5. The minimum and maximum possible viewing distances to each hole were used to compute spacing so that no two holes were closer together than 3°, a typical central field size [J. D. Pettigrew, T. Nikara, P. O. Bishop, *Exp. Brain Res.* **6**, 373 (1968)].
6. We verified the adequacy of the precautions prior to the investigation. A 35-mm camera with a wide angle lens, loaded with Tri-X film, was transported with its shutter locked open from the dark room to the sphere in the same lighttight bag to be used for the kitten. The camera was left in the sphere for a period of 30 minutes. With the film developed to its maximum sensitivity, we found no evidence of stray light or of shadows cast from the point sources to the blackened lower hemisphere.
7. Preliminary surgery was carried out under fluothane. After intravenous and tracheal cannulation, positioning in the head holder and craniotomy, ventilation was controlled with a mixture of oxygen, carbon dioxide, and nitrous oxide. Standard controls for corneal maintenance, eye position, stimulus presentation, and recording were used. [H. B. Barlow, C. Blakemore, J. D. Pettigrew, *J. Physiol. Lond.* **193**, 327 (1967).]
8. W. R. Levick, *Med. Biol. Eng.* **10**, 510 (1973).
9. The stimuli were bright spots which varied in size between 0.05° and 10°, extended black or white (or both) edges of all orientations, and bright line stimuli of all orientations which could be varied upward in size from 0.1° by 0.5°.
10. P. O. Bishop, W. Burke, R. Davis, *J. Physiol. Lond.* **106**, 409 (1962); P. O. Bishop and G. H. Henry, *Invest. Ophthalmol.* **11**, 346 (1972).
11. Since incoming fibers from the lateral geniculate nucleus in a normal cat have concentrically organized receptive fields, it might be thought that they would be confused with the spot detector cortical cells. But apart from waveform criteria, the spot detector cells could always be distinguished by their irregular field shape, absence of spatial summation and binocularity. The lateral geniculate nucleus fibers studied in this preparation were in marked contrast to those of a normal cat because of their tiny, hard-to-locate, regularly shaped receptive fields. The fields were only 0.2° in diameter, which is unusually small considering the 8° eccentricity at which they were recorded. In addition, they were monocular and exhibited an exact correspondence between field size and optimal stimulus size.
12. Area threshold estimations were carried out in one case for a unit with a field size of 1.7° by 2.7°. Over a narrow range of spot sizes (0.05° to 0.3°) we could maintain a constant response by increasing the spot size while decreasing intensity or by decreasing the spot size while increasing the intensity. A 0.5° spot, however dim or bright, gave no response, suggesting that the large field was made up of small subunits less than 0.5° in size.
13. The ocular dominance histogram was slightly atypical, with a bias toward cells dominated by the ipsilateral eye.
14. D. H. Hubel and T. N. Wiesel, *J. Neurophysiol.* **26**, 994 (1963); T. N. Wiesel and D. H. Hubel, *ibid.* **28**, 1029 (1965); D. H. Hubel and T. N. Wiesel, *J. Physiol. Lond.* **206**, 419 (1970).
15. H. B. Barlow and J. D. Pettigrew, *J. Physiol. Lond.* **218**, 98 (1971).
16. We thank B. Rogers and C. Olson for help with the investigation. Supported by PHS grants from the National Eye Institute to R.D.F. (EY01175) and H. B. Barlow (EY-00276).

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Oceanic Growth Models

Chase and Perry (*1*) have presented a model involving isotopic interactions between crustal and mantle rocks and oceanic waters that allows the calculation of δ_O, the $\delta^{18}O$ value (*2*) of the oceans, during the past 3.3×10^9 years. Using this model, they obtained a limit of about 10 percent for the amount of oceanic growth that would be compatible with the increase of 15 per mil in δ_O suggested by the $\delta^{18}O$ values of chert samples formed within this time period. Although the model itself is reasonable, some errors made by Chase and Perry in its evaluation nullify the conclusions they have drawn (*1, 3*).

The model assumes that just four processes control both the mass of the oceans (measured in terms of the moles of $^{16}O_2$ making up the water) and the value of δ_O. These are (i) outgassing of water from the mantle into the oceans, affecting both the mass and δ_O; (ii) subduction of water trapped in the oceanic crust, affecting the mass but not δ_O; (iii) formation of sediments, in isotopic equilibrium with ocean water, from igneous rocks; and (iv) formation of metamorphic rocks, having a constant fractionation with respect to ocean water, from both igneous rocks and sediments. These last two processes affect δ_O but not the mass of the oceans; they can be regarded as consisting of the 1 : 1 transformation (in terms of $^{16}O_2$ contents) of igneous rocks to either sediments or metamorphic rocks. The rate of change of δ_O with time *t* (in years) derived by Chase and Perry from these four processes can be written as

$$\frac{d\delta_O}{dt} = \frac{m_{UO}\delta_{UO} + q_{IS}\delta_{ISO} + q_{IM}\delta_{IMO} - (m_{UO} + q_{IS} + q_{IM})\delta_O}{M_O(0) + \int_0^t m_{UO}dt + \int_0^t p_{OU}dt} \quad (1)$$

where m_{UO}, q_{OU}, q_{IS}, and q_{IM} are the rates of processes (i) to (iv), respectively, in units of moles of $^{16}O_2$ transferred per year; δ_{UO} is the $\delta^{18}O$ value of the water outgassed from the mantle; $\delta_{ISO} = \delta_I - \delta_S + \delta_O$, where δ_I is the $\delta^{18}O$ value of igneous rocks and δ_S is the $\delta^{18}O$ value of sediments forming in equilibrium with the ocean at any given time; $\delta_{IMO} = \delta_I - \delta_M + \delta_O$, where δ_M is the $\delta^{18}O$ value of the metamorphic rocks being formed in equilibrium with the ocean at any given time; and $M_O(0)$ is the mass of the oceans (in moles of $^{16}O_2$) at the time $t = 0$. As defined in the model, δ_{UO}, δ_{ISO}, and δ_{IMO} are constants, p_{OU} is negative, and the denominator of Eq. 1 is always positive. Equation 1 is general, in the sense that all rates may be varied with time.

Two properties of the model are particularly relevant to a discussion of the conclusions of Chase and Perry. First, it can be seen from Eq. 1 that the value of δ_O should be subject to certain limits, independent of the various rates of transfer, determined only by the values of δ_{UO}, δ_{IMO}, and δ_{ISO}. When δ_O equals the largest of these three values, $d\delta_O/dt$ must be either zero or negative, and δ_O cannot become any larger. When δ_O equals the smallest of these values, $d\delta_O/dt$ must be either zero or positive, so that δ_O cannot become any smaller. Thus, if δ_O has a value at $t = 0$ lying within the limits set by δ_{UO}, δ_{IMO}, and δ_{ISO}, it must remain within these limits for all values of *t* greater than zero. Should δ_O have a value at $t = 0$ which lies outside these limits, the model will cause it to move within the limits and then remain there. The actual limits turn out to be determined by the values of δ_{UO}, approximately +7 per mil as chosen by Chase and Perry, and δ_{ISO}, which has an extreme value of about −30 per mil for the formation of pure chert sediments (*4*).

The second significant property of the model is seen when Eq. 1 is integrated. For the simplest situation, where all four processes have constant rates, there are two solutions: one for an ocean of constant mass ($m_{UO} + p_{OU} = 0$) and one for an ocean of changing mass ($m_{UO} + p_{OU} \neq 0$). For the second case, δ_O as a function of time is given by

$$\delta_O = \frac{A}{B} - \frac{A - B\delta_O(0)}{B} \times \left[\frac{M_O(0)}{M_O(0) + (m_{UO} + p_{OU})t}\right]^{B/(m_{UO} + p_{OU})} \quad (2)$$

where $A = m_{UO}\delta_{UO} + q_{IS}\delta_{ISO} + q_{IM}\delta_{IMO}$, $B = m_{UO} + q_{IS} + q_{IM}$, and $\delta_O(0)$ is the value of δ_O at $t = 0$. Inspection of Eq. 2 shows that, as *t* increases, δ_O changes monotonically from the value $\delta_O(0)$ to a final value of A/B. These initial and final values are independent of the rate of variation of the mass of the ocean (independent of $m_{UO} + p_{OU}$); only the path taken by δ_O between these initial and final values varies somewhat with the value of $m_{UO} + p_{UO}$, and δ_O for any particular *t* is as sensitive to the values of *A* and *B* as it is to the value of $m_{UO} + p_{OU}$. All models for which the rates of processes (i) to (iv) are similar functions of t will yield the same result as the model with constant rates.

My objections to the results in (*1*) can be understood in light of the above observations. It is implicit in the model that all ocean water ultimately was derived from the mantle, and therefore had an initial $\delta^{18}O$ value within the boundaries for δ_O mentioned above. Therefore, the extremely low δ_O values obtained for model II in figure 2 of (*1*) cannot be a correct result of Eq. 1. In fact, since δ_{ISO} was chosen as -9.5 per mil in (*1*), even model I in figure 2 yields δ_O values that are too low. Furthermore, the large discrepancy between models I and II is not due only to the difference between a constant and a growing ocean, as assumed in (*1*). Rather, it is due as well to a change in the parameters A and B of Eq. 2, in going from model I to model II. Finally, while the behavior of model III in figure 2 of (*1*) shows promise with respect to fitting the chert data, it was obtained by using a value of $+25$ per mil for the ratio A/B, whereas this ratio must in reality lie within the limits of δ_{UO} and δ_{ISO} (that is, between $+7$ and -30 per mil). The value of B in model III was also defined so that it becomes negative for times earlier than about 2.1×10^9 years ago, an unlikely situation in the real world.

Chase and Perry appear to have made the following error in calculating models I and II. Instead of accepting the value of -15 per mil for $\delta_O(0)$ at 3.3×10^9 years ago indicated by the chert data, assigning values to m_{UO}, p_{OU}, q_{IS}, and q_{IM} based on estimates in the literature (*5, 6*), and then varying one or more of these rates within the limits of uncertainty so as to obtain the present value for δ_O of 0 per mil, they chose to define the present value of δ_O as $\delta_O(0)$, and then attempted to calculate values of δ_O at earlier times by using a particular fixed set of values for q_{IS}, q_{IM}, and p_{OU}. They allowed m_{UO} to vary, as a means of varying the growth rate of the oceans. Their procedure unfortunately has two drawbacks. First, calculating backward is equivalent to changing the sign of the derivative in Eq. 1. When this is done, the calculation, instead of holding δ_O within the limits of δ_{UO} and δ_{ISO}, tends to result in runaway behavior for δ_O whenever $d\delta_O/dt \neq 0$ at $t = 0$. The time required for the runaway behavior to become apparent depends on the initial value of $d\delta_O/dt$, and therefore on the parameters in Eq. 1. Through a fortunate choice of these parameters, Chase and Perry obtained an apparently reasonable set of values for δ_O in model I. This model is, however, very close to a runaway situation.

The second drawback, related to the first, was the use of m_{UO} as the means of varying the rate of oceanic growth. Altering m_{UO} not only changes the value of the term $m_{UO} + p_{OU}$ in Eq. 1, which is responsible for growth of the ocean, it also changes the values of A and B. This plays a significant part in changing the near runaway behavior of model I into the actual runaway seen in model II. If Chase and Perry had chosen to reduce the value of p_{OU} by 25 percent instead of increasing m_{UO} by this amount, which would have been a legitimate procedure in view of the uncertainty of ± 40 percent given in (*5*) for the value of p_{OU} (*7*), then model II would have been significantly closer to model I in its behavior, because only the term $m_{UO} + p_{OU}$ would have been affected. However, even in this case, both models would still be incorrect representations of the behavior of δ_O, because of the reversal of time involved in their evaluations. Therefore, any conclusions with respect to a limit on the amount of oceanic growth since the early Precambrian based on these models are not justified.

In theory, Eq. 1, or a modified version of it (taking in additional processes), allows the calculation of oceanic growth over the entire history of the earth, and not just the last 3.3×10^9 years. In practice, however, without sufficient data to define the time dependence of q_{IS} and q_{IM}, the model of Chase and Perry contains too many variables to yield any useful information on the growth history of the oceans (*8*).

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References and Notes

1. C. G. Chase and E. C. Perry, Jr., *Science* **177**, 992 (1972).
2. The value of $\delta^{18}O$ is defined by

$$\delta^{18}O = \left[\frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{SMOW}} - 1\right] \times 1000$$

where SMOW is standard mean ocean water [see H. Craig, *Science* **133**, 1833 (1961)].
3. C. G. Chase and E. C. Perry, *Geol. Soc. Amer. Abstr. Programs* **4**, 469 (1972).
4. Sediments, for this model, may be viewed as consisting of two components: a chemical component in equilibrium with ocean water and a mechanical component with the same $\delta^{18}O$ value as its parent rock. Since only the chemical component has an effect on δ_O, the values for δ_{ISO} and q_{IS} must be chosen to reflect just this component. A realistic value for δ_{ISO} would be about -20 per mil, corresponding to a mixture of chert, carbonates, and clay minerals in sediments. The value of q_{IS} is then determined through this δ_{ISO} and the amount of excess per mil moles for sediments given in (*6*). It must be recognized that the true situation is somewhat more complicated than the two-component system. In addition to chemical sediment and unaltered igneous rock, there is a detrital metamorphic component which belongs in the total of metamorphic rocks, rather than sediments. Another component consists of detritus that may be only partially exchanged with ocean water, and which will therefore contribute to a lowering of the value of δ_{ISO}. A completely rigorous evaluation of the model in (*1*) must take these components into account.
5. K. Muehlenbachs, thesis, University of Chicago (1971).
6. E. C. Perry, Jr., and F. C. Tan, *Geol Soc. Amer. Bull.* **83**, 647 (1972).
7. The value given in (*1*) for p_{OU} is in any case 11 percent too high. Chase and Perry took the value given in (*5*) for the mass of H_2O subducted per year, rather than the value for the mass of oxygen making up this water, as their value for p_{OU}.
8. The model in (*1*) does have one interesting result. From the fact that, within the assumptions of the model, only process (iii) can reduce δ_O to a value below about -5 per mil (and then only if q_{IM} and m_{UO} are small relative to q_{IS}), and from the observation that δ_O was -15 per mil at 3.3×10^9 years ago, it must follow that either very little outgassing of water occurred during the first 10^9 years of earth history, or most of the sediments presently observed in the earth's crust formed during this time period. This second possibility would support the suggestion that an approximately constant amount of sedimentary material has been recycled by crustal processes several times within the last 3×10^9 years [see R. M. Garrels and F. T. MacKenzie, *Science* **163**, 570 (1969)].
9. I thank Drs. F. Ackermann and M. S. Brewer of the University of Heidelberg for their helpful discussions during the preparation of these comments. Support was provided by the Deutsche Forschungsgemeinschaft.

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Becker is correct in pointing out that our models I and II become quite similar if the oceanic growth is modeled by reducing p_{OU} instead of increasing m_{UO}. This does weaken the conclusion that these models place a limitation on the amount of oceanic growth since early Precambrian.

We do not believe, however, that the reversal of time involved in our calculations gives rise to any serious difficulties. There is no fundamental or numerical difference between starting at the present and calculating backward in time, or starting with $\delta_O = -15$ per mil at 3.3×10^9 years ago and calculating toward the present. In either case, a reasonable model is one that approximates the oceanic $\delta^{18}O$ evolution inferred by Perry and Tan (*1*). In particular, the models should be constrained to pass through the two end points.

Furthermore, it is not implicit in the

mathematical model that all ocean water ultimately was derived from the mantle. Any conclusion that there was no primordial ancestral ocean must be based on other arguments. At present there are no observational data constraining the $\delta^{18}O$ of the oceans before 3.3×10^9 years ago, so inferences about the isotopic ratio of the very early oceans must be speculative.

The problem of modeling the evolution of the oceans' isotopic ratio between two fixed end points can be studied with profit, however. If we assume that parameters A and B remain constant and that any change in volume of the oceans is linear with time, the evolution curves become functions of only two parameters.

For an initial starting time t_0 and an initial isotopic ratio $\delta_O(t_0)$, and a final t_1 and $\delta_O(t_1)$, we can define the dimensionless quantities

$$t' = \frac{t - t_0}{t_1 - t_0} \tag{1}$$

and

$$\delta' = \frac{\delta_O(t) - \delta_O(t_0)}{\delta_O(t_1) - \delta_O(t_0)} \tag{2}$$

for any time t between t_0 and t_1. The effects of A and B can be incorporated into a single parameter

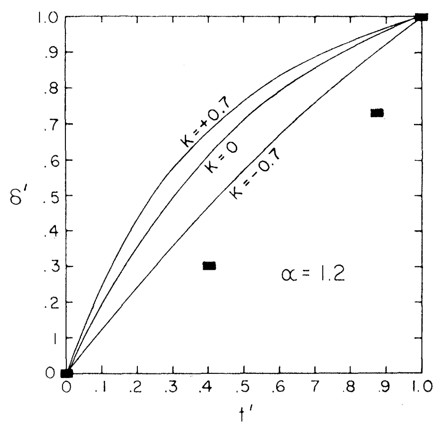
$$\alpha = \frac{A - B\delta_O(t_0)}{B[\delta_O(t_1) - \delta_O(t_0)]} \tag{3}$$

Introducing, with apologies, an ocean growth parameter

$$K = \frac{M_O(t_1) - M_O(t_0)}{M_O(t_0)} = \frac{(m_{UO} + p_{OU})\ (t_1 - t_0)}{M_O(t_0)} \tag{4}$$

we have for K not equal to zero

$$\delta' = \alpha\left\{1 - \exp\left[\frac{\ln(1-\alpha^{-1})\ln(1+Kt')}{\ln(1+K)}\right]\right\} \tag{5}$$



For the evolution curve to pass through the two end points, we must satisfy the criterion

$$\frac{-B(t_1 - t_0)}{K\,M_O(t_0)} = \frac{-B}{m_{OU} + p_{OU}} = \frac{\ln(1-\alpha^{-1})}{\ln(1+K)} \tag{6}$$

In the case of an ocean with constant volume, $K = 0$. The simpler expression

$$\delta' = \alpha[1 - (1 - \alpha^{-1})^{t'}] \tag{7}$$

results, and the criterion for satisfying the end points is

$$\frac{-B(t_1 - t_0)}{M_O} = \ln(1 - \alpha^{-1}) \tag{8}$$

The two end point criteria, Eqs. 6 and 8, provide a convenient means of checking whether a particular set of process rates and isotopic shifts can satisfy both the present δ_O, defined as 0 per mil, and an inferred ancient δ_O.

For the particular $\delta_O(-3.3 \times 10^9$ years$) = -15$ per mil (*1*), the process parameter α is not likely to be much greater than one, since it reduces to $\alpha = (A + 15B)/15B$. Figure 1 shows a sample calculation for $\alpha = 1.2$ and various values of K. The curve for $K = +0.7$ represents a 70 percent growth in ocean volume since 3.3×10^9 years ago, and the curve for $K = -0.7$ represents a 70 percent decrease. The ancient isotopic ratios inferred for the oceans by Perry and Tan (*1*) are shown by heavy black bars. It can be seen that a shrinking ocean model (*2*) gives a better fit to the data in this case than a model involving oceanic growth.

Fig. 1. Normalized evolution of the oceanic oxygen isotope ratio as a function of the oceanic growth parameter K; δ' is the normalized $^{18}O/^{16}O$ ratio, and t' is the normalized time. These variables and the parameters K and α are defined in the text. The heavy bars represent inferred ancient oceanic isotope ratios from Perry and Tan (*1*), with $t_0 = 3.3 \times 10^9$ years ago and $\delta_O(t_0) = -15$ per mil.

For smaller values of α, the curves would be more strongly curved upward and would give a poorer fit to the data. For any values of α, models involving oceanic growth will be convex upward, in contrast to the data, which define a curve that is concave upward. This is suggestive but by no means conclusive evidence against oceanic growth.

The mathematical model presented here is undoubtedly too simple, and more work is needed to further constrain the process rates and isotopic shifts. In addition, more measurements to pin down the actual history of $\delta^{18}O$ evolution of the oceans are needed before any firm conclusions can be drawn.

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1. E. C. Perry, Jr., and F. C. Tan, *Geol. Soc. Amer. Bull.* **83**, 647 (1972).
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