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12.740 Paleoceanography
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LIFESTYLES OF THE SMALL AND CALCAREOUS

Studies of $\delta^{18}\text{O}$ and foraminifera in the modern ocean: plankton tow, sediment trap, and culture studies as a tracer of planktonic foram behavior

I. Motivation

- A. Certain groupings of foraminifera show plausible correlations with surface ocean T. These correlations can be used to estimate surface T from counts of core-top forams: "faunal index".
- B. However, various planktonic species appear to grow at different depths, water masses, and/or different seasons. This knowledge, in view of the "correlation, not causation" aspect of paleoecological temperatures, leads us to accept the "faunal index" with some caution. We would like to know more about the likely stability of assemblages with time, and whether dissolution-driven changes in the sedimentary assemblages: e.g., G. ruber is dissolution-susceptible; N. dutertrei is somewhat dissolution-resistant. But in transfer functions, G. ruber contributes to warm temperatures while N. dutertrei contributes to moderate temperatures).
- C. Oxygen isotope studies can shed some light on the ecology of foraminifera. Early studies used fossils from sediments, but these studies have some inherent ambiguities: e.g., are the sedimentary foraminifera (average of dissolution-weighted flux over the last 500-2000 years) representative of the ocean of the last 50 years?; problem of seasonal progression information being lost by mixing; '100 year event' problem. These studies also pointed out that different sizes of foraminifera of the same species may have significantly different isotopic compositions. The first studies of plankton tow foraminifera gave signs of the problem: Shackleton et al. found that different species collected in the same plankton tows had significantly different $\delta^{18}\text{O}$. This difference could arise either from "vital effects" or from vertical migration of foraminifera.

- II. Be, Weibe, Fairbanks, Bishop: surface plankton $\delta^{18}\text{O}$ vs. water T; profiling $\delta^{18}\text{O}$ vs. equilibrium $\delta^{18}\text{O}$; abundance depth zonations. Sargasso Sea and Panama Basin results.
 - A. Surface Plankton tows:

1. Sometimes this approach seems to work (e.g. Williams et al. results on G. ruber).

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Source: Williams et al. (1991).

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Source: Williams et al. (1991).

2. Other times, forams appear to be out of equilibrium (in both directions)...Possible explanations include vertical migration, temperature changes since calcification (e.g. beginning or ending of upwelling events; eddy mixing), disequilibrium calcification, GOKW. Also: it is often noted that sediment core top forams often register colder temperatures compared to those taken from plankton tows or sediment traps. Is this difference due to selective dissolution of "warm" calcite (or individuals that grew in warm water) or 'gametogenic calcification' occurring deeper in the water column?
- B. Sub-surface plankton tows: Fairbanks & Wiebe MOCNESS (Multiply-Opening and Closing Nekton Ecological Sampling System):vertical array of plankton nets).
1. To compute $\delta^{18}\text{O}_{\text{equil}}$, one needs to know $\delta^{18}\text{O}_{\text{water}}$ and temperature (usually estimated from climatology (T,S) and $\delta^{18}\text{O}$ relationships).

Image removed due to copyright considerations.
Source: Fairbanks et al., 1982.

2. Vertical stratification of abundance: G. ruber, G.sacculifer are most abundant near the surface (due to symbiotic photosynthesizing algae?); most other species are most abundant at the subsurface productivity maximum; a few species appear to live at greater depth (e.g. G. theyeri).
3. Some species are found alive at depth, but their shell $\delta^{18}\text{O}$ implies that they cease to calcify below a certain depth.
4. What is the mechanism of vertical species stratification of foraminifera?
Temperature or density preference? Food?
5. Difference between flux and standing crop?
6. General O-18 disequilibrium (up to -1 permil)- or is it T-change?

III. Deuser et al. Sargasso Sea sediment trap results

- A. T & S at a given depth fluctuate with season down to 200m; leads to variations in equilibrium calcite $\delta^{18}\text{O}$.

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Source: Deuser et al. (1981).

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Source: Deuser et al. (1981), figure 2.

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Source: Deuser et al. (1981).

B. Flux of some species varies with season (e.g. G. truncatulinoides has high flux in winter, low flux in summer (factor of 100); there also appear to be 'phenotypic' variations (i.e. changes in the appearance of the shells of a given species).

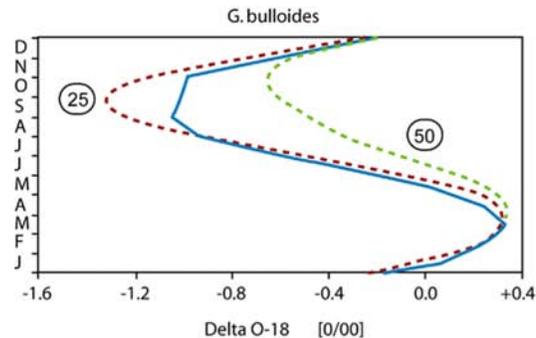
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Source: Deuser et al. (1981), figure 4.

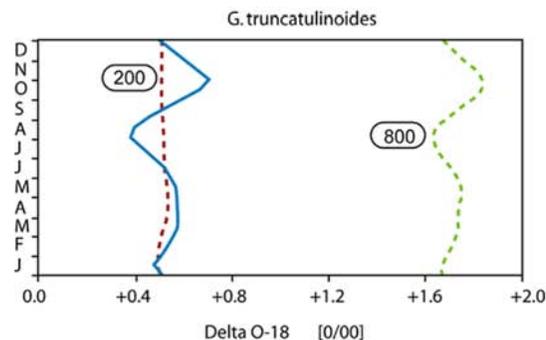
C. Some species appear to record the annual cycle of surface temperature year-round and therefore appear to live in the surface ocean the whole year.

Images removed due to copyright considerations.
Source: Deuser et al. (1981).

- D. Other species consistently show 'cold' $\delta^{18}\text{O}$ (e.g. *G. truncatulinoides* appears to live deeper in the water column during summer, shallower during winter. Given the large variations in the total flux, the annual weighted average will be recording the winter T.
- E. Some species appear only in a specific season, (e.g. *N. dutertrei* appeared to track surface T in spring; *G. conglobatus* registers surface T in winter).
- F. Some species just appear to be odd! (e.g. *G. bulloides*).
- G. Despite its obvious offset from equilibrium, *G. bulloides* records the annual surface temperature cycle quite well. *G. truncatulinoides*, however, shows a seasonal cycle that is more similar to that seen at 1000m!



Comparison of $\delta^{18}\text{O}$ variations of *G. bulloides* tests intercepted at 3,200 m (solid curve) with variations of equilibrium $\delta^{18}\text{O}$ for calcite at 25 and 50 m (dotted curves). The *G. bulloides* curve was shifted by +0.54‰ to account for a disequilibrium ("vital") fractionation of -0.54‰, and the dotted curves are shown with a delay (shift to the right) of half a month to compensate for the transfer time of *G. bulloides* record to 3,200 m.



Comparison of $\delta^{18}\text{O}$ variations of *G. truncatulinoides* tests intercepted at 3,200 m (solid curve) with variations of equilibrium $\delta^{18}\text{O}$ for calcite at 200 and 800 m (dotted curves). The dotted curves are shown with a delay of one month to account for the transfer time of the record of *G. truncatulinoides* to 3,200 m. Note that the average $\delta^{18}\text{O}$ of *G. truncatulinoides* is equal to that of the 200-m equilibrium curve, but that its average annual variation for the 1978-1984 period bears the imprint of the variations at 800 m.

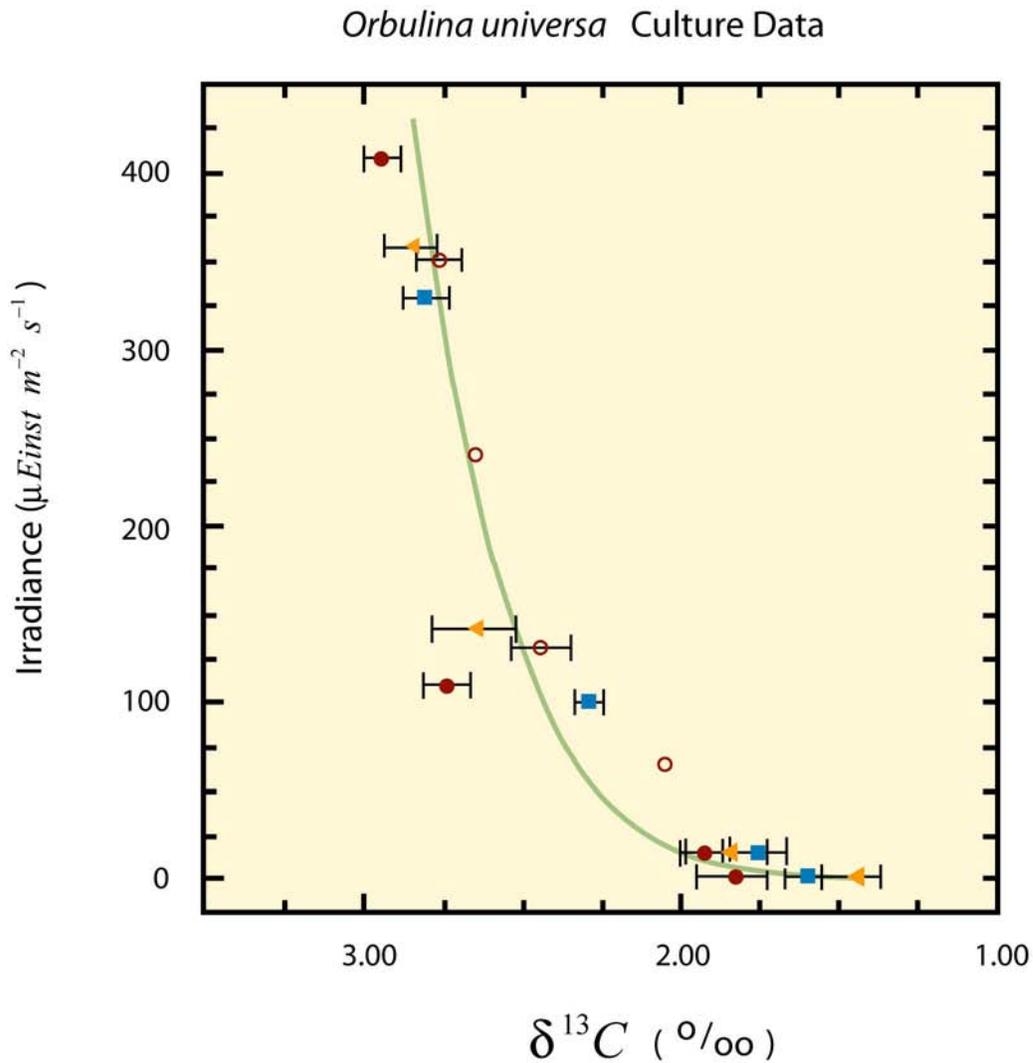
□
Figure by MIT OpenCourseWare. Adapted from source: Spero and Williams (1989).

- H. Conclusions: ' $\delta^{18}\text{O}$ stratification' in foram samples from core tops represents differences in depth habitat *and* seasonal variations in T and species flux. By inference, we can also expect that inter-annual, -decadal, and -centennial variability can matter.

IV. Direct experimental manipulation of forams: Bé, Erez, Jorgensen, Spero

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Source: Bijma et al. (1990), figure 1.

Image removed due to copyright considerations.
Source: Jorgensen et al. (1985).



Orbulina universa $\delta^{13}C$ versus irradiance relationship from laboratory culture experiments conducted at different temperatures. Data are combined from Spero and DeNiro [1987] at 20°C (○), and Spero and Williams [1988] at 25°C (■), 20°C (●) and 15°C (◄). Values are ± 1 s.d. These data are described by a power regression. At light intensities above P_{\max} (386 $\mu\text{Einst m}^{-2} \text{s}^{-1}$), the $\delta^{13}C$ value will remain constant since the symbiont photosynthetic rate is already maximum.

Figure by MIT OpenCourseWare. Adapted from source: Spero and Williams (1989).

V. Effect of carbonate saturation on foraminiferal isotope chemistry?

Images removed due to copyright considerations.
Source: Spero et al. (1997).

VI. Foram Lifecycle: can't be done in continuous culture

- A. Formation of gametes; fusion of gametes (for at least some species, gametogenic calcification – calcification immediately prior to gamete formation - is inferred)
- B. "Proluculus" (single-chambered foram) - only reported once, not duplicated

- C. *Some varieties have symbiotic photosynthetic algae*
- D. *Successive episodic growth of new chambers; precipitation of new layer of calcite on top of older chambers at same time. Vertical migration*
- E. *Reach reproductive maturity; possible vertical migration; form gametes*
- F. *Influence of vertical migration and calcification at different depths for planktonic foraminiferal isotopic and chemical composition.*

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***Neogloboquadrina pachyderma* (sinistral coiling) as paleoceanographic tracers in polar oceans: Evidence from Northeast Water Polynya plankton tows, sediment traps, and surface sediments**

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Abstract. The abundance and chemistry of the planktonic foraminifera *Neogloboquadrina pachyderma* (sinistral coiling) have long been used as tools for monitoring polar surface ocean changes and for correlating these changes to atmospheric and thermohaline circulation fluctuations. However, due to its remote habitat, very little is known about how modern *N. pachyderma* (s.) respond to changing environmental conditions in the polar seas. Modern samples of *N. pachyderma* (s.) from the Northeast Water Polynya provide a means for studying how environmental conditions affect the vertical distribution and chemistry of this species. Highest abundances of *N. pachyderma* (s.) were associated with the chlorophyll maximum in the surface 20-80 m, where they are exploiting their primary food source. Evidence suggests that the addition of a calcite crust modifies the calcite tests of some *N. pachyderma* (s.) between 50 and 200 m, increasing shell density and modifying shell chemistry. The shell mass of encrusted forms is 3-4 times greater than the nonencrusted forms between 50 and 200 m. The oxygen isotope composition of *N. pachyderma* (s.) shells increase by 1.5‰ in response to local water column gradients. The $\delta^{13}\text{C}$ values of *N. pachyderma* (s.) are basically invariant with depth in this region, are consistently 1.0‰ depleted in comparison with the $\delta^{13}\text{C}$ for equilibrium calcite, and remain basically constant during the shell-thickening process. Mass balance calculations suggest that encrustation occurs at all depths, but abundance counts suggest that the process occurs mostly at the depth of the main pycnocline.

Note: the conclusion about carbon isotopes only applies in this area. In other areas, there are strong $\delta^{13}\text{C}$ vertical gradients and we expect that deep calcification will influence $\delta^{13}\text{C}$.

VII. Calcification: do foraminifera really care about equilibrium?

- A. Most paleo work assumes that foraminiferal calcite is in isotopic equilibrium with the seawater in their immediate environment. But is this really true? Foraminiferal calcification proceeds rapidly (minutes to a day) but then we want that calcite to remain out of equilibrium with the bottom waters for tens of millions of years - can we be sure that foraminiferal calcite really forms at equilibrium? In some cases, we can say that some foraminifera definitely do NOT: species that register "isotopic temperatures" that are warmer than anything in the water column; coexisting benthic foraminifera that have different isotopic compositions (hence at least one of which must be out of equilibrium). But in other cases it is more difficult to be certain.
- B. We have to remember that foraminiferal calcite is the "home, sweet home" of these organisms, constructed deliberately and precisely by highly evolved genetic/molecular mechanisms. Given motivation to do so, foraminifera may manipulate the geochemistry of their shells to suit their circumstances.

C. Recent evidence by J. Erez indicates that foraminiferal calcification proceeds in two steps by two different mechanisms:

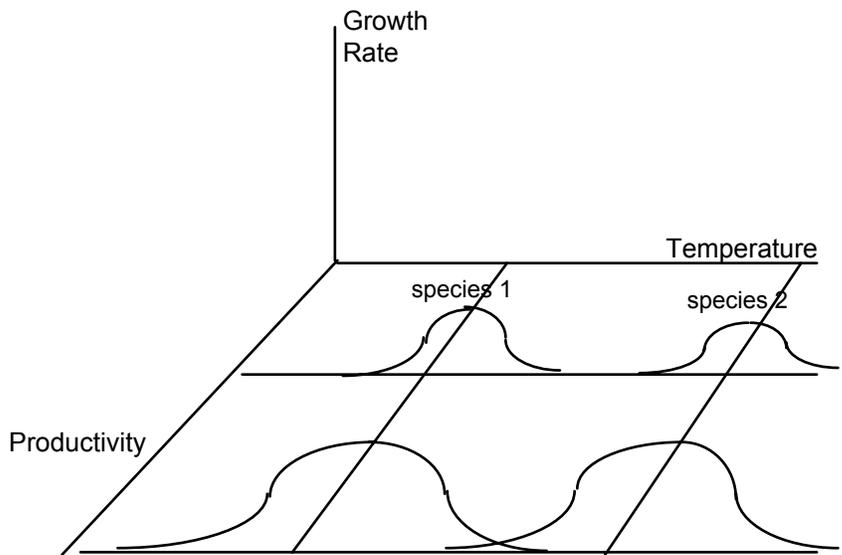
1. The foraminifera set down an organic template that is genetically determined to create the distinctive structure and form of the species. A thin layer of high-Mg calcite is set down upon that template by transporting birefringent membrane-encapsulated Ca-Mg-P bodies to the site of calcification and lysing the membranes to produce a pulse of extreme carbonate supersaturation that precipitates a high-Mg calcite layer.
2. After this initial calcification, the foraminifera transport vacuoles of modified seawater to the sites of calcification. These vacuoles originate when foraminifera use their cell membrane to "surround" seawater into vacuoles that are drawn within the cell membrane. These vacuoles are then chemically modified to remove Mg and increase the pH (H^+ exchange for Mg^{++} ?). They are transported to the site of calcification where low-Mg calcite is precipitated (note: in normal supersaturated normal seawater, calcite is not precipitated because Mg^{++} inhibits its nucleation. Hence the removal of Mg^{++} ...).
3. Given that most of the calcification proceeds from seawater that has been modified only slightly, it is reasonable to expect that shell chemistry will be related to the seawater chemistry.

VIII. What controls relative species abundance variations in sediments, and why do the assemblages correlate with surface T in the modern ocean? Are there circumstances when they might not?

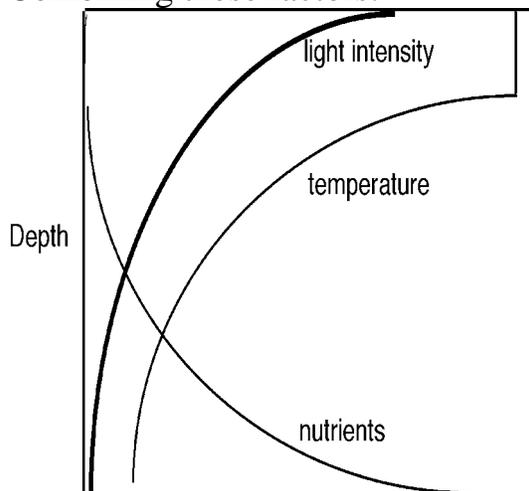
A. Two Ideas:

1. Individual foram species 'float' at a given density level (buoyancy control).
2. Individual foram species have an optimum growth T.
3. Of course, these two factors are correlated since T is the dominant control on density in the modern ocean.

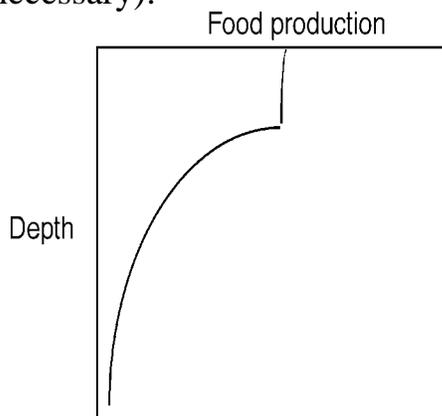
B. (T or density) preferences combine with availability of food at the optimum (T or density) (or, in the case of those species with symbiotic algae, with the availability of light) to control the rate of reproduction and calcification.



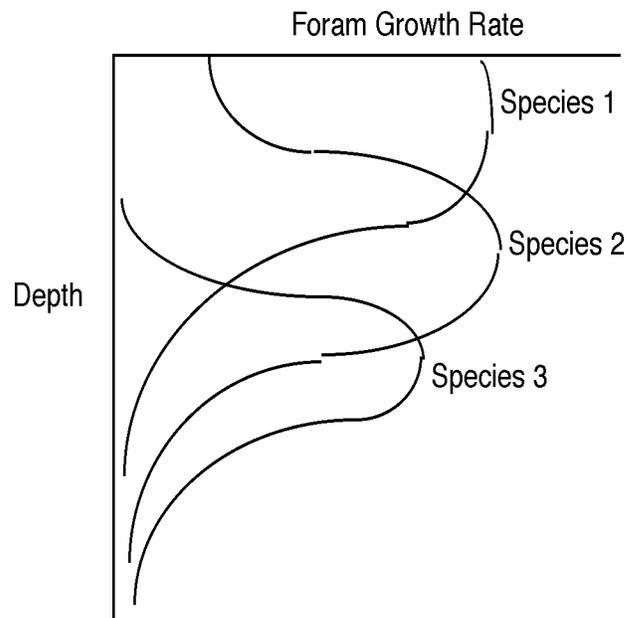
C. Combining these factors:



D. These factors combine to produce the following food concentration (typical but not necessary):



E. To produce species-dependent growth rates as a function of depth:



- F. All of which (of course) will be a function of the physical regime (region, season).
- G. The above produce the annual flux of foraminifera to the seafloor (complicated by the 100-year events); this flux is then modified by selective dissolution and fragmentation on the seafloor to produce surface sediments. (e.g. *H. pelagica* is a common foram in tows but it is hardly ever observed in sediments). This process may favor the retention of specimens which lived in environmental conditions favoring more robust tests, and thus produce a sedimentary O-18 record that differs from the annual sediment trap flux.
- H. This concept seems fine, but no one has successfully synthesized this model (or variants of it) to reproduce the results observed in plankton tows, sediment traps, and core-top sediments. Some people who have tried say it can't be done! Is the problem insufficient information (e.g. not enough spatial coverage, poor indicators of what the food source is really like [chl. max may not really be the productivity max.], etc.) or is it due to a deficiency of the conceptual model?
- I. Ravelo et. al. (1990): correlation of tropical foram factors with hydrographic profiles:

- IX. These data and ideas have implications for micropaleontological faunal T indices. There seems some hope that on the average they are OK - but also suggests that there are situations where they might be misleading. (esp. regions where the mixed layer is thin (e.g. equatorial ocean), or where there are large seasonal variations)
- X. There also is some evidence that some organisms may be better delimiters of water masses (both surface and shallow subsurface) than surface temperature or some other single environmental property.
- XI. Sedimentary complications: mixing and dissolution

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