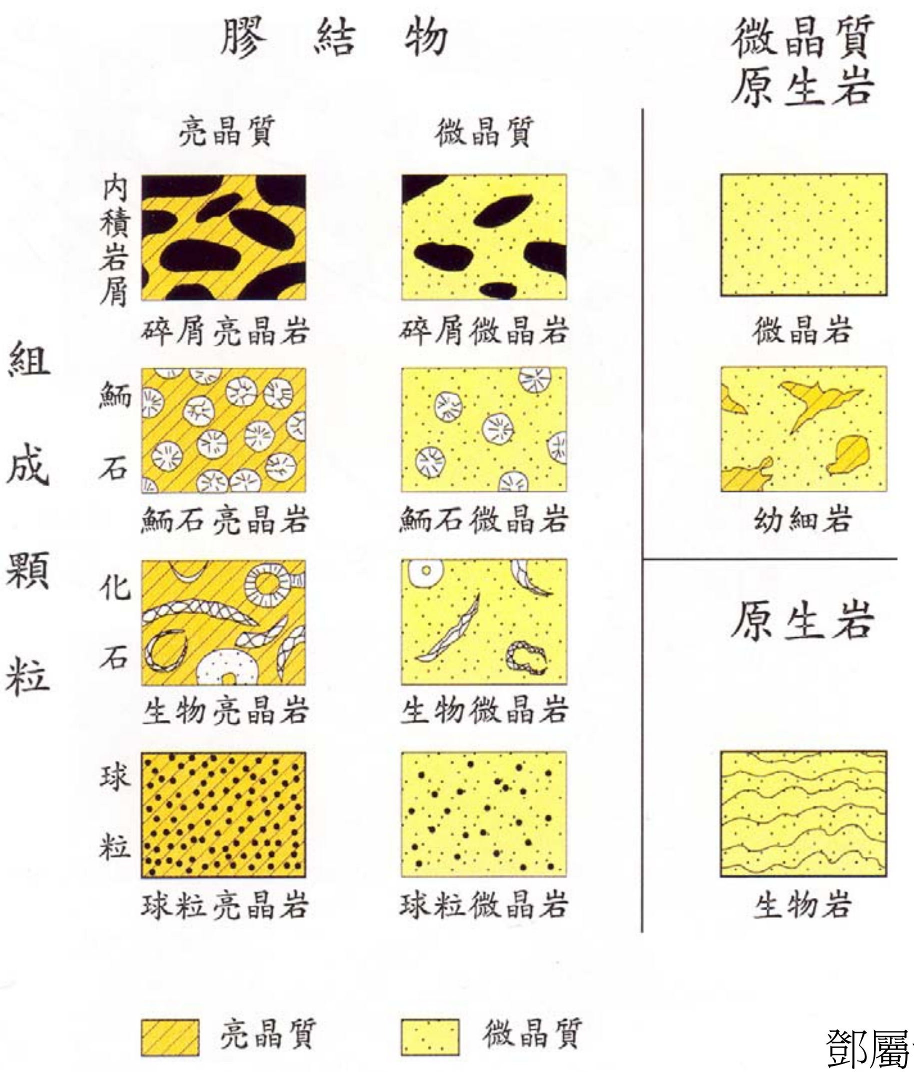



圖3-29 石灰岩分類圖(修改自Folk, 1962)

石灰岩以組成顆粒與膠結物的性質來分類(左半部)，倘若沒有粗粒的碎屑物，或僅有原生的生物體，則以右半部的原生岩命名。

The main allochems are *oöids (鮞石)*, *peloids(球粒)*, *bioclasts* (skeletal grains化石) and *intraclasts(內積岩屑)*.

Allochems > 10%

碎屑亮晶岩(Intrasparite)
鮞石亮晶岩(Oösparite)
生物亮晶岩(Biosparite)
球粒亮晶岩(Pelsparite)

碎屑微晶岩(Intramicrite)
鮞石微晶岩(Oömicrite)
生物微晶岩(Biomicrite)
球粒微晶岩(Pelmicrite)

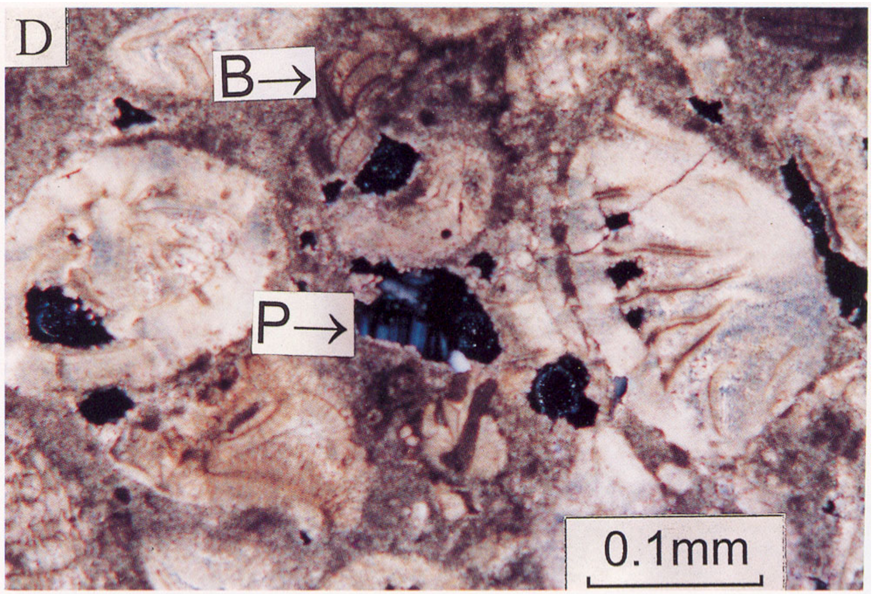
Allochems < 10%

微晶岩(micritic limestone)
幼細岩(dismicrite, micrite with cavities (usually spar-filled)

生物岩(biolithite, e.g, reef-rock or stromatolite)

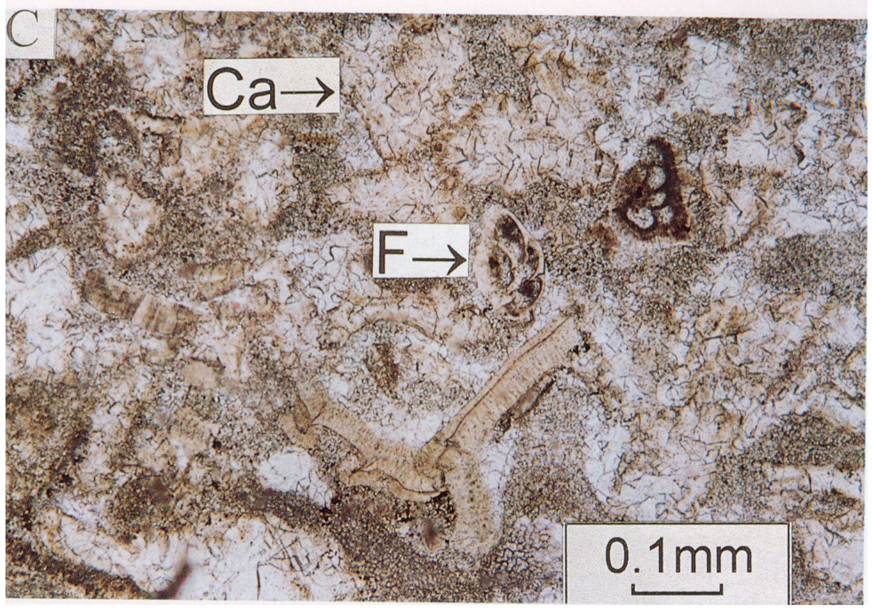
鄧屬予 (1997)


圖版四十一 【東河石灰岩二】
採自臺東縣東河鄉都巒山層頂部的上新統石灰岩，爲白色生物微晶岩(圖版A、B)，組成以有孔蟲(F)爲主，並有藻類(B)與少量的斜長石(P)。質地緻密，但孔隙仍多，生物組織明顯。顆粒間由微晶質方解石膠結，具有輕微的再結晶現象(圖版C、D)。

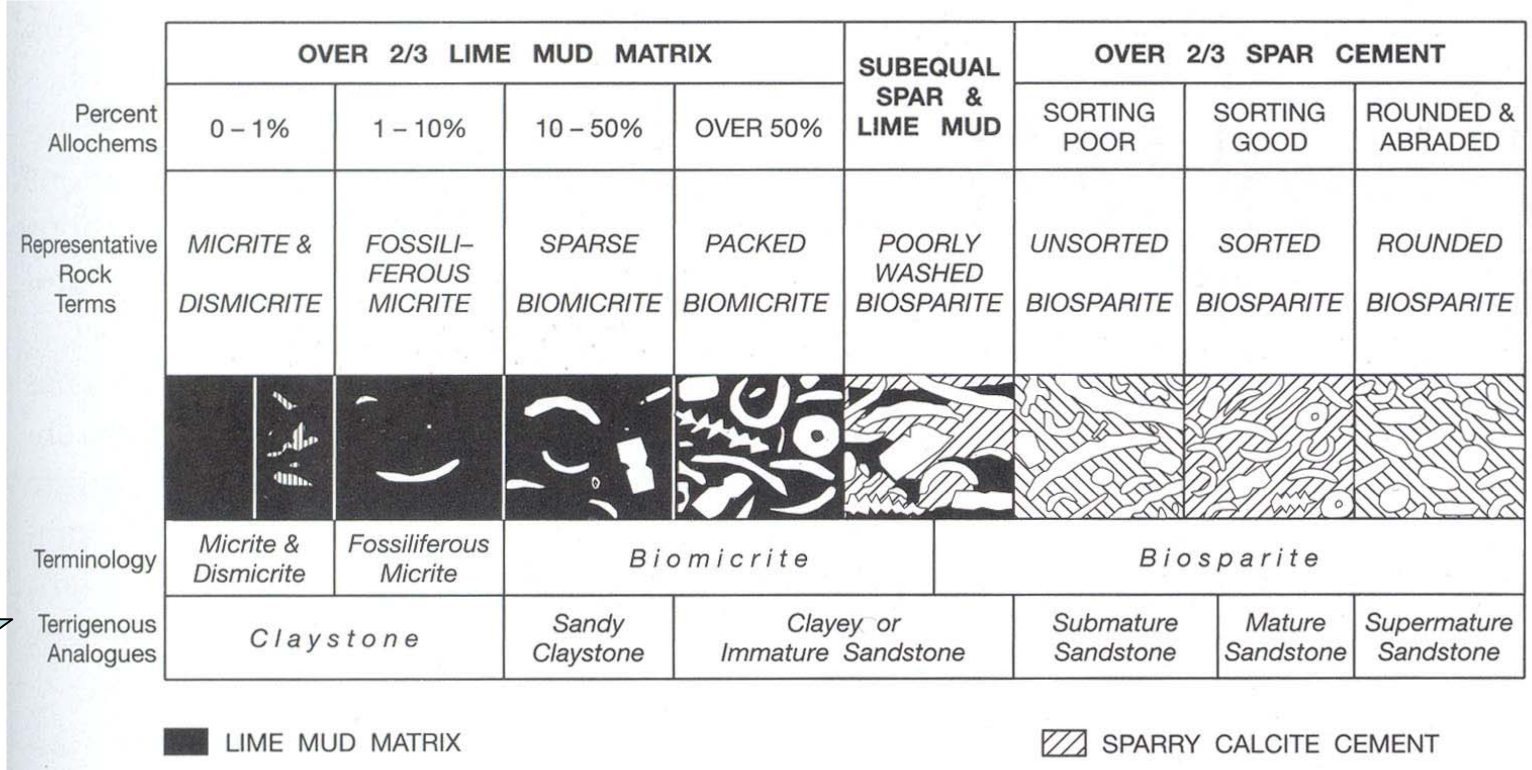




圖版十四 【半屏山石灰岩】
採自高雄市半屏山的更新統礁灰岩體，爲白色略帶粉紅色的生物亮晶岩(圖版A、B)，質地堅硬，有許多孔隙。組成以珊瑚(Co)爲主，另有貝類、藻類、有孔蟲(F)和少量的石英，顆粒間由亮晶質方解石(Ca)膠結(圖版C、D)。



Additional textural information can be added by use of the textural maturity terms shown here:



| | OVER 2/3 LIME MUD MATRIX | | | | SUBEQUAL SPAR & LIME MUD | OVER 2/3 SPAR CEMENT | | |
|---|---|---|---|---|---|---|---|---|
| Percent Allochems | 0 – 1% | 1 – 10% | 10 – 50% | OVER 50% | | SORTING POOR | SORTING GOOD | ROUNDED & ABRADED |
| Representative Rock Terms | MICRITE & DISMICRITE | FOSSILI-FEROUS MICRITE | SPARSE BIOMICRITE | PACKED BIOMICRITE | POORLY WASHED BIOSPARITE | UNSORTED BIOSPARITE | SORTED BIOSPARITE | ROUNDED BIOSPARITE |
| Terminology | Micrite & Dismicrite | Fossiliferous Micrite | Biomicrite | | | Biosparite | | |
| Terrigenous Analogues | Claystone | | Sandy Claystone | Clayey or Immature Sandstone | | Submature Sandstone | Mature Sandstone | Supermature Sandstone |



**Figure 6.8** Boggs (2006) p.171

Textural classification of carbonate sediments on the basis of relative abundance of lime mud matrix and sparry calcite cement and on the abundance and sorting of carbonate grains (allochems). [After Folk, R. L., 1962, Spectral subdivision of limestone types, *in*

Informal names for carbonate rocks:

• **<u>Coquina</u>** (殼灰岩屑) a mechanically sorted and abraded, poorly consolidated carbonate sediment consisting predominantly of fossil debris; Coquinite (殼灰岩) is the consolidated equivalent.

• **<u>Chalk</u>** (白堊) is soft, earthy, fine-textured limestone composed mainly of the calcite tests of floating micro-organisms, such as foraminifers.

• **<u>Marl</u>** (泥灰岩) is an old, rather imprecise, term for an earthy, loosely consolidated mixture of siliciclastic clay and calcium carbonate.

# B. Classification based on depositional texture (Dunham)

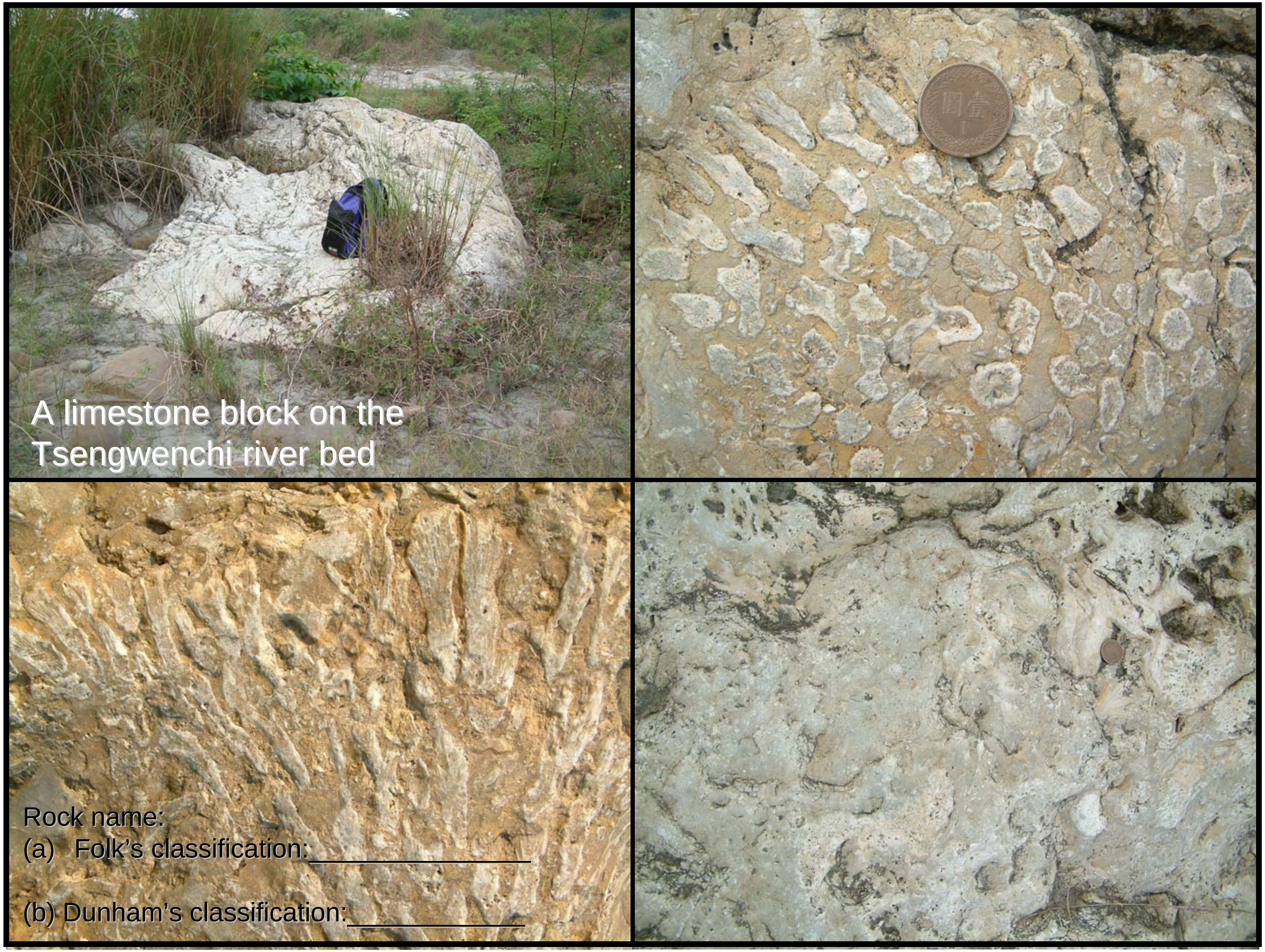
**Table 6.3** Classification of limestones according to depositional textures

<table>
<tr><td colspan="5">A DEPOSITIONAL TEXTURE RECOGNIZABLE</td><td>DEPOSITIONAL TEXTURE NOT RECOGNIZABLE</td></tr>
<tr><td colspan="4">Original components not bound together during deposition</td><td rowspan="4">Original components were bound together during deposition . . . as shown by intergrown skeletal matter, lamination contrary to gravity, or sediment-floored cavities that are roofed over by organic or questionably organic matter and are too large to be interstices.</td><td rowspan="5">CRYSTALLINE CARBONATE<br><br>(Subdivide according to classifications designed to bear on physical texture or diagenesis.)</td></tr>
<tr><td colspan="3">Contains mud<br>(particles of clay and fine silt size)</td><td rowspan="3">Lacks mud and is grain-supported</td></tr>
<tr><td colspan="2">Mud-supported</td><td rowspan="2">Grain-supported</td></tr>
<tr><td>Less than 10% grains</td><td>More than 10% grains</td></tr>
<tr><td>MUDSTONE</td><td>WACKESTONE</td><td>PACKSTONE</td><td>GRAINSTONE</td><td>BOUNDSTONE</td></tr>
</table>

<table>
<tr><td colspan="6">B ALLOCHTHONOUS LIMESTONE<br>Original components not organically bound during deposition</td><td colspan="3">AUTOCHTHONOUS LIMESTONE<br>Original components organically bound during deposition</td></tr>
<tr><td colspan="4">Less than 10% >2 mm components</td><td colspan="2">Greater than 10% >2 mm components</td><td rowspan="4">By organisms that build a rigid framework</td><td rowspan="4">By organisms that encrust and bind</td><td rowspan="4">By organisms that act as baffles</td></tr>
<tr><td colspan="3">Contains lime mud (<0.03 mm)</td><td>No lime mud</td><td rowspan="4">Matrix-supported</td><td rowspan="4">>2 mm component-supported</td></tr>
<tr><td colspan="2">Mud-supported</td><td colspan="2" rowspan="3">Grain-supported</td></tr>
<tr><td rowspan="2">Less than 10% grains >0.03 mm <2 mm</td><td rowspan="2">Greater than 10% grains</td></tr>
<tr><td colspan="3">BOUNDSTONE</td></tr>
<tr><td>MUD-STONE</td><td>WACKE-STONE</td><td>PACK-STONE</td><td>GRAIN-STONE</td><td>FLOAT-STONE</td><td>RUD-STONE</td><td>FRAME-STONE</td><td>BIND-STONE</td><td>BAFFLE-STONE</td></tr>
</table>

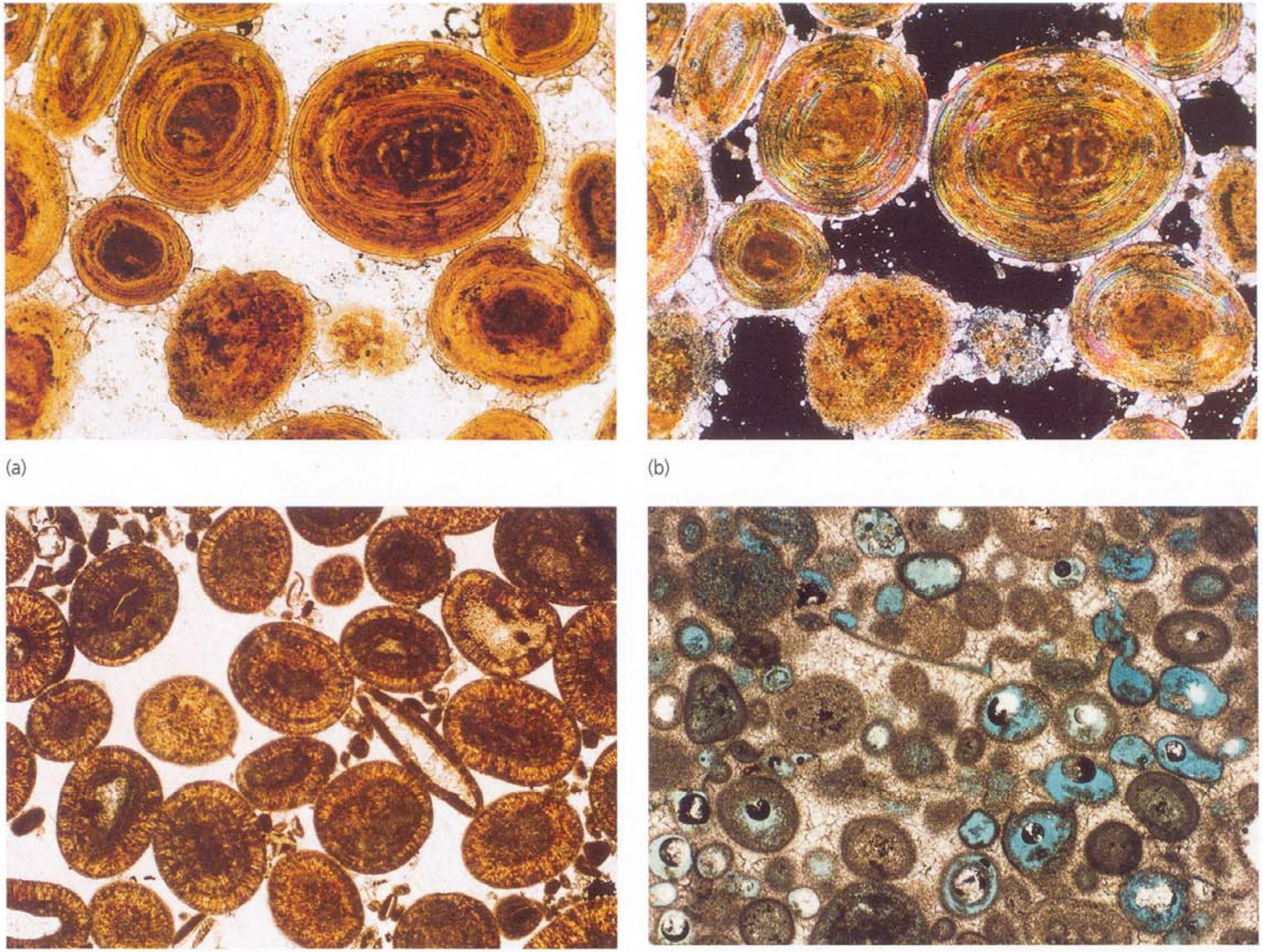
Source: A, After Dunham, R. J., 1962, Classification of carbonate rocks according to depositional textures, in Ham, W. E., ed., Classification of carbonate rocks: *Am. Assoc. Petroleum Geologists Mem.* 1. Table 1, p. 117, reprinted by permission of AAPG, Tulsa, Okla. B, after Dunham, R. J., 1962, as modified by Embry, E. F., III and J. E. Klovan, 1972, Absolute water depth limits of late Devonian paleoecological zones: Geol. Rundschau, v. 61. Fig. 5, p. 676, reprinted by permission.

Boggs (2006) p.173


A limestone block on the
Tsengwenchi river bed
Rock name:
(a) Folk’s classification:_______________
(b) Dunham’s classification:_____________

a, b: Ooids composed of aragonite showing concentric structure and a nucleus. Meniscus cement (b) precipitated in vadose zone; c: calcite ooids, Oolitic grainstone; d: formerly aragonitic ooids, now composed of calcite with poor preservation of original concentric structure and oomoulds.

**Plate 6**
**(a, b)** Holocene ooids composed of aragonite showing concentric structure and a nucleus, several of which are peloids, and one in the centre of the biggest ooid is a bioclast. Structureless oval grain at lower left is a peloid. Also present is a meniscus cement of calcite precipitated in the meteoric vadose zone. The white areas between grains in (a) and the black areas in (b) are pore space: **(a)** plane-polarized light; **(b)** crossed polars. Joulters Cay, Bahamas. Field of view 1.2 × 0.8 mm.
**(c)** Primary, calcitic ooids with strong radial-concentric structure and nuclei mostly of peloids. Bivalve fragment, now composed of clear calcite spar crystals, is also coated. Notice contact between grains; a little interpenetration indicating some burial compaction before cementation. The ooids are contained in a very large poikilotopic calcite cement (here appearing white). Oolitic grainstone, Jurassic. Lincolnshire, England. Field of view 3 × 2 mm.
**(d)** Formerly aragonitic ooids, now composed of calcite with poor preservation of original concentric structure and oomoulds (filled with blue resin). Some compaction of oomoulds indicating that the drusy calcite spar cement is a burial precipitate. Oolitic grainstone, Smackover Formation, Jurassic. Subsurface Arkansas, USA. Field of view 3 × 2 mm.



(a) (b) (c) (d)

Tucker (2001)

a: Peloids; b,c: bivalve fragments with micrite envelope; d: peloids and bivalve with micrite envelope; e: sponge boring filled with micrite.

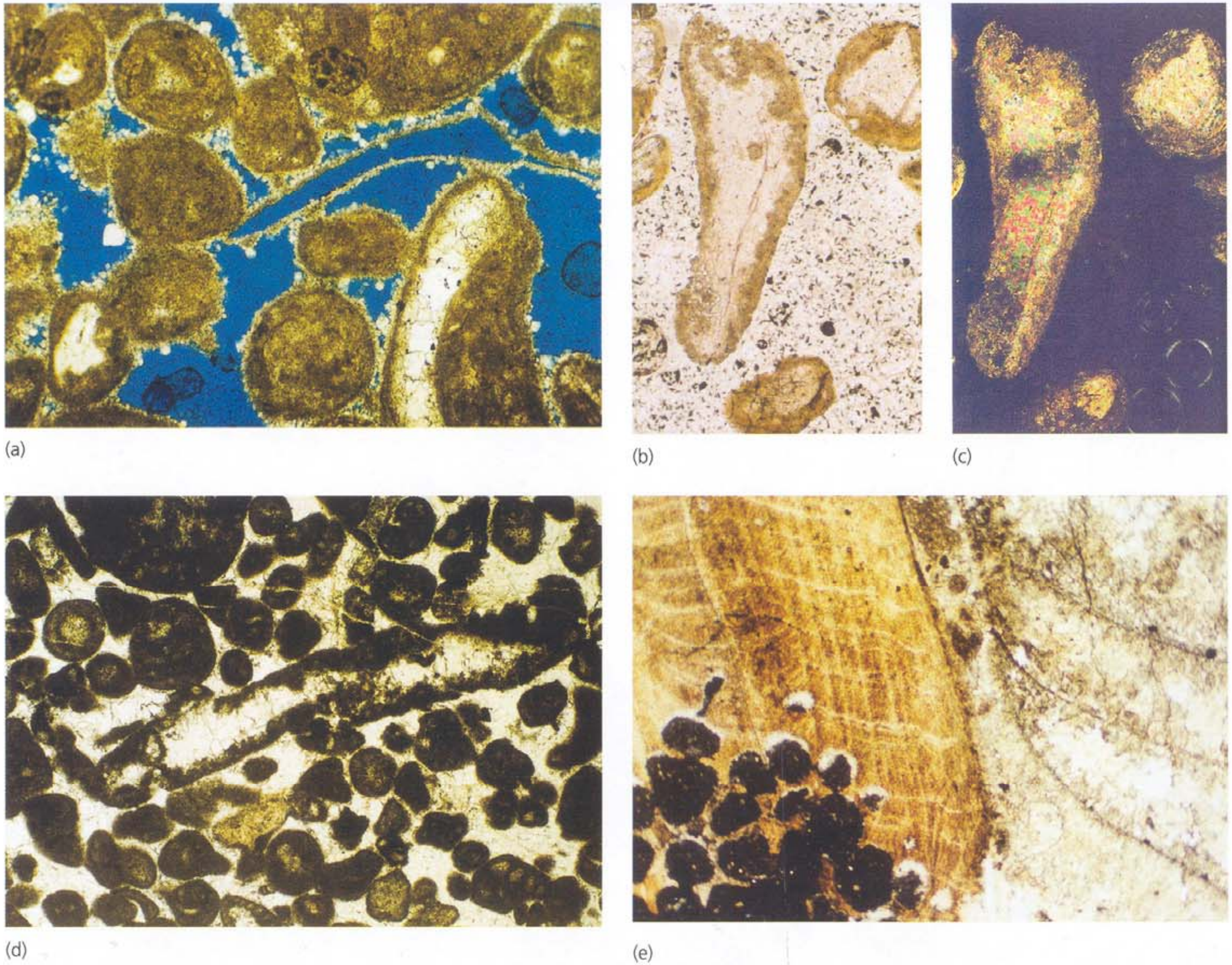
**Plate 7**

**(a)** Peloids; many are micritized bioclasts and ooids, some are faecal pellets. Micrite envelope defines a bivalve shell that has dissolved away; bivalve shell within coated grain is replaced by coarse calcite crystals. The sparse cement consists of small, stubby calcite crystals of probable meteoric phreatic origin. Small dolomite rhombs also present. Blue resin shows porosity. Jurassic. Dorset, England. Field of view 0.8×0.8 mm.

**(b,c)** Modern bivalve fragment with micrite envelope. Shell, composed of aragonite, consists of minute crystallites giving a sweeping extinction under crossed polars **(c)**. Abu Dhabi, UAE. Field of view 0.8×1.0 mm.

**(d)** Bivalve fragment (the elongate grain) in centre with a prominent micrite envelope and shell now composed of drusy calcite spar, a cement. The micrite envelope has fractured (in the centre) as a result of compaction. Also present are numerous peloids, most of which are micritized bioclasts, and some crinoid fragments, in a sparite cement.Urgonian, Cretaceous. Vercors, France. Field of view 3×2 mm.

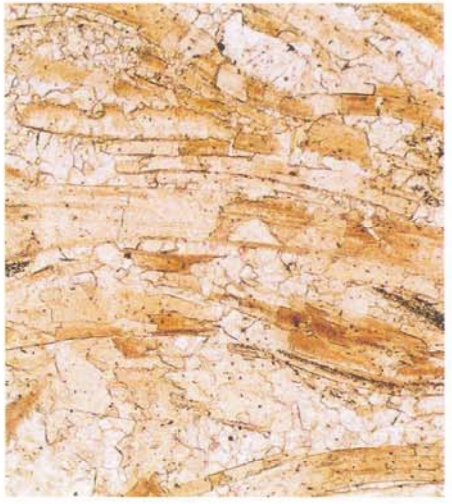
**(e)** Hippuritid rudist bivalve (the conical, attached valve) showing brown, well-preserved fibrous calcite outer wall, and thinner inner wall with tabulae, which originally were aragonite, but are now composed of calcite spar. Round areas of sediment (micrite) are the fills of sponge borings. Cretaceous. Provence, France. Field of view 6×4 mm.

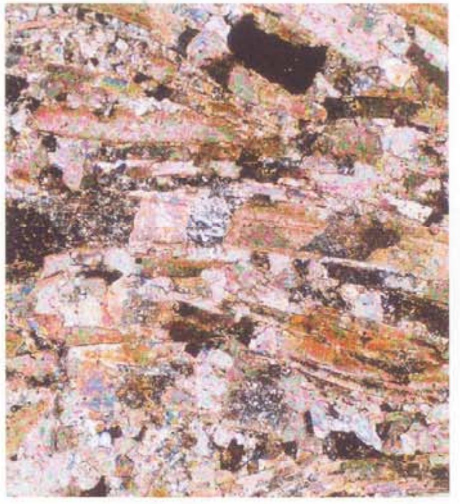



Tucker (2001)

a, b: calcitized bivalve shells with sparry calcite cement; c: gastropods (腹足類); d,e: Brachiopod(腕足類)

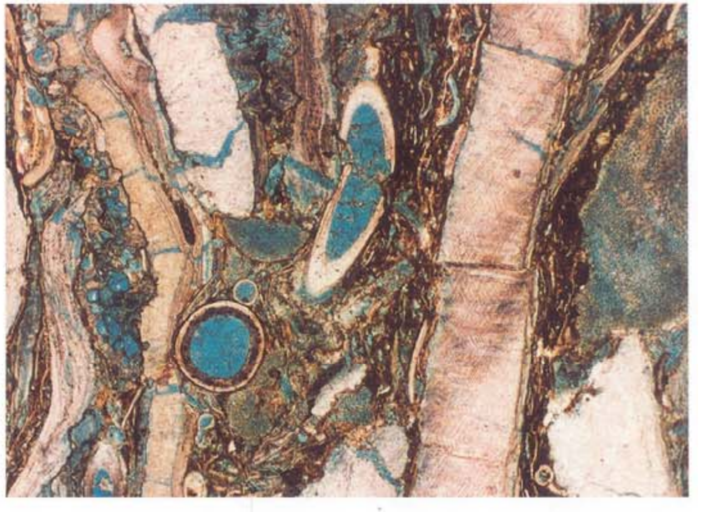
**Plate 8**
**(a, b)** Calcitized bivalve shells. Shells originally composed of aragonite but replaced by calcite with some retention of original shell structure. Calcite crystals cross-cut the shell structure and are pseudopleochroic (different shades of brown on slide rotation): **(a)** plane-polarized light and **(b)** crossed polars. Jurassic. Dorset, England. Field of view 0.8 ×0.8 mm.
**(c)** Gastropods, in long- and cross-section, defined by thin micrite envelopes (black). The shells, originally aragonite, dissolved out and voids were filled by marine fibrous calcite cement (pale brown). A later clear calcite cement filled remaining pores (white). Jurassic. Sicily, Italy. Field of view 4 ×4 mm.
**(d)** Brachiopod shell with puncti, some filled with lime mud sediment, showing preservation of internal structure consisting of obliquely arranged fibres. Other grains are micritized bioclasts (peloids). Bioclastic grainstone. Cretaceous. Vercors, France. Field of view 3×2 mm.
**(e)** Brachiopod shells and spines with well-preserved shell structure, but limestone has suffered compaction and many shells are broken. Thin-section is stained with Alizarin Red S and potassium ferricyanide; bioclasts are pink (calcite) and cement is blue (ferroan calcite). Cement occurs within cracks showing that it is a burial precipitate. Crinoids and clay (brown) also present. Bioclastic packstone. Carboniferous. Northumberland, England. Field of view 6×4 mm.


(a)


(b)


(c)


(d)

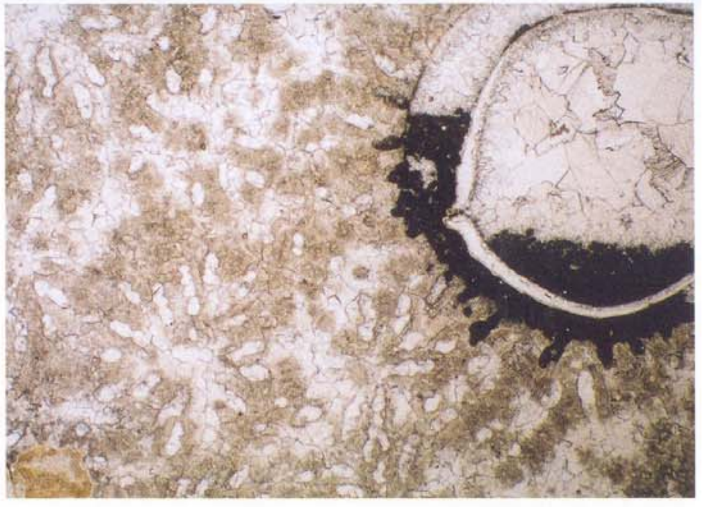

(e)

Tucker (2001)

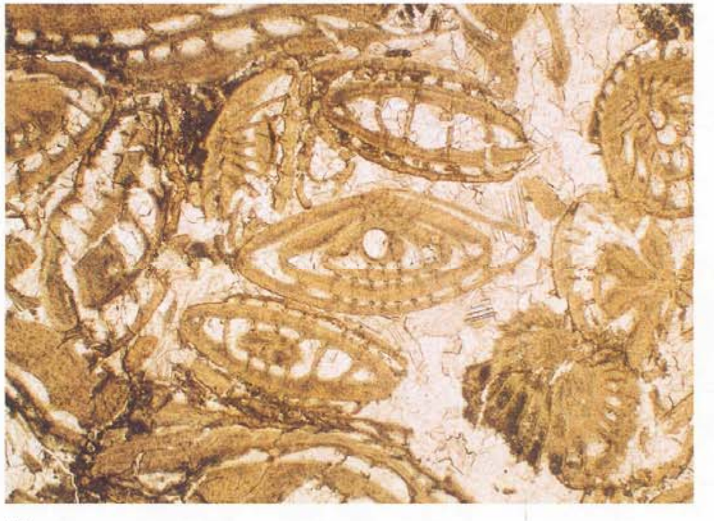
a: Rugose coral (四射珊瑚); b: Scleractinian coral (石珊瑚) and a boring with geopetal structure; c; Forams; d Nummulites (貨幣石) ; e: Miliolids.

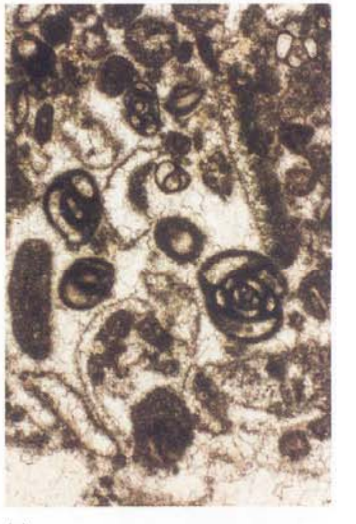
**Plate 9**
**(a)** Rugose coral (*Lithostrotion* sp.) showing internal plates (septa, tabulae and dissepiments). The pores within the coral are partly filled with an initial isopachous fibrous marine cement and then by internal sediment. Carboniferous. Durham, England. Field of view 6×4 mm. **(b)** Scleractinian coral from a Jurassic patch reef showing variable preservation of structure as a result of replacement of the original aragonite by calcite. Also present, on the right, is a boring made by a lithophagid bivalve (shells present); the boring shows a geopetal structure, with sediment below (dark) and drusy calcite spar above (white). Yorkshire, England. Field of view 6×4 mm.
**(c, d, e)** Foraminifera. **(c)** Endothyracid foram, crinoid to left, cut by a calcite vein. Carboniferous. Clwyd, Wales. Field of view 4×2 mm. **(d)** *Nummulites*. Bioclastic grainstone, Eocene. Tunisia. Field of view 6×4 mm. **(e)** Miliolids, also bivalve fragments. Cretaceous. Vercors, France. Field of view 4×2 mm.


(a)


(b)


(c)

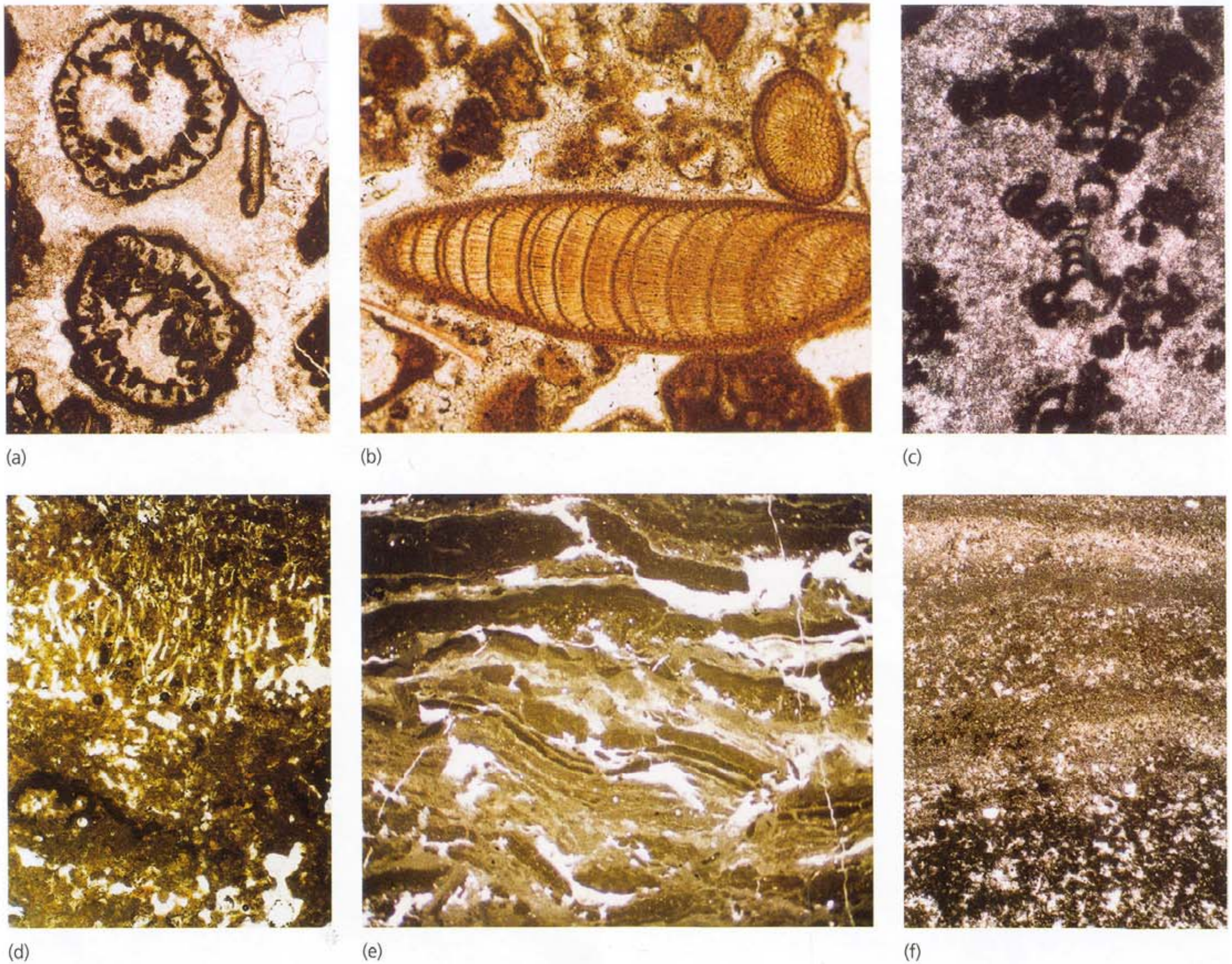

(d)


(e)

Tucker (2001)

a: Dasyclad algae; b: calcareous red algae, isopachous marine cement; c: calcified microbes; d: microbial mat of dolomite; e, f: stromatolite

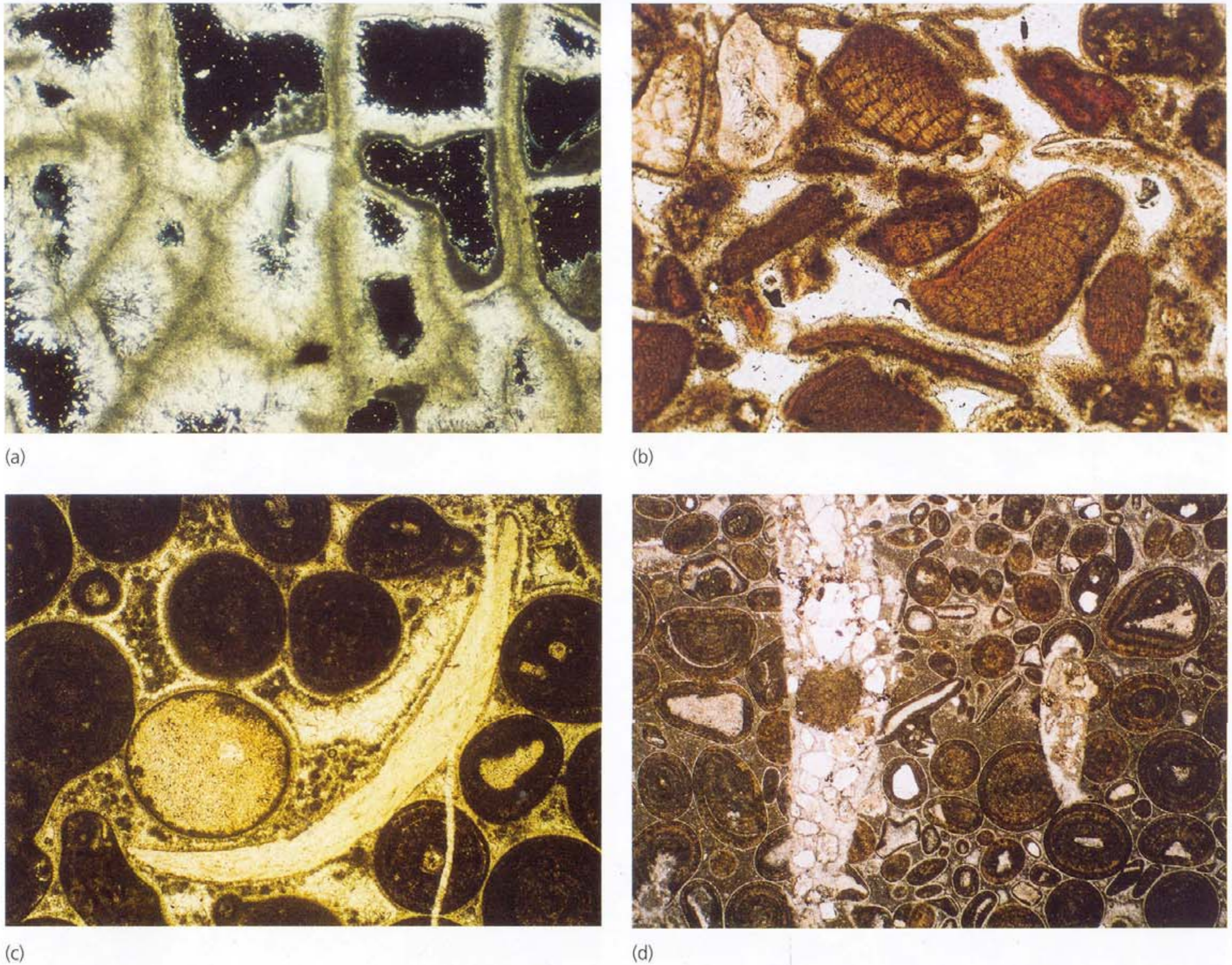
**Plate 10**
**(a)** Dasyclad algae. Capitan, Permian. Texas, USA. Field of view 4×2 mm.
**(b)** Calcareous red algae, *Lithothamnion* in longitudinal section (showing seasonal growth zones) and cross-section. The grains here are cemented by isopachous high-Mg calcite marine cement. Recent. Belize. Field of view 1.0×0.8 mm.
**(c)** Calcified microbes, *Renalcis*. Devonian. Guilin, China. Field of view 4×2 mm.
**(d)** Modern microbial mat composed of dolomite. The filaments of the cyanobacteria are clearly visible, but the dolomite crystals are submicroscopic. Recent. Bahamas. Field of view 4×2 mm.
**(e)** Stromatolite (microbial mat) composed of micrite laminae and laminoid fenestrae, with some intraclasts from desiccation. Carboniferous. Glamorgan, Wales. Field of view 5×4 mm.
**(f)** Stromatolite composed of micritic and grainy laminae, and small spar-filled fenestrae. Precambrian. Flinders, Australia. Field of view 4×2 mm.




Tucker (2001)

a: coral with agragonite cement; b: isopachous calcite cement; c: isopachous marine cement, then internal sediment of peloids, followed by drusy calcite cement; d: hardground.

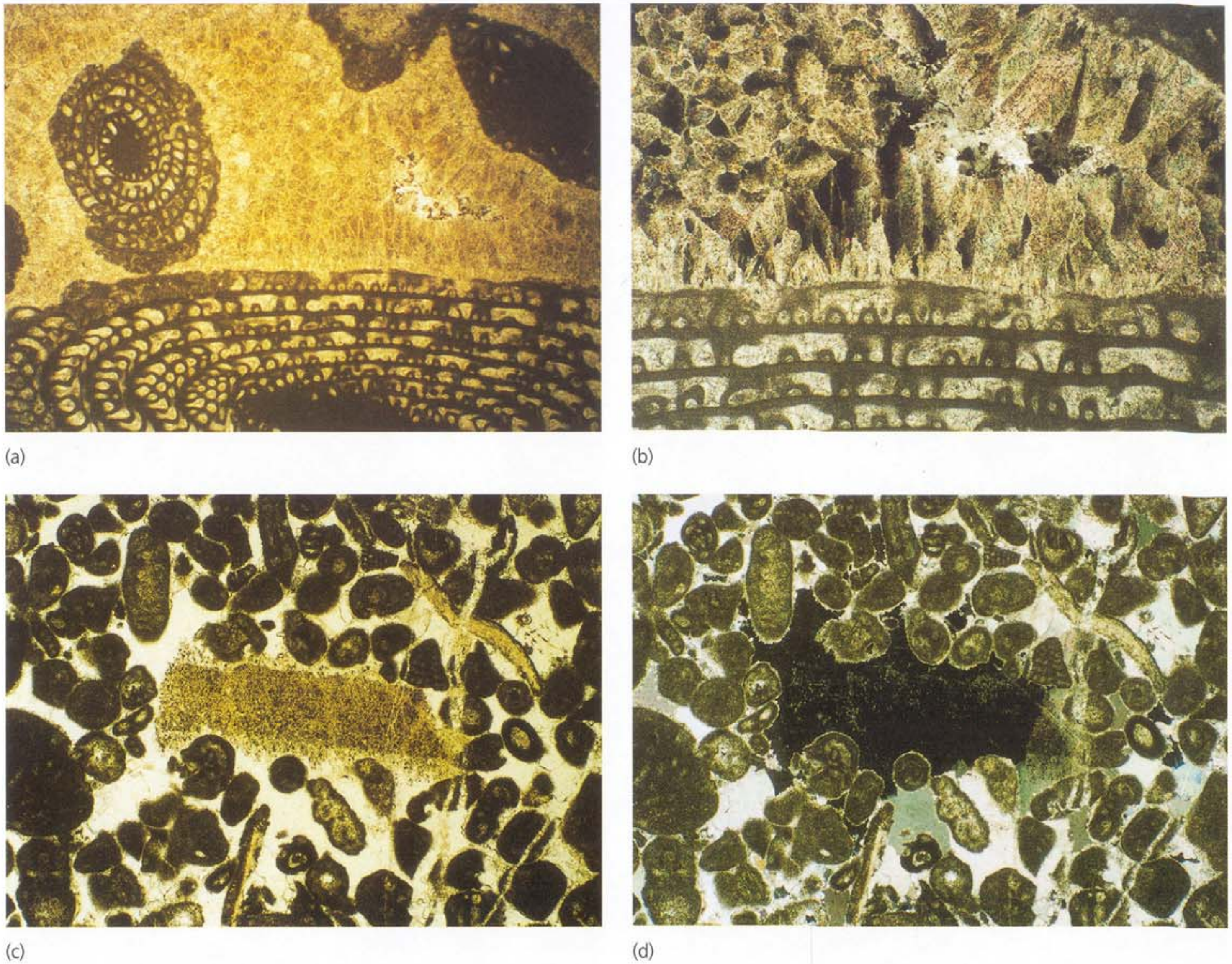
**Plate 11**
**(a)** Coral with aragonite cement—needles and a botryoid within the corallites, and lime mud internal sediment (black) and peloids in other pores. Crossed polars. Recent. Belize. Field of view 6×4 mm.
**(b)** Isopachous high-Mg calcite cement around skeletal grains (including calcareous red algae). Recent fore-reef debris. Belize. Field of view 1.2×0.8 mm.
**(c)** Oolitic grainstone with brachiopod and crinoid fragments (with thin micrite envelope—black) cemented by early isopachous fibrous marine cement (calcite), then some internal sediment of peloids, followed by drusy calcite spar cement. Carboniferous. Glamorgan, Wales. Field of view 6×4 mm.
**(d)** Hardground with ooids surrounded by thin isopachous marine cement fringe and then pore space filled by lime mud, now micrite. Cemented rock then cut by annelid borings, which later filled with quartz grains. Jurassic. Gloucestershire, England. Field of view 6×4 mm.




Tucker (2001)

a, b: Fusulinid foraminifer cemented by radiaxial fibrous calcite; c, d: syntaxial calcite overgrowth cement.

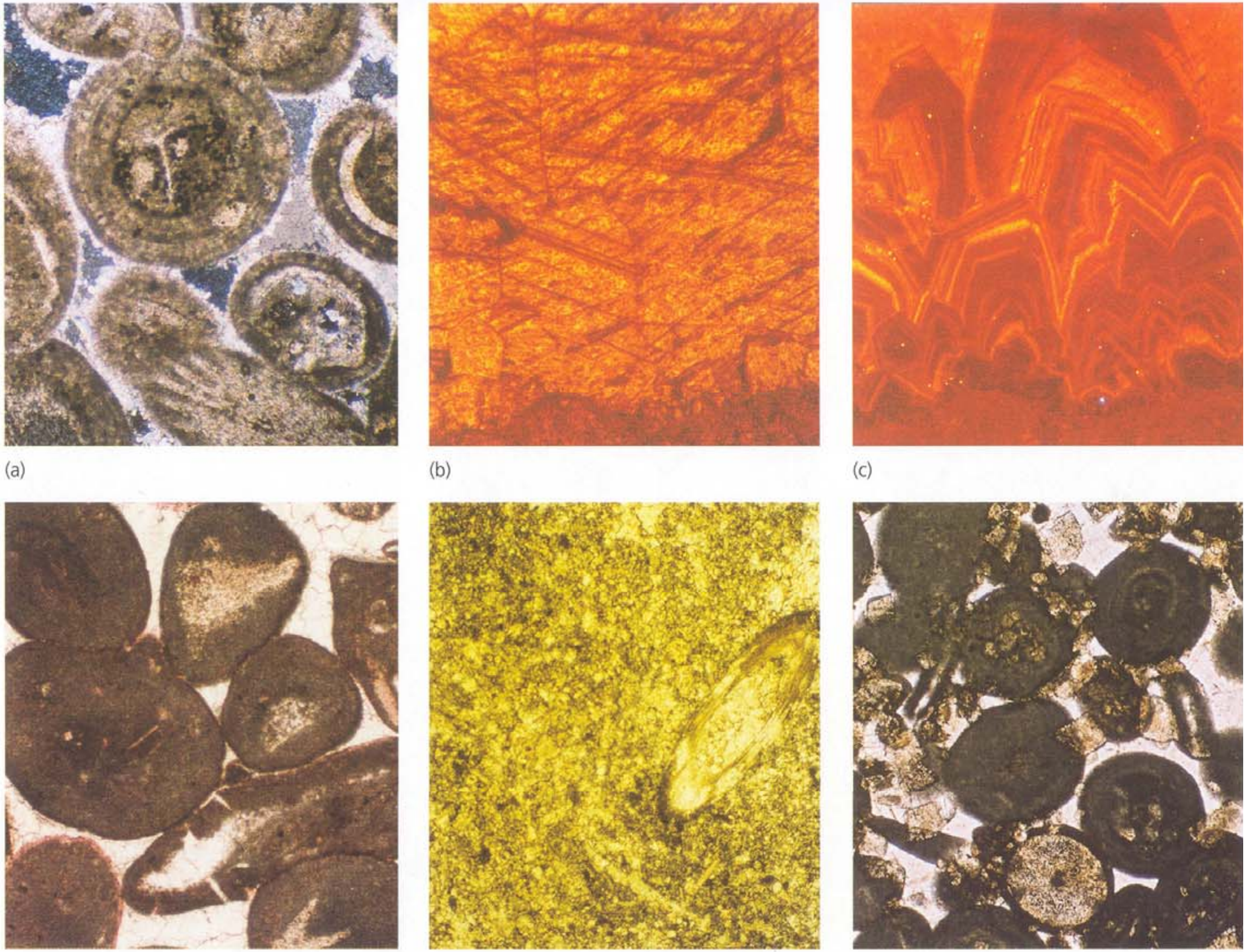
**Plate 12**
**(a,b)** Fusulinid foraminifer cemented by radiaxial fibrous calcite. The crystals are columnar and cloudy with inclusions, and have undulose extinction under crossed polars. Small area of clear calcite spar: **(a)** plane-polarized light, field of view 6×4 mm; **(b)** crossed polars, field of view 3×2 mm. Capitan, Permian. Texas, USA. **(c,d)** Syntaxial calcite overgrowth cement on crinoid grain. Early part of overgrowth calcite cloudy with inclusions is probably a marine precipitate; clear later overgrowth a burial precipitate. Grains mainly peloids, micritized bioclasts and faecal pellets, showing concavo-convex/interpenetrative contacts, indicating some compaction. Very thin isopachous calcite cement fringes around grains seen in **(d)** are probably marine precipitates. Rock also cut by thin calcite veins. **(c)** Plane-polarized light; **(d)** Crossed polars. Cretaceous. Alps, France. Field of view 3×2 mm.




Tucker (2001)

a: cementing in meteoric vadose zone; b, c: calcite spar; d: sutured contacts because of compaction; e: microspar-pseudospar formed during neomorphism; f: Ooids with scattered dolomite rhombs.

**Plate 13**
**(a)** Calcite cement at grain contacts and irregularly around grains, indicating near-surface, meteoric vadose environment. Later precipitation of large poikilotopic calcite (black, in extinction) took place during burial after some compaction. Crossed polars. Carboniferous. Glamorgan, Wales. Field of view 0.8×0.8 mm.
**(b, c)** Calcite spar.
**(b)** Calcite spar under plane-polarized light showing drusy fabric (crystal-size increase away from the substrate) and prominent twin planes. **(c)** Same field of view under cathodoluminescence showing delicate growth zones resulting from subtle variation in manganese and iron contents. Triassic. Glamorgan, Wales. Field of view 2×2 mm.
**(d)** Sutured (microstylolitic) contacts and concavo-convex contacts between grains (micritized ooids and bioclasts) and mechanical fracture of lower grain. Calcite spar between grains is a post-compaction burial cement. Jurassic. Burgundy, France. Field of view 2×2 mm.
**(e)** Microspar–pseudospar formed through aggrading neomorphism with fossil relics (brachiopod spine on right). Carboniferous. Yorkshire, England. Field of view 2×2 mm.
**(f)** Oolitic grainstone with scattered dolomite rhombs precipitated after early compaction (see grain contacts), before calcite spar cement. Carboniferous. Glamorgan, Wales. Field of view 2×2 mm.



(a) (b) (c)
(d) (e) (f)

Tucker (2001)

a: Dolomitized oolite with stylolite. Xenotopic dolomite below stylolite and idiotopic dolomite above; b: dolomitized grainstone; c: Baroque dolomite; d: delolomite; e: dolomite moulds

**Plate 14**

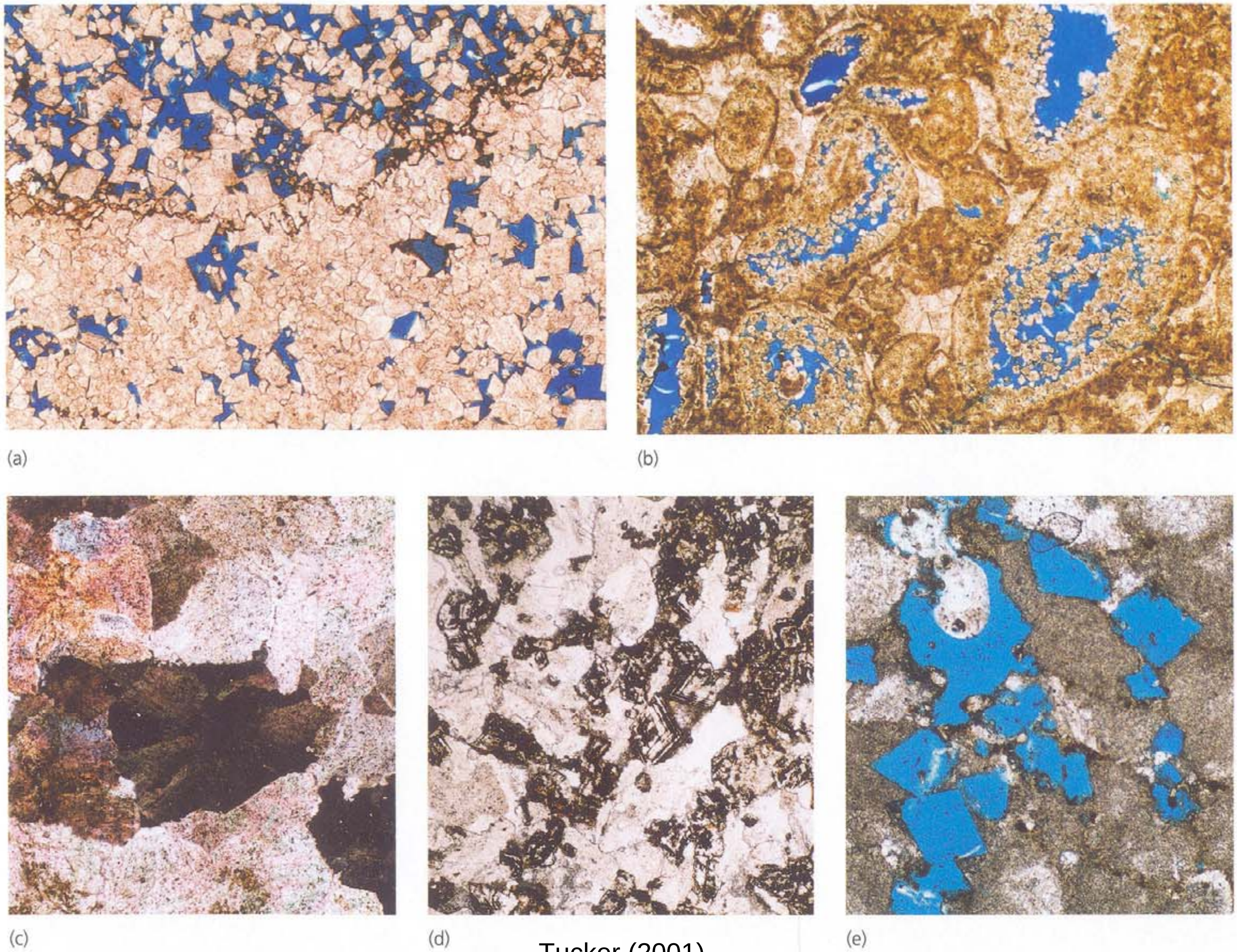
**(a)** Dolomitized oolite (no relics of original grains) with stylolite, highlighted by iron-rich clay. Xenotopic dolomite (anhedral crystals) below stylolite and idiotopic dolomite (euhedral crystals) above. Intercrystalline porosity shown through impregnation with blue resin. Arab Formation. Offshore UAE. Field of view 3 × 2 mm.

**(b)** Dolomitized grainstone with moderate preservation of original ooids. Intercrystalline porosity is present, shown up by impregnation with blue resin. Cretaceous. Offshore Angola. Field of view 6 × 4 mm.

**(c)** Baroque dolomite: coarse crystals with undulose extinction. Rock is an oolite but there are no relics. Crossed polars. Carboniferous. Glamorgan, Wales. Field of view 2 × 2 mm.

**(d)** Dedolomite: crinoidal grainstone with overgrowths containing scattered dolomite rhombs that have been replaced by calcite. The dark material is iron oxide/hydroxide, suggesting the dolomite was originally ferroan. Carboniferous. Northumberland, England. Field of view 2 × 2 mm.

**(e)** Dolomite moulds: grainstone with scattered dolomite rhombs that have been dissolved out to give a good porosity, as shown by blue resin. Stylolitic contacts between grains. Jurassic. Burgundy, France. Field of view 0.8 × 0.8 mm.




Tucker (2001)

# Examples of modern carbonate platforms

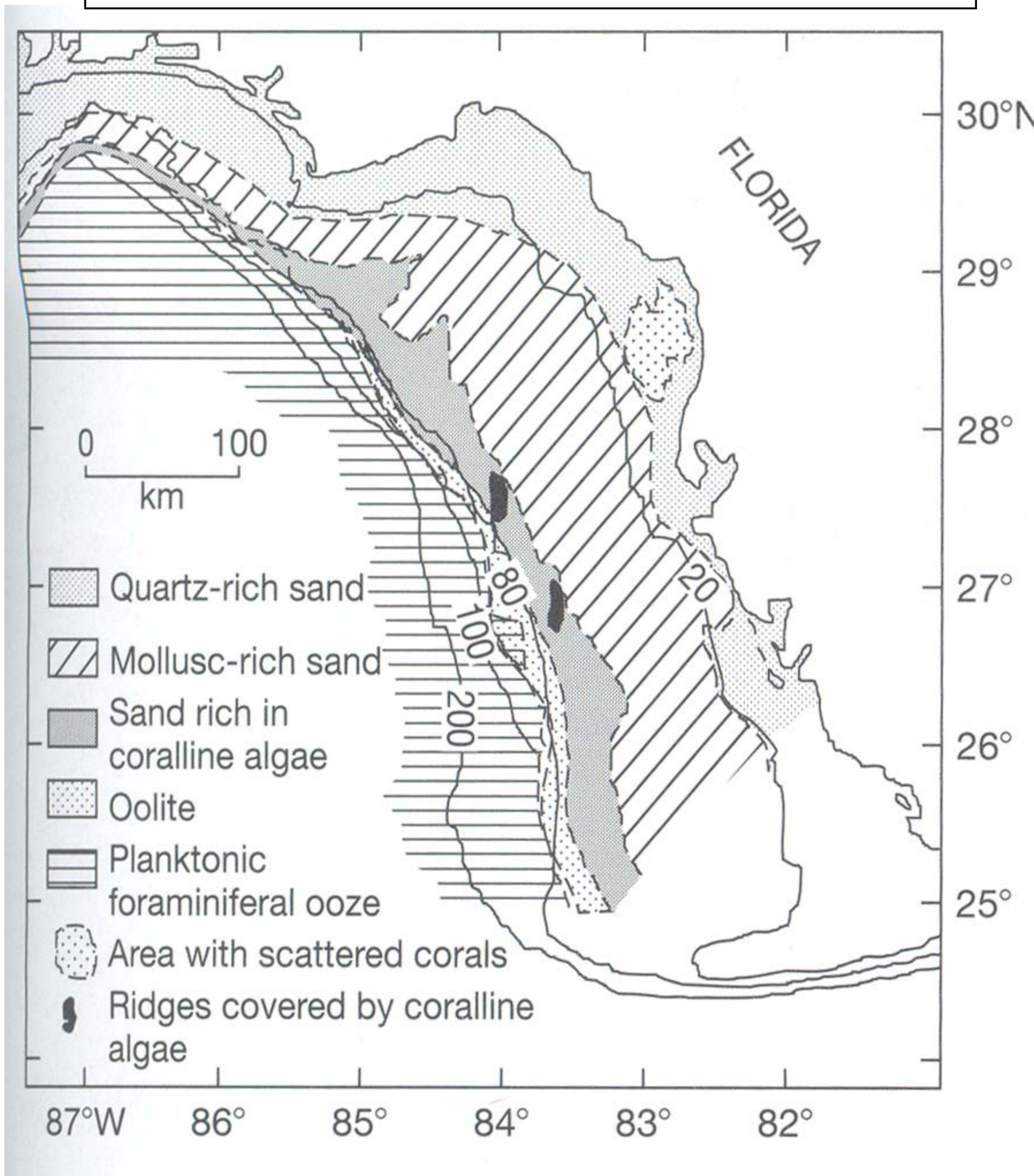
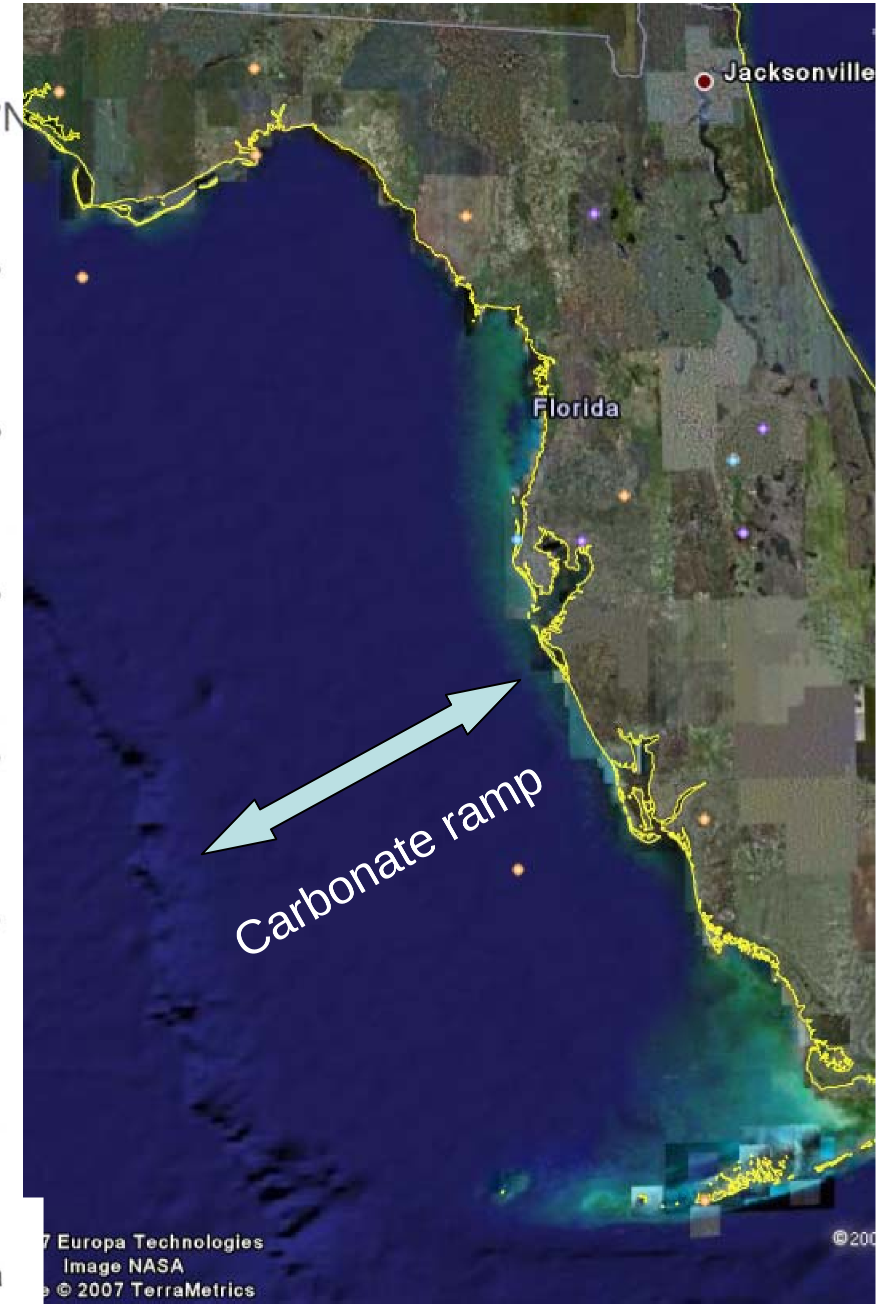



**Figure 11.5**
Example of an open shelf or carbonate ramp, the West Florida Shelf in the eastern Gulf of Mexico. [From Sellwood, B. W.,



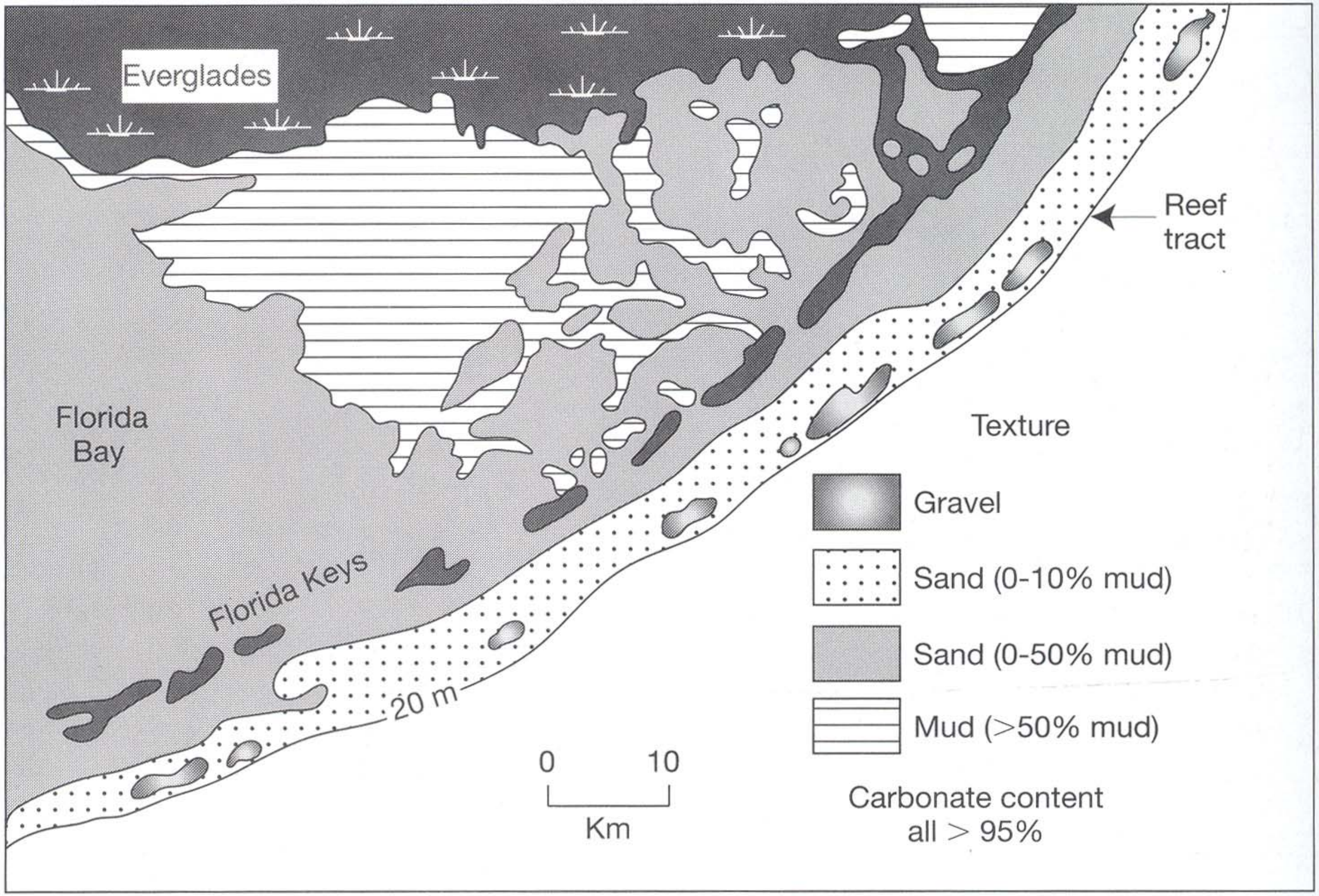
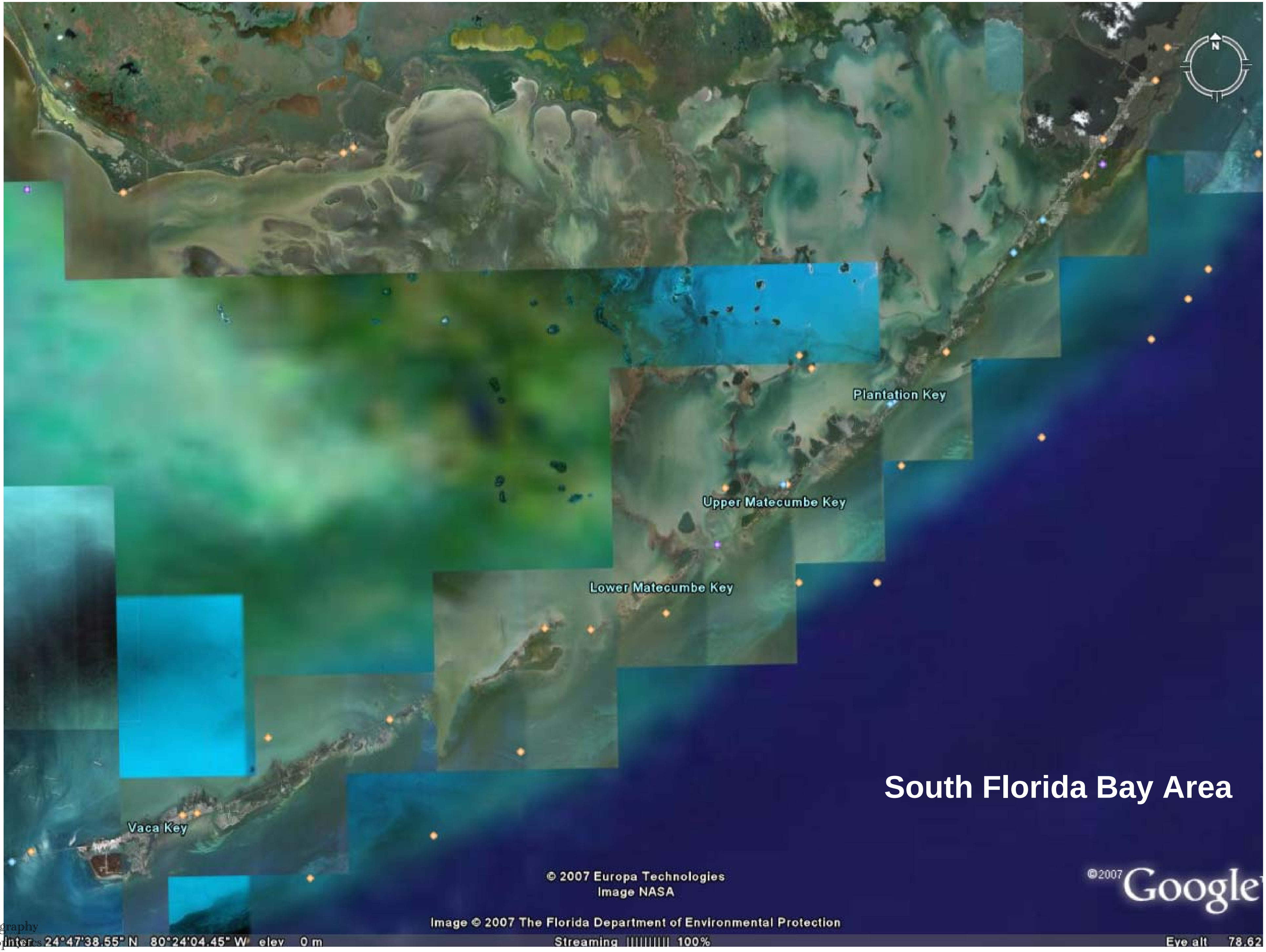
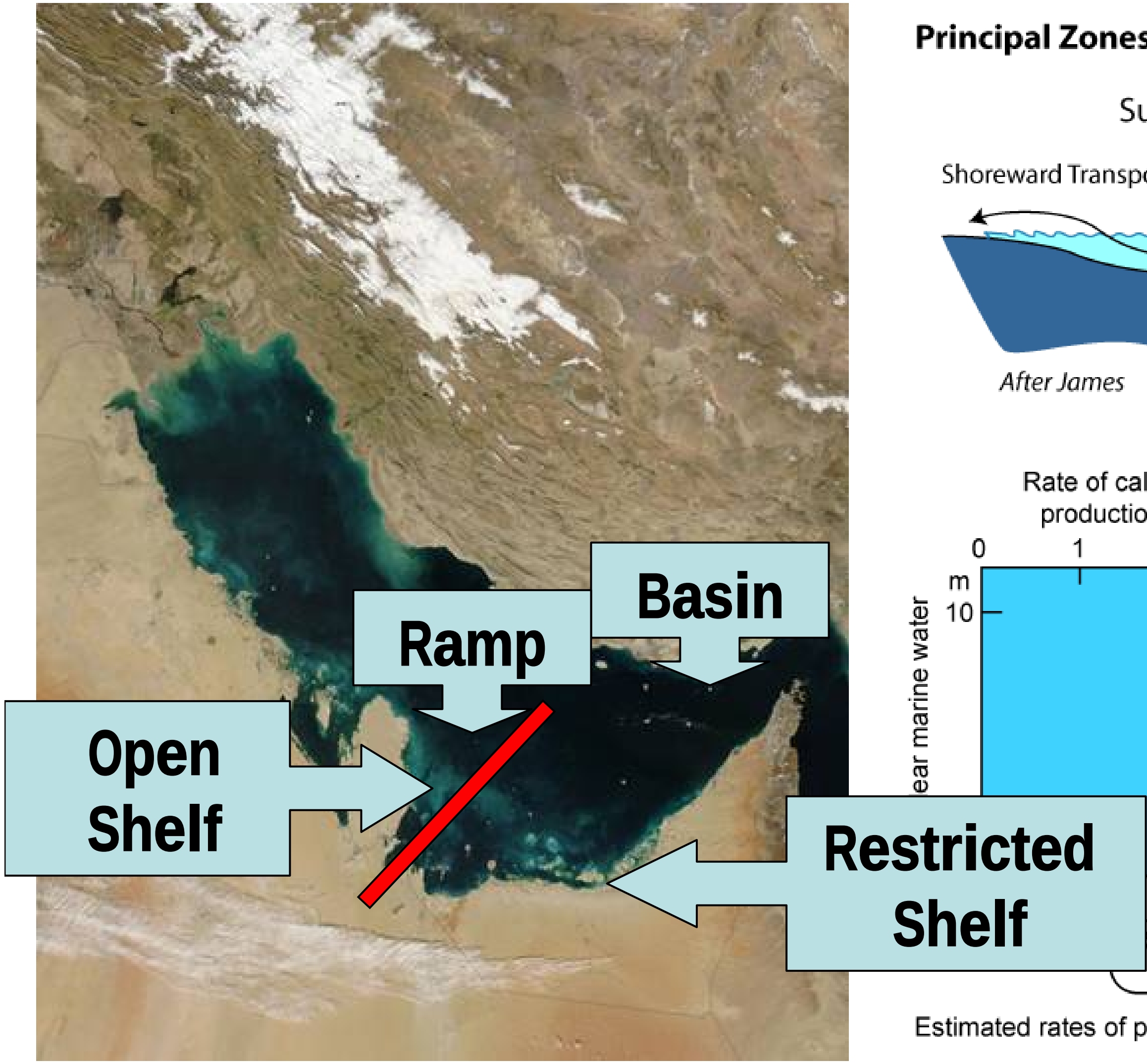


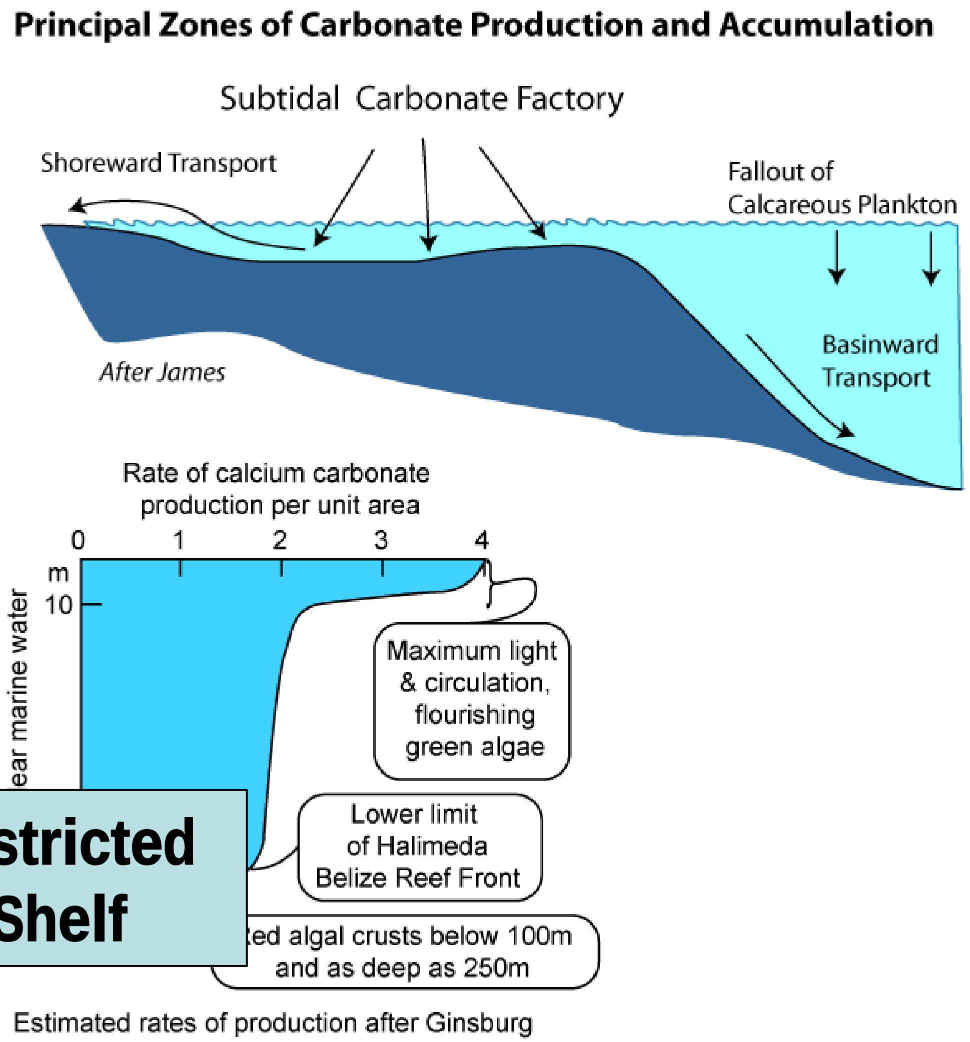

**Figure 11.6**

Sediment map of South Florida Bay area, an example of a modern rimmed carbonate shelf, showing the distribution of carbonate sediment by grain size on the shelf platform. [After Sellwood, B. W., 1978, Shallow-water carbonate environments, *in* Reading, H. G. (ed.),

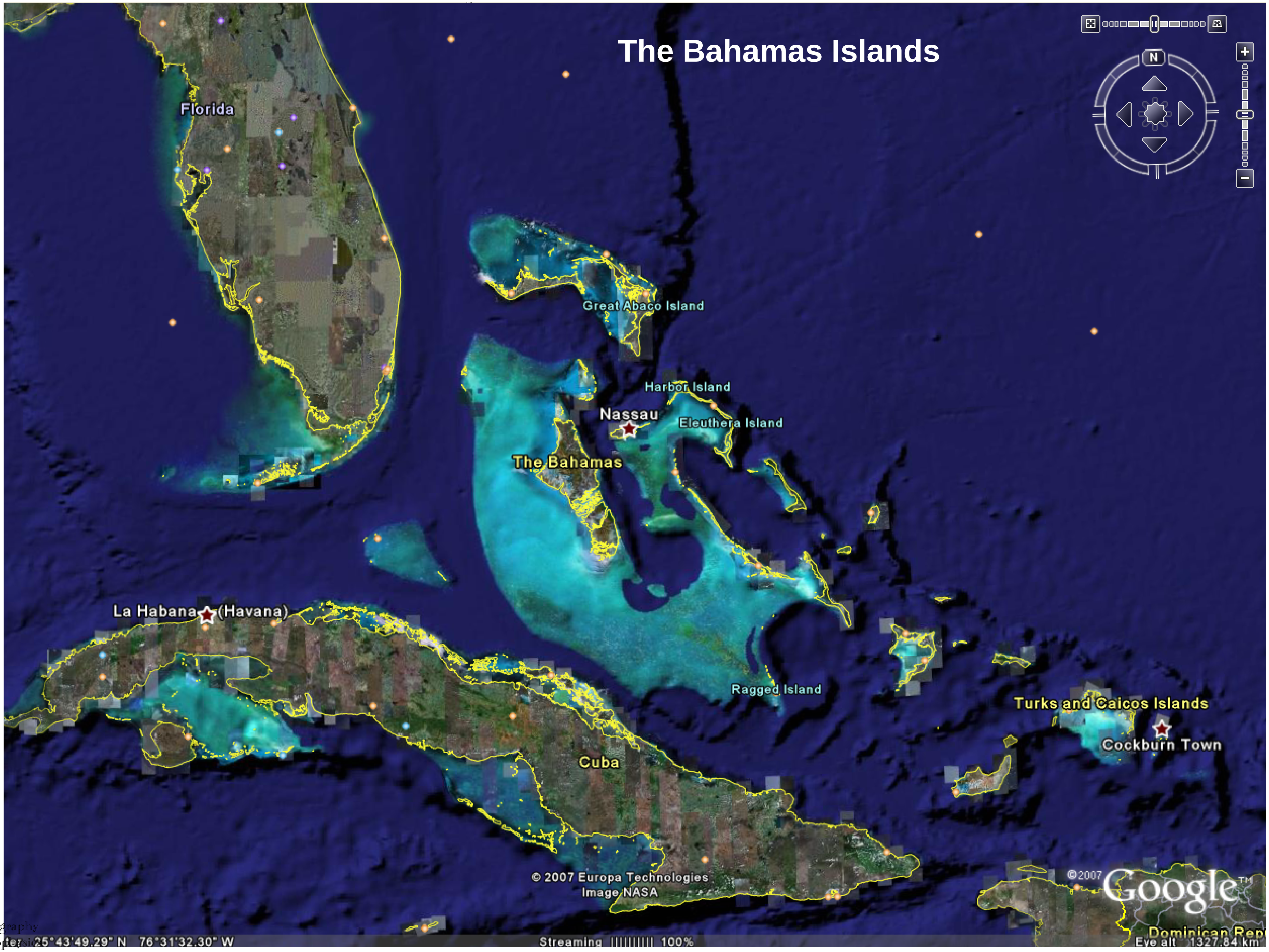

South Florida Bay Area
Plantation Key
Upper Matecumbe Key
Lower Matecumbe Key
Vaca Key
© 2007 Europa Technologies
Image NASA
Image © 2007 The Florida Department of Environmental Protection
©2007 Google
24°47'38.55" N 80°24'04.45" W elev 0 m
Streaming 100%
Eye alt 78.62

Examples of modern carbonate platforms




Sequence Stratigraphy
Institute of Geophysics
National Central Univ., Taiwan
Prepared by Dr. Andrew T. Lin


The Bahamas Islands
Florida
Great Abaco Island
Harbor Island
Nassau
Eleuthera Island
The Bahamas
La Habana (Havana)
Ragged Island
Turks and Caicos Islands
Cockburn Town
Cuba
© 2007 Europa Technologies
Image NASA
©2007 Google
Dominican Rep
25°43'49.29" N 76°31'32.30" W
Streaming 100%
Eye alt 1327.84 km

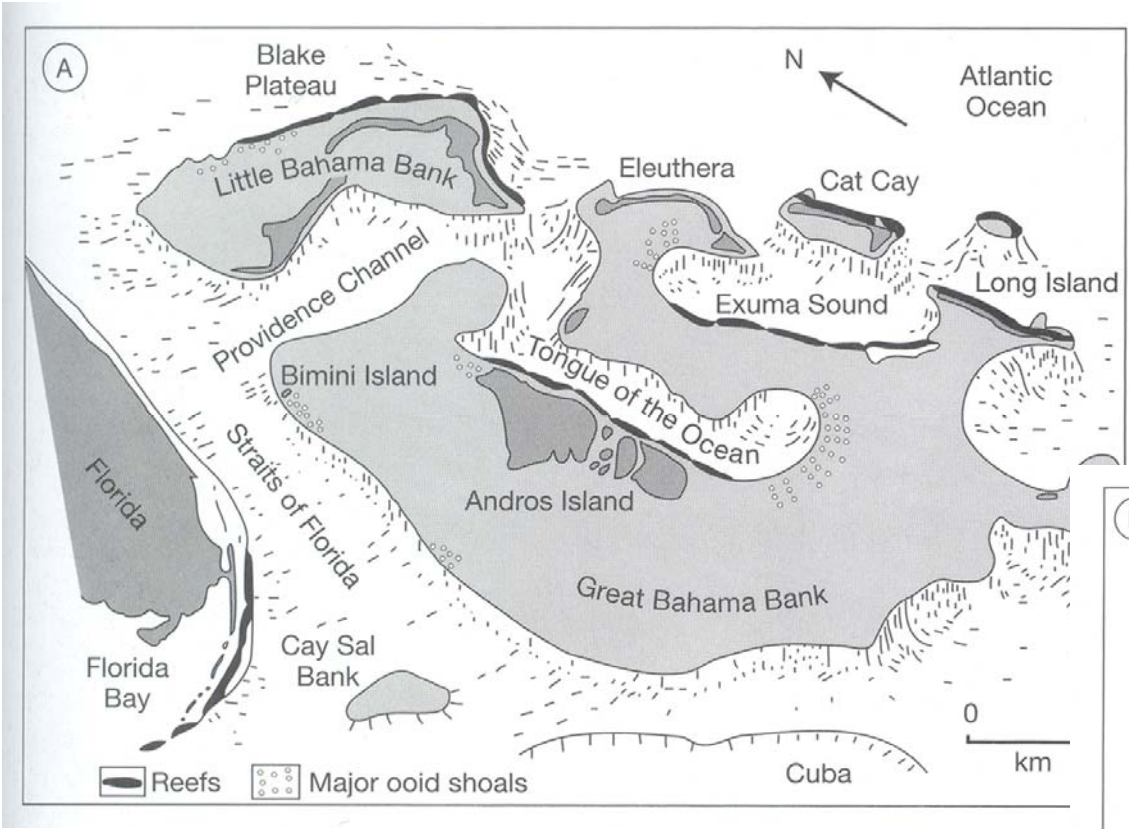
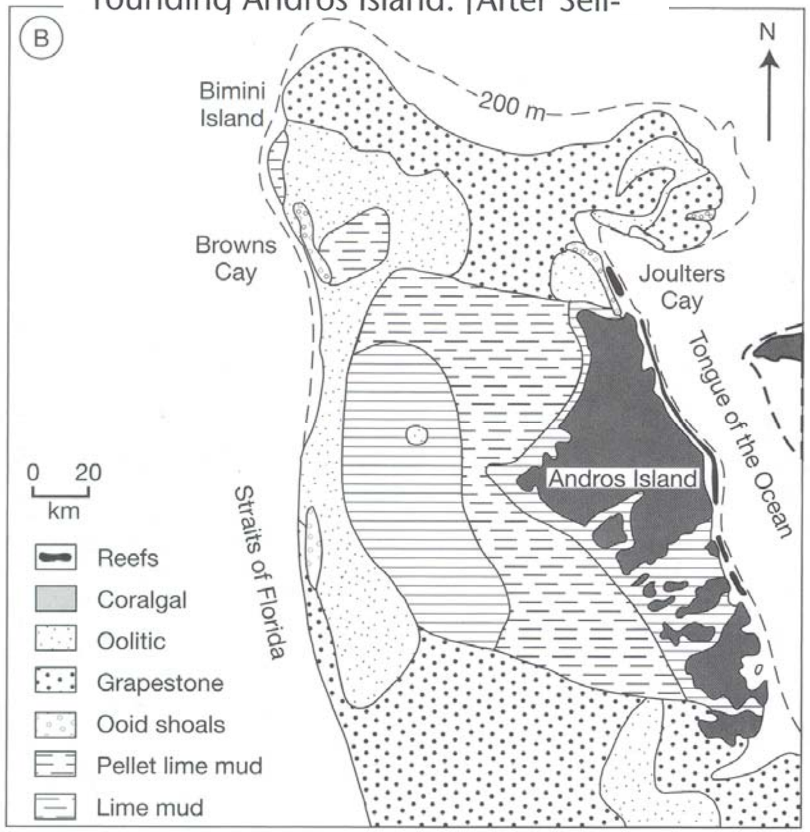
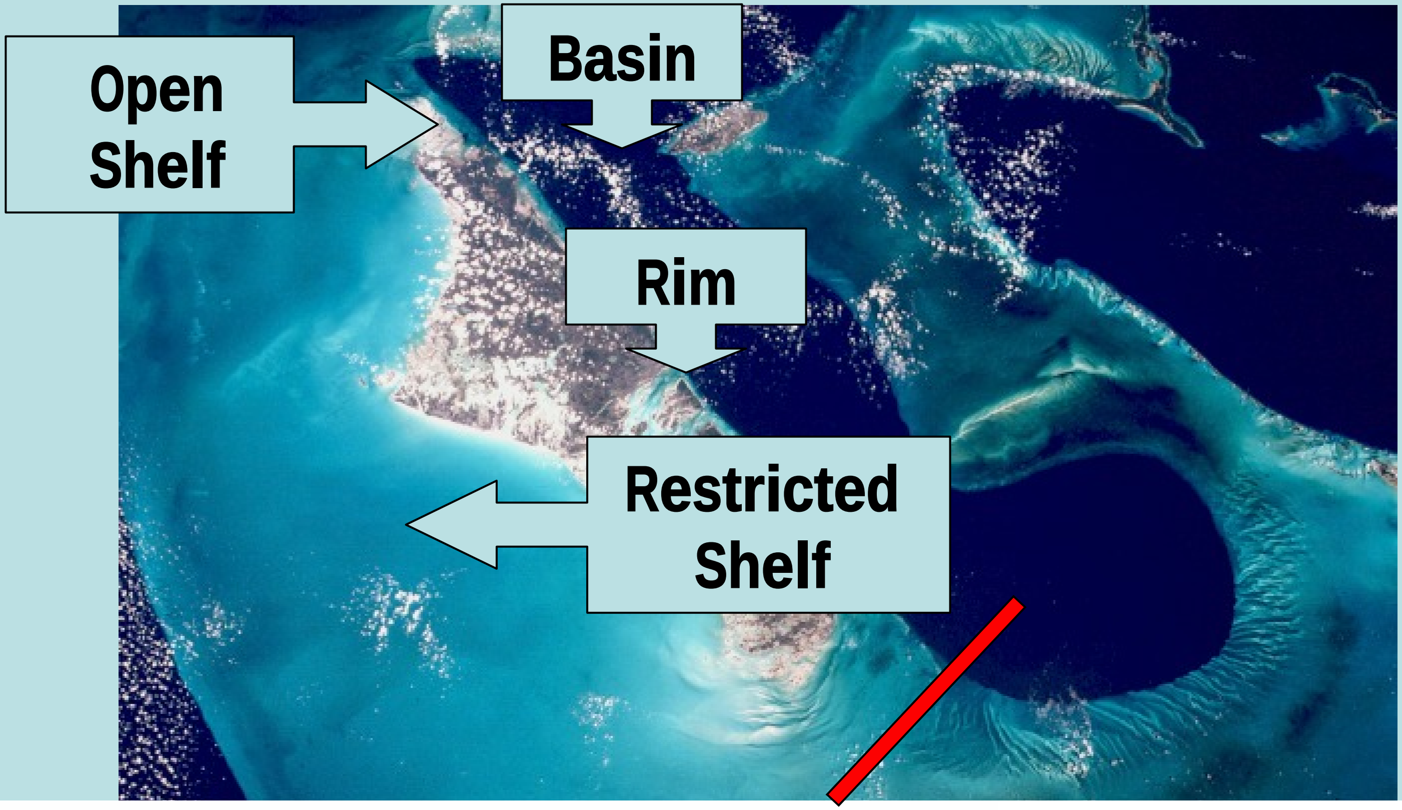
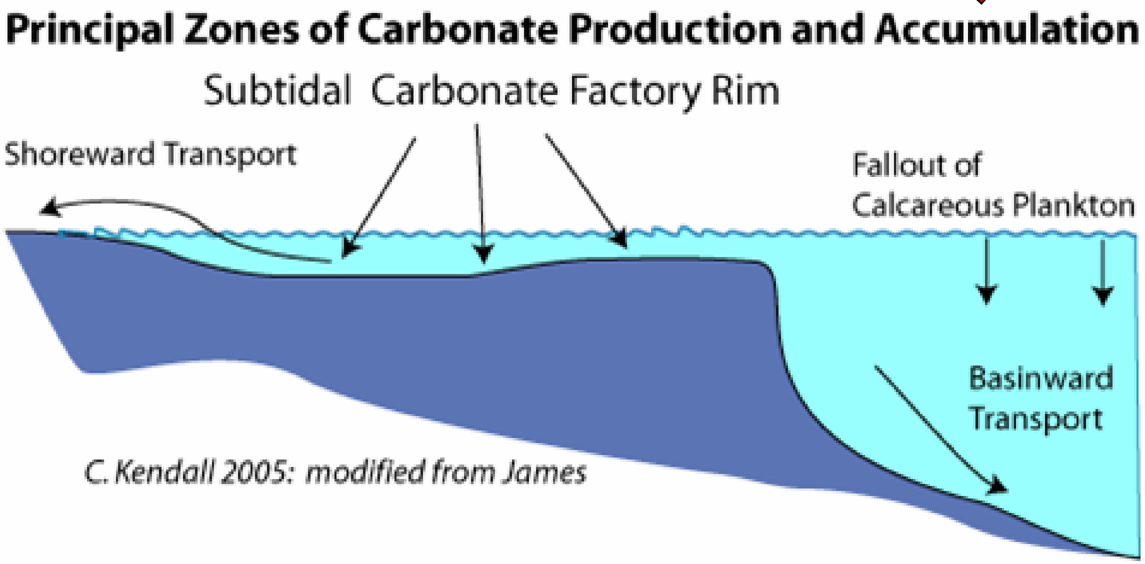
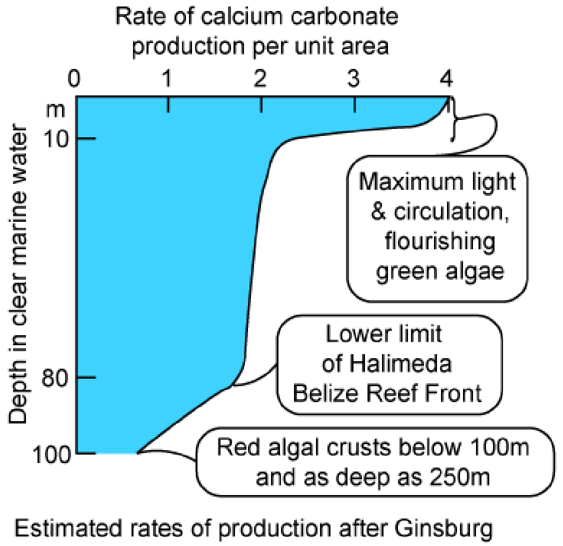


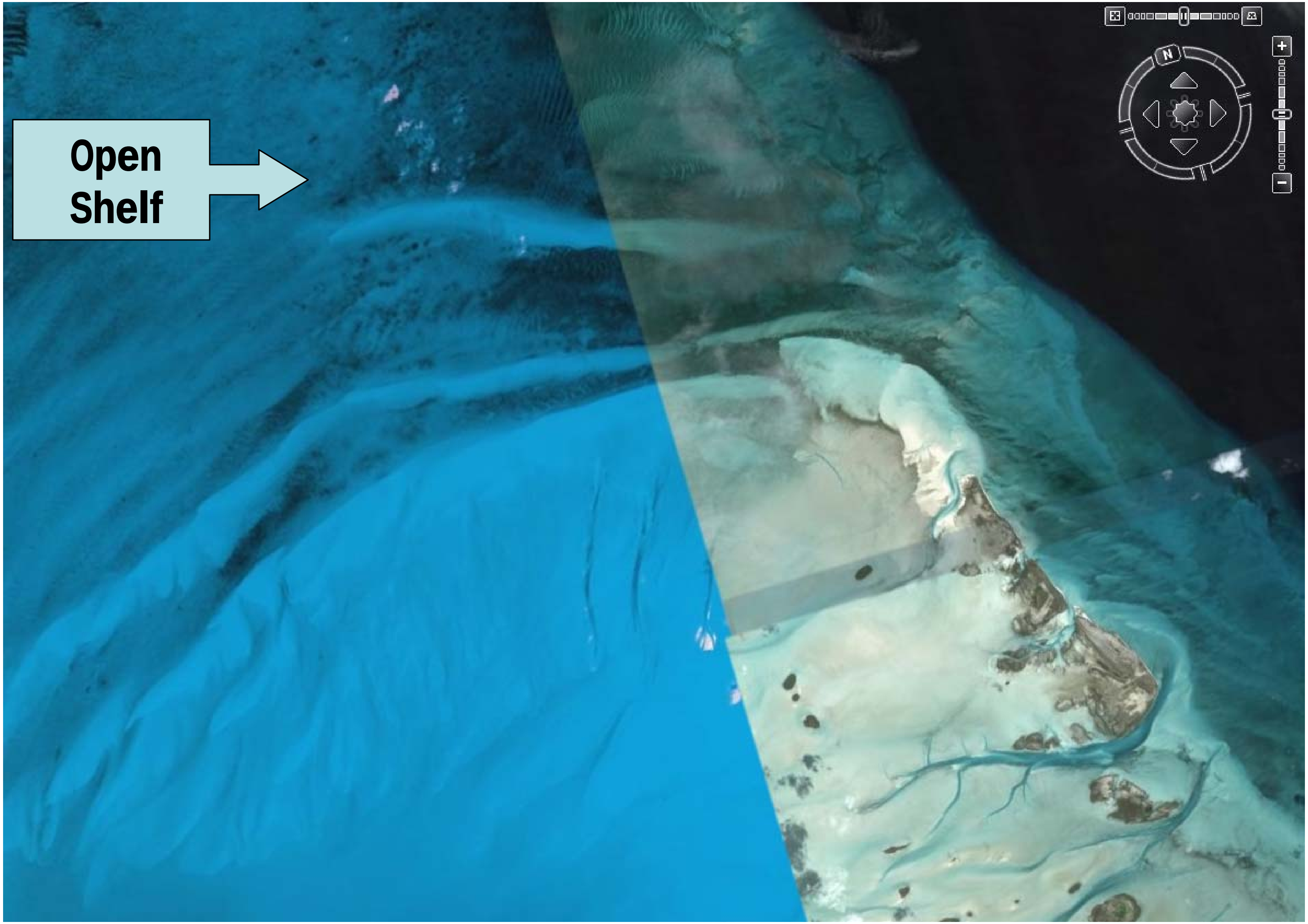

**Figure 11.7**
Carbonate sediment distribution on an isolated carbonate platform, the Great Bahama Banks. Figure A shows the positions of the major banks and channels in the Bahama area. [After Geblein, C. D., 1974, Guidebook for modern Bahaman plaform environments: Geological Society of America Annual Meeting, 1974, Fig. 18, p. 22.] Figure B shows sediment distribution on a portion of Great Bahama Bank surrounding Andros Island. [After Sell-



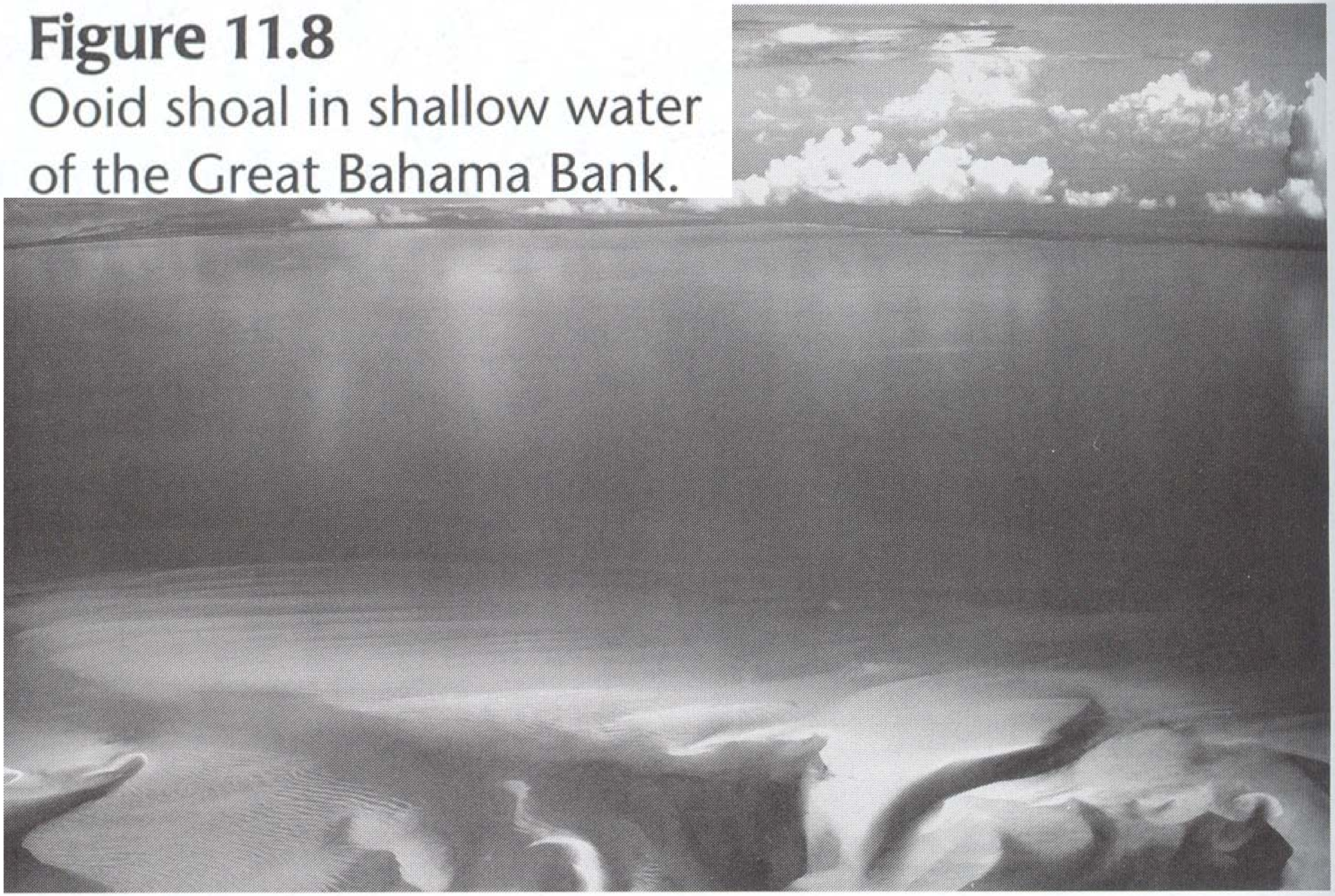

Open Shelf
Basin
Rim
Restricted Shelf

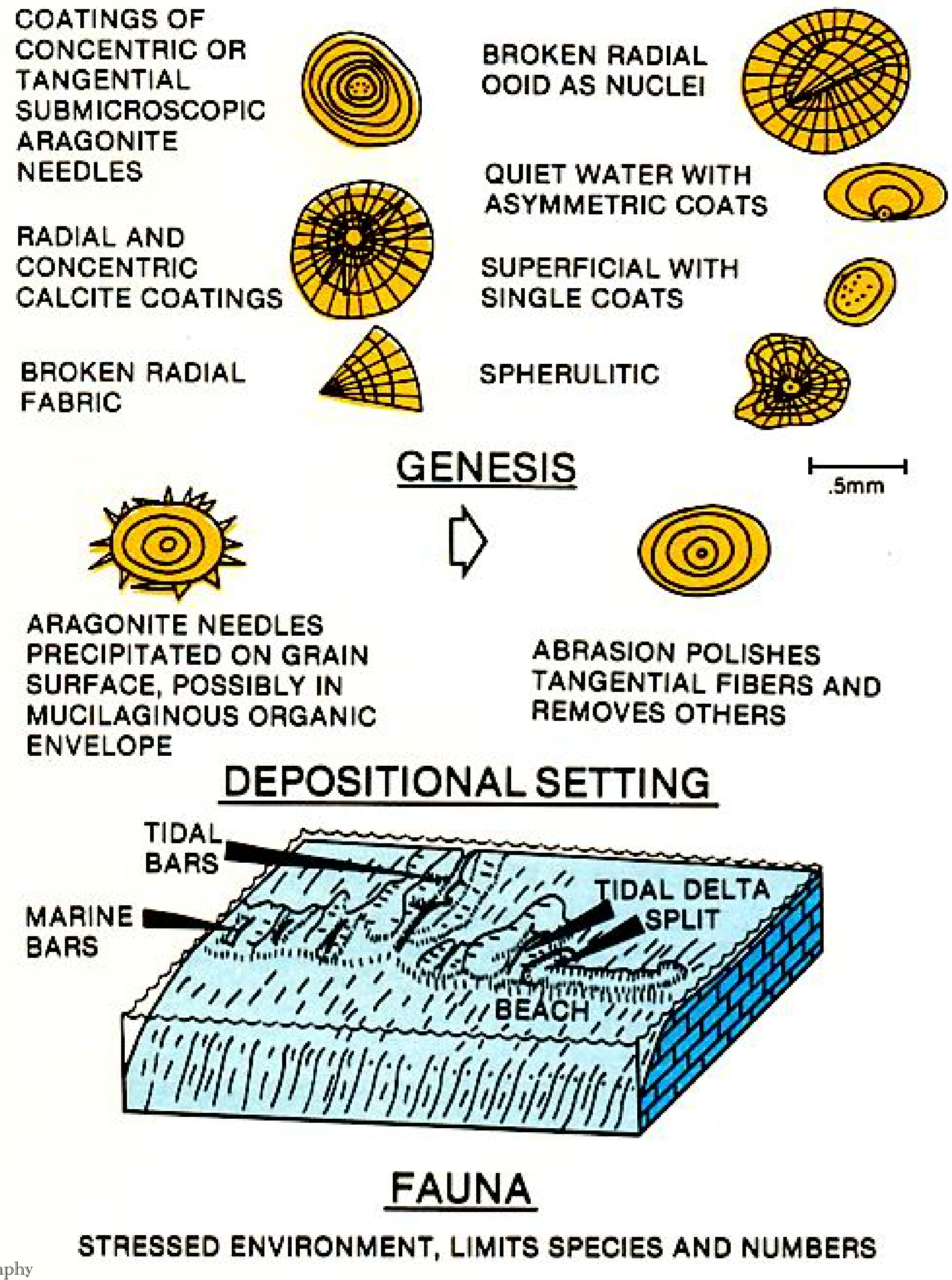

Principal Zones of Carbonate Production and Accumulation
Subtidal Carbonate Factory Rim
Shoreward Transport
Fallout of Calcareous Plankton
Basinward Transport
C. Kendall 2005: modified from James


Rate of calcium carbonate production per unit area
0
1
2
3
4
m
10
80
100
Depth in clear marine water
Maximum light & circulation, flourishing green algae
Lower limit of Halimeda Belize Reef Front
Red algal crusts below 100m and as deep as 250m
Estimated rates of production after Ginsburg


Open
Shelf
N

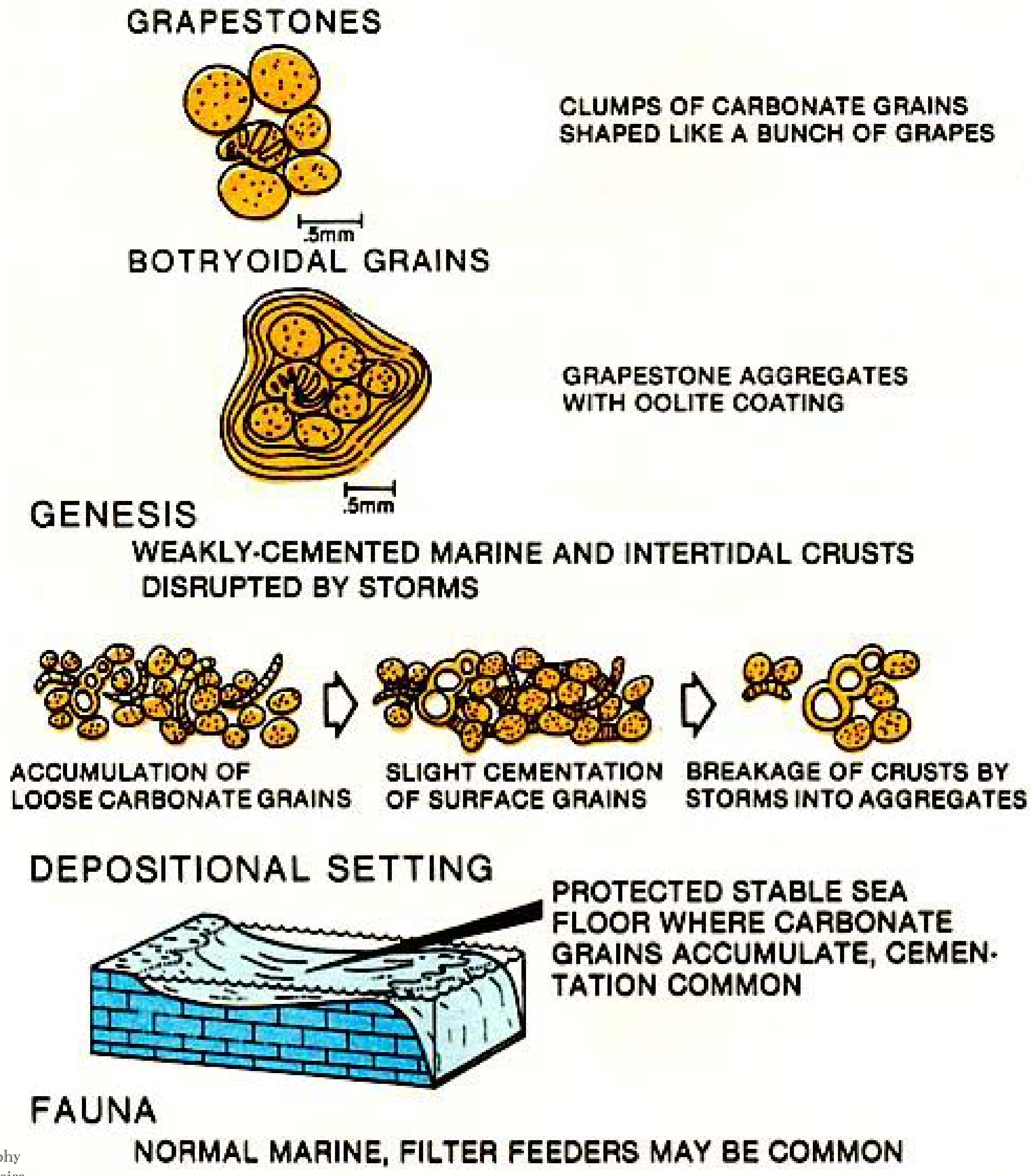
# Figure 11.8
Ooid shoal in shallow water of the Great Bahama Bank.






# Ooid Shoals

- Form linear bodies parallel to basin
- Shoaling upward cycles common
- Sheets not uncommon
- Locally confined “channel fill”
- Fauna stressed but moderately cosmopolitan

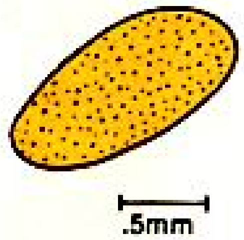



# Grapestone Shoals

- Commonly grains form top of shoaling upward cycles
- Sheet-like geometry common
- Fauna moderately cosmopolitan

# Pelloid Shoals

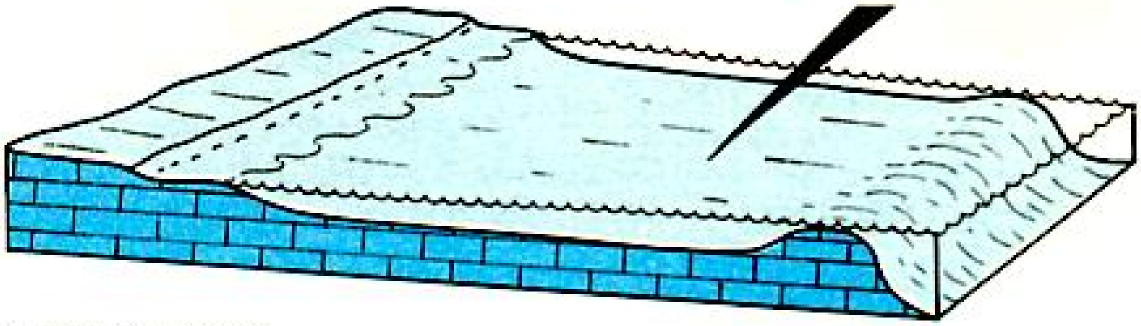
- Grains occur within shoaling upward cycles
- Sheet-like geometry common
- Fauna low diversity




GENESIS

EXCRETION

DEPOSITIONAL SETTING

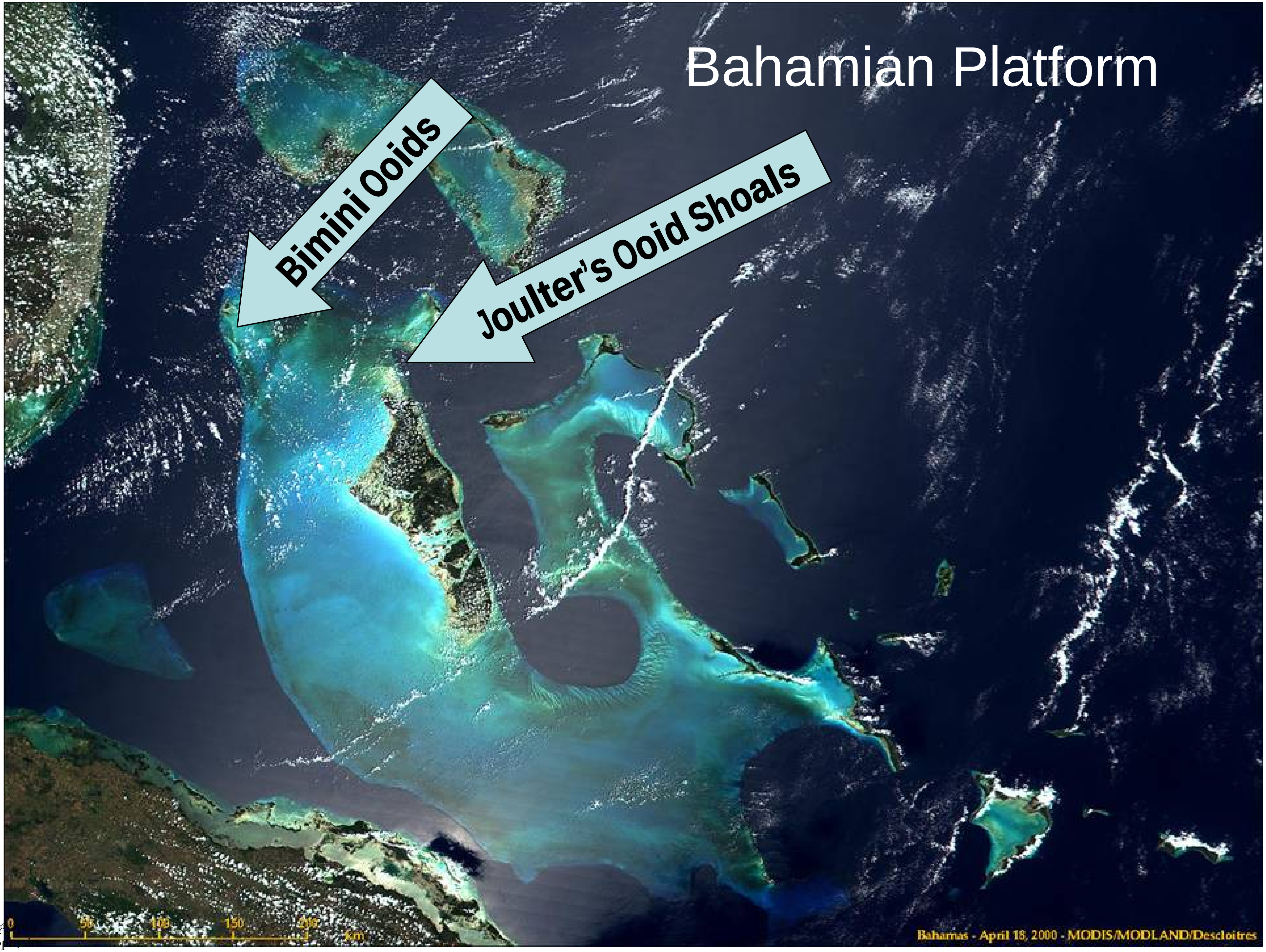



DIAGENESIS

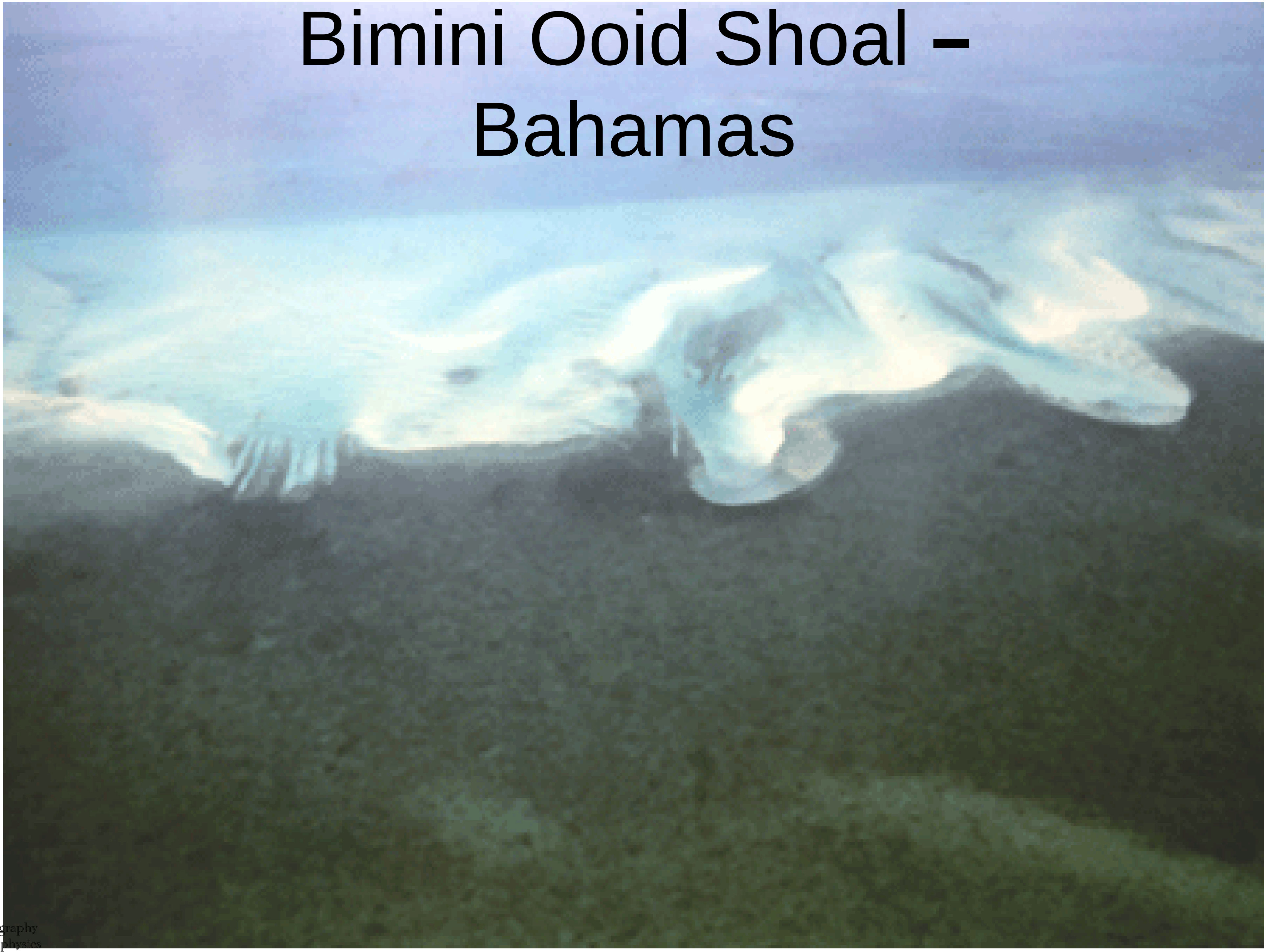
MOST PRESERVED PELLETS IN ROCK RECORD MUST HAVE BEEN CEMENTED PENECONTEMPORANEOUSLY. MOST LIME MUDS WERE PROBABLY COMPOSED OF SQUASHED SOFT FECAL PELLETS.

FAUNAL ASSOCIATION

HIGH NUMBERS, LOW DIVERSITY, FILTER FEEDERS COMMON


Bahamian Platform
Bimini Ooids
Joulter's Ooid Shoals
0 50 100 150 200 km
Bahamas - April 18, 2000 - MODIS/MODLAND/Descloitres

# Bimini Ooid Shoal – Bahamas



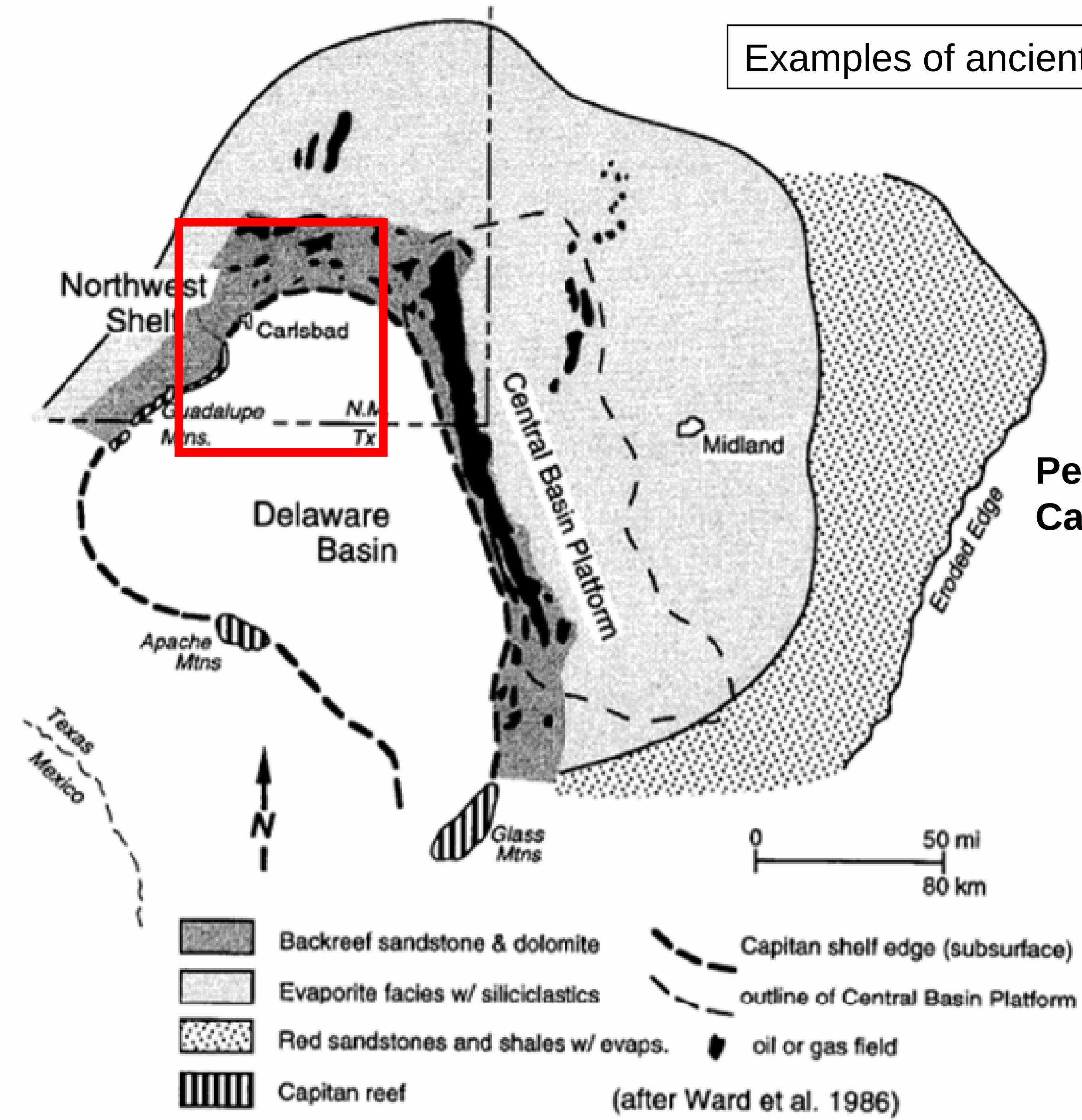
Joulter's Keys Ooid Shoals

-

Wide spread Sheet of parallel bodies

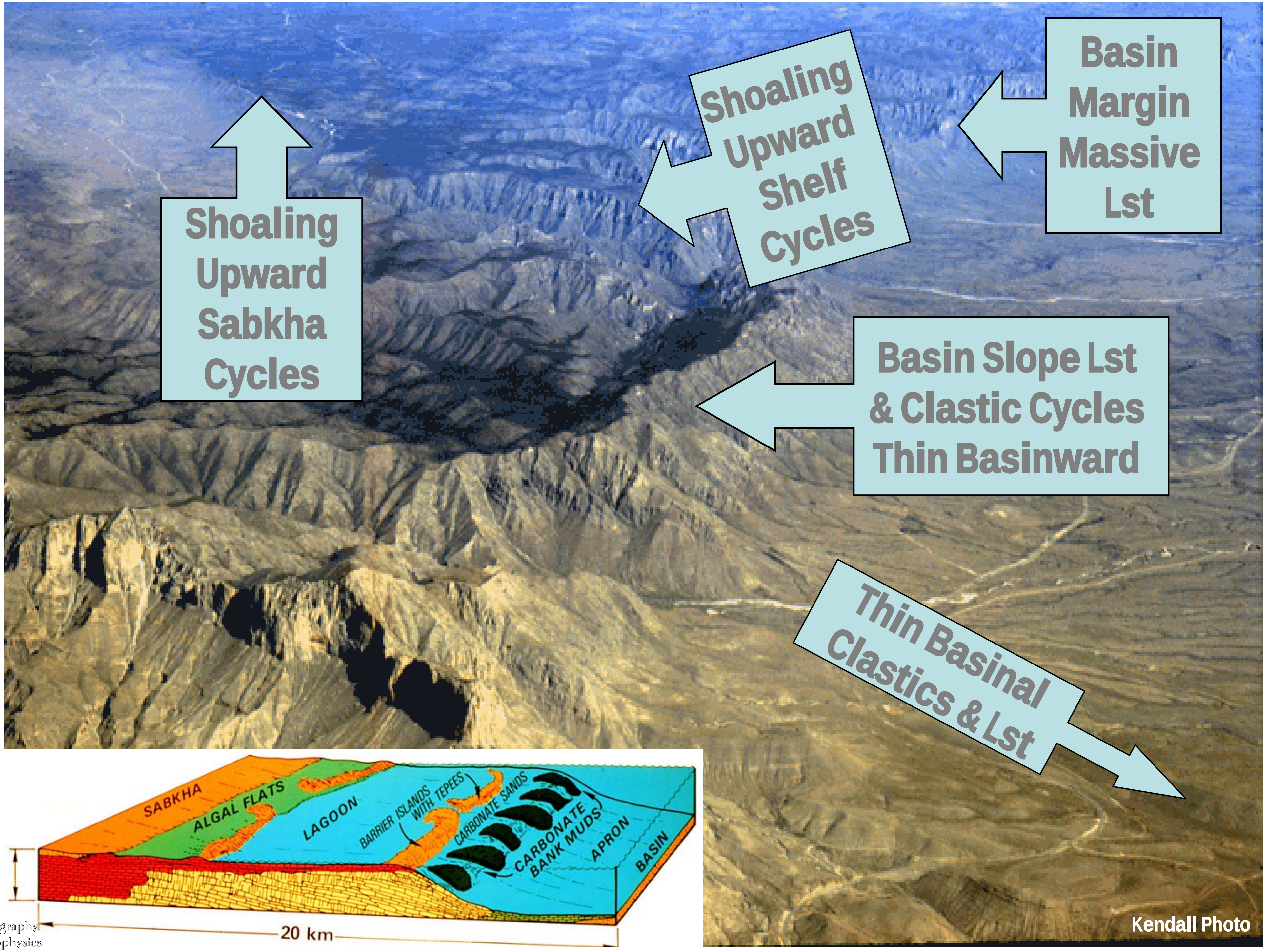
# Joulter’s Key Tidal Channel

## Examples of ancient carbonate platforms




**Delaware Basin (western Texas and southern New Mexico)**

**Permian (Guadalupian) Carbonate**


Shoaling Upward Sabkha Cycles
Shoaling Upward Shelf Cycles
Basin Margin Massive Lst
Basin Slope Lst & Clastic Cycles Thin Basinward
Thin Basinal Clastics & Lst
Kendall Photo
SABKHA
ALGAL FLATS
LAGOON
BARRIER ISLANDS WITH TEPEES
CARBONATE SANDS
CARBONATE BANK MUDS
APRON
BASIN
20 km

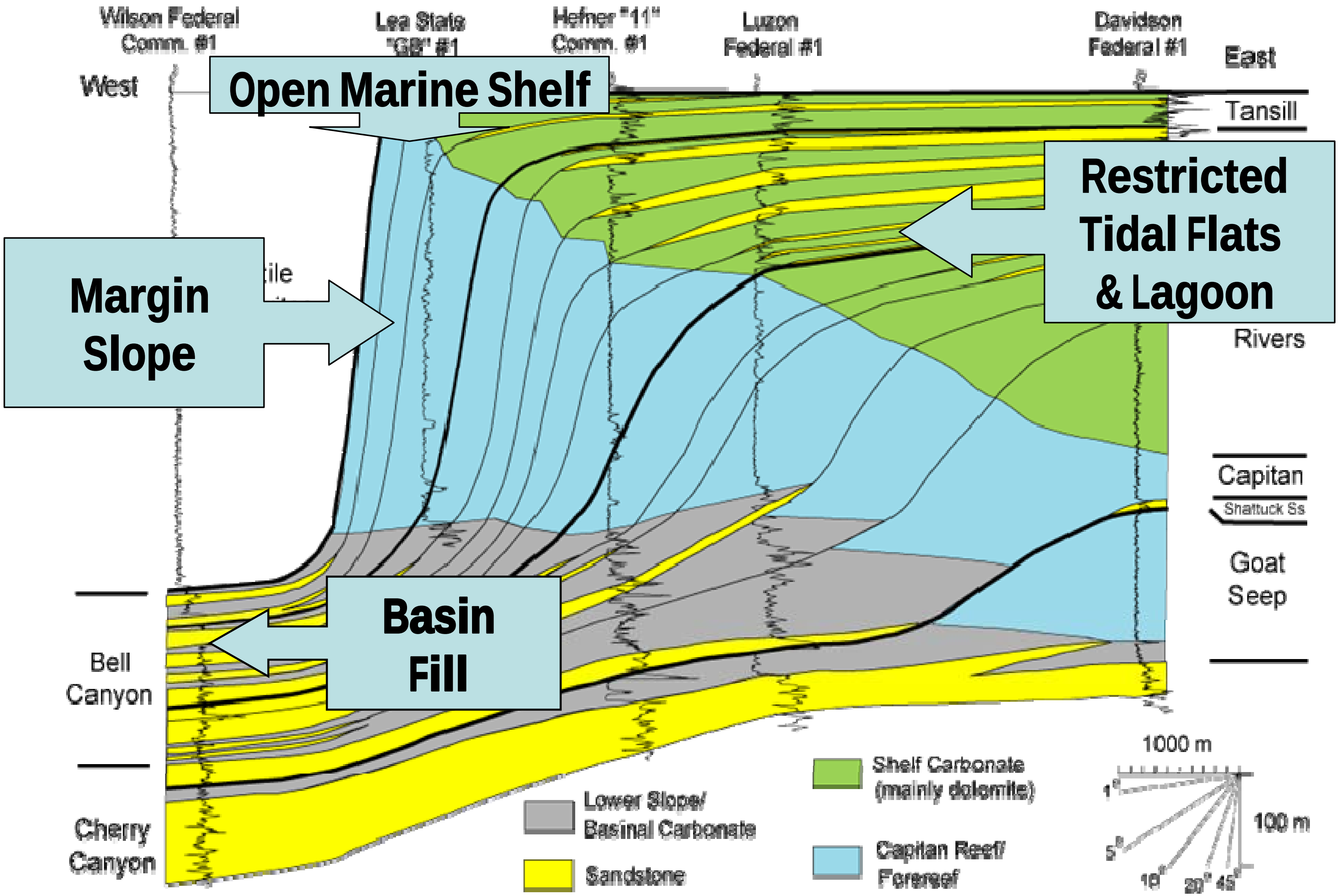
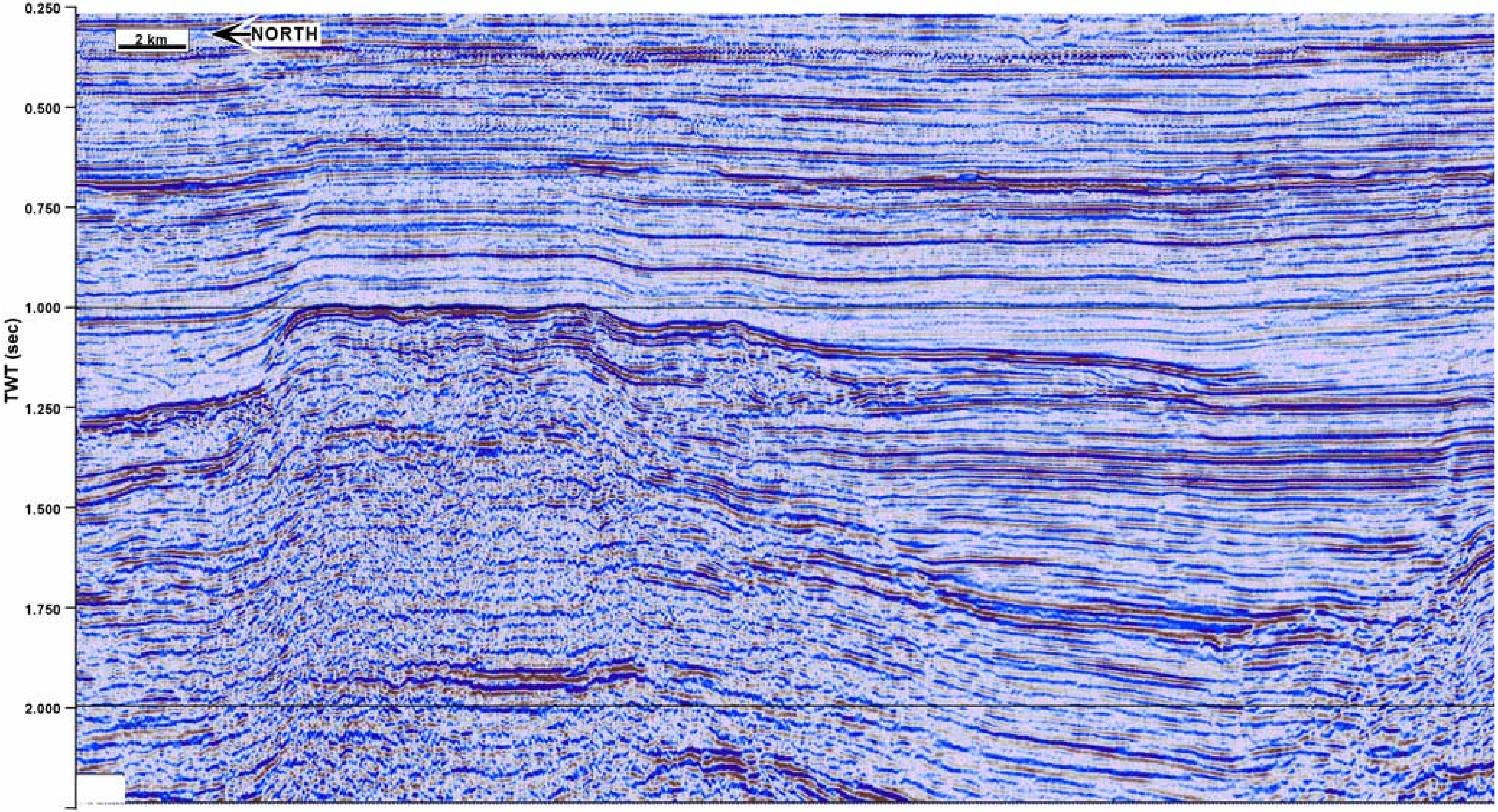

Wilson Federal Comm. #1
Lea State "GB" #1
Hefner "11" Comm. #1
Luzon Federal #1
Davidson Federal #1
West
East
Open Marine Shelf
Restricted Tidal Flats & Lagoon
Margin Slope
Basin Fill
Tansill
Rivers
Capitan
Shattuck Ss
Goat Seep
Bell Canyon
Cherry Canyon
Lower Slope/ Basinal Carbonate
Sandstone
Shelf Carbonate (mainly dolomite)
Capitan Reef/ Forereef
1000 m
100 m
1°
5°
10°
20°
45°

**Figure 11.9**
Bold cliffs of massive Capitan Limestone (reef) that formed the rim of a huge Permian carbonate platform. The platform (shelf) carbonates extend toward the back of the photograph; deeper-water, basinal sediments are present in the foreground. Photo-




Miocene Isolated Platform, East Natuna Basin, South China Sea.

# 8.3 Slope/Basin Carbonates

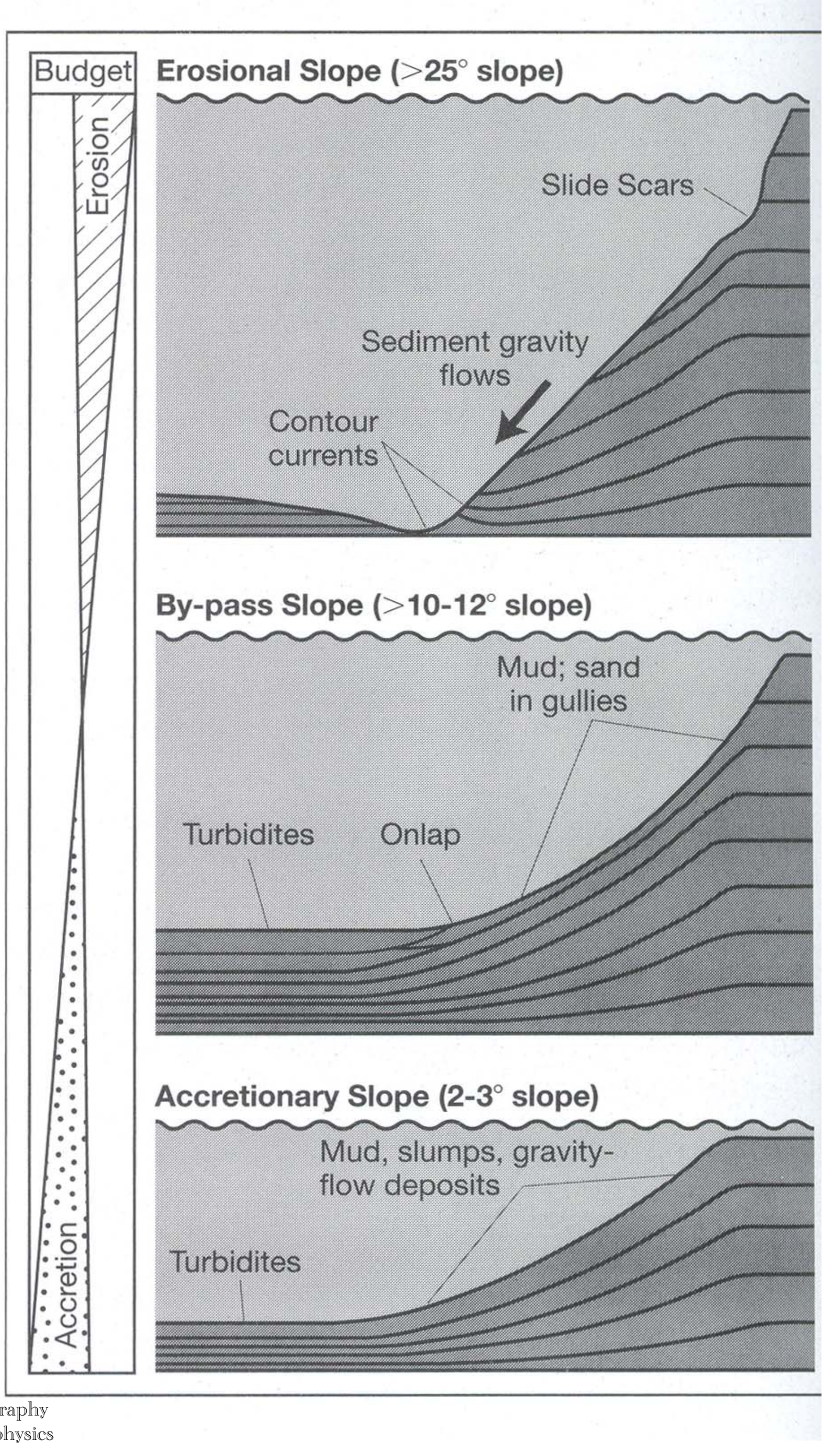



**Figure 11.10**
Principal kinds of carbonate slopes, based on examples from the Bahama Platform. [After Schalger, W., and R. N. Gins-

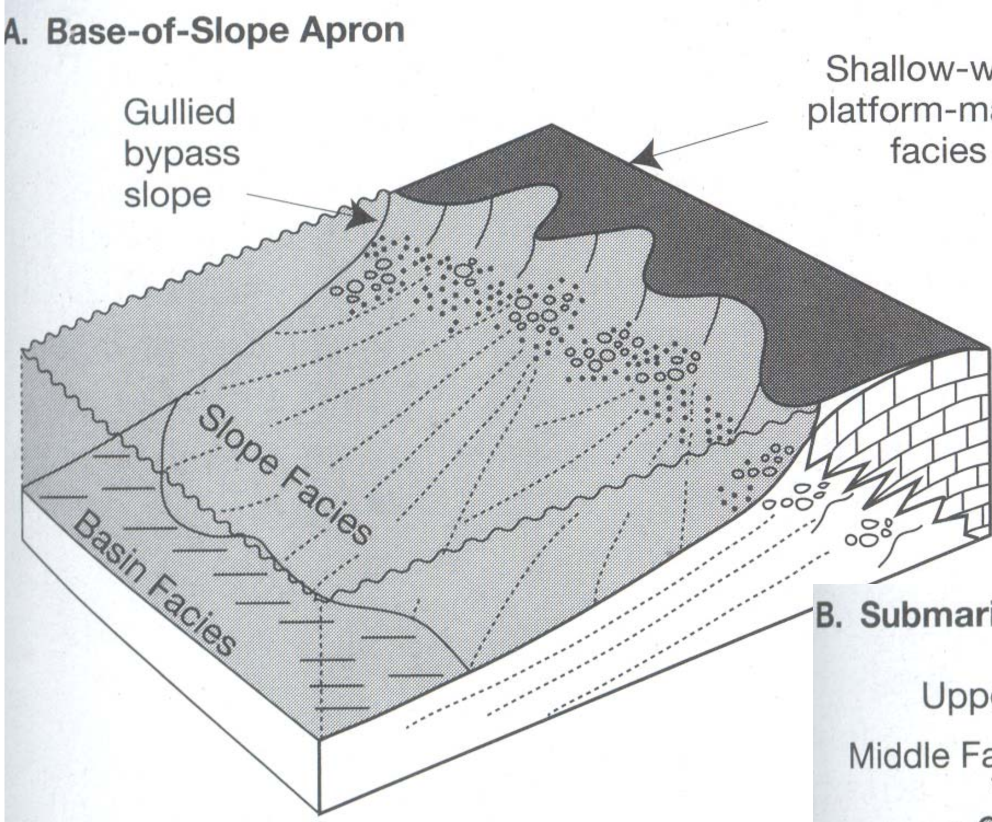
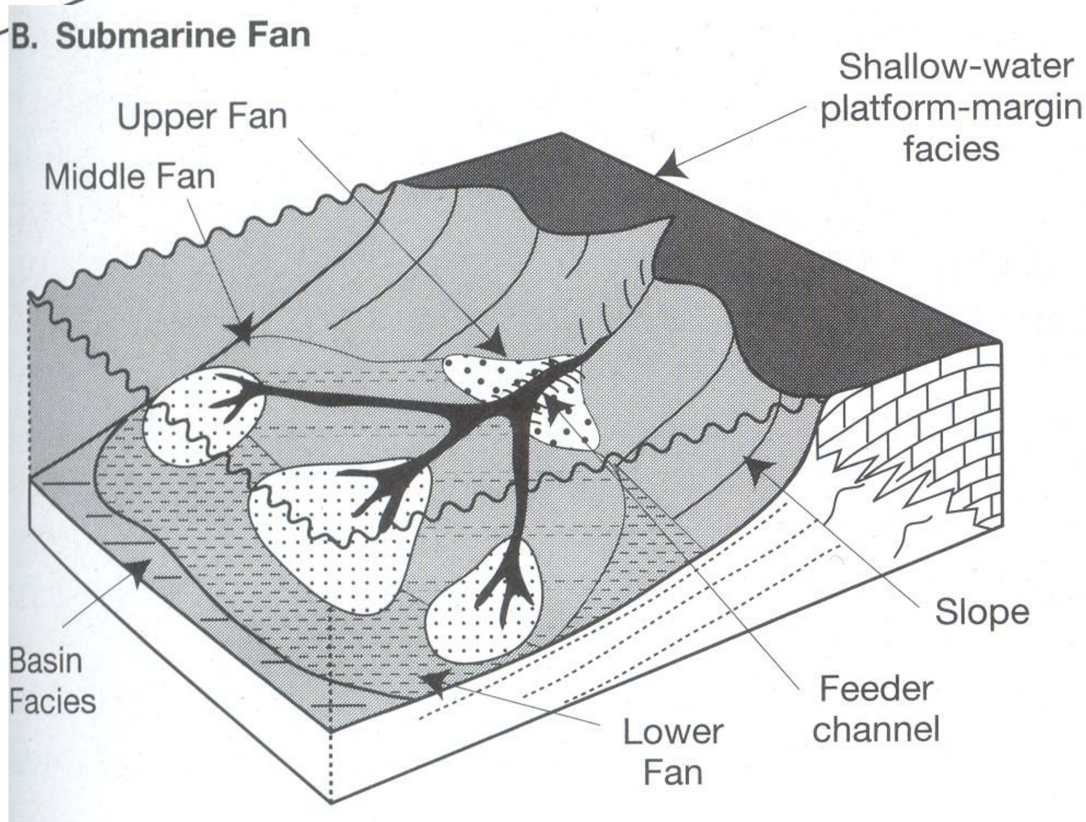



**Figure 11.11**
Schematic block diagrams illustrating models for two fundamental kinds of carbonate slopes: slope aprons and carbonate submarine fans. A. Shows the kind of apron that develops along rimmed platforms where slopes range between ~4 and 15°. B. Shows an idealized carbonate submarine fan. [A. after Mullins, H. T., and H. E.



# 8.4 Organic Reef Environments

## Modern reef and reef enviroments

### Depositional Setting

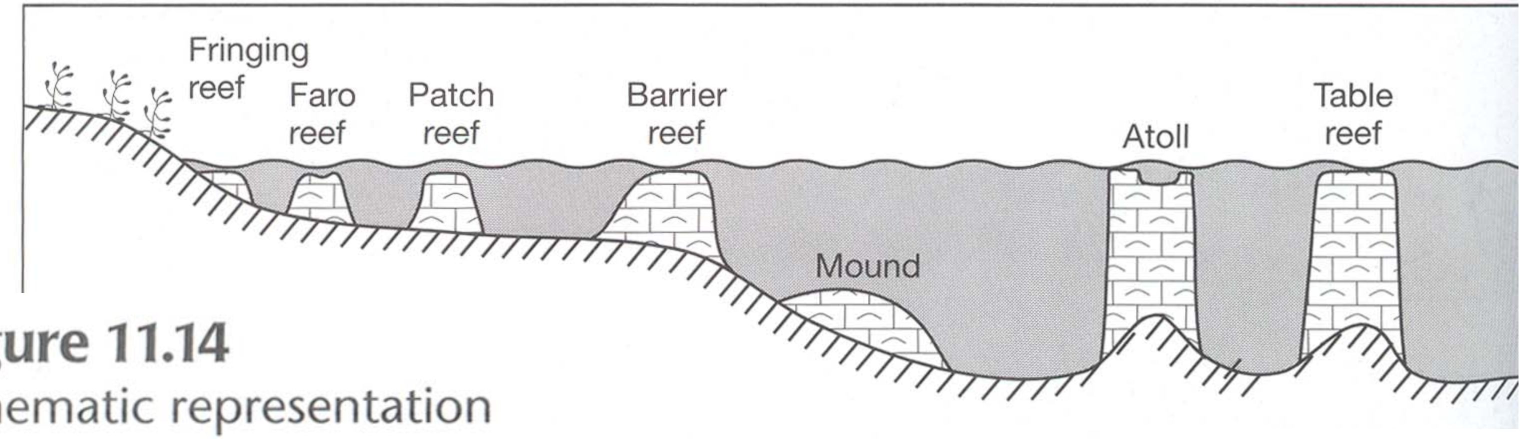



**Figure 11.14**
Schematic representation of the principal kinds of reefs. Based on Tucker. M.

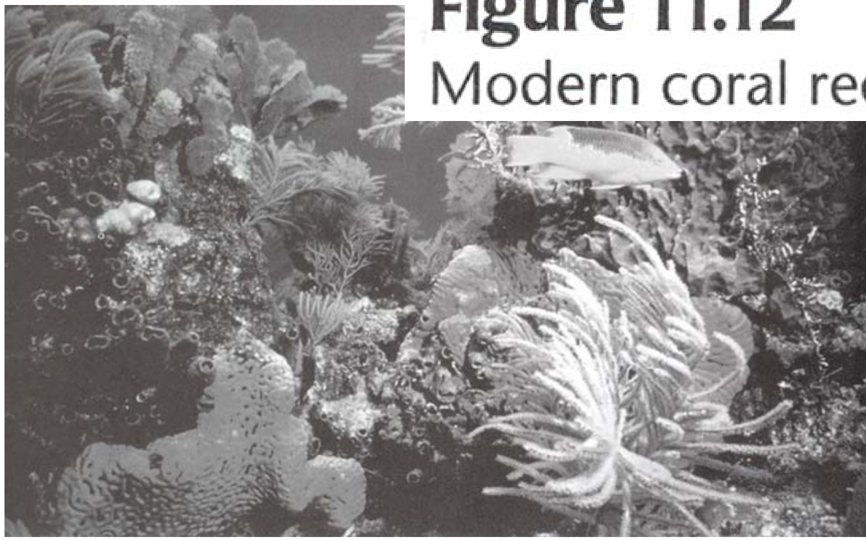
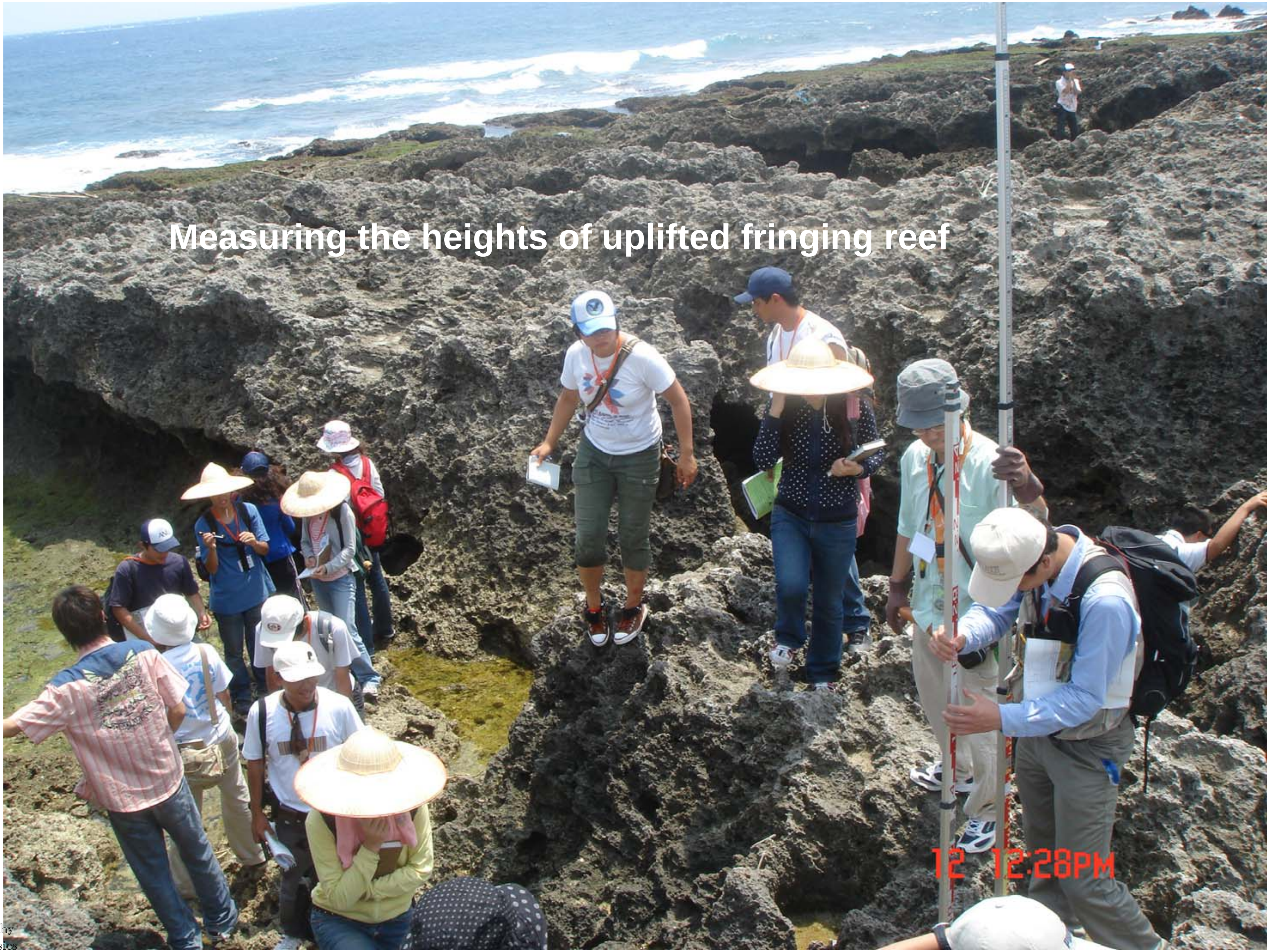


**Figure 11.12**
Modern coral reef.

**Figure 11.13**
The Great Barrier Reef off the coast of Queensland, Australia.

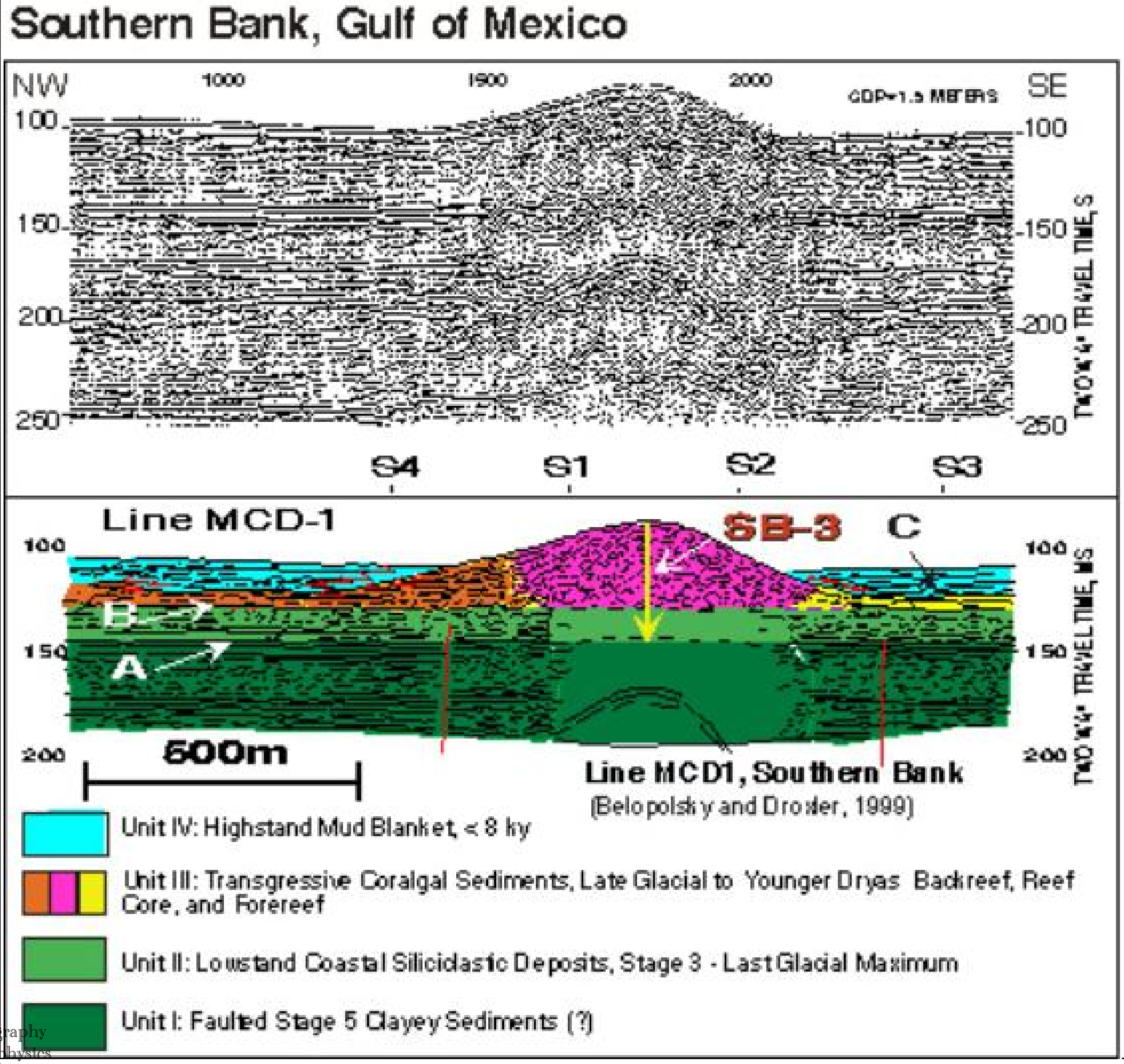
# Fringing Reef (Lungkeng, Hengchun)



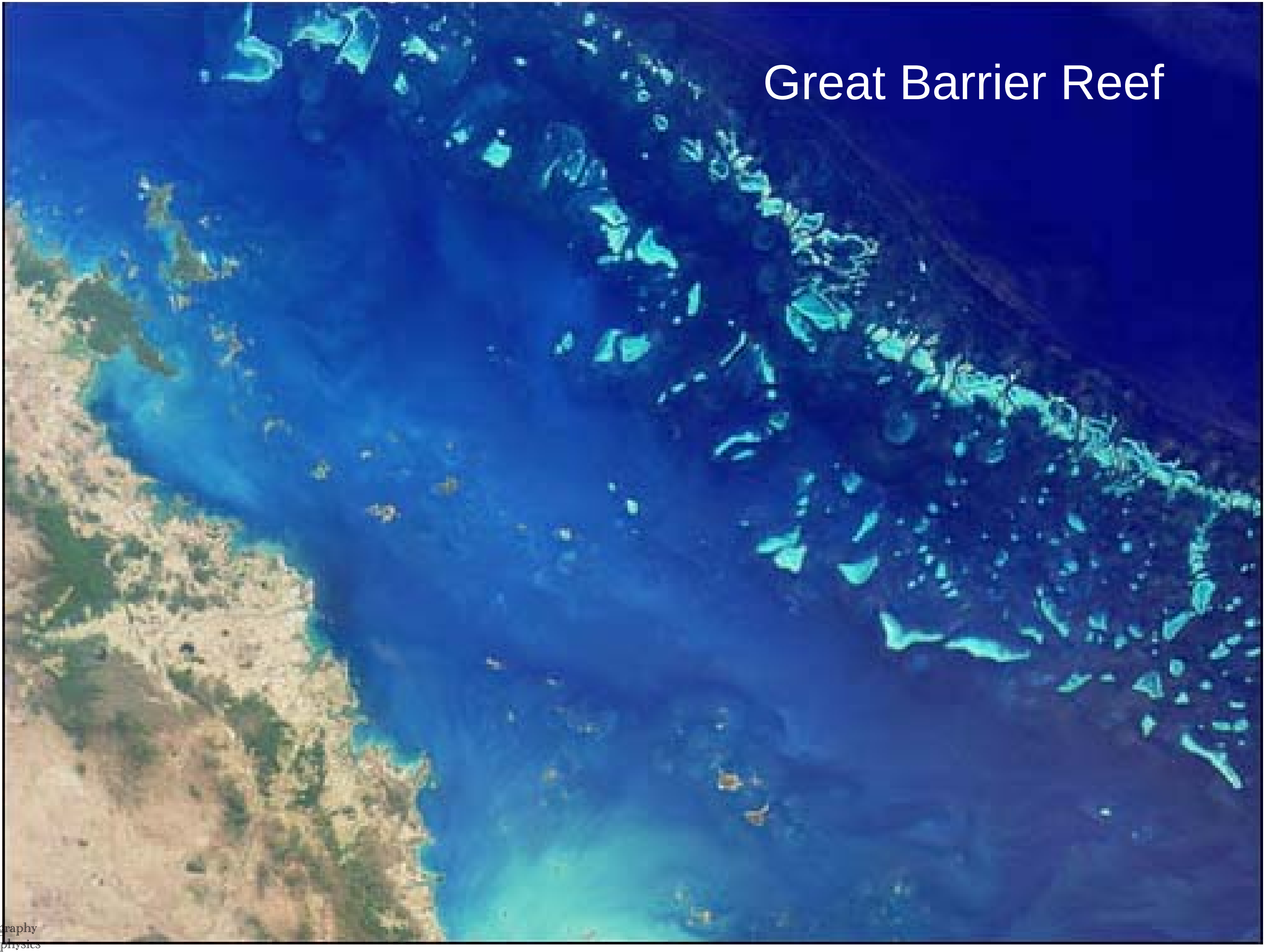

Sequence Stratigraphy
Institute of Geophysics
National Central Univ., Taiwan
Prepared by Dr. Andrew T. Lin

# Patch Reefs – Belize

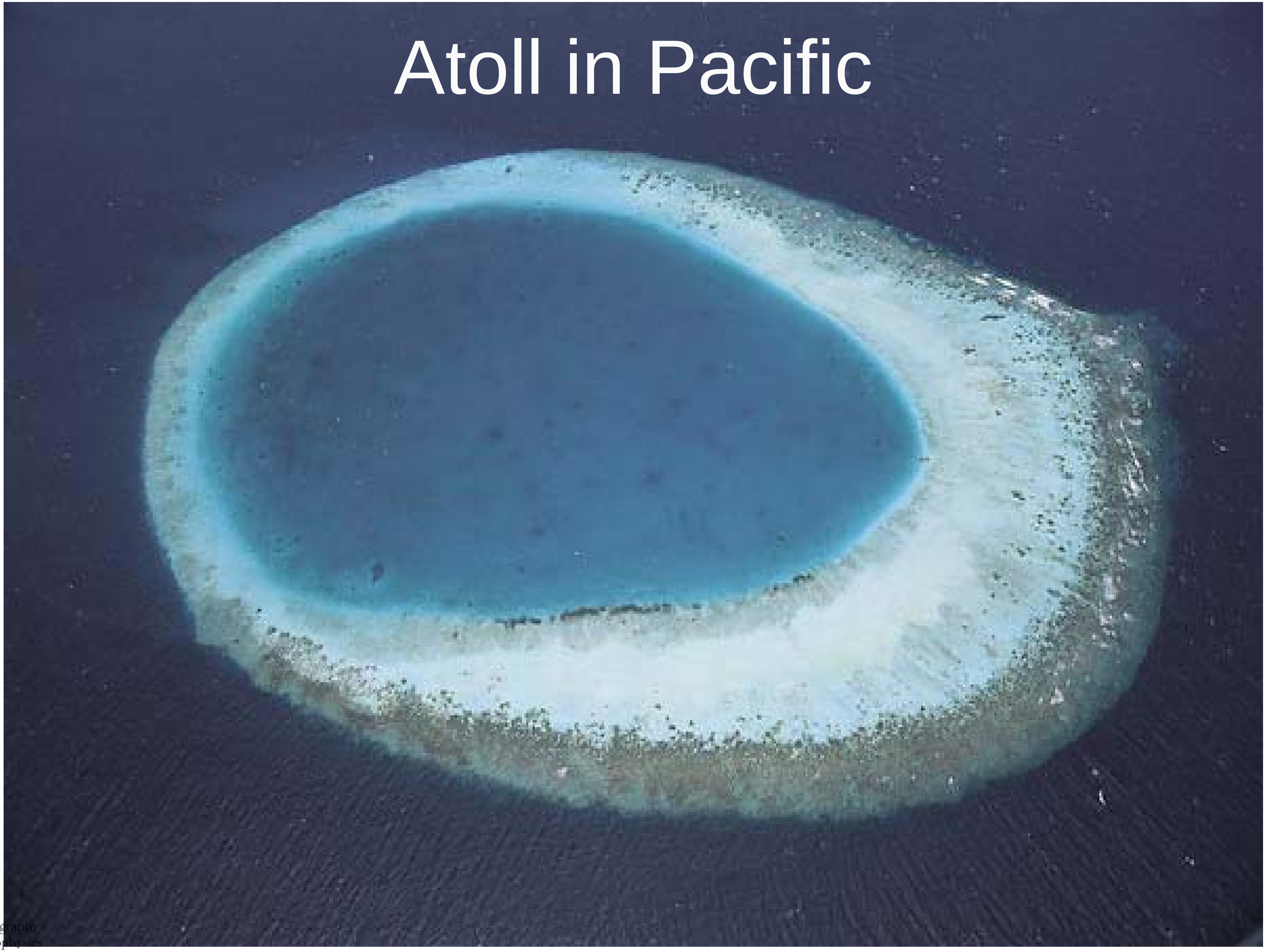
# Carbonate Shelf Buildups

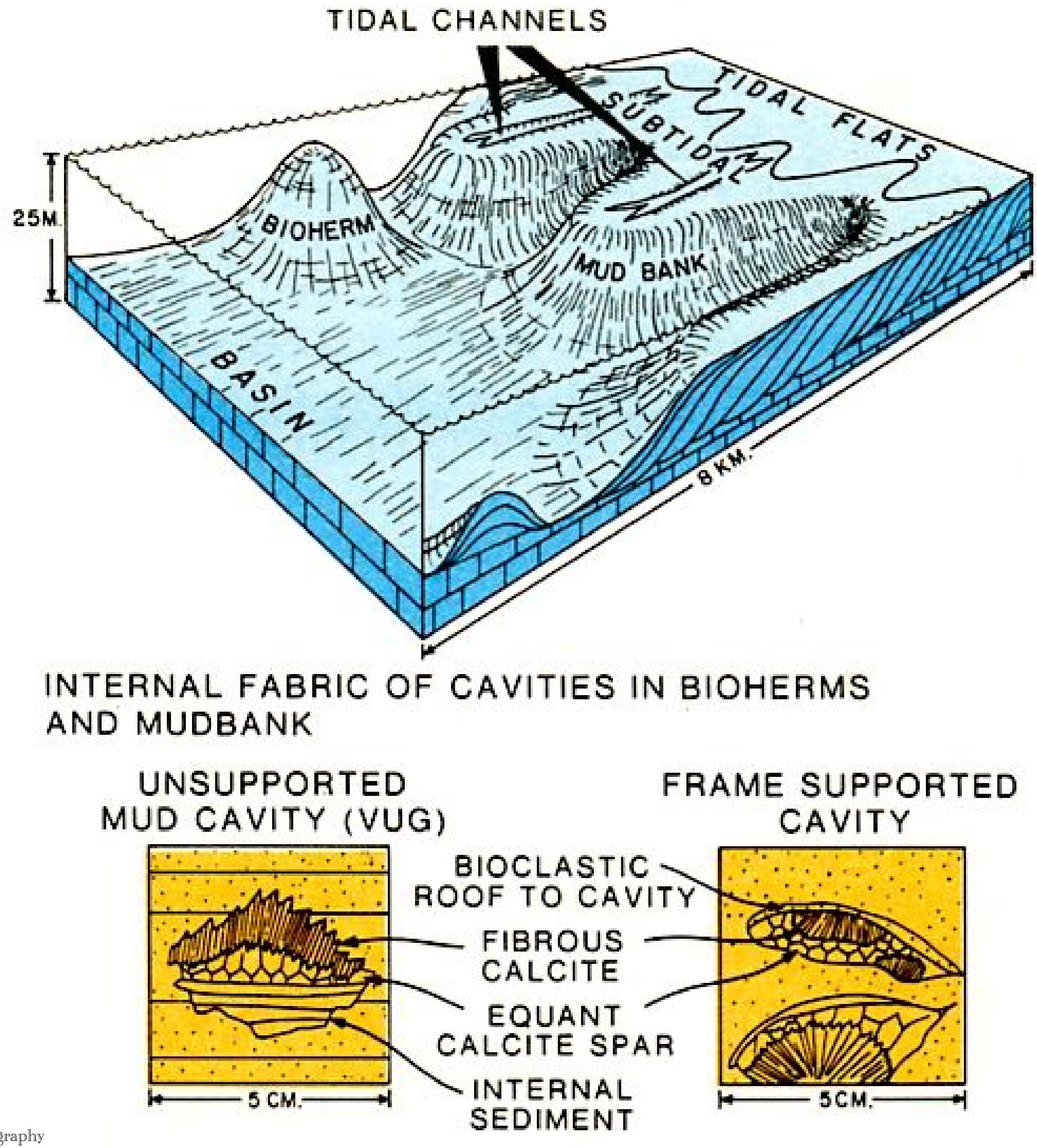



- Organic build ups shoal up Setting: break in slope to local highs
- Sediment: bioclastic sands, rubble, silts & muds
- Subaerial to submarine erosion surfaces
- Fauna: restricted stressed basal pioneer to diverse at crest


Great Barrier Reef


**Atoll in Donhsha (東沙環礁)**


Atoll in Pacific




# Marine Shelf Mud Mounds

- Lenses of organically constructed build ups with channels
- Prograde horizontally or shoal up
- Break in slope of a beach or local highs
- Sediments trapped by organisms inludes carbonate muds, silts to bioclastic sands and rubble
- Shoal up from restricted pioneer community to climax fauna
- stromotactis cavities in carbonate silts & muds

# Reef organisms

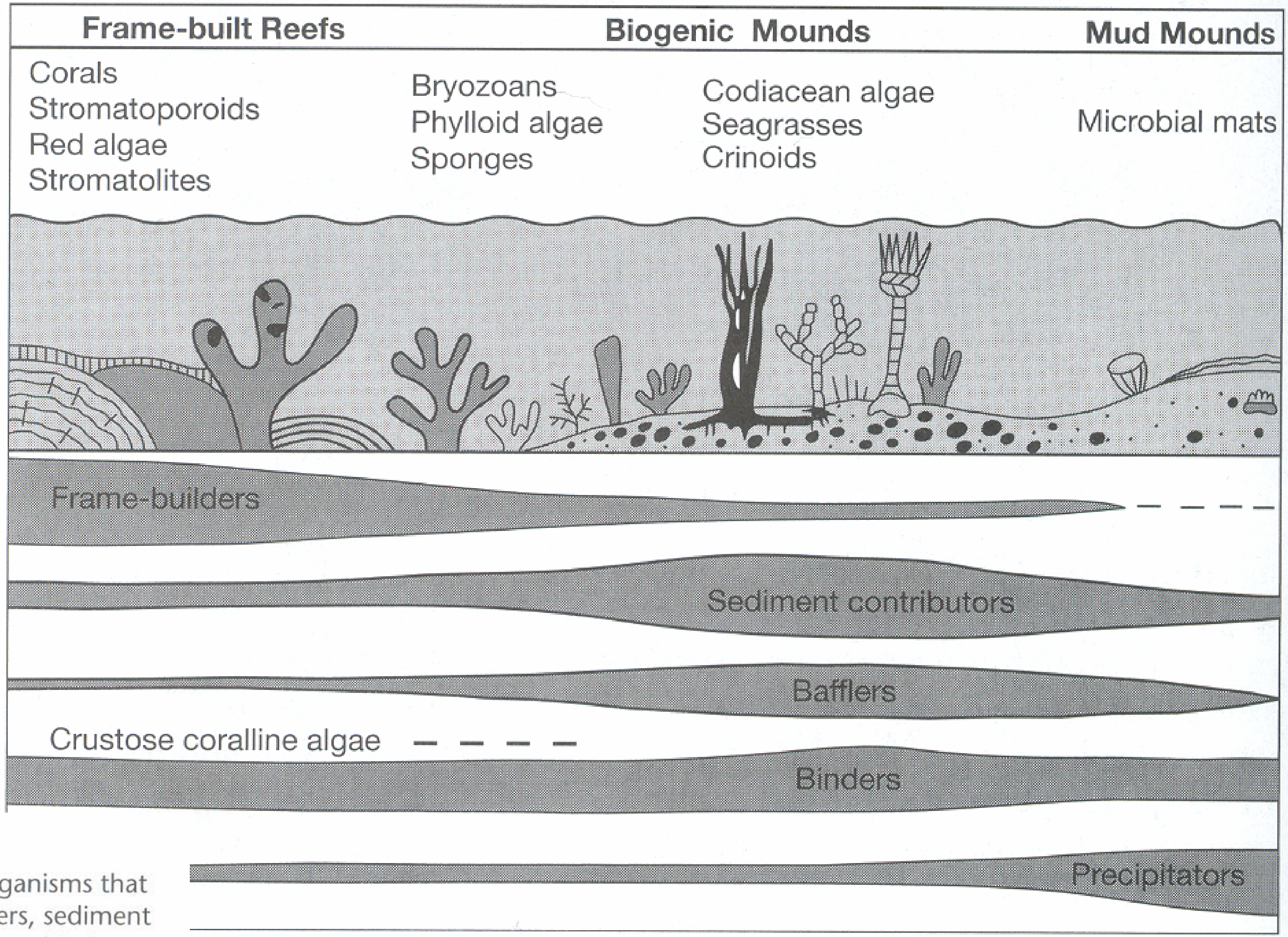



**Figure 11.15**
Some common organisms that act as frame-builders, sediment contributors, bafflers, binders, and precipitators in reefs and mounds. The thickness of the horizontal bars indicates relative importance. [After Tucker, M. E., and

| A Growth Forms | | Environment: Wave Energy | Environment: Sedimentation |
|---|---|---|---|
| | Delicate, branching | low | high |
| | Thin, delicate, plate-like | low | low |
| | Globular, bulbous, columnar | moderate | high |
| | Robust, dendroid, branching | moderate-high | moderate |
| | Hemispherical, domal, irregular, massive | moderate-high | low |
| | Encrusting | intense | low |
| | Tabular | moderate | low |

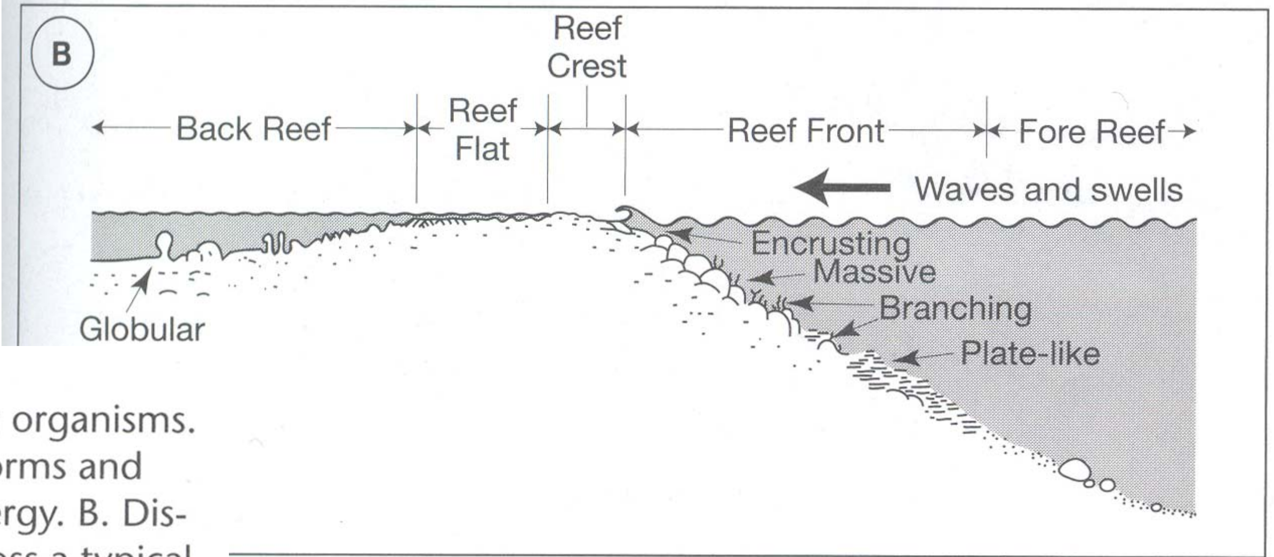
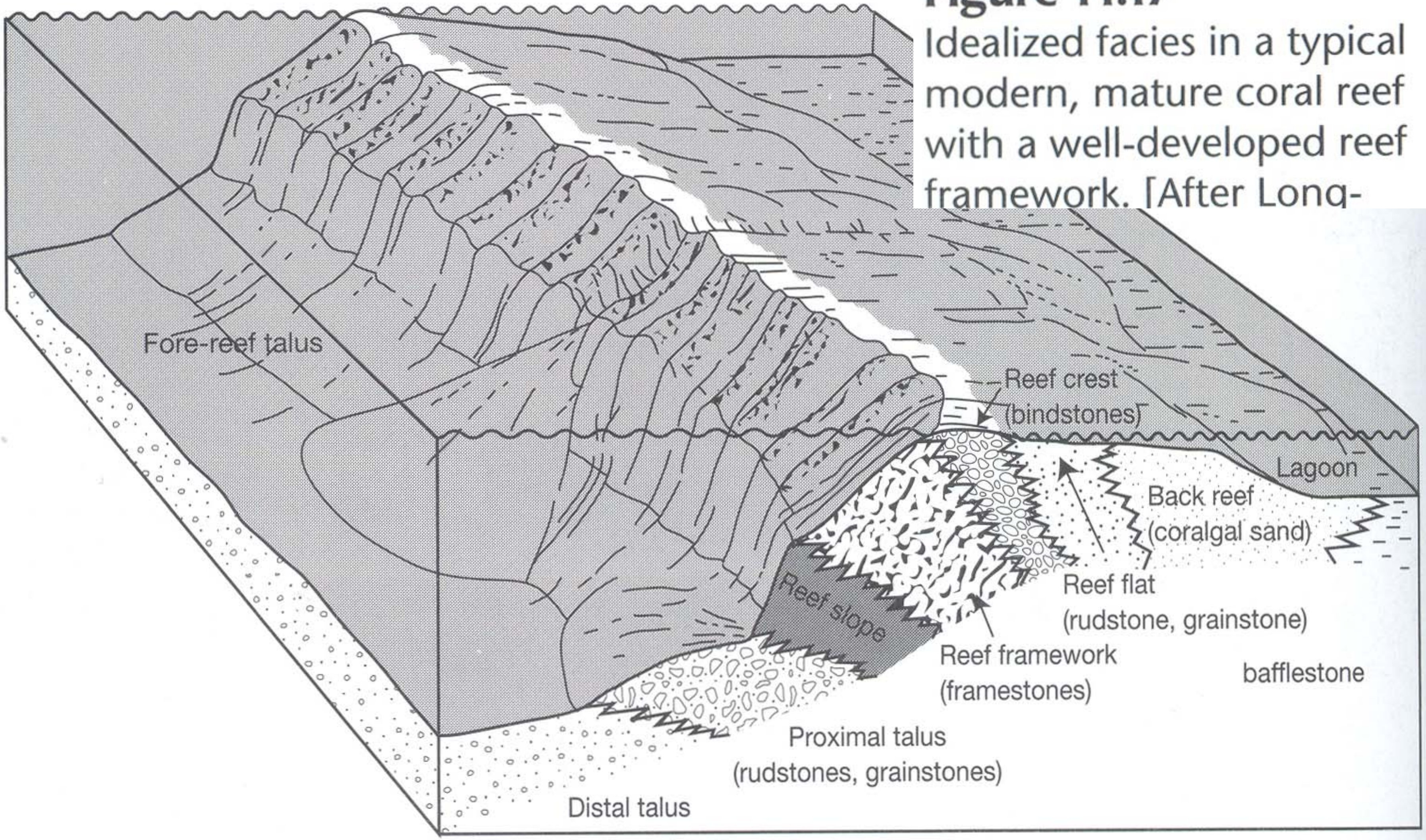



**Figure 11.16**
Growth forms of reef-building organisms. A. Principal kinds of growth forms and their relationship to water energy. B. Distribution of growth forms across a typical reef. [A. after James, N. P., 1983. Reef en-

# Reef deposits

**Figure 11.17**
Idealized facies in a typical modern, mature coral reef with a well-developed reef framework. [After Long-



# Ancient Reefs

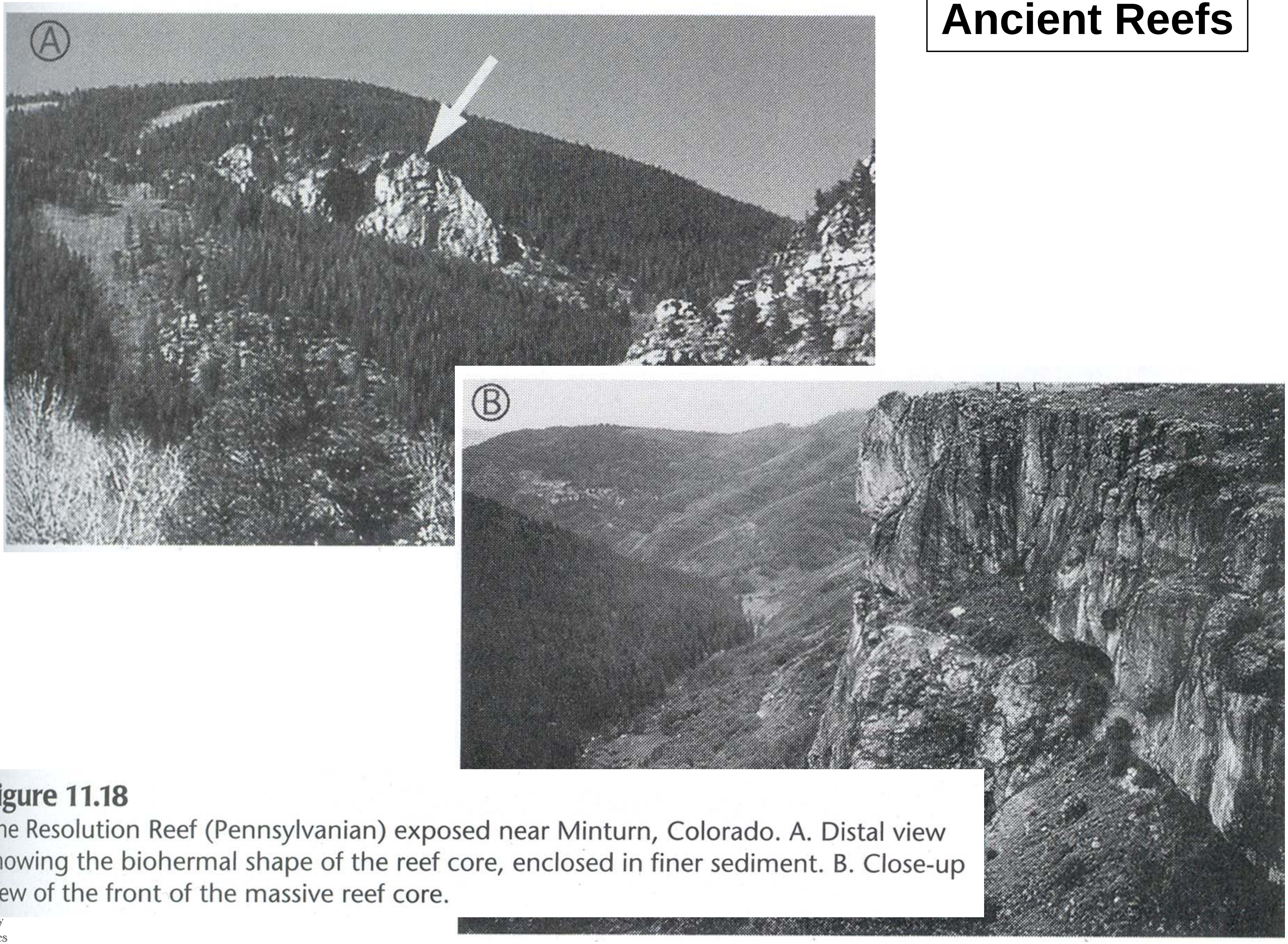
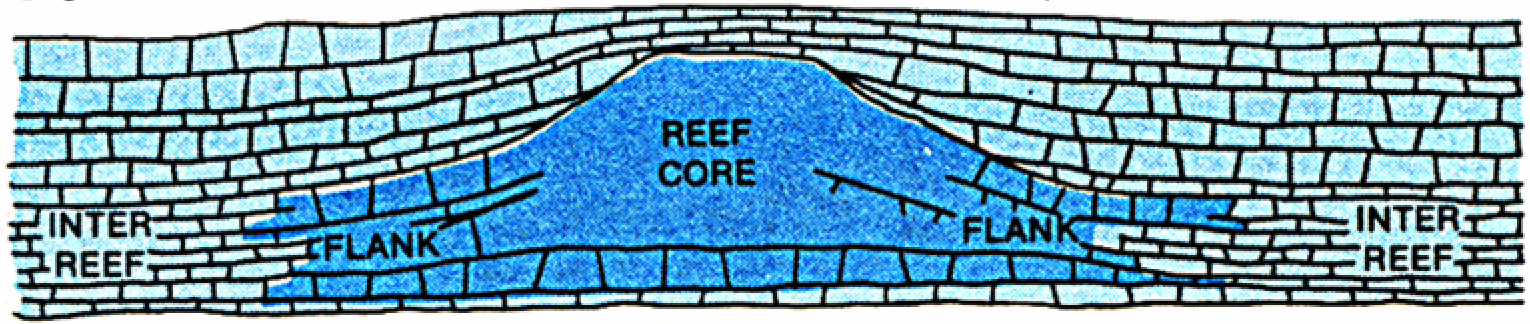


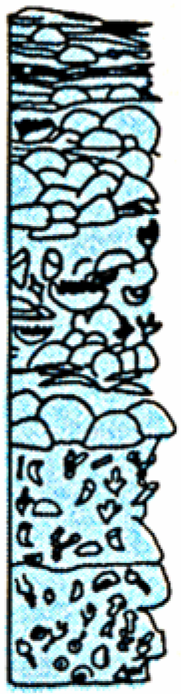

**Figure 11.18**
The Resolution Reef (Pennsylvanian) exposed near Minturn, Colorado. A. Distal view showing the biohermal shape of the reef core, enclosed in finer sediment. B. Close-up view of the front of the massive reef core.

# Patch Reefs

A




B



| STAGE | TYPE OF LIMESTONE | SPECIES DIVERSITY | SHAPE OF REEF BUILDERS |
|---|---|---|---|
| DOMINATION | bindstone to framestone | low to moderate | laminate encrusting |
| DIVERSIFICATION | framestone (bindstones)<br>mudstone to wackestone matrix | high | domal<br>massive<br>lamellar<br>branching<br>encrusting |
| COLONIZATION | bafflestone to floatstone (bindstone) with a mudstone to wackestone matrix | low | branching<br>lamellar<br>encrusting |
| STABILIZATION | grainstone to rudstone (packstone to wackestone) | low | skeletal debris |

*Major Reef Deposits in Cross Section (A) and Core Facies in Detail (B). From James (1979).*

**Organic build ups**

**Shoal up**

**Break in slope or local high**

**Sediments include bioclastic sands, rubble, muds, silts**

**Restricted pioneer community to climax fauna**

# Carbonate Shelf – Jurassic - Morocco

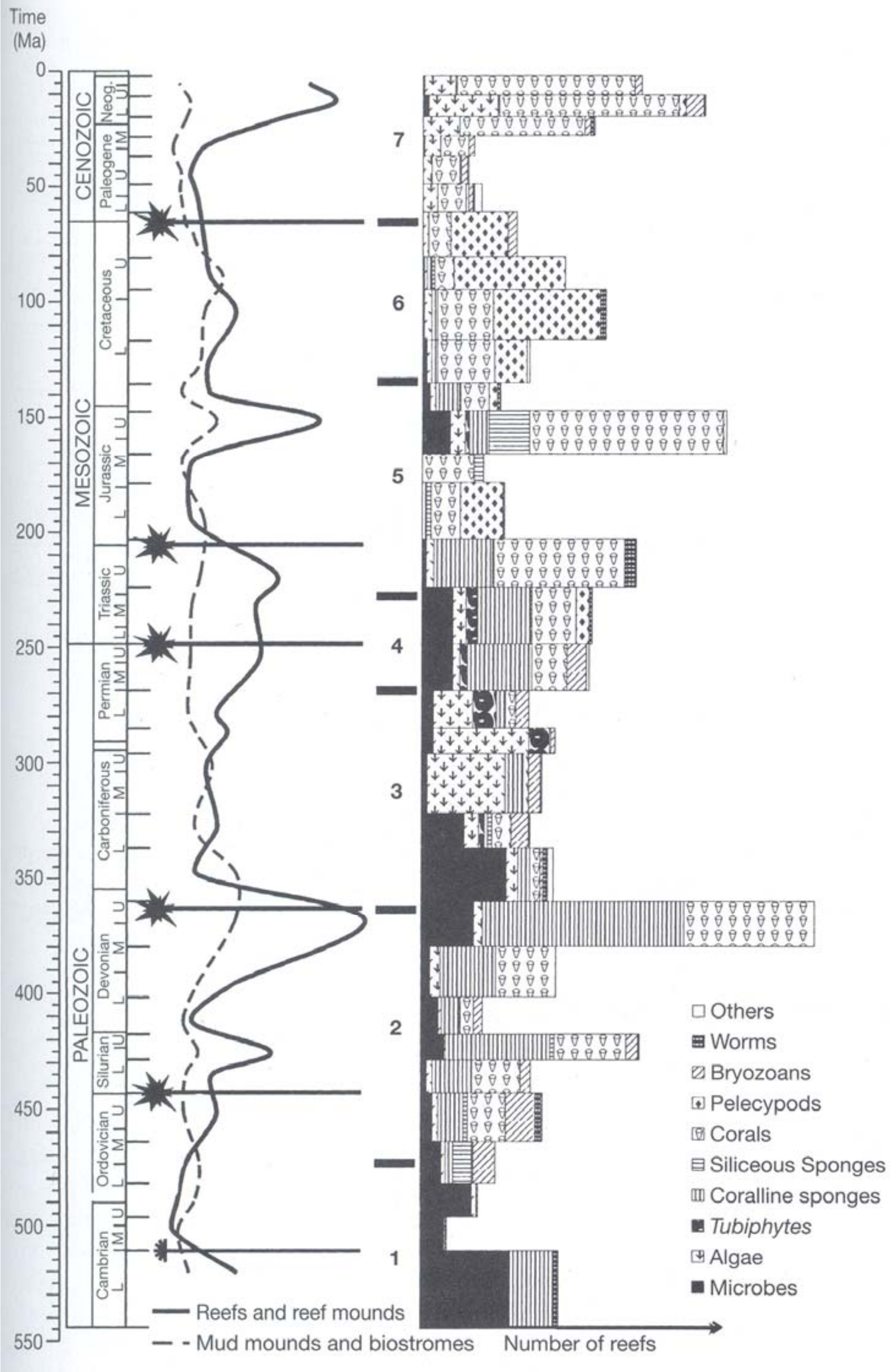



**Figure 11.19**
Distribution of reefs through Phanerozoic time showing both reefs and mud mounds as well as the dominant organisms that make up the reefs and mounds. "Others" refers to brachiopods, pelmatozoans, and foraminifers. The numbers 1–7 refer to seven major cycles of Phanerozoic reef building. Starred lines indicate times of mass extinctions. Curves to the left show the cumulative number of reefs and mounds in each time interval, and horizontal bars on the right depict the cumulative number of reefs in which a particular fossil group is dominant. [From

# 8.5 Mixed Carbonate-Siliclastic Systems

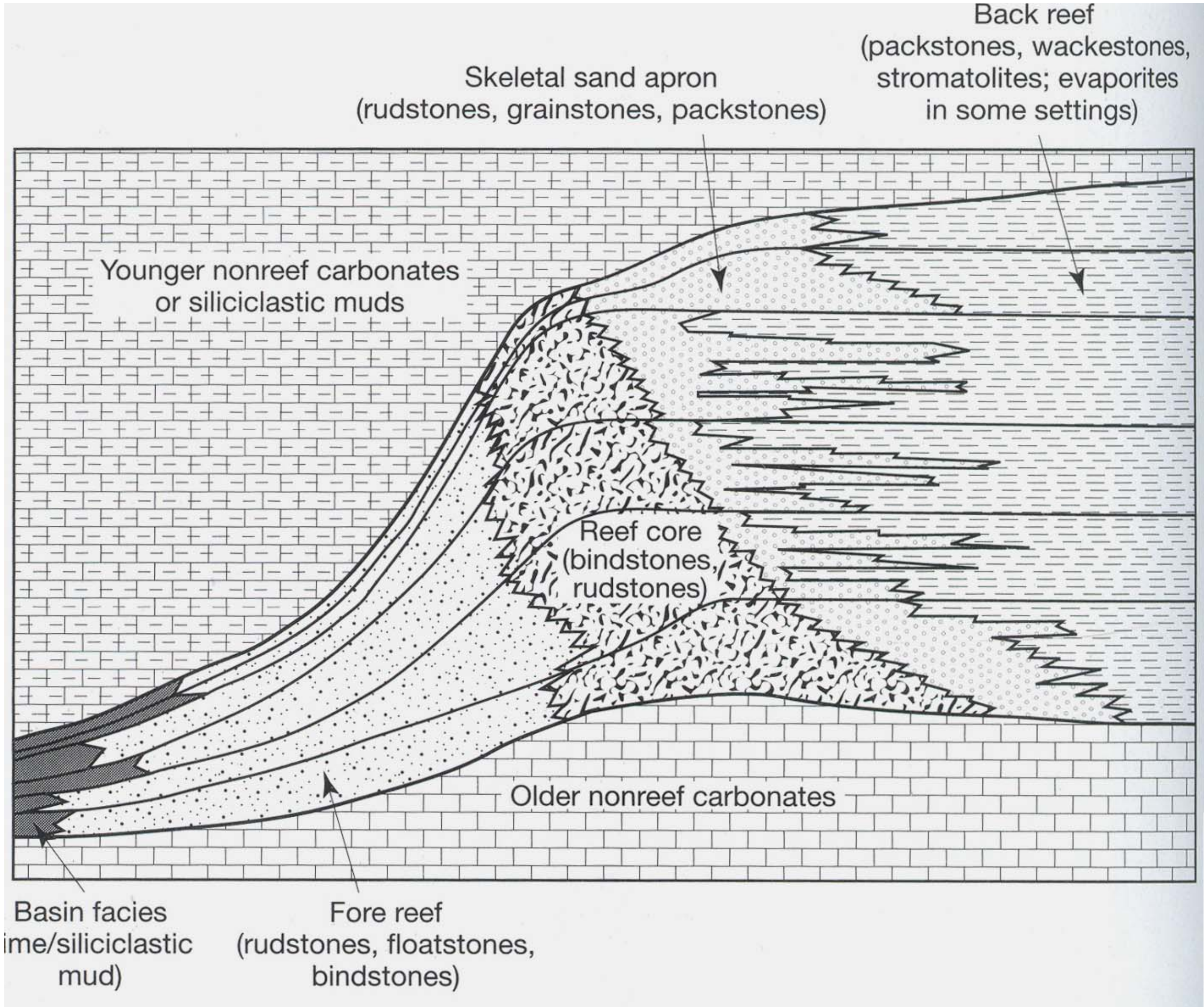



**Figure 11.20**
Idealized, schematic representation of an ancient barrier reef deposit illustrating typical reef, fore-reef, and back-reef facies. Based in part on the Upper Devonian Swan Hills Reef Buildup, central Alberta, Canada (Viau, 1983).

# 8.6 Evaporite Environments

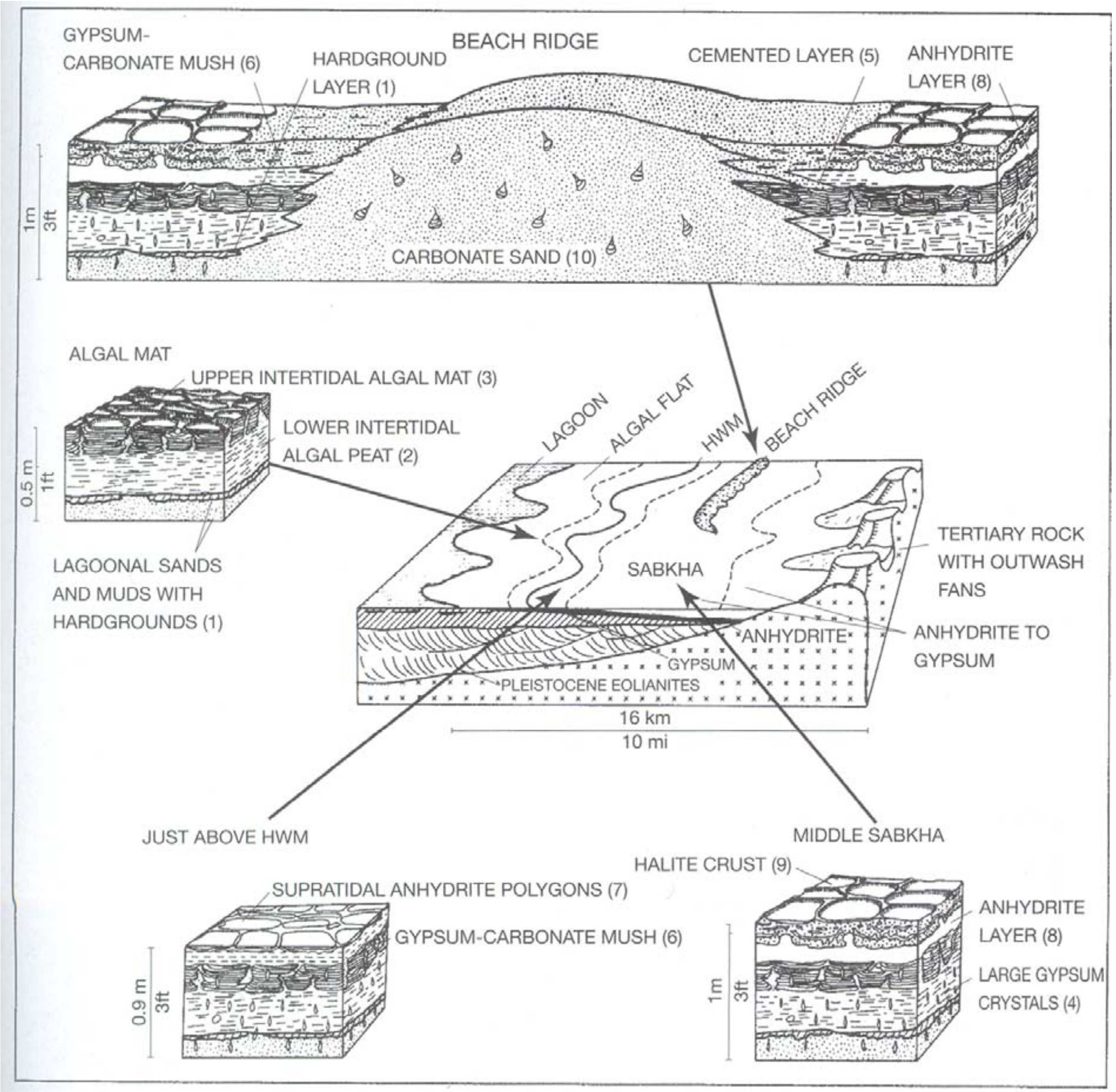
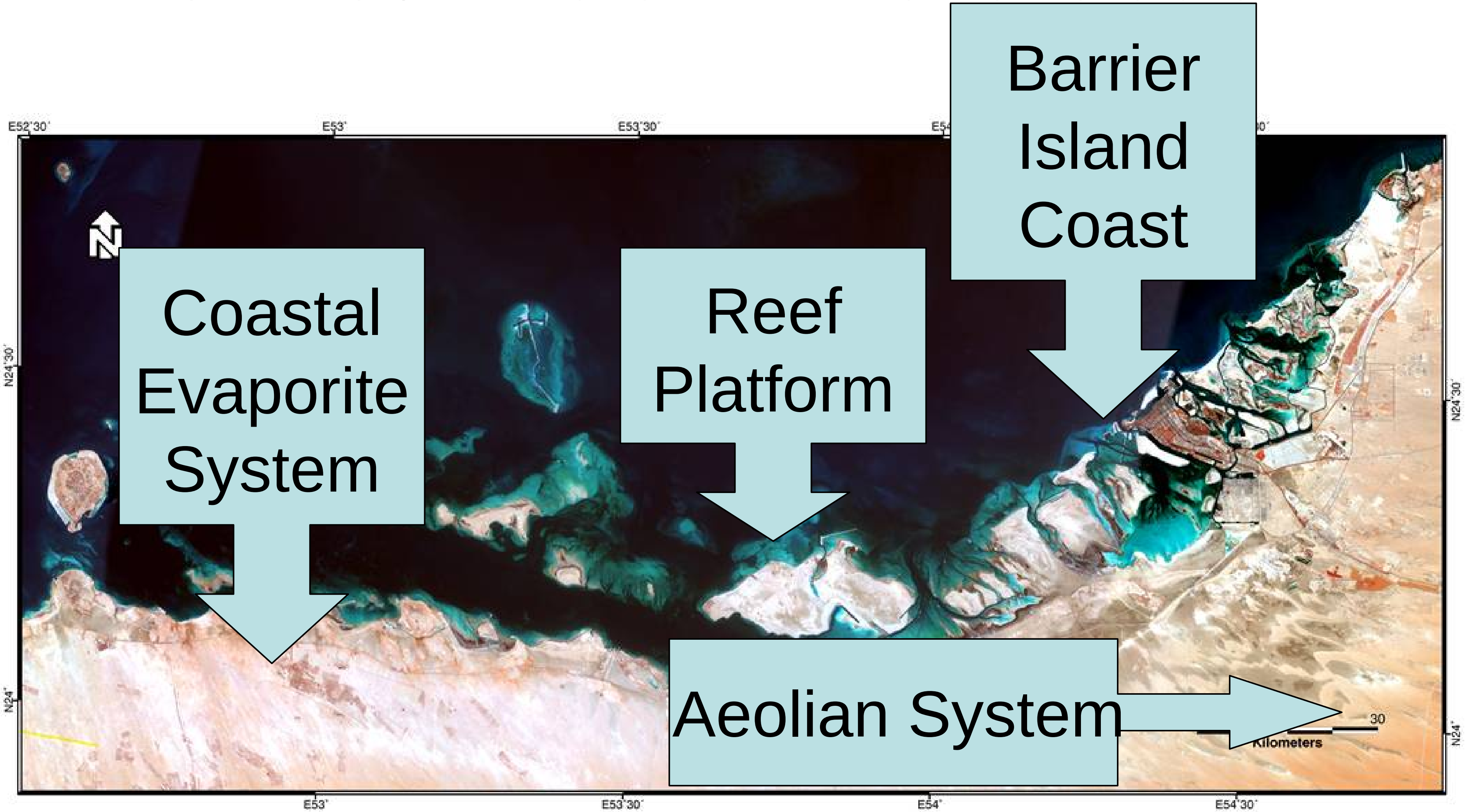



**Figure 11.21**
Schematic representation of vertical and lateral facies relationships in sabkhas of the Arabian Gulf. HWM = high-water mark.

Arid Climate

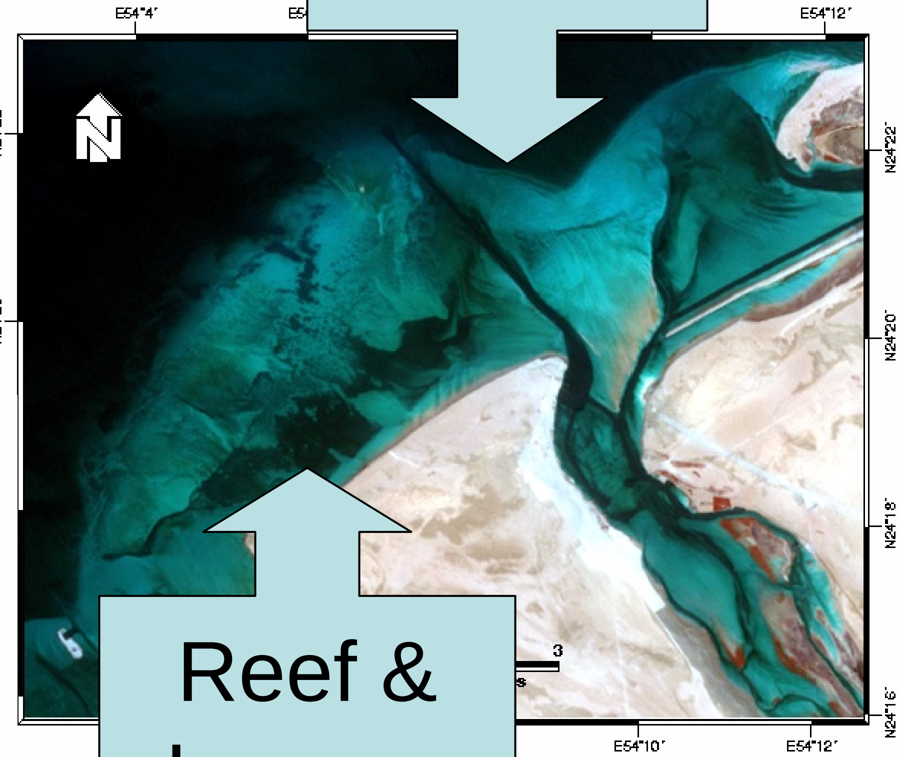
# ***United Arab Emirate Coast***



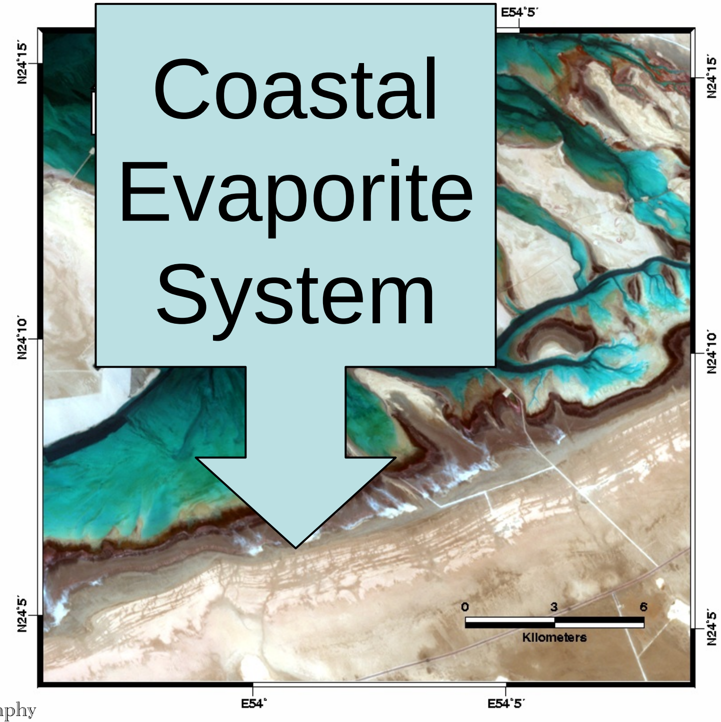
# United Arab Emira st

Tidal Deltas

Arid Climate




Reef & Lagoon




Coastal Evaporite System

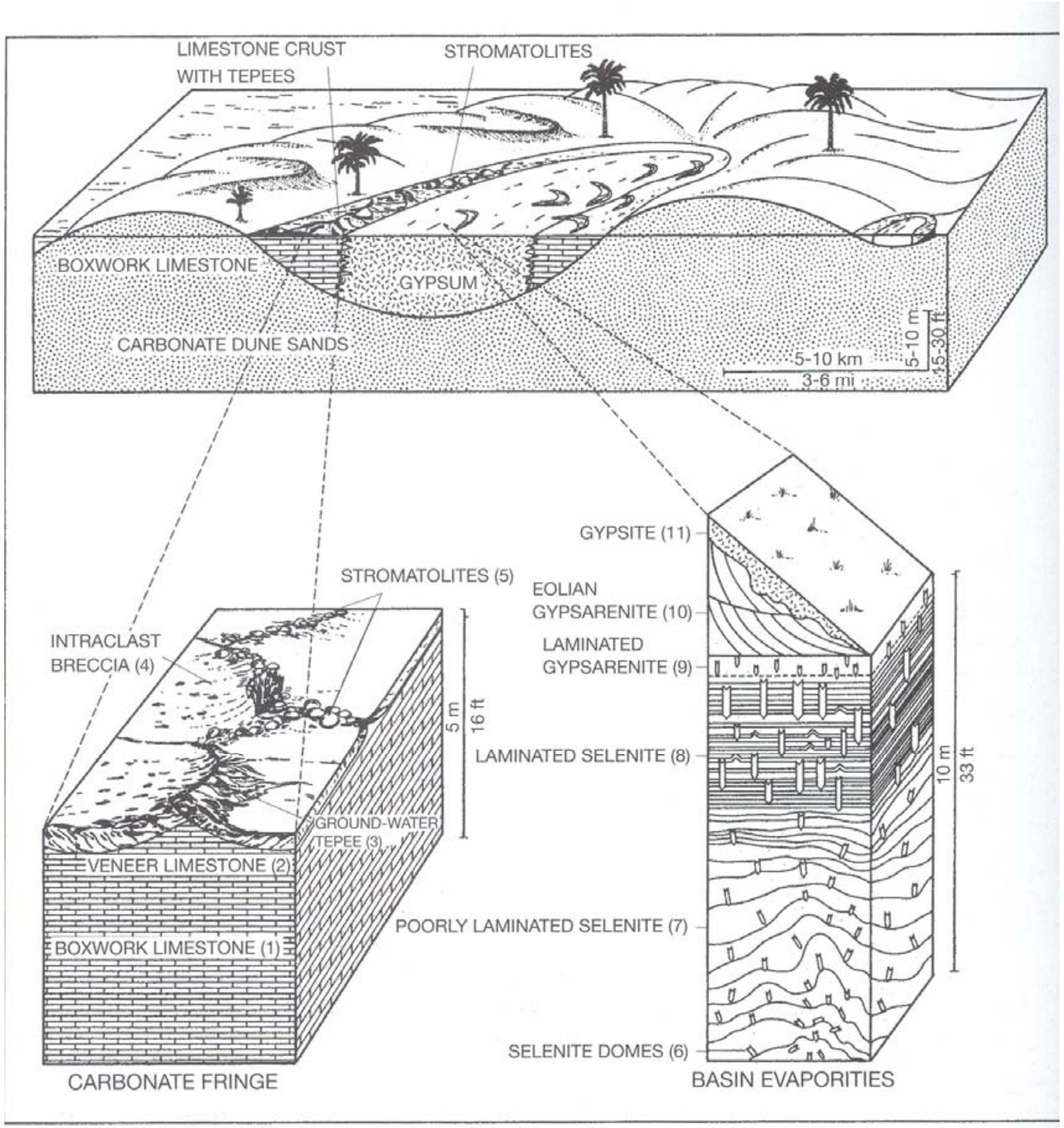



**Figure 11.22**
Environmental setting and typical evaporite facies in southern Australia salinas.

## Ancient Evaporite Environments

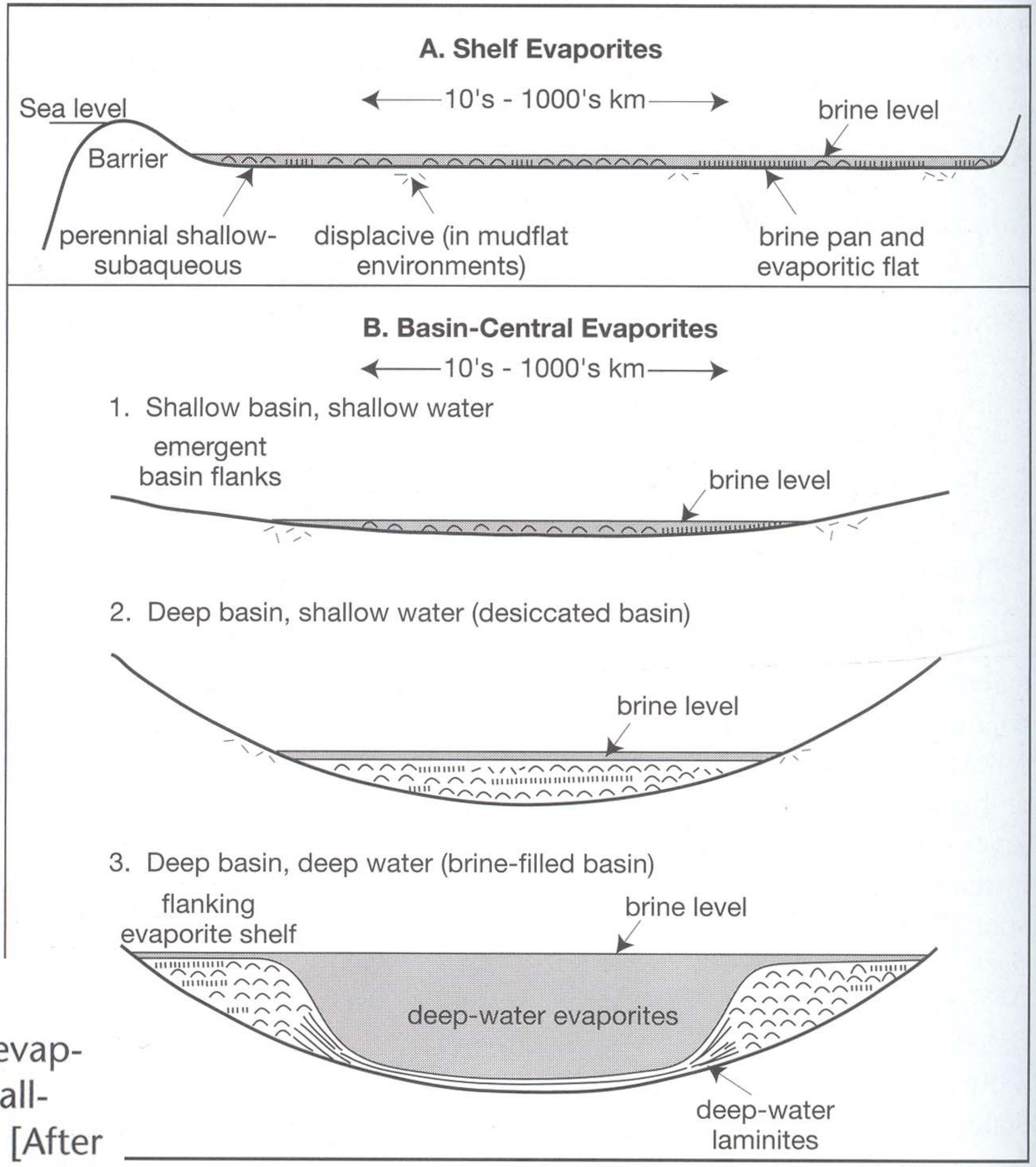
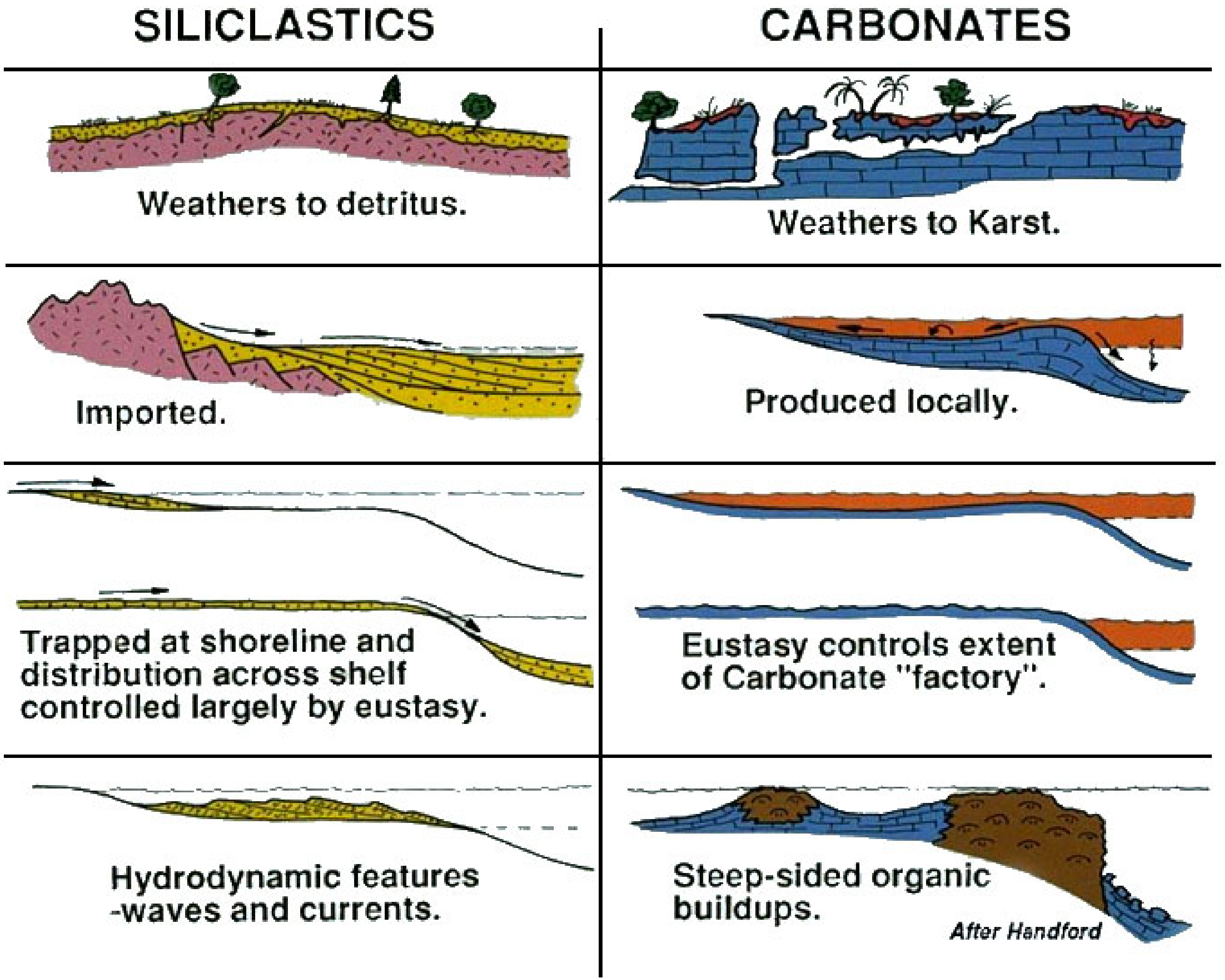
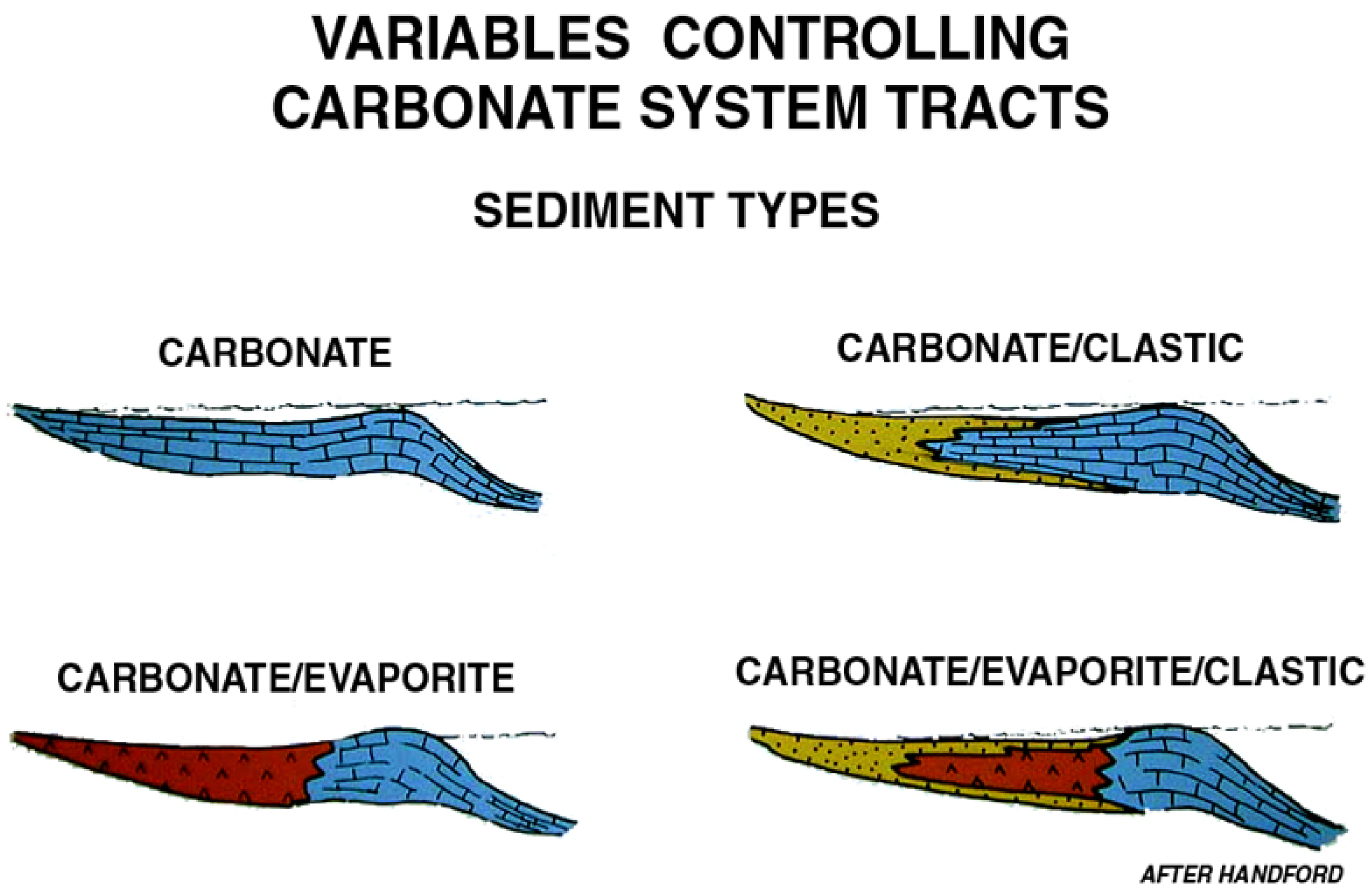



**Figure 11.23**
Principal kinds of ancient marine evaporite environments (excluding small-scale coastal sabkhas and salinas). [After

# Differences between Clastics & Lst



# Major Variables in Carbonates



# Lecture Conclusions

- Shelf has wide spread continuous sheets that tend to shoal up
- Outer shelf:- heterogeneous carbonates with mix of linear bodies  parallel to basin & perpendicular to it! Local build up form lenses
- Inner shelf:- dominated by mud prone sheets with evaporites & or clastic channels and sheets
- Margin:  Massive and heterogeneous, most porous but least prone to seal
- Down slope sheets that thin down slope & may be grain prone in distal portions
- Basinal couplets of mud & shale from mix of pelagic & shelf sources
- Evaporites occur when basin is isolated