om, the reaction in gel with the human serum was abolished.

The antiserum to CoF was reacted in immunoelectrophoresis with whole *Naja naja* serum, and a strong reaction was observed with a β-mobility protein in the cobra serum. The material in the cobra serum converted to some extent to a more rapidly migrating protein on incubation at 37°C for 1 hour. However, this conversion was much more marked on incubation of the snake serum with endotoxin (*16*) (Fig. 2). Neither zymosan nor antigen-antibody precipitate made from rabbit antibody had an effect on this protein in cobra serum when incubated at 2 mg of precipitate per milliliter of cobra serum. Incubation of cobra serum with $0.15M$ hydrazine for 30 minutes at 37°C produced conversion of about half of the cross-reacting material to a more slowly migrating protein.

Immunofixation (*17*) of whole cobra serum, whole cobra venom, and purified CoF (*18*) is shown in Fig. 3. The protein in cobra serum forms a single, sharp band, whereas CoF either in whole venom or in the isolated state produces a series of electrophoretically slower bands all of which are antigenically identical.

These observations suggest that CoF is closely related to a cobra serum protein with many of the characteristics of C3. The electrophoretic appearance of CoF compared with that of the native material in serum suggests that the material in the venom has been altered, and perhaps acted on by proteolytic enzymes.

Incubation of cobra serum with CoF at 10 μg/ml at 37°C for 30 minutes did not result in increased conversion of the CoF-reactive material of the snake serum, although, as expected, CoF at 10 μg/ml induced marked C3 conversion in human serum, as judged by immunoelectrophoresis. When cobra serum was incubated with ^{125}I-labeled CoF for 3 hours at 37°C (*19*), the labeled CoF was converted to more rapidly migrating material on prolonged agarose gel electrophoresis and radioautography (Fig. 3). Incubation with purified human C3b inactivator or buffer produced no alteration in the electrophoretic appearance of CoF. Furthermore, incubation of CoF at 10 μg/ml with cobra serum at 37°C for 1 hour destroyed the ability of the mixture to induce C3 conversion in human serum. Similar incubation of CoF with barbital-buffered isotonic saline containing $1.5 \times 10^{-4}M$ Ca^{2+} and $10^{-3}M$ Mg^{2+} and 1 percent human serum albumin, or a solution of purified human C3b inactivator (*20*) at 10 μg/ml, did not destroy its ability to convert C3 in human serum. When a mixture of equal parts of cobra serum and human serum were incubated at 37°C for 30 minutes, the extent of human C3 conversion was similar to that of human serum incubated alone.

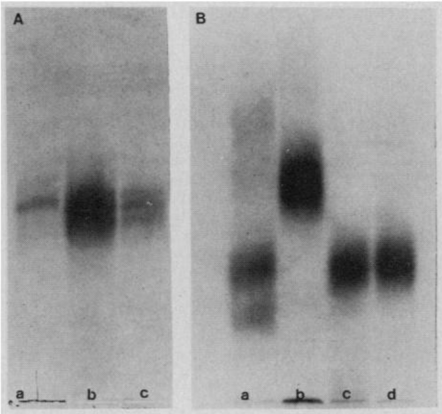

Fig. 3. (A) Immunofixation patterns developed after prolonged agarose gel electrophoresis with antiserum to CoF of (a) cobra serum, (b) isolated CoF, and (c) whole cobra venom. (B) Radioautograph after prolonged agarose gel electrophoresis of mixtures of ^{125}I-labeled CoF and (a) normal human serum, (b) cobra serum, (c) cobra venom, and (d) barbital-buffered saline with Mg^{2+} and Ca^{2+} containing 1 percent human serum albumin. All mixtures were incubated for 3 hours at 37°C prior to electrophoresis. The slower band in (a) represents a complex between CoF and Bb (*12*). The most rapid band is unidentified. The mobility of CoF in (c) and (d) is the same as that of untreated CoF. The native mobility of CoF disappeared on incubation with cobra serum and one or two bands with more rapid mobility appeared.

These observations suggest that CoF is a form of cobra C3 (perhaps the analog of human C3b) which has the active site for forming the alternative pathway convertase in human serum. Its very potent activity would, therefore, derive from its lack of susceptibility to the human C3b inactivator. On the other hand, its failure to convert cobra serum C3 and its conversion in cobra serum suggest its susceptibility to an inactivating mechanism in cobra serum which might be analogous to the human C3b inactivator.

The fact that CoF is probably cobra C3b or a fragment of C3 very similar to C3b explains the observation that CoF incubated with serum from a patient homozygous for C3 deficiency results in normal C5 inactivation and normal passive hemolysis of unsensitized guinea pig erythrocytes (*21*) since activated C3 is being supplied to the C3-deficient serum. The observations in this report also supply a reasonable explanation for the otherwise enigmatic highly specific interaction of a snake venom protein with mammalian serum, an enigma that has been with us for the past 80 years.

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9 September 1975; revised 5 January 1976

Laboratory Plate Tectonics: A New Experiment

Abstract. *A "continent" made of a layer of hexagonally packed black polyethylene spheres floating in clear silicon oil breaks into subcontinents when illuminated by an ordinary incandescent light bulb. This experiment may be a useful model of plate tectonics driven by horizontal temperature gradients. Measurements of the spreading rate are made to establish the feasibility of this model.*

Plate tectonics is now accepted by most earth scientists as a useful paradigm for understanding the evolution of the major features of geology (*1*). Attempts to understand the physics of the process have been limited by the extreme complexity of the problem (*2*). Only limited success has been achieved with analytic (*2*) and experimental (*3*) approaches.

A major outstanding problem is the

question of the driving mechanism. A number of mechanisms, most of them thermal in nature, have been proposed (*2, 4*). Of these, only the hypothesis of motions below the plates caused by lateral temperature inhomogeneities, propounded by Howard *et al.*, Whitehead, and Elder (*5*), has the advantage of incorporating an observed phenomenon, excess radioactivity in continental rocks.

The important parameters for any model of this process are the Prandtl number, $\sigma = \nu/\kappa$, the ratio of the kinematic viscosity ν to the thermal diffusivity κ, and the Peclet number (*5, 6*), which can be written in terms of the heating rate Q as

$$R = \frac{g\alpha Q d^3}{\nu \kappa^2} \qquad (1)$$

where g is the gravitational acceleration, α is the coefficient of thermal expansion, Q is the differential heating rate, and d is the thickness of the asthenosphere (*7*).

The Prandtl number in the upper mantle is very large, 10^{23} to 10^{24}. The Peclet number is more difficult to estimate, as many of the parameters entering into the estimate are uncertain. A reasonable maximum value for an asthenospheric thickness of 300 km, a temperature contrast of 200°C (*8*), $\nu = 2 \times 10^{21}$ cm^2/sec, $\kappa = 1.5 \times 10^{-2}$ cm^2/sec, $\alpha = 2 \times 10^{-5}$ °C^{-1} (*2*), and $g = 980$ cm/sec^2 is 3×10^5. In any case, R is likely to be large as compared to unity.

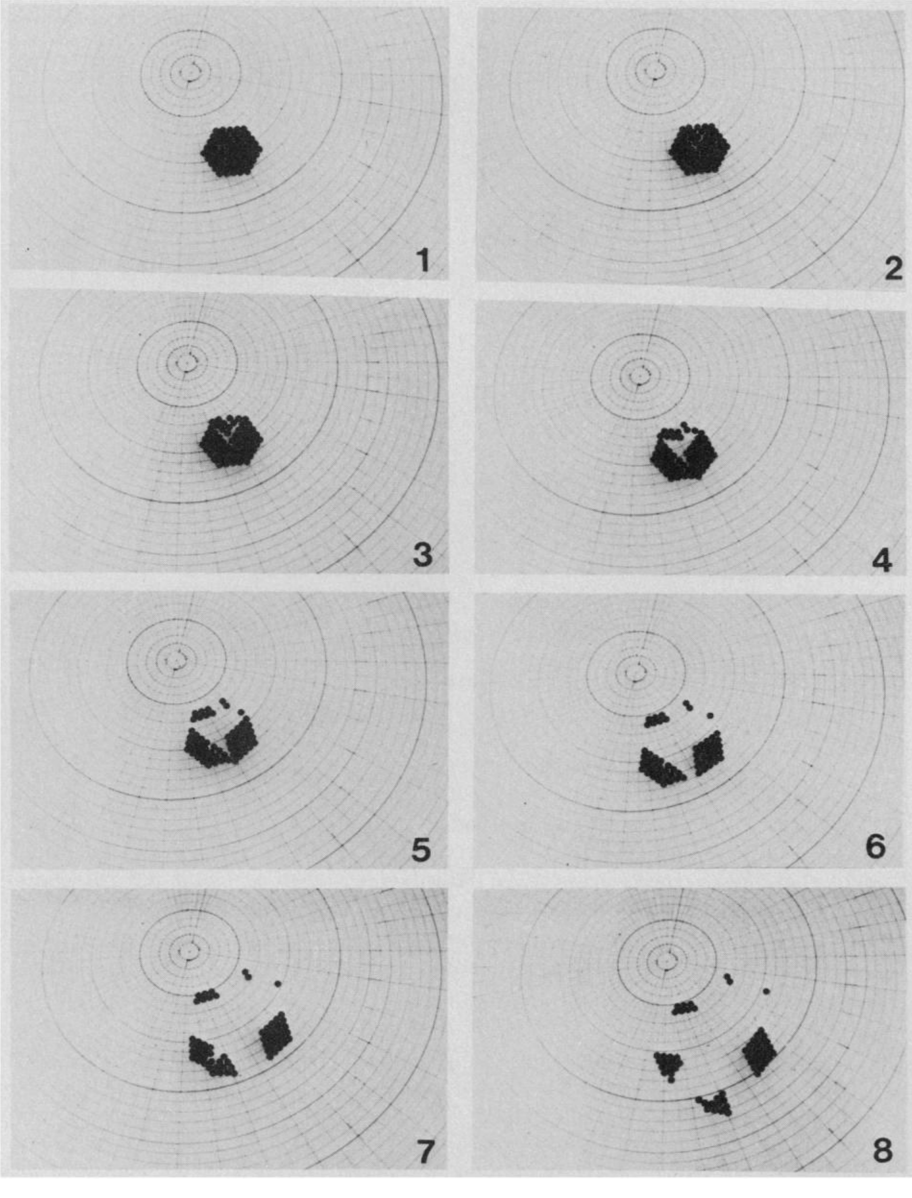
The experimental continent is an arrangement of black spherical polyethylene balls, each 0.318 cm in diameter, floating in a layer of silicon oil (Dow Corning 200 fluid), held together by surface tension. The horizontal temperature inhomogeneity arises when the apparatus is illuminated with an ordinary incandescent bulb. Figure 1 shows several photographs from a spreading event.

A reproducible continent is a regular hexagon. The experiments have been carried out with 61-ball continents, 5 balls per side (*9*). The basin containing the oil is 61 cm in diameter. I used 350-centistoke (ν = 3.5 cm^2/sec) silicon oil in a layer 1 cm thick. Because of imprecise leveling and distortions of the plastic bottom of the basin, the depth of the oil varied by ± 1 mm over the basin.

Other physical constants of the oil (from the manufacturer's data sheet) are a thermal diffusivity of 1.1×10^{-3} cm^2/sec and a coefficient of thermal expansion of 9.6×10^{-3} °C^{-1}. The Prandtl number is thus 3182.

The heat source for these experiments was a 100-watt incandescent bulb hanging above the center of the basin, which gives a Peclet number of the order of 300 (*10*). Preliminary temperature measurements indicate a temperature contrast of a few hundredths of a degree, giving an estimate for R' of about 100. Discrepancies between these approximations involve albedo estimates and errors in temperature measurement as well as a difference in definition.

The spreading rate can be measured with the experiment as described above. I



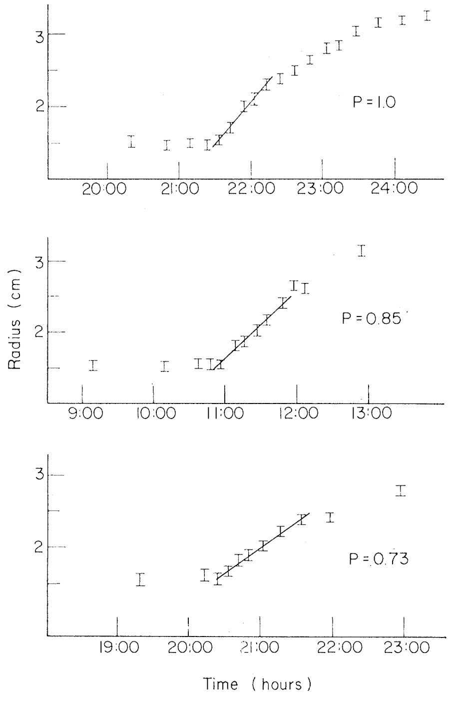


Fig. 1 (left). Photographic record of a spreading event. Times for photos 2 through 8 are, respectively, 19, 49, 59, 69, 80, 104, and 312 minutes after the beginning of the event (photo 1). Fig. 2 (above). Spreading at three different power levels: radius of the enclosing circle versus time. In each case there are three stages of spreading: a buildup of the convection during which there is little motion; the rapid linear spreading arising from the original cell; and the erratically variable spreading in the region dominated by subcontinent splitting.

define the spreading rate as the rate of change of the radius of the smallest circle enclosing all of the balls. Figure 2 shows the radius of this circle as a function of time for three different power levels. In all three cases the initial point marks the turning on of the light. In each case there are three regimes. The first period is a gradual buildup of the underlying convection cell, during which the radius is essentially constant. The second is a period of linear growth in radius, corresponding to spreading under the influence of the initial cell. The third is an erratic region. Here the spreading is an amalgam of spreading rates from secondary continental breakage.

I located the continental fragments at any given time visually. The bottom of the basin is scribed with a polar grid with radiants 5° apart and circles at radial intervals of 0.5 cm. I sketched the location of the continental fragments on polar graph paper, making an effort to minimize parallax error. It takes 1 to 2 minutes to make such a drawing; movement during this time is less than half a millimeter, less than the overall error.

The radius of the minimum circle enclosing all the balls was found by superposing a circular grid over each sketch and estimating the smallest circle that would include all the particles. The center of this enclosing circle shifts negligibly during the first phase of uniform spreading.

Useful spreading rates are obtained by graphically taking the slope of the steep segment of homogeneous spreading. Within the limits of error of this demonstration experiment, the spreading rate is directly proportional to the power level. This result appears to be consistent with earlier theoretical work (*5*, *6*), to the limited extent that the situations are similar.

The model as described is in the same general region of parameter space as the earth (*11*). It is an improvement over the various "kinematic" models and has more flexibility than the other dynamic models that have been explored. It also has simplicity. There remain, however, a number of difficulties that will need to be resolved as the work becomes more quantitative. These include the necessity of quantifying the strength of the continent and the coupling between the continent and the asthenosphere. Even the drag of a partially submerged sphere at low Reynolds number appears not to have been calculated (*12*). Because the temperature contrasts are so small, it appears likely that the variation of surface tension with temperature will be unimportant.

Despite these caveats, I feel the model is sufficiently useful to justify further study, and I offer the following comments on its qualitative resemblance to the picture of plate tectonics. When the total picture of plate tectonics over the last 2×10^8 years is drawn, one can see two features that are apparent in this model, and in no other model of which I am aware (*13*). One is the episodic nature of spreading, in which spreading directions change and secondary spreading episodes take place. One can compare figures 4 and 5 of Dietz and Holden's reconstruction (*13*) with the sequence in Fig. 1. In the Jurassic the North Atlantic has opened by pivoting around a still connected Greenland-Scandinavia; in the Cretaceous the South Atlantic has opened, spreading in a different direction. These events can be compared to the sequence in photos 6, 7, and 8 in Fig. 1.

A frequent objection to the plate tectonic hypothesis is that the fit is not so good as claimed (*14*). I have not quantified the goodness of fit associated with the continents in my model, which I know to have been together, but it is clear from direct observation that internal distortions have made the fit less than perfect, a feature unique to this model.

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9. The size of the plate, as opposed to the continent, is indeterminate, as some amount of the surrounding fluid surface is included. I hope to explore this using shadowgraph techniques at some future time.
10. Several measurements of flux versus bulb displacement quite close to the bulb, made with an International Thermal Instrument Company thermal fluxmeter coated to absorb radiation, indicate a total available power of 17.2 ± 1.2 watts. Translation of this information to the experimental situation is complicated by the difficulty of making albedo measurements. I calculated the number given in the text, assuming a fraction of 17 watts equal to the area of 61 balls divided by the total area at a distance of 50 cm.
11. One might object to the small lateral extent as compared with the geophysical situation; however, there is no reason why one cannot use more beads. The only difficulty is the tedium involved in assembling large continents. It takes several hours to get a 219-ball continent ready.
12. I have searched *Physics Abstracts* from 1950. Interest in this problem is no doubt limited because flow at very low Reynolds number is relevant to blood flow, for which there are no free surfaces, whereas the flow of objects near a free surface is relevant to naval matters, and these flows have high Reynolds numbers.
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15. My interest in this problem was first awakened when I was a student at the University of California, Los Angeles, and I thank L. N. Howard, W. V. R. Malkus, and J. A. Whitehead, all of whom were there at that time.

1 October 1975; revised 15 December 1975

Marine *Oscillatoria* (*Trichodesmium*): Explanation for Aerobic Nitrogen Fixation Without Heterocysts

Abstract. *Nitrogen fixation in marine* Oscillatoria *appears to be associated with differentiated cells located in the center of the colony. These central cells exhibit reduced pigmentation relative to peripherally located cells and do not incorporate* $^{14}CO_2$ *in photosynthesis. Central cells apparently do not produce* O_2 *which would deactivate nitrogenase. When central cells are exposed to* O_2 *via disruption of the colonies,* N_2 *fixation (acetylene reduction) decreases sharply even though individual trichomes remain intact. Disruption of colonies in the absence of* O_2 *does not cause reduced nitrogenase activity. In the sea, turbulence from wave action apparently separates trichomes allowing* O_2 *to enter thus decreasing nitrogenase activity. These observations explain how* Oscillatoria *is able to fix* N_2 *without heterocysts in an aerobic environment and why its blooms virtually always occur in calm seas.*

Oscillatoria (*Trichodesmium*) spp. is a planktonic myxophyte alga inhabiting near-surface waters of tropical and subtropical seas. It is capable of fixing atmospheric nitrogen (*1*). In view of the critical importance of combined nitrogen as a limiting nutrient in the ocean (*2*), it can play a central role in the nitrogen budget of the