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Stable Isotopes in Benthic Foraminifera: Seasonal Variation in Large Tropical Species

Abstract. *The shells of large benthic foraminifera contain a record of seasonal temperature ranges and life history stages.* Marginopora vertebralis *and* Cyclorbiculina compressa *show distinct differences in life history, growth rate history, and life-span, as reflected in stable isotope patterns within their shells.*

Large, shallow-water, tropical foraminifera are an important component of modern and ancient carbonate reefs. These forams are usually associated with dinoflagellate or diatom symbionts ("zooxanthellae") (*1, 2*). This association gives rise to unusually high population densities in places and thus ultimately leads to a considerable contribution (10 to 15 percent) to carbonate deposition in shallow, warm-water areas (*3*). Rapid growth (50 to 100 times that of most temperate species) and a long life-span (one to several years) appear to be characteristic of most large to very large, tropical foraminifera (*4*). Their calcareous shells, therefore, should contain a record of seasonal variation at the time and place of growth. We report here evidence, based on the stable isotope composition of the shells, showing that this is so. Our findings imply that the growth rate and hence the carbonate production of large foraminifera can readily be determined, even in fossil specimens, if they are well preserved.

We chose two common representatives of large tropical forams for our seasonality test, *Marginopora vertebralis* and *Cyclorbiculina compressa*. The first grew in tropical waters with but little seasonal temperature variation. The second grew in warm-temperature waters with a considerable temperature range.

Marginopora vertebralis was collected in January 1979 in shallow water (1 to 3 m) 50 m off Hadsan Beach Resort, Mactan, Cebu, Philippines (temperature range, 26° to 30°C; minimum in February and maximum in July) (Fig. 1a). Three stages of shell construction are known for *M. vertebralis*: embryonic, laminate, and reproduction chamber stages (*5*). The foraminifera is host to at least one species and perhaps several species of symbiotic dinoflagellates.

Cyclorbiculina compressa was collected in April 1978 in Harrington Sound, Bermuda, in 10-m water (temperature range, 16° to 29.5°C; maximum in August and minimum in February) (Fig. 1b). Three stages of shell construction are known for this foram, which partially depends on symbiotic algae for nutrition (*6*). Lee *et al.* (*2*) recently noted a new symbiont from *C. compressa*, the chlorophyte *Chlamydomonas provasolii*.

The specimens of *Marginopora* and *Cyclorbiculina* analyzed here had undergone asexual reproduction, and the adult tests contained little or no protoplasm. The protoplasm was concentrated in the two-chambered embryos present within the reproduction chambers. We subsampled the specimens, using a scalpel to separate individual chamber rings from each test. Depending on their size, one to ten rings were used for each analysis. To remove the organic matter attached to the test, each subsample was soaked in a 10 percent aqueous solution of H_2O_2 for 1/2 hour. Then it was washed five times with deonized water, dried at 60°C, and heated for 30 minutes at 300°C under a vacuum. Analytical procedures were standard (*7*). The analytical precision was 0.1 per mil (one standard deviation).

Results show that the $\delta^{18}O$ variations follow closely those expected from ambient temperature variations, if the equation of Epstein *et al.* (*8*) is used (Fig. 1). The actual $\delta^{18}O$ values of *Marginopora* and *Cyclorbiculina* appear to be offset (by -0.5 and $+0.75$ per mil, respectively) from values expected for equilibrium precipitation at the two locations after corrections are made for water $\delta^{18}O$ compositions based on established relations between salinity and $\delta^{18}O$ (water) (*9*). Although depletion in ^{18}O is not unusual in benthic foraminifera (*10, 11*), an enrichment in ^{18}O is unexpected. The fact that the shell material consists of magnesium-rich calcite may be significant. For the Soritidae, of which *Marginopora* and *Cyclorbiculina* are members, values of 15 to 18 mole percent $MgCO_3$ have been reported (*12*). For an enrichment in ^{18}O by 0.06 per mil per mole percent $MgCO_3$ (*13*), an increase in $\delta^{18}O$ of about 1 per mil would be expected for each species. If this calculation is correct, both species are actually depleted in ^{18}O. Any variations in the $\delta^{18}O$ composition of the seawater apparently were negligible (*14*).

A linear growth scale is assumed for *Marginopora vertebralis* (Fig. 1a). It is broken at radius 1.2 mm (test diameter, 2.4 mm), because the high $\delta^{18}O$ value of the test center suggests initial growth in midwinter (January 1977). This inference is further supported by field observations of midwinter reproduction in January 1979. The subsequent linear fit suggests that there was little change in growth rate during the transition from laminate to reproductive chambers (marked *R* in Fig. 1a). Growth apparently ceased in late summer (at a radius of 6.8 mm), and the foraminifera then waited until winter to produce offspring, which were found to occupy the test between 4.7 and 6.8 mm from the center. The tests of these embryos are distinctly enriched with $\delta^{18}O$ as compared with the last-formed chambers of the adult test. Our life-span estimate of 2 years for this species is in good agreement with direct observations by Ross (*5, 15*).

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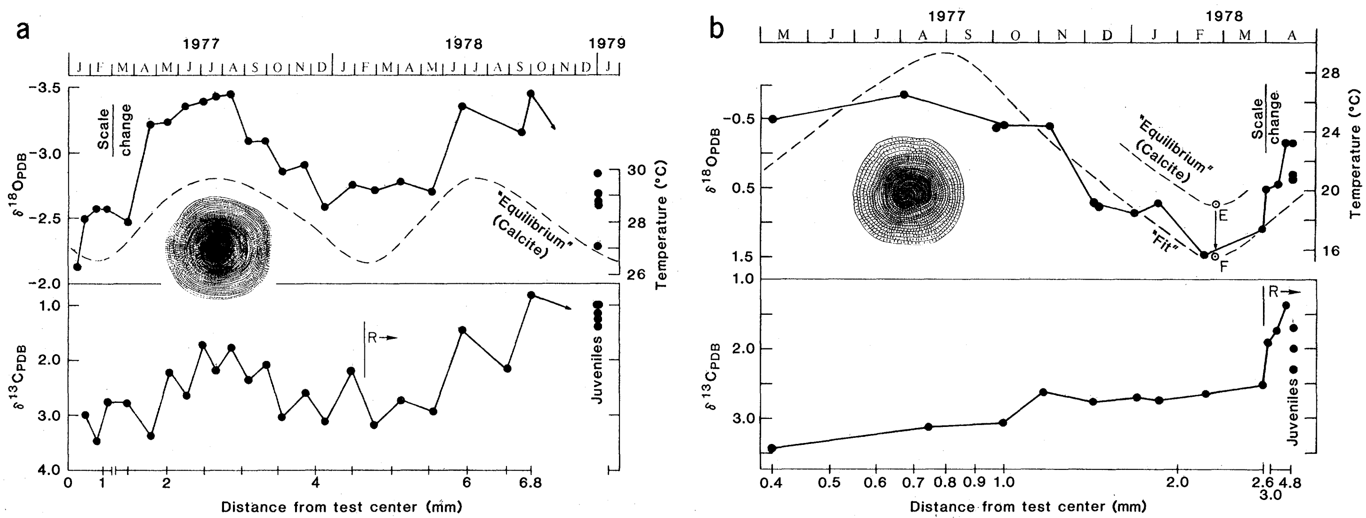

Fig. 1. (a) (top) Comparison of temperature variation (dashed line) in 5-m water off Maribago, Mactan, Philippines, between January 1977 and January 1979, with $\delta^{18}O$ variations (per mil) in the larger foraminifera *Marginopora vertebralis* (solid line); *PDB*, Pee Dee belemnite standard. The temperature and the oxygen isotope scale are matched by means of the equation of Epstein *et al.* (*8*) and the seawater composition data of Craig and Gordon (*9*). Temperature data [from the Cebu Harbour Project (*26*)] are plotted to show equilibrium (calcite) values. (bottom) Variations (per mil) in $\delta^{13}C$ in *M. vertebralis* as a function of the linear distance from the shell center. Note the scale change at 1.2 mm. (b) (top) Comparison of temperature variation (dashed line) in 10-m water in Harrington Sound, Bermuda, between May 1977 and April 1978, with $\delta^{18}O$ variations (per mil) in the foraminifera *Cyclorbiculina compressa* (solid line). The temperature and oxygen isotope scales are matched as in (a); an offset of +0.75 per mil (*E* to *F*) provides the "fit" (by eye). See text for calculation of the magnesium effect. Temperature data are from the Bermuda Inshore Waters Investigations (*27*). (bottom) Variations (per mil) in $\delta^{13}C$ in *C. compressa* as a function of the logarithmic distance from the shell center. Note the scale change at 2.6 mm.

Cyclorbiculina compressa appears to increase its growth rate with age; hence, we have chosen a logarithmic size scale to fit the oxygen isotope data to the seasonal temperature variations (Fig. 1b). There is a scale change at radius 2.6 mm (test diameter, 5.2 mm) to account for the rapid buildup of reproductive chambers (nine in number, producing a size increment from 5.5 to 9.6 mm). Fast buildup is clearly indicated from seasonal size distributions (*6*); it apparently is responsible for the relatively light oxygen isotope values of the reproductive chambers. Summer temperatures had not been reached at the time of collection (April). The values for the tests of the juveniles reflect this same ^{18}O depletion (unlike the case for *Marginopora*). The new *Cyclorbiculina* tests apparently are constructed from redissolved adult test wall; this inference receives added support in view of the increasing fragility of the reproductive chambers during reproduction (*6, 16*). Our estimate for the lifespan of 1 year is in accord with the field and laboratory observations of Lutze and Wefer (*6*).

The carbon isotope composition of Recent foraminifera has received much less study than the oxygen isotope composition. Although for oxygen isotopes the main cause of variation appears to be temperature (with the average level determined by the water composition and any more or less constant vital effect), no such simple cause has been identified for carbon isotope variations. Our results (Fig. 1) show (i) carbon isotope values much lighter than expected equilibrium values [3.5 to 4.5 per mil (*17*)], (ii) an overall correlation between oxygen and carbon values for *Marginopora* but not for *Cyclorbiculina*, and (iii) a tendency, with age, toward lighter-than-average $\delta^{13}C$ values for both *Marginopora* and *Cyclorbiculina*.

A positive correlation between $\delta^{13}C$ and $\delta^{18}O$ values in the calcareous hard parts of the same organism has been noted for ahermatypic coral (*18*) and for the otoliths of a rattail fish (*19*).

The tendency toward light carbon values with increasing age, observed in both *Cyclorbiculina* and *Marginopora*, is unexpected because the opposite has been found in planktonic foraminifera (*20*), where $\delta^{13}C$ tends toward heavier values with size (and age). We have analyzed other large benthic foraminifera (*21*) and have found the lighter-with-age trend in *Praesorites*, *Peneroplis*, and *Archaias*, which, like *Cyclorbiculina* and *Marginopora*, are members of the Miliolina (*22*). We did not find this trend in *Heterostegina* and *Calcarina*, which are members of the Rotaliina (*22*). These latter genera, on the whole, were 2 to 3 per mil lighter in their $\delta^{13}C$ values than the former species.

We propose that the carbon isotope data in the two species we studied can be explained as follows. (i) The ambient seawater HCO_3^- composition determines the general level of $\delta^{13}C$ values, as would be expected if it is extracted from seawater during calcification (*23*). (ii) The overall deviation and the fluctuations about this level reflect "vital effects" (*24*) stemming from the incorporation of metabolic CO_2 into the shell, which derives both from the activity of symbionts (*11*) and from other changes in metabolism (for example, growth rate effects) (*25*). (iii) The ^{13}C depletion of shell carbonate during terminal growth reflects increased metabolic activity associated with reproduction.

In a very general way and subject to the usual caveats, one might say that in the shells of these larger foraminifera the oxygen isotope signal records the seasons, and the carbon isotope signal reflects the metabolic responses of the organisms to the seasonal progression.

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The Meteorite-Asteroid Connection: The Infrared Spectra of Eucrites, Shergottites, and Vesta

Abstract. *Infrared reflectance spectra have been obtained for the meteorites Shergotty and Allan Hills (ALHA) 77005, a unique achondrite apparently related to the shergottites. Comparisons with the reflectance spectra of eucrites and asteroid 4 Vesta indicate that the surface of Vesta is covered with eucrite-like basalts and that, if shergottite-like basalts are present on the surface of Vesta, they must be a minor rock type. The paradox that both the eucrite and shergottite parent bodies should presently exist is examined. The preferred solution is that both eucrites and shergottites are derived from Vesta, and that this asteroid is compositionally and isotopically heterogeneous; however, other possible solutions cannot be ruled out.*

One of the principal goals of the study of meteorites is the attempt to place the chemical and petrogenetic information obtained in an astronomical context. Thus far this endeavor has met with mixed success. Three meteorites (Pribram, Lost City, and Innisfree) for which orbits may be calculated from photographic records of their atmospheric entry (*1*) appear to have originated in the main asteroid belt, whereas some meteor showers are associated with cometary orbits (for example, the η-Aquarids and Orionids with comet P/Halley). A more direct association has been made by McCord *et al.* (*2*) between asteroid 4 Vesta and the basaltic achondrites. McCord *et al.* and other workers (*3, 4*) have noted that the visible and near-infrared reflectance spectrum of Vesta is unique among main belt asteroids of diameter greater than ~ 50 km and is closely matched by two subclasses of the basaltic achondrites, the eucrites and howardites. This development led Consolmagno and Drake (*5*) to calculate the bulk composition of the parent planet of the eucrites. These investigators concluded that the mantle of the eucrite parent planet should constitute > 90 percent of the planet and should be dominated by olivine with lesser amounts of pyroxene, plagioclase, spinel, and metal. Had the parent planet been completely disrupted, Consolmagno and Drake (*5*) concluded that we would expect to observe at least nine times as many meteorites representative of the mantle as meteorites representative of the basaltic crust (eucrites and howardites). The absence of a single meteorite with the characteristics of this mantle leads to the conclusion that the eucrite parent planet must still be intact and should be covered with basalts. Consolmagno and Drake (*5*) argued on dynamical and geochemical grounds that all major planets and their satellites, together with comets, could be eliminated from candidacy, although Drake (*6*) listed certain caveats. By default, the asteroids remain as the possible location of the eucrite parent body. As Vesta is the only large (diameter, > 50 km) asteroid with an appropriate surface composition, Consolmagno and Drake (*5*) proposed that Vesta is the source of basaltic achondrites. Certain dynamical objections to this proposition have been raised by Wetherill (*7*) and have been discussed by Hostetler and Drake (*8*).

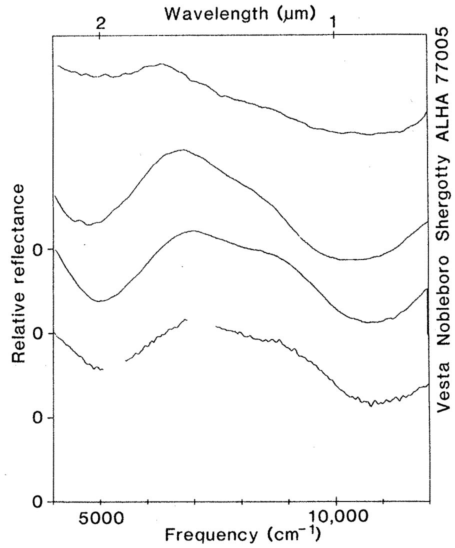

Fig. 1. Spectral reflectance of asteroid 4 Vesta and meteorites Nobleboro (a eucrite), Shergotty (a shergottite), and ALHA 77005 (a shergottite-related achondrite). All spectra were obtained with a Fourier spectrometer in the spectral range 4,000 to 12,000 cm^{-1} (0.8 to 2.5 μm) with a resolution of 25 cm^{-1}.

The eucrites are not the only type of meteoritic basalts, and it has been noted (*6, 9*) that the arguments presented by Consolmagno and Drake (*5*) in favor of Vesta as the eucrite parent body apply equally well to the shergottites. The shergottites are basaltic lavas derived by the melting of a material with different oxygen isotopic composition and volatile content from those of the eucrites (*10*). If the spectral reflectances of shergottites are indistinguishable from those of eucrites, astronomical observations of Vesta could not resolve this ambiguity. In

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