Of particular interest is the basal drag (or brittle) thermomechanical model proposed by Lachenbruch and Sass (*2*) that explains the regional heat flow data. This model is similar to that shown in Fig. 3; shear stress increases rapidly with distance from a weak fault, and a resistive shearing traction at the base of the plate balances the change in horizontal shear. The increase in shear stress with distance from the fault is consistent with the Lachenbruch and Sass model, too. However, prior to rigorous pursuit of any model, reliable vertical stress gradients should be determined.

If shear stress on the San Andreas fault is limited to about 100 bars, the fault is yielding at an extremely low stress. Furthermore, nearly total stress release occurs during earthquakes. It is not clear how this release occurs. The applicability of laboratory-derived frictional coefficients to faulting has been demonstrated for induced earthquakes at the Rangely oil field in Colorado, active normal faults in the Texas coastal area, and elsewhere (*12*). Furthermore, geodetic data appear to verify the basic concept of elastic strain energy accumulation and release along the San Andreas fault. Thus, sliding experiments do seem to be a reasonable analog for earthquakes. However, since the frictional coefficients of all common rock types and minerals are similar, explanations of low fault strength cannot be based on fault zone composition (*13*). One means for lowering the strength of a fault is by reducing the effective stress normal to the fault plane with high (nearly lithostatic) pore pressure. Although anomalously high pore pressure has been proposed to exist throughout the region of the San Andreas fault (*14*), the maintenance of high pore pressure throughout the active history of the fault would require either extremely low regional permeability or some mechanism for regenerating pore pressure within the fault zone itself.

In terms of earthquake prediction, it is clear from these results that if the fault zone is anomalously weak and stress is almost totally relieved during great earthquakes, the accuracy of long-term prediction could be greatly enhanced by stress measurements in critical areas. Furthermore, fault zone monitoring for short-term prediction may be quite straightforward if generation of pore pressure within the fault zone is the mechanism responsible for weakening the fault.

MARK D. ZOBACK
JOHN C. ROLLER
U.S. Geological Survey,
Menlo Park, California 94025

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9. The higher the compressive tangential (hoop) stress at the azimuth of the fracture, the harder it is to detect. Thus, fracture orientations from the wells distant from the fault could not be determined as reliably as those from wells near the fault.
10. M. C. Sbar, T. Engelder, R. Plumb, and S. Marshak [*J. Geophys. Res.* **84**, 156 (1979)] report surface stress measurements in this area. The measurements at the well sites near the fault show considerable scatter in the direction of maximum compression.
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Seasonal Oxygen Isotopic Variations in Living Planktonic Foraminifera off Bermuda

Abstract. *Seasonal variations in the oxygen-18/oxygen-16 ratio of calcite shells of living planktonic foraminifera in the Sargasso Sea off Bermuda are a direct function of surface water temperature. Seasonal occurrence as well as depth habitat are determining factors in the oxygen isotopic composition of planktonic foraminifera. These relationships may be used to determine the seasonal temperature contrast of oceans in the past.*

The $^{18}\text{O}/^{16}\text{O}$ ratio in calcite is dependent on the temperature and isotopic composition of seawater (*1*). During the Pleistocene, changes in global ice volume induced characteristic changes in the ^{18}O content of the oceans. Thus, the oxygen isotopic composition of calcareous foraminifera in deep-sea sediments provides important stratigraphic records of temporal changes in both global ice volume and ocean water temperatures (*2*).

To fully utilize the ^{18}O content of planktonic foraminifera as a paleoecological tool, it is necessary to identify the factors that determine the $^{18}\text{O}/^{16}\text{O}$ ratio of different species. In isotopic studies of fossil planktonic foraminifera it is generally assumed that calcite secretion takes place in isotopic equilibrium with ambient seawater, although a few studies of living planktonic foraminifera have suggested the contrary (*3, 4*). An important consideration is that planktonic foraminiferal shells reflect a range of hydrographic conditions depending on their life-spans, depth habitat preferences, and vertical migration. In addition, planktonic foraminifera exhibit a characteristic seasonal succession in species composition in temperate regions (*5*), resulting in a death assemblage in deep-sea sediments composed of species that lived in the same region but during different seasons and therefore under different hydrographic conditions.

To investigate some of these variables, we determined the oxygen isotopic composition of six species of living planktonic foraminifera collected in surface plankton tows at a station 6 km southeast of Bermuda on an approximately biweekly schedule during an 18-month period (July 1975 to December 1976) (*6*). Hydrographic data were collected biweekly at station S (32°06′N, 64°39′W) about 16 km from our plankton station (*7*).

Isotopic determinations were made on monospecific samples of the following species (*8*): *Globigerinoides ruber* (pink and white varieties separately), *Globigerinoides conglobatus*, *Globigerinella aequilateralis*, *Globorotalia truncatulinoides*, *Globorotalia hirsuta*, and *Pulleniatina obliquiloculata*. *Globigerinoides ruber* had the best sample coverage because it occurred throughout the year in the surface waters off Bermuda. The foraminiferal shells were grouped in various size classes to determine possible isotopic differences due to growth rate or ontogenetic stage. No systematic differences between different size fractions of the same species were found (*9*).

Our results show that seasonal varia-

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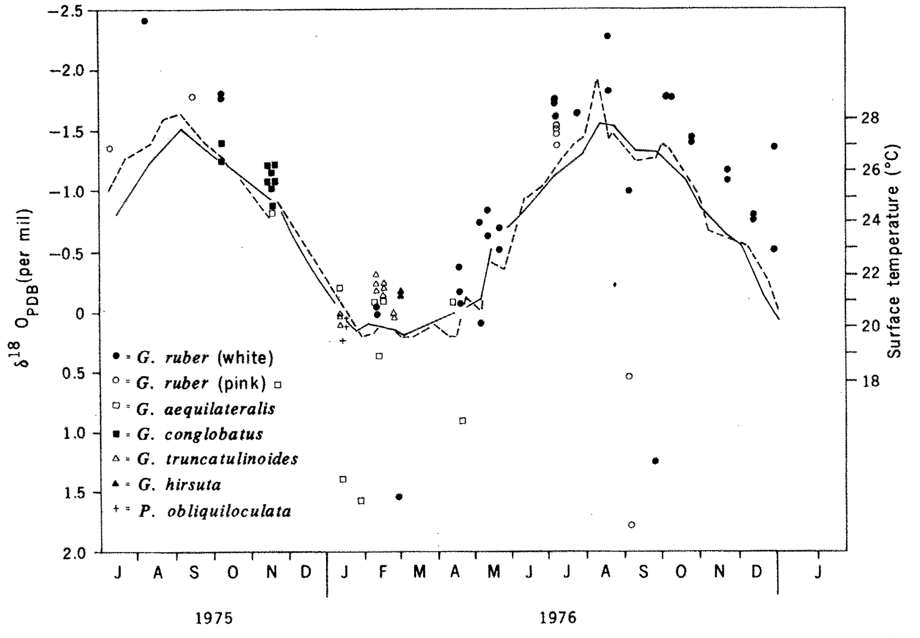

Fig. 1. Seasonal variation of $\delta^{18}O$ of living planktonic foraminifera collected off Bermuda. (Solid line) Surface water temperature measured at the time of plankton collection. (Dashed line) Predicted isotopic composition of calcite deposited in oxygen isotopic equilibrium with surface seawater (*10*).

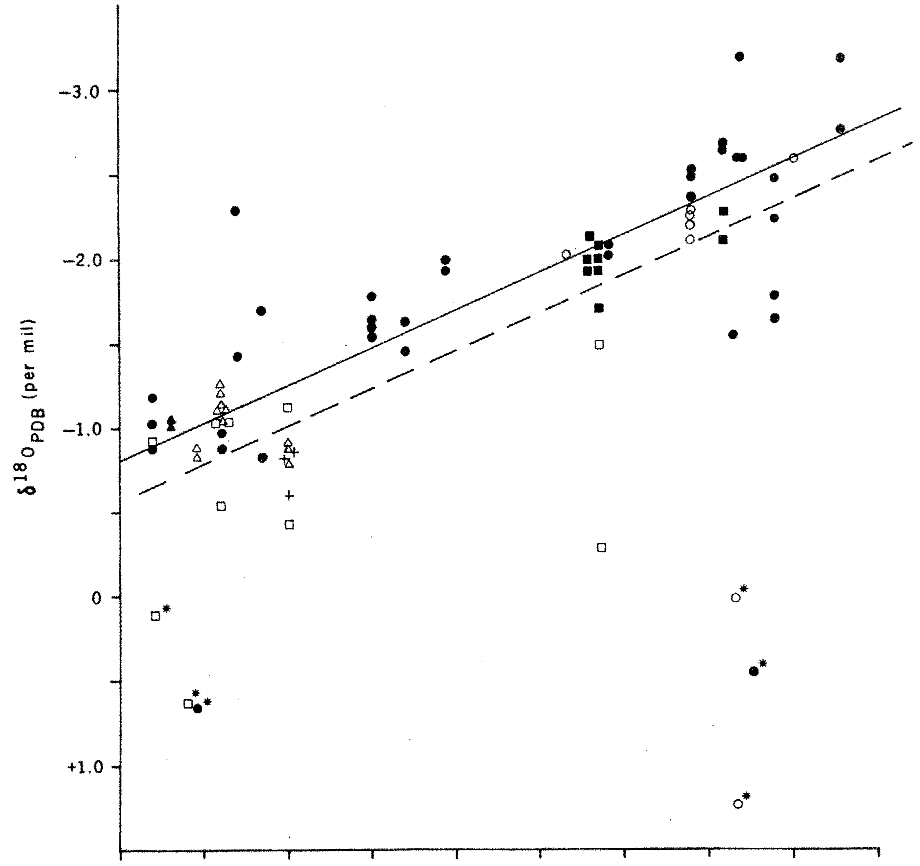

Fig. 2. Plot of $\delta^{18}O_c - \delta^{18}O_w$ against surface water temperature at the time of plankton collection, showing a $\delta^{18}O$ temperature dependence in foraminiferal calcite that is very close to the equilibrium fractionation factor. (Solid line) Regression line for the foraminiferal data corrected for the isotopic composition of seawater; slope = −0.22 and $r = -.84$. (Dashed line) Predicted oxygen isotopic composition of calcite (relative to PDB) deposited in isotopic equilibrium with surface seawater (*10*). Values with an asterisk were not included in the regression analysis and are shown here for completeness (*9*). The key for the symbols appears in Fig. 1.

tions in the $^{18}O/^{16}O$ ratio of planktonic foraminiferal calcite are a direct function of surface water temperature (Fig. 1). The oxygen isotopic compositions of the foraminiferal species undergo cyclic variations with time, with depleted values during the summer months and enriched values during the colder months in winter and early spring. The seasonal range in surface temperature during the study period is 27.6° to 19.4°C, and the salinity varies between 36.96 and 36.27 per mil. Except for a few analyses of *G. aequilateralis* and *G. ruber*, the isotopic compositions generally fall close to or slightly above the estimated equilibrium line (*11*) (Fig. 1).

Linear regression analysis illustrates the strong correlation between the $\delta^{18}O$ of foraminiferal calcite and surface water temperature (correlation coefficient $r = -.84$) (Fig. 2). The regression line through the foraminiferal data has a slope of −0.22 and approximately parallels the line of the equilibrium fractionation equation over the same temperature range.

We therefore conclude that the $\delta^{18}O$ composition of living planktonic foraminifera is a function of surface water temperature and, as such, records the seasonal temperature cycle in oceanic waters off Bermuda. Good agreement exists between the seasonal range in isotopic composition between foraminiferal and equilibrium calcite. There is some evidence that spinose planktonic foraminifera have life-spans of a few weeks or less (*12*), and our data suggest that no considerable time lag exists between seasonal temperature fluctuations and $\delta^{18}O$ changes in the foraminiferal calcite.

Before these results can be extrapolated to paleoecological studies of deep-sea sediments, however, we need to consider the seasonal succession and productivity of these species. *Globigerinoides ruber* lives year-round in surface waters of the Sargasso Sea (*5*) and therefore records different $\delta^{18}O$ values as a function of seasonal temperature changes at the surface. Species such as *G. truncatulinoides* record seasonal depth migrations because the species occurs abundantly at the surface only during the winter and is restricted to depths below the euphotic zone during the summer (*5*). We conclude that both seasonal occurrence and depth habitats contribute to the isotopic composition of planktonic foraminiferal specimens in sediment assemblages. This suggests that previous interpretations of the $\delta^{18}O$ composition of foraminiferal species in terms of their depth habitats only (*13*) are not entirely correct.

Preliminary evidence indicates that this seasonal temperature record may be preserved in the isotopic record of deep-sea sediments. The equation describing the ^{18}O fractionation with temperature in living foraminifera off Bermuda is nearly identical to that describing the isotopic composition of *G. ruber* analyzed from fossil assemblages of the Indian Ocean (*14*). In addition, *G. ruber* and *G. truncatulinoides* fossils (from regions of the Indian Ocean with a seasonal range in surface temperature equal to that off Bermuda) have an isotopic difference similar to the seasonal isotopic change in living species off Bermuda (*14*). We believe that these similarities between the living and fossil foraminifera are too close to be fortuitous and that, with further calibration, these relationships could be used to determine the seasonal temperature contrast and isotopic paleotemperatures of oceans in the past.

DOUGLAS F. WILLIAMS
Department of Geology and
Belle W. Baruch Institute, University of South Carolina, Columbia 29208
ALLAN W. H. BÉ
RICHARD G. FAIRBANKS
Lamont-Doherty Geological Observatory, Columbia University, Palisades, New York 10964

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6. Horizontal tows were taken with plankton nets (200-μm mesh) over a depth range of 0 to 10 m at a station located at 32°16′N, 64°39′W, approximately 6 km southeast of Castle Harbour, Bermuda.

7. Unpublished Bermuda Biological Station hydrographic data for 1975 and 1976, analyzed at the Woods Hole Oceanographic Institution by E. Schroeder.

8. The foraminiferal specimens were carefully cleaned of adhering debris with a brush, measured, and oven-dried at 50°C. Each foraminiferal sample was roasted in vacuo for 1 hour at 400°C and reacted in vacuo with concentrated phosphoric acid at 50°C. The isotopic difference between the derived sample CO_2 and the Pee Dee belemnite (PDB) standard was determined with an on-line VG micromass 602-C mass spectrometer. All values are reported as

$$\delta^{18}O = \left[\frac{(^{18}O/^{16}O)_{\text{sample}}}{(^{18}O/^{16}O)_{\text{PDB}}} - 1 \right] \times 10^3 \text{ per mil}$$

Duplicate analyses of the foraminiferal samples have an average standard deviation (S.D.) of ± 0.06 per mil for $\delta^{18}O$. Isotopic analyses were also made of four species of living foraminifera removed from two portions of a freshly collected plankton tow that were either frozen or preserved in 5 percent formalin solution buffered with hexamethylenetetramine. The results obtained with the specimens preserved by the two different methods indicate that formalin does not significantly affect the oxygen or carbon isotopic compositions of the calcite shells. All the isotopic differences are within the experimental error of ± 0.1 per mil (1 S.D.) (D.F.W., unpublished data).

9. The complete isotopic data set will be published separately (A. W. H. Bé, D. F. Williams, R. G. Fairbanks, in preparation) and is available on request.

10. The calcite (c) equilibrium line was computed using the isotopic paleotemperature (*T*) equation from S. Epstein, R. Buchsbaum, H. A. Lowenstam, and H. C. Urey (*1*).

$$T = 16.5 - 4.3\,(\delta^{18}O_c - \delta^{18}O_w) + 0.14\,(\delta^{18}O_c - \delta^{18}O_w)^2$$

Here $\delta^{18}O_w$ (PDB) = $0.59S - 20.68$ for water (w) relative to PDB; where *S* is salin → [S. Epstein and T. Mayeda, *Geochim. Cosmochim. Acta* **4**, 213 (1953); H. Craig and L. I. Gordon, in *Stable Isotopes in Oceanographic Studies and Paleotemperatures*, E. Tongiorgi, Ed. (Consiglio Nazionale della Ricerche, Laboratorio di Geologia Nucleare, Pisa, 1965), pp. 1–22].

11. Possible systematic errors in estimating calcite equilibrium include (i) calibration of laboratory reference gas BIG II to PDB, (ii) estimation of $\delta^{18}O$ of seawater near Bermuda, and (iii) accuracy of the paleotemperature equation. None of the factors are accurate to better than ± 0.1 per mil. From these data alone we cannot resolve the question of whether planktonic foraminiferal species calcify in oxygen isotopic equilibrium. Additional analyses of planktonic foraminifera from surface tows and laboratory cultures and direct measurement of $\delta^{18}O$ of ambient seawater are in progress and should help resolve this question.

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Silicon in Carbonaceous Chondrite Metal: Relic of High-Temperature Condensation

Abstract. *Electron microprobe analyses of an extraordinarily large metal grain from the Murchison type 2 carbonaceous chondrite gave 0.24 mole percent silicon. Thermodynamic calculations show that this is a natural consequence of condensation of alloys from the solar nebular gas at a total pressure* $10^{-5} \leqslant P_{\text{tot}} < 10^{-3}$ *atmosphere, provided they failed to equilibrate with it after cooling to* < 1200 *kelvins.*

A wide range of oxidation states is represented in chondritic meteorites (*1*). In fact, so variable is the oxidation state that it is used as the basis for the broad classification of chondrites. Carbonaceous chondrites are the most oxidized, the majority containing only trace amounts of metallic nickel-iron. Most of the iron in these meteorites is present as FeO dissolved in silicates and even Fe_2O_3 dissolved in the mineral magnetite, Fe_3O_4. Enstatite chondrites are the most reduced, containing virtually no oxidized iron in solid solution in silicates. Their iron occurs principally as the metal and sulfide. These meteorites are so reduced that elements normally combined with oxygen are present as sulfides (Ca, Mn), nitrides (Ti), and metal [Si dissolved in the nickel-iron phase in concentrations of 1.0 to 3.7 percent by weight (*2*)]. We report here the discovery of Si in the metal phase of a normal carbonaceous chondrite. We offer an explanation in terms of condensation processes from a nebular gas of solar composition.

Type 2 carbonaceous chondrites contain a variety of coarse-grained, anhydrous silicate and oxide phases disseminated in a very fine-grained matrix of hydrated phyllosilicates. Among the anhydrous materials are whole and broken euhedral crystals of forsteritic olivine, reaching 1 mm in size. Within these are found grains of a Cr-rich nickel-iron alloy, ranging from < 1 to 10 μm in size. This is the predominant mode of occurrence of metal in type 2 carbonaceous chondrites. In previous papers (*3, 4*) we discussed the origin of these olivines and their inclusions in terms of condensation from a high-temperature solar nebular gas. Rarely, metal grains are found isolated in the matrix (*5*).

In all these occurrences, the metal is embedded in silicates. In performing electron microprobe analyses, although the beam diameter can be narrowed to less than that of some of the larger metal grains, the actual volume excited into x-ray emission is often larger than the volumes of these grains. This results in the appearance of 0.0*x* to 0.*x* percent of fictitious Si in the metal analysis because of excitation of Si x-rays in surrounding sil-

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