Utility of Foraminifera in Paleoenvironmental and Paleoceanographic Research

A Foram Primer by R. Mark Leckie – University of Massachusetts, Amherst

Foraminifera are single-celled **protists**. They have a long geologic record that extends back at least to the Cambrian Period (>500 Ma). **"Forams"** are sand-size microfossils (63 to 1000 microns, or 0.063 to 1.0 mm), which have a shell (or **test**) composed of calcium carbonate or agglutinated particles. There are a few naked forms that live in fresh water and brackish environments, and there are a diverse number of species, modern and ancient, that are larger than 1 mm and are typical of tropical reef environments. Most species have tests composed of multiple chambers that increase in size during growth. There are ~40 living planktic species and >4000 extant benthic species. **Forams are ubiquitous in marine and marginal marine environments**; they range from the tropics to the polar seas, from the surface ocean to the deepest seafloor to salt marshes and estuaries. Together with the remains of other mineralized plankton (coccolithophorids and other calcareous nannofossils, diatoms, radiolarians, and pteropods), foram tests comprise the sediment that covers vast areas of the seafloor beyond the continental margins and above the calcite compensation depth (CCD) in the deep sea.

Planktic foraminifera are stratified in the upper water column from the surface mixed layer down through the thermocline, with the greatest concentration of species and individuals in the upper 100-150 m (Figure 1). **Benthic foraminifera** are stratified from the sediment-water interface (epifaunal species) to within the upper 10 cm of sediments (infaunal species; Figure 2). **Symbioses** are common in both planktic and benthic forams, including phototrophic algae in near-surface dwelling planktic species and in larger reef dwelling benthic species, as well as chemoautotrophic bacteria in some low oxygen dwelling benthics. Scanning electron micrographs of some planktic and benthic foraminifera are shown on Plates 1 and 2.

Foraminifera are very useful to academic and industry geologists as powerful tools for **relative age** determination (biostratigraphy and chronostratigraphy), **correlation** from one location to other far away locations, and for **paleoenvironmental reconstruction**. Forams are especially valuable tools in our geology/geobiology arsenal of **ocean-climate change research**. For one, there are **planktic** (floating near-surface dwelling) **and benthic** (bottom-dwelling) forms, which allow us to simultaneously consider the **character of the upper water column and conditions at the seafloor** based on time-averaged sediment assemblages. We can study foram assemblages as paleobiological communities, which can inform us about the **ancient ocean-climate system**, **depositional environment**, **biotic response to global change**, and patterns of **evolution**. In addition, we can analyze the **geochemistry** of their calcium carbonate shells, which provide a variety of **proxies** (indirect evidence) of ancient ocean conditions.

Examples of the utility of foraminifera in paleoenvironmental and paleoceanographic research:

1. **Relative age** information based on assemblages and the known (calibrated) first and last occurrences (**datums**) of key **marker** species; this is referred to as **biostratigraphy** and it's what shipboard paleontologists actively do during academic or industry drilling operations. **Ages of planktic foram datums** have been established based on integration with **magnetostratigraphy or calibration by astrochronologic tuning** of time series data such as oxygen isotopes, sediment magnetic susceptibility, color reflectance, and various physical properties (Figure 3).

2. **Correlation** of one site to another based on the assemblages of microfossils (i.e., establishing **age equivalence** between localities).

3. Planktic foraminiferal species are distributed vertically in **different layers of the upper water column** (i.e., warm and less dense **mixed layer** overlying gradually cooler and increasingly more dense waters of the **thermocline** and **sub-thermocline** waters with increasing depth). **Assemblage (population) analysis** serves as a valuable biotic proxy for conditions of the upper water column. For example, the **ratio of mixed layer to thermocline species** is a proxy for upper water column structure, seasonality, and/or productivity. **Dominance of mixed layer species** in well preserved sediment assemblages of planktic forams indicates a depressed thermocline and suppressed productivity; while **dominance of thermocline and sub-thermocline species** indicates (seasonal) shoaling of the thermocline, upwelling, and increased productivity. This can be tested with stable isotope data (Figures 1 and 4).

4. Planktic foraminiferal species have a **zonal distribution** in the world ocean, which approximate the zonal climate belts (tropical-subtropical, transitional, temperate, subpolar, polar). Therefore planktic foram assemblages are very useful in studies of **paleobiogeography and ocean circulation** (Figure 5).

5. **Benthic forams are very useful proxies for paleoenvironment** because specific taxa and assemblages have distinctive distributions relative to proximity to shore, water depth (a complex of variables), productivity (food availability), and dissolved oxygen. The **ratio of epifaunal to infaunal benthic forams** is a proxy for conditions at the seafloor, particularly the availability of food (flux of organic matter) and dissolved oxygen content, while the **ratio of planktic to benthic** (% planktic forams to total forams) is a proxy for water depth and distance from shore along siliciclastic continental margins, or a proxy for sea level and carbonate productivity along carbonate margins (Figures 2, 4, and 6).

6. Dissolution of their **calcium carbonate shells** yields CO_2 gas that can be analyzed on a **mass spectrometer**. **Stable isotopes of oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$)** are widely used tools in paleoceanography and paleoclimatology (Figure 1):

- **$\delta^{18}O$ of surface-dwelling (mixed layer) planktic forams** is an important **proxy for ancient sea surface temperatures** (SSTs).

- **$\delta^{18}O$ and $\delta^{13}C$ of multiple species of planktic forams** can be used to reconstruct the **temperature structure of the upper water column** (e.g., thermocline) and the **productivity** by establishing the isotopic gradients between species that live in the surface mixed layer and species that live along or below the thermocline.

- **$\delta^{18}O$ and $\delta^{13}C$ of benthic forams** can be compared with planktic foram values in order to **reconstruct temperature structure of the entire water column** or the nature of **productivity** in the surface waters.

- **$\delta^{13}C$ of benthic forams** are also very useful in establishing **deep/bottom water age** and therefore changes in the nature of **thermohaline circulation** through time (i.e., establishing where deep/bottom water masses form at the surface and sink to fill the deep ocean basins).

7. There are **other geochemical analyses** that can be conducted on the shells of planktic and benthic forams. For example, the **Mg/Ca ratio** in planktic and benthic foram calcite is a valuable **proxy for paleotemperature** and a test for the $\delta^{18}O$ paleotemperature proxy. **Cd/Ca ratio** in benthic forams is a **proxy for the nutrient concentration/age of deep waters**.

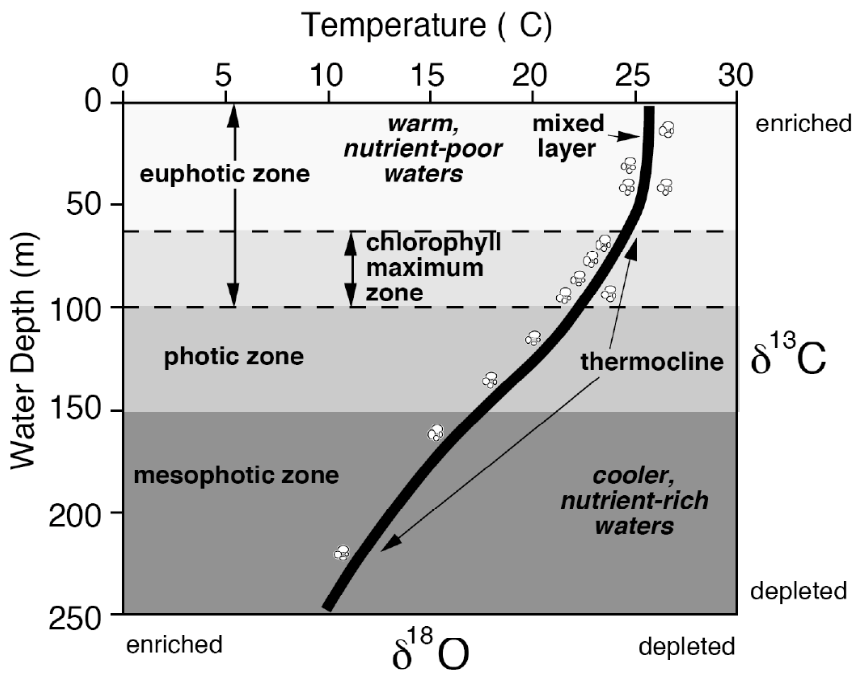

Figure 1. **Planktic foraminifera are stratified in** the upper water column. **Isotope paleoecology** can be used to reconstruct preferred depth habitats. Illustration by R. Mark Leckie.

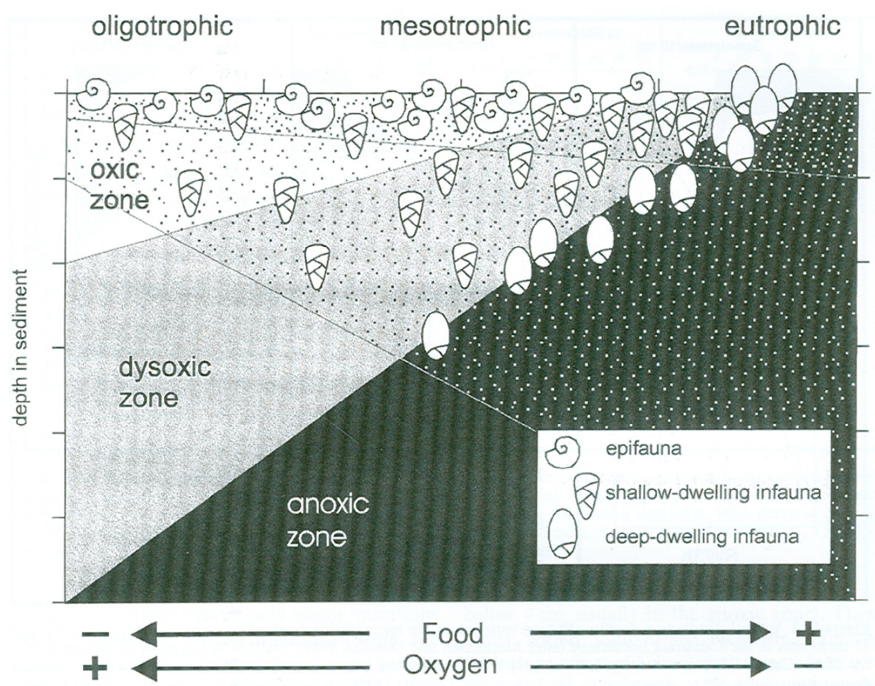

Figure 2. Hypothetical scheme showing influence of food and oxygen on the **distribution of infaunal and epifaunal benthic foraminifera**. Illustration by Henko De Stigter, from Jorissen et al., 1999.

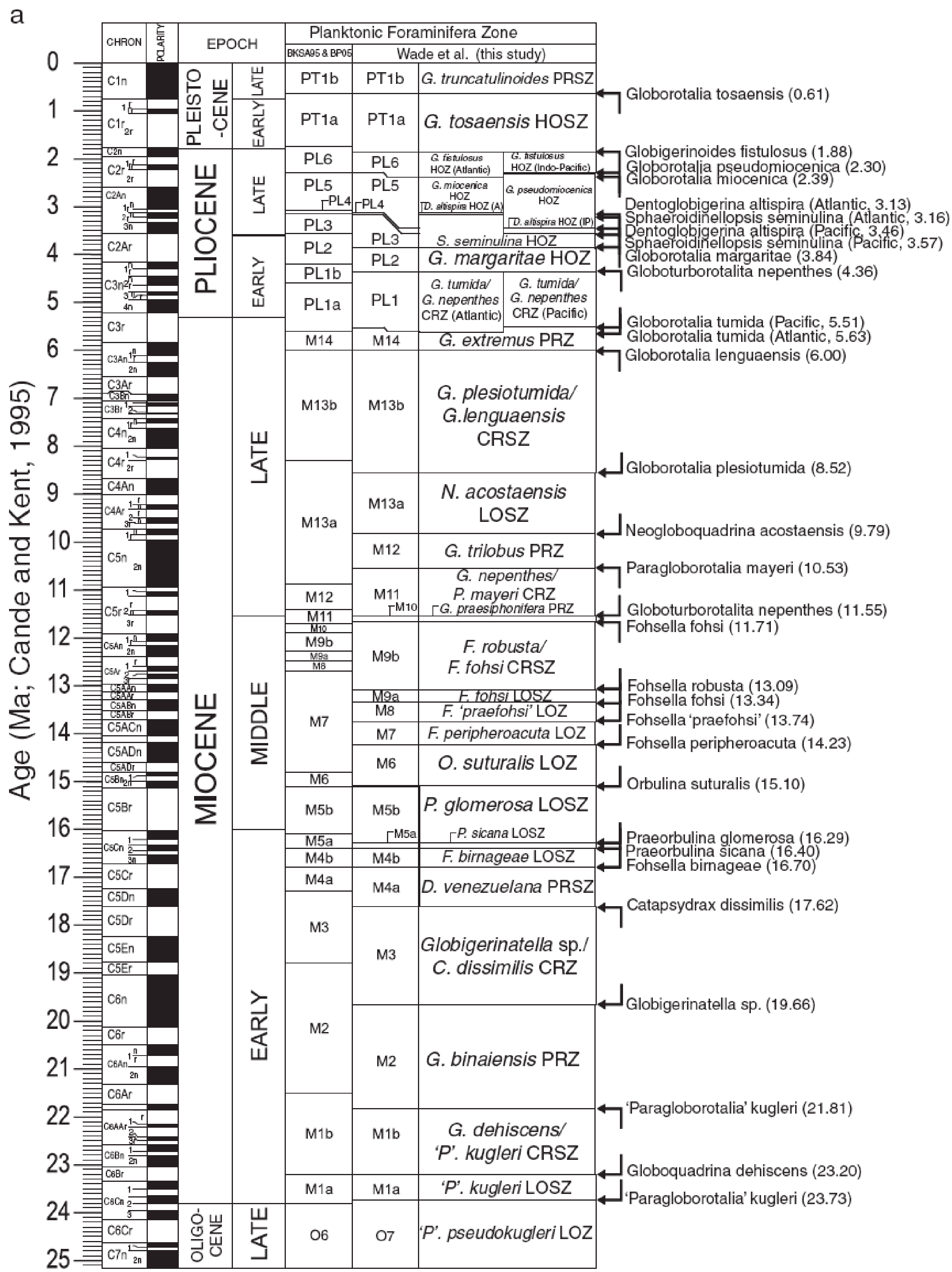

Figure 3. **Planktic foraminiferal biostratigraphy** for the past 25 million years. Bent arrows represent first or last occurrence datums of particular species and their ages. From Wade et al., 2011: *Earth Science Reviews*, v. 104:111-142.

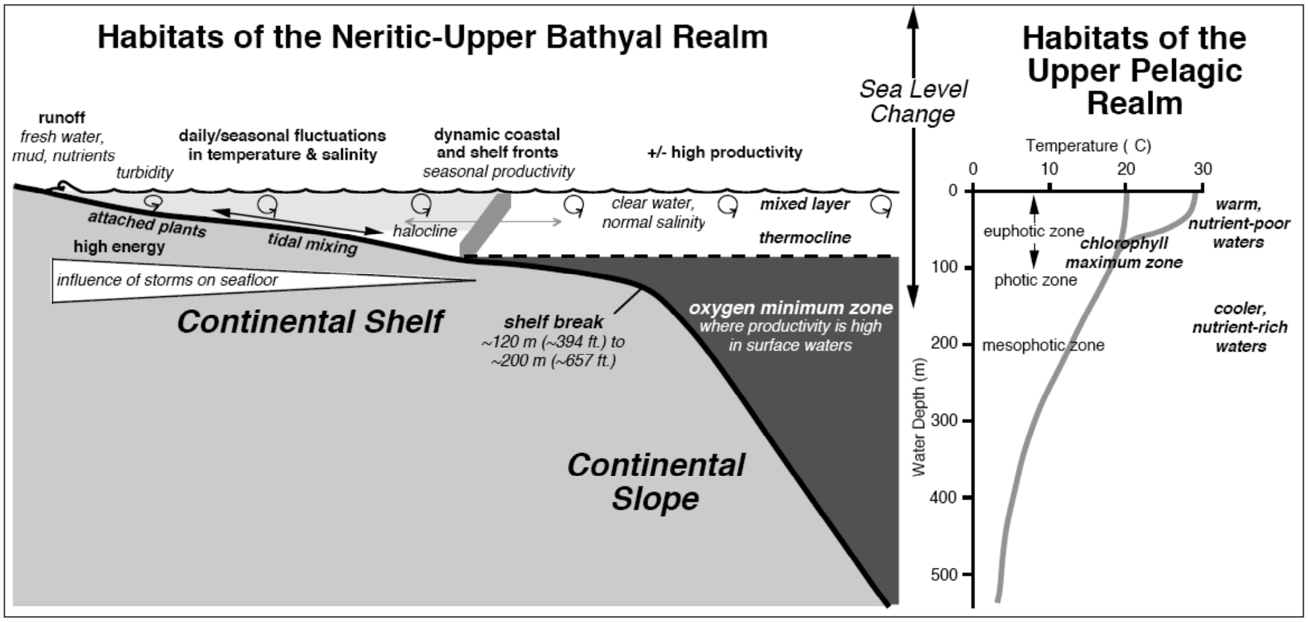

Figure 4. **Environmental variables that control the distribution of both planktic and benthic forams**. Important variables include changing sea level and presence/absence of an oxygen minimum zone. Illustration by R. Mark Leckie (adapted from Leckie et al., 1998 and Leckie and Olson, 2003).

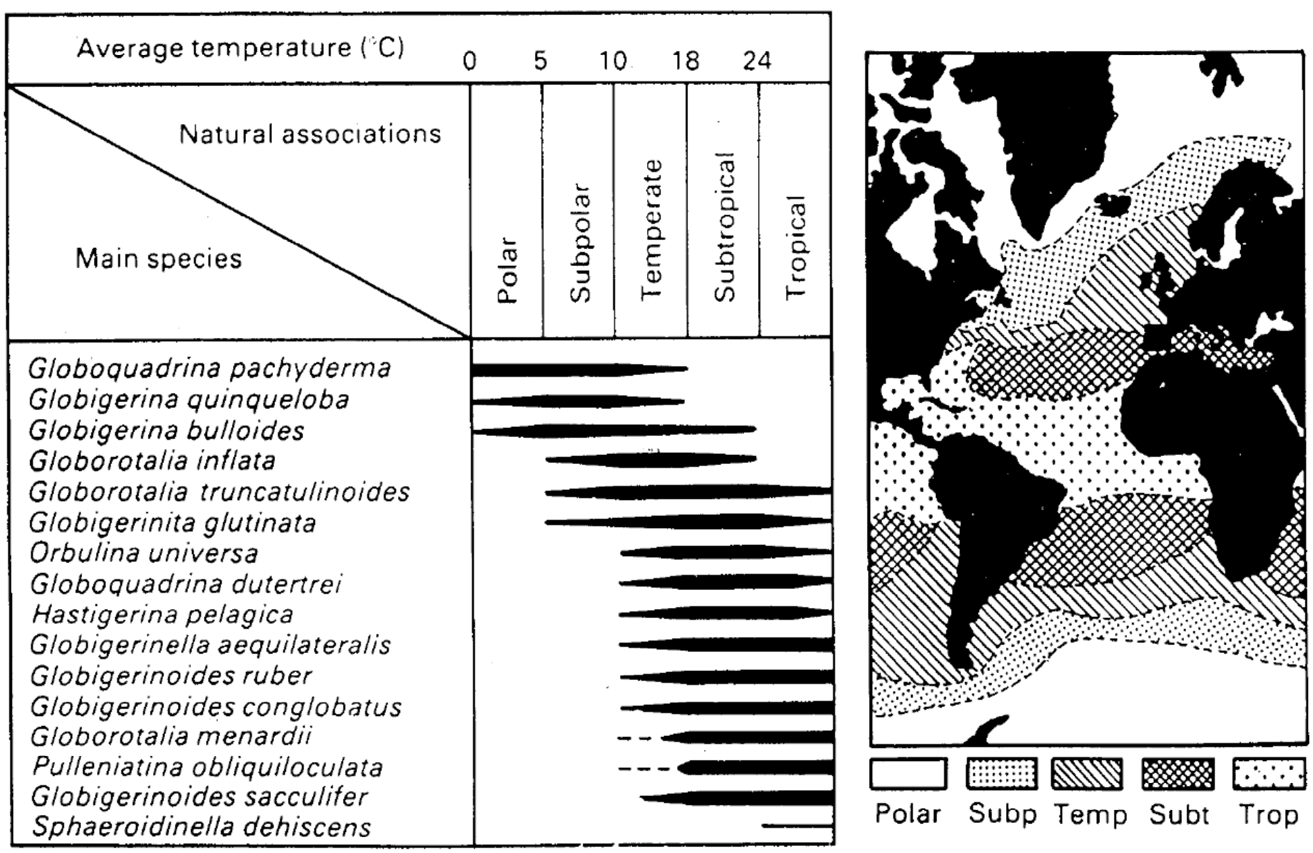

Figure 5. **Zonal distribution of planktic forams** in the Atlantic Ocean. Data from Be and Tolderlund (1971).

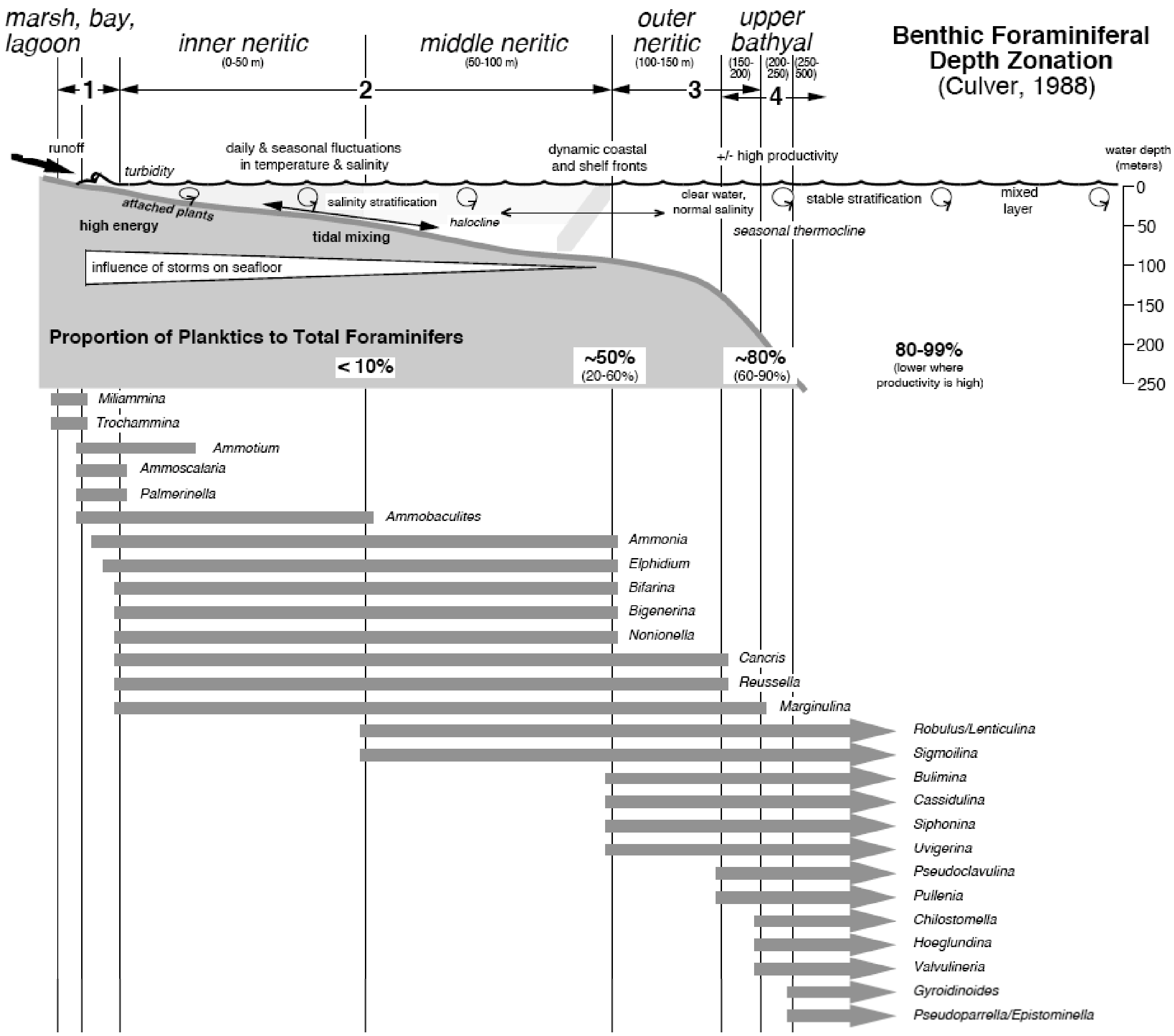

Figure 6. **Benthic foraminiferal species distribution** changes with increasing water depth and distance from the shore. It is not depth per se that is the controlling factor. Availability of **food** (flux of organic matter out of the surface ocean) and **dissolved oxygen** are probably the two most important influences on benthic foraminiferal abundance and species distributions. Other factors include sunlight, substrate, temperature, and pH. From Leckie and Olson, 2003; In, Olson and Leckie, eds., *Micropaleontologic Proxies for Sea-Level Change and Stratigraphic Discontinuities*, SEPM Special Publication 75: 5-19.

Plate Captions.

All specimens are **late Pleistocene** in age and come from one of two localities: Ceara Rise in the western tropical Atlantic, and Ontong Java Plateau in the western equatorial Pacific. It is interesting that the Ontong Java Plateau sample (ODP Site 807) comes from a glacial interval based on the presence of cool water planktic foram taxa including *Neogloboquadrina 'pachyderma'* (dextral), *Globigerina bulloides* and *Globorotalia inflata*, which are not typical of the tropics.

Plate 1. These are all **planktic species**. Planktic forams live at various depths in the uppermost 200 m of the water column according to density, temperature, light, and food availability. Some live in the sunlit mixed layer while others are stratified at various depths along the thermocline. The top two rows are taxa that spend most of not all of their lives (2-4 weeks) in the mixed layer. Many of the mixed layer species have spines, including the species of the genera *Globigerinoides, Orbulina, Globigerina,* and *Globigerinatella*; note the presence of spines preserved on several of the specimens shown on this plate. This group of mixed layer planktic forams includes several taxa that are used to make estimates of past sea-surface temperatures (SSTs) based on oxygen isotopes and Mg/Ca ratios of their shells: *Globigerinoides ruber*, *G. sacculifer*, and *Globigerina bulloides*. The bottom two rows are taxa that live along the thermocline, of these *Globorotalia menardii* lives in the upper thermocline and *Globorotalia scitula* and *G. truncatulinoides* can live much deeper on the thermocline. All views are umbilical unless noted otherwise. 1. ***Globigerinoides ruber***; 2. ***Globigerinoides conglobatus***; 3. ***Globigerinoides sacculifer*** (spiral view); 4. ***Orbulina universa***; 5. ***Candeina nitida*** (side view); 6. ***Beella digitata***; 7. ***Globigerina bulloides***; 8. ***Globigerinatella siphonifera*** (or ***G. aequilateralis***); 9. ***Globorotalia menardii***; 10. ***Globorotalia tumida***; 11. ***Neogloboquadrina dutertrei***; 12. ***Neogloboquadrina 'pachyderma'*** dextral or right coiling (not a true *pachyderma*; more correctly called ***N. incompta***); 13. ***Globorotalia scitula***; 14. ***Globorotalia truncatulinoides***; 15. ***Globorotalia inflata***; and 16. ***Pulleniatina obliquiloculata*** (edge view).

Plate 2. These are all **benthic species**. Benthic forams live at/near the sediment-water interface on the seafloor (epifaunal habitat) or live >2 cm into the sediment (infaunal habitat). The elongate/rectilinear forms are all infaunal species, most of the others shown here are epifaunal to shallow infaunal. This group includes several taxa that are used in paleoceanographic research by analyzing their shells for stable isotopes and trace metals: *Cibicidoides, Planulina wuellerstorfi, Oridorsalis umbonatus*, and *Uvigerina peregrina*. Specimens 13-15 have agglutinated walls; all others have calcite walls. 1. ***Cibicidoides* sp.** (spiral view); 2. ***Planulina wuellerstorfi*** (umbilical view); 3. ***Oridorsalis umbonatus*** (spiral view); ***Pullenia quinqueloba*** (side view); 5. ***Epistominella exigua*** (umbilical view); 6. ***Anomalinoides globulosus*** (spiral view); 7. ***Melonis pompiloides*** (side view); 8. ***Laticarinina pauperata*** (umbilical view); 9. ***Pyrgo* sp.** (side view); 10. ***Sphaeroidina bulloides*** (umbilical view); 11. ***Gyroidina* sp.** (umbilical view); 12. ***Uvigerina peregrina*** (side view); 13. ***Textularia* sp.** (side view); 14. ***Karreriella bradyi*** (side view); 15. ***Martinottiella* sp.** (side view); 16. ***Lagena gracilis*** (side view); 17. ***Guttulina* sp.** (side view); and 18. ***Ehrenbergina?* sp.** (side view).

Plate 1. Modern planktic foraminifera. SEM images by Mark Leckie (UMass Amherst).

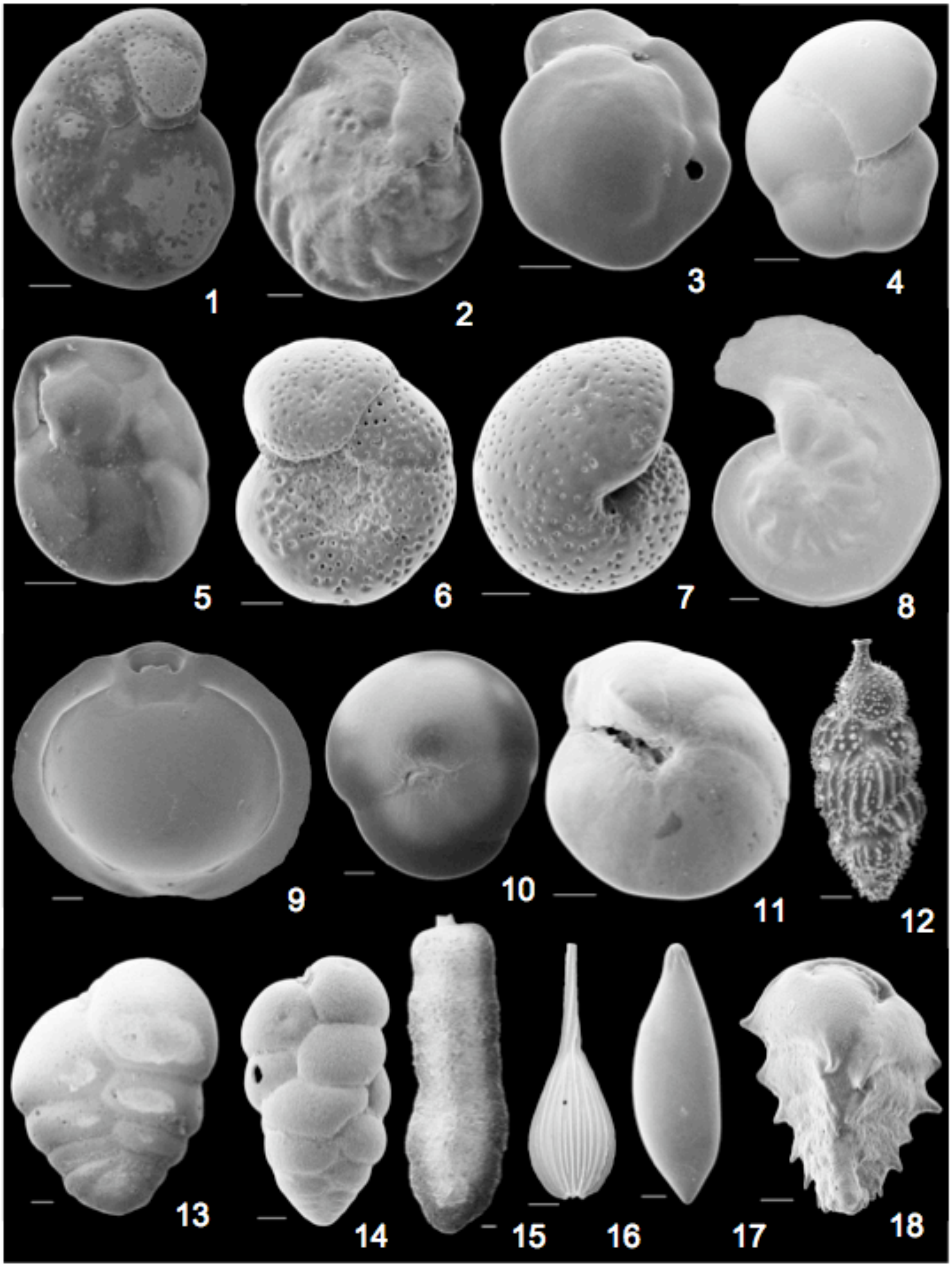

Plate 2. Modern benthic foraminifera. SEM images by Mark Leckie (UMass Amherst).