Eras and stages of Earth's mineral evolution[12]

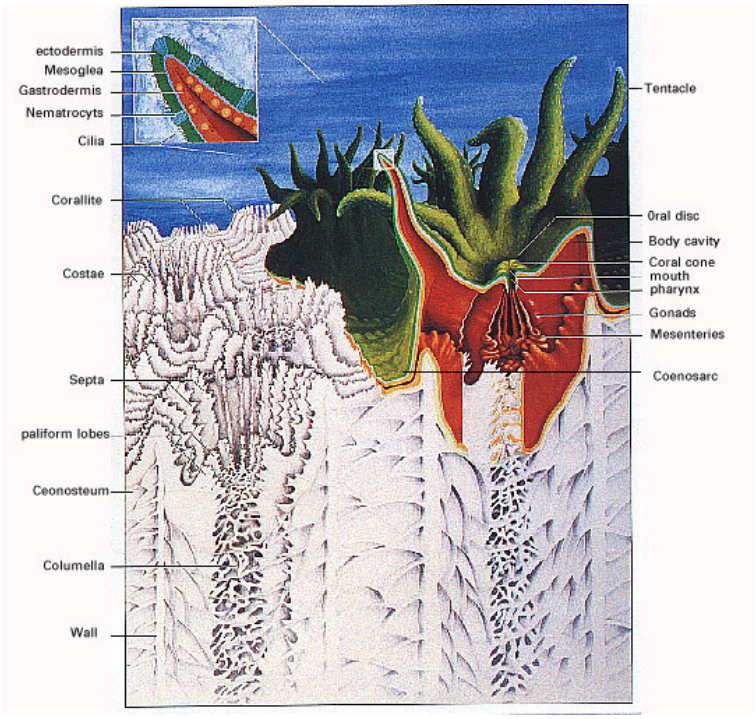
Era/stage		Age (Ga)	Cumulative no. of species
Prenebular "Ur-minerals"	—	>4.6	12
Era of planetary accretion (>4.55 Ga)	1. Sun ignites, heating nebula	>4.56	60
	2. Planetesimals form	>4.56–4.55	250
Era of crust and mantle reworking (4.55–2.5 Ga)	3. Igneous rock evolution	4.55–4.0	350–420[a]
	4. Granitoid and pegmatite formation	4.0–3.5	1000
	5. Plate tectonics	>3.0	1500
Era of biologically mediated mineralogy (2.5 Ga – present)	6. Anoxic biological world	3.9–2.5	1500
	7. Great Oxidation Event	2.5–1.9	>4000
	8. Intermediate ocean	1.85–0.85[15]:181	>4000
	9. Snowball Earth events	0.85–0.542	>4000
	10. Phanerozoic era of biomineralization	<0.542	>5413[13]

These are typically unicellular yellow-brown dinoflagellate algae that are endosymbiotic with corals. They live in the gastrodermis of coral polyps

For coral: provides color, oxygen, carbohydrates, and speeds up secretion and calcification of coral minerals
For algae: receives carbon dioxide and nitrogen (in the form of ammonia) from coral

HARD WORK: Hard, or stony, corals (like the star coral above) have protective external skeletons made of calcium carbonate. Inside are the corals' saclike polyps, which contain a type of algae called zooxanthellae. The zooxanthellae photosynthesize to provide food to the polyps, which in turn devote *their* energy to laying limestone—thus building the reef.

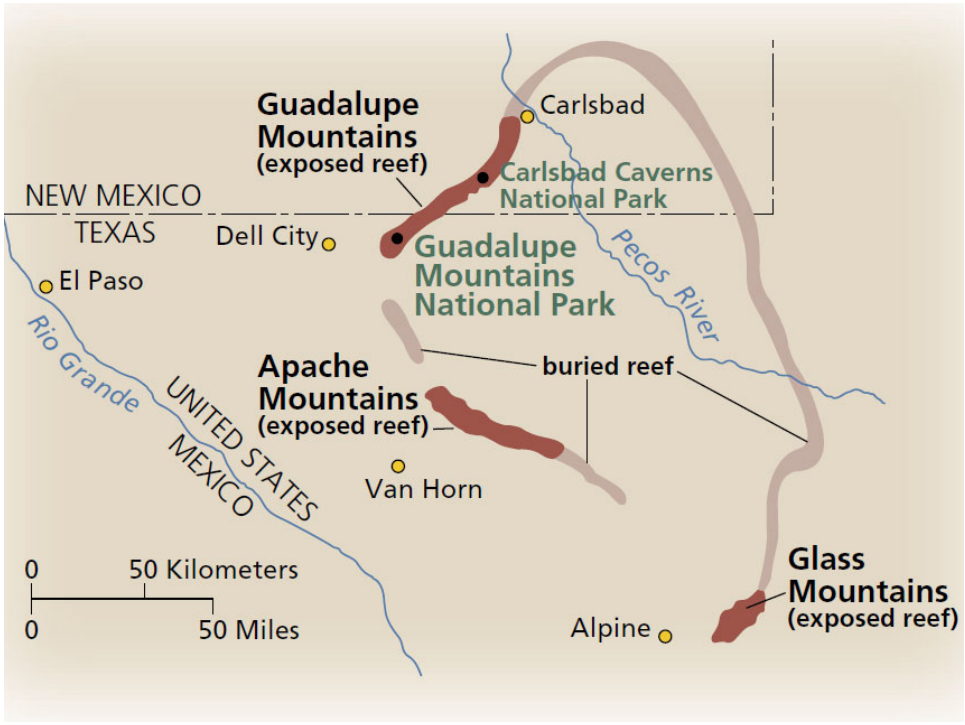
MOUTHS TO FEED: In addition to their photosynthesizing zooxanthellae, hard and soft corals also have mouths ringed by a halo of stinging tentacles (above). While most hard corals get 98 percent of their dietary needs from the zooxanthellae, soft corals—which thrive in strong currents—rely largely on their tentacles to capture plankton that float within reach.


ectodermis
Mesoglea
Gastrodermis
Nematrocyts
Cilia
Corallite
Costae
Septa
paliform lobes
Ceonosteum
Columella
Wall
Tentacle
0ral disc
Body cavity
Coral cone
mouth
pharynx
Gonads
Mesenteries
Coenosarc

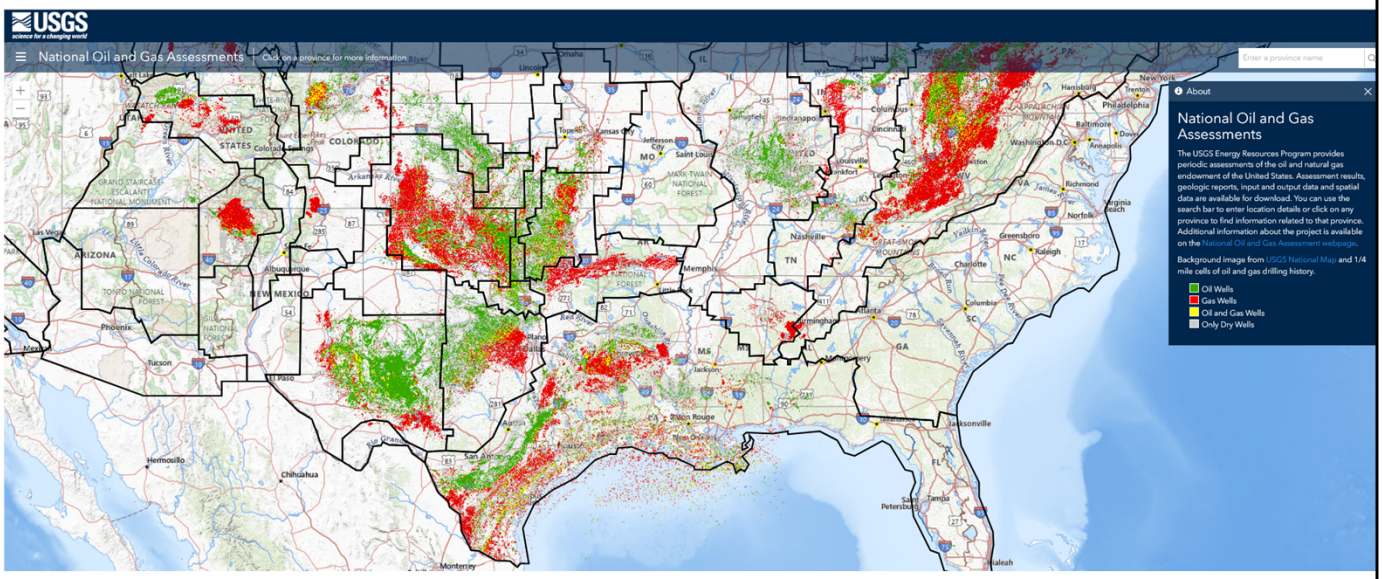
Capitan Reef of the Guadalupe Mountains, TX and NM

Trails here can span a sea floor profile extending from a 700 m deep basin floor to the top of the shallow water shelf, crossing an extensive transect of the well-documented Capitan Reef.

https://iugs-geoheritage.org/geoheritage_sites/permian-reef-complex-of-the-guadalupe-mountains/


Guadalupe Mountains (exposed reef)
Carlsbad
Carlsbad Caverns National Park
NEW MEXICO
TEXAS
Dell City
Guadalupe Mountains National Park
Pecos River
El Paso
Rio Grande
UNITED STATES
MEXICO
Apache Mountains (exposed reef)
buried reef
Van Horn
0
50 Kilometers
0
50 Miles
Glass Mountains (exposed reef)
Alpine

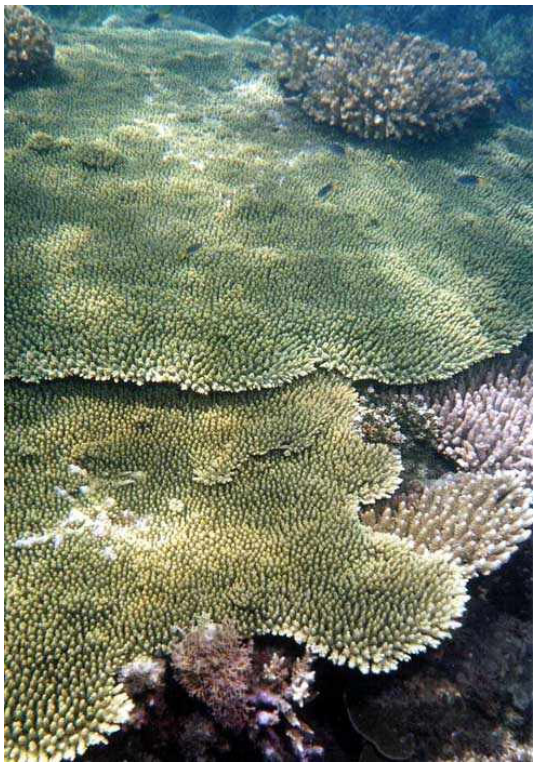

104°
102°
100°
34°
32°
30°
TEXAS
NEW MEXICO
MEXICO
Pecos
Colorado
Rio Grande
NORTHWESTERN SHELF
Capitan Reef
CENTRAL BASIN PLATFORM
MIDLAND BASIN
EASTERN SHELF
Carlsbad
Midland
Odessa
El Paso
Guadalupe Mts.
DELAWARE BASIN
DIABLO PLATFORM
SHEFFIELD CHANNEL
SOUTHERN SHELF
Marathon
HOVEY CHANNEL
OUACHITA-MARATHON OROGENIC BELT
VAL VERDE BASIN
0 50 100 miles
0 50 100 150 km
Carbonate reef
Platforms
Basins



The coral reefs in the Permian Basin hold oil because the ancient reef structures acted as natural traps for organic matter that decomposed and transformed into oil over millions of years, with the porous nature of the reef providing a reservoir for the trapped hydrocarbons, while the surrounding rock layers acted as a barrier preventing the oil from migrating further; essentially, the reef provided a perfect geological structure for oil accumulation.

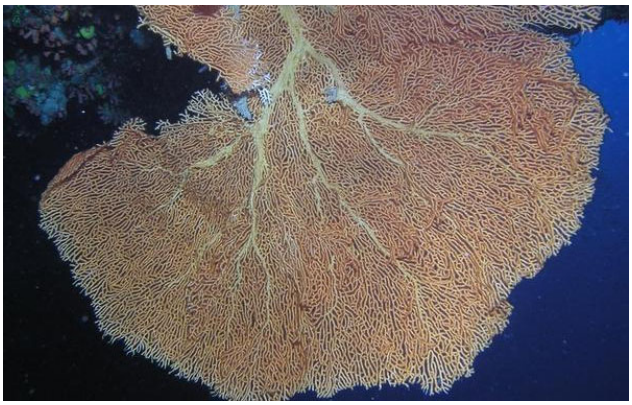
https://www.usgs.gov/media/images/map-united-states-oil-and-gas-wells-2017

- Phylum Cnidaria
- Class Anthozoa
- Subclass Hexacorallia
- Order Scleractinia
  - Dominant reef-building ‘hard’ coral
  - First appeared in the Middle Triassic
  - Filled the ecological niche once held by tabulate and rugose corals.



Subclass Octocorallia

- Soft corals lack the rigid calcium carbonate skeleton of hard corals.
- They have a flexible, fibrous structure made of protein and tiny skeletal elements called spicules.
- Soft corals do not contribute significantly to reef building



Soft corals can form reef-like structures at deeper depths because some species do not have zooxanthellae, thus no need for ample sunlight for them to photosynthesize. Soft corals can dominate in areas where water quality or temperature are unsuitable for hard corals.

Soft corals are distributed worldwide (in polar, temperate & tropical waters)

Other biomineralizing organisms

- May build reef as individuals in the absence of hard corals (stromatolites) or contribute to hard reef structure
  - Stromatolites
  - Sponges
  - Bivalves
  - Benthic foraminifera
  - Bryozoans
  - Calcareous algae

Stromatolites are mounds of prokaryotic algae and cyanobacteria. Modern stromatolites occur today along the Australian coast.

Banded iron formations. Stromatolite reef created the first oxygen in the atmosphere, making conditions less oxidizing and more hospitable for non-photosynthesizing organisms.

When cyanobacteria evolved and started photosynthesizing, they began oxygenizing the atmosphere. In the presence of oxygen, surface veneers (oxides) form on the surface of many metallic elements (for example, rust forms on iron in the presence of oxygen). Banded iron formations are the fossil evidence for the emergence of oxygen on planet Earth through the metabolism of cyanobacteria in stromatolites.

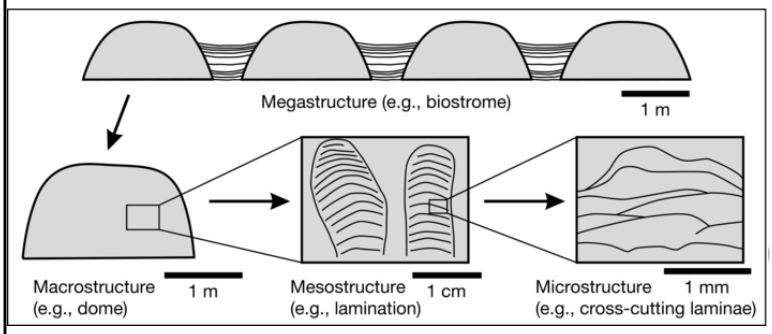
Stromatolites

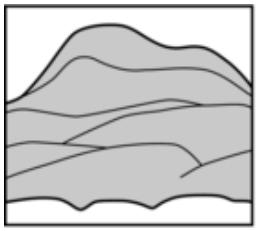
- Mounds of prokaryotic (single-celled) organisms: algae and cyanobacteria.
- Modern stromatolites occur today along the western Australian coast.
- Comprised the first reefs in geologic history
- Have been found on Earth for 2 billion years
- Do not typically occur with coral reef

Stromatolites encode the role that ancient microorganisms played in the evolution of life on earth and in shaping earth's environments. The fossil record of stromatolites is astonishingly extensive, spanning 4 billion years of geological history with the forming organisms possibly having occupied every conceivable environment that ever existed. Today, stromatolites are nearly extinct in marine environments, living a precarious existence in only a few localities worldwide. Modern stromatolites were first discovered in Shark Bay, Australia in 1956, and through out western Australia in both marine and non-marine environments. New stromatolite localities have continued to be discovered in various places such as the Bahamas, the Indian Ocean and Yellowstone National Park, to name but a few localities. Stromatolites are most often described as biogenically-produced structures formed by colonies of photosynthesizing cyanobacteria.

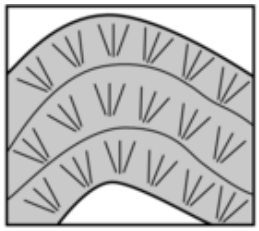
Hamelin Pool Marine Reserve near the boardwalk, Western Australia

Stromatolites are mounds of prokaryotic algae and cyanobacteria. Modern stromatolites occur today along the western Australian coast.





Agglutinated



Precipitated

Cryptozoön, the first reported and formally named stromatolite. It occurs along a glaciated surface, showing cabbage-head like structures. Coin (24 mm) for scale. Upper Cambrian Hoyt Limestone, Petrified Gardens, Saratoga Springs, New York State, United States.

https://www.abc.net.au/news/science/2017-05-10/early-life-on-land-in-3.5bn-year-old-hot-spring-in-pilbara/8497594

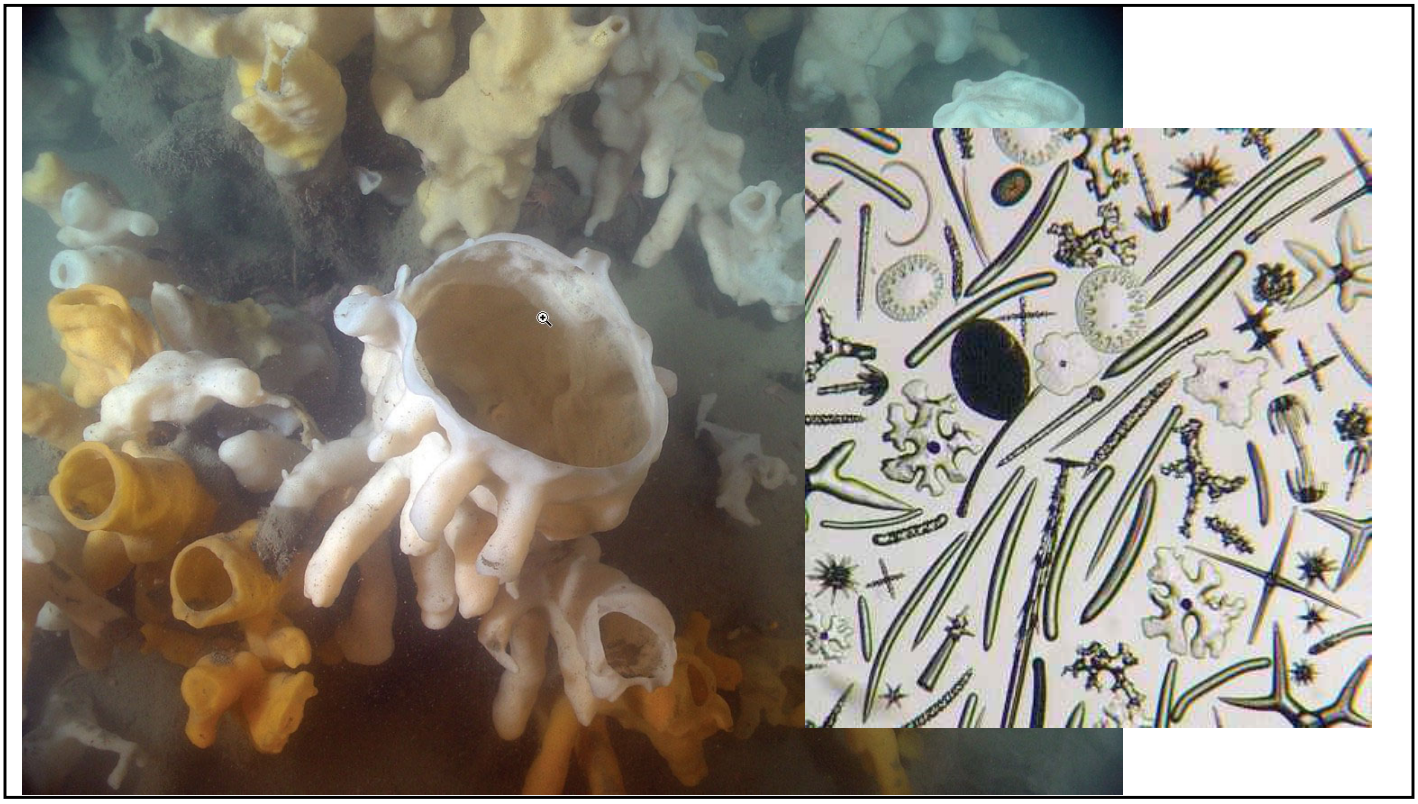
Western Australia

Sponges can form reefs on their own, and contribute to coral reef by their detritus, notably the spicules that give rigid form to their bodies. Spicules can be made of silica or calcium carbonate.

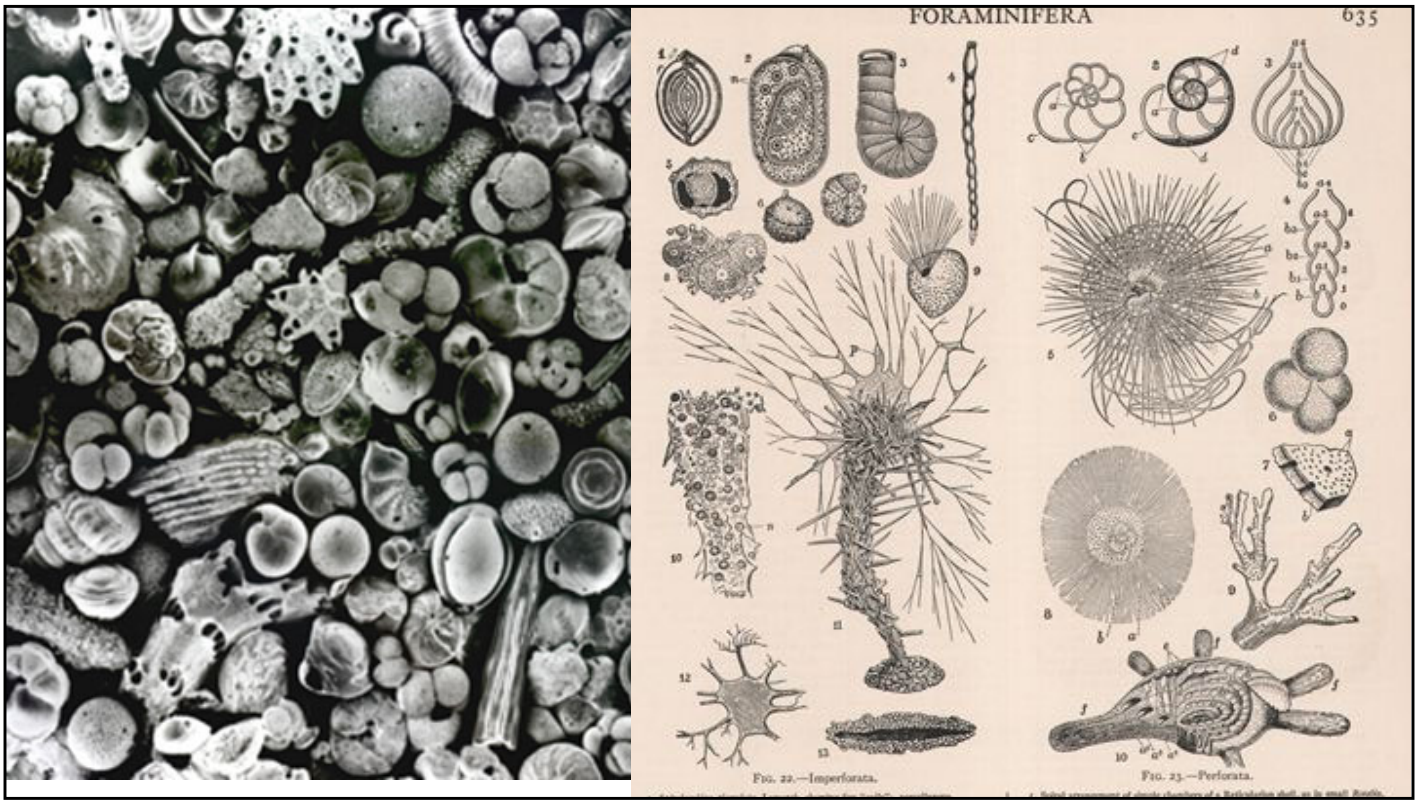
Sponges have a water-based circulation system. Sponges can enhance coral growth by filter feeding and keeping water clear. Large sponges can filter thousands of liters of seawater per day via the motion of cilia lining its internal anatomy.

Sponges may also be symbiotic with algae.

Evolved in the Devonian (450 million ya)



- Yes, sponge reefs exist in various parts of the world, though they are relatively rare and fascinating. Here are some notable examples:
- **1. Glass Sponge Reefs (Hexactinellid Sponges) in British Columbia, Canada**
- The most famous examples of sponge reefs are the glass sponge reefs found off the coast of British Columbia, in areas like Hecate Strait and Queen Charlotte Sound.
- These reefs are formed by species of glass sponges that create intricate, calcium carbonate-based structures.
- They were thought to have gone extinct millions of years ago, only to be rediscovered in the late 20th century, making them often referred to as "living fossils."



Foraminifera

A colony of forams (*Marginopora vertebralis*) growing on a coral reef on the Wheeler Reef system in the Great Barrier Reef off the coast of Townsville in Queensland, Australia.
The shells from these forams are believed to be the source of over 50% of the calcareous sedimentary rock formed on the sea bottoms. Forams do not build large reef as much as they contribute to the calcareous sediments in and around reef.
Foraminifera (forams) are microscopic, single-celled organisms that do not form reefs in the traditional sense, like corals or sponges. However, they play a significant role in reef ecosystems and can contribute to the formation of reef-like structures under certain conditions. Here's how:

1. Foraminiferal Sand and Reef Formation

•Many forams have calcareous shells, which, upon their death, contribute to sediment production. These sediments accumulate and can cement over time to form limestone and reef-like structures.
•For example, certain tropical forams, such as those in the genus *Amphistegina* or *Heterostegina*, produce significant amounts of calcareous material in reef environments.

2. Role in Bioconstruction

•Large benthic forams, like *Homotrema* and *Archaias angulatus*, are often found in reef environments, where their skeletons contribute to the reef's overall calcium carbonate budget.
•In regions like the Bahamas and the Indo-Pacific, foram-derived sands can dominate beaches and lagoon areas, indirectly supporting reef development.

3. Ancient Foram Reefs

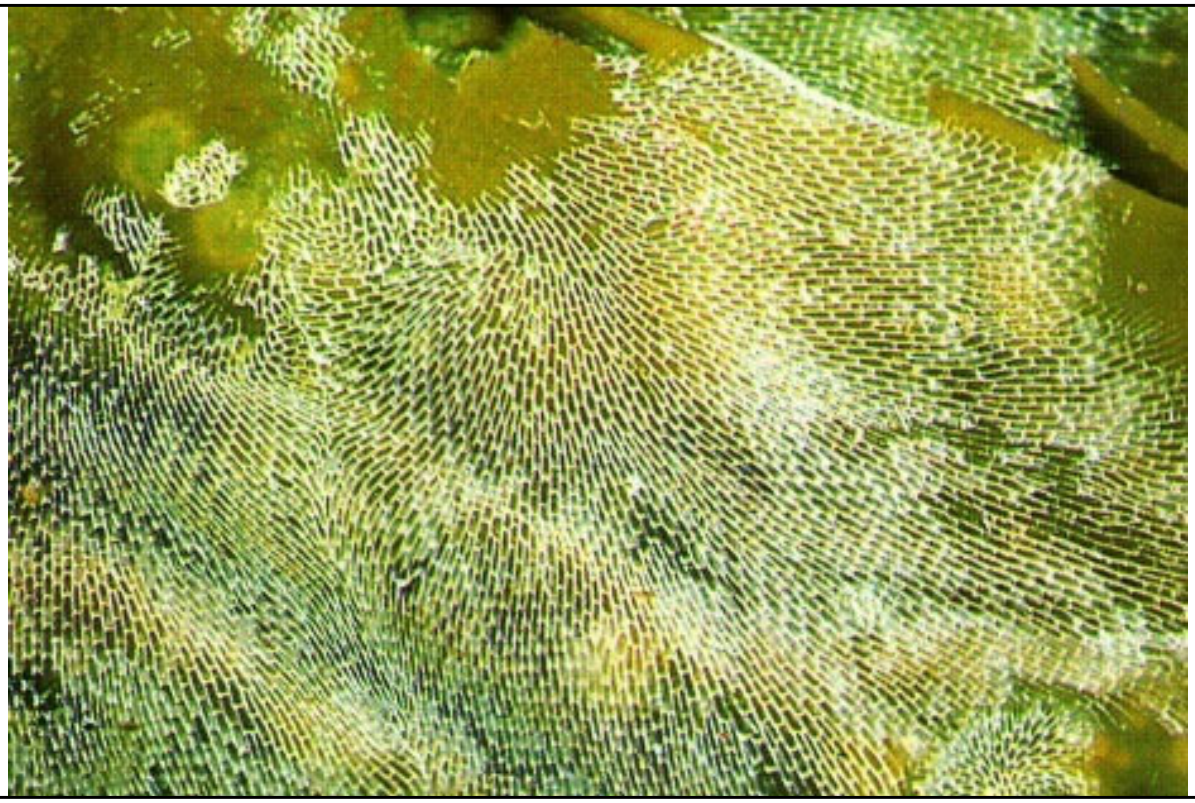
•In the geologic past, particularly during the Paleozoic and Mesozoic eras, some foraminifera, like the fusulinids and larger nummulitids, contributed to reef-like carbonate buildups.
•The Eocene-aged "Nummulitic Limestone" of the Mediterranean region, composed largely of the shells of foraminifera, is an example of massive foram involvement in reef-like structures.

4. Modern Foram Ecosystems

•While modern forams don't form true reefs, they live symbiotically with algae, contribute to carbonate production, and support reef resilience by recycling nutrients and providing a food source for reef organisms.

In summary, while forams don't form reefs themselves, they contribute significantly to the carbonate framework and sediment of reef ecosystems, and in the past, their contributions were substantial enough to form reef-like structures.

Homotrema rubrum



Bryozoans may be found on all types of hard substrates

Bryozoans are also colony-forming animals. Many millions of individuals can form one colony. The colonies range from millimeters to meters in size, but the individuals that make up the colonies are tiny, usually less than a millimeter long. In each colony, different individuals assume different functions.

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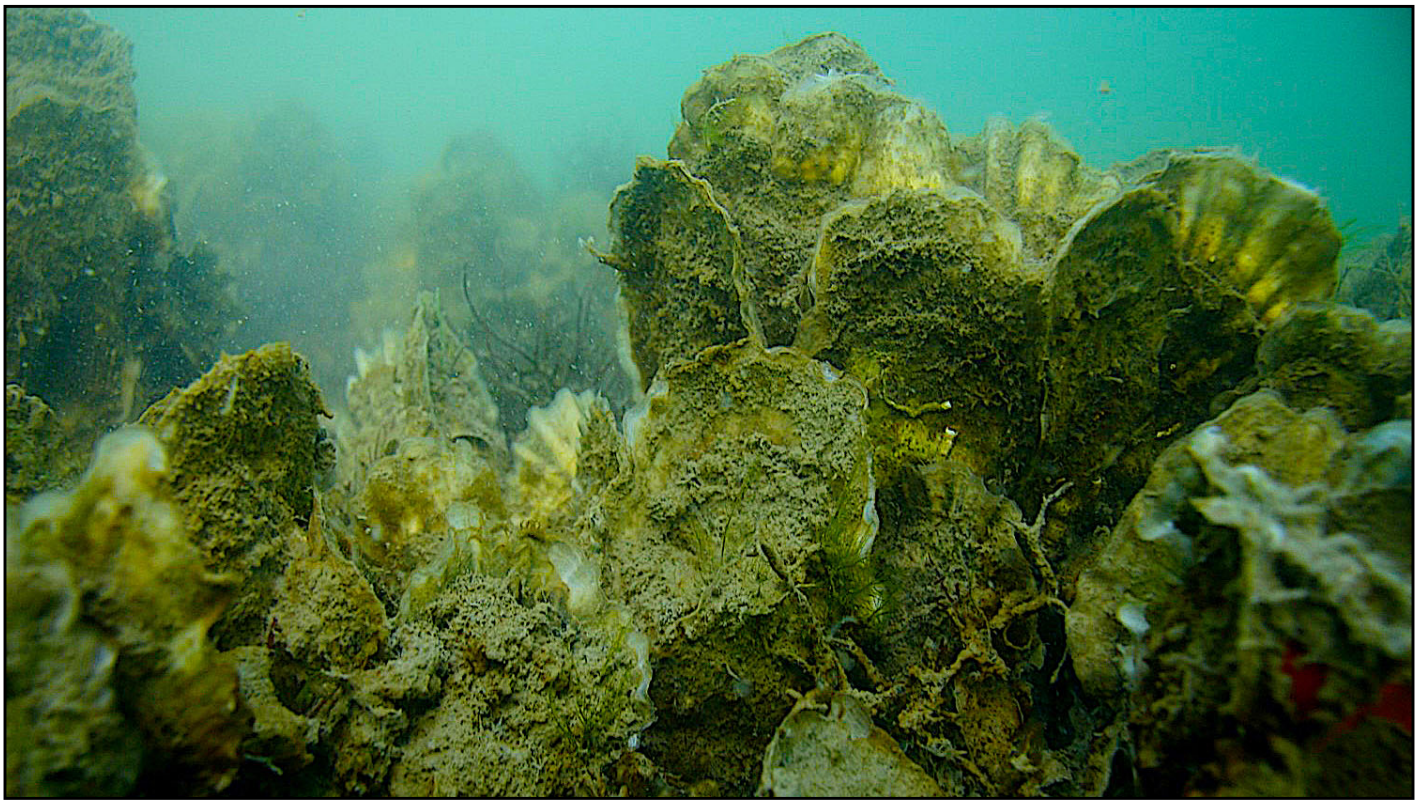
Bryozoans

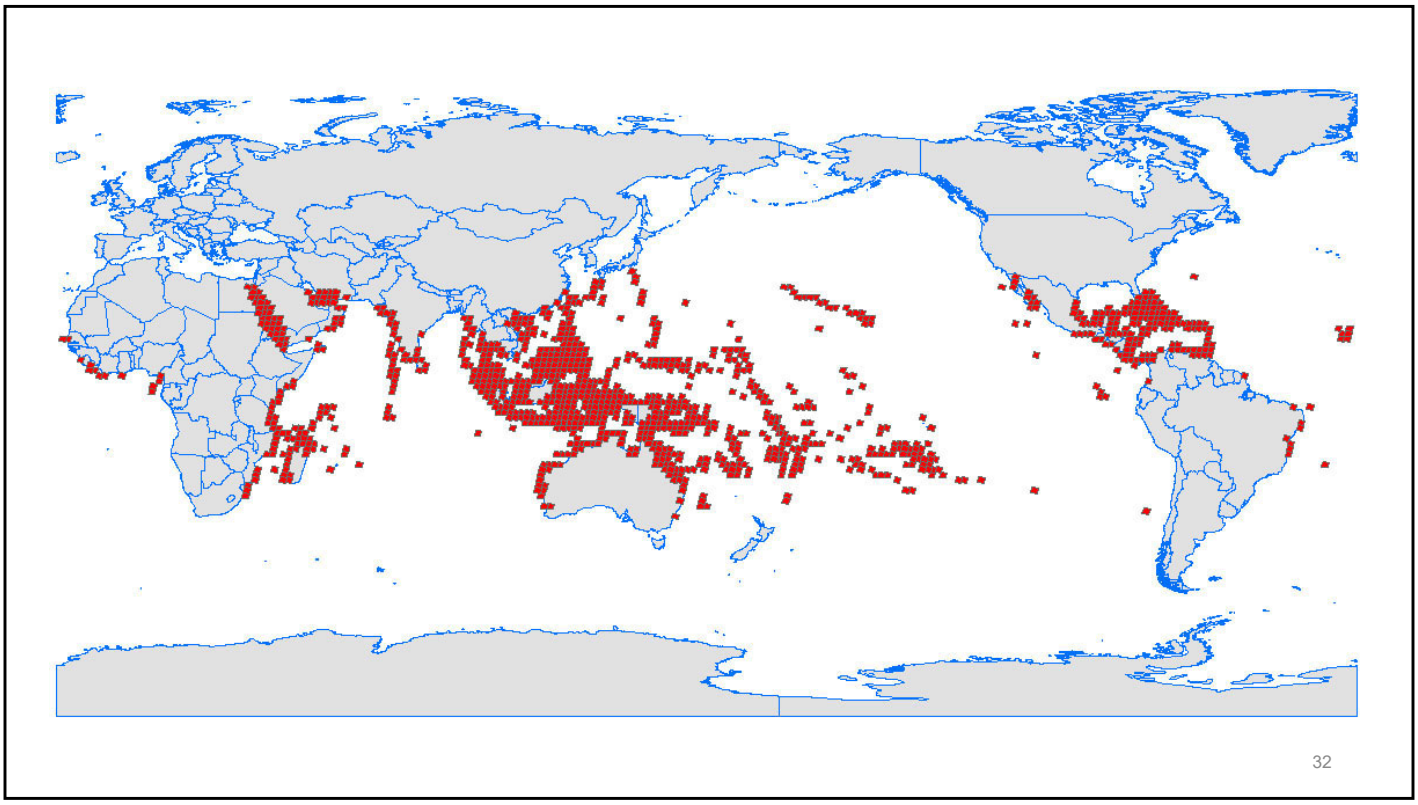
Phylum Mollusca



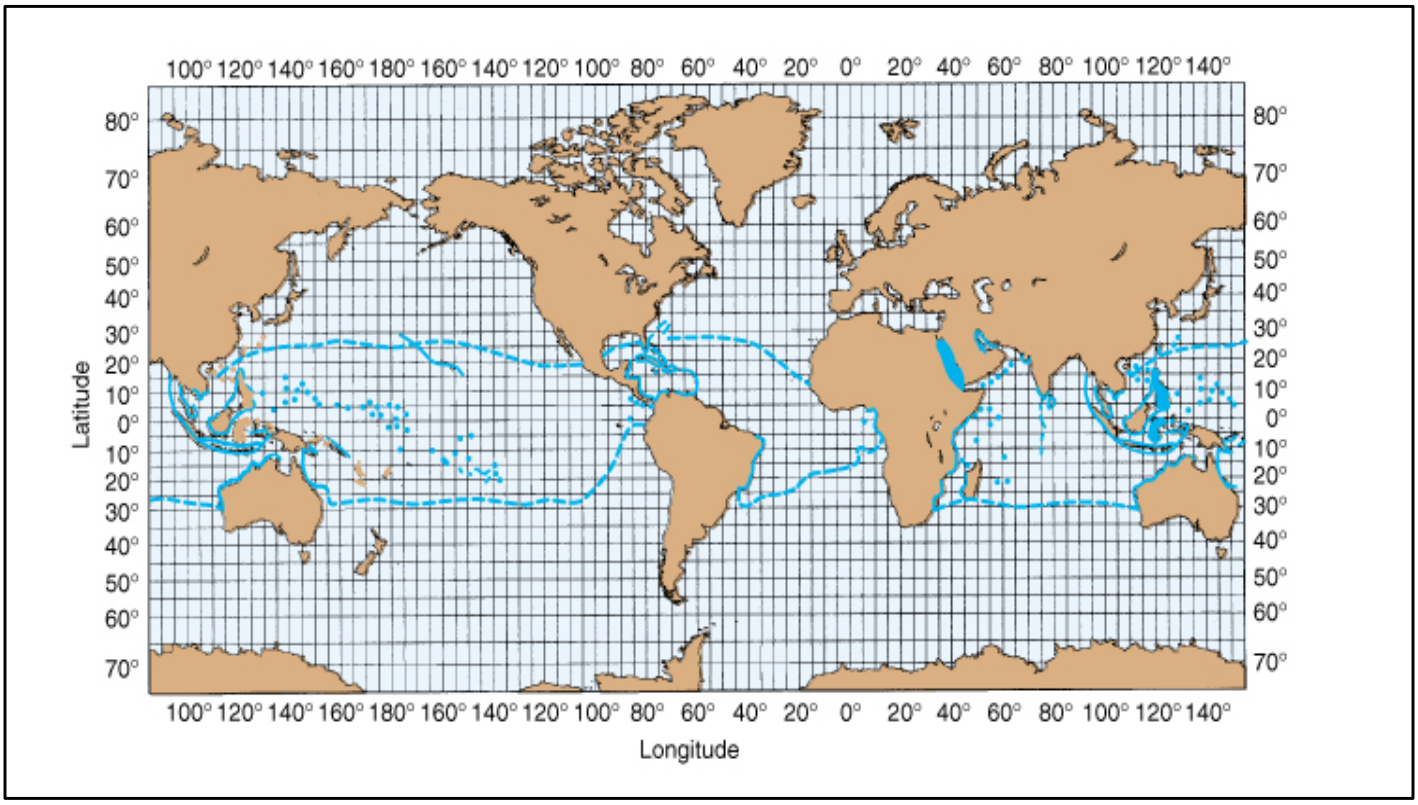
Phylum Mollusca

https://ncseagrant.ncsu.edu/hooklinescience/how-have-oyster-reefs-changed-over-the-last-six-decades/

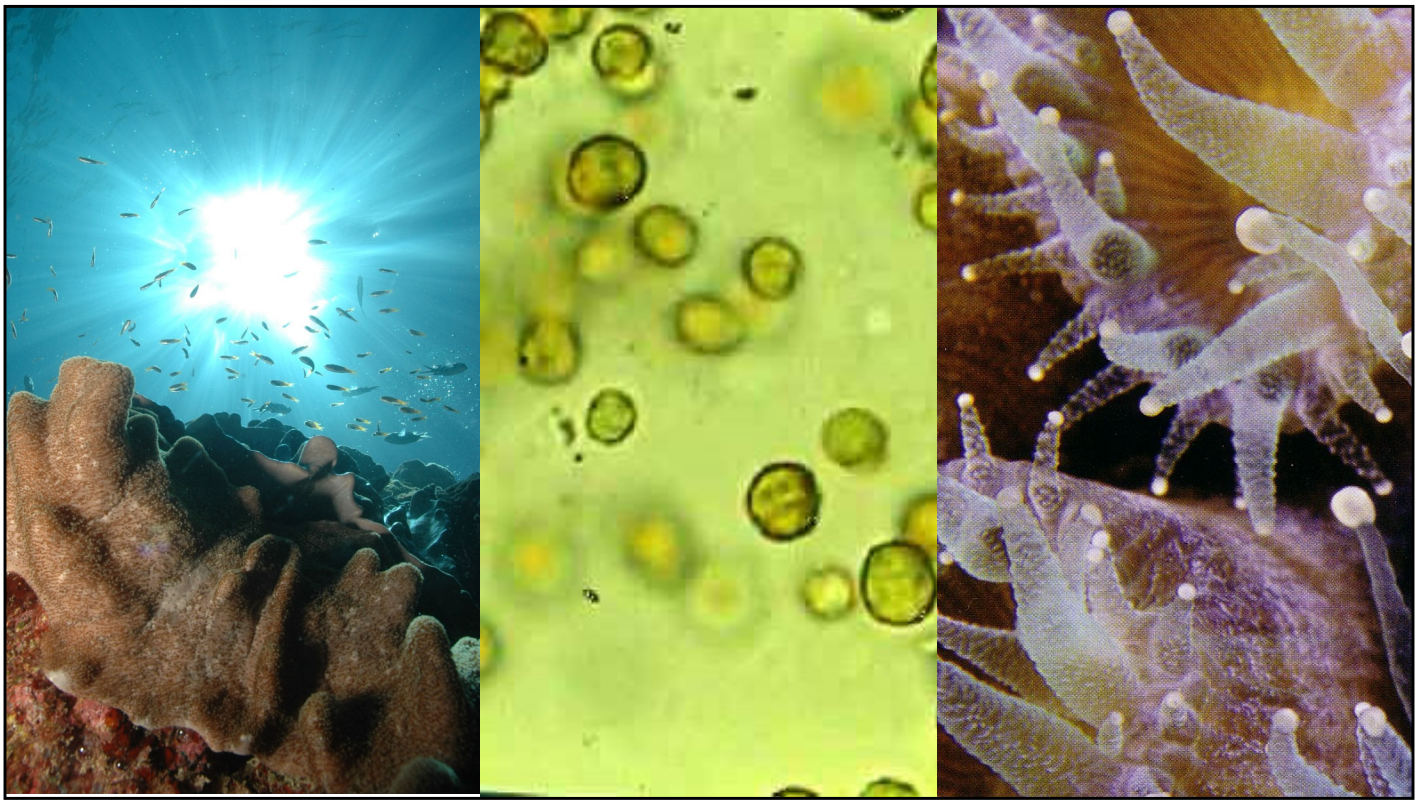
Calcareous algae (*Halimeda* sp.)



Coral reef

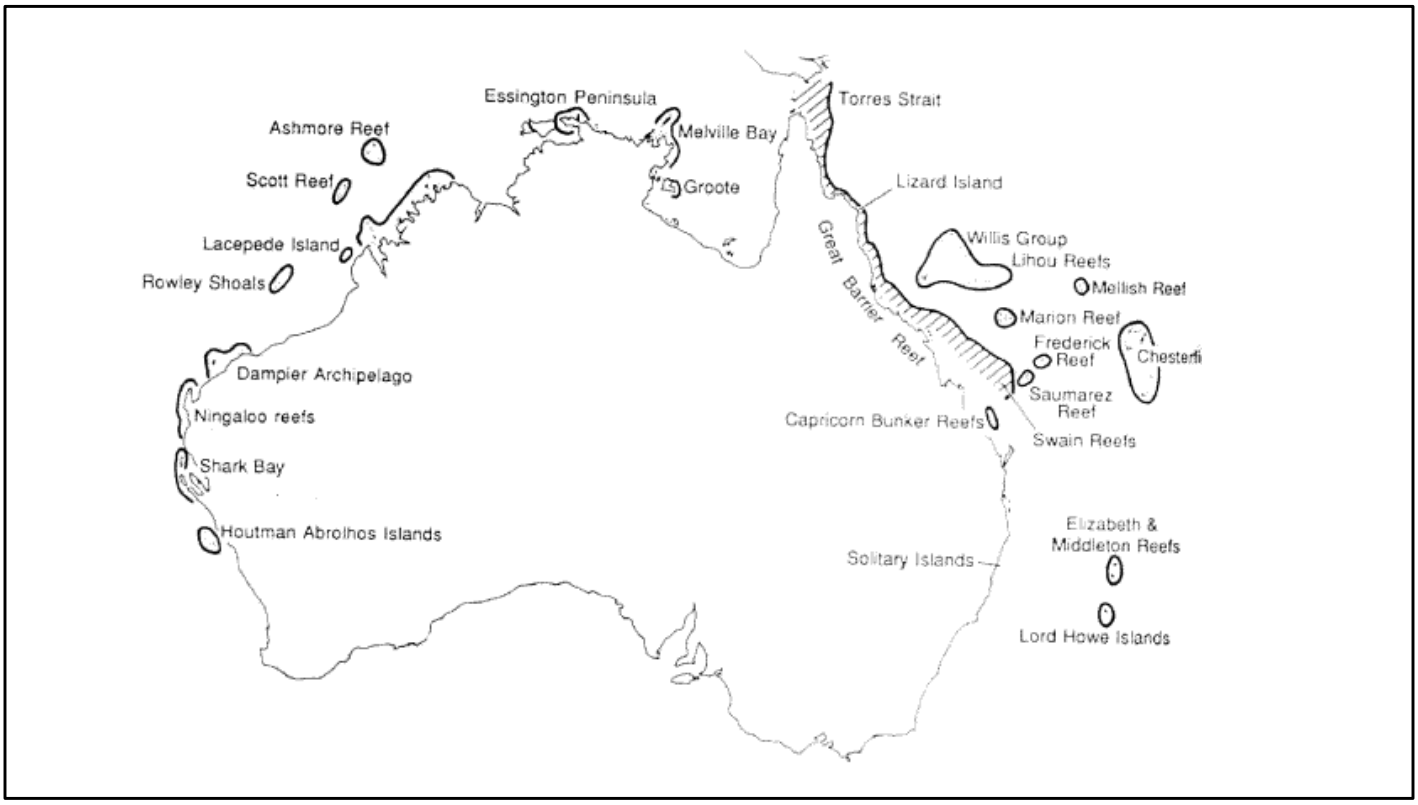


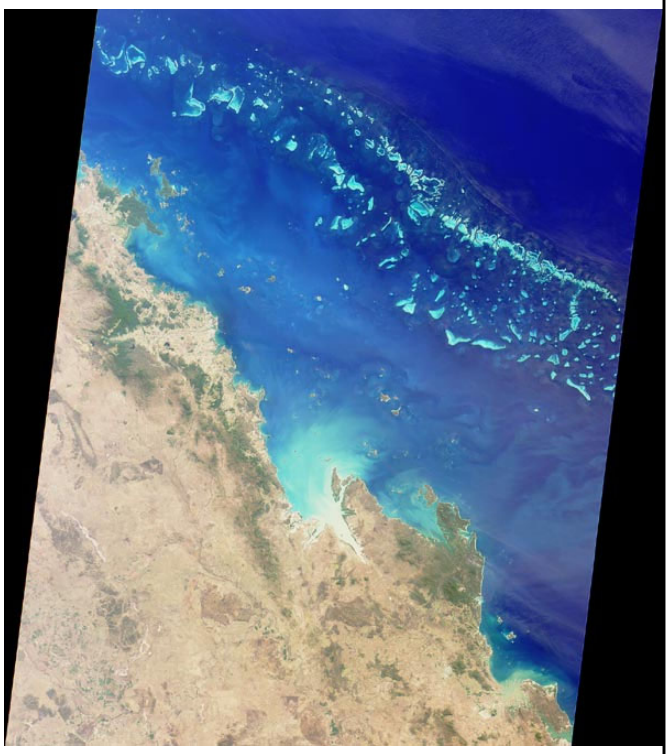
Optimal temp. 85 F

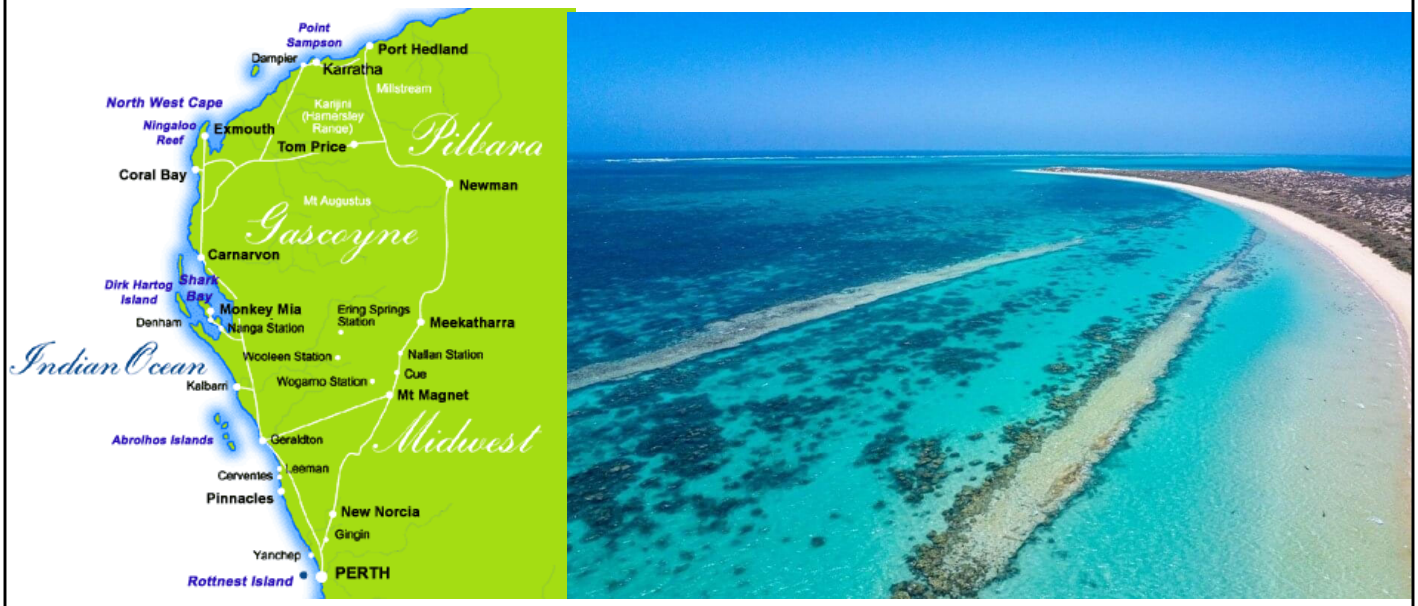


High light, clear and shallow warm water levels promote photosynthesis.

Hard reef building corals limited to upper 30 meters due to light attenuation with depth.


Essington Peninsula
Torres Strait
Ashmore Reef
Melville Bay
Scott Reef
Groote
Lizard Island
Lacepede Island
Willis Group
Great Barrier Reef
Lihou Reefs
Rowley Shoals
Mellish Reef
Marion Reef
Frederick Reef
Chesterfi
Dampier Archipelago
Saumarez Reef
Ningaloo reefs
Capricorn Bunker Reefs
Swain Reefs
Shark Bay
Houtman Abrolhos Islands
Elizabeth & Middleton Reefs
Solitary Islands
Lord Howe Islands

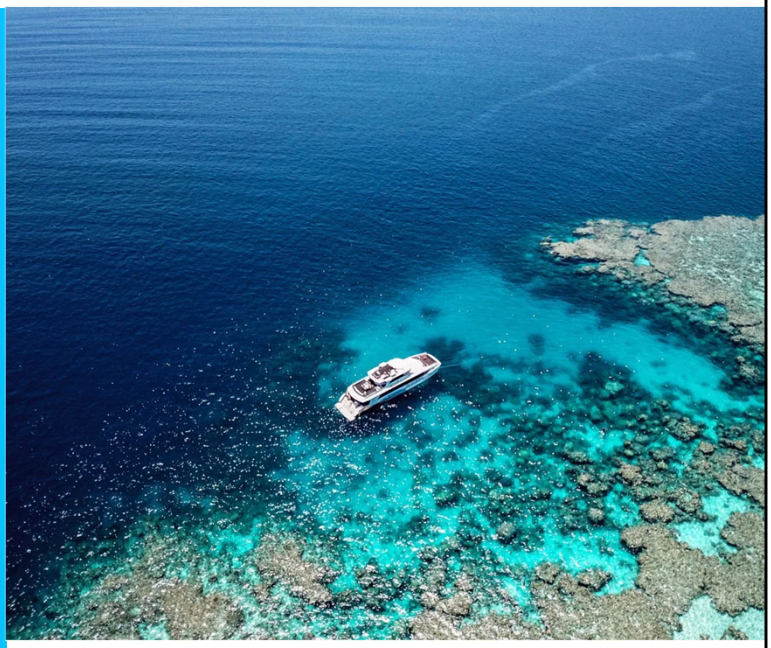


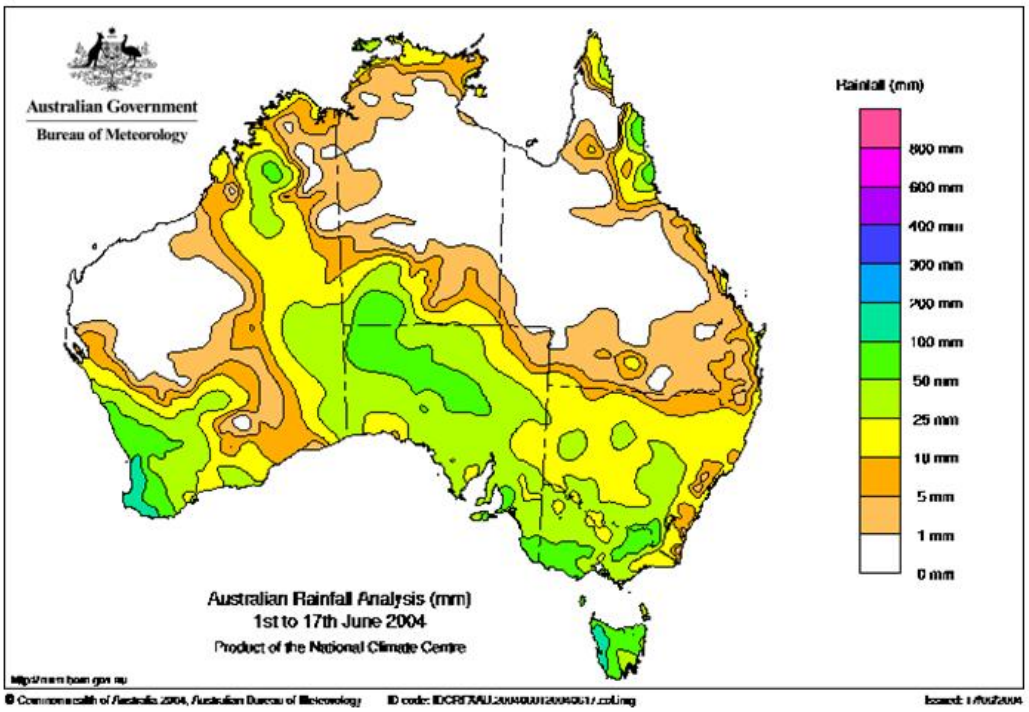


High salinities: corals have low tolerance for brackish water

Why are fringing reefs better developed on the west coast of Australia (Ningaloo Reef and Coral Bay) than along the east coast?


Agincourt Reefs
Port Douglas
Cairns
Townsville
Airlie Beach





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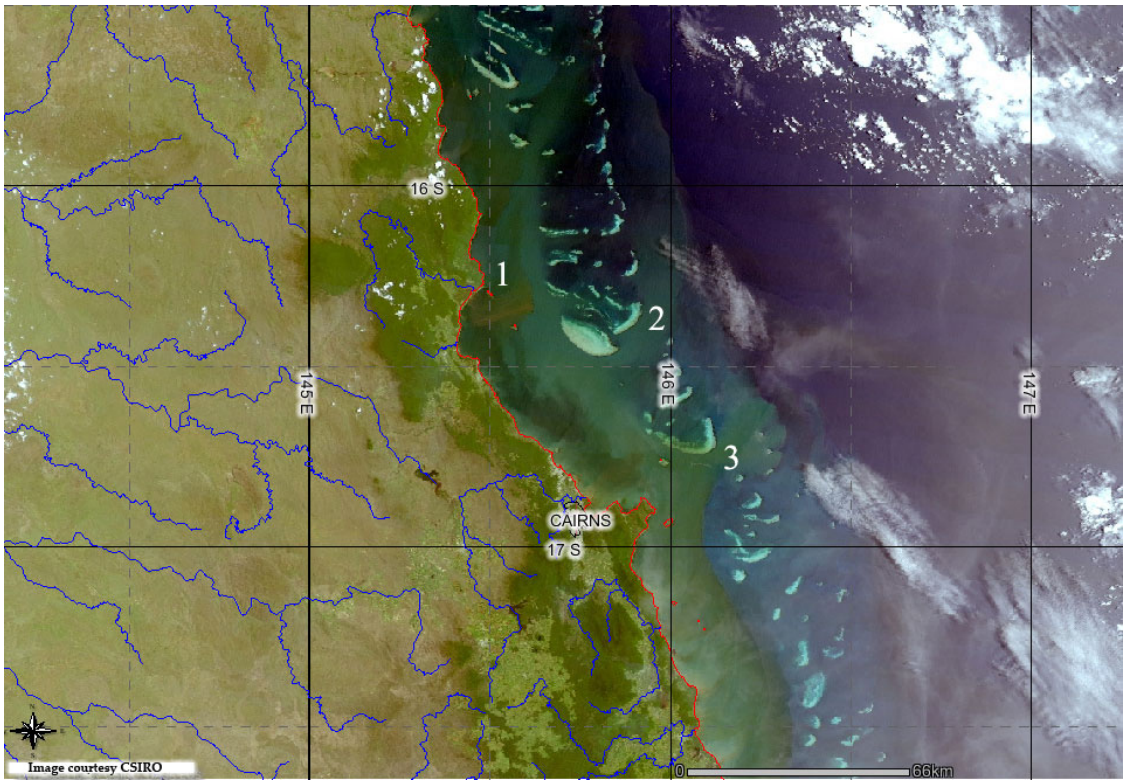
Cairns
Tully
Barron

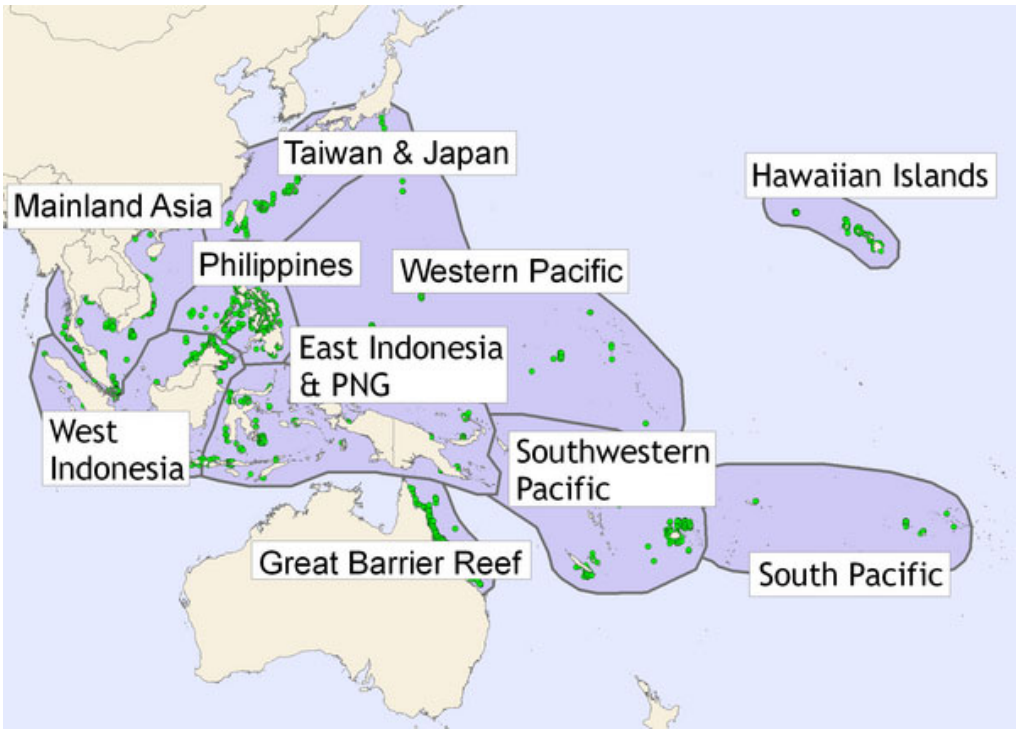


40

Low suspended sediment conditions better. Sedimentation can smother corals; reduce light penetration in water; require some wave action to lessen sedimentation

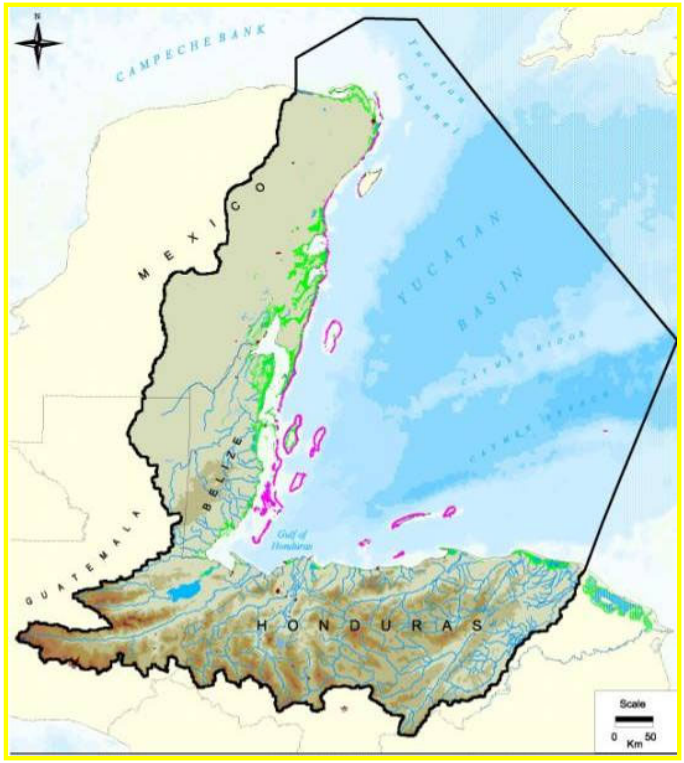
Corals require immobile substrates for the coral organism to attach and begin growing


Image © 2024 Airbus
Google



43

Locations where these conditions ideally met include the Indo-Pacific Coral Triangle



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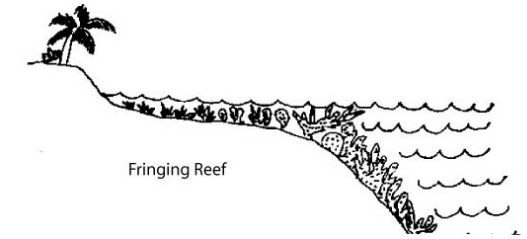
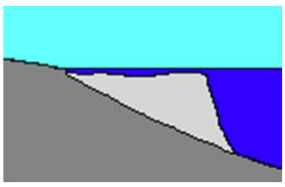
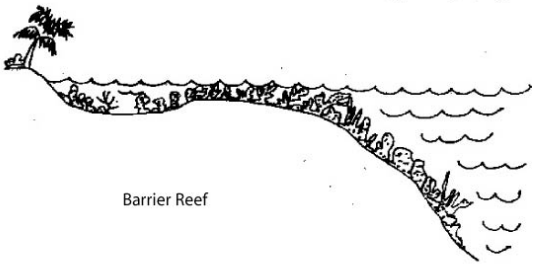
Mesoamerican Barrier Reef, the second largest barrier reef in the world

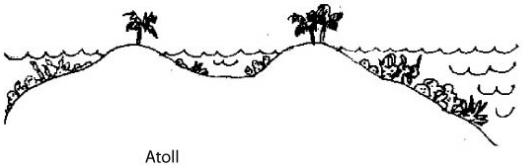
Coral reef and related landforms

- Fringing reefs
- Barrier reefs
- Patch reefs
- Atolls
- Carbonate platforms
- Coral cays and beaches
- Carbonate cays and beaches


Fringing Reef



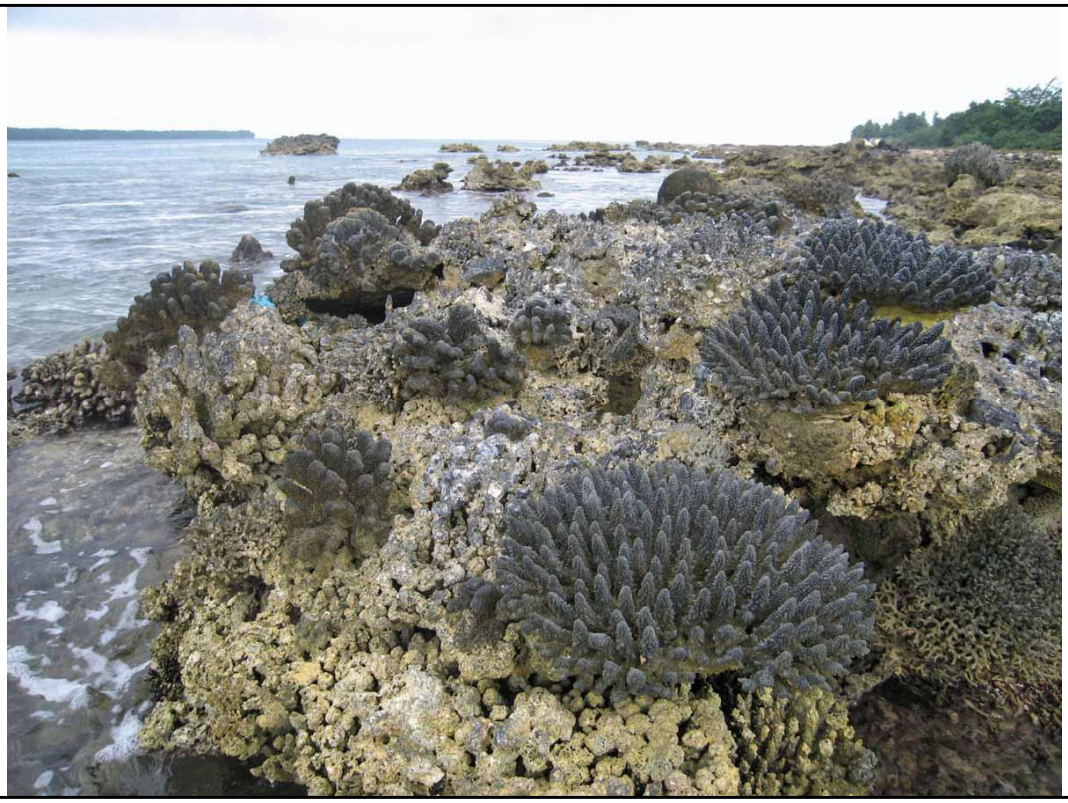

Barrier Reef


Atoll

The only place where two World Heritage Areas meet. Cape Tribulation and GBR

48

Fringing reef off the coast of Israel



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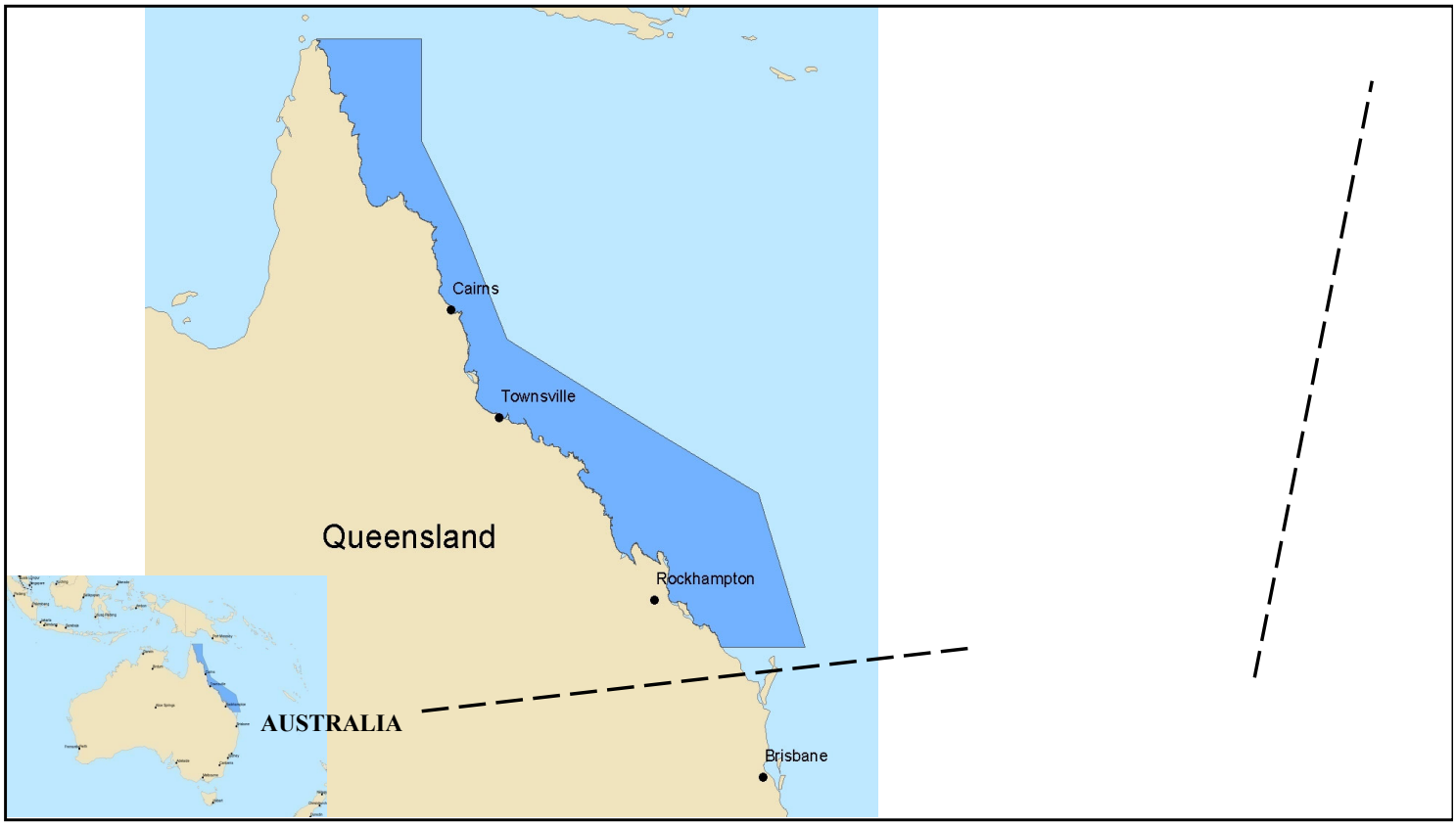
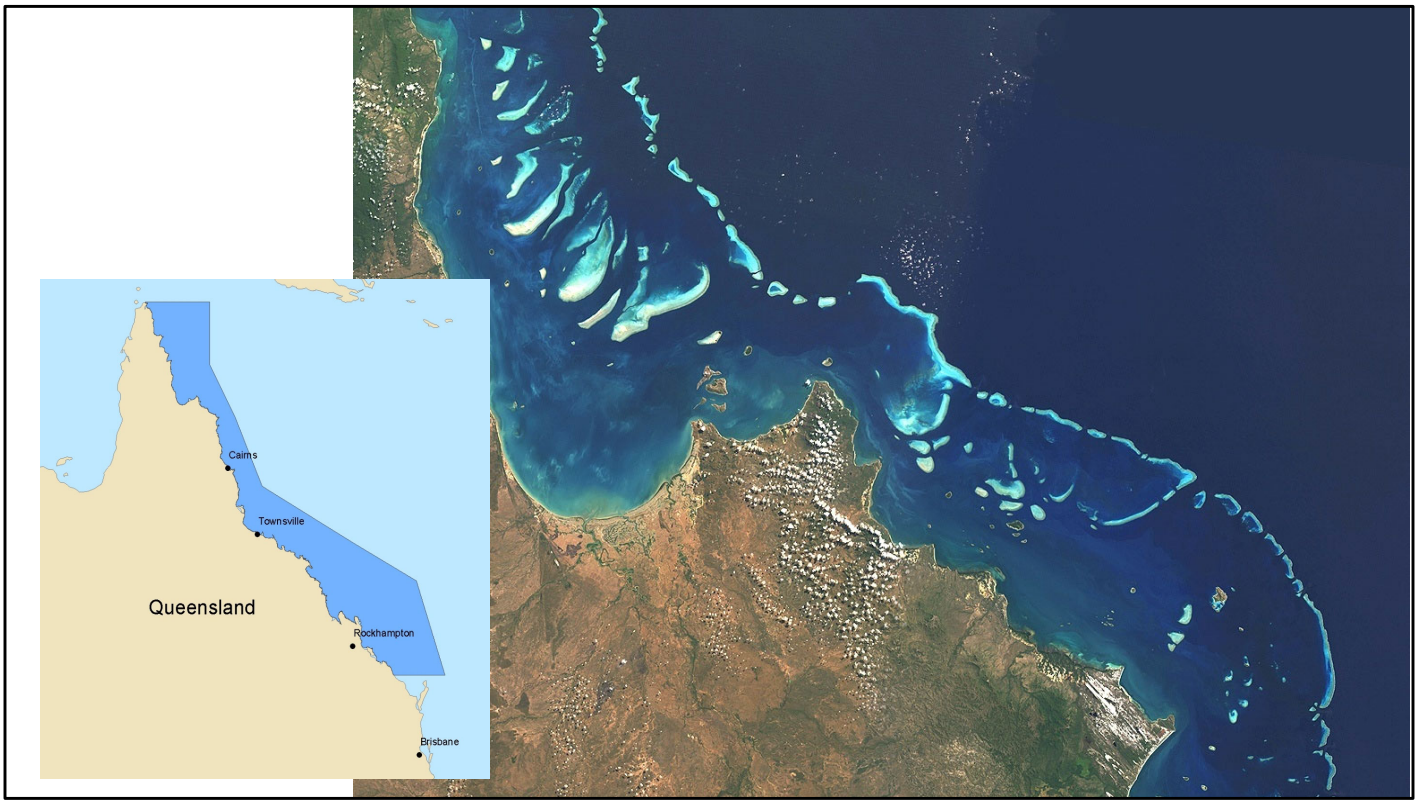
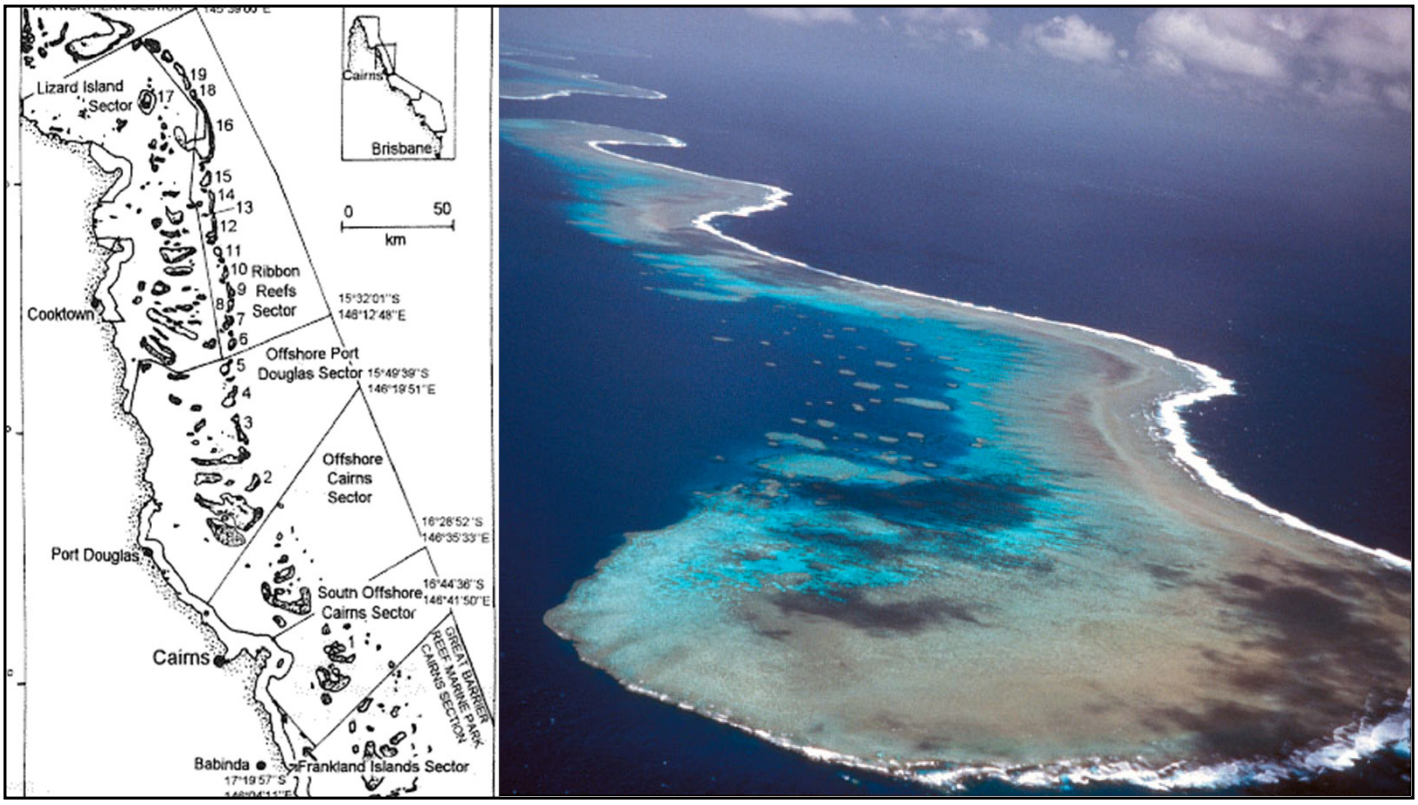
http://environment.newscientist.com/article/dn11603



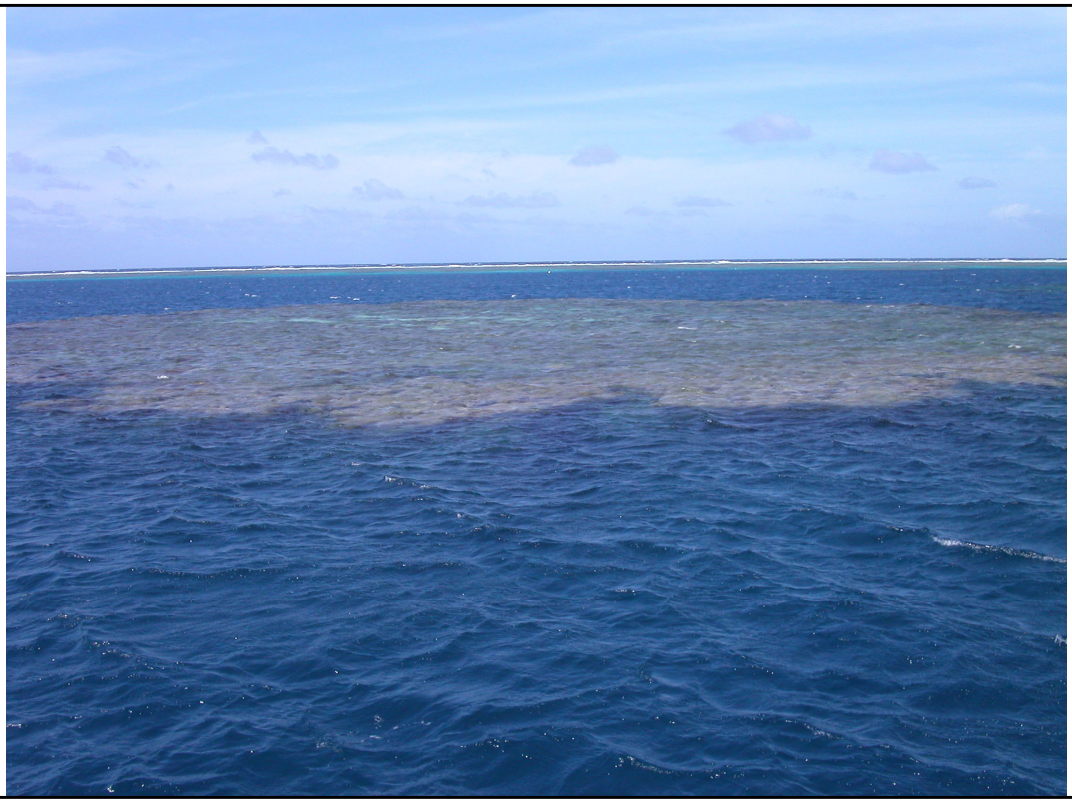
The Great Barrier Reef lies along the northeast coast of Australia adjoining the coast of the State of Queensland.

The entire area was declared a federal marine park in 1975, extending from low water mark on the mainland coast out to a maximum of 250 kilometres offshore.

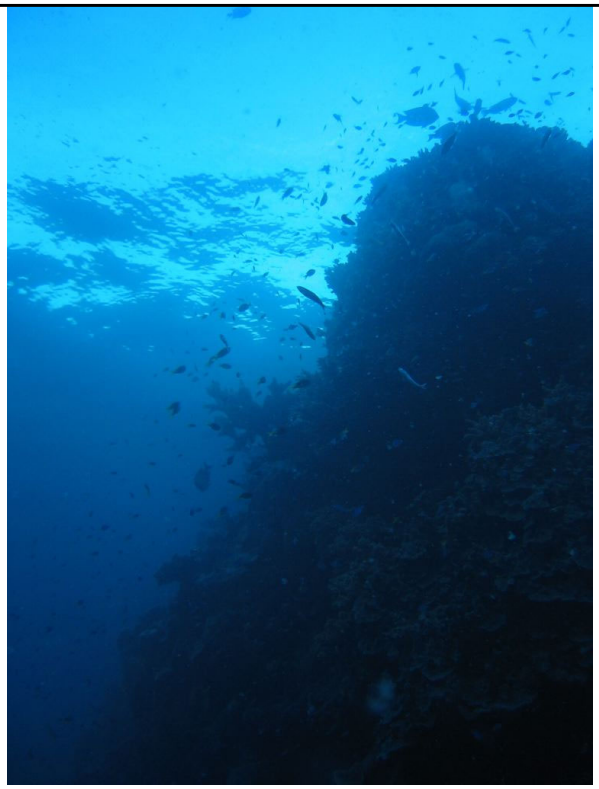

Cairns
Townsville
Queensland
Rockhampton
Brisbane



This is a ribbon reef on the GBR



Patch reef



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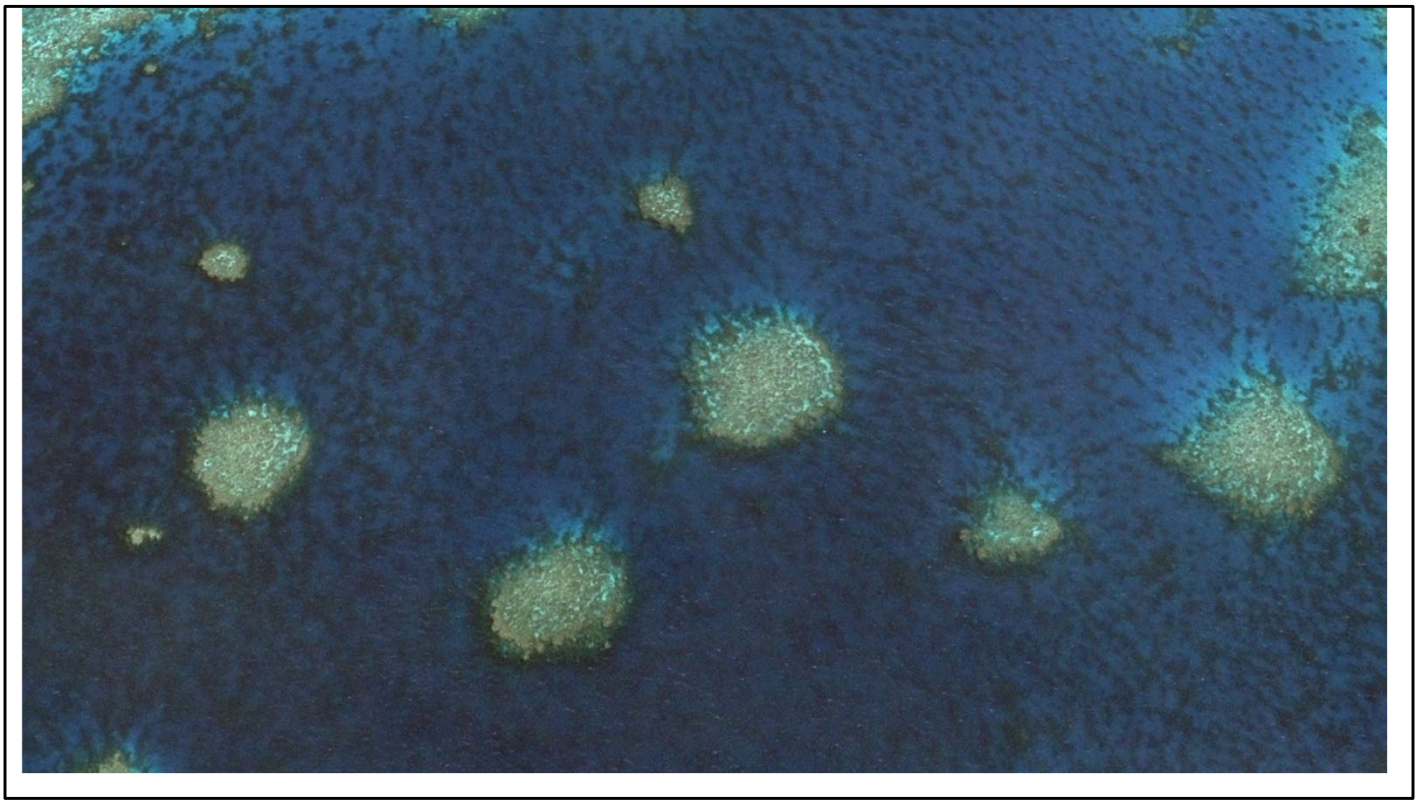
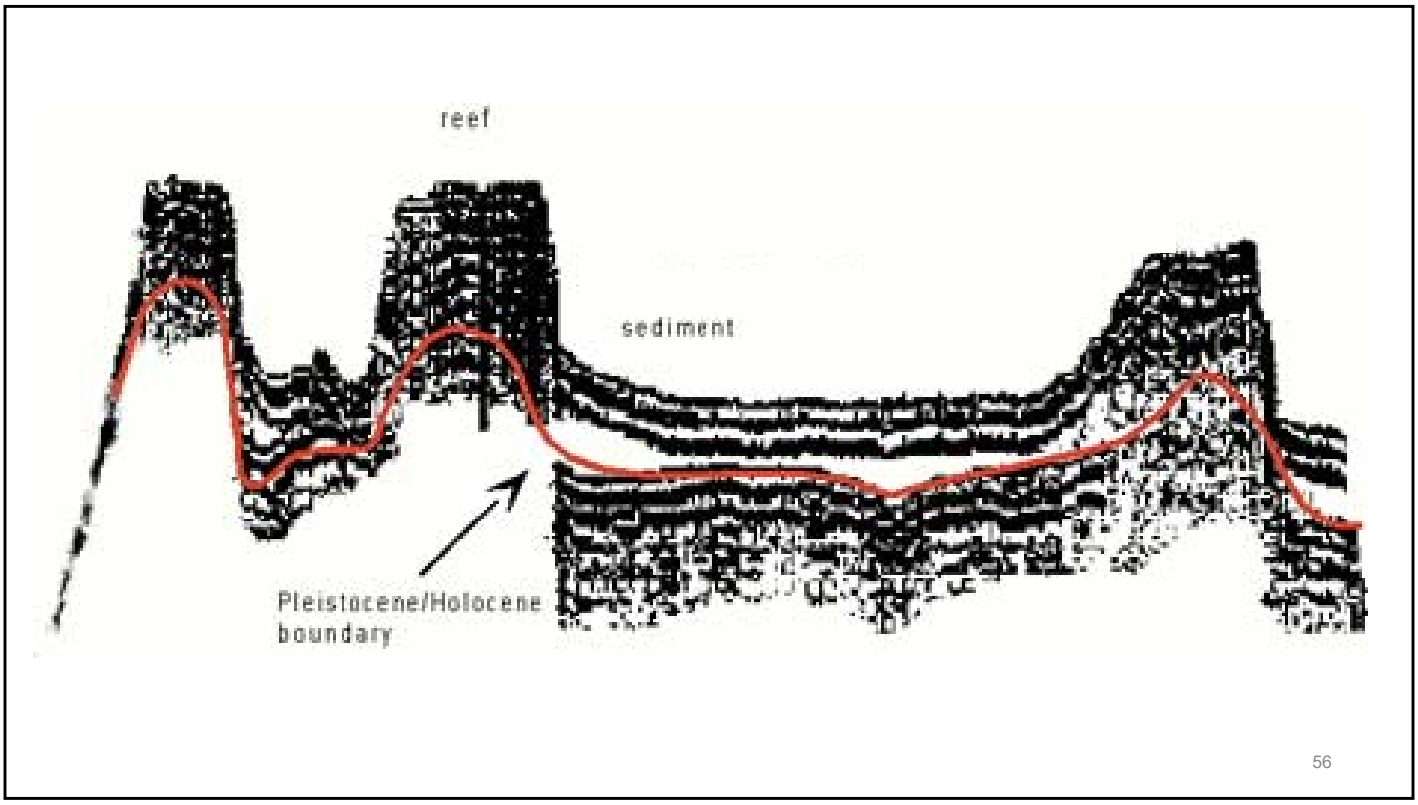
Patch reef

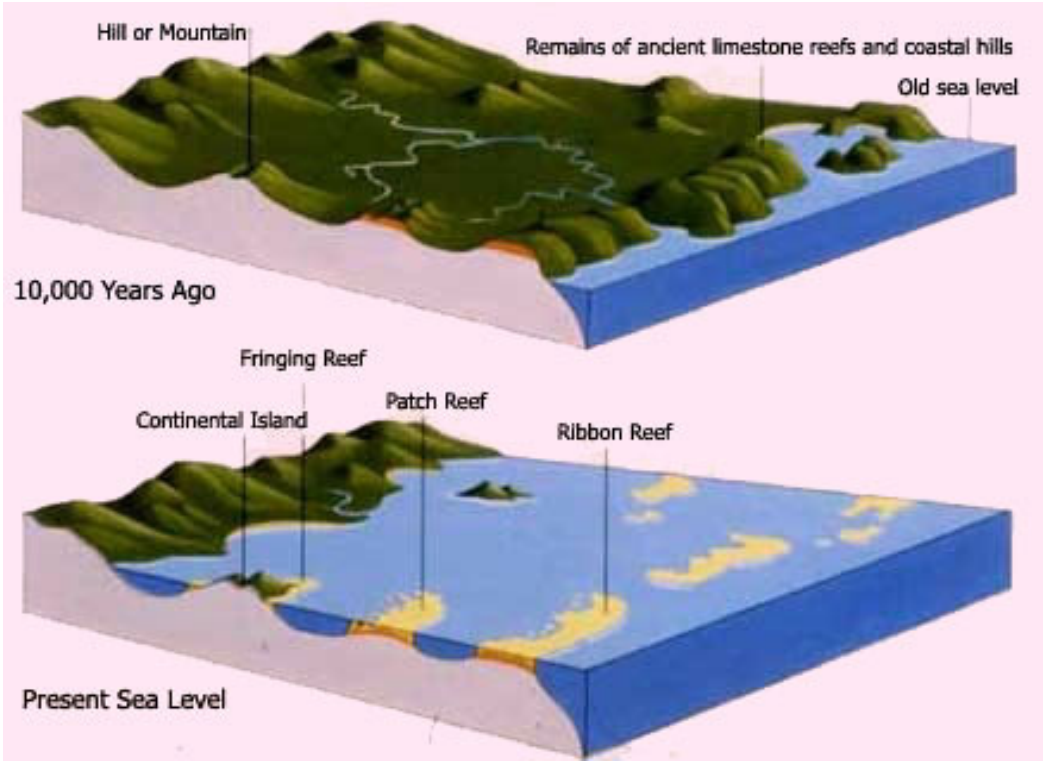
Platform reefs may become coral cay if sand and vegetation stabilize substrate.



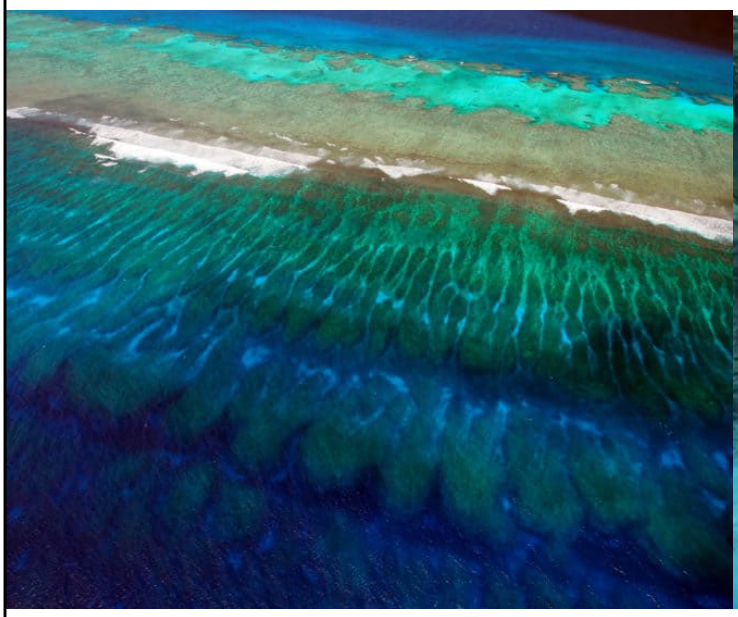
Patch reef (bommies) Agincourt Reef, Great Barrier Reef



Patch reef grow on antecedent topographic highs



Antecedent topography (topography in the past, in this case, when sea levels were lower) shapes the distribution of reef types and shapes today

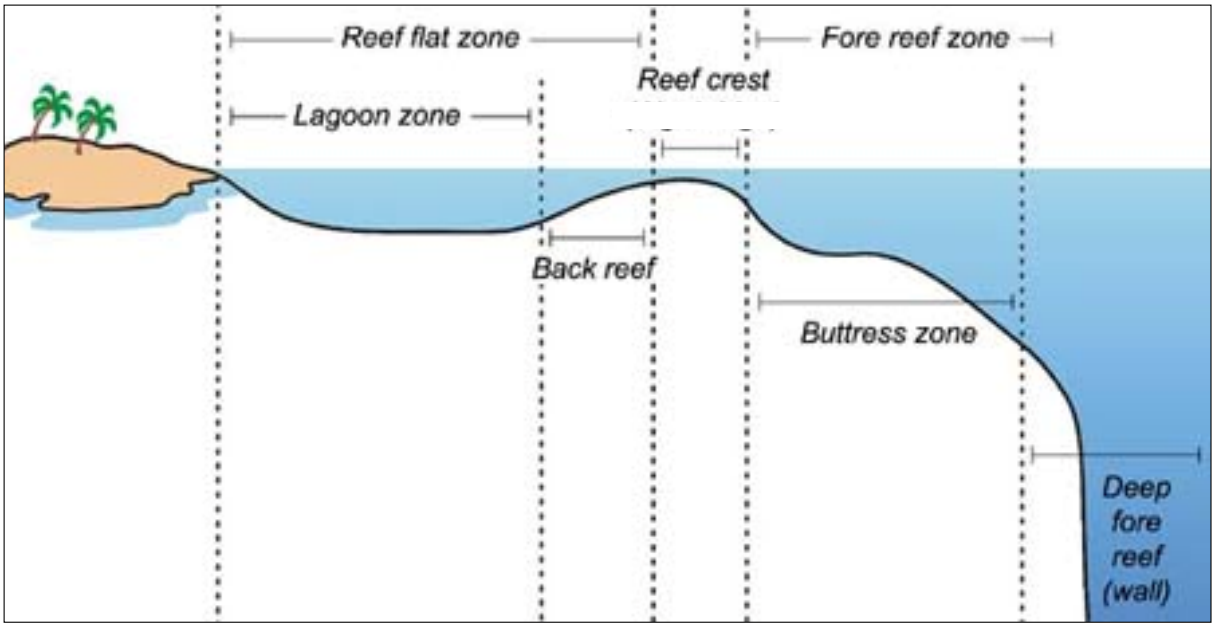



58

Carved by currents and erosion in front of reef

Buttress and canyon structures, also called spur (rock) and groove (sand)

Spur and groove in reef off the coast of Tobago (right)
Prony Bay, New Caledonia (left)


Reef flat zone
Fore reef zone
Reef crest
Lagoon zone
Back reef
Buttress zone
Deep fore reef (wall)

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Coral growth versus reef growth

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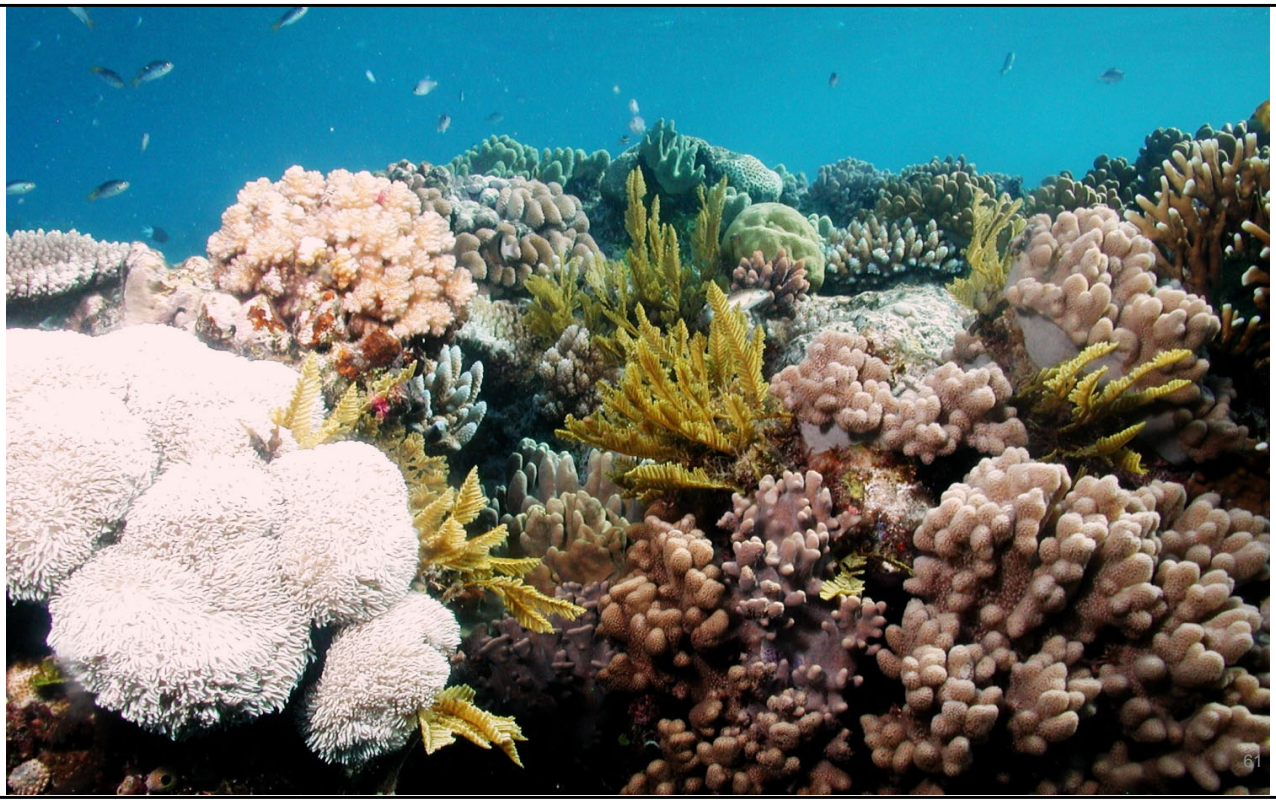
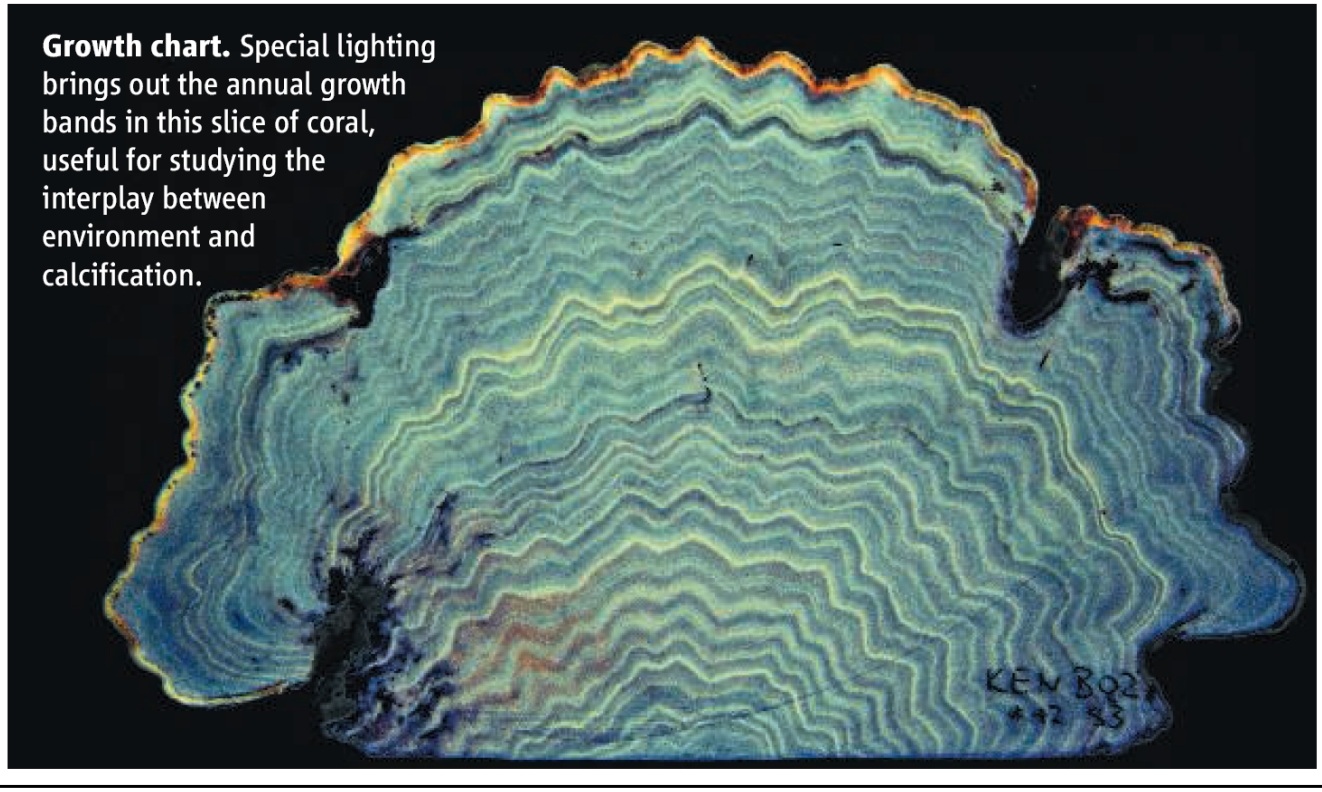


Growth of individual coral (a few mm to 10 -15 cm per year) should not be equated with growth of reef. To construct a reef, more has to occur than just coral growth.



Growth chart. Special lighting brings out the annual growth bands in this slice of coral, useful for studying the interplay between environment and calcification.

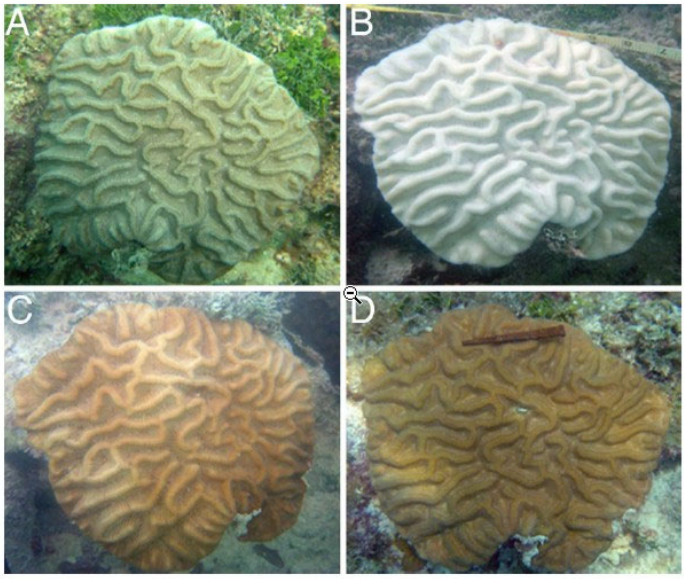
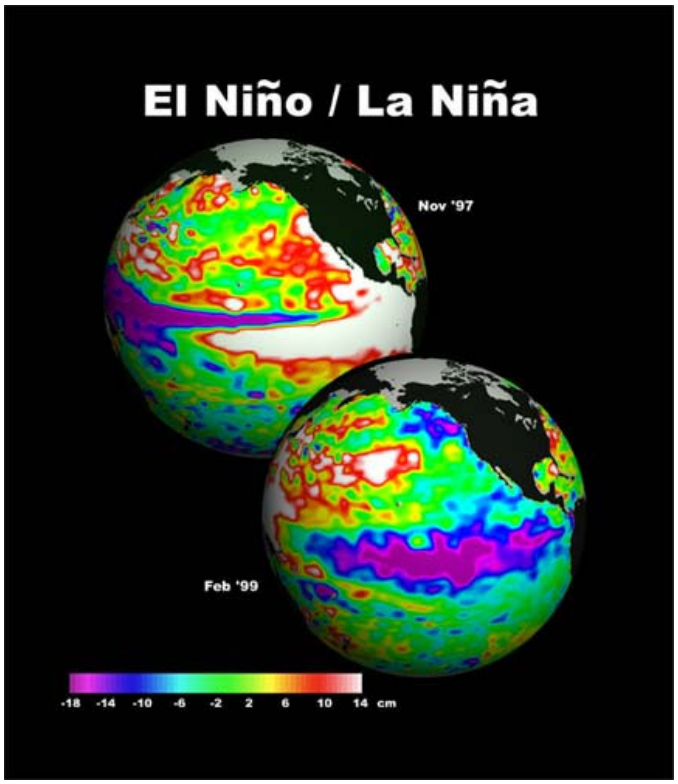


Fig. 4. Time-series of bleached coral (*Colpophyllia natans*) at Coral Gardens, Florida Reef Tract. (*A*) Prebleaching (August 11, 2005). (*B*) Bleached (September 6, 2005). (*C*) Nearly recovered (November 9, 2005). (*D*) Recovered with normal pigmentation (March 2, 2006). Nail in *D* is 8.3 cm long.



El Nino brings coral bleaching to central-eastern Pacific and Caribbean.
La Nina brings bleaching events to Australia and the western Pacific

Reef growth involves biologic and geomorphologic processes

- Primary framework: living coral “skin” and the coral skeleton underneath it.

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- Secondary framework: coralline algaes, encrusting corals, bivalves, foraminifera, sponges, soft corals.
- This secondary framework binds the primary framework into “reef rock”

66

- Tertiary framework: bioerosion and weathering and erosion of reef materials (waves, storms) generates coral fragments, sand, and silt that veneer the reef and spaces between it

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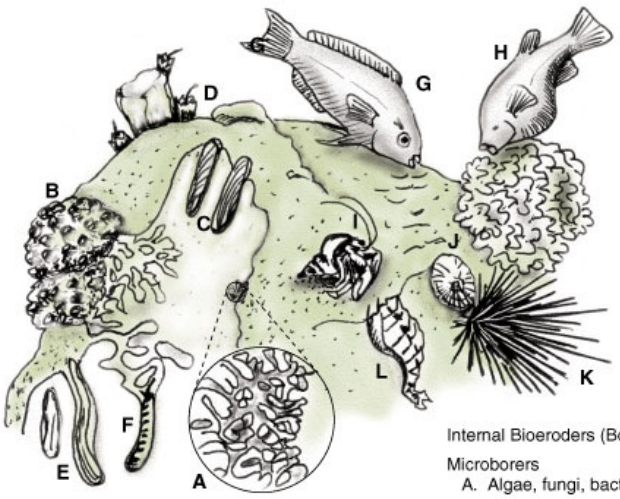
Effects of 2004 Tsunami, Thailand



Internal Bioeroders (Borers)

Microborers
A. Algae, fungi, bacteria

Macroborers
B. sponges *(Clionidae)*
C. Bivalves *(Lithophaga)*
D. Barnacles *(Lithotrya)*
E. Sipunculans *(Aspidosiphon)*
F. Polychaetes *(Eunicidea)*

External Bioeroders *(Grazers)*
G. Parrotfish *(Scaridae)*
H. Pufferfish *(Arothron)*
I. Hermit crab *(Aniculus)*
J. Limpet *(Acmaea)*
K. Urchin *(Diadema)*
L. Chiton) *(Acanthopleura)*

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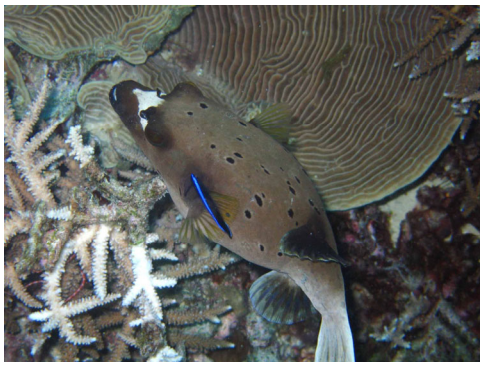
Bioeroders



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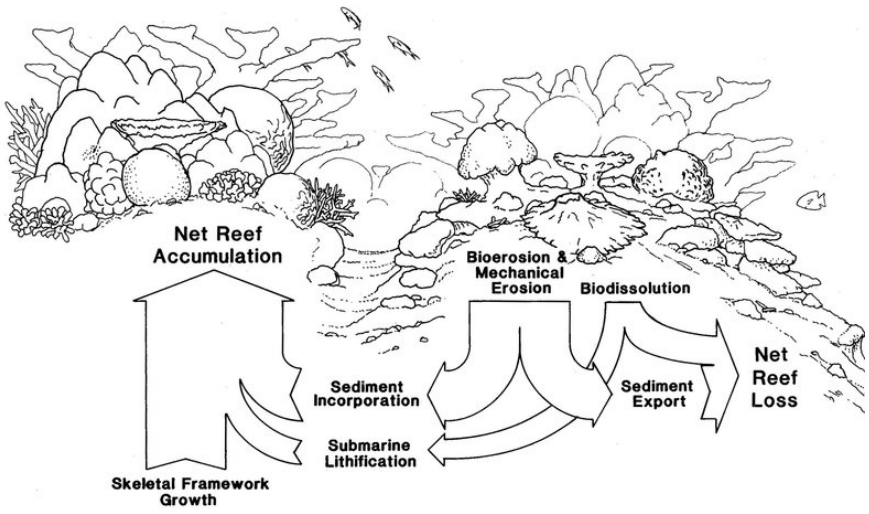
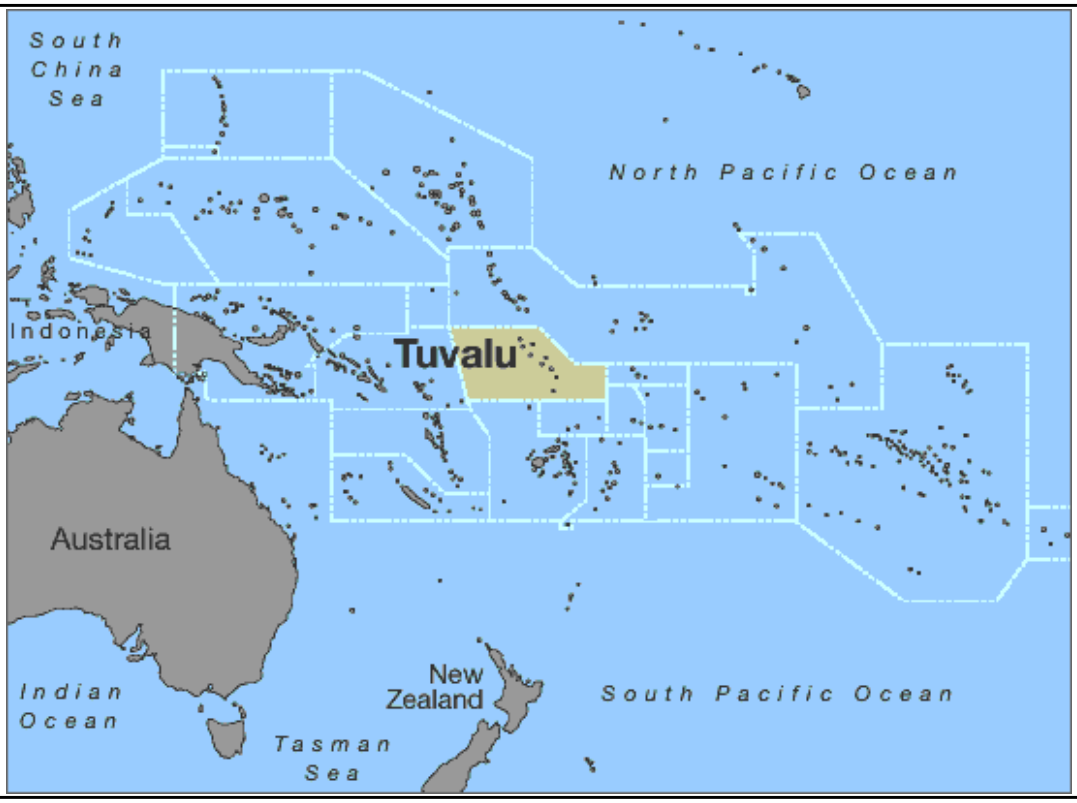
Fish poop?
BLUE
WORLD

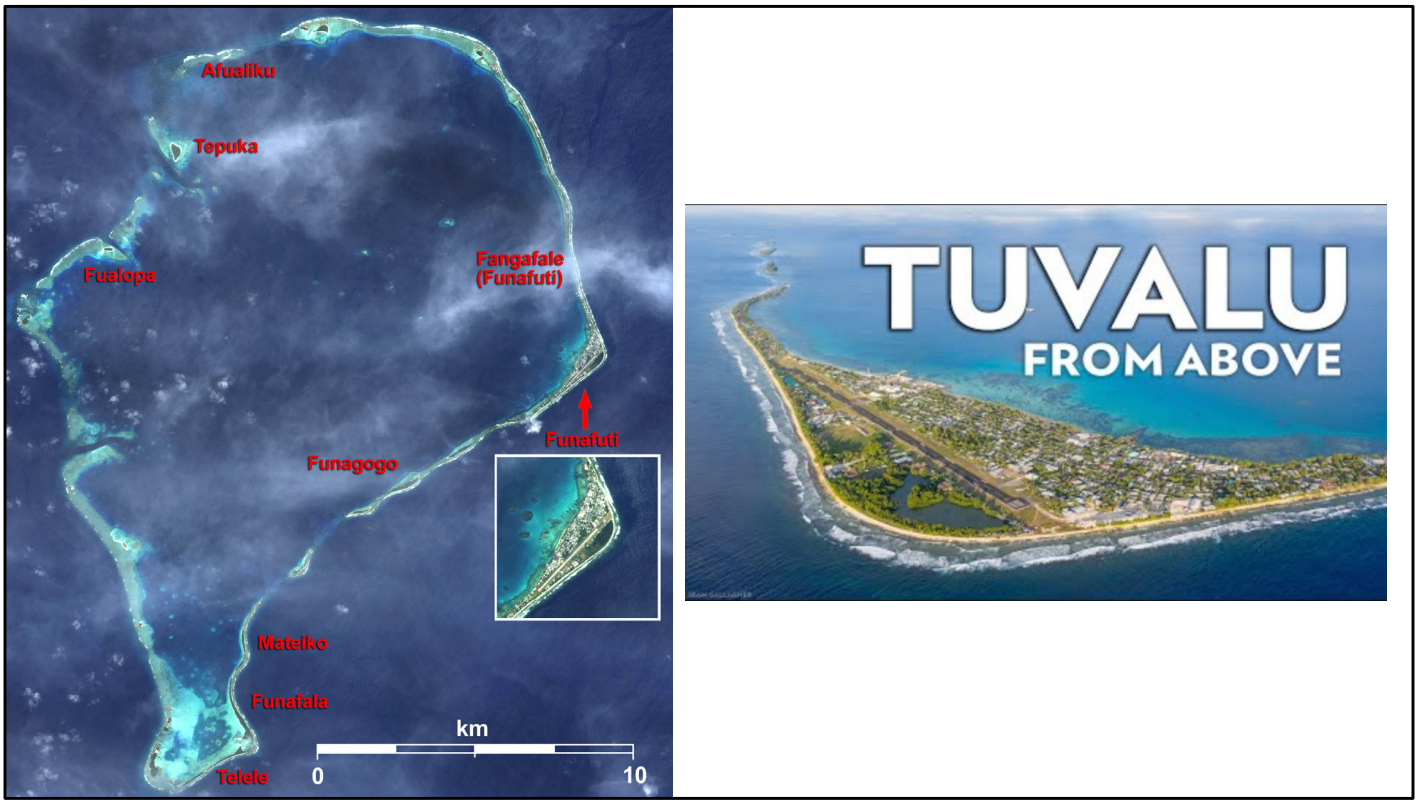
- Final stage is lithification
- Coral fragments and sediments become welded to primary and secondary framework to form final reef fabric.
- Reef growth is the balance between these aggradational and degradational processes





Pacific Island nations: Tuvalu. It is a lower income country, with limited natural resources and a small economy.

Tuvalu



Tuvalu is a coral atoll

https://youtu.be/Ey8Uhis0T20?si=yZUXYbrkPHXSETFr

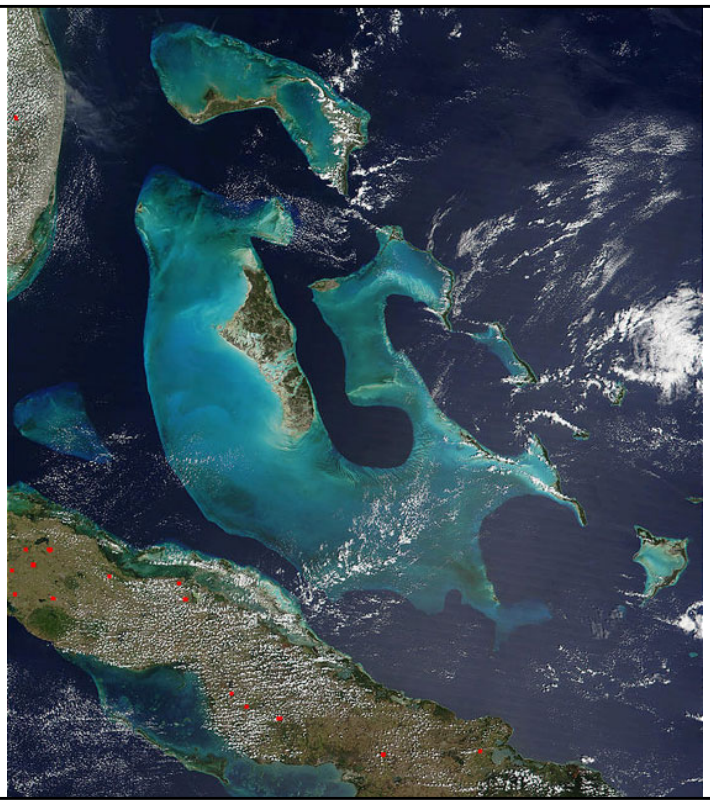
Simon Kofe, Tuvalu's foreign minister, has filmed a speech to climate summit COP26 knee-deep in the ocean.

https://www.benarnews.org/english/news/pacific/tuvalu-climate-change-spokesman-simon-kofe-resigns-07302023232405.html

On some atolls, elevation is maintained by coral debris that is pushed up on the islands by waves and storms. In some cases, this may slow inundation for sea level rise so long as coral reefs remain healthy. This runs counter to the discourse that all island nations are disappearing from sea level rise.

One one study that analyzed thirty Pacific and Indian Ocean atolls—comprising 709 islands in total—revealed that 89 per cent of islands were either stable or had grown in land area, while only 11 per cent had decreased in size. In Tuvalu, a small Pacific nation often singled out by the media as one of the first nations likely to disappear entirely due to sea level rise in the future, a recent study found that between 1971 and 2014, eight of Tuvalu's nine atolls and almost three-quarters of the 101 reef islands had grown in size. This increased Tuvalu's total land area by 3 per cent, even though in Tuvalu sea levels rose at twice the global average.

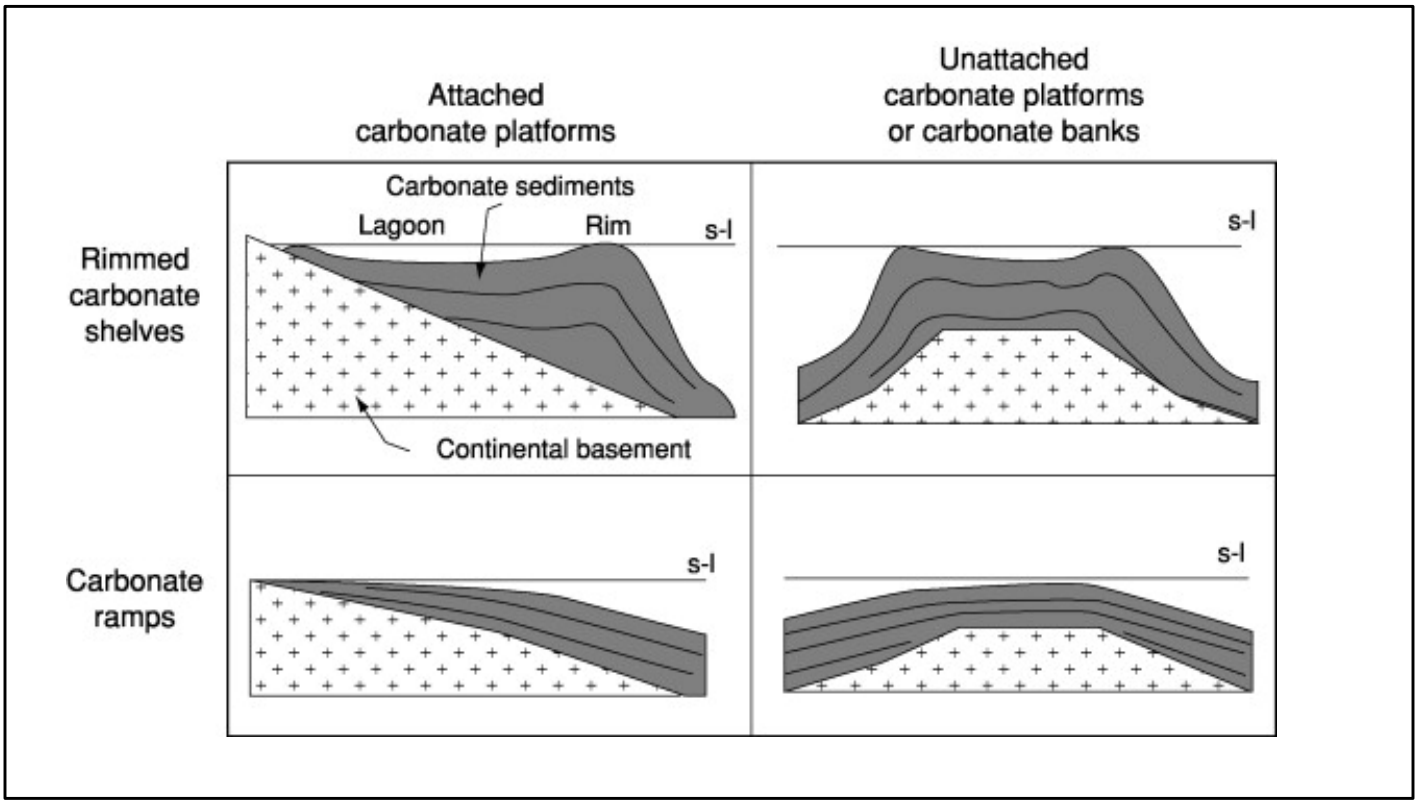
Duvat, V. K. (2019). A global assessment of atoll island planform changes over the past decades. *Wiley Interdisciplinary Reviews: Climate Change*, *10*(1), e557.



Bahama Banks, a carbonate platform

A carbonate platform is a large, shallow, submarine area that primarily accumulates carbonate sediments, typically composed of limestone or dolomite due to the activity of marine organisms like corals, algae, and mollusks. These platforms are usually found in warm, tropical marine settings, where clear, warm, and shallow waters allow for high rates of biological carbonate production. Some platforms are rimmed by coral reef or carbonate sand shoals that act as barriers, protecting the inner platform and creating lagoon-like conditions.

In supersaturated waters, calcium carbonate can precipitate directly from the water, forming ooids and micrite. Warm, shallow waters often favor such precipitation.

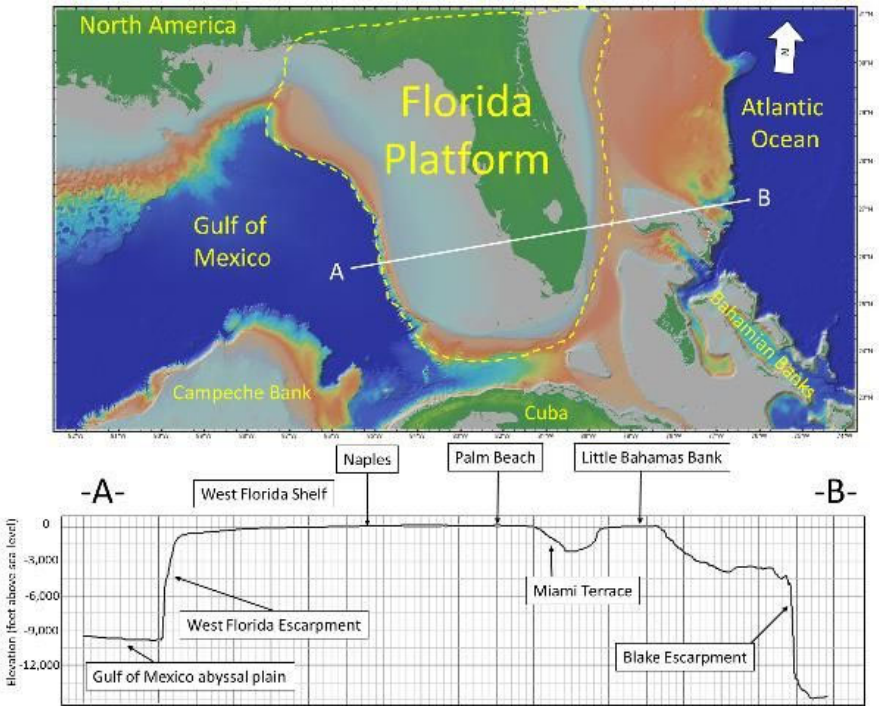

Attached
carbonate platforms
Unattached
carbonate platforms
or carbonate banks
Rimmed
carbonate
shelves
Carbonate
ramps
Carbonate sediments
Lagoon
Rim
s-l
Continental basement
s-l
s-l
s-l

Modern carbonate platforms

- A large, shallow, sedimentary structure primarily composed of carbonate sediments, such as limestone and dolostone, deposited in marine settings.
- Sediments derived from:
  - Biogenic processes: the marine organisms that make carbonates
  - Abiotic processes: calcium carbonate precipitates directly out of sea water,
- Some platforms are rimmed by coral reef that act as barriers, protecting the inner platform and creating lagoon-like conditions

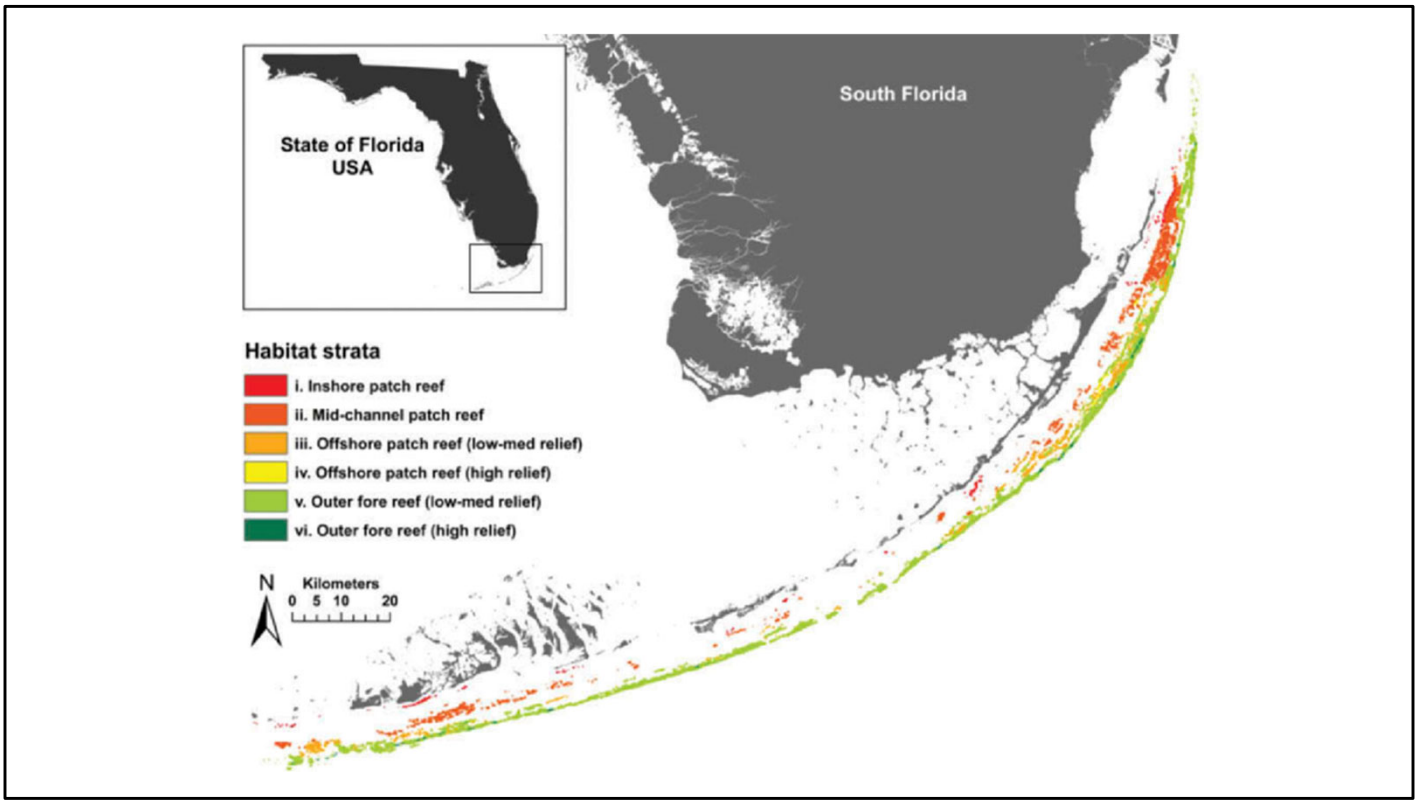
Carbonate platforms can also be large sedimentary structures of lithified carbonates. Sediments deposited long ago have been transformed into solid rock.

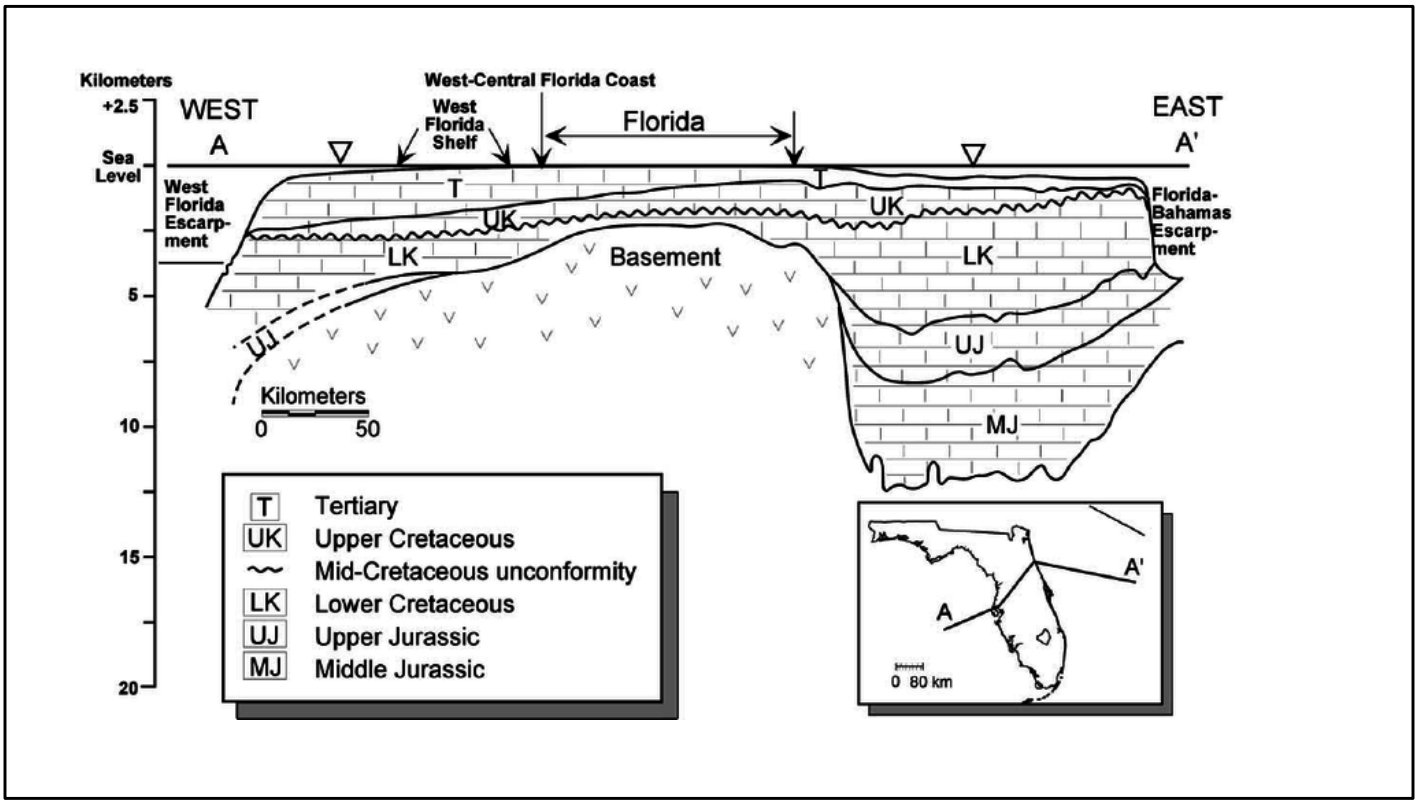
Florida Carbonate Platform



Its development is tied to the accumulation of carbonate sediments produced by marine organisms in warm, shallow seas, as well as tectonic stability and subsidence that allowed for sustained sedimentation. Some of this sedimentation can also be abiotic and derived through the precipitation of carbonate directly out of sea water.

Parts of the platform are very old, millions of years, and in places it is covered by a veneer of new carbonate sediments, particularly in the Bahamas. The Bahamas is basically one large carbonate platform that is still producing carbonate sediments. The Bahamas are a modern analogue of the environments in the past that have produced large thicknesses of carbonates.


State of Florida
USA
South Florida
Habitat strata
i. Inshore patch reef
ii. Mid-channel patch reef
iii. Offshore patch reef (low-med relief)
iv. Offshore patch reef (high relief)
v. Outer fore reef (low-med relief)
vi. Outer fore reef (high relief)
N
Kilometers
0 5 10 20



DOI:10.1016/S0025-3227(03)00161-0

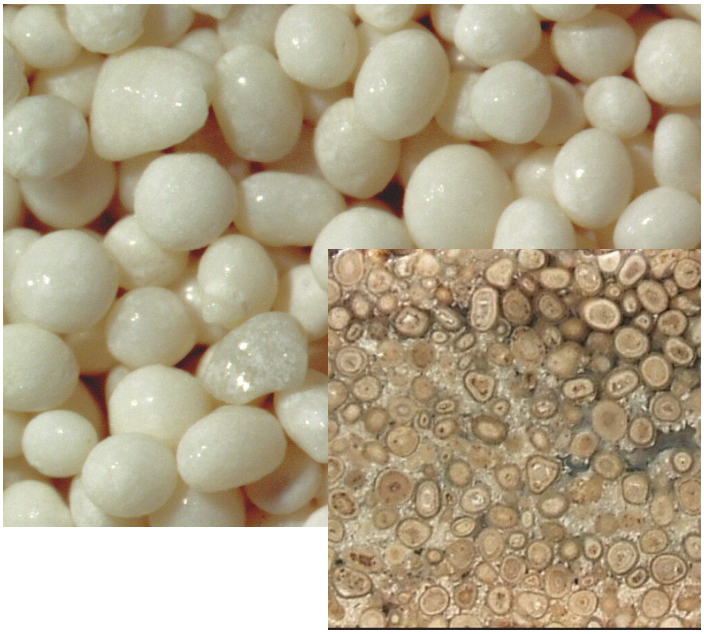
Florida Carbonate Platform and the Bahamas Platform

Carbonate platforms vs coral reef

- As with coral reef, many organisms contribute to sediment production on a platform (calcareous algae, mollusks, and foraminifera).
- Coral is not a direct and dominant contributor on a platform
- Ooids are unique to carbonate platforms. They are tiny spherical grains of calcium carbonate chemically precipitated out of sea water – an abiotic process.
- Nearby coral reef can contribute sediments indirectly to a platform in the form of eroded and weathered coral and live rock

Ooids

- Small, spherical carbonate grains that form from abiotic processes on carbonate platforms
- Their carbonate minerals are precipitated directly out of ocean water
- Wave motion creates their round form
- Once buried they can become lithified into an oolitic limestone



Oolitic sand grains from Joulter Cays, Bahamas

https://commons.wikimedia.org/wiki/File:Ooids,_Joulter_Cays,_Bahamas.jpg

ISS004E8777

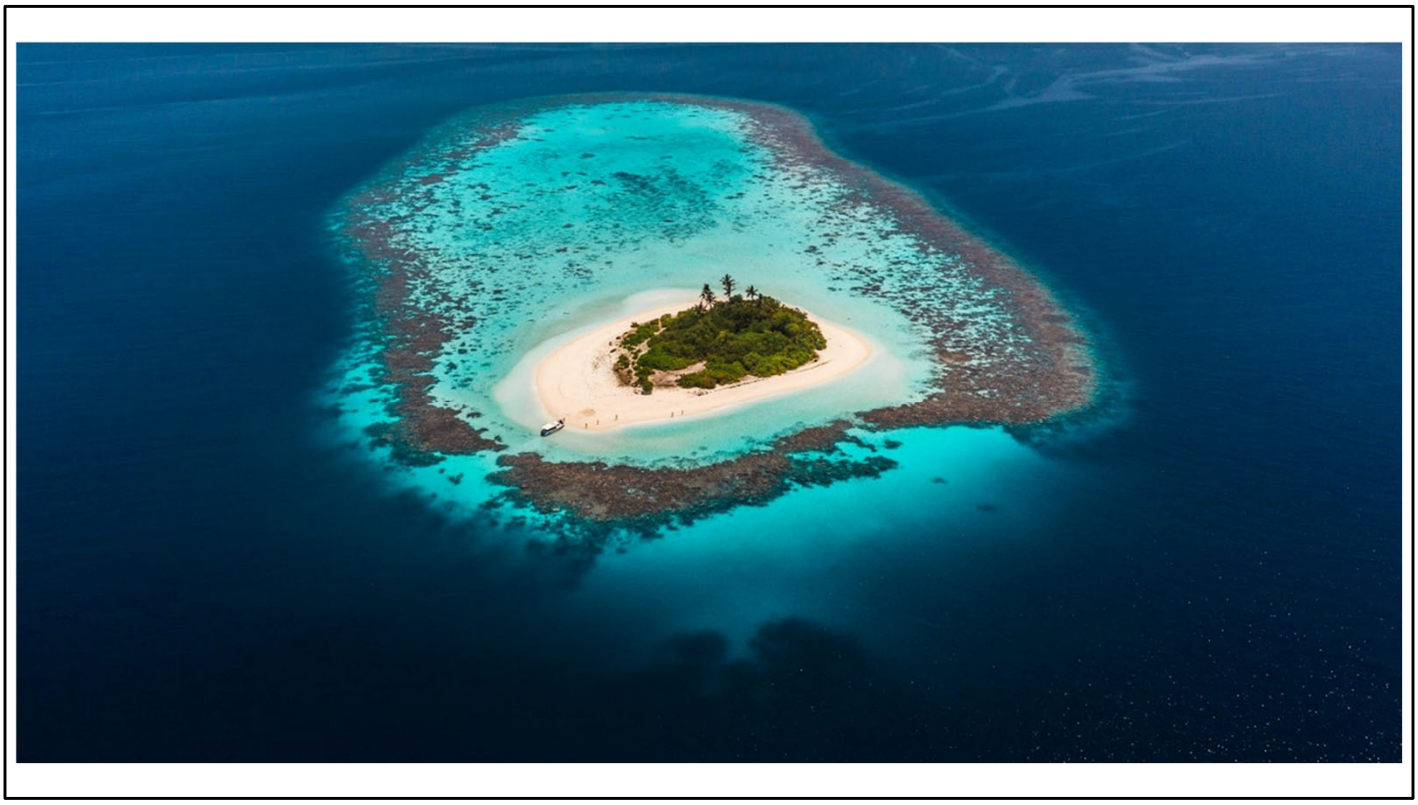
A tropical carbonate factory on the Great Bahama Bank at the south end of Eleuthera Island, blanketed by ooid shoals, sandwaves, and ooid-filled gullies (2002)
Image credit: NASA-ISS https://www.nasa.gov/topics/earth/earthday/gall_island.html.

Reef is best developed online on the northern and eastern sides of the Bahama Islands.

Carbonate platforms vs coral reef

- Are often associated with each other but have different environmental controls
- Coral reefs are sensitive to narrow range of temperature, salinity, light, and water clarity. They thrive in clear nutrient-poor tropical waters.
- Carbonate platforms can develop in more varied conditions, including areas with higher nutrient levels, fluctuating salinity, or broader temperature ranges

Microbialite is a benthic sedimentary deposit made of carbonate mud (particle diameter less than 5 μm) that is formed with the mediation of microbes. Photo is of microbialite carbonates in Lake Salda (Turkey) rocks



This is a cay, a body of sediment derived from erosion and redeposition of sediments and larger sized particles to form an island that can sometimes be colonized by vegetation. This is a coral cay (with a coral beach) in the Great Barrier Reef.

Carbonate vs coral cays and beaches

- The cays of the Bahamas are generally classified as carbonate cays and are distinct from classic coral cays.
- While coral cays form directly on coral reef systems, the Bahamian cays occur on a carbonate platform (the Bahama Banks)
- It is possible for a cay or beach to be a mixture of both carbonate platform sediment and sediment derived from coral reef organisms

Bahamas carbonate cay and beach

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Coral cay and beach, Great Barrier Reef

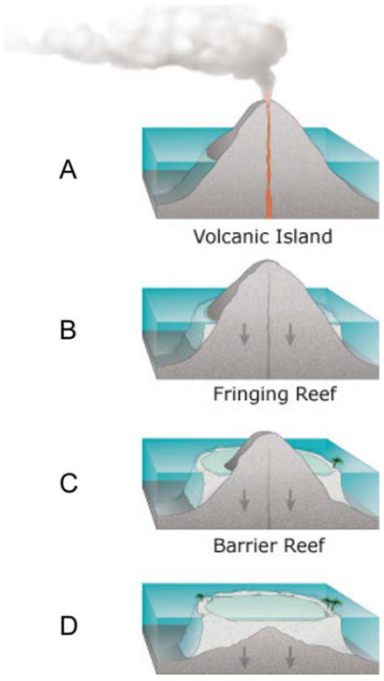
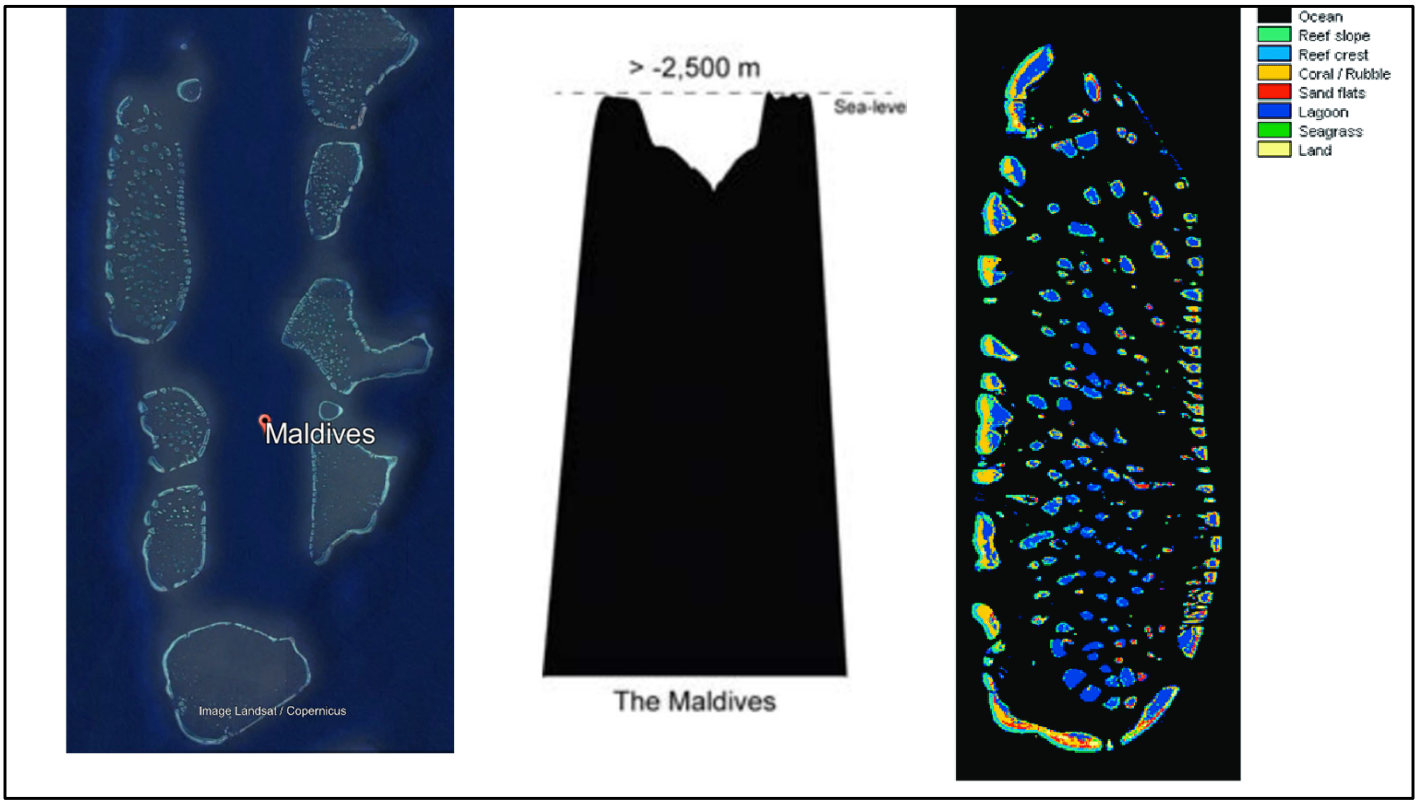


Figure D. This chart illustrates the development of an atoll according to Charles Darwin's ideas. A) Volcanic island. B) Fringing reefs developed on the slopes of the volcanic island. C) A barrier reef developed due to the slow subsidence of the volcanic island and the coral reefs tendency to grow upwards in order to remain in the light-saturated part of the ocean. D) The volcanic island is fully submerged and an atoll developed with a reef rim and a lagoon. Image courtesy of the U.S. Geological Survey.

Atoll, fringing reef, barrier reef, and carbonate platform – islands in the Maldives can be all of these

Maldives

Atolls
Fringing reef
Carbonate platform


Maldives
Image Landsat / Copernicus
> -2,500 m
Sea-level
The Maldives
Ocean
Reef slope
Reef crest
Coral / Rubble
Sand flats
Lagoon
Seagrass
Land

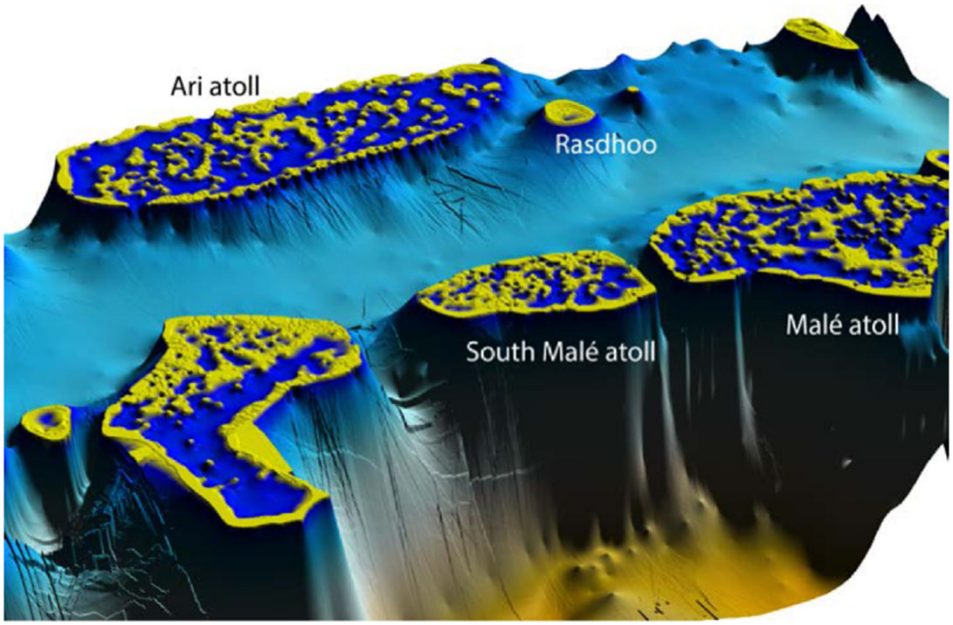


Figure B. A three-dimensional model of the Maldives carbonate platform, illustrating the unique submarine morphology of this archipelago. The model was built using depth soundings taken from the British Admiralty charts for the Maldives.

DOI:10.1007/s00338-003-0366-6