no evidence from radio echo sounding for near-vertical shear planes or convection plumes in the Antarctic ice sheet.

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31 December 1970; revised 22 March 1971

When I wrote my *Science* report (*1*), I relied on the tentative conclusion of Robin *et al.* (*2*) that the near-vertical reflections were "deep shear surfaces." When Harrison's paper (*3*) appeared, I wondered if those reflections might in fact be unreal. However, Bentley has evidence for anisotropy in the West Antarctic Ice Sheet, and he suspects that convection may be involved (*4*).

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14 May 1971

Oxygen-18 Studies of Recent Planktonic Foraminifera

Recently, Hecht and Savin (*1*) published results on variations of oxygen isotopes in shells of Recent planktonic Foraminifera. However, we contend that their results, in which various phenotypes with and without abnormal final chambers are compared, do not warrant the conclusions they draw, but are open to interpretations which are more compatible with recent field observations.

First, they have analyzed too few samples to be able to see any significant and consistent differences between the phenotypes. For example, one out of two samples showed a significant difference in ratios of O^{18} to O^{16} in pairs of phenotypes of *Globoquadrina dutertrei*. Significant differences were found in only one out of three samples for *G. cultrata*, three out of seven samples for *G. trilobus-sacculifer*, and one out of four samples for *G. conglobatus*. Only *G. ruber* phenotypes showed significant differences in all three samples. Thus, their results do not warrant the sweeping conclusion that diminutive final chambers develop as a response to environmental stress. It is curious that in the one instance where they did compare a sample consisting exclusively of saclike final chambers with whole shells of *G. sacculifer* (core G-1290) the isotopic difference is neglible.

With regard to *Sphaeroidinella dehiscens*, Hecht and Savin (*1*) concluded that it is not a late-stage encrusted phenotype of *G. sacculifer*, but that the two are distinct species. Here again, their interpretation is not warranted on the basis of their oxygen isotope results. Their conclusion depends largely on the purity of the so-called "outer-crust" of the last four chambers, which they regarded as 100 percent pure after having mechanically removed the spinose, inner chambers. In reality their outer crust is not homogeneous, but consists of a spinose *"sacculifer"* stage and a cortex ["calcite crust" of Bé and Hemleben (*2*)] of widely varying thickness (Fig. 1). Depending on its developmental stage, the translucent cortex can vary from less than 1 μm to about 40 μm in thickness (*2*). From Fig. 1 it is clear that it is impossible to separate mechanically the two intertwined units.

Our contention is that the reason why Hecht and Savin found so little difference in δO^{18} (*3*) between outer crust and whole tests of *S. dehiscens* is that the test wall of the last four chambers consists of late-stage secretion (our cortex) plus shell material secreted earlier (spinose *sacculifer* stage). The crucial factor determining the magnitude of δO^{18} difference is the ratio of cortex to *sacculifer* materials contained in the outer crust of *S. dehiscens*.

We have reinterpreted the values for *S. dehiscens* (core C-1), assuming different degrees of outer crust purity and using a value of δO^{18} of $+0.14$ per mil for the whole test, $+0.04$ per mil for measured outer crust, and -0.78 per mil for *G. sacculifer* (*G. trilobus* of Hecht and Savin). For example, if we assume that the outer crust is composed of 70 percent pure cortex and 30 percent *sacculifer* shell, then the calculated value of δO^{18} for the cortex would be $+0.39$ per mil. In this case, the total *S. dehiscens* composition would be 79 percent cortex and 21 percent *sacculifer* stage. Also the temperature at which this cortex would have been secreted would be about 5°C cooler than the temperature at which the *G. sacculifer* would have secreted its shell. This would indicate that the cortex is secreted onto the spinose *sacculifer* stage at greater depth in the water column. If we assume that the outer crust consists of 50 percent pure cortex and 50 percent *sacculifer* shell, we would get a calculated value

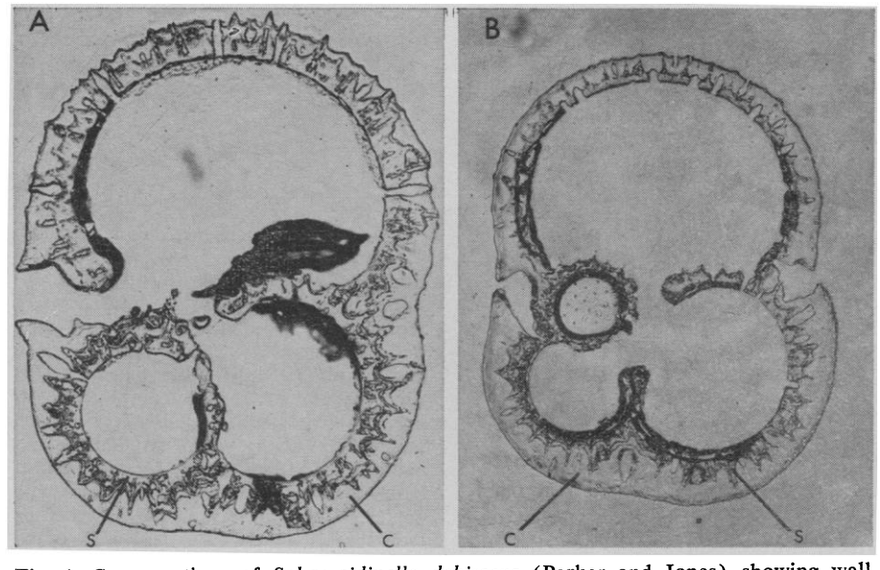

Fig. 1. Cross sections of *Sphaeroidinella dehiscens* (Parker and Jones) showing wall structure; *C*, cortex; *S*, spinose *sacculifer* stage. The cortex is thinner in (A) (× 116) than in (B) (× 94).

of δO^{18} for the cortex of + 0.86 per mil. The total composition of *S. dehiscens* would then be 56 percent cortex and 44 percent *sacculifer*. In this case the data would be equivalent to cortex secretion at about 15°C and 140 m deep for summer conditions at station C-1.

With respect to the depth habitat of *S. dehiscens*, Bé and Hemleben (*2*) have shown recently that it does occur in the upper 300 m of water. Thus our reinterpreted δO^{18} values of Hecht and Savin would not conflict with the observation that *S. dehiscens* is a late-stage encrusted phenotype of *G. sacculifer*.

Ratios of oxygen isotopes are useful in determining average depth habitat, but the latter cannot be used as conclusive argument for or against infraspecific genetic variation. Isotopic temperatures of planktonic Foraminifera (*4*) generally indicate average depth habitats in the upper 200 m, whereas observations based on plankton tows show that protoplasm-filled tests of viable specimens occur over a wide range of depths (0 to 1500 m) (*5*). We believe that, although the vertical range of depth habitats is extremely wide, the bulk of shell secretion does take place in the upper few hundred meters of water.

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20 April 1971

Bé and van Donk have stated that our model (*1*), in which diminutive final chambers develop as a response to environmental stress, is not supported by our data because only in the case of *Globogerinoides ruber*, a shallow-water tropical species, did populations with diminutive final chambers give isotopic temperatures consistently colder than normal populations. Consistent differences between the forms were not observed for *G. cultrata* and *G. dutertrei* which inhabit intermediate depths (100 to 200 m). It is exactly these results, however, which we feel are best explained by the environmental stress model.

Figure 1 schematically depicts our model, in which the habitats of a shallow-water species and a species from an intermediate depth are each stratified by depth into optimum and nonoptimum (or stress) zones. The zones are defined in terms of all physical and biological variables that may affect the growth of the species (*2*). For a species best adapted to shallow tropical waters, like *G. ruber*, conditions of environmental stress would occur in deeper water than the optimum environment and thus, if the model is correct, phenotypes with diminutive final chambers would be expected to record colder isotopic temperatures than would phenotypes with normal final chambers. This indeed was the case. On the other hand, for species like *G. dutertrei* and *G. cultrata*, which occur at intermediate depths, stress zones could lie in shallow water, in deeper water, or in both simultaneously. If this were the case, no consistent differences would be expected between the isotopic temperatures of the two forms of a given species; this again is what was observed. Thus, although our isotopic data do not prove the validity of the model in which populations with diminutive final chambers develop in stressed environments, they are in every case consistent with this model.

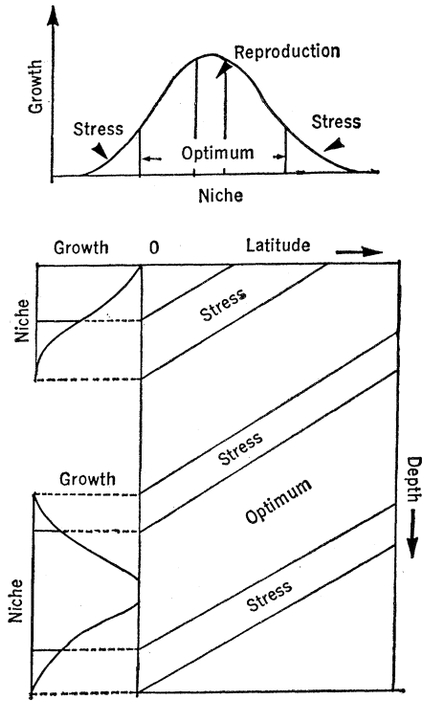

Fig. 1. (Top) Idealized growth model. Environmental range is divided into zones of reproduction, optimum growth, and nonoptimum growth. The actual shape of the curve and the area within the zones depend on the environmental variables being considered. (Bottom) Idealized growth model applied to depth stratification in planktonic Foraminifera for species of both shallow water and intermediate depths. Within this framework it may be seen that if a species is best adapted to tropical shallow waters, the nonoptimum zone of its environmental niche would mostly likely lie toward higher latitudes or deeper depths.

Our model is further supported by direct observations of the abundances of forms with normal or diminutive chambers in planktonic tows at various depths from the eastern Pacific Ocean (*3*). Berger (*3*) observed that for *G. ruber* the number of forms with diminutive chambers increased with depth, as would be expected for a shallow-water species. However, *G. dutertrei* showed a high percentage of forms with diminutive chambers in shallow waters.

Because the data for *G. conglobatus* and *G. trilobus–G. sacculifer* do not pertain to populations with diminutive as opposed to normal final chambers, it is misleading to use them in discussing the environmental stress model. Our isotopic data for these species bear on problems other than the significance of growth of diminutive final chambers, as outlined in our original report (*1*). In the case of *G. sacculifer* and *G. trilobus* we sought data which might bear on the environmental significance of the inflated final chamber. Our data show that *G. sacculifer* and *G. trilobus* record similar isotopic temperatures, and presumably grow at similar depths. In contrast is the work of Jones (*4*) who observed that in plankton tows *G. sacculifer* was found at shallower depths than *G. trilobus*. In a comparison between the saclike final chamber in *G. sacculifer* and the whole animal we found no isotopic difference. We prefer not to consider these data as "curious" but rather as significant in that they show that the inflated final chamber develops at a temperature similar to that of the rest of the test. The discrepancy between the isotopic data and the plankton tow data suggests to us that in some cases individuals may

be observed and may spend substantial portions of their lives at depths other than those at which they secrete their tests.

Finally, in the case of *Sphaeroidinella dehiscens*, we recognize that our results depend on the visual estimation of crust (cortex) and inner material (spinose *sacculifer*). We cannot deny that the cortex includes some spinal growth. For the sample from the Atlantic Ocean (C-1) we estimate that the cortex contained less than 50 percent inner material since the cortex was relatively thick and its exterior was not perforated by spinal growth. Even if we assume that in the crustal material we analyzed the cortex was contaminated by the presence of up to 50 percent spinose material we find the depth of secretion of the cortex would be no greater than 140 m. The calculated depth is considerably shallower than the depths of greater than 300 m previously suggested by Bé and Hemleben (*5*).

We have not suggested that isotopic data could prove whether or not *S. dehiscens* is encrusted *G. sacculifer*, but we maintain that the isotopic data do set limits on the depths at which test formation has occurred.

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How Did Venus Lose Its Angular Momentum?

Singer's proposed mechanism (*1*) for reducing a higher primordial angular momentum of Venus to its present value has one unfortunate side effect: it may destroy the planet in the process. Singer suggests that the angular momentum was reduced by tidal interactions with a captured moonlike body, which then disappeared by crashing into Venus. He writes (*1*, p. 1198).

> The moon is fated to crash into the planet's surface and will presumably disappear. Yet a "smile of the Cheshire cat" may remain. . . . Should events have taken place in this manner, then capture of a moon may have provided the trigger for the internal melting of Venus, for the formation of a core, and for the copious production of an atmosphere through volcanic emissions. . . .

The mass calculated for this hypothetical moon is about twice that of the earth's moon (*1*, p. 1198), and the disposal of this body thus involves a hypervelocity collision between a satellite that is about 30 percent larger in diameter than our moon and a primary that is about 5 percent smaller than the earth. A brief consideration of the kinetic energy involved in such an impact suggests that the effects of such a collision will be much stronger than Singer has implied and might even involve significant fragmentation of Venus itself.

The kinetic energy of impact is:

$$E = \tfrac{1}{2}\, m\, v^2 \qquad (1)$$

where m is the mass of the moon and v is the impact velocity. The calculated mass of the moon is 1.46×10^{26} g (*1*, p. 1198). A minimum value for the impact velocity is given by the circular velocity v_c at the surface of Venus, which may be calculated from the relation

$$v_c = (Rg)^{1/2} \qquad (2)$$

where R is the radius of Venus (6.06×10^8 cm) and g is the surface acceleration of gravity (877 cm sec^{-2}) (*2*, pp. 49, 673). The minimum impact velocity of the moon onto the surface of Venus is thus

$$v = v_c = 7.29 \text{ km/sec}$$

The minimum kinetic energy of the impact is thus

$$E = \tfrac{1}{2}\, m\, v_c^2 = 3.9 \times 10^{37} \text{ ergs} \qquad (3)$$

The specific kinetic energy per gram of target mass, E/M, is thus 8.0×10^9 erg/g. [The mass of Venus, M, is 4.87×10^{27} g (*2*, p. 673).]

Complete destruction of the hypothetical moon requires that the impact with the surface of Venus occur at an angle that is large enough so that ricochet and spallation of the projectile are not significant. For this case, by using the value for the kinetic energy of impact, it is possible to estimate the diameter (D) of the resulting crater by using scaling laws (*3–5*) of the form

$$E/E_0 = (D/D_0)^n \qquad (4)$$

where E_0 and D_0 are the energy and diameter, respectively, of a reference crater and n is usually between 3 and 4. I use Meteor Crater, Arizona, as a standard for which $E_0 = 7.11 \times 10^{22}$ ergs and $D_0 = 1.189$ km (*4*). The case where $n = 4$ (gravitational scaling) (*5*) sets a probable minimum diameter; for $n = 4$, $D = 5760$ km. For $n = 3$ (cube root scaling), a probable maximum diameter is $D = 97{,}400$ km. Since the diameter of Venus is only 12,120 km (*1*, p. 1198; *2*, p. 673), it is not clear that the planet could contain the crater produced by the proposed impact.

It can be argued that such scaling laws, developed for relatively small craters, cannot be meaningfully applied to such a catastrophic event. However, more general considerations of the mechanics of hypervelocity impact cratering (*4*, *6*) lead to the same conclusions. In such events, the diameter of the resulting crater is generally from 10 to 30 times the diameter of the projectile, and the projectile itself generally penetrates the target for distances of two to five times its own diameter during crater formation.

The diameter of the hypothetical moon can be calculated from the relation

$$m = 4/3\, \pi\, r^3 \rho \qquad (5)$$

If a density of $\rho = 3.34$ g/cm^3, equal to that of our moon, is used, the calculated diameter is 4370 km. (The exact density is not critical, since a change of a factor of 2 in density produces only about a 30 percent change in diameter.) Substitution of this diameter into the general cratering relations discussed above also indicates the production of an impossibly large and deep crater relative to the size of Venus itself.

Severe alteration of Venus by the impact is also indicated simply by the large kinetic energy involved. The specific kinetic energy of impact per gram of target mass (Venus) is 8.0×10^9 erg/g, nearly three orders of magnitude greater than that required for complete