Insights into the lives of foraminifera, versatile microbes with a big fossil record

WOODS HOLE OCEANOGRAPHIC INSTITUTION

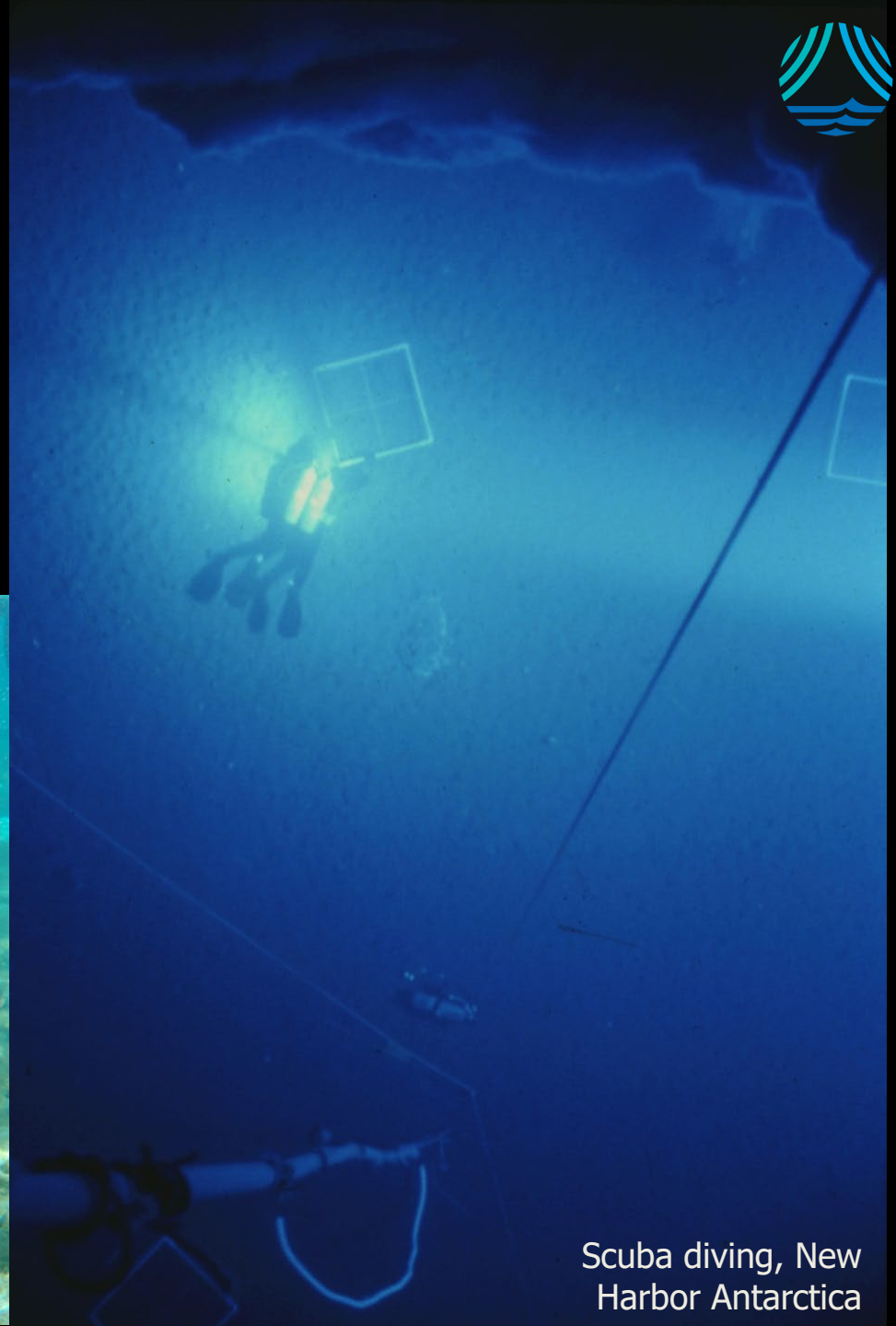
Joan M. Bernhard
Senior Scientist
Geology & Geophysics Department
jbernhard@whoi.edu

Background & Highlights:

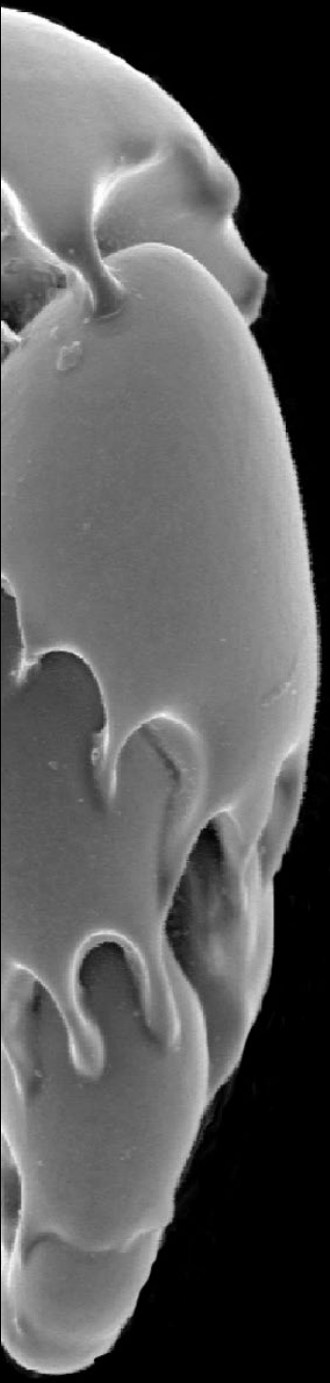
- BA & MS in Geology; PhD in Biological Oceanography; Post-Doc in Cell Biology
- Geomicrobiologist
- 198 scuba dives under Antarctic ice
- 4 *Alvin* dives; 67 research cruises on 23 different ships
- Field work in Shark Bay (stromatolites)

First *Alvin* dive

Snorkeling in Shark Bay, Western Australia



Scuba diving, New Harbor Antarctica

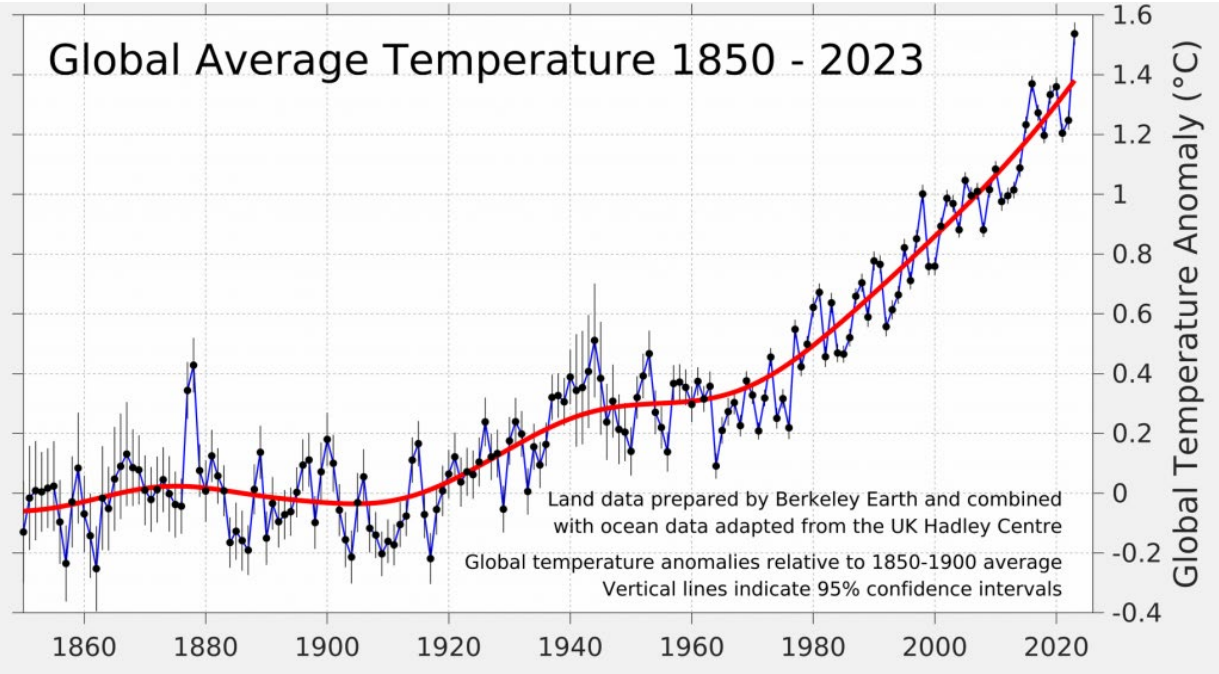


Overview

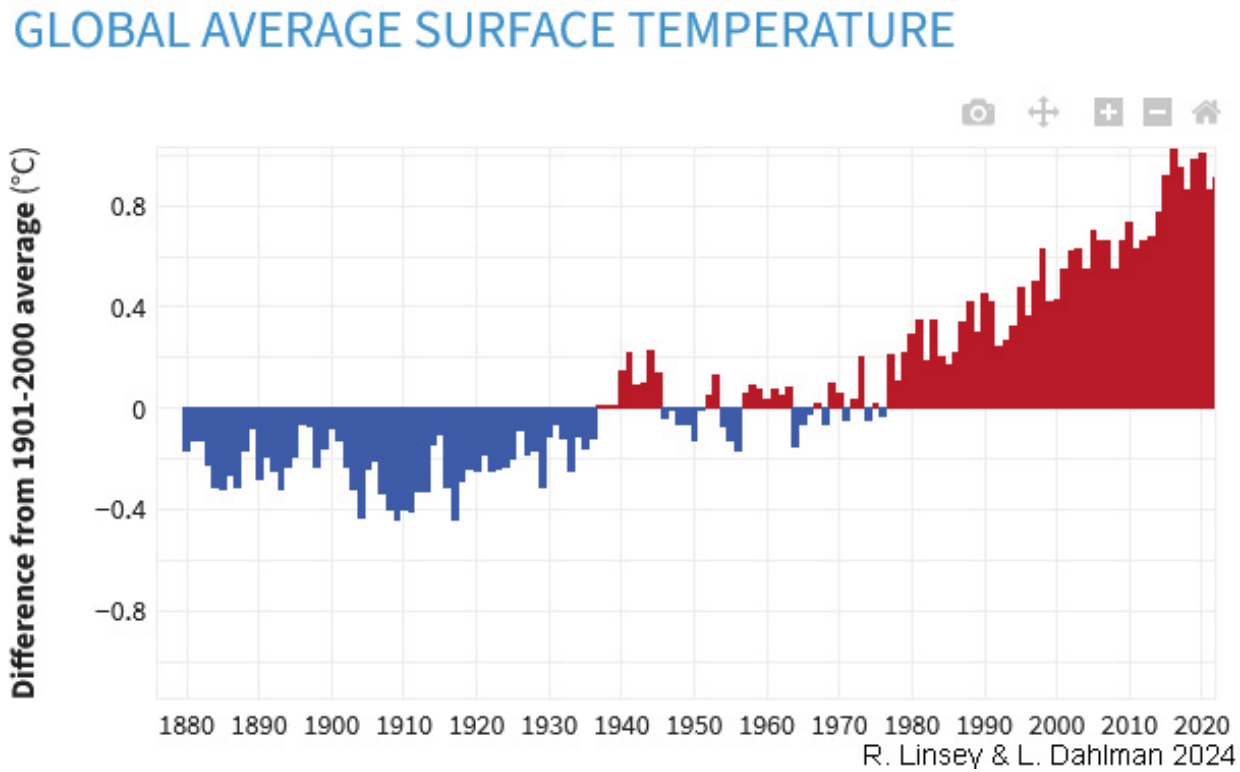
1. Rationale
    1. Earth is warming
    2. Ocean deoxygenation (reduction in oxygen content)
    3. Increased stress on fisheries (seafood in general)
    4. Thus, understanding dynamics of oceanic oxygen concentrations is important to society
2. Foraminifera (single-celled eukaryotes, protist) respond to changes in oxygen
    1. Biology – What are they?
    2. Ecology– Where do they live?
    3. When did they evolve?
    4. Why are they a keystone for paleoclimate understanding?

3. Throughout talk, items will be passed around. Please be sure they make their way back to me

Earth is warming

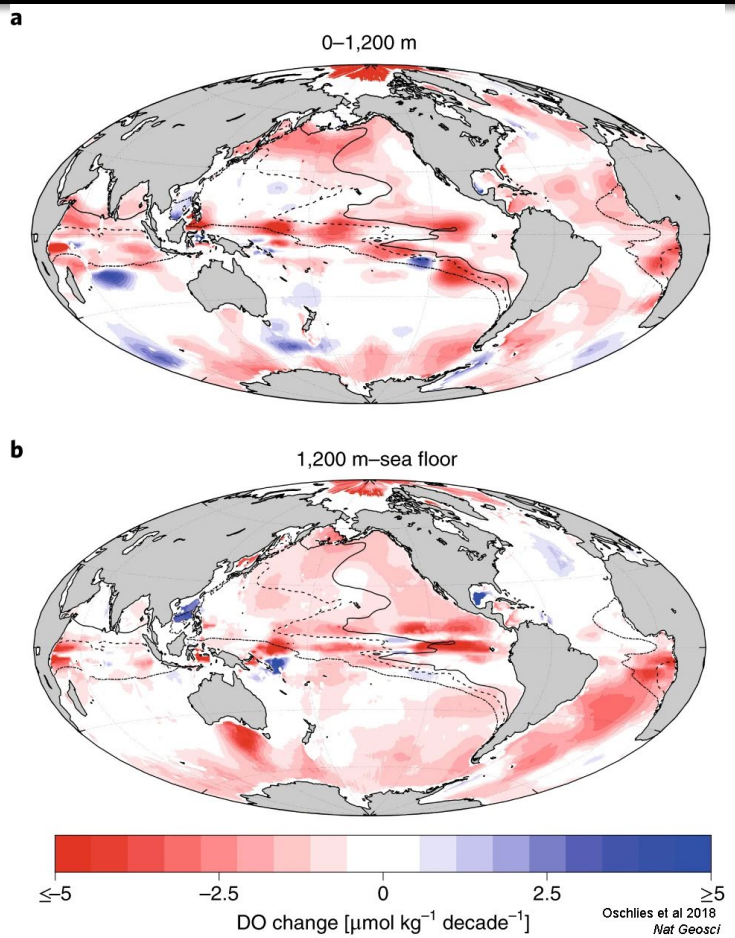


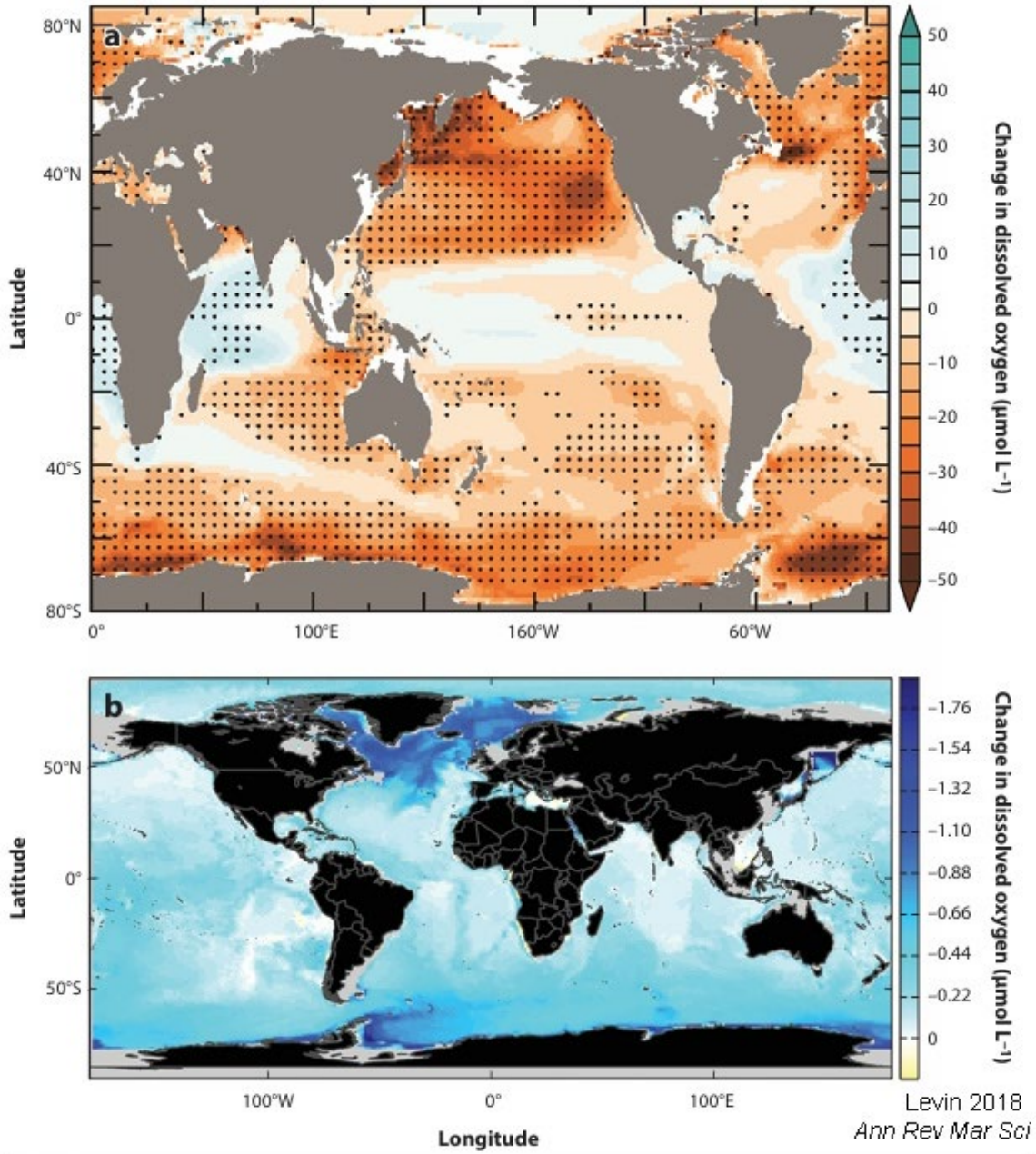
Berkeley Earth



Warming results in ocean deoxygenation

Loss of O_2 in certain regions/depths due to decreased ventilation (circulation)





Projected changes in oxygen from the present to 2100 (*a*) at 200–600 m under representative concentration pathway (RCP) 8.5 and (*b*) at the seafloor. Panel *a* adapted from Bopp et al. (2013) under the Creative Commons Attribution 3.0 Unported license (**https://creativecommons.org/licenses/by/3.0**); panel *b* adapted from Sweetman et al. (2017) under the Creative Commons Attribution 4.0 International license (**https://creativecommons.org/licenses/by/4.0**).

Low oxygen negatively impacts fisheries

- Motile marine animals (most fish, shrimp) will move up in the water column to maintain access to sufficient O_2 concentration; become crowded
- Some fish (halibut) and others (crabs, lobsters, clams) are benthic so must move laterally along seafloor to gain access to better conditions (or die)
- Some octopus can tolerate relatively low oxygen concentrations

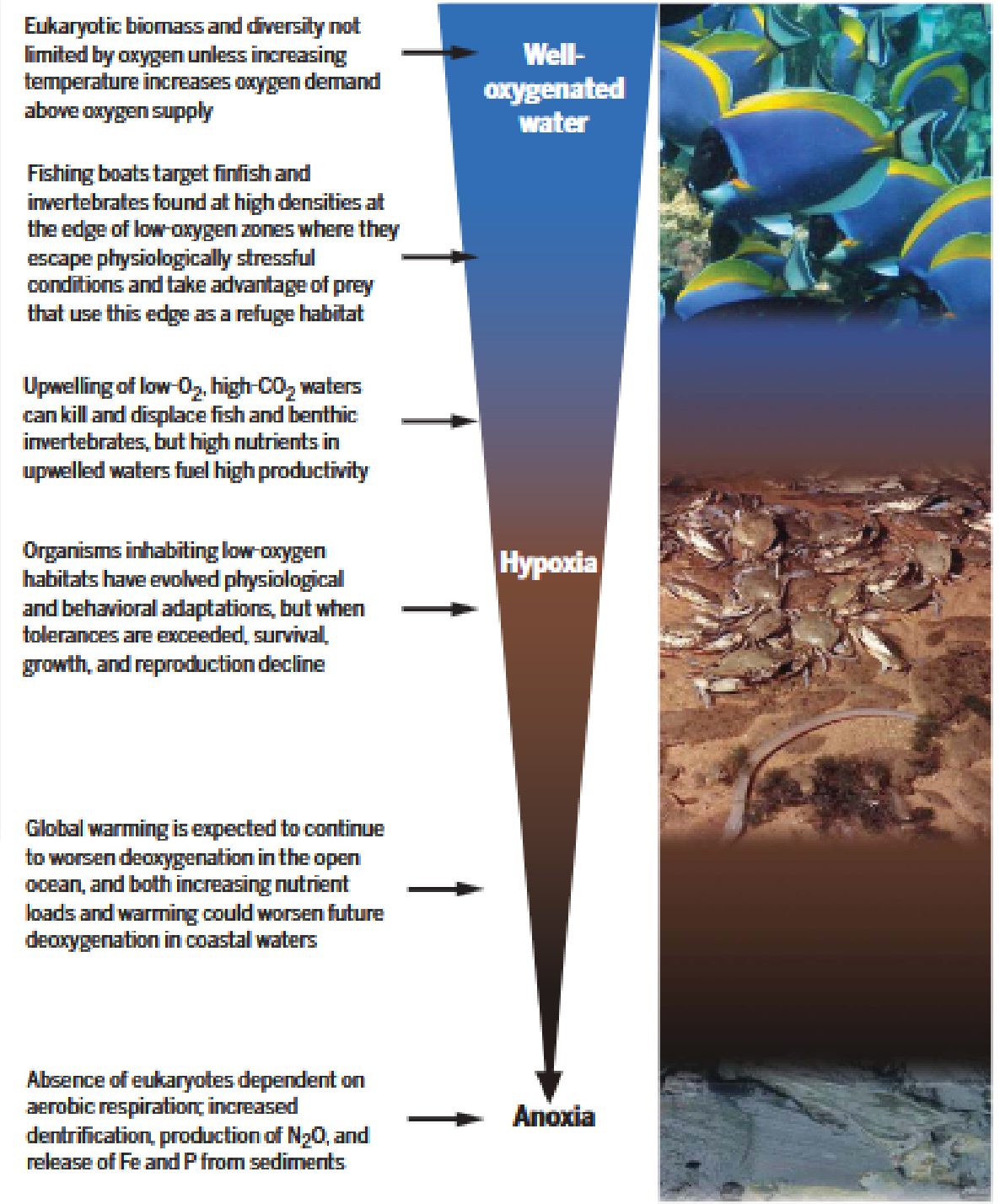


Fig. 4. Oxygen exerts a strong control over biological and biogeochemical processes in the open ocean and coastal waters. Whether oxygen patterns change over space, as with increasing depth, or over time, as the effects of nutrients and warming become more pronounced, animal diversity, biomass, and productivity decline with decreasing levels of oxygen. At the edge of low-oxygen zones, where nutrients are high and predators and their prey are concentrated into an oxygenated habitat, productivity can be very high, but even brief exposures to low oxygen levels can have strong negative effects. (**Top**) Well-oxygenated coral reef with abundant fish and invertebrate assemblages. (**Middle**) Low-oxygen event in Mobile Bay, United States, in which crabs and fish crowd into extreme shallows where oxygen levels are highest. (**Bottom**) Anoxic mud devoid of macrofauna.

Breitburg et al 2018 *Science*

Understanding the dynamics of oxygen concentrations in the ocean is important

A stock photo shows dead fish at the surface of water.
papa1266/Getty

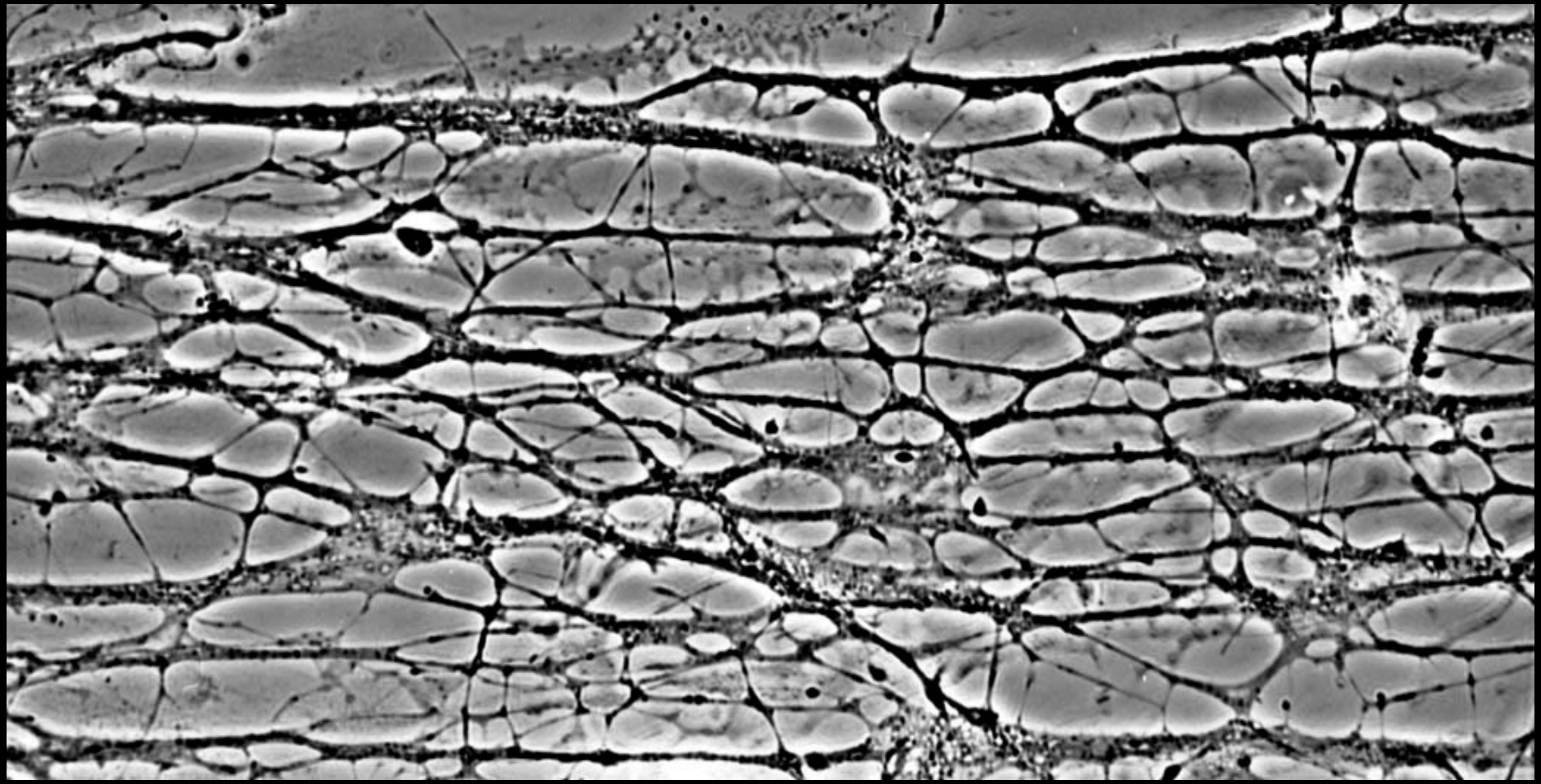
Oxygen concentrations in past oceans

- Key to the future is the past
- Remarkably, there are few "proxies" to help determine past oxygen concentrations of the oceans
- Dr. Wang will discuss this point in more detail in the next talk
- One emerging proxy for paleo-O_2 involves foraminifera, single-celled eukaryotes (i.e., protist) that are nearly ubiquitous in the marine realm

What is a foraminifer?

Depends who you ask

Wikipedia: Foraminifera (/fəˌræməˈnɪfərə/, Latin meaning hole bearers; informally called "forams") are members of a phylum or class of amoeboid protists characterized by … [reticulopodia] for catching food and other uses; and commonly an external shell (called a "test") of diverse forms and materials…



Reticulopods (branching pseudopods) via Light Microscopy

From SS Bowser

Reticulopod videos:

https://www.youtube.com/watch?v=17eq1gOHaSI
(*Quinqueloculina* sp., anonymous, uploaded to YouTube 18 Oct 2012)

https://www.youtube.com/watch?v=-jpJhDHSWow
unknown rotalid, © www.microscopeitaly.it, uploaded July 2012)

Reticulopod Functions

- Trophic mechanisms (e.g., feeding)
- Locomotion to/within suitable habitat
- Control buoyancy (anchor into sediment; attach to solid surfaces; “float” on air-water interface)
- Reproduction (cell division; pairing & brood chamber construction; progeny dispersal)
- Metabolic exchange
- Test (shell) construction

Slide modified from Sam Bowser

Why Foraminifera?

- Abundant, especially in some chemoclines (steep redox gradient)
- Environmentally sensitive
- Fossil record
  - Taxa (assemblages; oil exploration- age and location)
  - Geochemical proxies
- Species gradation with $[O_2]$

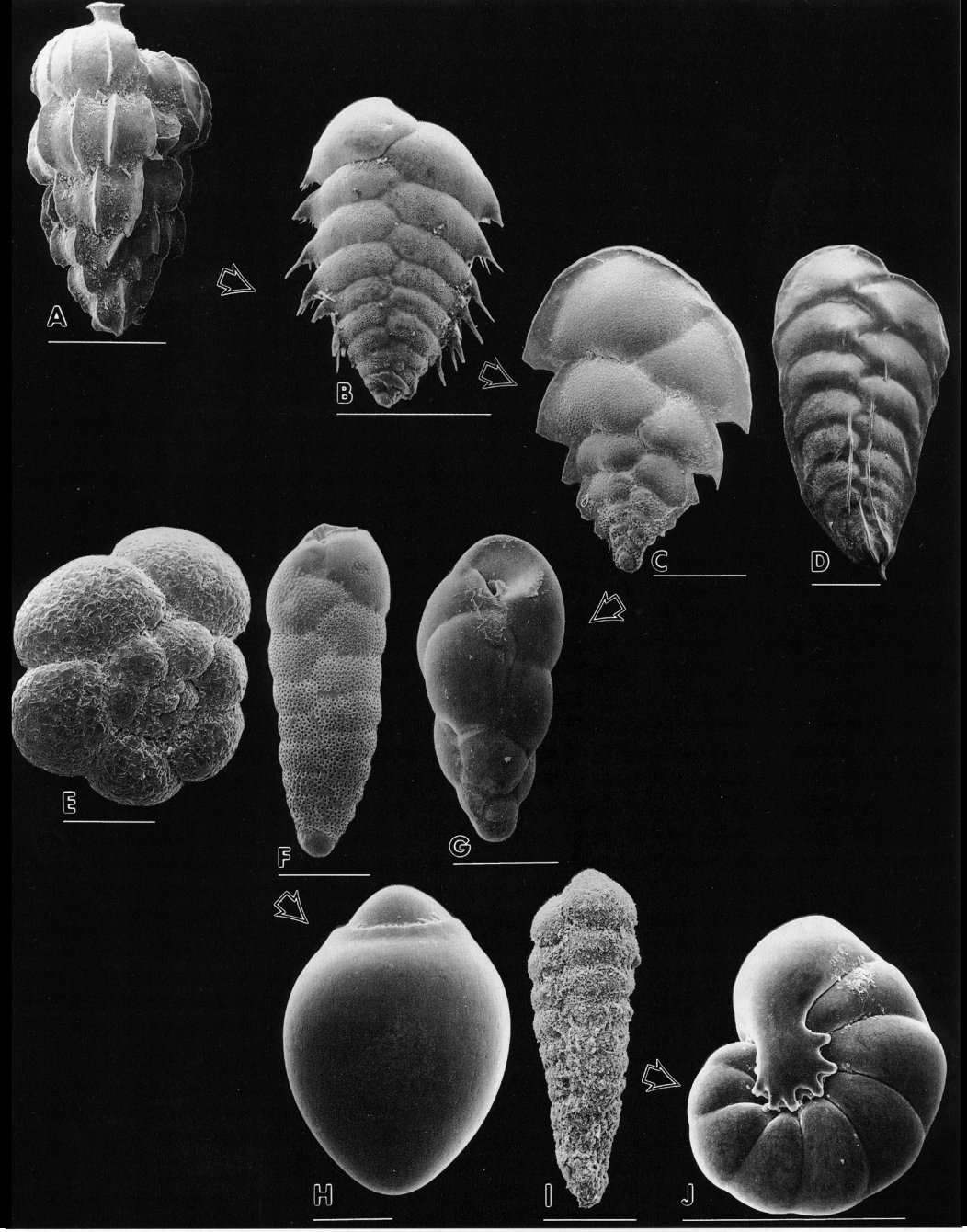


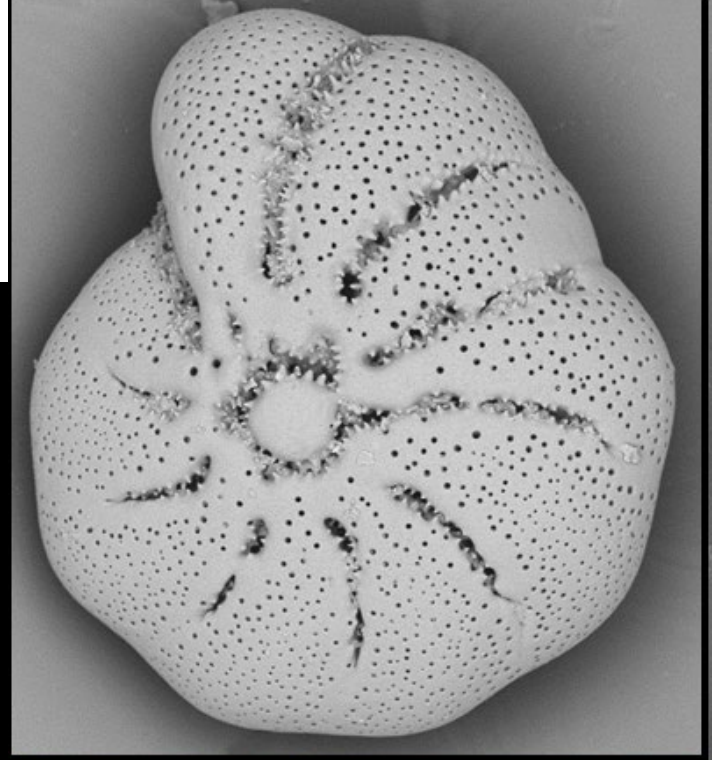
FIGURE 5. Scanning electron micrographs of common foraminiferal species in the Santa Barbara Basin. Species are arranged in a progression from those occurring in higher $[O_2]$ (for example, *Uvigerina juncea*) to those occurring with lowest bottom water $[O_2]$ (that is, *Nonionella stella*). A, *Uvigerina juncea*; B, *Suggrunda eckisi*; C, *Loxostomum pseudobeyrichi*; D, *Bolivina argentea*; E, *Trochammina pacifica*; F, *Bolivina seminuda*; G, *Buliminella tenuata*; H, *Chilostomella ovoidea*; I, *Spiroplectammina earlandi*; J, *Nonionella stella*. Scale bars = 200 μm.

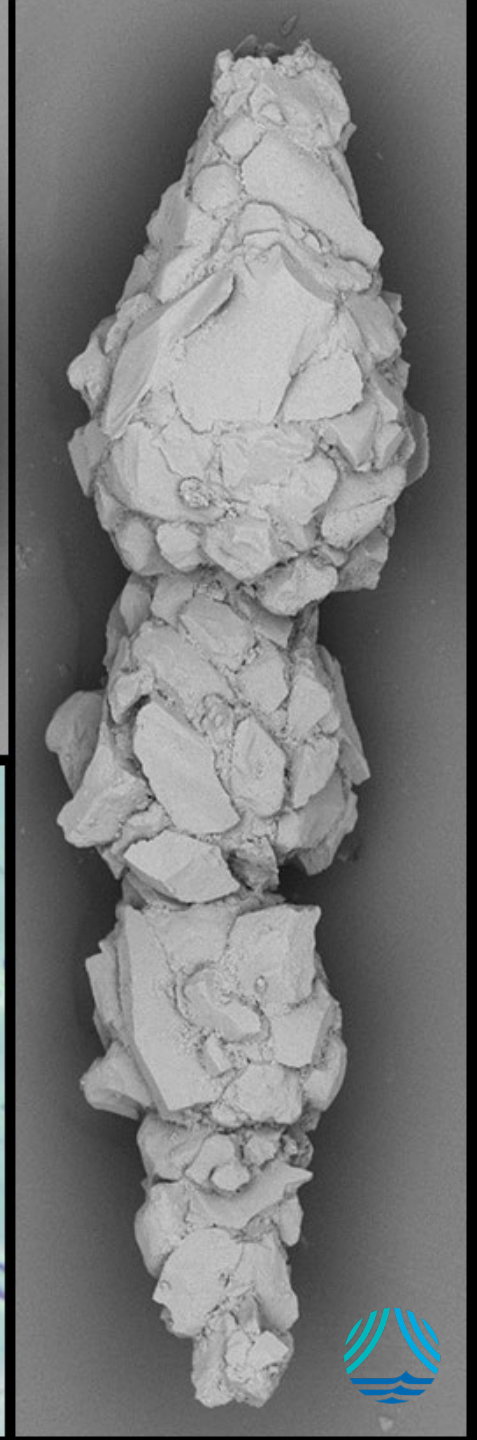
Plate from Bernhard et al. 1997 *JFR*

Test composition

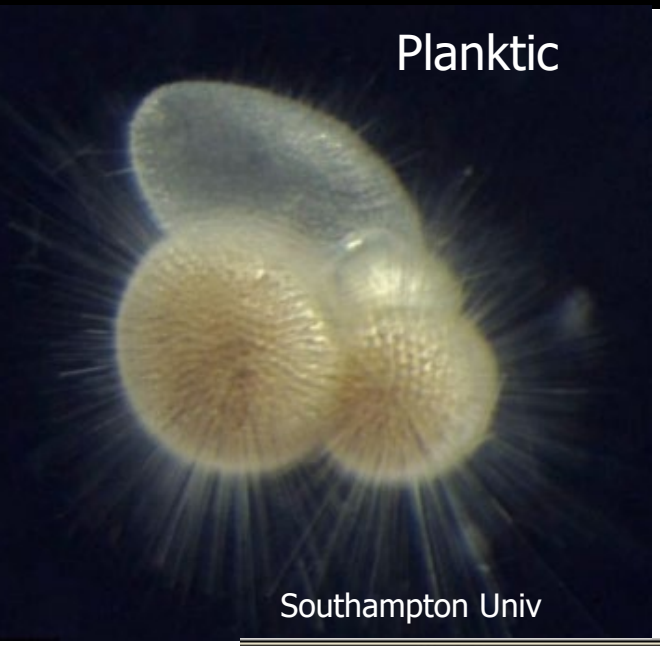
- Tests (shells) made of either:
  - secreted calcium carbonate
  - accumulated mineral grains secured with organic or carbonate cement
  - organic test (thecate)
  - "naked" (indistinct cell body)


Freshwater foram





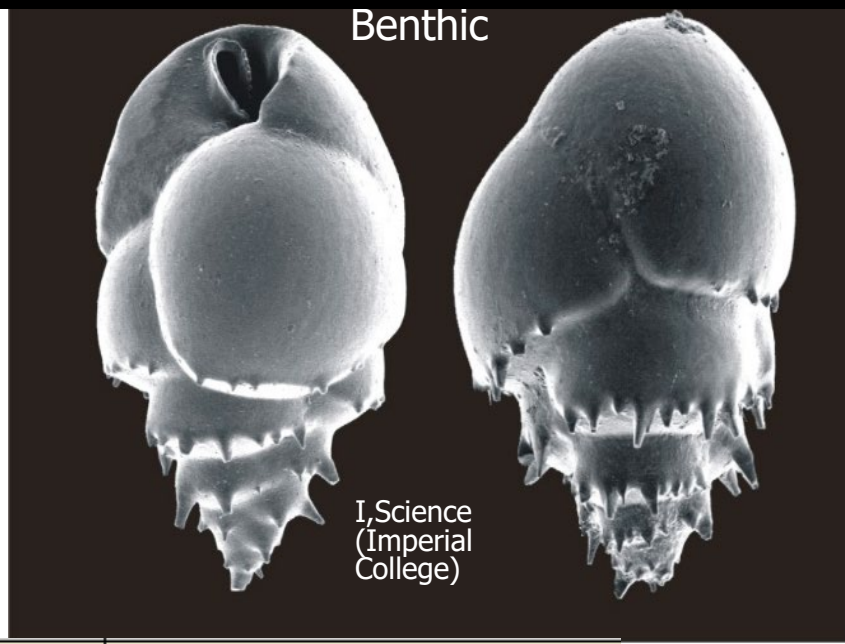
Life Styles

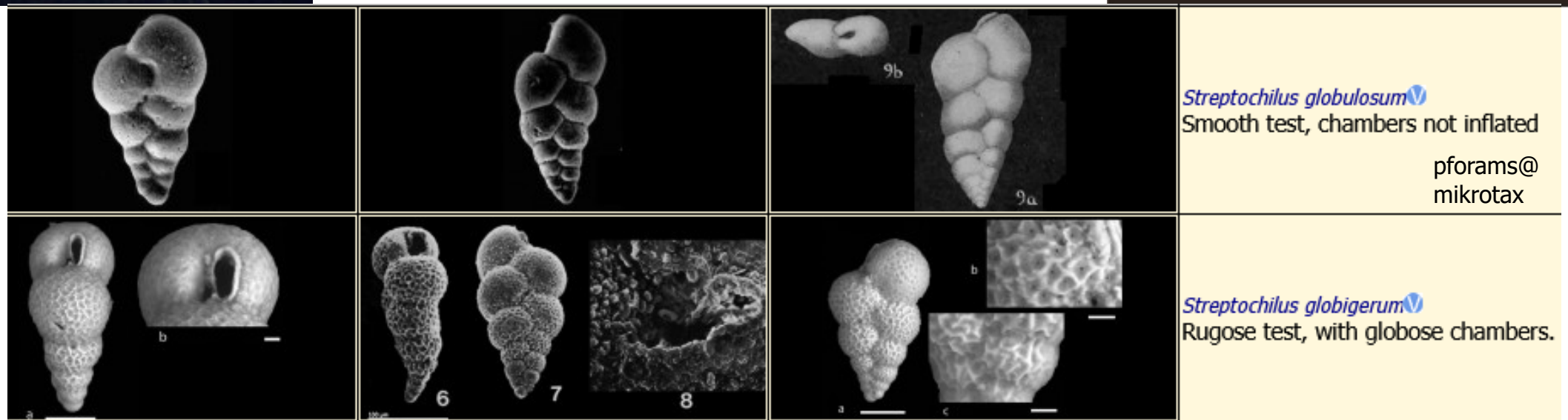


Planktonic: Live in water column;
~50 extant species

Benthic: Live on or in sea/lake floor;
~8000 - 9000 extant species

Tychopelagic (both): Darling et al. 2009 *PNAS*
Streptochilus globigerus/ Bolivina variabilis





Habitats

- Live almost everywhere
  - ocean waters
  - ocean sediments
  - freshwater sediments (ponds)
  - terrestrial leaf litter

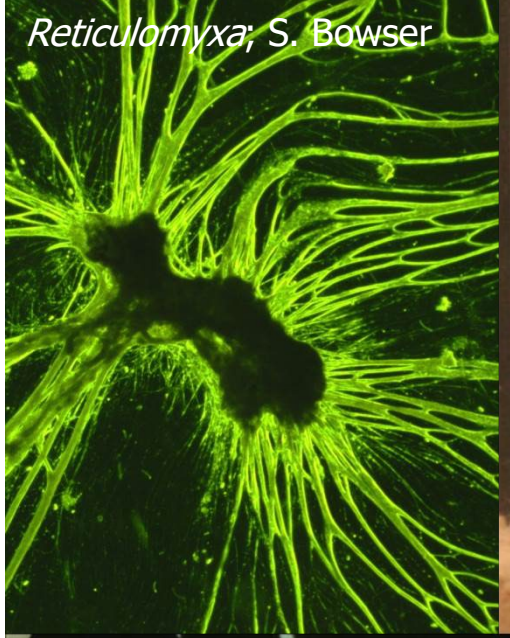
- Shallow to deep water
  - mud flats/salt marshes
  - deepest ocean trenches
- Polar to equator
- Reef/reef flats (e.g., *Homotrema rubrum,* sessile; most forams are motile)

Side view of mudflat surface (most fluorescent items are forams), Jauffrais et al., unpubl

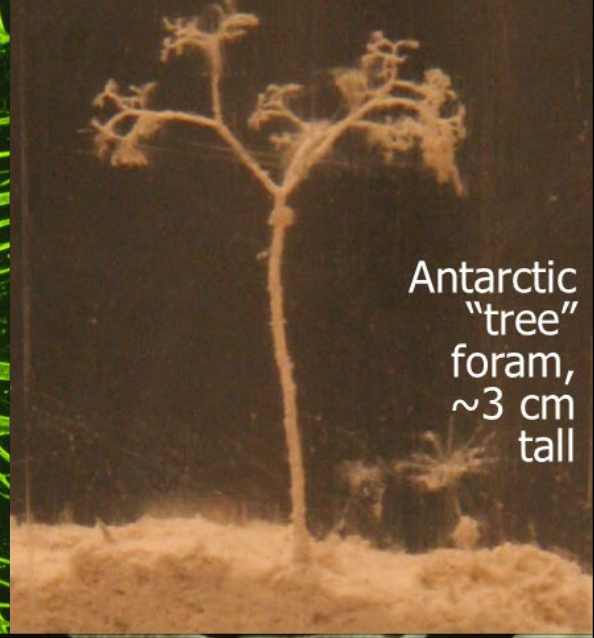
Nano-reef.com

Test Shape

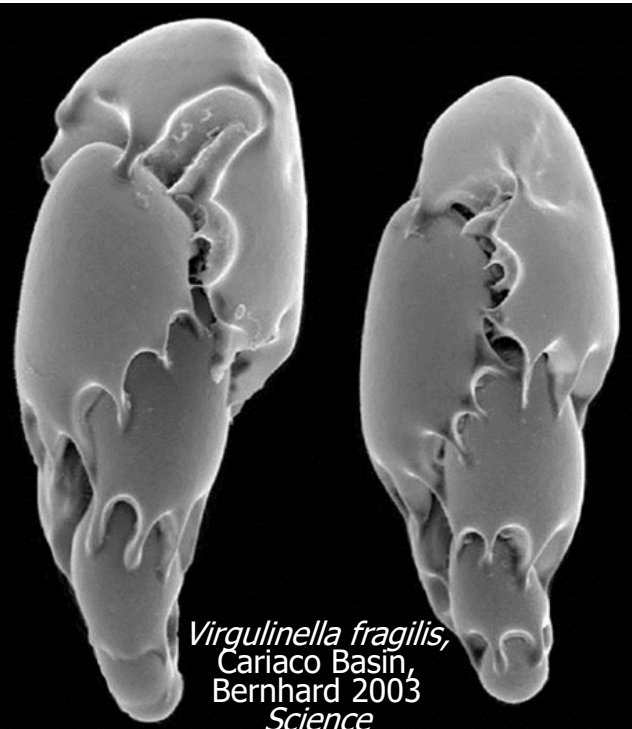
- Most geometric shapes
  - Sphere, Spheroid (prolate, oblate), Cylinder (short, long), Enrolled cylinder, Planoconvex, Cone, Biconvex, etc
- Freeform
- Stars
- "Trees"



Reticulomyxa; S. Bowser



Antarctic "tree" foram, ~3 cm tall



Virgulinella fragilis, Cariaco Basin, Bernhard 2003 *Science*

Star sands (*Baculogypsina, Calcarina*) Okinawa reef flat

Star Sands

- *Baculogypsina*
- Coral-reef shallows
- Tropical
- Imagine waves breaking & cries of seagulls
- What role do you think the bumps serve?

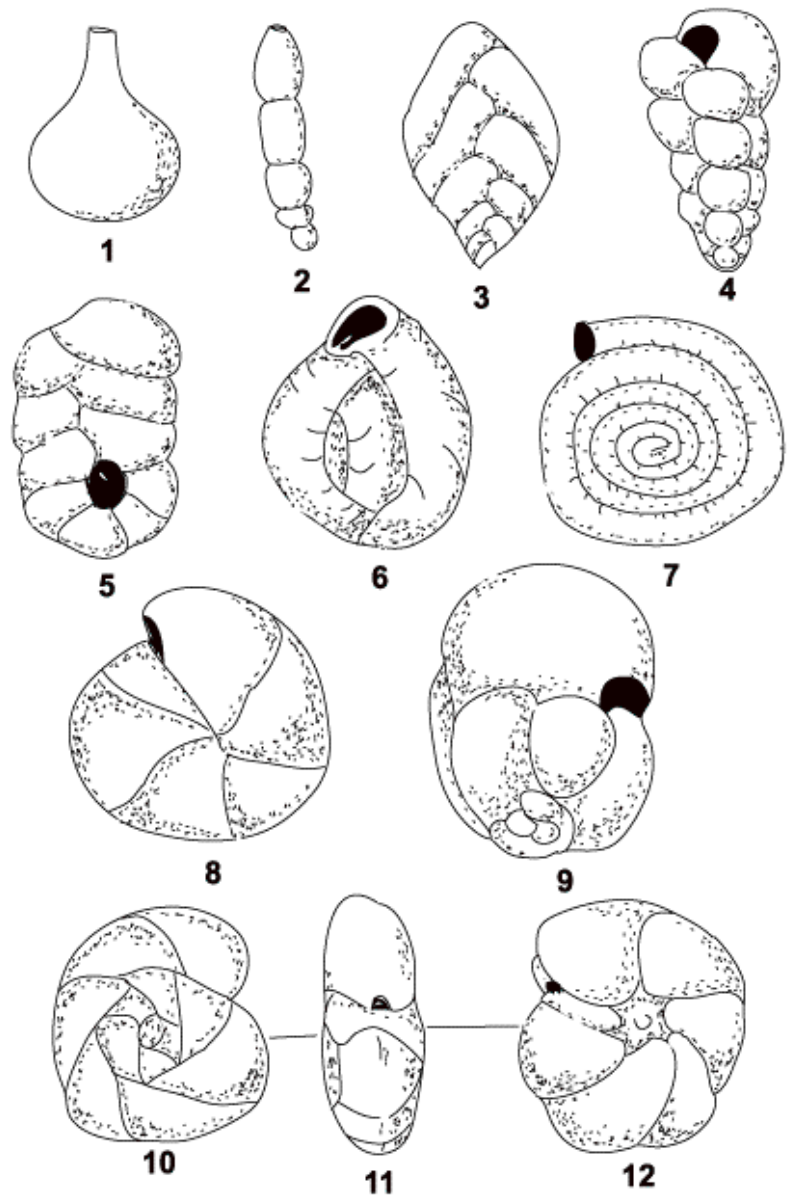
Star sands (*Baculogypsina, Calcarina*) Okinawa reef flat

Shape: Chamber Arrangement

- Single chamber
- Multilocular
  - Uniserial
  - Biserial
  - Triserial, etc
- Spiral
  - Trochospiral
  - Planispiral
- Enrolled
  - Evolute
  - Involute

Single chamber: Monothalamid; tectinous (organic test)

Bernhard et al. (2006)



Principle types of chamber arrangement. 1, single chambered; 2, uniserial; 3,biserial; 4, triserial; 5, planispiral to biserial; 6, milioline; 7, planispiral evolute; 8, planispiral involute; 9, streptospiral; 10-11-12, trochospiral (10, dorsal view; 11, edge view; 12, ventral view). Redrawn from Loeblich and Tappan 1964.

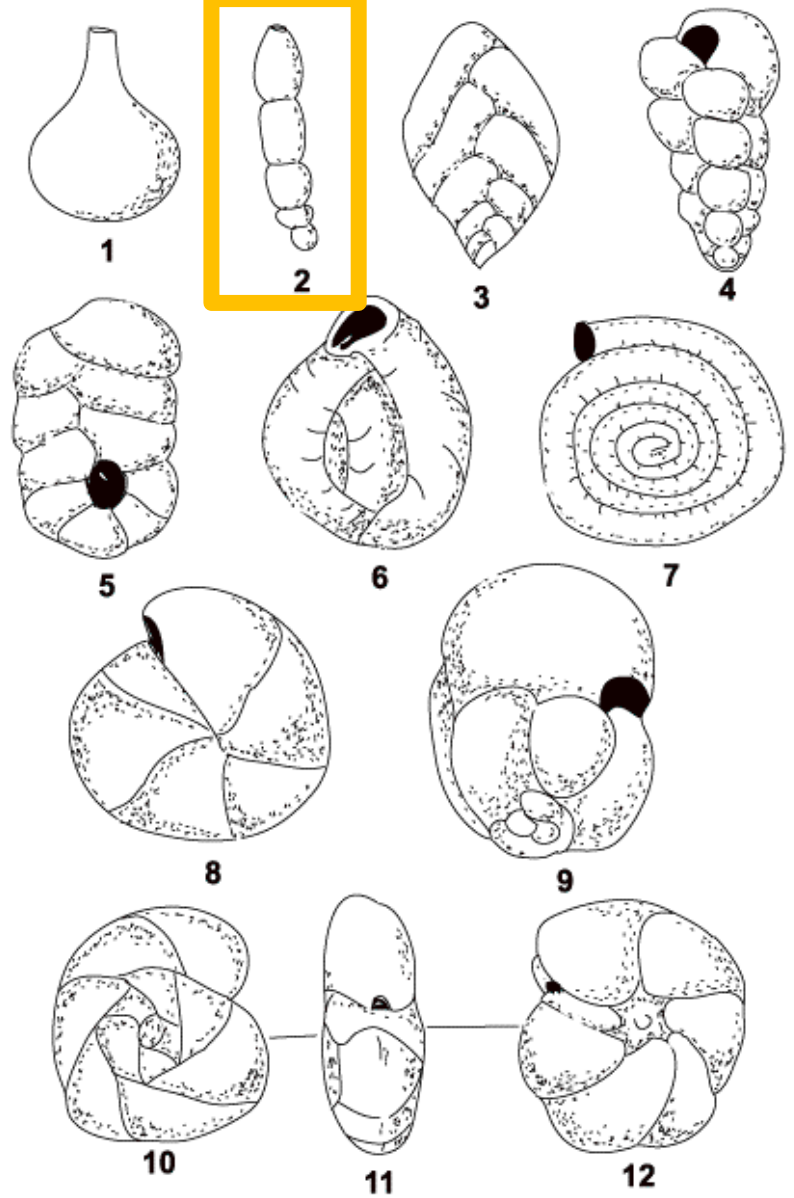
From Marcelle BouDagher-Fadel, online ppt

Shape: Chamber Arrangement

- Single chamber
- Multilocular
  - Uniserial
  - Biserial
  - Triserial, etc
- Spiral
  - Trochospiral
  - Planispiral
- Enrolled
  - Evolute
  - Involute

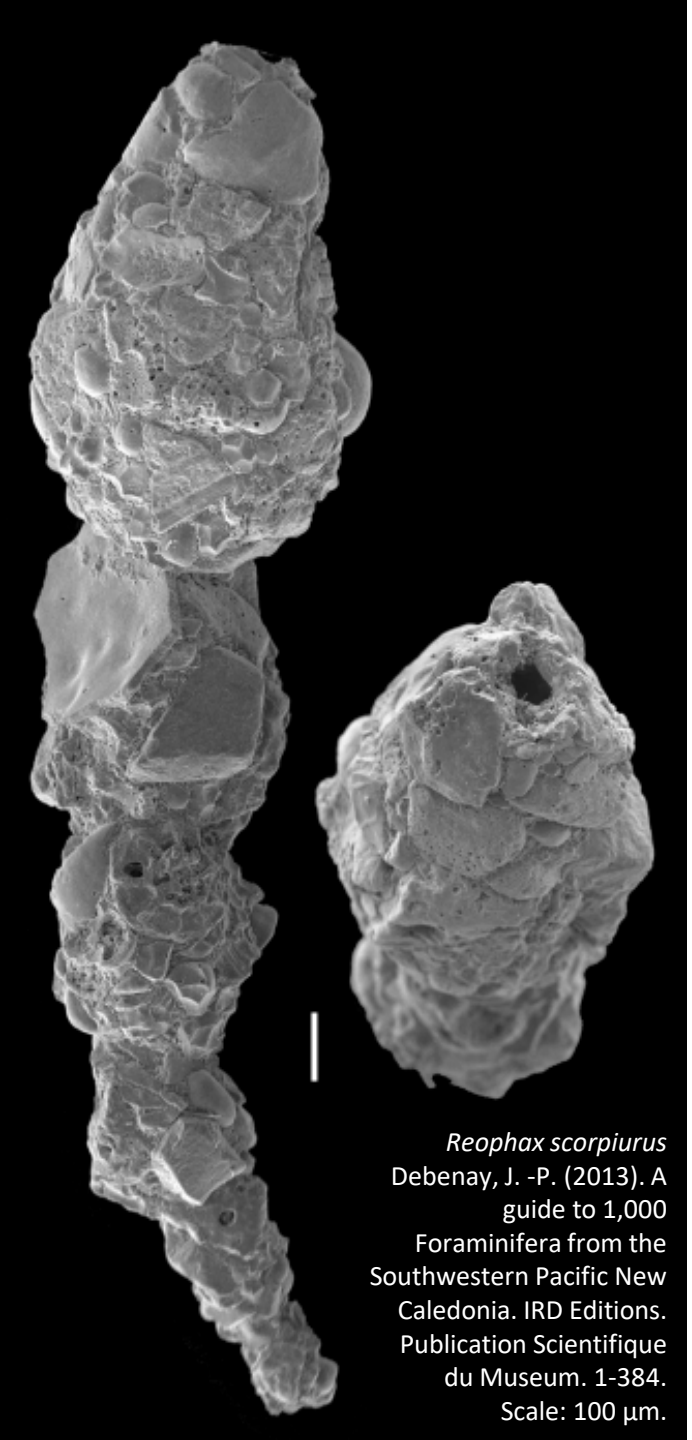
Single chamber: Monothalamid; tectinous (organic test)

Bernhard et al. (2006)

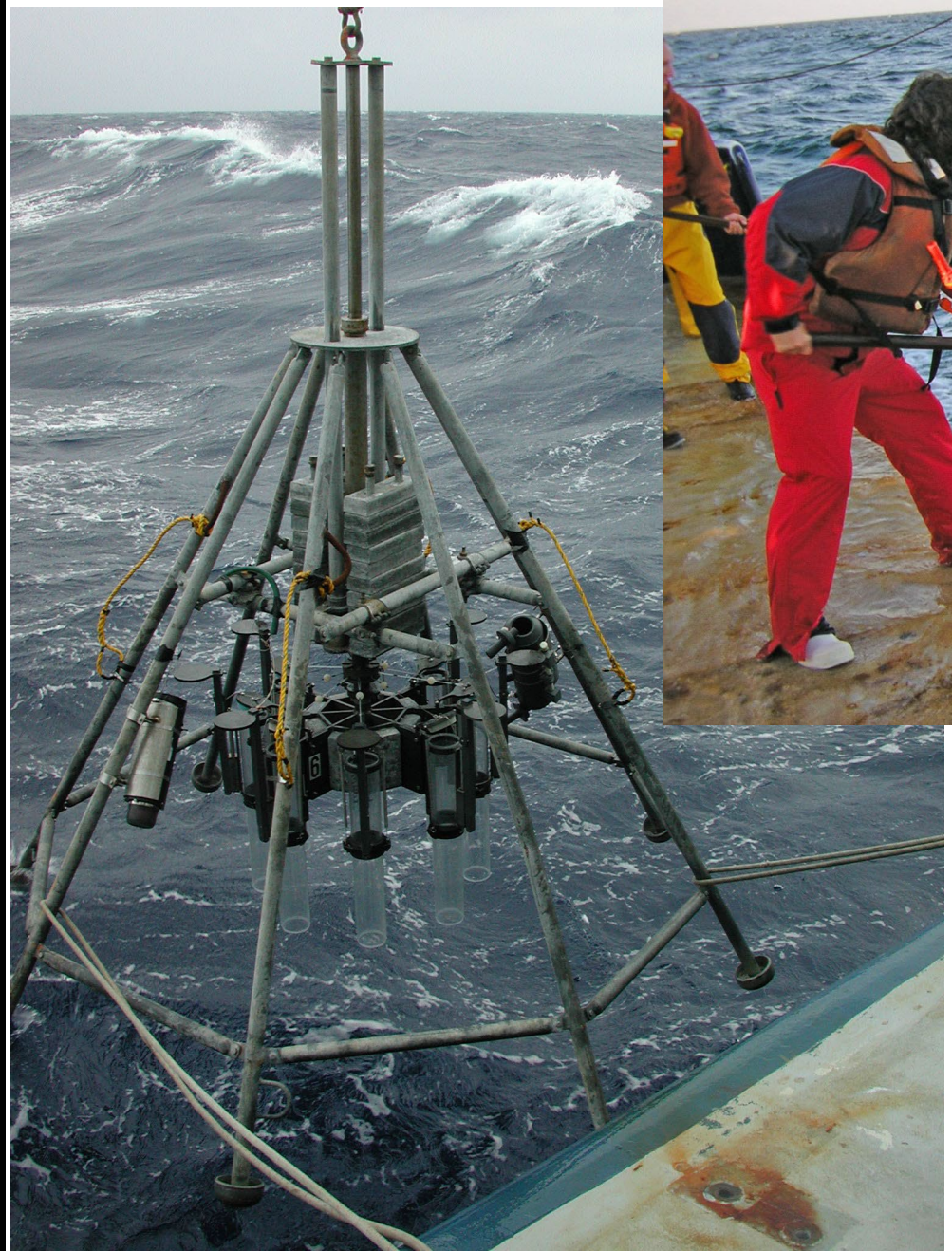


Principle types of chamber arrangement. 1, single chambered; 2, uniserial; 3,biserial; 4, triserial; 5, planispiral to biserial; 6, milioline; 7, planispiral evolute; 8, planispiral involute; 9, streptospiral; 10-11-12, trochospiral (10, dorsal view; 11, edge view; 12, ventral view). Redrawn from Loeblich and Tappan 1964.

From Marcelle BouDagher-Fadel, online ppt



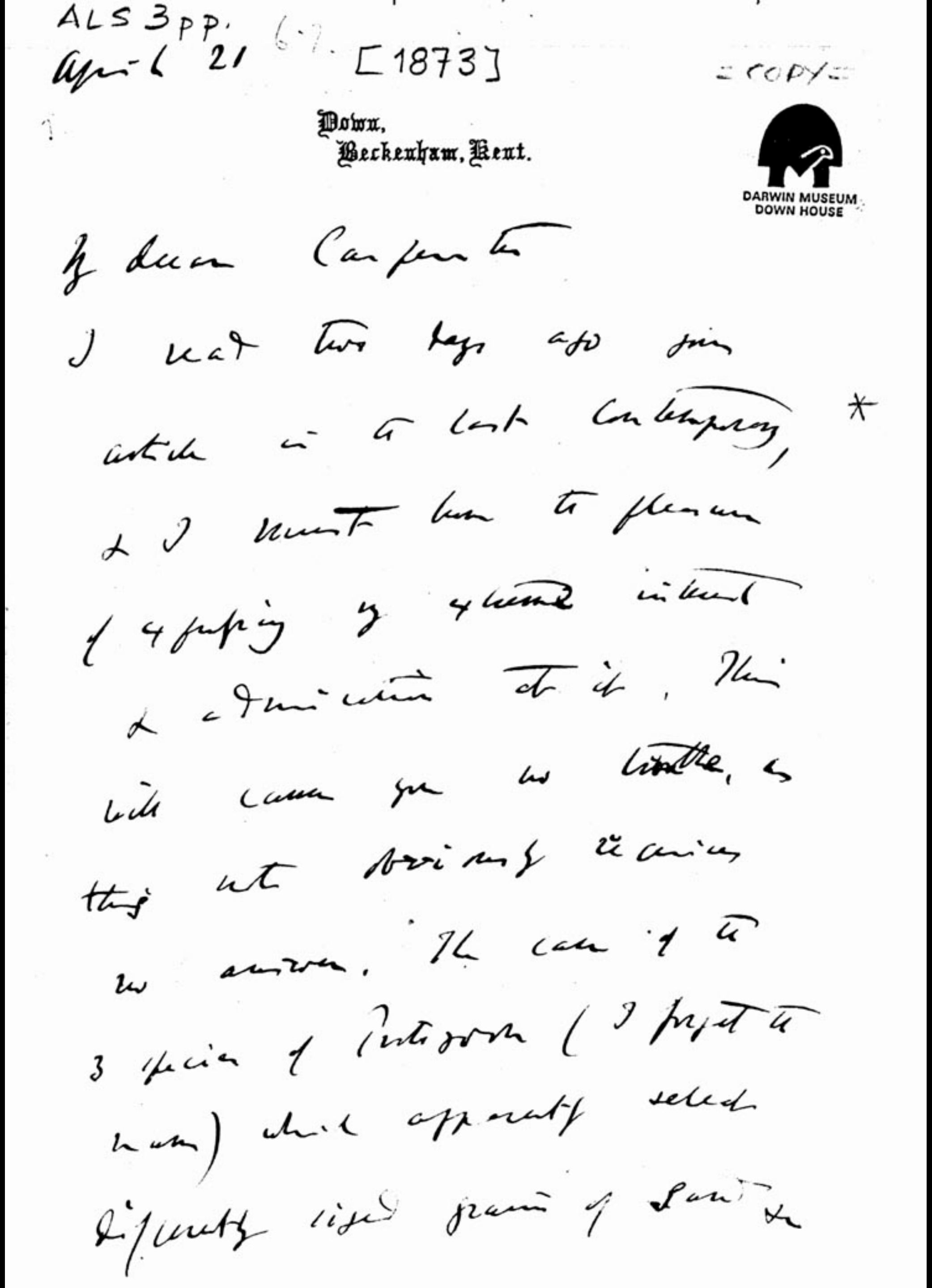
Reophax scorpiurus
Debenay, J. -P. (2013). A guide to 1,000 Foraminifera from the Southwestern Pacific New Caledonia. IRD Editions. Publication Scientifique du Museum. 1-384.
Scale: 100 µm.

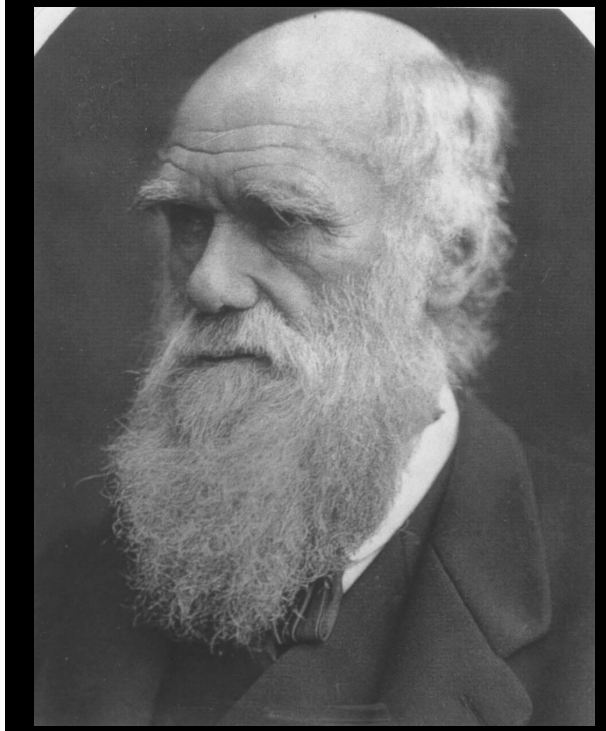


- Coring the deep sea for foraminifera-bearing sediments (middle: multicorer; right: top of a box corer).
- Imagine whine of winch for over an hour…

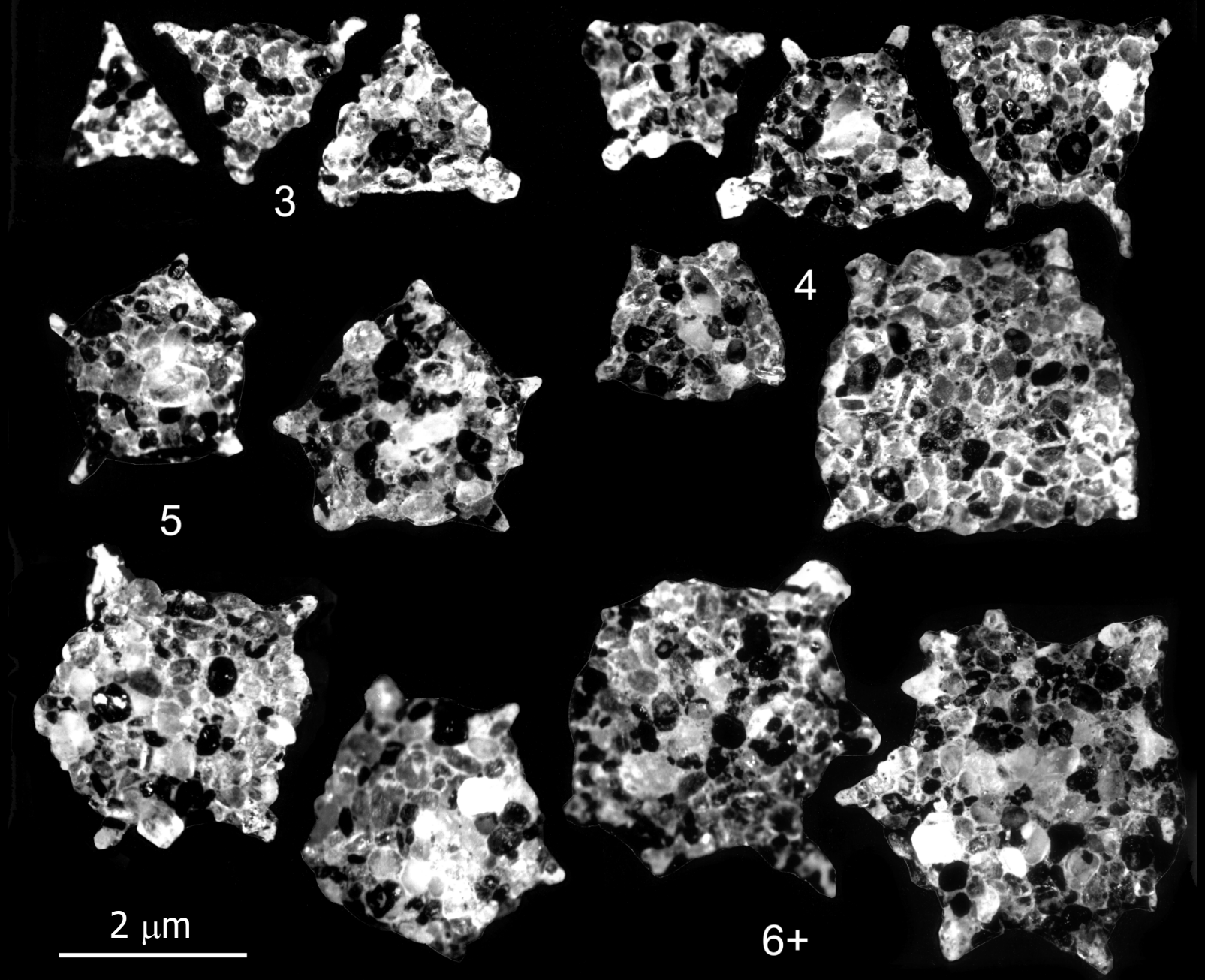
Growth / test construction: Agglutination

- Early fascination with agglutinated test building (Charles Darwin & WB Carpenter)
- "My dear Carpenter… The case of the 3 species of Protozoa (I forget the names) which apparently select differently sized grains of sand…"





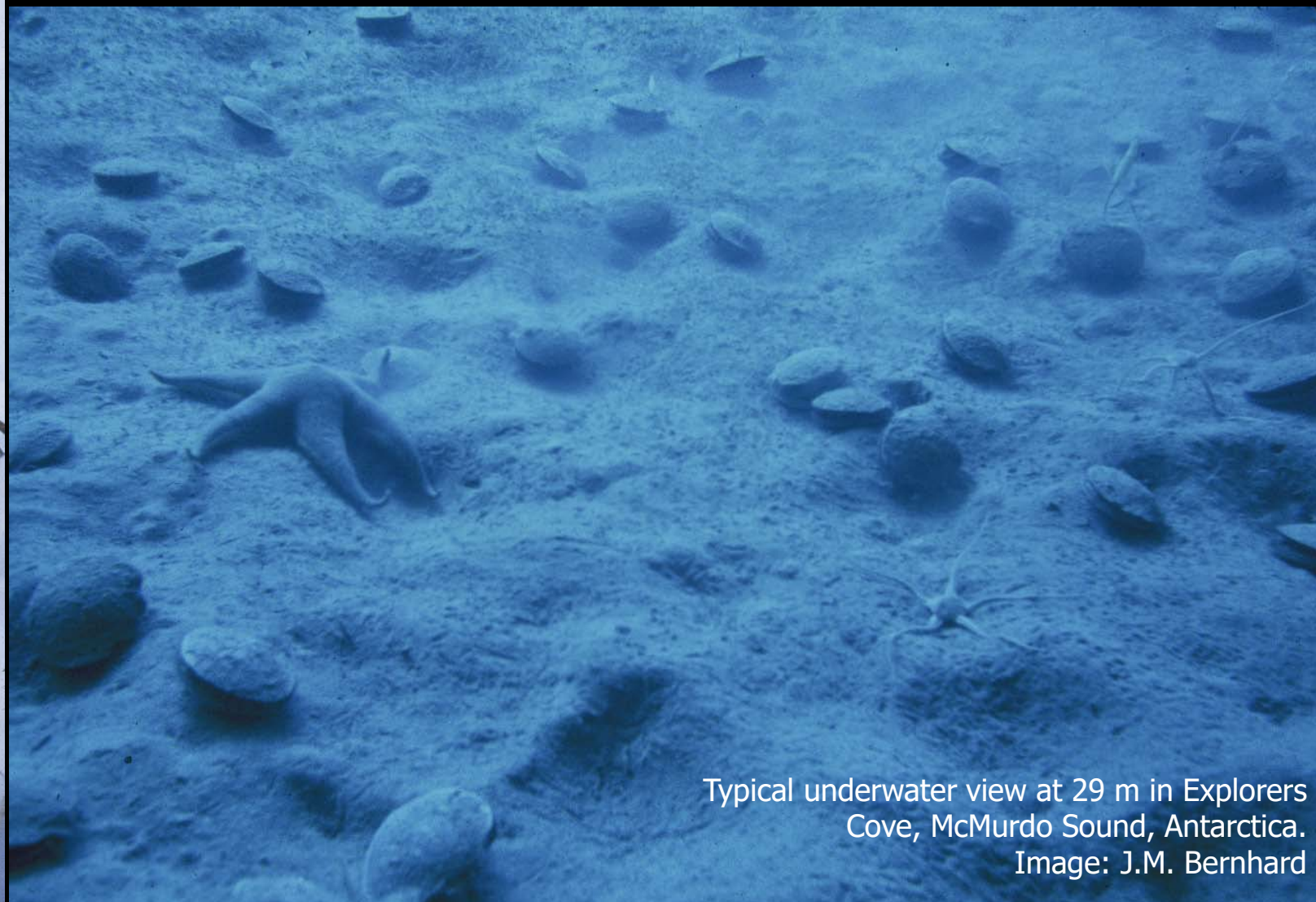
"...is about the [most] wonderful fact I ever heard of. One cannot believe that they have mental power enough to do so, + how any structure or kind of viscidity(?) can lead to this result defies all understanding."



Astrammina triangularis morphological progression; Bowser et al. 2002 *JFR*

Astrammina triangularis collected with Scuba, 29-m water depth, Antarctica

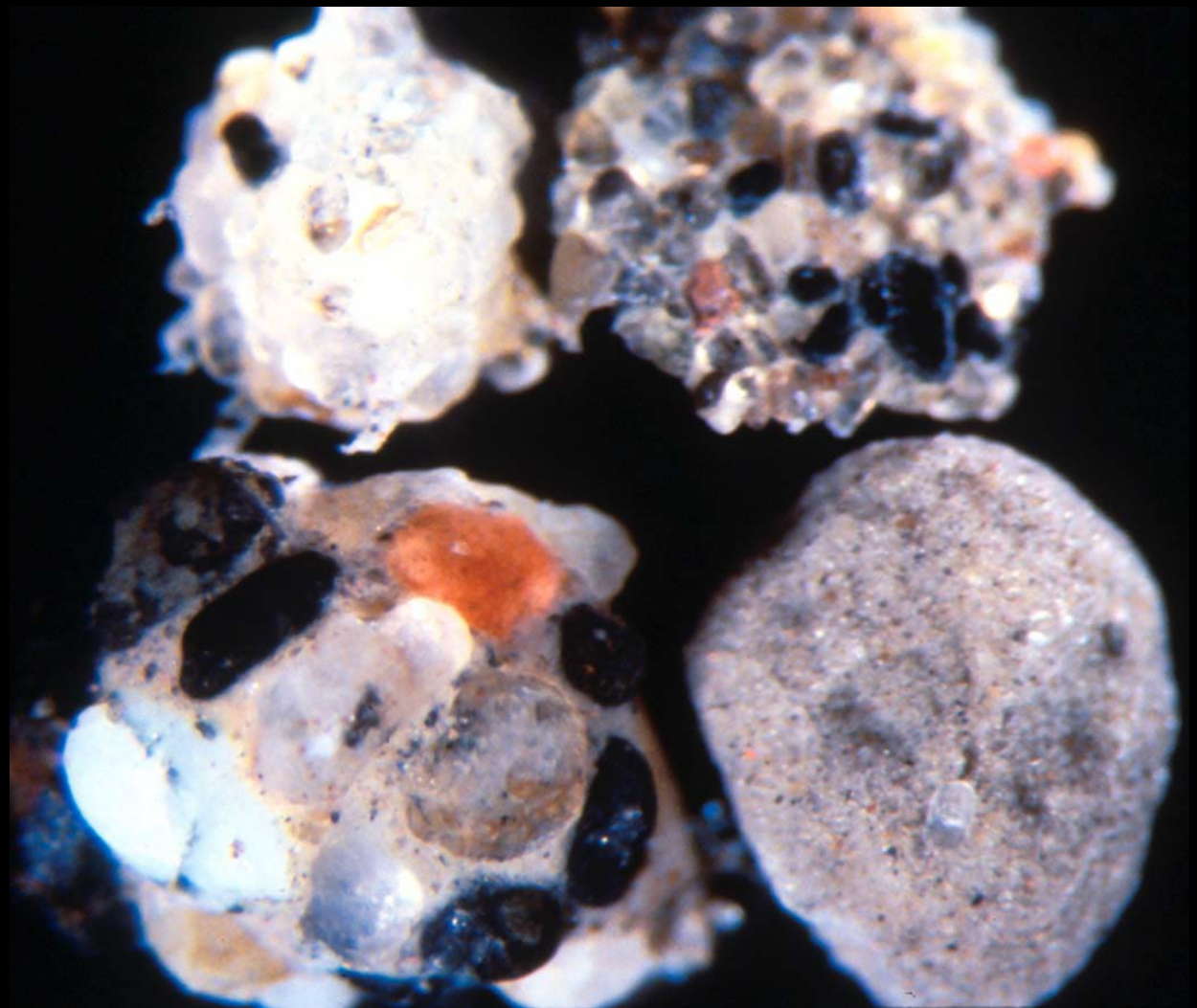
1986, Cape Evans (Scott's Hut)



Typical underwater view at 29 m in Explorers Cove, McMurdo Sound, Antarctica. Image: J.M. Bernhard

Growth / test construction: Agglutination

- Explorers Cove, Antarctica dominant co-occurring forams
- Grain size selectivity & composition



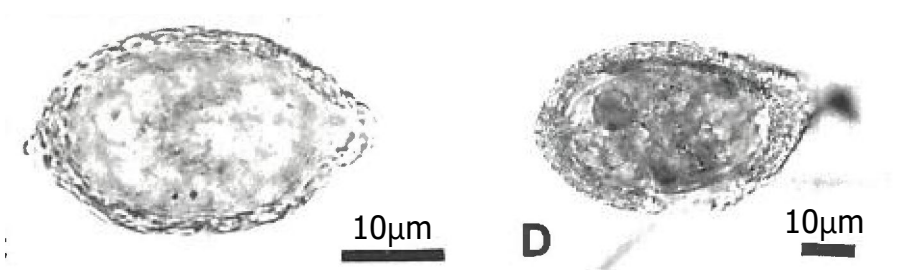
S Bowser, unpubl

Particle gathering

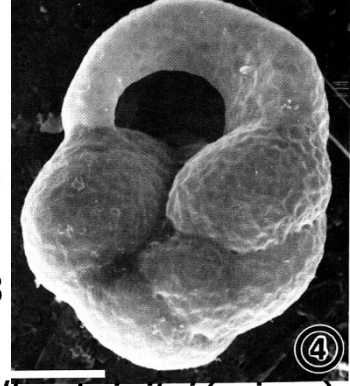
Bernhard & Bowser, unpubl

Size

- Smaller than a sand grain to a tennis ball

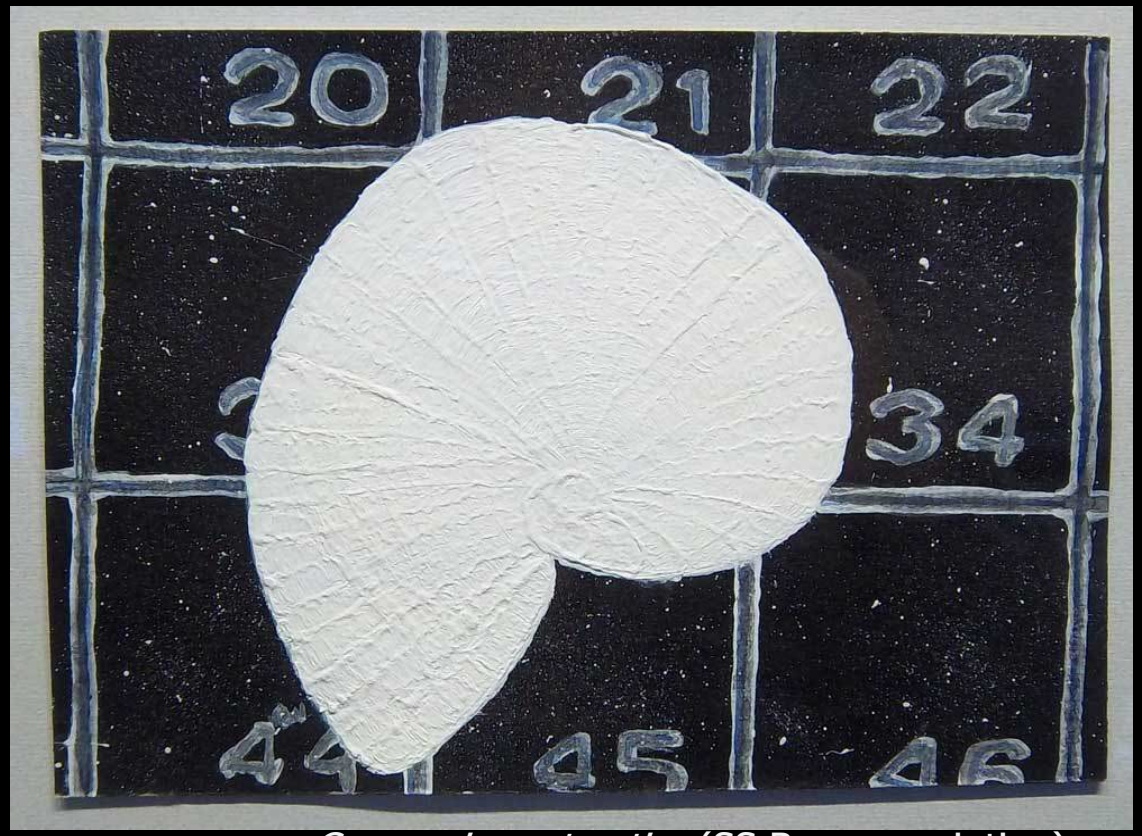


Gooday et al. '95; Pawlowski et al. '93

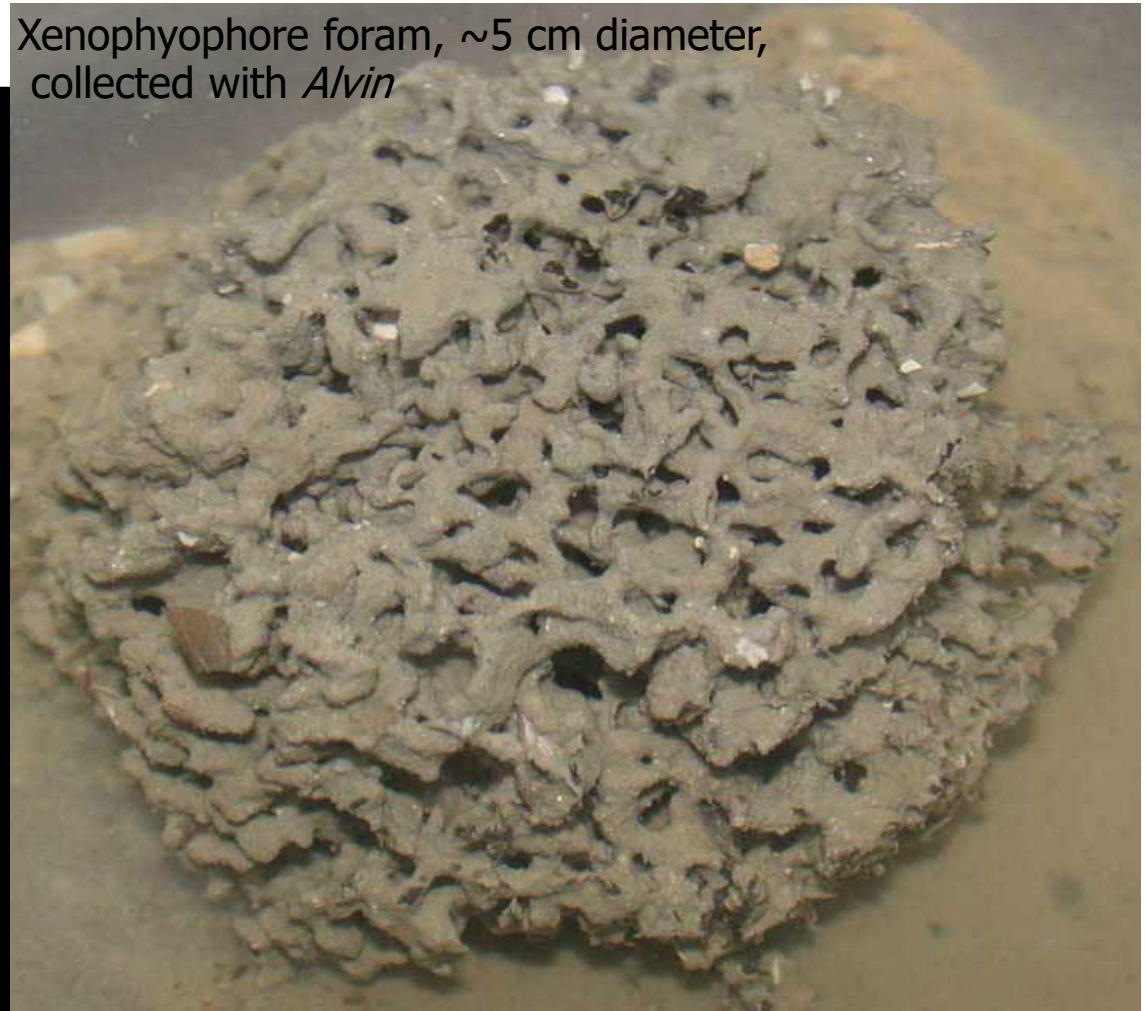


Rubratella steinitzi (micro)

- Nanoforams (15-31µm residue)
- Microforams (31-100µm)
- Most range from ~125µm to 1mm
- Xenophyophores can be "huge"



Cornuspira antarctica (SS Bowser painting)



Xenophyophore foram, ~5 cm diameter, collected with *Alvin*

In sum, wide variety of morphologies, sizes, & test compositions

Heron-Allen Collection, Natural History Museum (UK), Nature Plus

In sum, wide variety of morphologies, sizes, & test compositions…

Heron-Allen Collection, Natural History Museum (UK), Nature Plus

…leads to a wide variety of biological abilities

Physiology / Metabolism

Forams can be:

- Canonical aerobes (use oxygen, like vast majority of life on Earth)
- Facultative anaerobes (can use O_2 and nitrate; certain bacteria, few protists (including some forams), fungi, but NO metazoa)
- Obligate anaerobe (certain bacteria, certain protists, NO metazoa for whole life cycle); a colleague & I are describing an obligately anaerobic foram now

Bernhard et al. (2006)

Physiology / Metabolism

Forams can be:

- Canonical aerobes (use oxygen, like vast majority of life on Earth)
- Facultative anaerobes (can use O_2 and nitrate; certain bacteria, few protists (including some forams), fungi, but NO metazoa)
- Obligate anaerobe (certain bacteria, certain protists, NO metazoa for whole life cycle); a colleague & I are describing an obligately anaerobic foram now
- *This physiological plasticity is one reason for their use as a proxy for past oxygen concentrations*

Bernhard et al. (2006)

Forams respond to environmental conditions

- Species gradation with $[O_2]$
- Species at upper left is aerobe (does not occur in low O_2 settings)
- Species at bottom right is anaerobe (but can also use O_2)
- Keep in mind spatial manifestation of foram occurrence but also over time (when environments change)

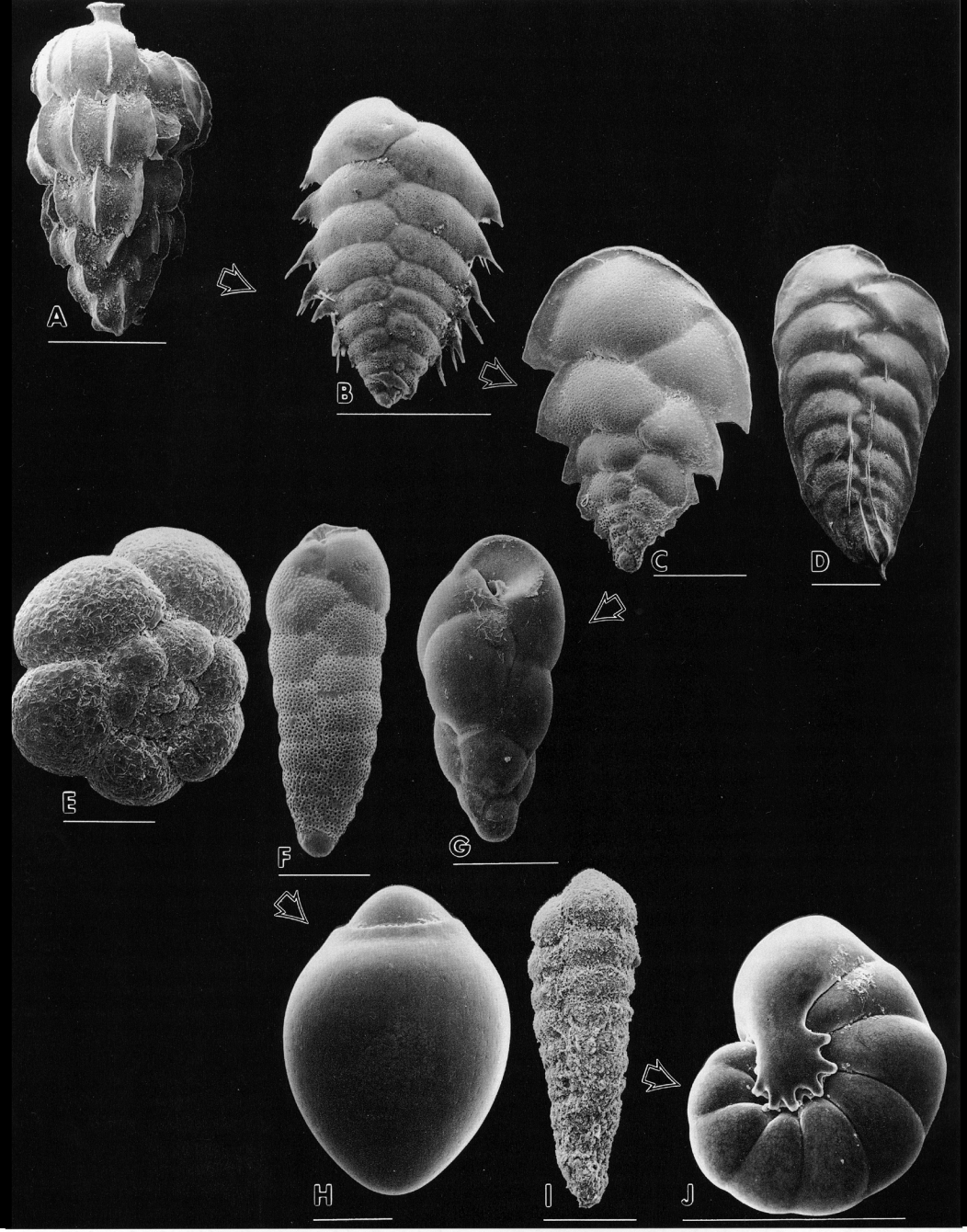


FIGURE 5. Scanning electron micrographs of common foraminiferal species in the Santa Barbara Basin. Species are arranged in a progression from those occurring in higher $[O_2]$ (for example, *Uvigerina juncea*) to those occurring with lowest bottom water $[O_2]$ (that is, *Nonionella stella*). A, *Uvigerina juncea*; B, *Suggrunda eckisi*; C, *Loxostomum pseudobeyrichi*; D, *Bolivina argentea*; E, *Trochammina pacifica*; F, *Bolivina seminuda*; G, *Buliminella tenuata*; H, *Chilostomella ovoidea*; I, *Spiroplectammina earlandi*; J, *Nonionella stella*. Scale bars = 200 μm.

Plate from Bernhard et al. 1997 *JFR*

Uses of (fossil) remains

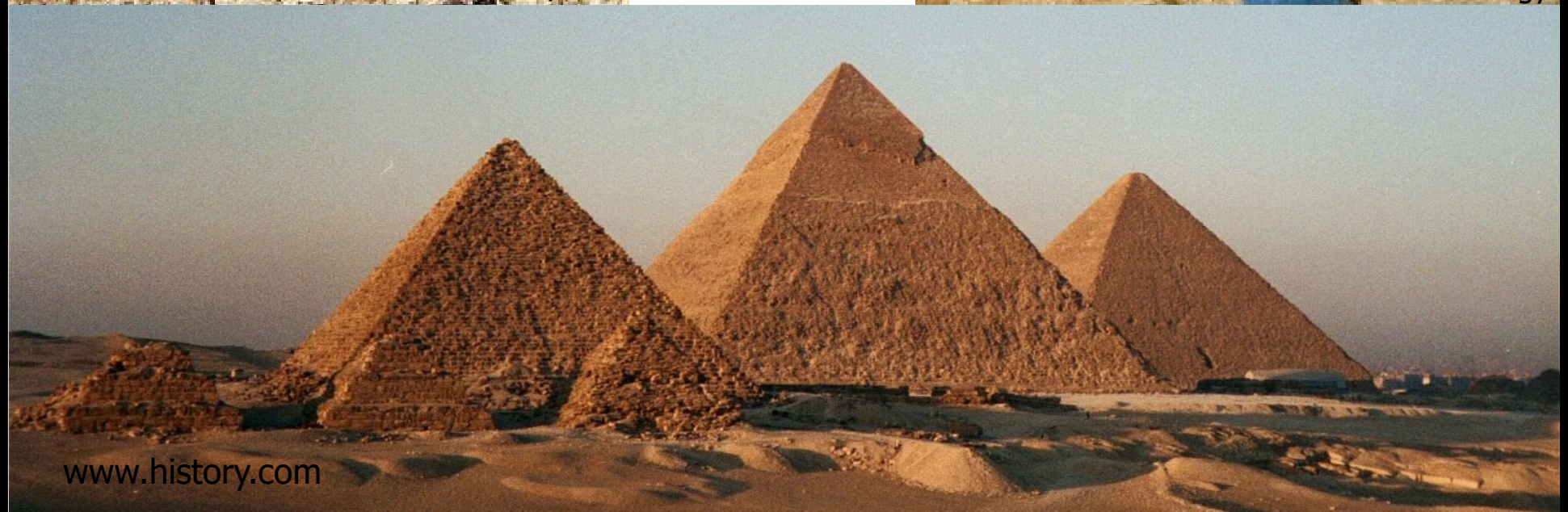
- Extensively used for oil exploration
  - age [biostratigraphy]
  - environment [paleoecology]
- Environmental monitoring (pollution & remediation)
- Paleoclimate/Paleoceanography: Recorded geochemical signatures (stable isotopes, elemental ratios) used to interpret past ocean/climate conditions
  - Salinity, nutrients (variation in primary productivity)
  - Temperature, pCO_2 (ocean acidification)
  - Some, like O_2, still being developed (& ground truthed)

Uses by Society

TheEarthStory.com

Building materials

Univ California Museum of Paleontology



www.history.com

Uses by Society: Recreation


Geocaching

Pink sand beaches (*Homotrema rubrum* and coralline algae)


Median Intelligence


The Cruising Biologists

What is a foraminifer?

Depends who you ask

Wikipedia: Foraminifera (/fəˌræməˈnɪfərə/, Latin meaning hole bearers; informally called "forams") are members of a phylum or class of amoeboid protists characterized by … [reticulopodia] for catching food and other uses; and commonly an external shell (called a "test") of diverse forms and materials…

What is a foraminifer?

Fascinating!

Which is your favorite fascinating foraminifer?

Which is your favorite fascinating foraminifer?

Next, we will hear from Dr. Yi Wang about using forams to decipher past oceanic oxygen concentrations