Cenozoic Evolution of Carbonate Shelf and Ramp Habitats: Insights from Paleoceanography*

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Abstract

Understanding biological, geochemical, and oceanographic processes influencing modern shelf and ramp carbonate deposition is essential when interpreting carbonate sedimentation in the geologic record. Yet recognizing the limitations of uniformitarianism is equally important. Cenozoic carbonate-producing ecosystems emerged from the remnants of Cretaceous biotas, evolving in the warm alkaline oceans of a Greenhouse world, then modifying in response to emerging Icehouse conditions. The latter included stronger latitudinal and bathymetric temperature gradients, declining carbon dioxide concentrations in the atmosphere, and declining calcium concentrations and alkalinity in the oceans. Paleocene-Eocene photic-dependent carbonates tended to be dominated by calcitic coralline red algae and larger benthic foraminifers (LBF), with aragonitic corals and calcareous green algae restricted temporally and spatially. Conceptual models suggest that episodic changes in ocean circulation and thermocline stratification that accompanied high latitude cooling during the Cenozoic provided impetus for turnover in light-dependent (chlorozoan) biotas. For example, comparison of Eocene through Miocene paleotemperature data for surface to thermocline gradients with the history of LBF assemblages indicates that the latter were most diverse and productive when deeper waters were warmest and gradients were weakest. Higher extinction rates corresponded with times when surface to thermocline gradients increased. In contrast, zooxanthellate corals, while relatively diverse in the Eocene, were restricted as reef builders. As Icehouse conditions emerged, aragonite production by corals and calcareous algae became more widespread, with a setback in the early and middle Miocene when coralline algae again dominated. Moreover, the proliferation of reef-building coralline algal taxa into shallow-water habitats in the late Miocene paralleled the emergence of shallow-water corals and new clades of zooxanthellae, indicating co-evolution of these critical reef taxa. Implications of these observations indicate that enhanced understanding of deeper photic-zone (30-100 m) carbonate systems can enhance interpretations especially of Paleogene shelf and ramp carbonate depositional environments, and likely older carbonate systems, especially those deposited during Greenhouse conditions.

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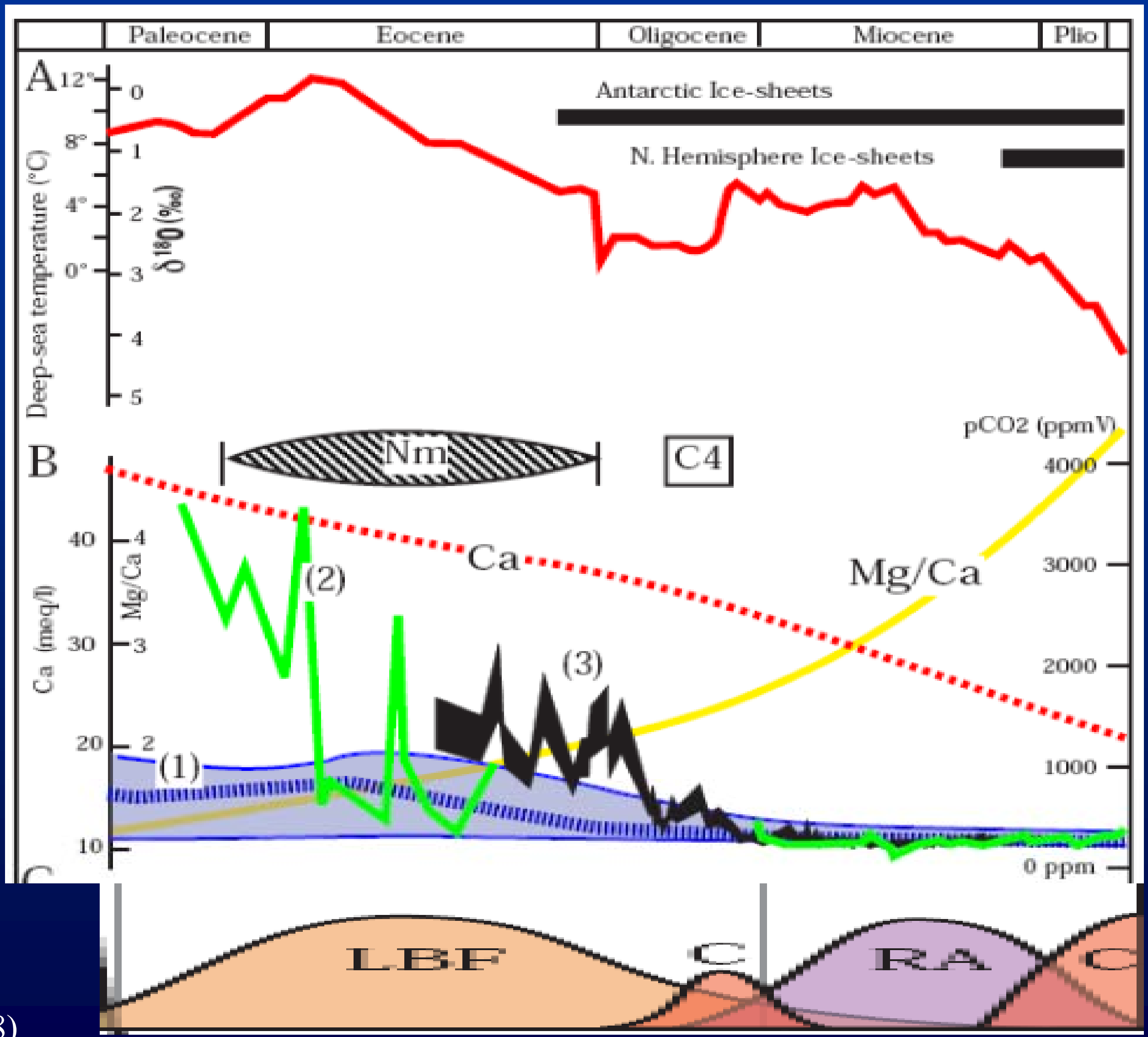
1 mm

The Paradox of the Cenozoic

Why did larger forams thrive in the Greenhouse World?
Why do coral reefs thrive in the Icehouse World?



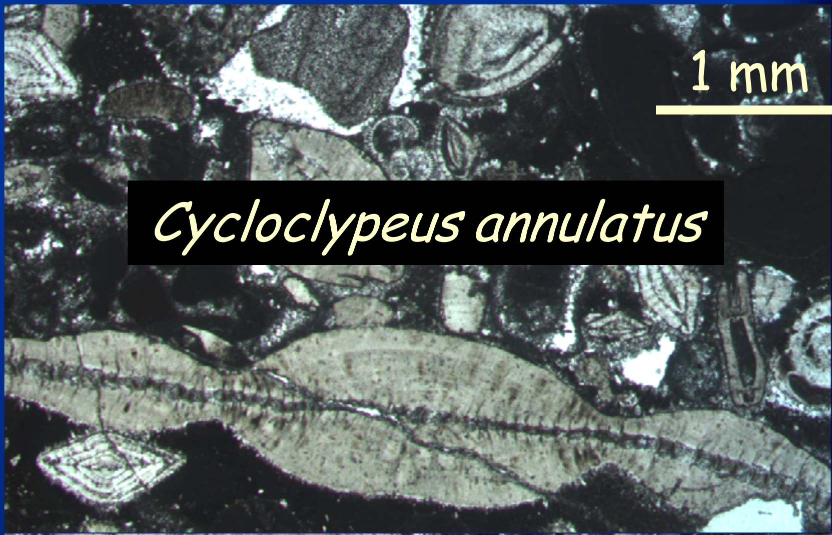
Pomar and Hallock (2008)

Overview

- Paleoenvironmental indicators for carbonate shelves and ramps
  - Larger benthic foraminifers (LBF)
- Paleoceanographic influences on LBF evolution
- Risk-benefit considerations of algal symbiosis
- How do changes in modes and rates of ocean circulation influence LBF?
- How do deep-sea paleotemperatures compare with diversification and extinction rates of Cenozoic LBF?
- New interpretations
- Concluding remarks

Larger Benthic Foraminifers (LBF)

- Important benthic carbonate producers in Cenozoic
  - Especially prevalent in Paleogene
- Morphologies adapted to algal symbiosis
  - Complex interior morphologies
  - Overall shape trends

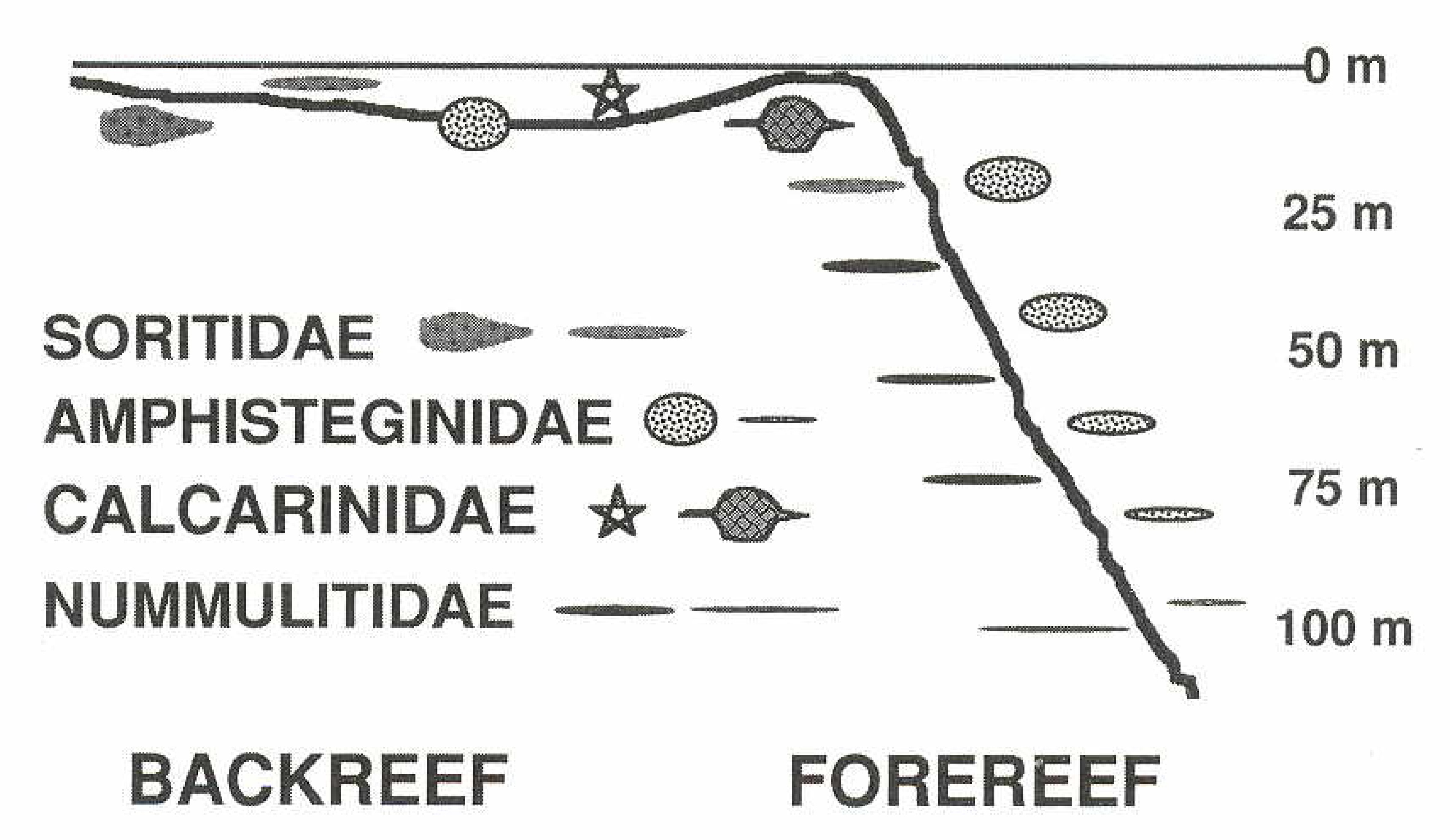


Cycloclypeus annulatus


Lepidocyclina "badjirraensis"

Distributions of modern LBF:

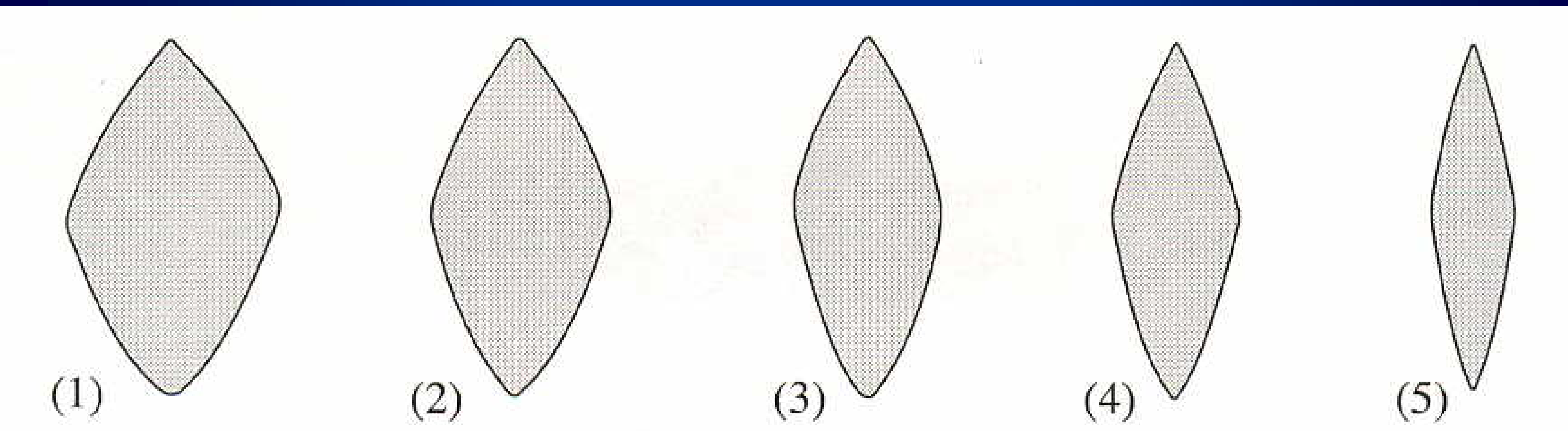
strongly dependent on light and hydrodynamics



Shape as a function of environment

Interspecific differences

A. lobifera | *Amphistegina lessonii* | *A. papillosa*



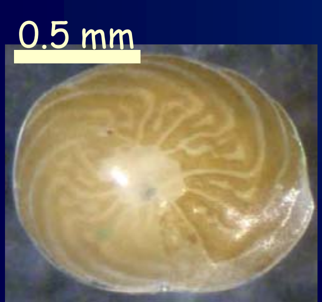
High light
High energy

High light
High energy

High light
Low energy

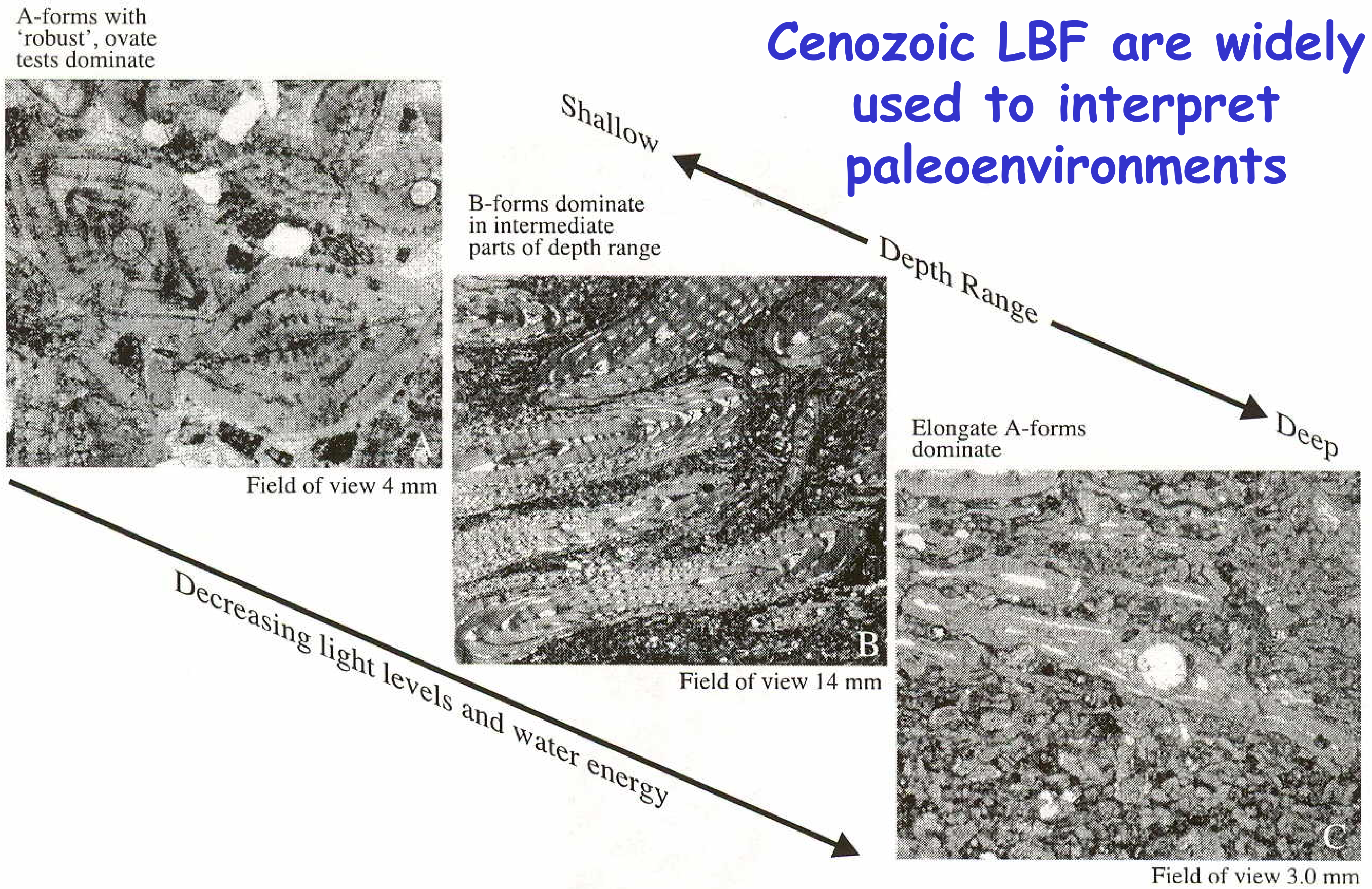
Low light
Low energy

Low light
Low energy

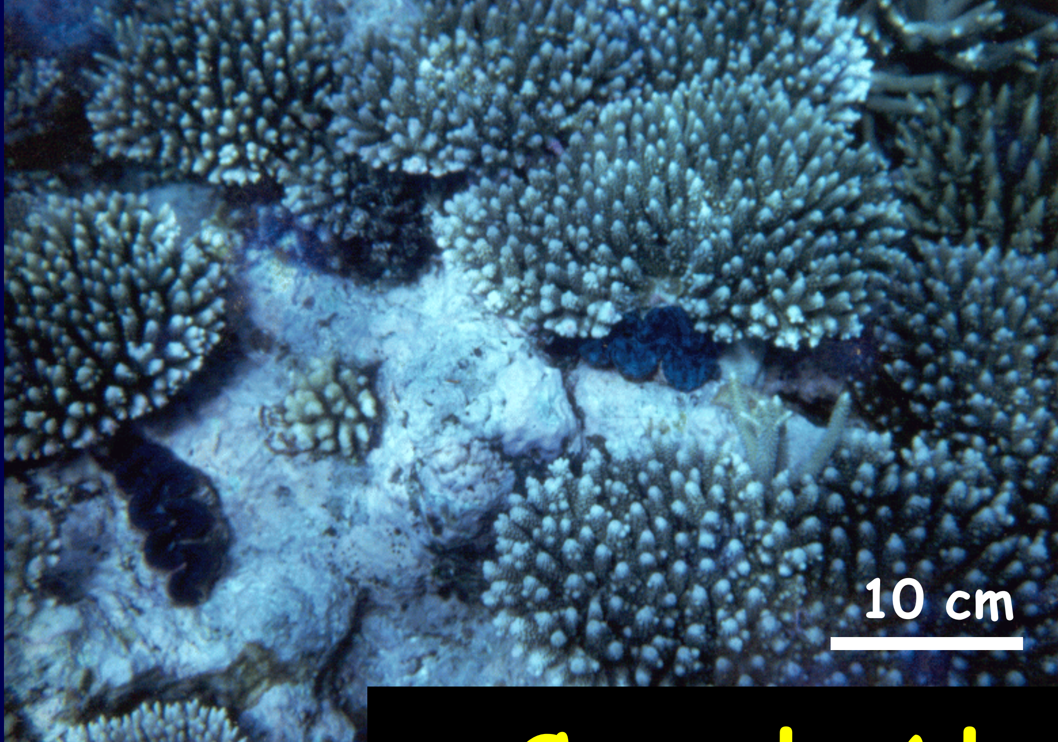


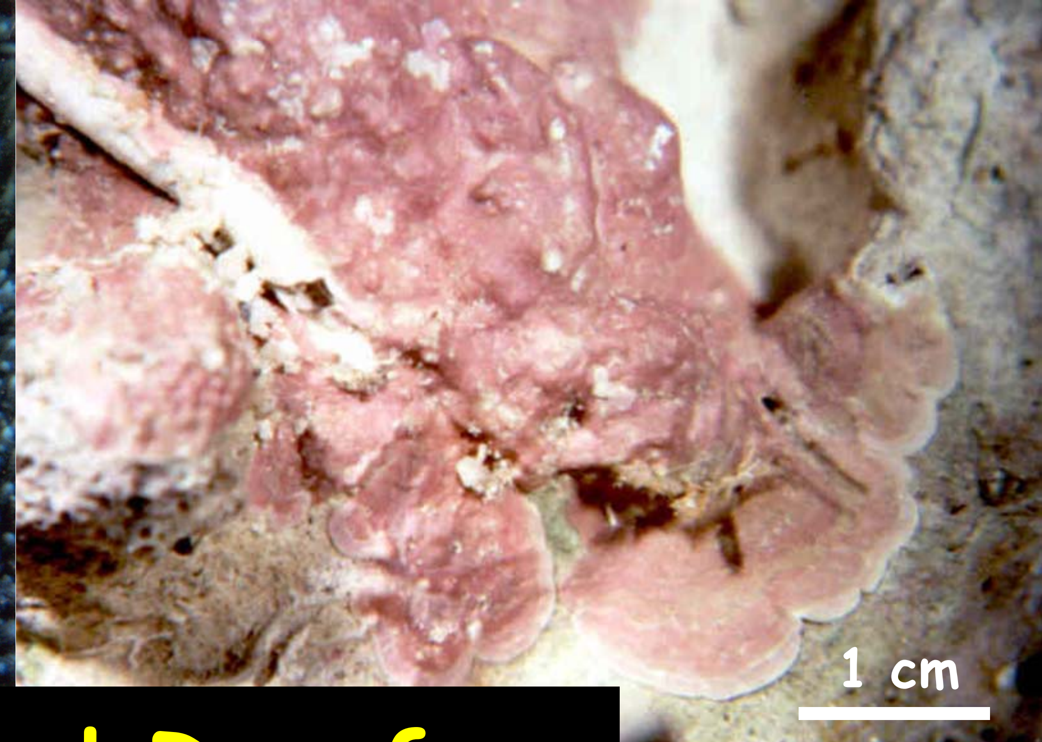
Intraspecific variability

Cenozoic LBF are widely used to interpret paleoenvironments

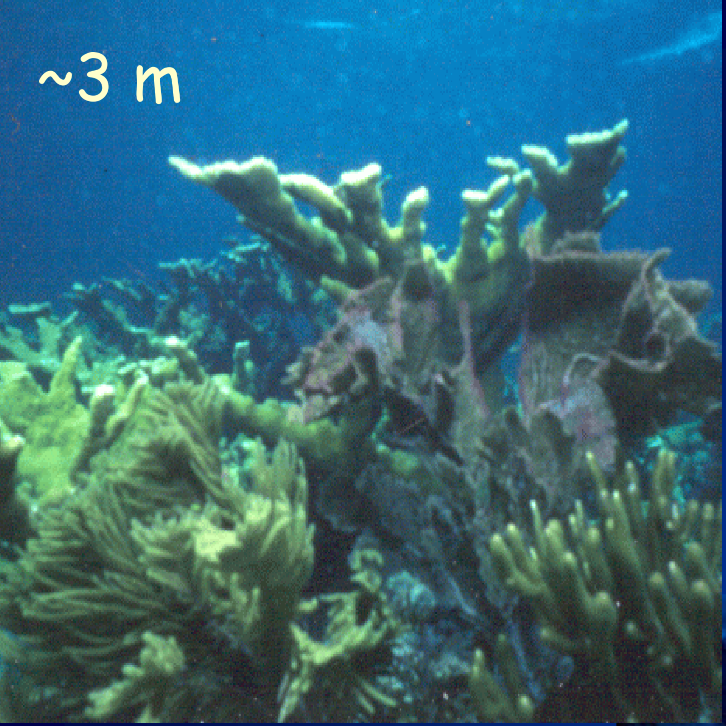


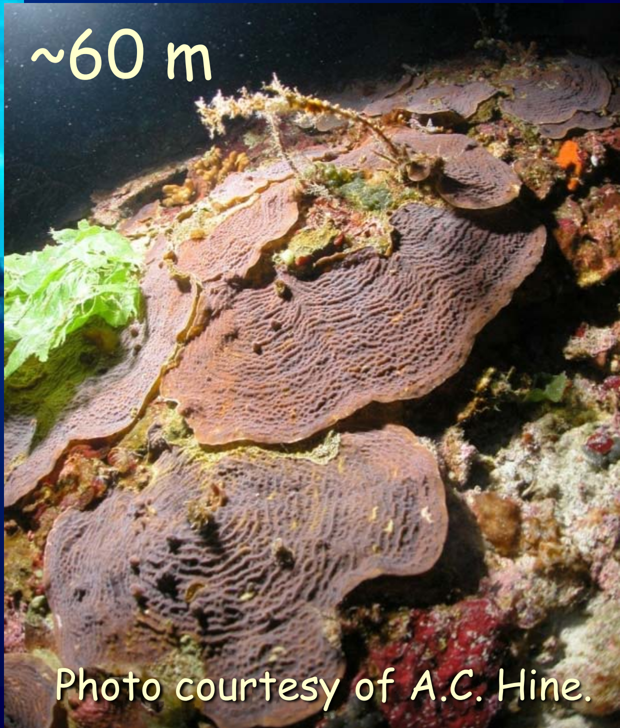
Coral-Algal Reefs





Coral morphologies also vary predictably with light and hydrodynamics



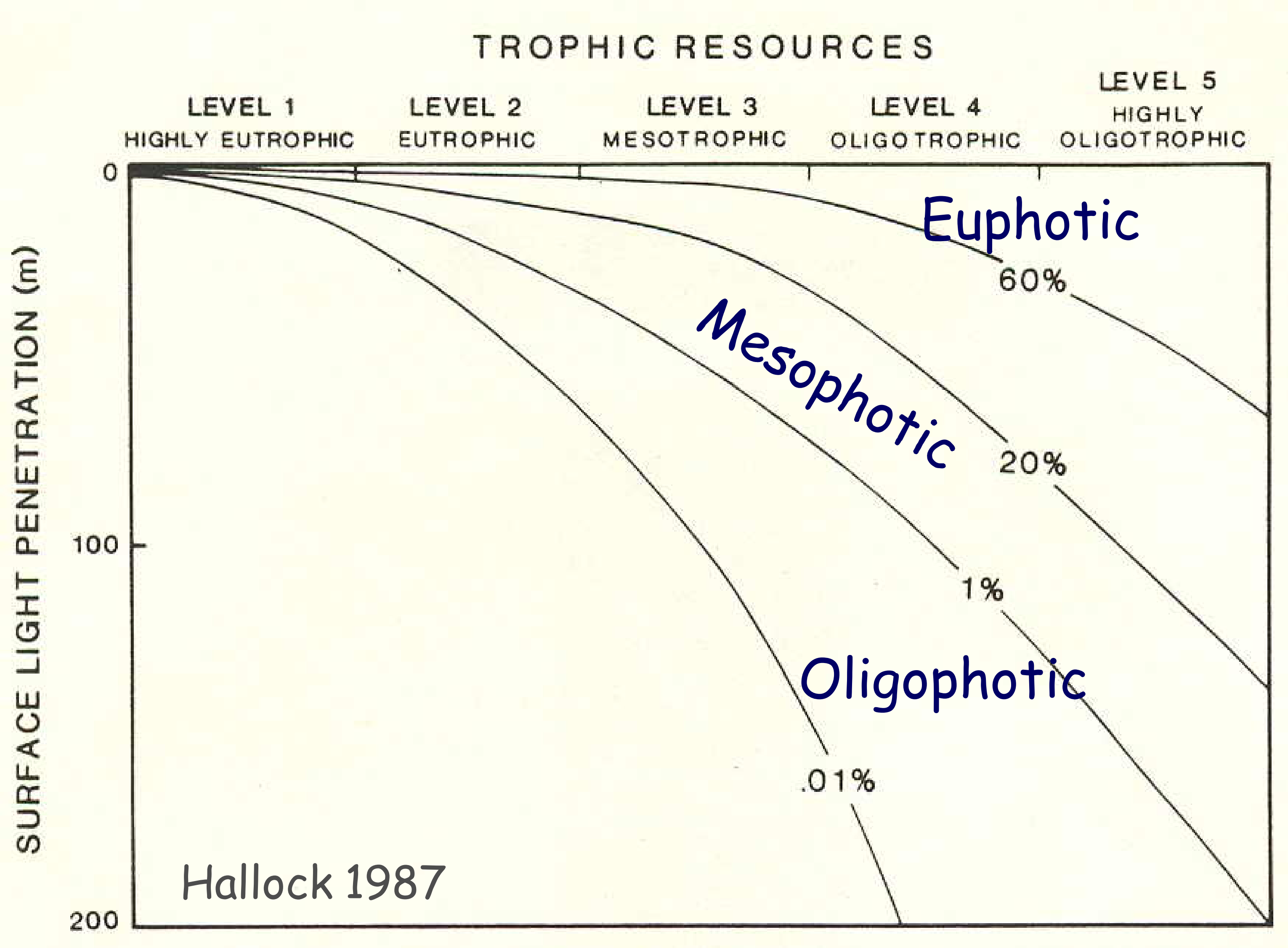


Trophic (nutritional) resources

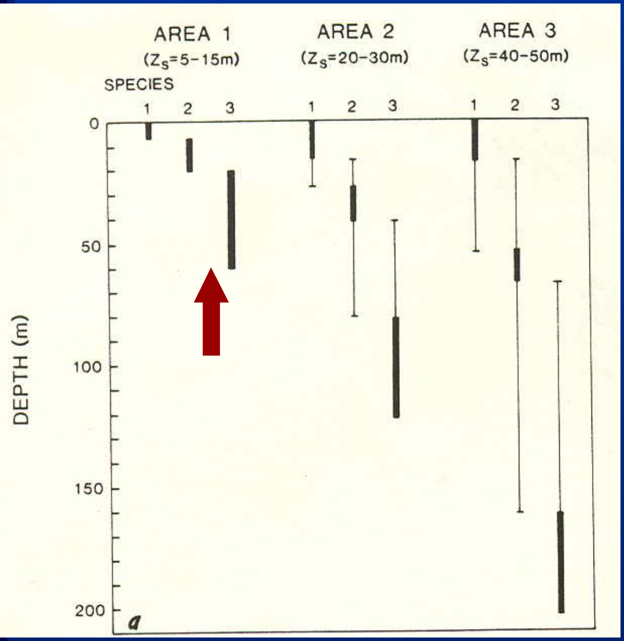
- In sunlight, trophic resources are functions of temperature and nutrient flux (N, P, trace nutrients)
- Below the photic zone, organic carbon = trophic resources
- Algal symbiosis is energetically most advantageous in resource-poor, warm, sunlit environments
- Diversities of habitats are strongly influenced by trophic resources
- Changes in trophic resources are linked to changes in ocean circulation
- Paleogene planktic and LBF evolutionary trends linked to paleoceanographic events

[Hallock 1981, 1987, 1988; Hallock & Schlager 1986; Hallock et al. 1991]

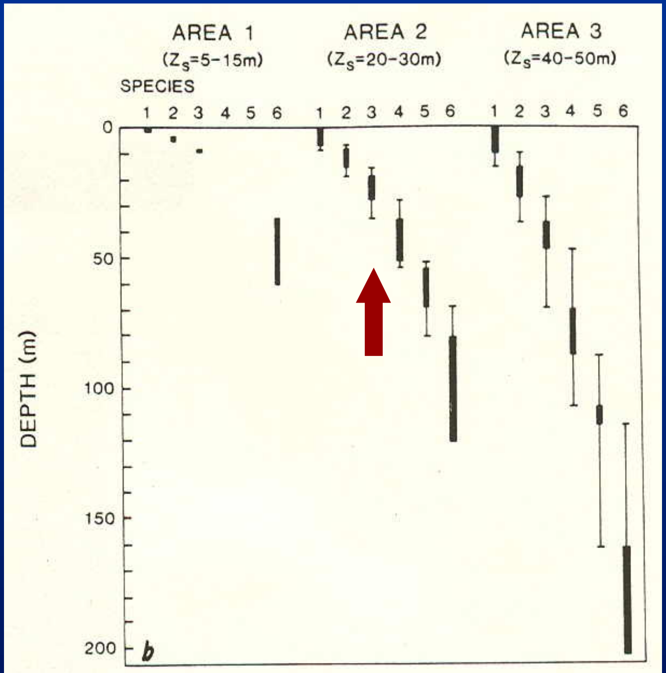
Trophic Resources and Light Penetration:
inversely related



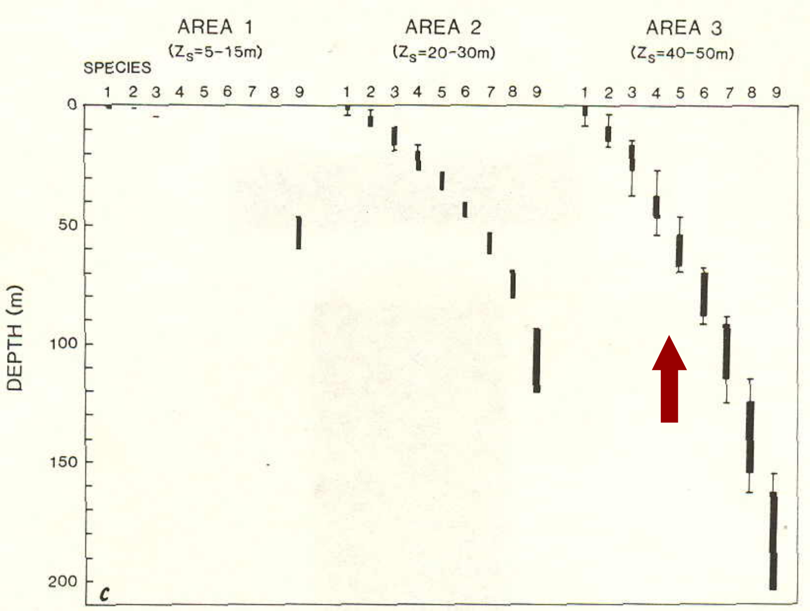
Predictably transparent seawater provides maximum potential for niche specialization in taxa dependent upon photosynthesis



Limited light penetration accommodates 3 species

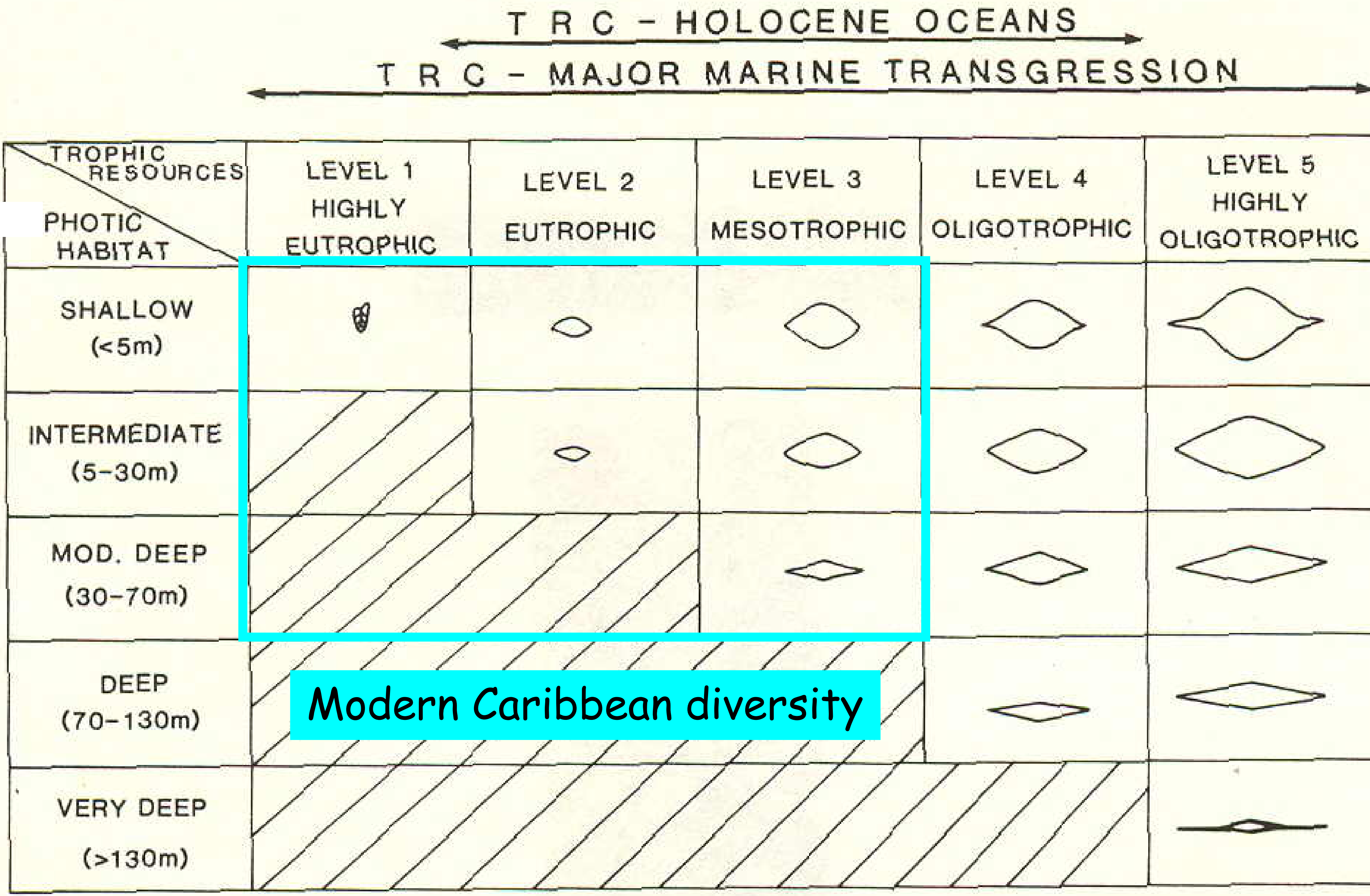


Medium light penetration accommodates 6+ species

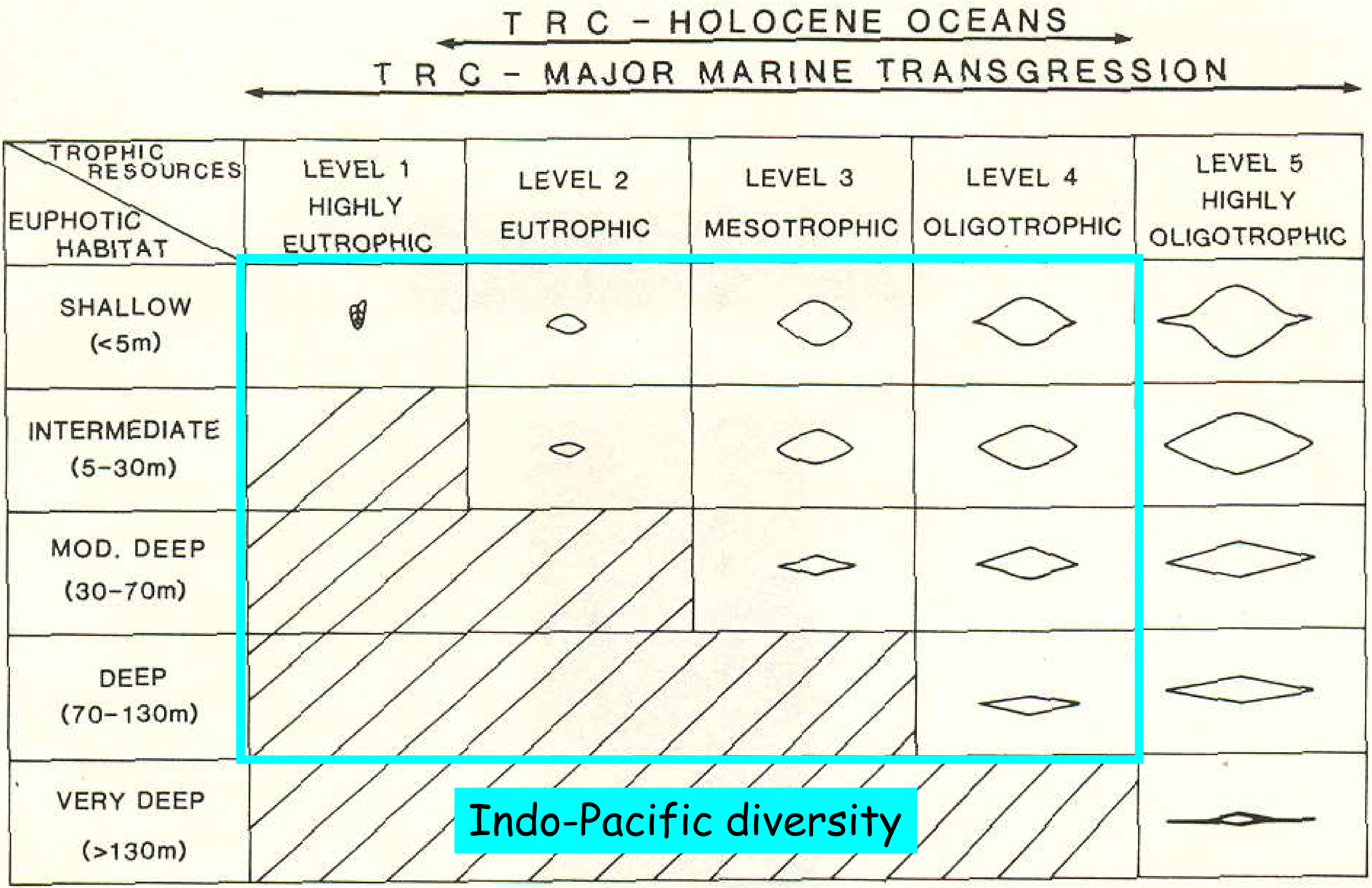


Very clear water accommodates 9+ very specialized species

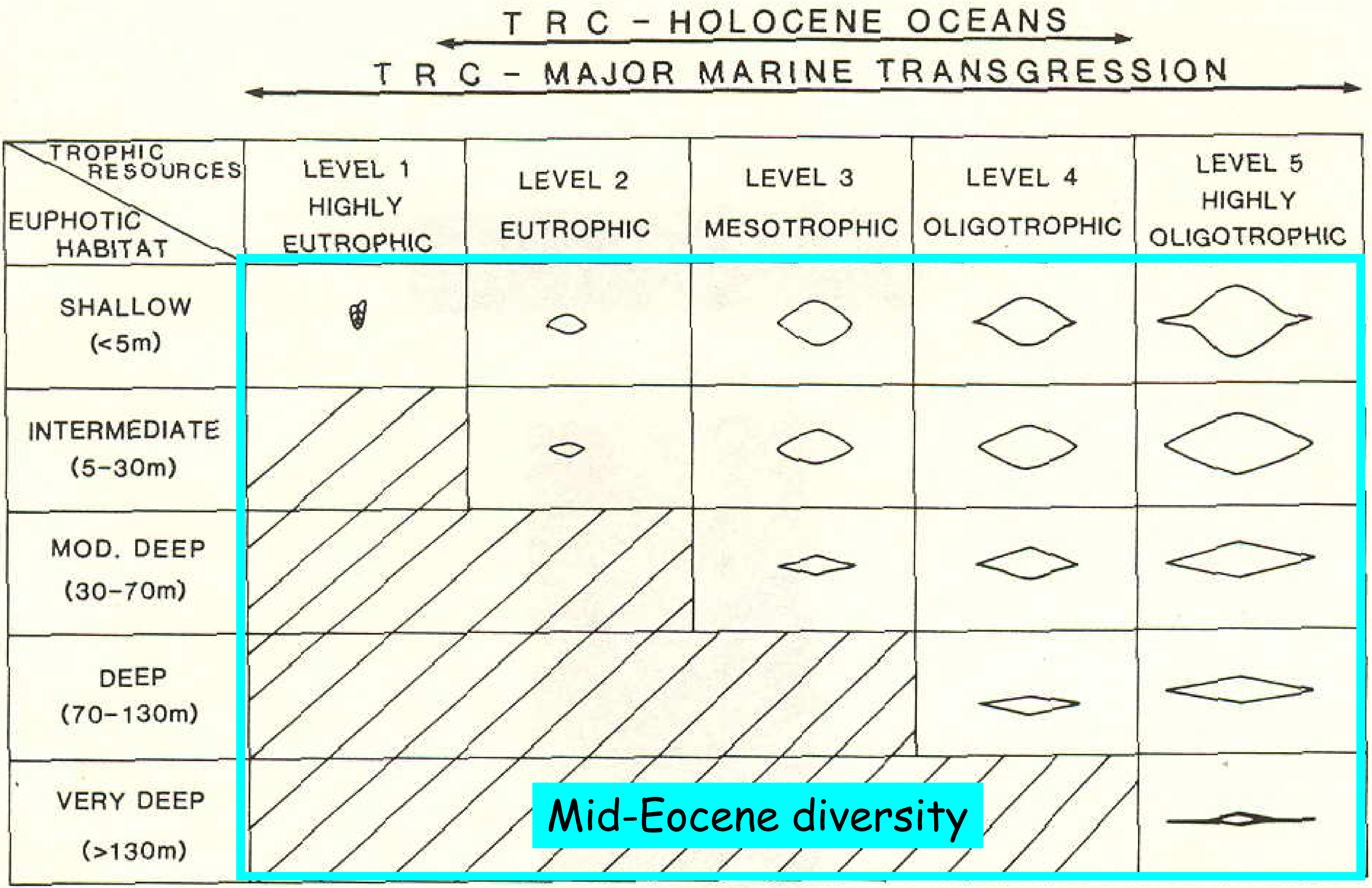
Simple model by Hallock (1987)



Hallock 1987



Hallock 1987



Hallock 1987

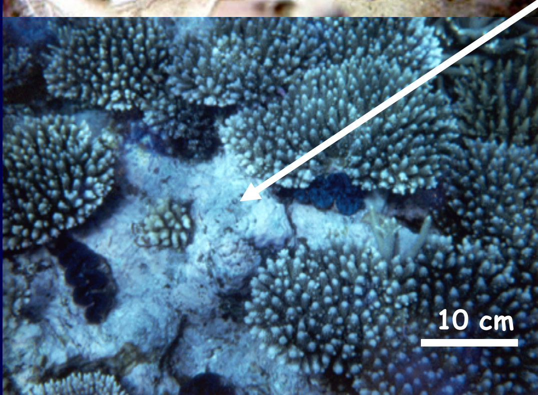
HYPERCALCIFICATION TYPICALLY INVOLVES PHOTOSYNTHESIS
[Stanley and Hardie 1998]

Aragonite Producers

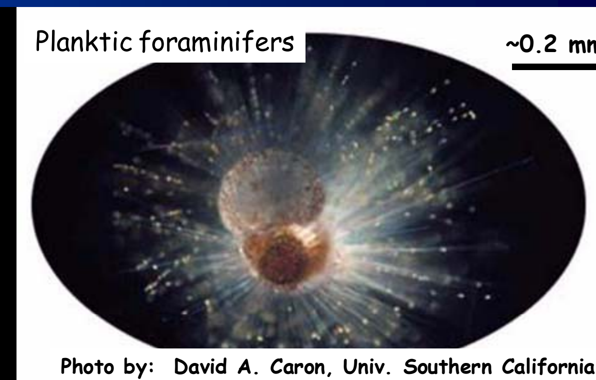
Most scleractinian corals

Mg-Calcite Producers
(> 8 mole% $MgCaCO_3$)

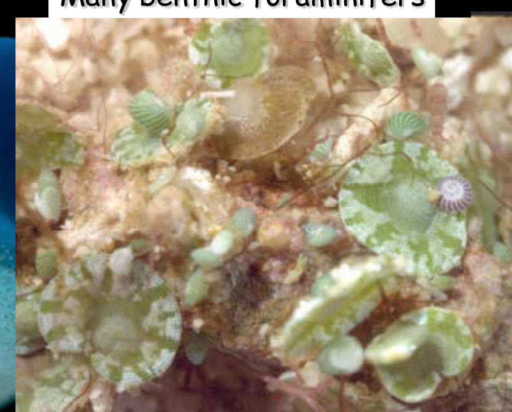
Coralline red algae



Calcite Producers



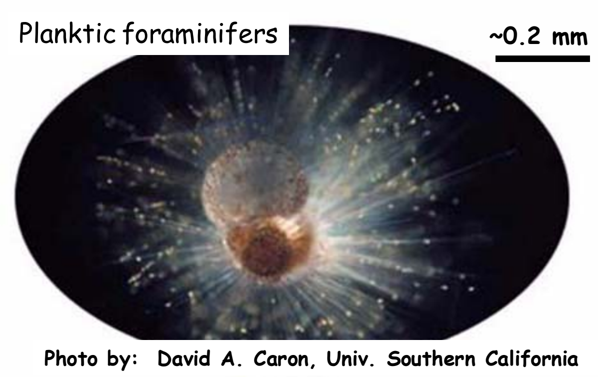
Many benthic foraminifers



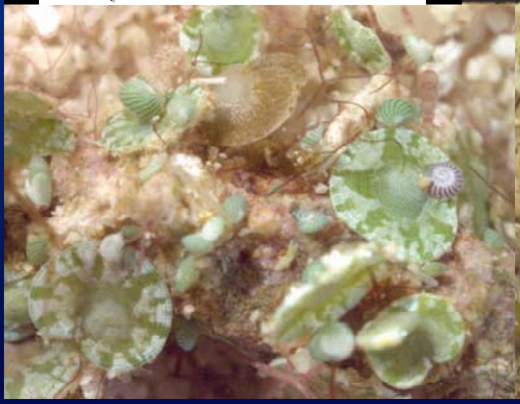
What are the costs of algal symbiosis?

Aragonite Producers

Calcite Producers



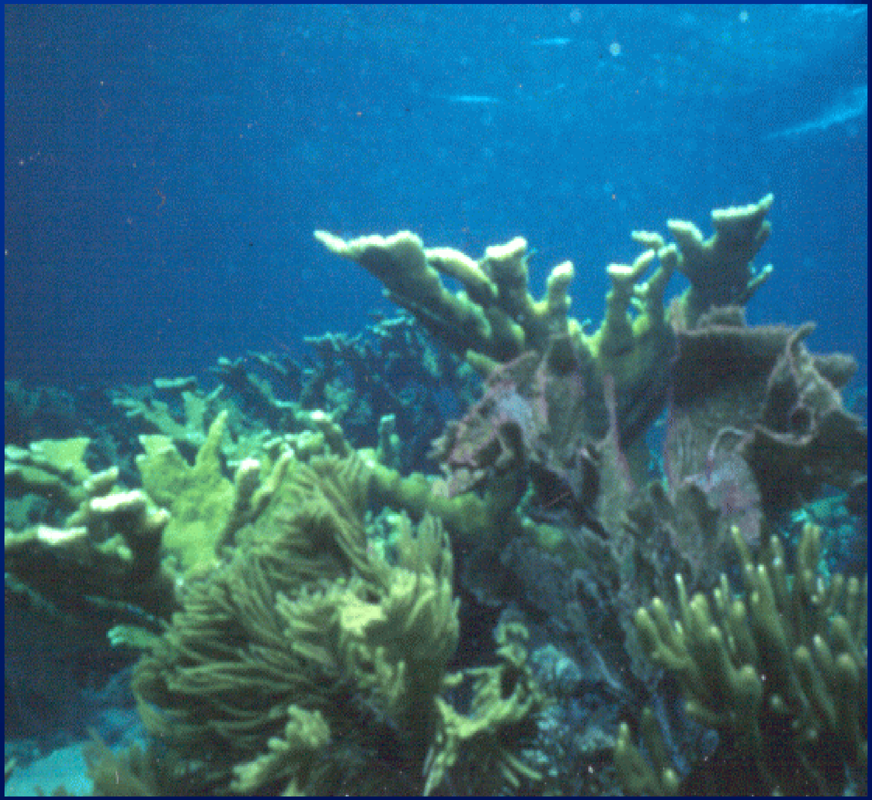
Many benthic foraminifers



Risk-benefit considerations in high light environments

Euphotic – high energy/ high risk

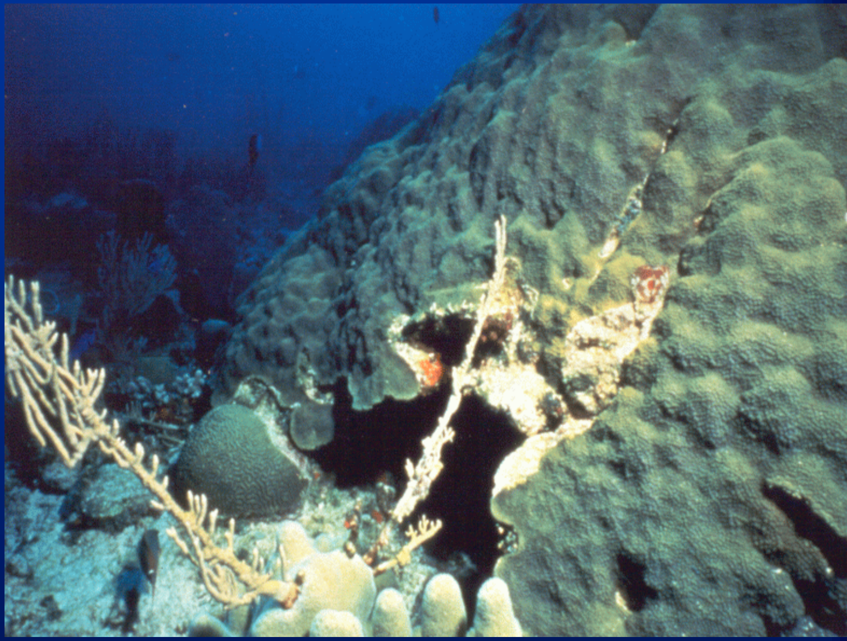
+ abundant energy for/from photosynthesis
- high potential for photo-oxidative stress (bleaching)
- high potential for physical damage
- limited POC resources in very clear waters



Risk-benefit considerations in intermediate light environments

Mesophotic – moderate energy/low risk

+ substantial energy for/from photosynthesis
+ low potential for photo-oxidative stress
+ limited risk of physical damage
- potential for insufficient solar energy with turbidity events
+ potential for energy supplementation with particulates



Risk-benefit considerations in very low light environments?

Oligophotic – low energy/high risk

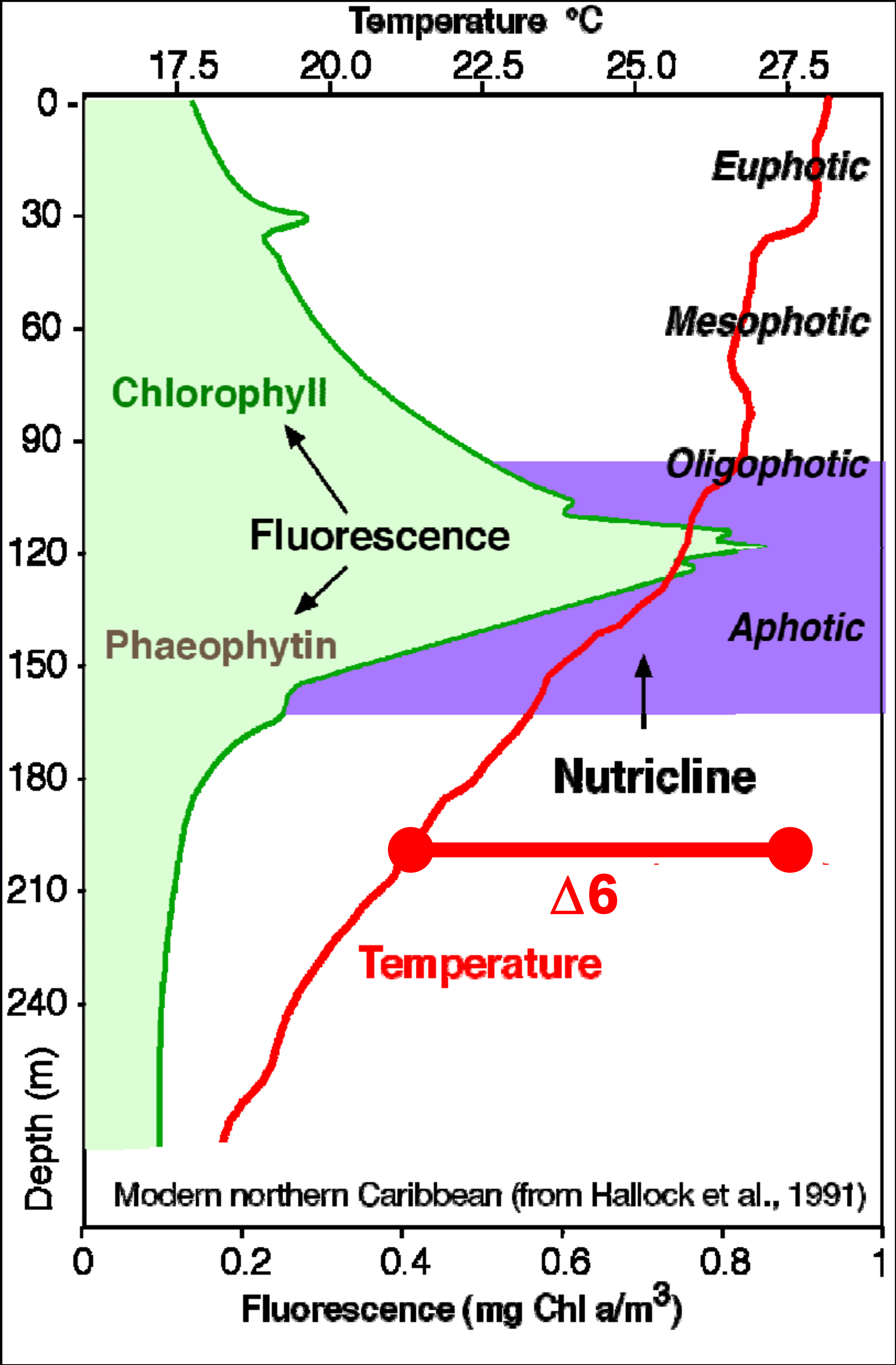
- limited energy for/from photosynthesis
+ relatively abundant nutrients and particulates
+ low potential for photo-oxidative stress
+ low potential for physical damage
- predictably clear water is essential for symbiosis to be worth the "infrastructural" costs

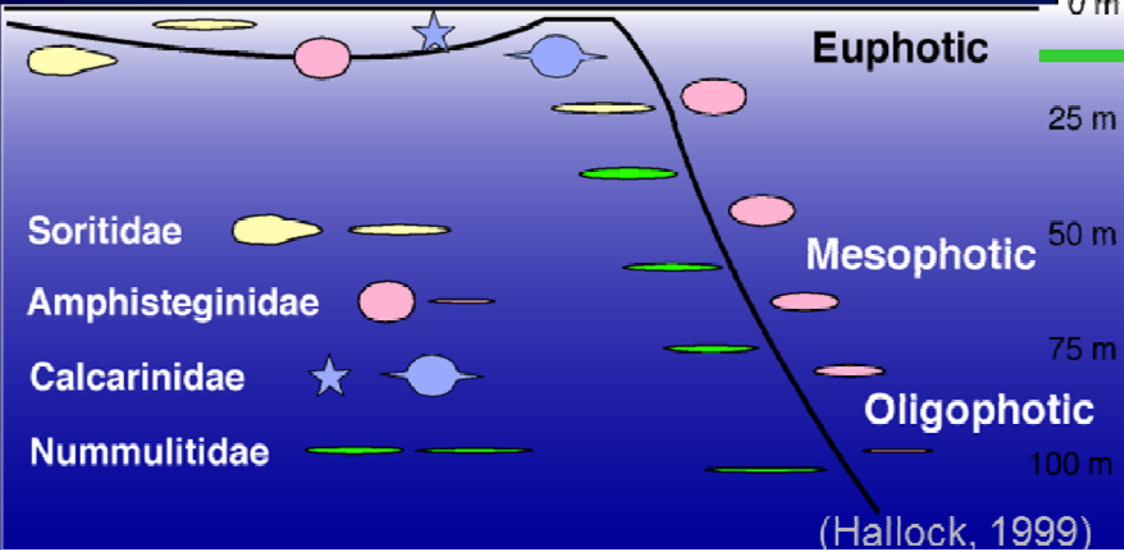
Photo courtesy of A.C. Hine.

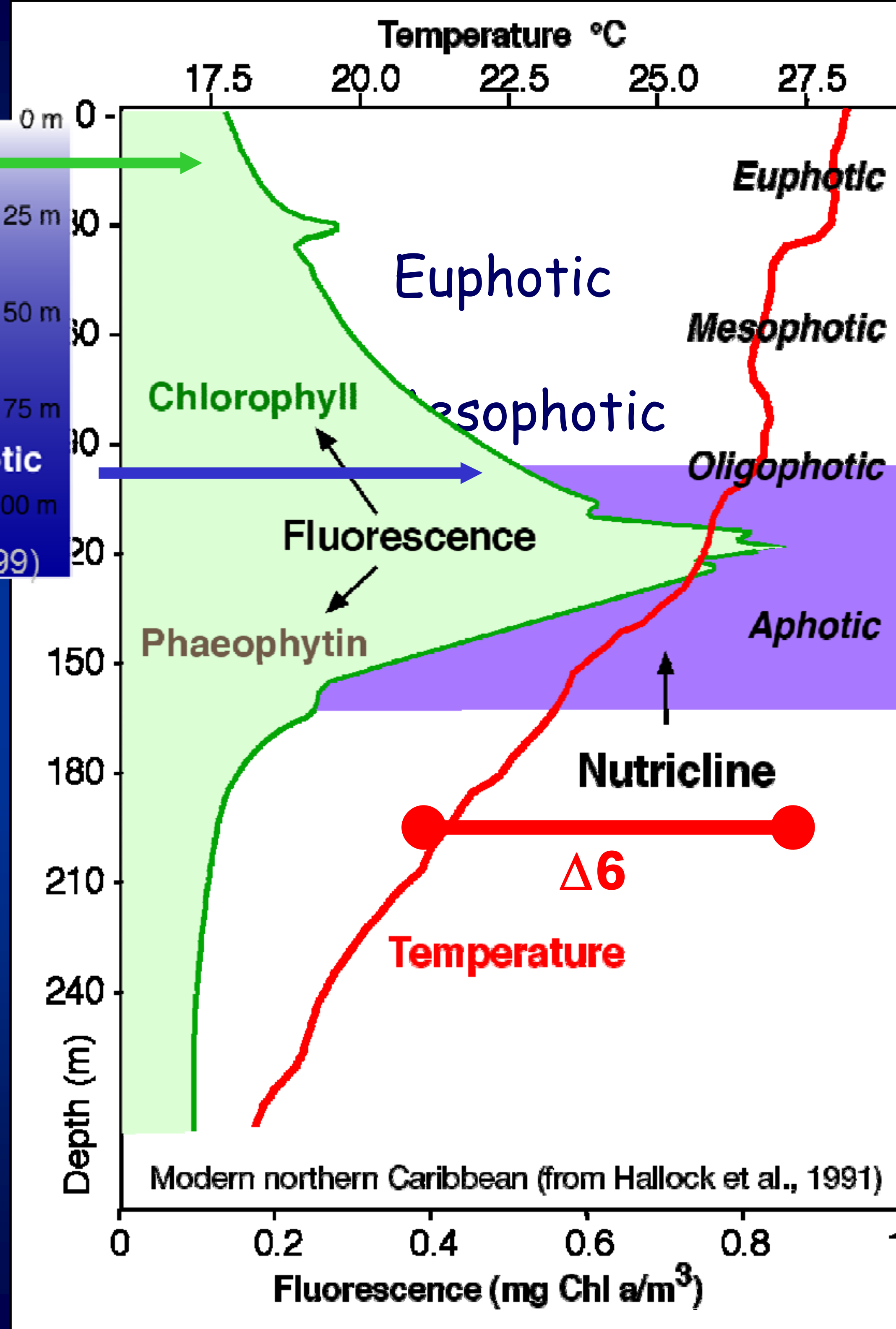
Temperature and chlorophyll profiles for modern Caribbean

- 4X change in food supply in 120 m
- 6 degree change in temperature in 200 m

Hallock et al. 1991



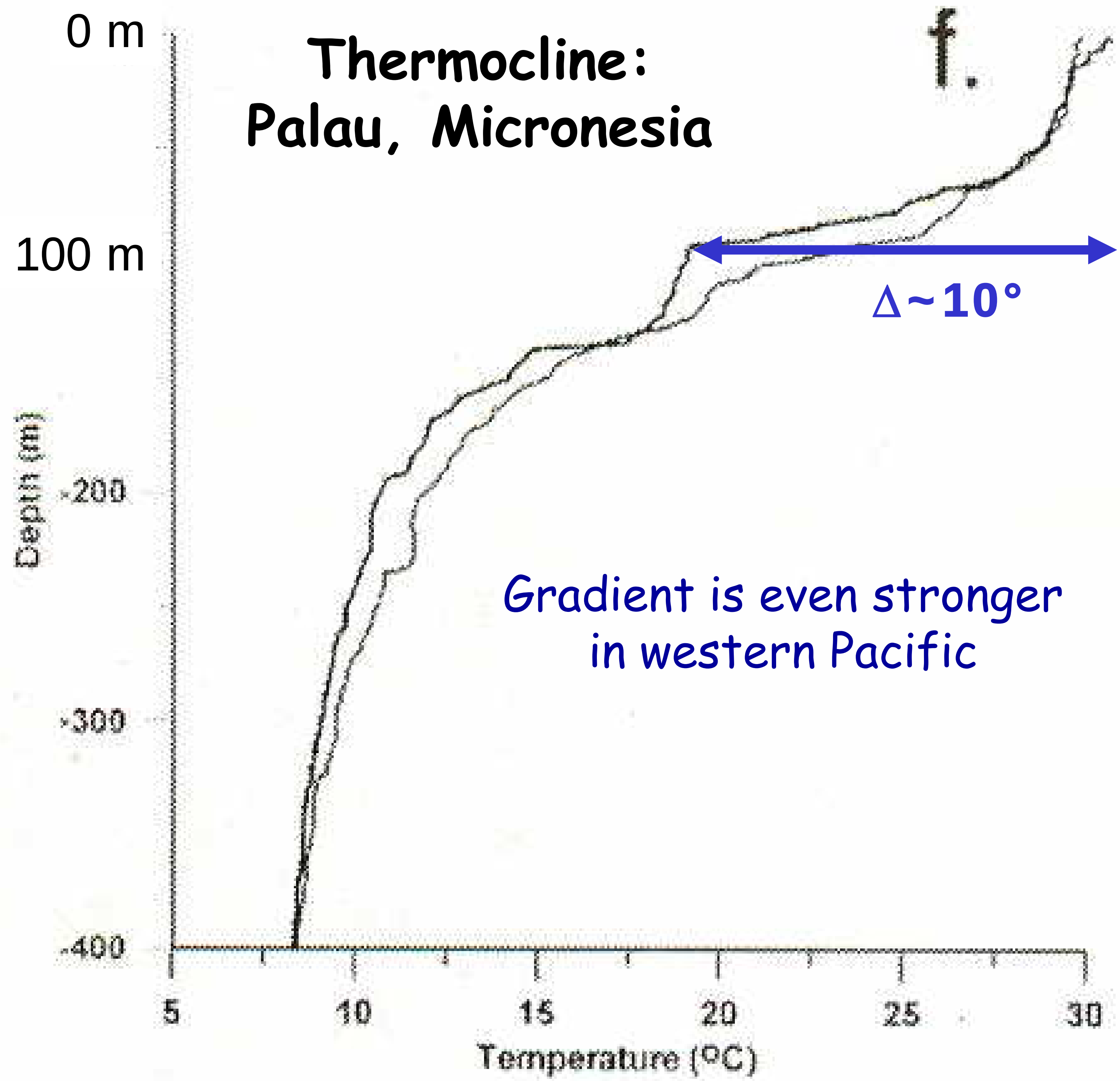




Shallow environments very different than mesophotic & oligophotic environments

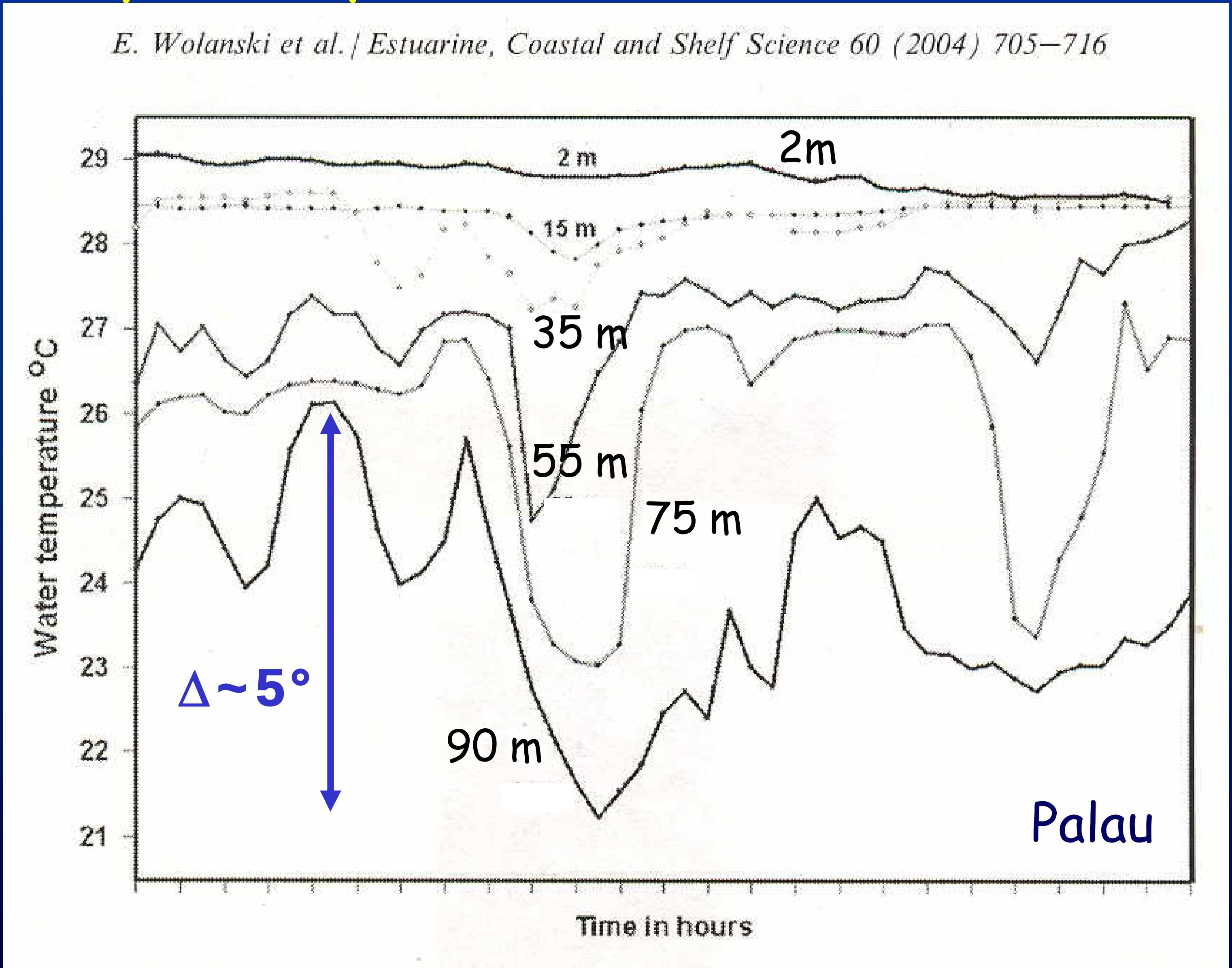
- Solar energy
- Hydrodynamics
- Food supply
- Temperature

Thermocline: Palau, Micronesia

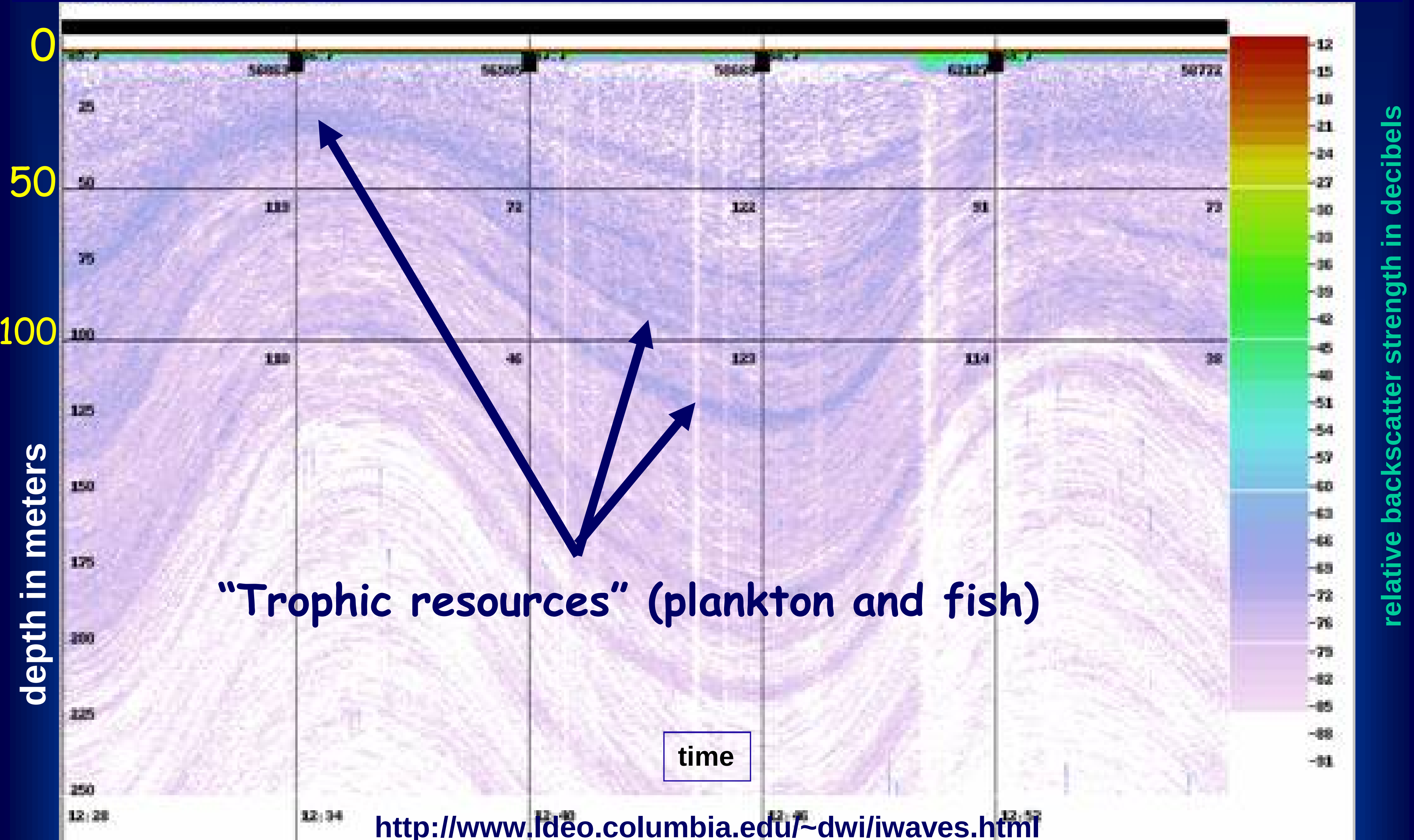


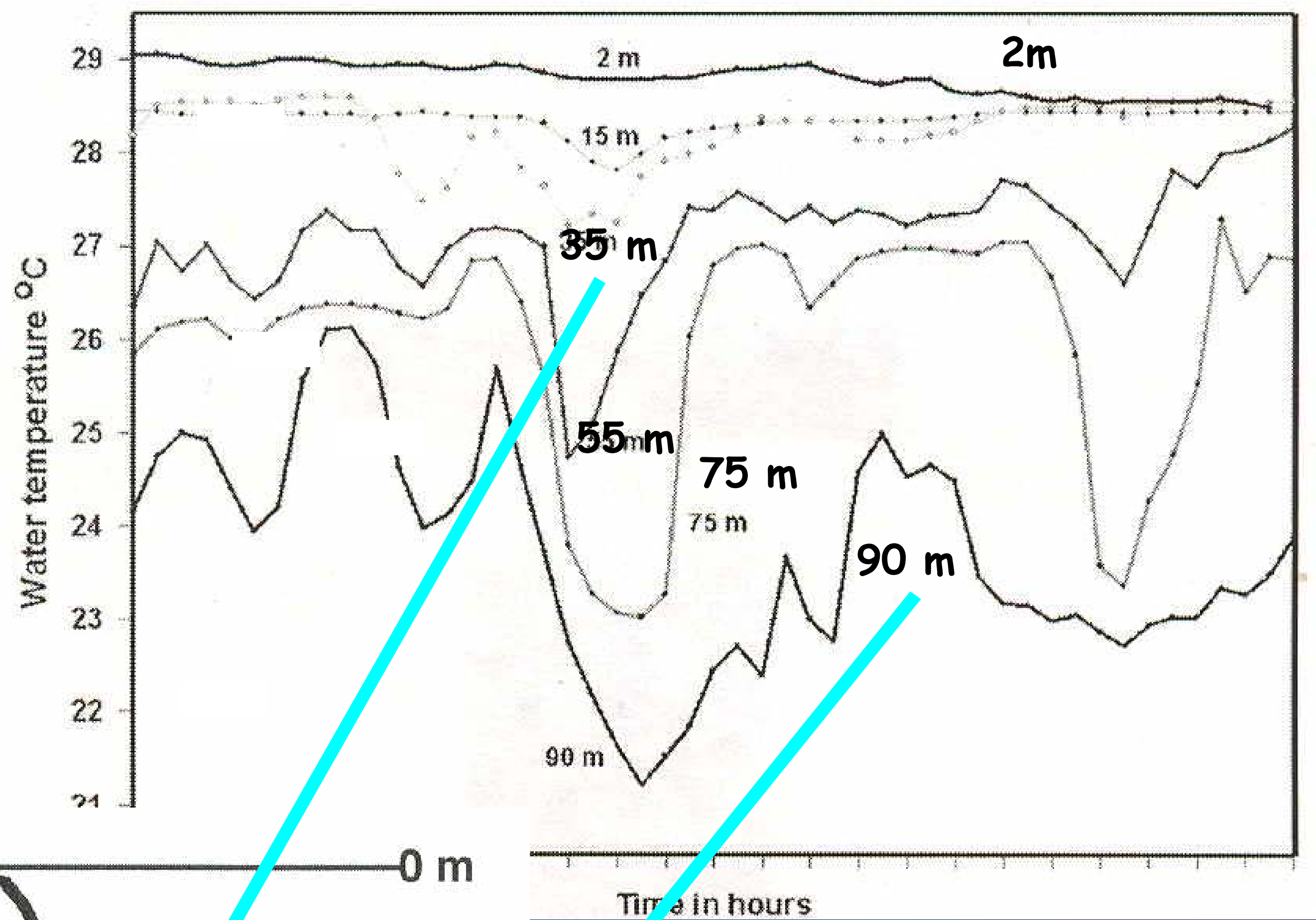
Wolanski et al. 2004

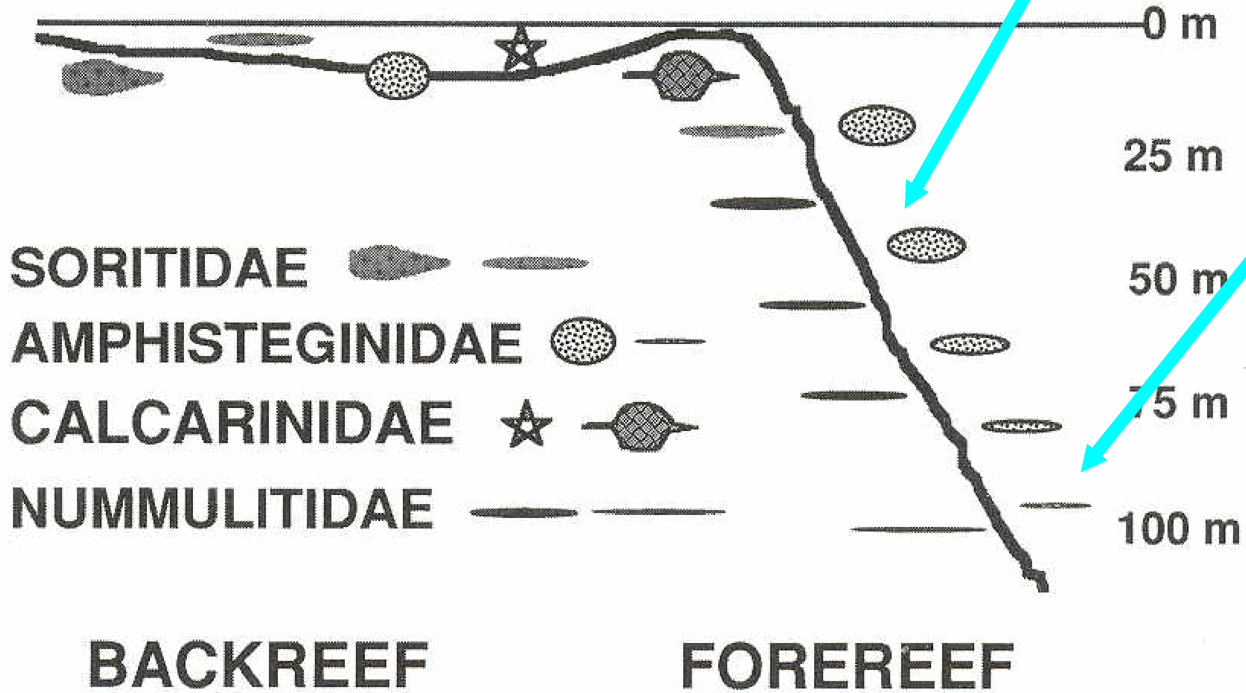
Where depth gradients are strong, internal waves also impart variability on tidal cycles, especially between 30 and 100 m



38 kHz echogram of internal waves in the Lombok Strait, Indonesia: wavelength ~1.8 km; speed ~1.5m/s; wave amplitude (peak to trough) > 100 m. Higher backscatter values indicate higher plankton concentration or large schools of fish (Susanto et al, 2005)

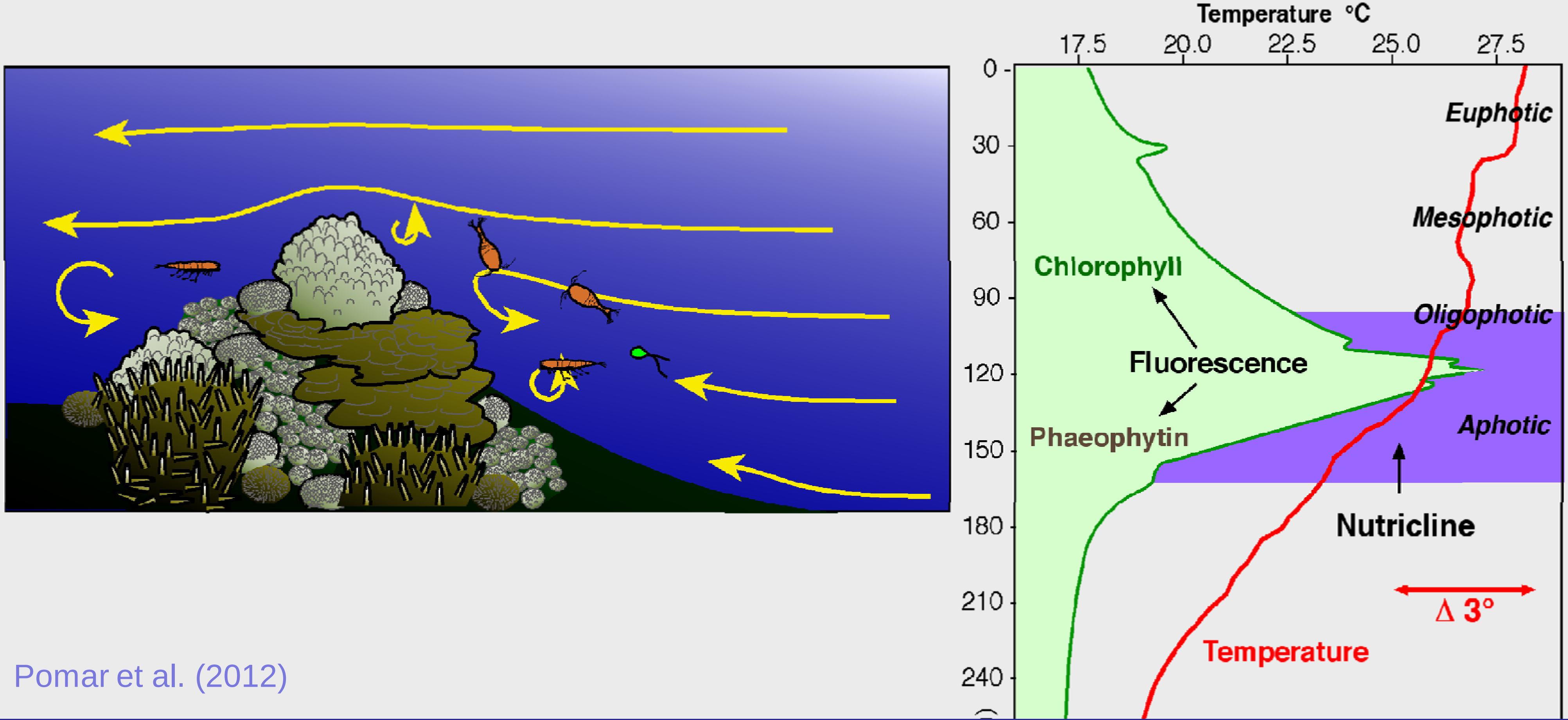






Modern mesophotic and oligophotic environments are eurythermal

Internal waves and metazoan buildups



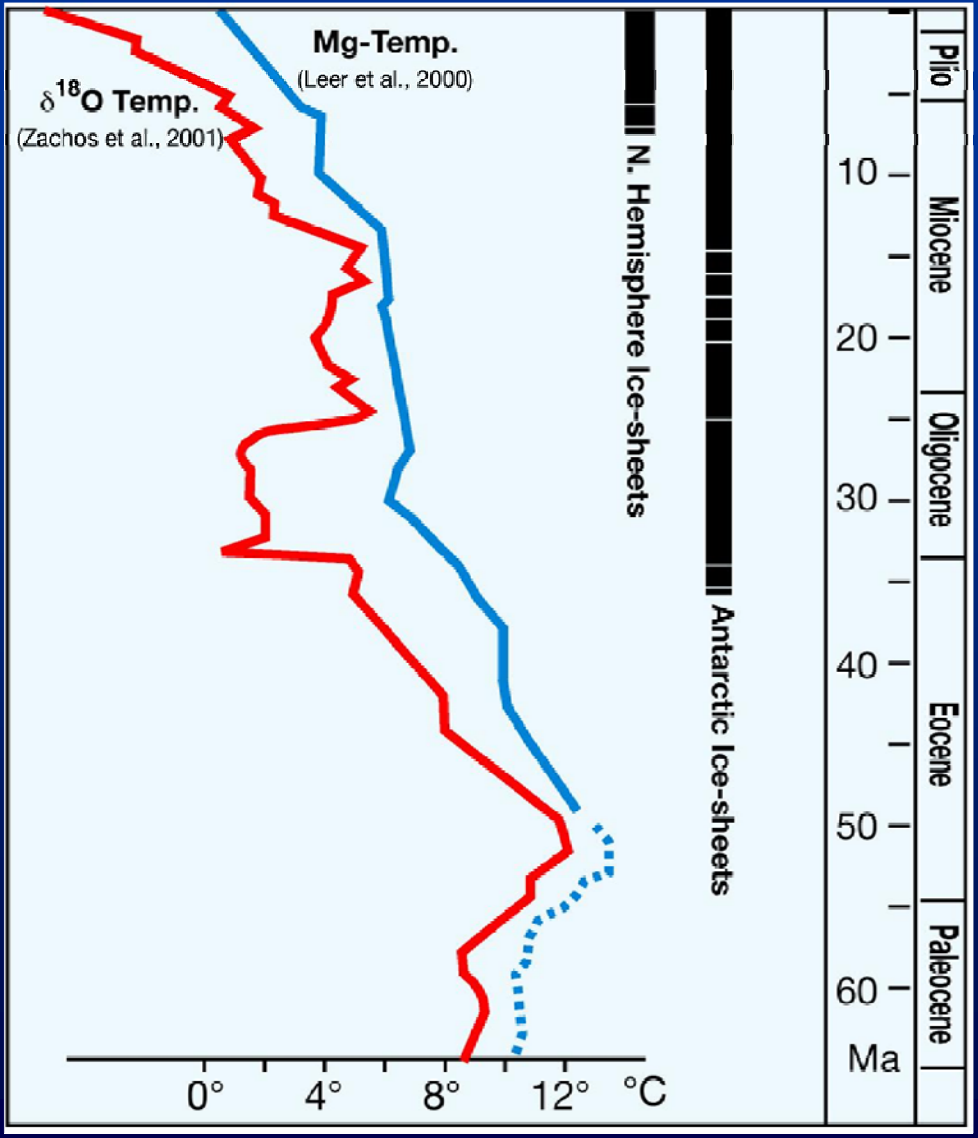
Pomar et al. (2012)

Internal waves (Leichter et al. 1998)

- a predictable, periodic source of transport for shelf-margin reefs
- an important influence on the spatial and temporal heterogeneity of suspended food particles and larval delivery to the benthos

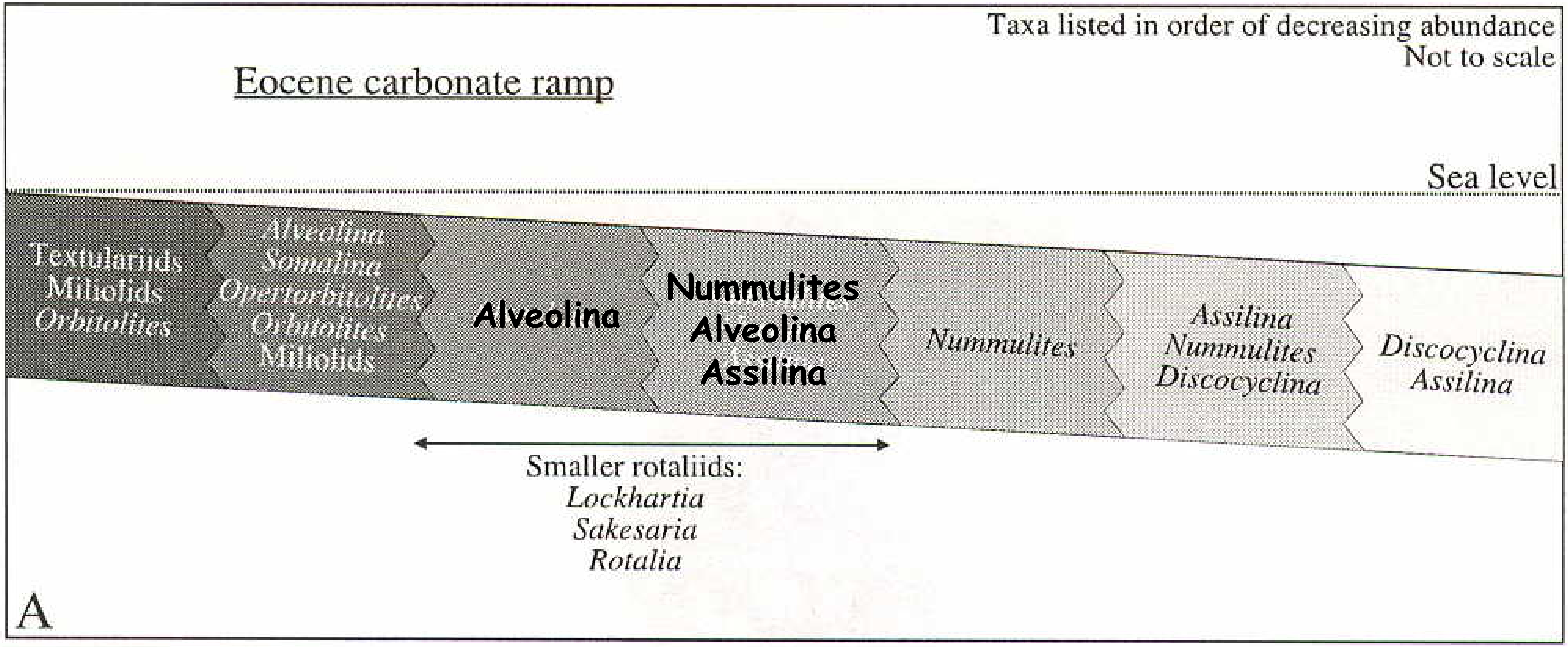
Internal waves provide food resources without limiting light for photosynthesis

Can deep sea paleotemperatures provide clues for shelf and ramp habitats?



Eocene larger benthic foraminifers

- Highly specialized horizontally and vertically
- What stratification and variability did they encounter?



Beavington-Penney & Racey 2004

Deep sea paleotemperatures and Paleocene-Eocene LBF lineages

Extinctions when bottom temperatures < ~10o

Extinctions of orthophragmines

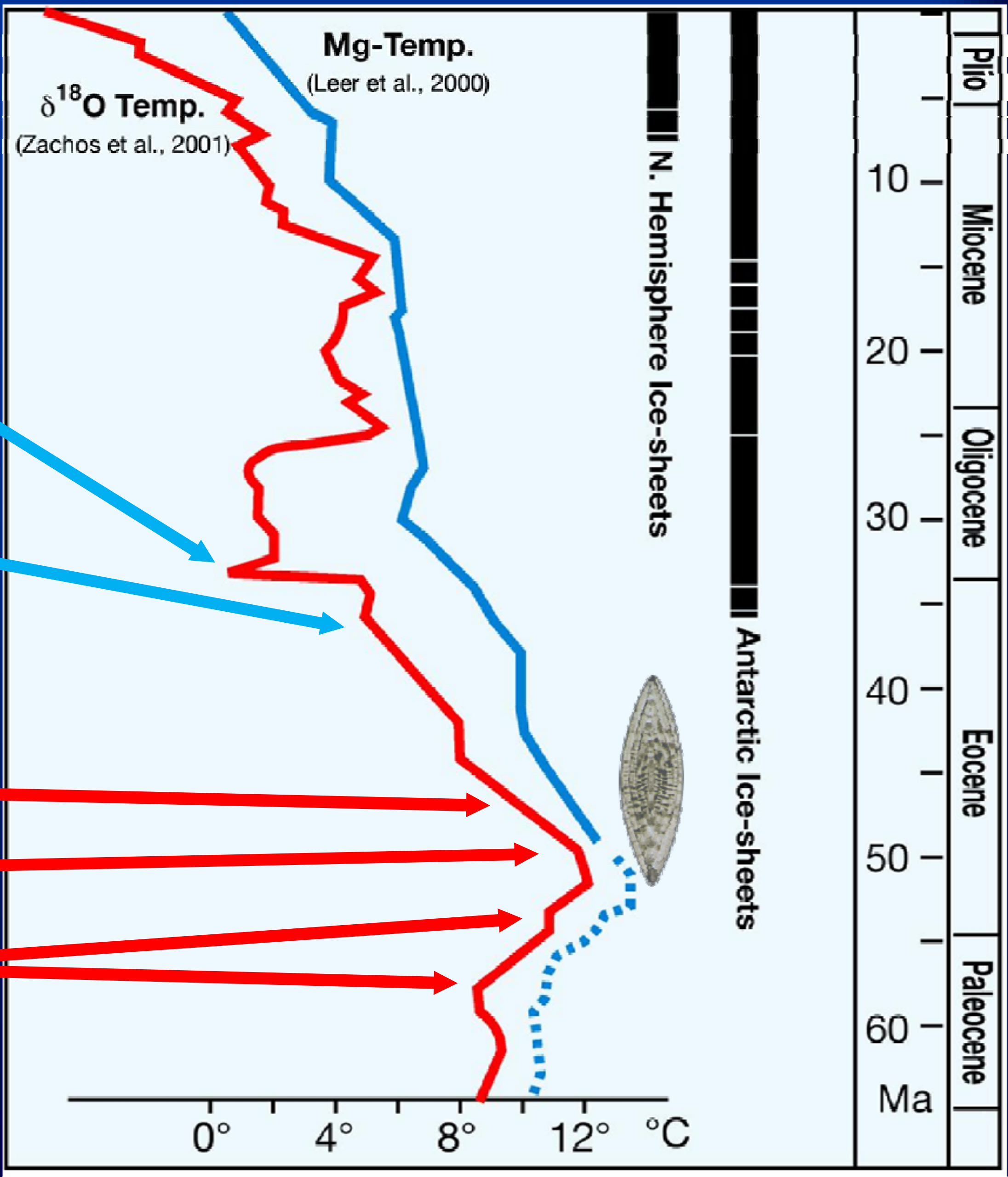
Extinctions of large nummulites and some orthophragmines

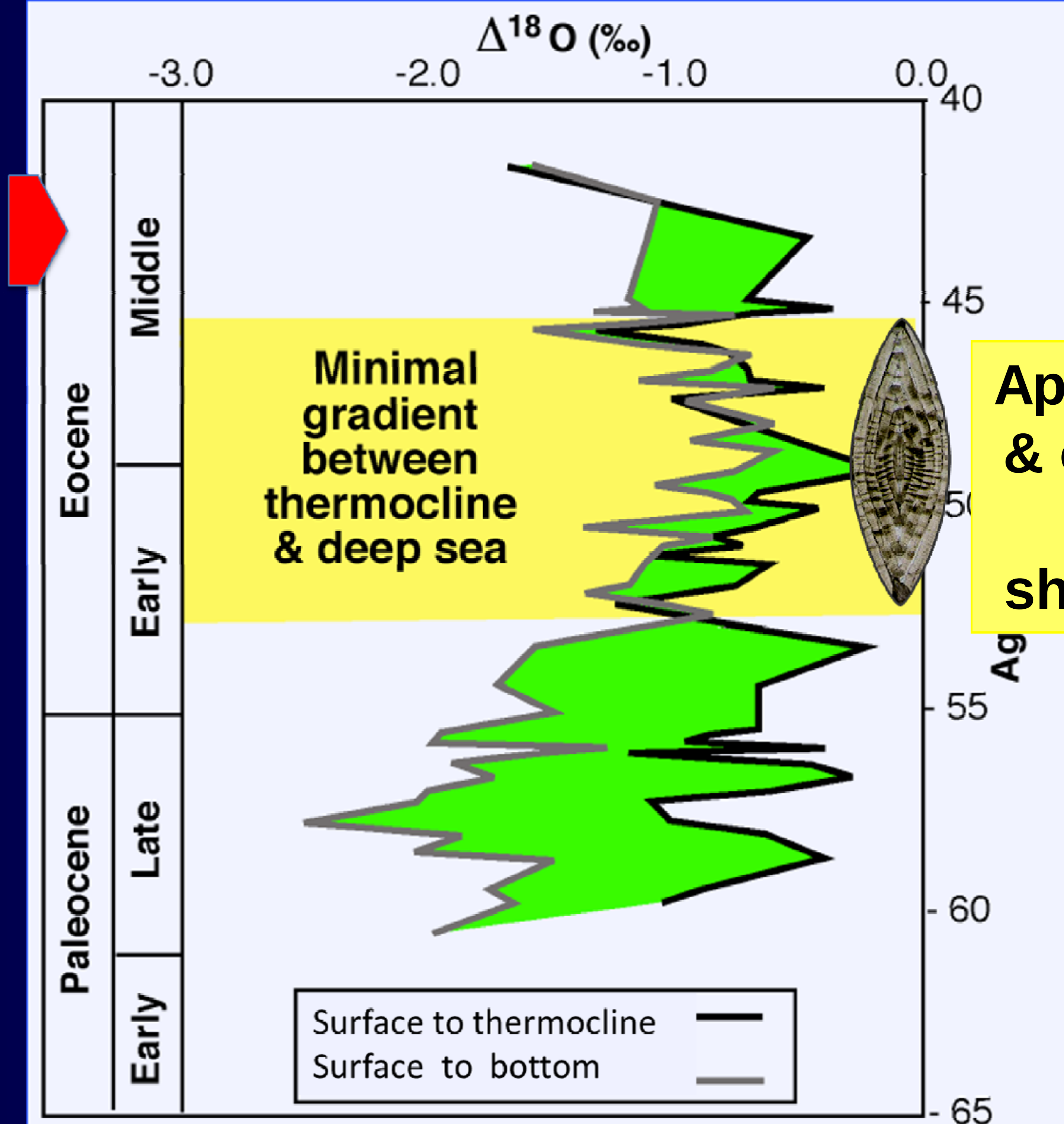
Diversification and peak at bottom temperatures > ~10°

Large nummulites peak

1st large nummulites

Diversification of forams with complex morphologies





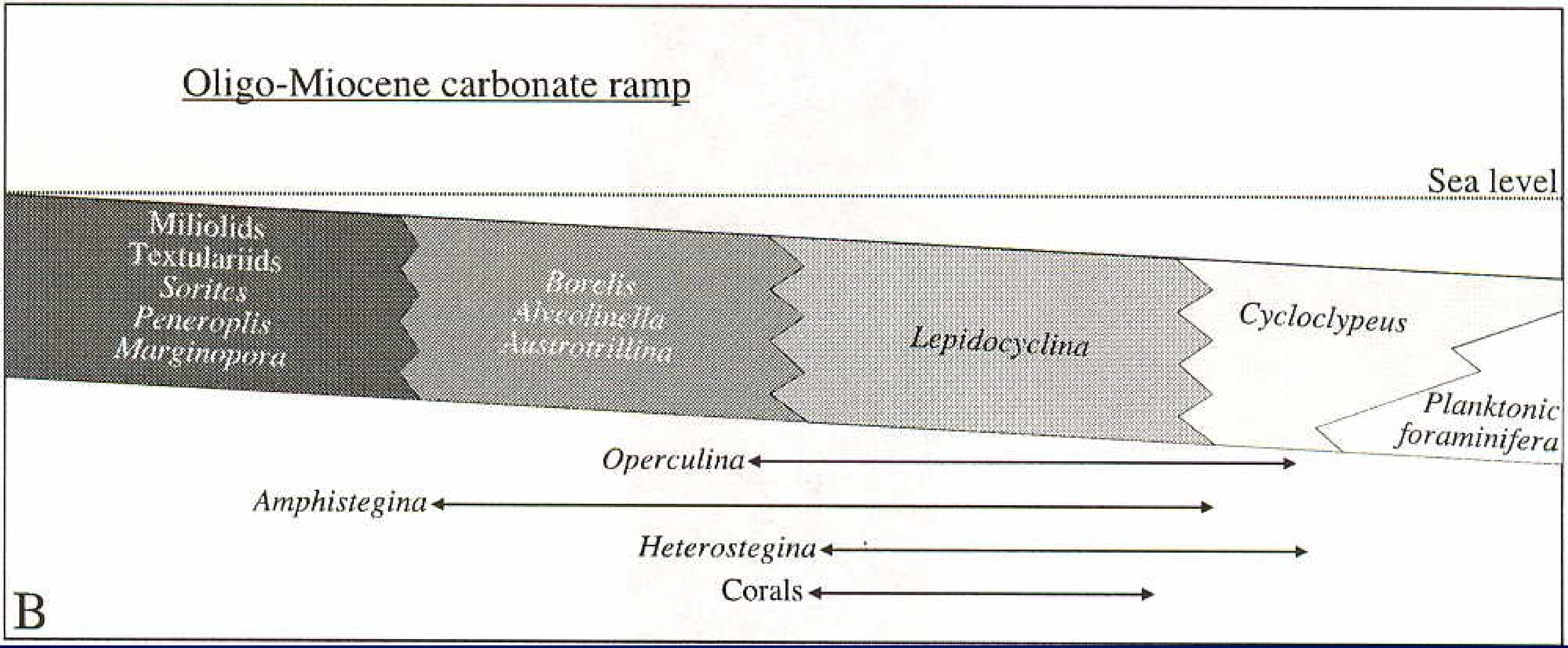
(Dutton et al., 2005)

Apex of nummulites & orthophragmines living in outer shelf/ramp habitats

Surface to thermocline vs. surface to bottom temperature gradients in subtropical North Pacific (Shatzky Rise)

Oligo-Miocene LBF Assemblages

- Lower diversity horizontally and vertically
- What stratification and variability did they encounter?



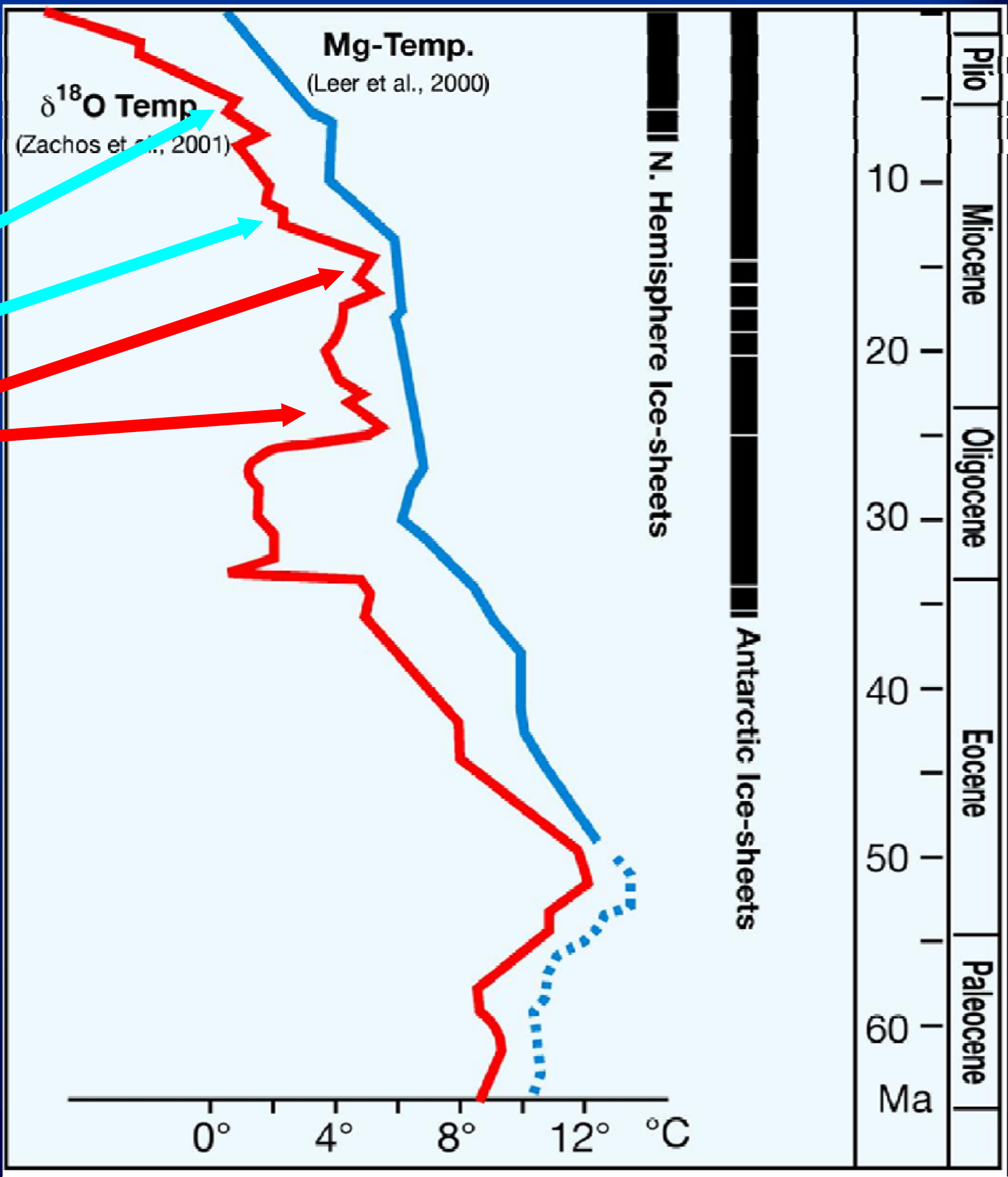
Beavington-Penney & Racey 2004

Deep sea paleotemperatures and Oligo-Miocene LBF lineages

Extinction of lepidocyclinids

Decline in lepidocyclinids

Peak for lepidocyclinids
and other O-M LBF



From various sources

Summary: deep sea temperatures and LBF lineages

Modern assemblages

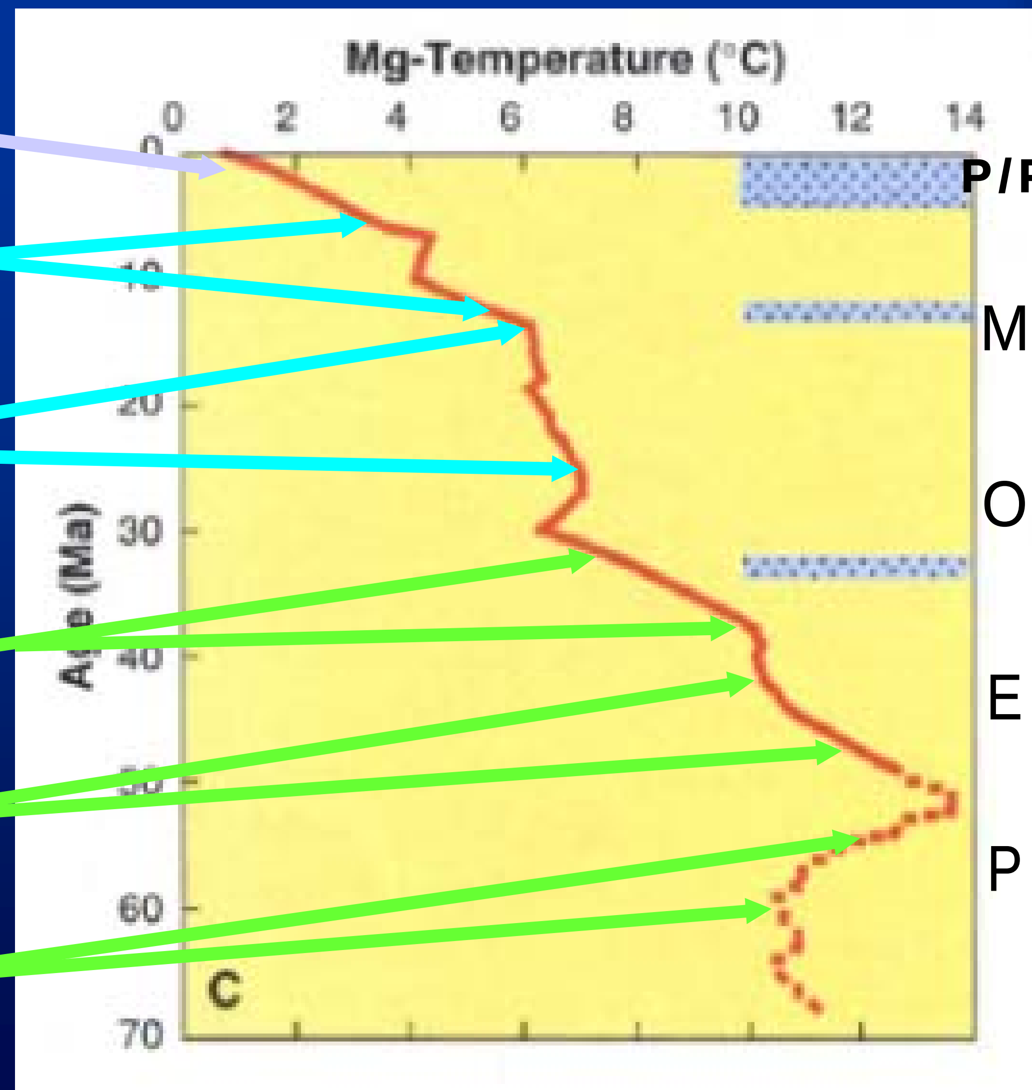
Extinctions of lepidocyclinids

Peak for lepidocyclinids and other O-M LBF

Nummulite & orthophragmine extinctions

Large nummulites peak

Diversification of LBF



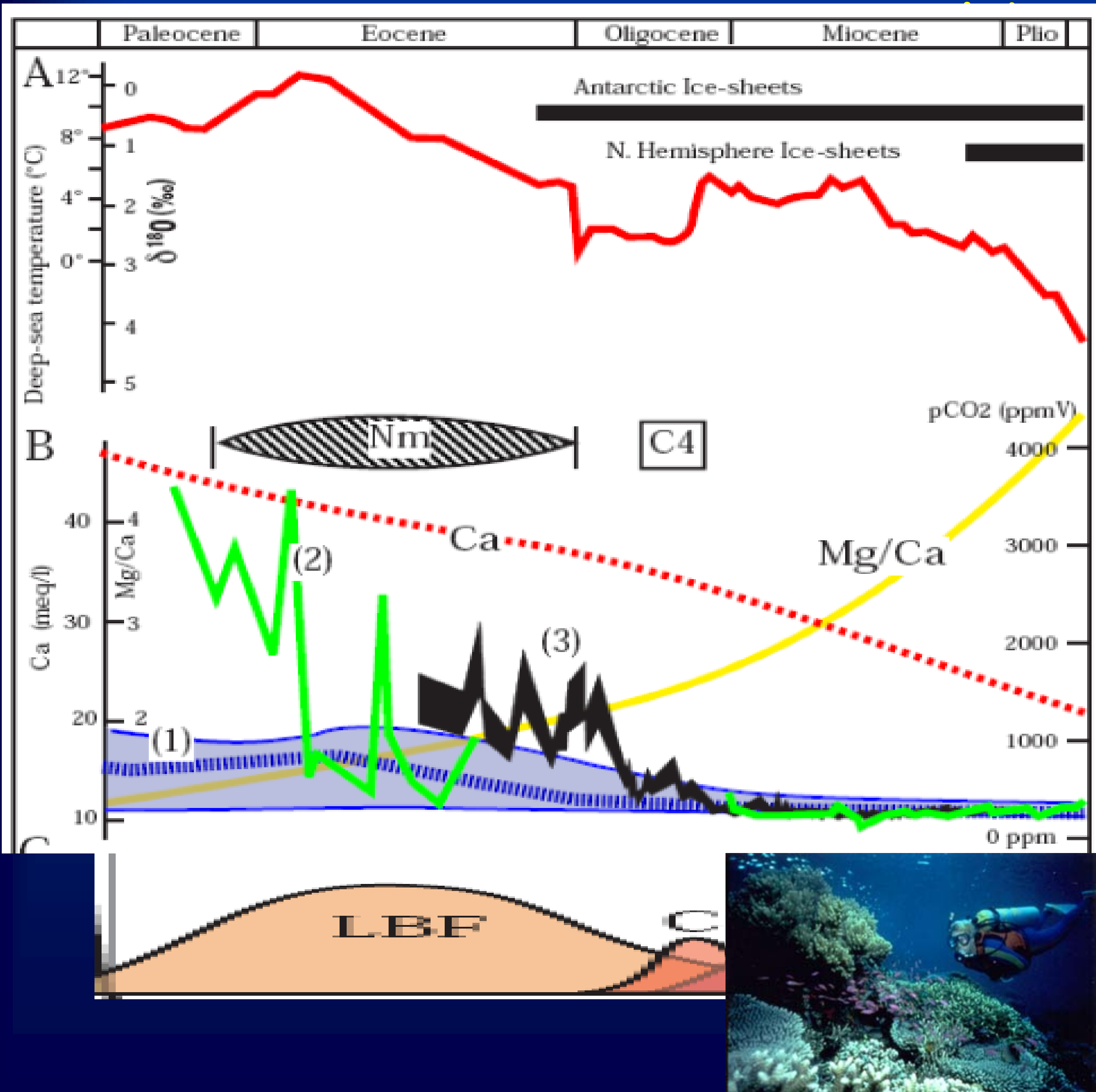
From various sources

Leer et al. 2000

Interpretations

1. Cenozoic changes in ocean circulation increased bathymetric as well as latitudinal temperature gradients
   - Also likely influenced bathymetric nutrient gradients
2. Increasing bathymetric temperature gradients strongly influenced mesophotic to oligophotic environments
3. Largest LBF taxa live at oligophotic depths
4. Turnovers in LBF lineages coincide with strong declines in deepwater paleotemperatures
5. Declining diversities in "peak" LBF biotas are consistent with increasing temperature variability in mesophotic to oligophotic environments through the Cenozoic

The Paradox of the Cenozoic:
So why do coral reefs like the Icehouse



- Greenhouse → Icehouse
  - [Ca^{2+}] ↓
  - [Mg^{2+}] ↑
  - pCO_2 ↓
- Succession
  - Calcite/Mg-calcite → aragonite/Mg-calcite
  - LBF/RA → corals/RA
- Neogene co-evolution of red algae, corals & light-tolerant zooxanthellae into shallow, high light environments
  - Provided energy for hypercalcification

Pomar and Hallock (2008)

Concluding Remarks

- Synthesis builds upon previous interpretations of LBF paleoecology and influence of algal symbiosis
- Presents new understanding of temporal variability of shelf environments at 30-100+ m
- Bathymetric gradients have changed dramatically on mid-low latitude ramps and shelf margins through the Cenozoic
- Provides new context to utilize planktic paleotemperature data to better understand evolutionary trends
  - in Cenozoic LBF assemblages
  - in Cenozoic carbonate ramp/shelf communities

Previous and Current Sources of Funding for LBF Studies

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USGS
science for a changing world
Center for Coastal Geology
St. Petersburg, FL

NSF

1983 2003
OCEAN DRILLING PROGRAM

NOAA
National Undersea Research Center
University of North Carolina at Wilmington

NOAA
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

Florida Hurricane Mitigation Alliance

MUSC
Medical University of South Carolina

Sea Grant

Note: Funding does not imply endorsement of views presented


Thank you