Depositional Environments
Lec. 11 Carbonate reefs


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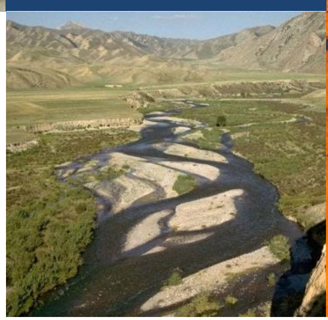

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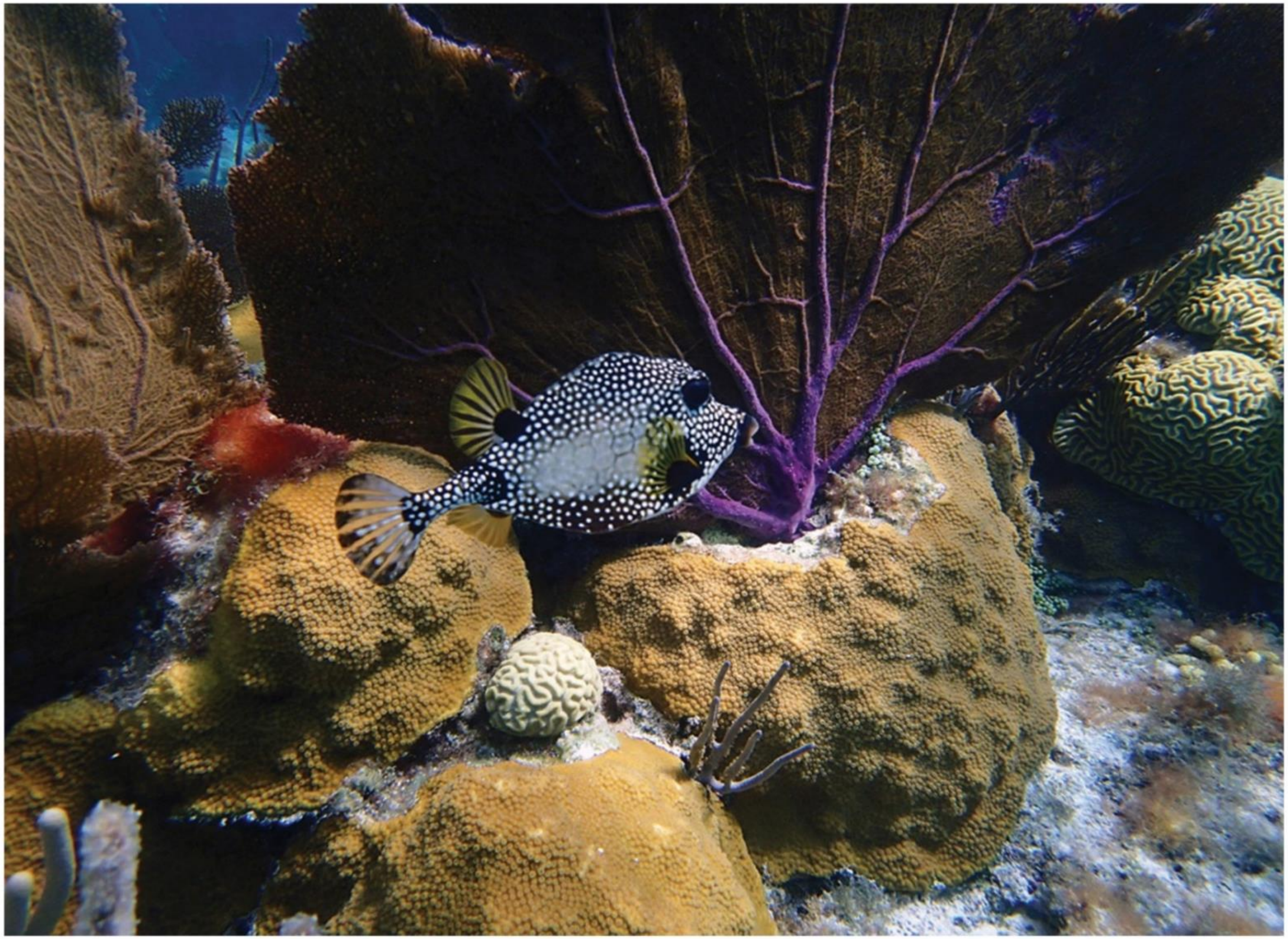
Damietta University

Carbonate Reef



Frontispiece A shallow water (~3 m deep) coral reef composed of a variety of corals and a trunkfish, Bermuda. Image width 1 m. Photograph by W. Martindale. Reproduced with permission.

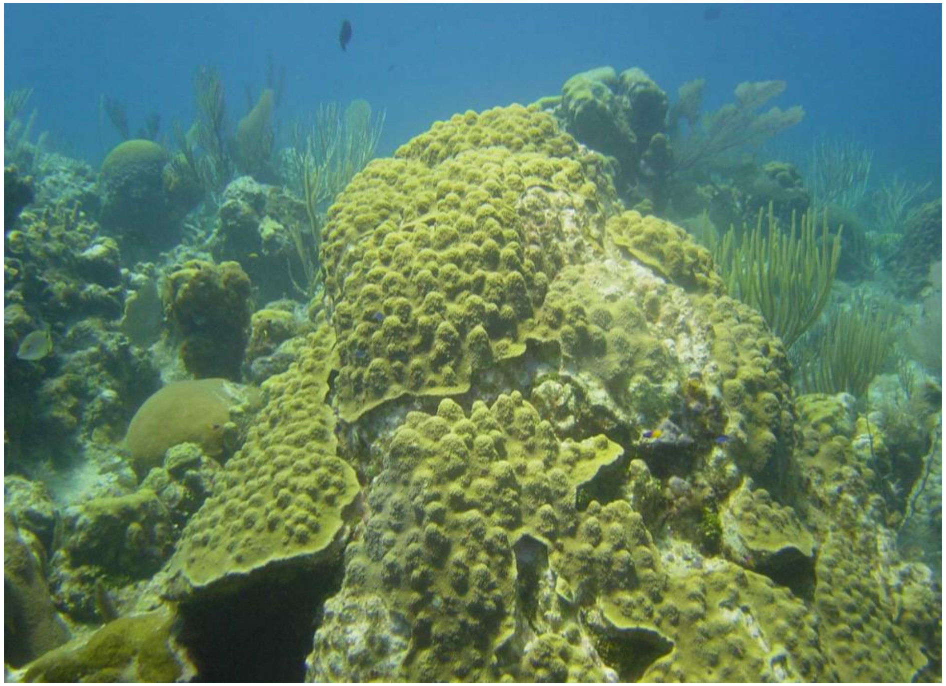
Outline

1. The reef mosaic
2. Reef growth
3. Shallow-water reefs
4. Zonation of a reef
5. Deep-water reefs

The reef mosaic

1. Biologically constructed reliefs rigid, wave-resistant structure
2. Bathymetric relief above seafloor
3. Form *in situ* by organic growth (rarely by mineral precipitation)
4. Complex communities of calcareous and non-calcareous organisms, inorganic and organic carbonate precipitates

Modern reefs are nearly range from corals to microbes in shallow tropical water.

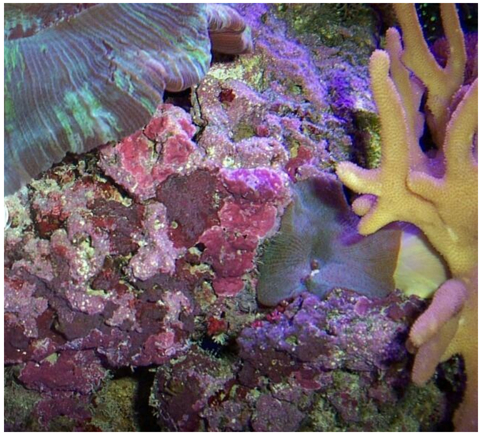


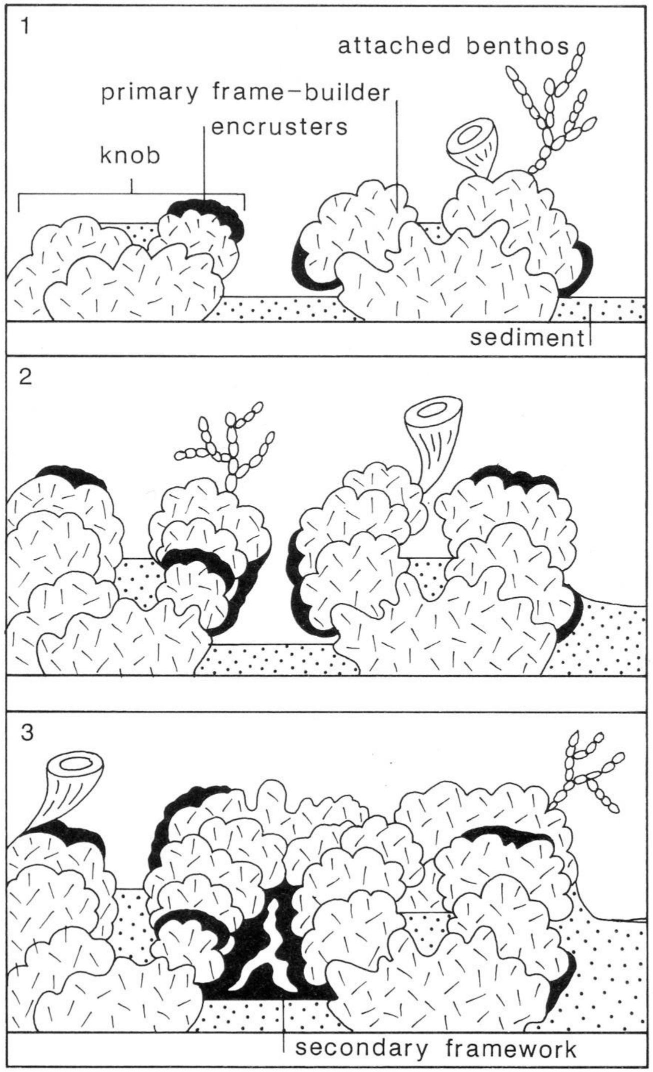
The reef mosaic

- Reef formation is a balance between constructive and destructive processes

- <u>Constructive processes</u>:

- Growth of organic framework
- Binding by encrusters
- Sediment trapping by bafflers





The reef mosaic

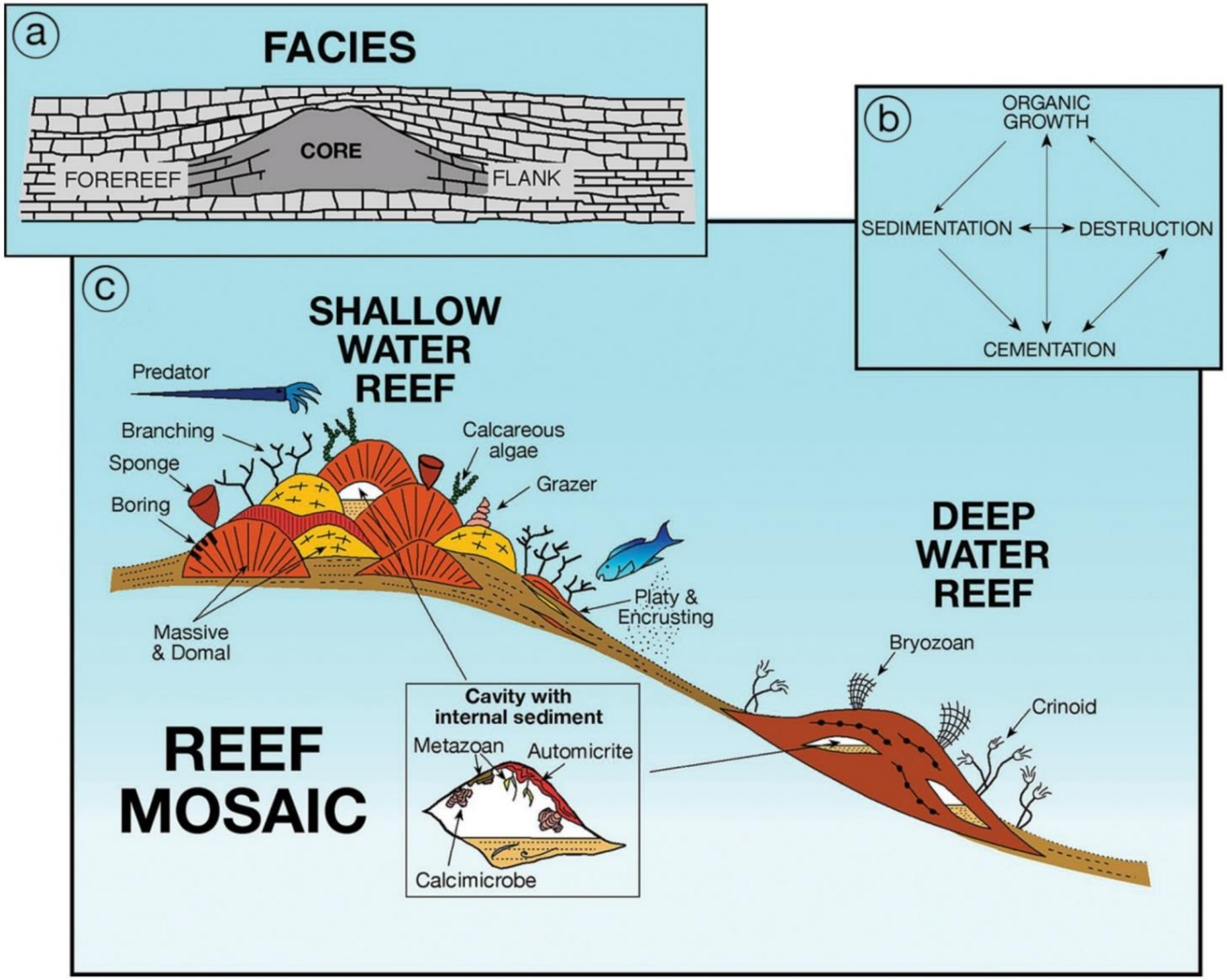


Figure 14.2 A series of sketches illustrating (a) cross-sectional geometry of a typical reef as exposed in outcrop; (b) complex interrelationship between processes that control reef composition; and (c) main attributes of shallow-water and deep-water reefs. Source: James and Wood (2010). Reproduced with permission of the Geological Association of Canada.

The reef mosaic

Corals

- Today, the major reef-builders are scleractinian corals (Figure 14.3), cnidarians that evolved in the Triassic.
- These animals are mixotrophs, sessile micropredators whose tissues also house symbiotic photosynthetic cyanobacteria or microalgae. The most important symbionts are dinoflagellates called zooxanthellae.
- The coral ingests food whereas the symbionts produce carbohydrates and lipids via photosynthesis; these substances can be used by the coral.
- By providing almost limitless energy, zooxanthellae allow hermatypic (reef-building) corals to produce calcium carbonate several times faster than ahermatypic (non-reef-building) corals.
- Corals without symbionts are mostly confined to deep, dark nutrient poor environments

The reef mosaic

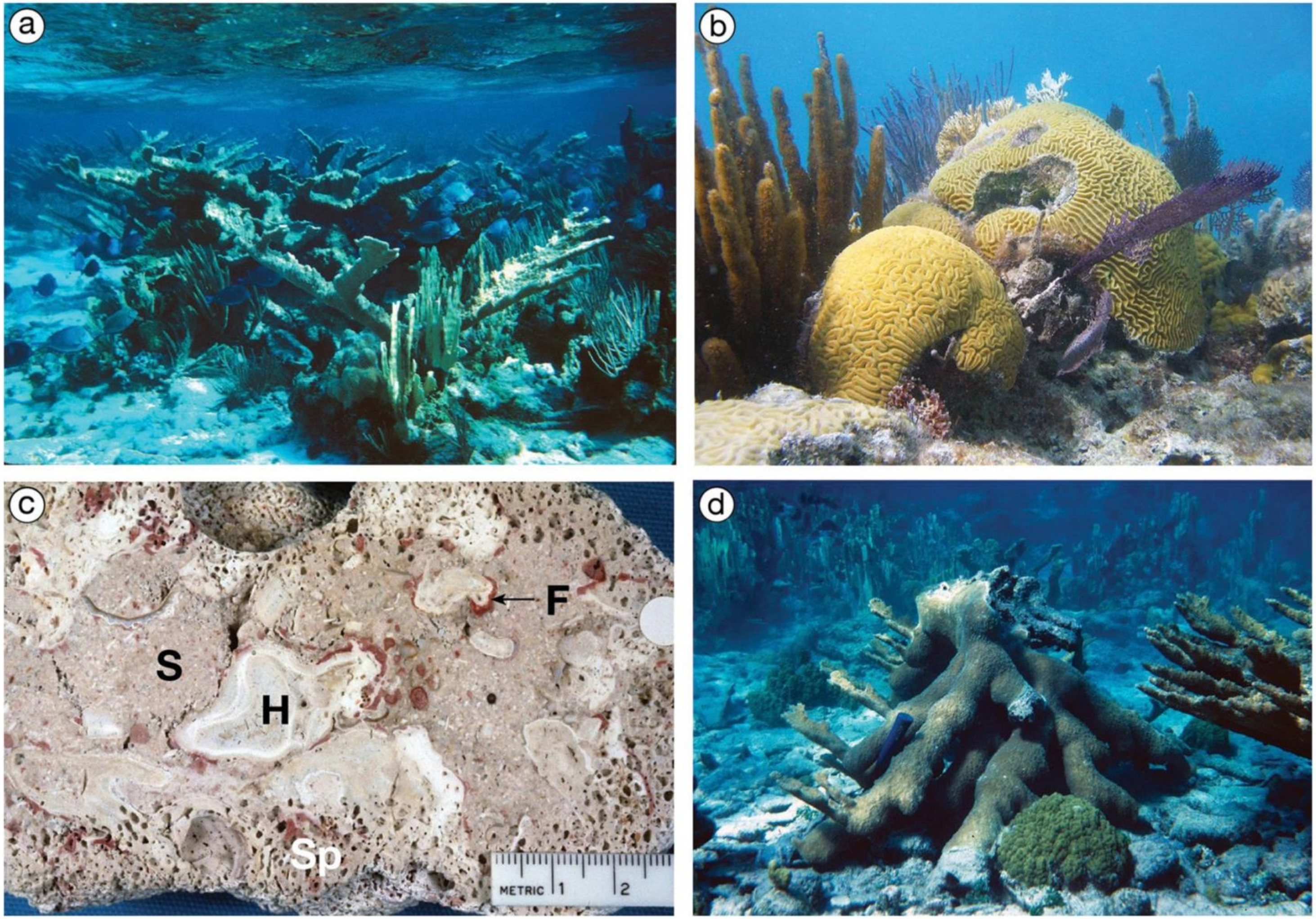


Figure 14.3 (a) Large branching (~3 m across) coral *Acropora palmata* in ~2 m of water off Grand Cayman, Caribbean. (b) Two species of the hemispherical coral *Diploria* (*D. strigosa* and *D. labyrinthiformis*) in ~2 m of water off the Bermuda islands. Image width 3 m. (c) A cut slab of modern reef rock (^{14}C age 1500 years BP), Bermuda, composed of hydrozoans (H), encrusting foraminifers (F), and biofragmental sand cemented by magnesium calcite cement (S) and bored by sponges (Sp) (numerous holes). (d) A large *Acropora palmata* colony ~2 m high in ~2.5 m depth of water off Grand Cayman, that has been toppled by a recent hurricane.

The reef mosaic

Microbes and algae

- A significant amount of reefal carbonate precipitation, especially in the Proterozoic, is associated with microbes.

- These range from peloidal, clotted, or laminated micrite (automicrite) to calcified microbial sheaths (calcimicrobes), with a spectrum of intermediate structures whose attributes depend upon seawater carbonate saturation and post-mortem preservation.

- Encrusting red algae are critically important in modern reef systems because they bind and stabilize reef frameworks and produce sediment.

- Branching and segmented green algae on modern reefs are, in contrast, mainly sediment producers.

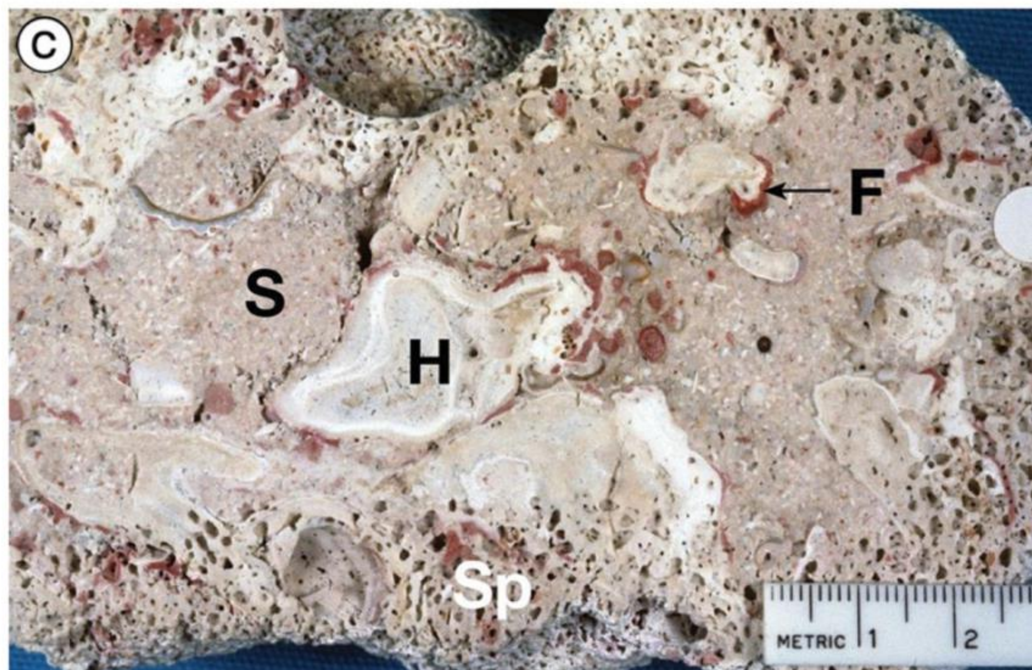
The reef mosaic

Internal cavity systems

- They have a surprising volume of open space because cavities are formed as a byproduct of the intricate metazoan-algal-microbe growth architecture.

- Cryptic organisms that encrust walls and hang down from cavity ceilings populate many of these voids.

A Cut slab of modern reef rock (^{14}C age 1500 years BP), Bermuda, composed of hydrozoans (H), encrusting foraminifers (F), and biofragmental sand cemented by magnesium calcite cement (S) and bored by sponges (Sp) (numerous holes).




The reef mosaic

Internal cavity systems

- They range from photic organisms near the openings to heterotrophs in the dark, lightless interiors.
- Cavities are also sites where fine-grained sediment (internal sediment) accumulates.
- This material is composed of tiny biofragments and mud-grade sediment that trickles into the holes from above or of skeletons that drop from the walls and ceiling after deathings populate many of these voids.

Synsedimentary lithification

- Many reefs are lithified immediately below the living surface by a variety of calcite or aragonite cements.

- Much of this cement is microcrystalline and therefore not obvious, but other cements are spectacular, precipitating as large botryoidal crystal arrays from the walls and ceilings of cavities or among sediment grains.

- Cements help to make reefs rigid wave-resistant structures and can also fill much of the original pore space.

The reef mosaic

Bioerosion, grazing and predation

- Organisms that erode the living reef structure via boring, grazing, and predation.

- These actions enhance organism diversity, weaken reef structure, and produce particulate sediment. Sponges, bivalves, and worms dominate the modern endolithic (boring) biota.

- Grazing (scraping and rasping) by herbivores, particularly gastropods, fish, and echinoderms, removes seaweed, algal and microbial coatings, and hard calcareous algae, thus significantly eroding the growing reef.

- Herbivores reduce the proliferation of fast-growing soft algae and seaweed and therefore create bare open space for the settlement and colonization of reef-building calcareous metazoans.

Reef growth

The coral reef growth window

- The combination of many factors that control the growth of coral.
    1. Light
    2. Nutrients
    3. Temperature and salinity
    4. Sedimentation

Reef Growth

Carbonate reef

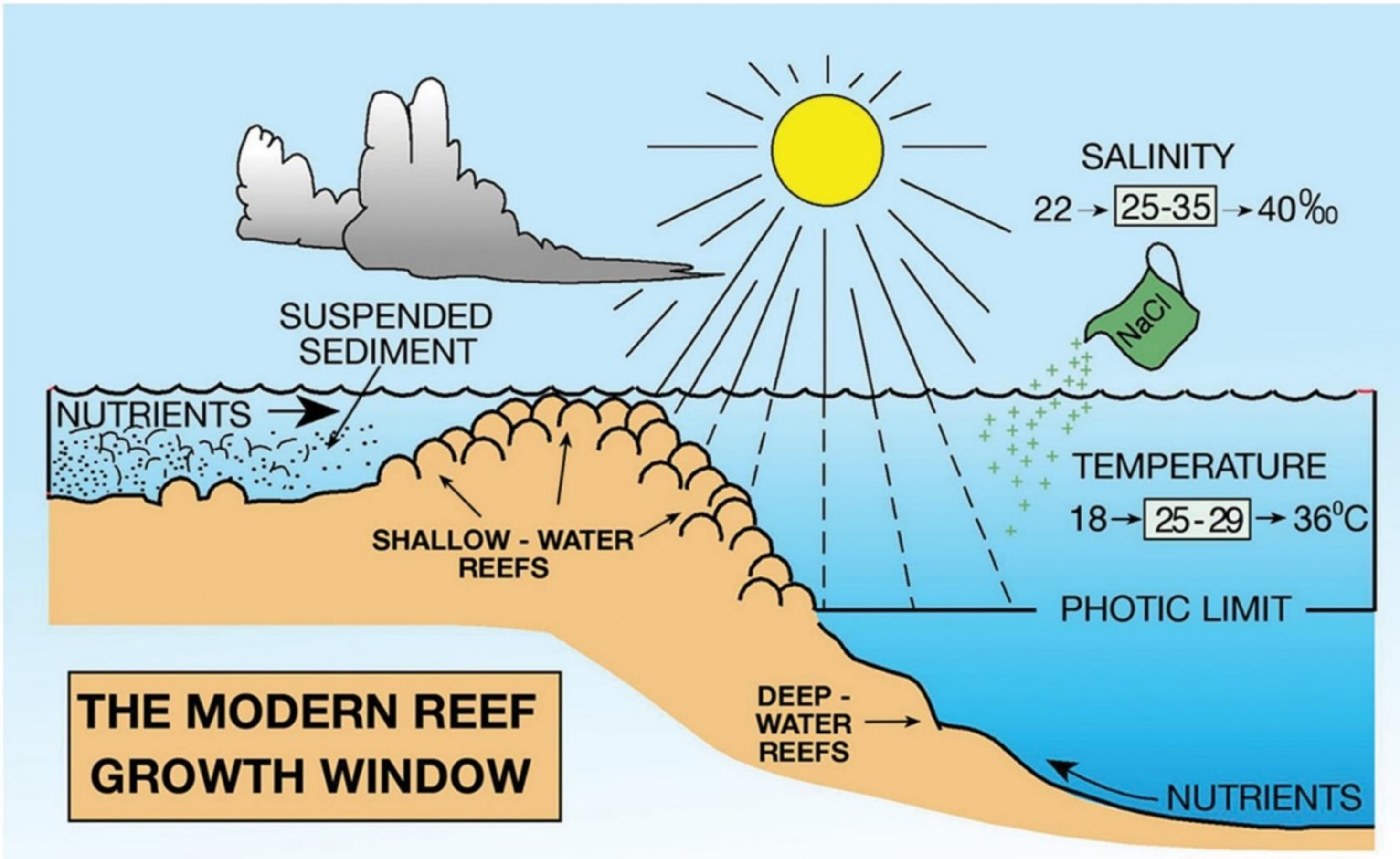
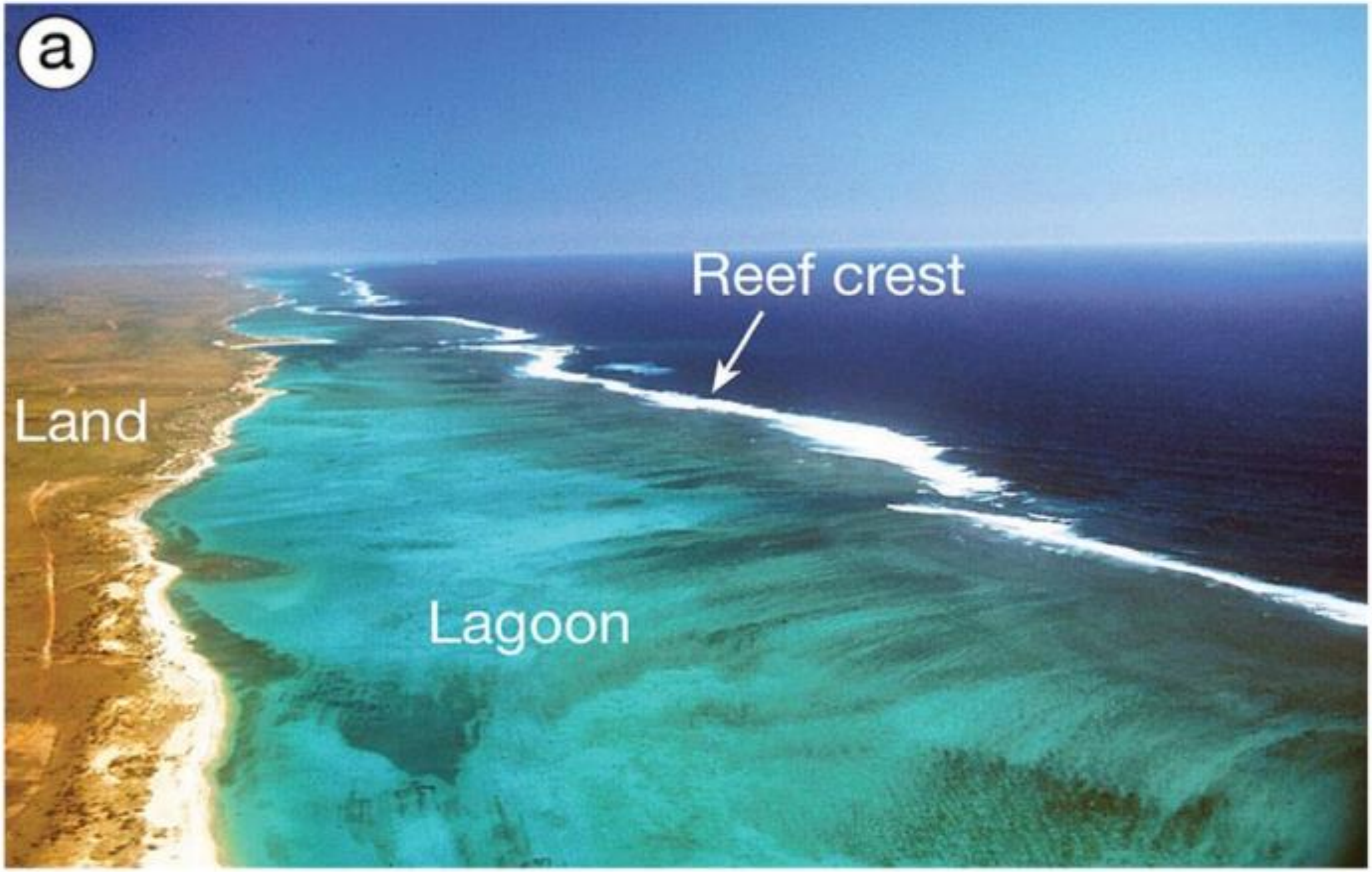


Figure 14.4 Sketch of the environmental parameters that define the growth window of modern mixotroph coral reefs. Source: Adapted from James and Wood (2010). Reproduced with permission of the Geological Association of Canada

Reef growth

Carbonate reef



Reef growth

- Growth forms and skeletal diversity are strongly controlled by hydrodynamic energy and available space.
- The shape of reefs in plan view varies from
  linear fringing reefs (Figure 14.5a)
  and barrier reefs (Figure 14.5b) to
  atoll reefs (Figure 14.1),
  subcircular cup reefs,
  and patch reefs (Figure 14.5c).

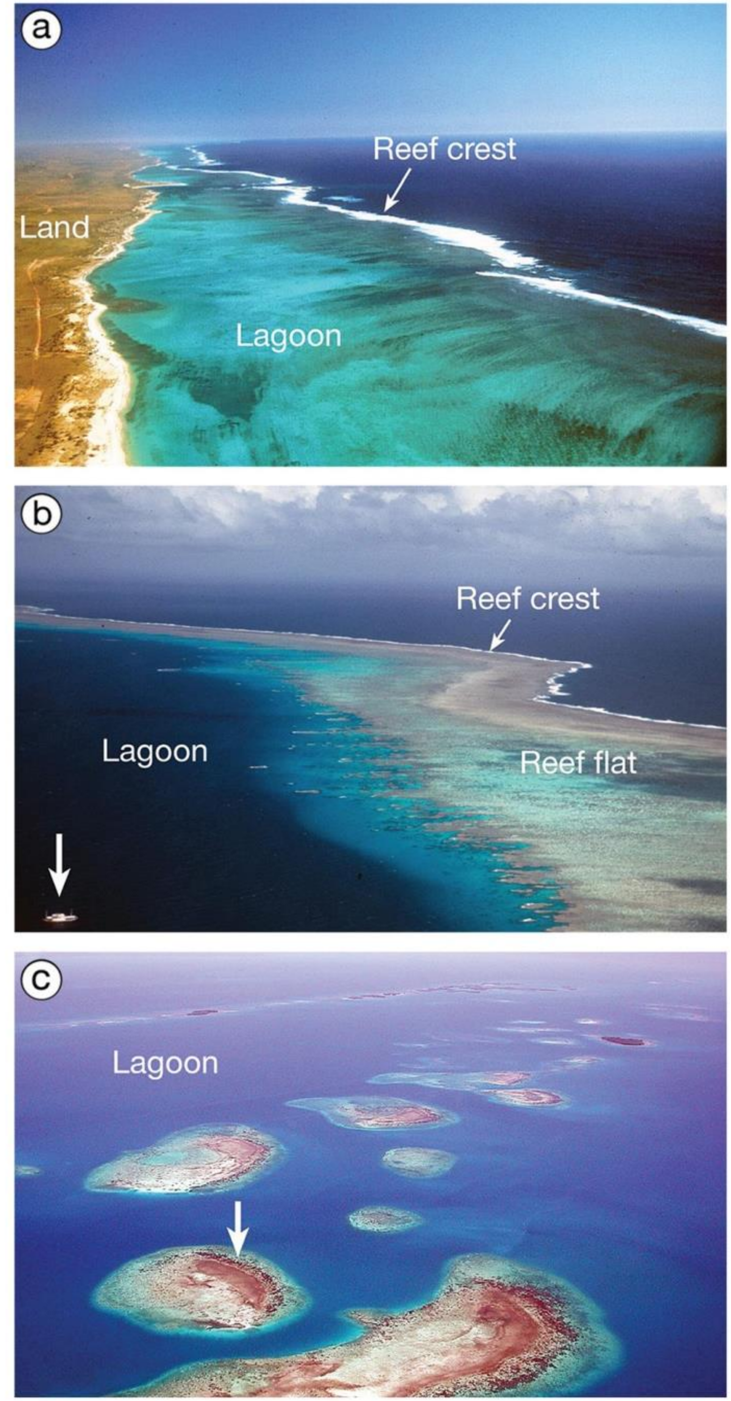


Figure 14.5 (a) Aerial image of the Ningaloo fringing reef off the coast of Western Australia, lagoon width ~4 km. (b) Aerial image of the outer part of the Great Barrier Reef east of Cairns in the Coral Sea; note the dive boat of length 40 m for scale (arrow). (c) A series of coral patch reefs in the Belize barrier reef lagoon on a very calm day. Circular reef in foreground (arrow) is 30 m across. Photograph by W. Martindale. Reproduced with permission.

Shallow-water reefs

- Coral reefs
- Coralline algal reefs
- Other shallow-water reefs

Zonation of a reef

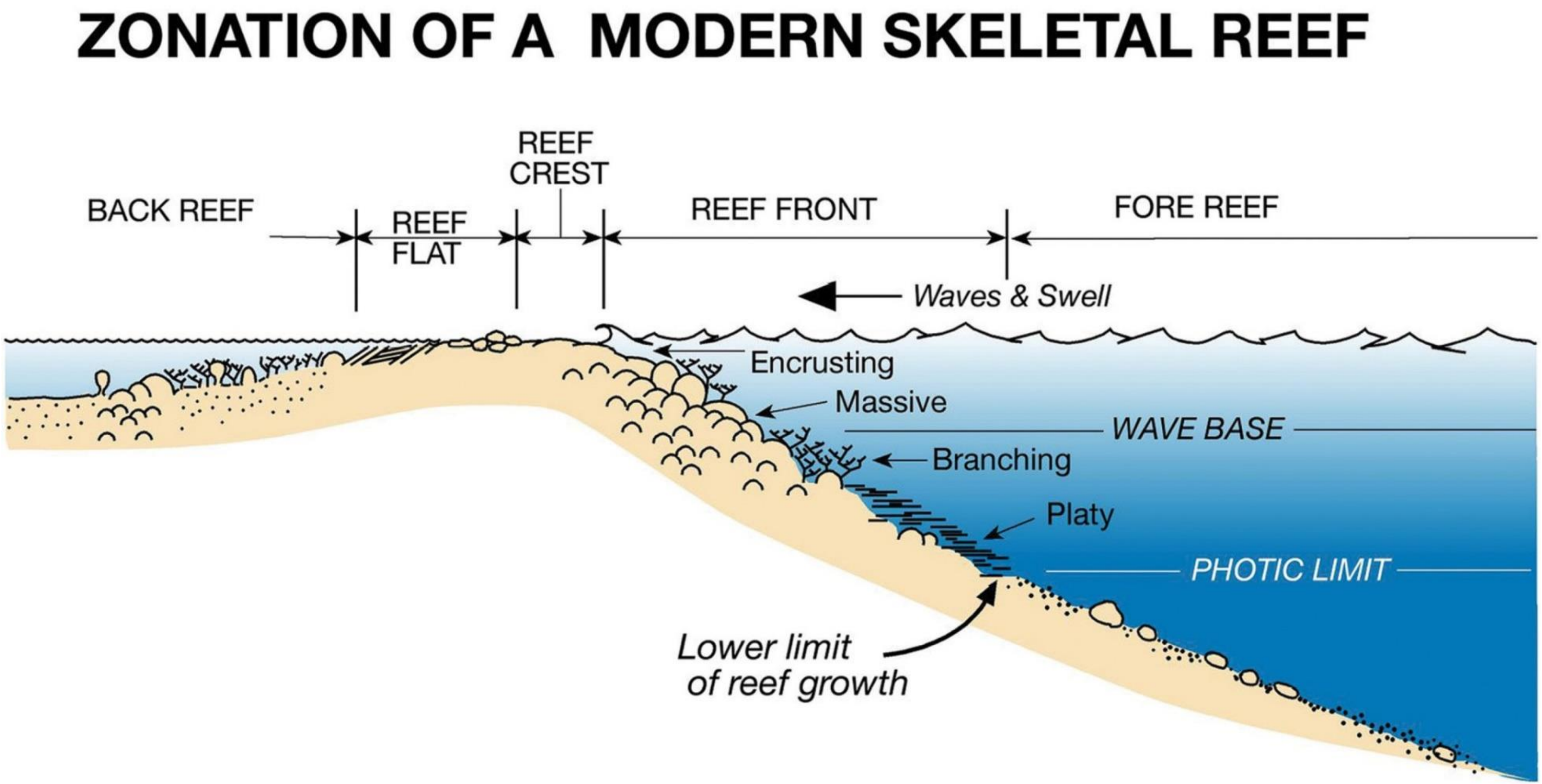
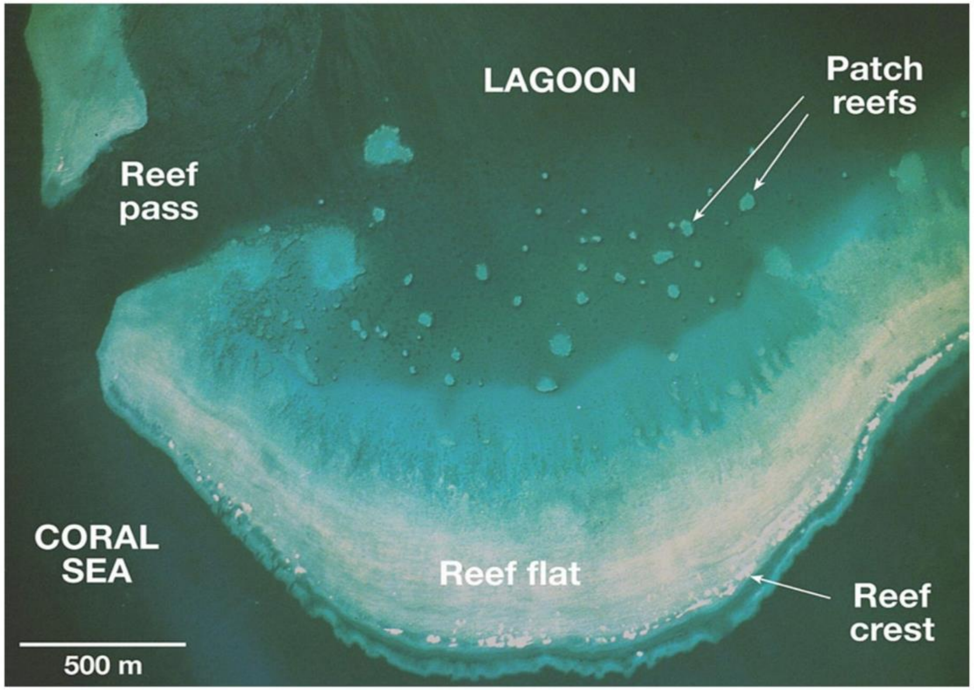


Figure 14.6 Sketch illustrating the facies of a modern mixotroph skeletal reef growing on the windward margin of a carbonate platform. Source: James and Wood (2010). Reproduced with permission of the Geological Association of Canada.

Zonation of a reef

- Zonation is best developed in windward locations.
- This zonation is particularly sensitive to perturbations of the growth window, especially a decrease in light, which leads to shallowing of all zones.

A vertical aerial photograph of ribbon reef No. 5 Great Barrier Reef off Cairns, Australia



Zonation of a reef

- The *reef crest*, which can extend to a depth of ~15 m, receives most of the wind and wave energy (next Figure).
  - ✓ Only organisms that can encrust, generally sheet-like forms, are able to survive where wind and swell are constant and intense.
  - ✓ Under the most energetic conditions of continuous pounding by waves and rolling swells, the crest is an *algal ridge* composed of encrusting corallines, encrusting foraminifers, vermetid gastropods, and hydrocorals that can, under exceptionally rough conditions, extend downward to 10 mwd.
  - ✓ The seaward portion of this zone in living reefs is typically a series of seaward-trending ridges and intervening channels called ‘spurs and grooves’.

Zonation of a reef

(a) Prolific coral and coralline algal growth among the surging swells at the reef crest of the Great Barrier Reef, Australia. Note people for scale (arrow).

Zonation of a reef

- The *reef flat* (Figure 14.8b) varies from a pavement of cemented, large skeletal clasts with scattered rubble and coralline algal nodules in areas of intense waves and swell, to shoals of well-washed lime sand in areas of moderate wave energy.
- Most material comes from the reef crest and is swept back onto the pavement during cyclonic storms. The vagaries of wave refraction can pile the sands into cays and islands that in turn protect small, quiet water environments behind the reef crest (Figure 14.1).

Zonation of a reef

Looking across the cemented reef flat pavement toward the reef margin at the outer edge of the Great Barrier Reef, Australia, at low tide. Circled hammer for scale.

Zonation of a reef

- The protected *back reef* (Figure 14.9a, b) is where much of the mud formed on the reef comes out of suspension.

- Low-energy conditions, coupled with the prolific growth of sand- and mud producing bottom biota such as calcareous green algae, also increases the relative proportion of mud-rich sediment.

- Corals here are stubby and dendroid or large globular forms that extend above the substrate, hence able to withstand both episodic agitation and quiet times when mudgrade sediment settles.

Zonation of a reef

(a) Exposed corals (mostly *Acropora* and *Porites* spp.) in the lagoon of Lady Elliot reef off eastern Australia. Note hammer, 15 cm length, for scale.

(b) Prolific growth of the coral *Acropora cervicornis* in the lagoon of the Florida Reef Tract, USA. Coral in foreground is 1 m high.

Zonation of a reef

- The seaward *reef front* lies between about 10 m (the base of surface wave action) and 100 m.
- This is an environment of diverse reef-builders (Figure 14.9c) varying in shape from hemispherical to branching to columnar to dendroid to platy.

- Accessory organisms and various niche dwellers such as bivalves, gastropods, coralline algae, segmented calcareous algae, and sponges are common.

- Below about 30 m depth, wave intensity is lower, light is attenuated, and most reef corals are prone and plate-shaped (Figure 14.9d) or delicately branching. Pockets, streams, and chutes of skeletal sand, especially calcareous algal particles, accumulate seaward between the spurs and grooves.

Zonation of a reef

(c) Prolific coral growth on a reef in ~2 m of water off Heron Island, Great Barrier Reef, Australia. Image width ~3 m.

(d) Growth of plate-like corals (*Montastraea cavernosa*) in ~40 m of water off northern Jamaica (Discovery Bay). Image width ~4 m.

Zonation of a reef

- The *fore-reef facies* below the zone of coral and algal growth is dominated by gravel and sand composed of whole or fragmented skeletal debris, blocks of reef limestone, and skeletons of reef-builders (Figure 14.10).

- Such deposits grade basinward into muds exhibiting many of the attributes described in the chapter on carbonate slopes.

Zonation of a reef

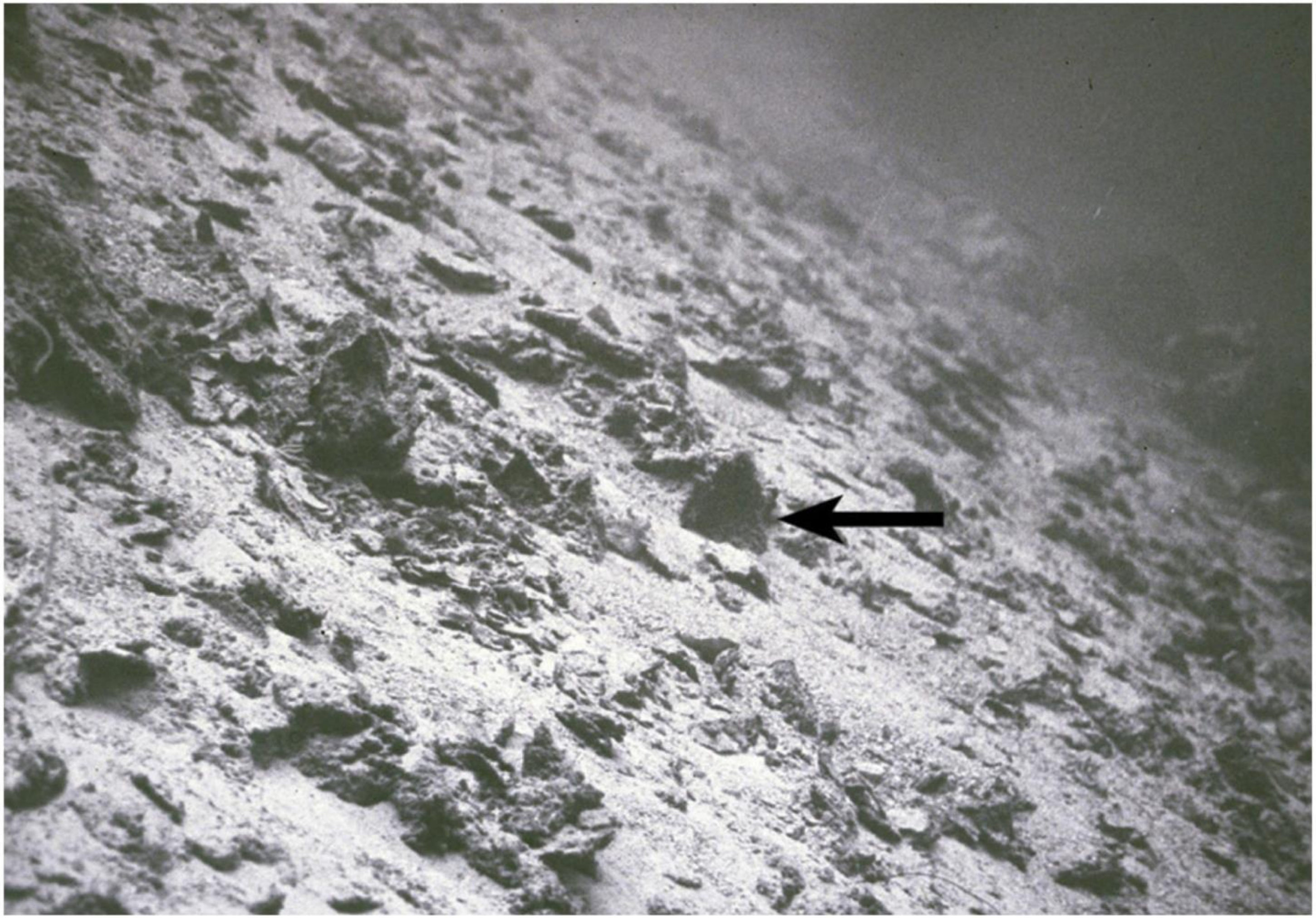


Figure 14.10 The steeply dipping fore-reef slope in ~130 m depth of water off Tobacco Cay, Belize. Blocks of coral in foreground (arrow) ~1 m high.

Zonation of a reef

Nutrient–sediment zonation

- There is typically a cross-shelf zonation in reef composition that partly reflects the seaward decrease in fine sediment and nutrients.

    - ✓ *Inner shelf reefs* are characterized by: (1) quickly growing corals with a high tolerance for fine sediment and low salinity, and an inability to withstand turbulent waters; (2) large and abundant heterotrophic-only sponges; (3) low epifaunal diversity; (4) few soft corals; (5) abundant soft algae; and (6) few calcareous algae.

    - ✓ *Outer shelf reefs* (in areas of little upwelling) are distinguished by: (1) slow-growing mixotrophic corals that cannot withstand suspended sediment or low salinities, but are adapted to high-energy conditions; (2) reduced numbers of sponges, some of which contain photosynthetic symbionts; (3) common tridacnid bivalves in the Pacific; (4) high epifaunal diversity; and (5) prolific calcareous algae.

Zonation of a reef

Energy zonation

- The preceding section describes the nutrient–sediment zonation across the platform, but there is also a striking energy zonation. As waves decrease in intensity inboard, so different corals dominate reefs in a predictable succession (Figure 14.11). Domal corals and algae first replace the robust branching forms; for example, in the Caribbean *Montastraea* sp. And *Diploria* sp. replace *Acropora palmata* and coralline algae. As waters become calmer in the same settings, delicate branching types such as *Porites porites* replace these massive corals forming coral algal banks (see below).

Zonation of a reef

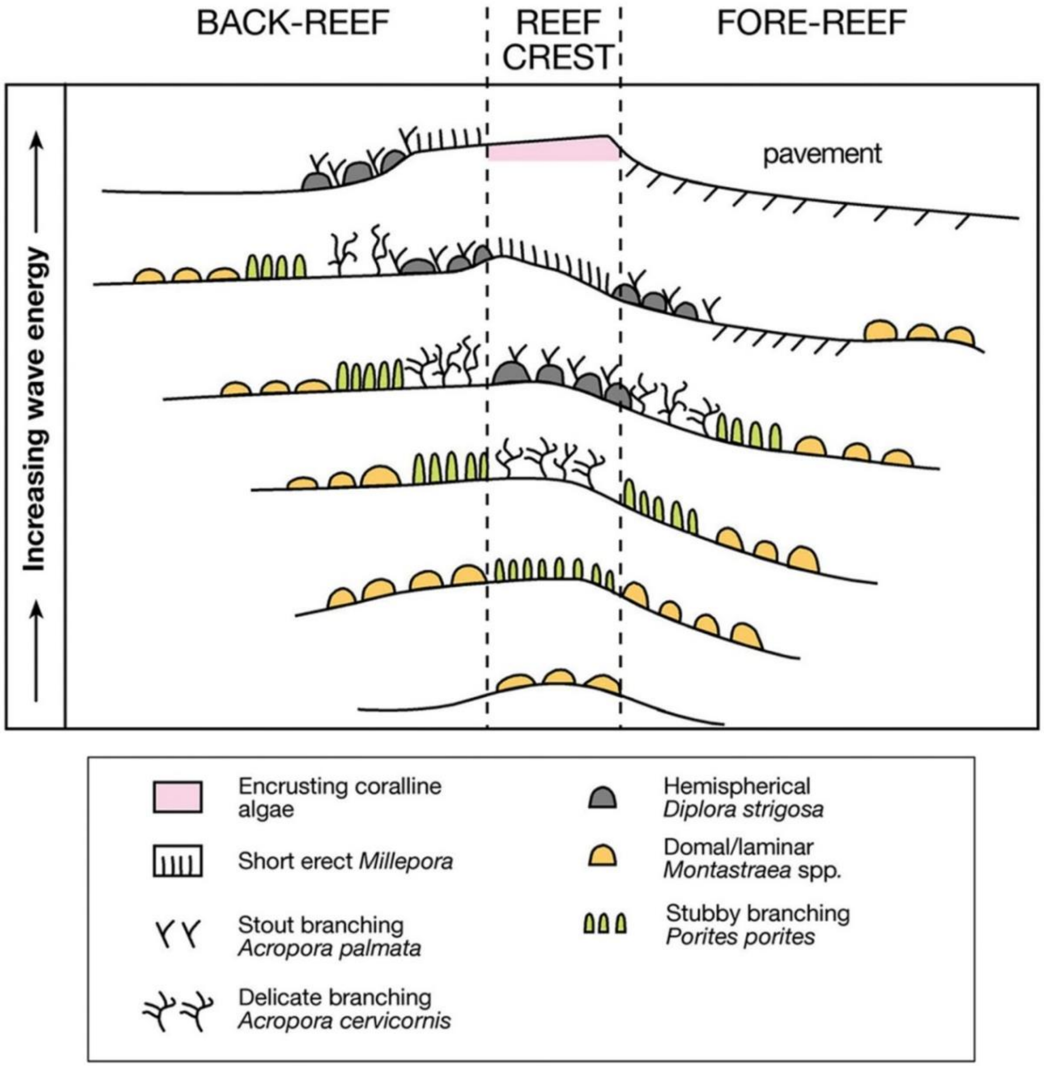


Figure 14.11 Sketch illustrating the change in modern coral zonation in response to increasing wave energy.

Shallow-water reefs

Coralline algal reefs

- up to 10 m high and a few tens of meters in diameter and grow on the seaward margins of platform.

- They are similar in composition to the intertidal to shallow subtidal coralline algal ridges, but grow in situations where water temperature or turbidity prevent the growth of the robust branching reef crest coral (*Acropora* spp.) community.

- This algal-dominated community also grows in the intertidal zone along rocky coasts in the Mediterranean, but does not form reefs.

Shallow-water reefs

Other shallow-water reefs

- other bioconstructions in modern shallow-water settings that barely qualify as reefs but have analogs in the rock record that have many reef attributes.
  - **Coral-algal banks.**
    - ✓ The lowest-energy accumulations in the modern shallow-water reef spectrum are typified by nearshore banks that grow seaward of the Florida Keys, and are protected from open ocean waves by the Florida reef tract (Figure 14.13).
    - ✓ These banks of delicate branching corals and a variety of calcareous algae are 1 to 3 km long, rise 2 to 4 m above the seafloor, and areexposed at spring low tide.
    - ✓ They are zoned with a windward margin of branching coral and branching coralline algae that passes landward into seagrasses with a rich calcareous green algal flora and an infaunal bivalve and burrowing crustacean fauna.

Shallow-water reefs

- Other shallow-water reefs
- other bioconstructions in modern shallow-water settings that barely qualify as reefs but have analogs in the rock record that have many reef attributes.

  - ***Halimeda* (green algal) reef mounds.**
    - Structure rich in the green calcareous alga *Halimeda*, are found in the Java Sea, Timor Sea, the Great Barrier Reef, and the Caribbean.
    - They all rise to within 40–15 m of the sea surface and do not occur in shallow water. They range from living to relict, but are nevertheless Holocene in age.
    - Structures have seafloor relief of 2 to 20 m, steep margins, and thicknesses of up to 50 m. They are dominated by *Halimeda* spp. but may have accessory encrusting sponges, bryozoans, and octocorals.
    - The sediment is mostly sand-grade *Halimeda* fragments with accessory coralline red algae, small corals, and ostracods in some places or mollusks, bryozoans, and large benthic foraminifers in others.

Shallow-water reefs

- Other shallow-water reefs
- other bioconstructions in modern shallow-water settings that barely qualify as reefs but have analogs in the rock record that have many reef attributes.
  - **Linear mud banks.**
    - ✓ These elongate features rise 3 to 4 m above the surrounding seafloor in lagoonal settings (Florida Bay and Belize).
    - ✓ Their origin is partly hydrodynamic and partly biogenic. Storms or tides sweep soft pellets into shoals as if they were sand grains. Roots of prolific seagrasses bind the sediments, preventing erosion.
    - ✓ Since the pellets are not lithified, these structures would be preserved as mud in the rock record with no evidence of hydrodynamics except local winnowed shell lags.

Zonation of a reef

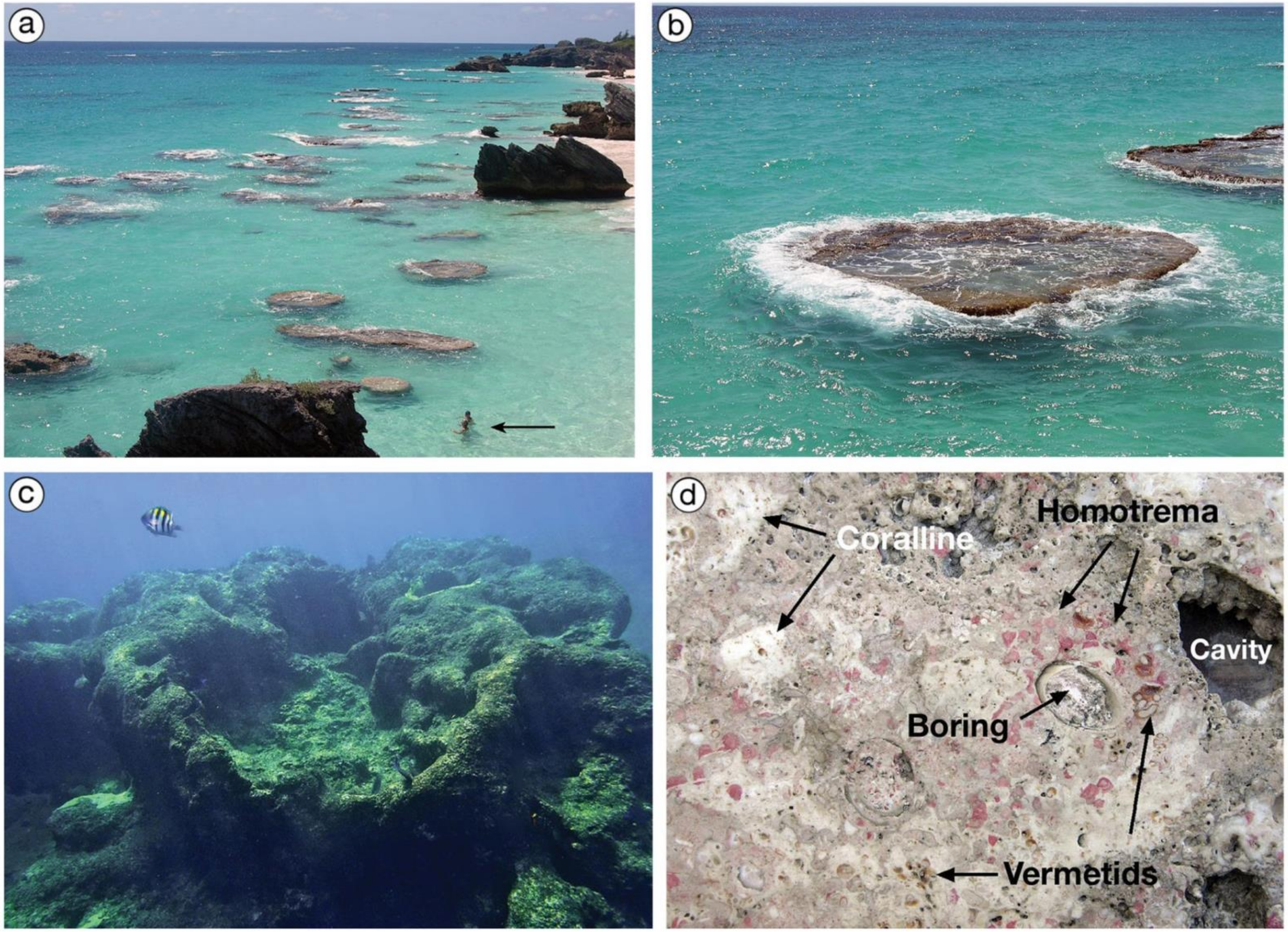


Figure 14.12 Coralline algal reefs, Bermuda. (a) Numerous cup reefs along the shallow inshore, south coast (persons for scale, arrow). (b) Close-up of the surface geometry and water surging around the periphery (structure 3 m across). (c) Underwater view of a small cup reef ~5 m across illustrating the deep depressed center and lack of corals. Photograph by W. Martindale. Reproduced with permission. (d) Slabs of cup reef limestone (Bermuda) composed of coralline algae, vermetid gastropods, the encrusting red foraminifer *Homotrema*, and cemented carbonate sand that is bored by the bivalve *Lithophoga*, and filled by lithified sand. Image width 6 cm.

Deep-water reefs

- Modern deep-water reefs that grow in dark, cold waters in areas such as Norway and New Zealand are constructed by azooxanthellate scleractinian corals, such as the branching form *Lophelia pertusa*, that lack photosymbionts.
- These reefs are most numerous between water depths of 250 and 1500 m where temperatures range from 4 to 12°C. Structures can be up to 5 km long and 40 m high, generally with steep sides.
- Reefs appear to thrive best on bathymetric highs such as seamounts, drowned glacial moraines, subaqueous dunes, and sediment drifts.
- They are also located in areas of elevated nutrients such as fronts between large-scale water masses or areas of upwellling. Others are sited on top of cold hydrocarbon seeps.
- The corals range from small centimeter-scale cups to meter-scale dendroid bushes.

Deep-water reefs

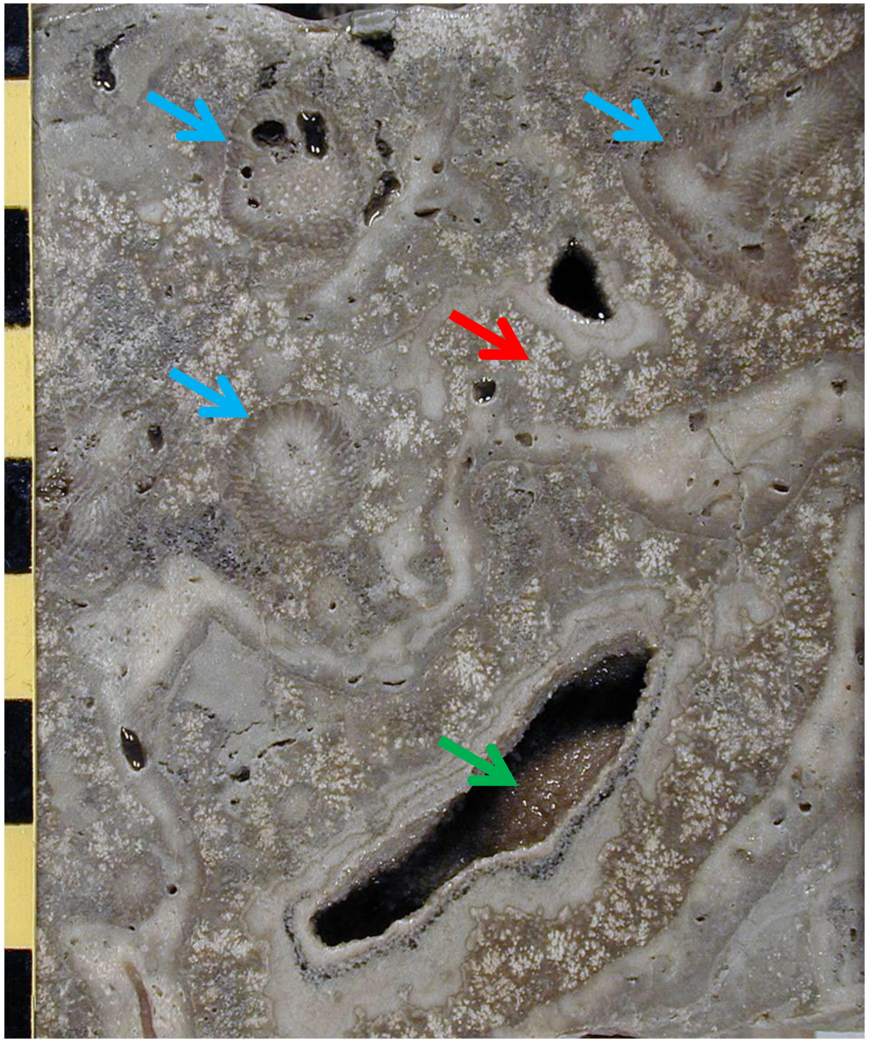
soft corals with spicules (alcyonarians), stylasterene hydrocorals, zoanthids (anemones), crinoids, spiculate and calcareous lithistid

Figure 14.13 (a) Aerial view of Tavernier Key, a coral and algal bank topped by a small island just off the Florida Keys (in background). (b) A plastic impregnated core of sediment from just below the surface of Tavernier Key composed of the branching coral *Porites porites*, prolific green algal plates (*Halimeda* sp.), and carbonate mud.

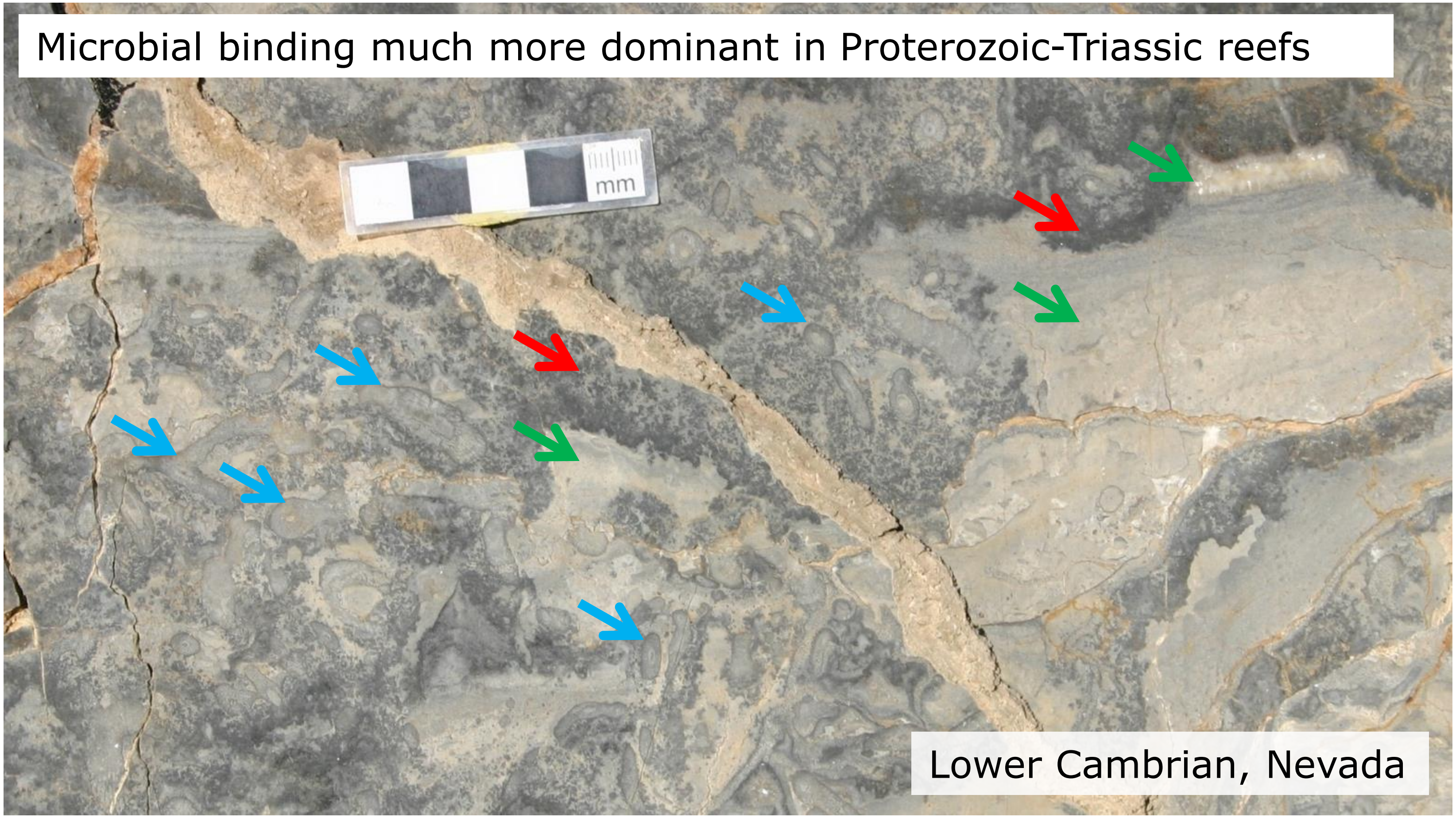
Carbonate reef

❖ Reef limestones composed of:

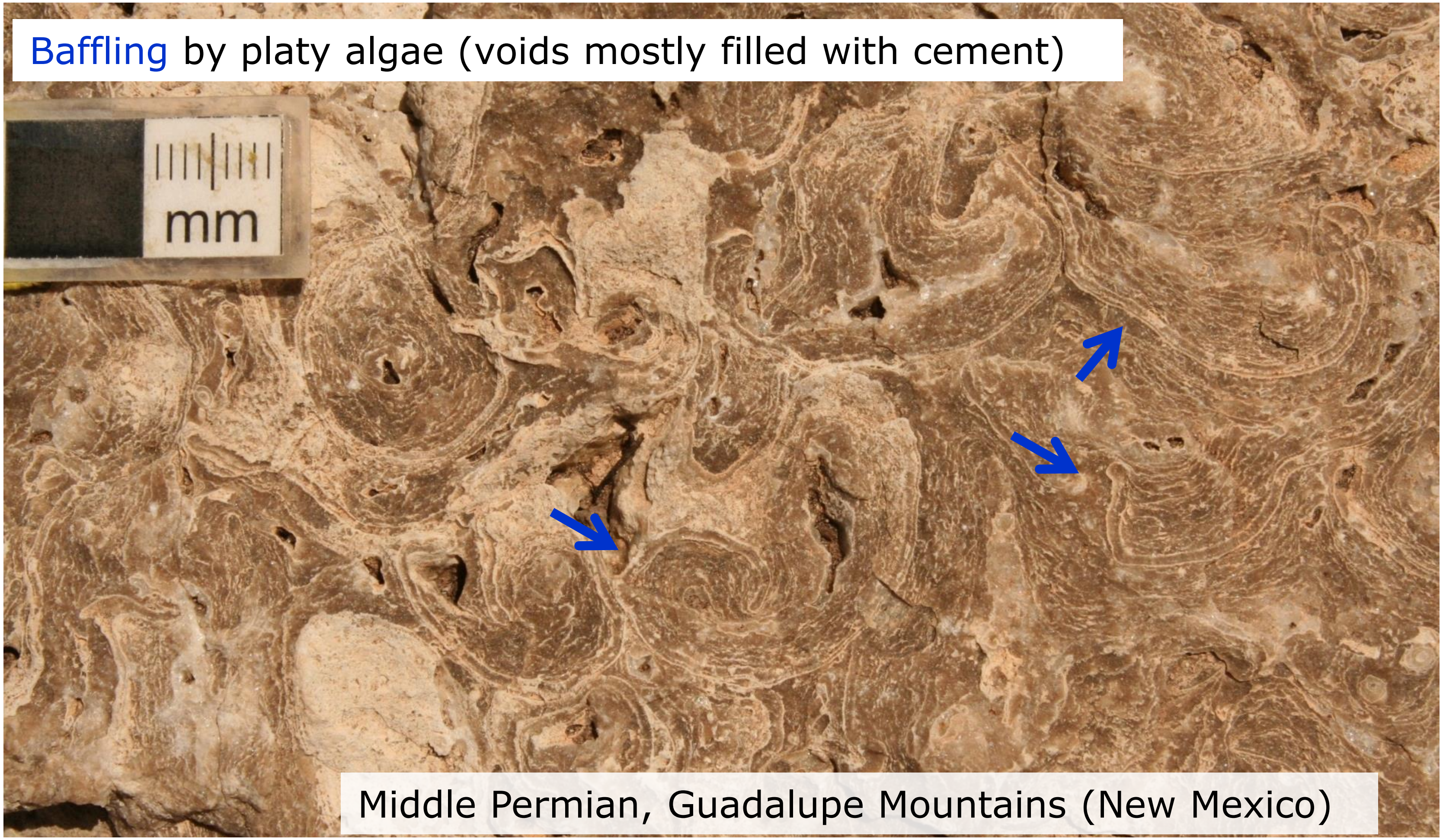
1. Framework constructing organisms
2. Encrusting algae, microbes, animals
3. Platy "baffling" organisms
4. Cavities filled by sediment and/or cement



Shoal rimmed platform



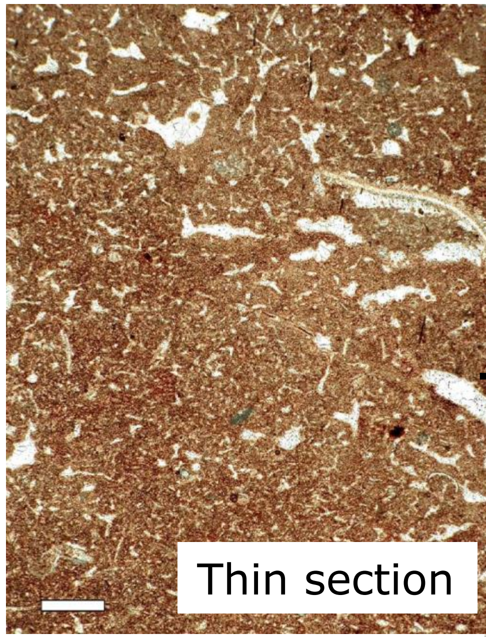
Shoal rimmed platform

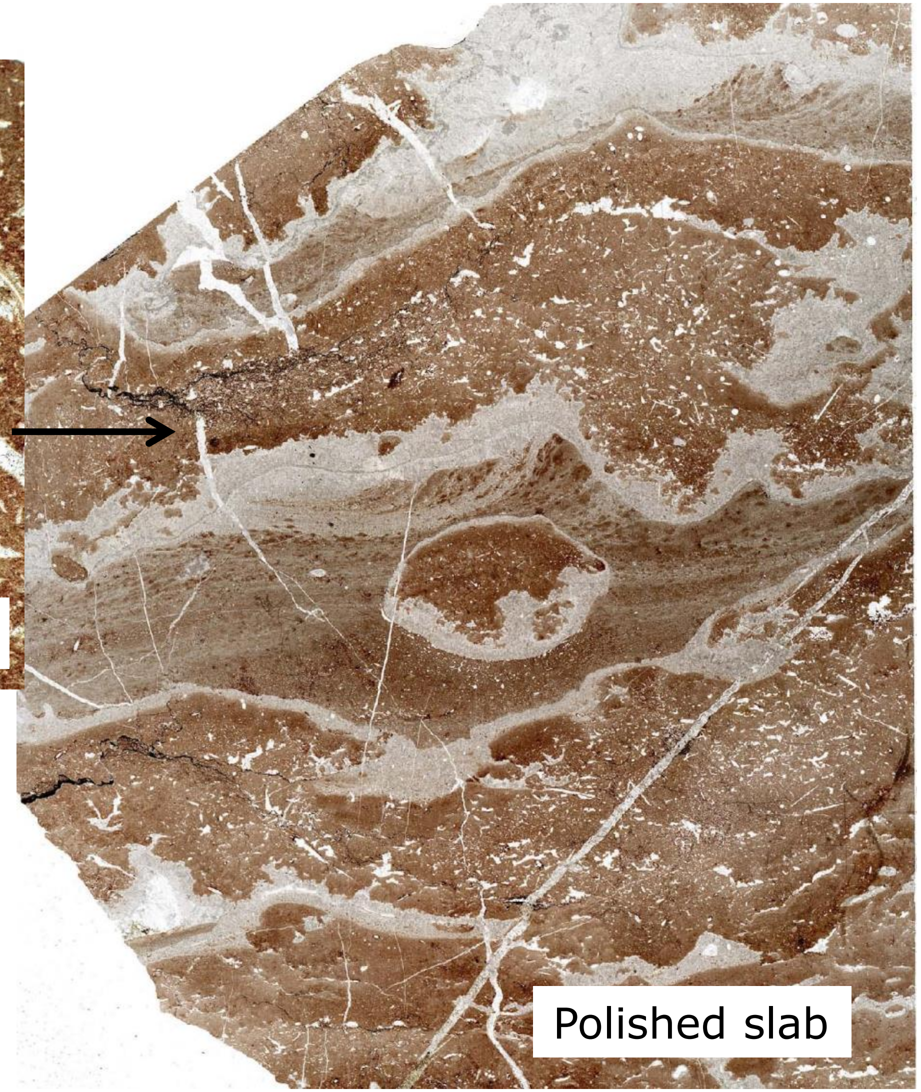


Shoal rimmed platform

<u>Mud mounds</u>: buildups ("bioherms") with bathymetric relief but no organism framework

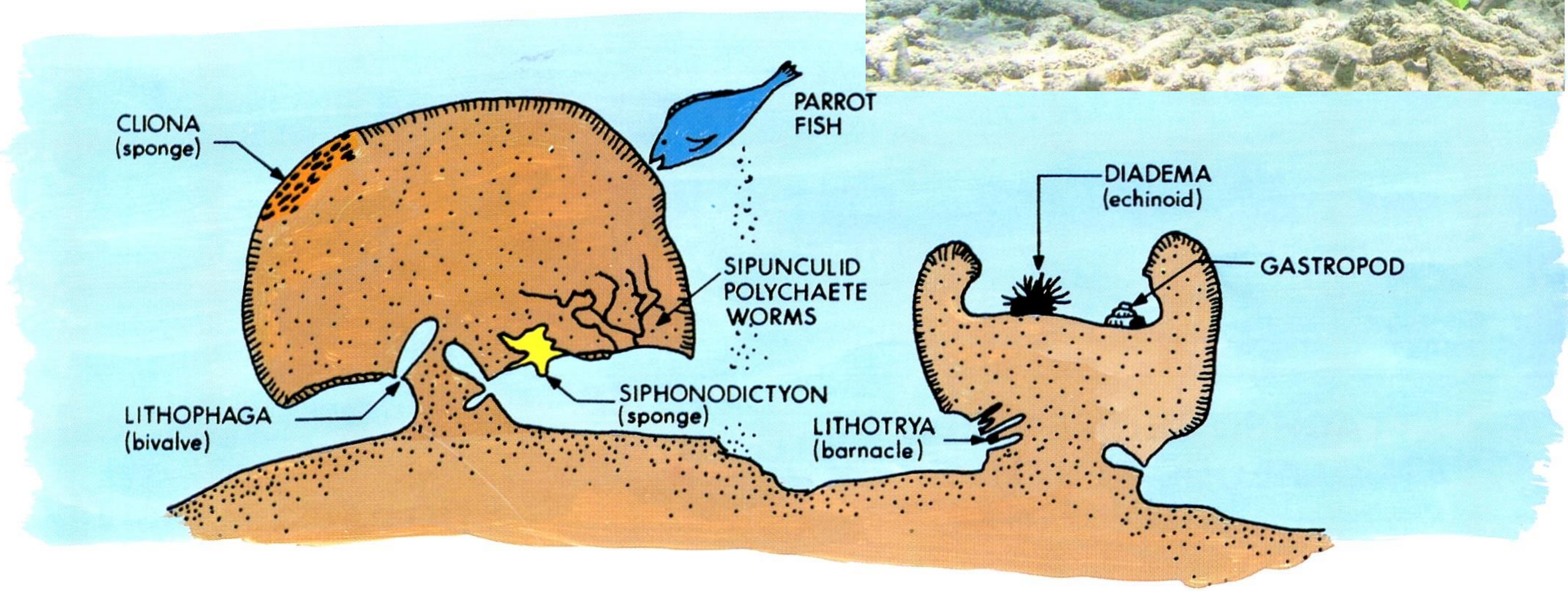
Dominated by mud trapped by bafflers or precipitated by microbes, or by cement



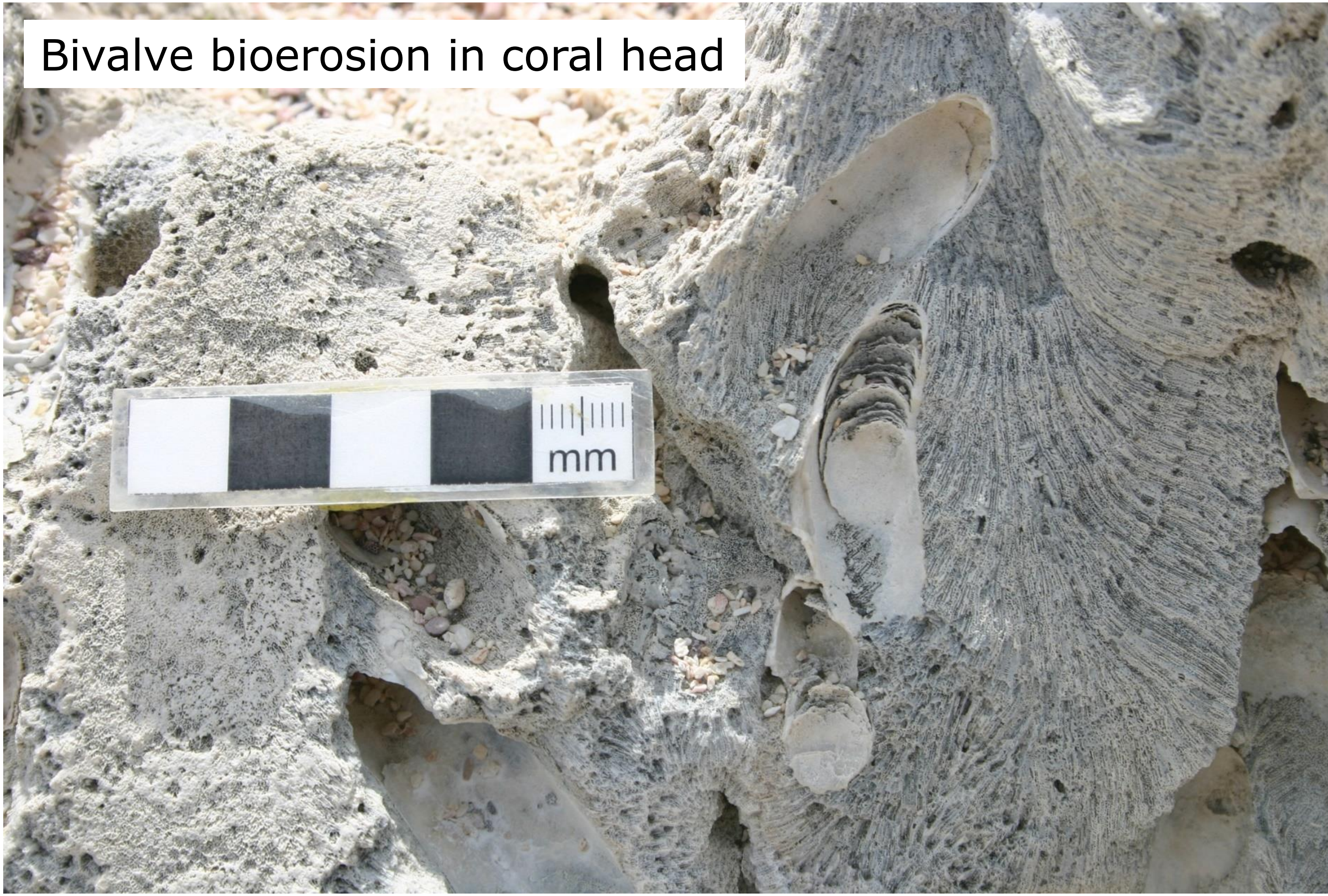


Destructive process

- Wave energy (especially storms and hurricanes)
- Bioerosion (dominant destructive process in the Mesozoic and Cenozoic)



Destructive process



Bivalve bioerosion in coral head

Thank You !

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