can be tailored in a way which is impossible with a mixed audience.

The lecture technician and his staff of assistants have the setting up of the experiments as their main duty; this experience makes them very clever in this art, and at using the lecture room equipment such as closed-circuit television, magnetic blackboards, overhead projection, matched lanterns for double projection, and motion-picture projection. They must be backed by a good preparation room, ample store rooms, and the services of a workshop.

To sum up, the more one concentrates on an organization whose main function is to present a continuous series of lectures to young people, rather than an occasional series undertaken as an extra to other activities, the more one can streamline the organization with a great increase in efficiency and improvement in quality. The less also is the strain on the lecturer. If a highly specialized staff prepares the demonstrations for him and can be counted on to see that all goes smoothly in the lecture, his work is much lighter. He is like a surgeon entering an operating theater when skilled assistants have made all ready for him and he can concentrate on his expert task.

The simplifying of the lecturer's task is very important. Outstandingly good lecturers are generally busy people and reluctant to take on anything which makes large demands on their time. The really good ones with a gift for talking to young people are few, and every possible aid must be given them in order to secure their help. They are people who can project themselves into the minds of the audience, who can in fact be at the same time both audience and speaker and sense the effect on their listeners of what they are saying. They have to be able to ask themselves "How did I think when I was 17 years old, what points puzzled me, what explanation satisfied me?" It is astonishing how many great scientists are unable to project themselves in this way and quite fail to give a good talk to the young. On the other hand, by search and trial one can find the gifted few who possess the art.

Science Centers

I am convinced that organizations of this kind, devoted to giving scientific talks to young people and specially planned for that purpose, would be of the very greatest benefit in increasing the scientific potential of a country. They can only function in places where there is a concentration of population sufficient to give them continuous use, but this concentration need not be very great, because the school population is so large. The main part is that the more such organizations are planned for the special function the greater is their efficiency, and the more continuously they can be used the less is the cost in time and money needed for creating one more enthusiastic devotee of science.

CURRENT PROBLEMS IN RESEARCH

Vertical Density Currents

These currents seem to carry particles downward much more rapidly than settling according to Stokes's law.

W. H. Bradley

Fritz Nipkow's classic study (*1*) of the bottom deposits of Zürichsee established the fact that, in certain lime-rich, eutrophic lakes that have a hypolimnion, well-defined and highly characteristic annual layers, or varves, form. Indeed, Nipkov explained in a most satisfying manner everything about the formation of these varves except how the very-slow-settling constituents could have reached the bottom (at depths of 100 to 140 m) in the same year in which they were produced in the surface waters. If the particles settled in accordance with Stokes's law, even the very small calcite particles (2 μ in diameter), which crystallized out from the surface waters, would have required 1.3 years to reach bottom. How much more slowly the frustules of the delicate diatom *Stephanodiscus hantzschii* Grunow might have settled we can only guess. Yet Nipkow shows that a short burst of growth of this diatom is represented within the varve of the year in which the burst occurred by a thin, clearly defined layer characterized by these frustules.

We must conclude that most of the particles in the Zürichsee varves could not have reached the bottom of that deep lake as discrete individuals settling in accordance with Stokes's law. Some other mechanism is necessary to account for the facts Nipkow observed.

One possible mechanism to account for the observed proper sequential order in bottom sediments of microscopic constituents whose individual settling rates differ by several orders of magnitude is that of vertical density currents. The concept of vertical density currents can most conveniently be examined by considering the behavior of calcite particles generated in the surface waters of Zürichsee. These particles originate in the surface waters of the lake (*2*) in two ways: (i) in, or on, the mucilage of planktonic algae through marked decrease in the carbon dioxide pressure by photosynthesis of the algae, and (ii) in the water itself through decrease in the carbon dioxide pressure by progressive warming of the surface water. By either means, in normal years, such vast numbers of calcite particles are formed that the surface waters become milky. Inasmuch as these particles are created in the surface water and are numerous enough to make it turbid, it occurred to me that if, by some means, the particles in any part of the surface water are brought closer together, they and the water containing them will together be

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heavier per unit volume than water with less sediment, and therefore they should sink vertically as a density current.

Experimental Tests of the Concept

The inference that vertical density currents do form was tested in the laboratory in two series of experiments. In one, small natural crystals of calcite were used; in the other, spherical glass beads. In the first series, clean, dry calcite crystals were dropped into the water through an electrically vibrated fine sieve set a few centimeters above the water surface. In the second series a dilute slurry of the glass beads was introduced into the tank just below the water surface. In neither series of experiments, probably, was there close approximation to the conditions that obtain in Zürichsee. Nevertheless, the experiments revealed some interesting properties of the vertical density currents that formed in the tank, and perhaps these results will one day induce an inquisitive, scuba-diving limnologist to make some critical observations below the thermocline in Zürichsee, or in some other lake that generates calcite particles in its epilimnion.

The calcite crystals used in the first series were not rhombohedrons, like those that form in Zürichsee, but short stubby prisms whose sides and ends are rounded. The equivalent calcite spheres have a median diameter close to 18 microns and range from a little less than 10 to about 40 microns in diameter. Before use the crystals were cleaned in acetone and kept in a desiccator to keep the grains free-running. To keep the dry grains from floating on the surface film, an aerosol was added to the water. The rectangular leucite tank used was 75 centimeters deep and 30 by 30 centimeters in cross section (inside dimensions). The circular sieve was 7.6 centimeters in diameter and was centered over the vertical axis of the tank, a few centimeters above the water surface.

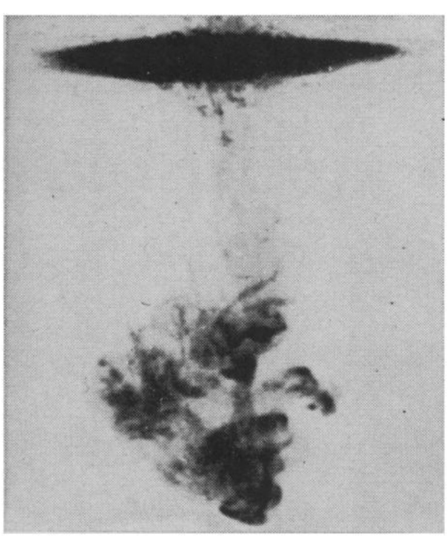

Fig. 1. A cloud of calcite particles descending through water from the air-water interface (indicated by the dark, elliptical shadow of the sieve). The bluntly pointed cloud is followed by a vertical density current in which the population of calcite particles is less dense than in the cloud.

In all the experiments in this first series, a dense population of particles was introduced into the uppermost part of the water column; in all but one particularly significant experiment, described below, vertical density currents formed. Characteristically, in this series, an irregular but somewhat pointed cloud of particles forms (see Fig. 1), and, though its form slowly changes, the cloud maintains this general shape until it is distorted and destroyed by return water currents rising from the bottom. Without exception, these leading clouds are followed by a columnar trail that extends up to the surface of the water. This cylindrical column has a rather uniform cross section and is clearly a stream of fluid carrying a rather sparse population of particles. In none of the experiments described in this article was there any tendency for the particles to flocculate. Even where they were most closely spaced, the particles moved freely about one another. Evidently, when they approached one another closely, a repelling force came into play. Moreover, this repelling force operated in distilled water, in strong saline solutions, and in concentrated sugar solutions. This behavior is consistent with the behavior of clusters of falling spheres in a viscous fluid described by Jayaweera, Mason, and Slack (*3*).

Because a tank of fluid is a closed system and the fluid is incompressible, any downward flow must be compensated by a rising current from the bottom. In these experiments a dye showed that the currents rising from the bottom rose very slowly along, or near, the side walls. Nevertheless, the pertinent observations of the density currents were made only in the upper half of the tank.

One density current of this sort was photographed with a moving picture camera so as to measure its rate of flow. In 31 centimeters of travel the rate was 1.58 centimeters per second and was remarkably uniform. The rate of fall, as calculated from Stokes's law, of single calcite spheres having the same mean diameter (18.2 μ) as the calcite crystals used is 0.03 centimeter per second. According to these figures the particles in the density current fall at a rate nearly 53 times that calculated, from Stokes's law, for the individual particles.

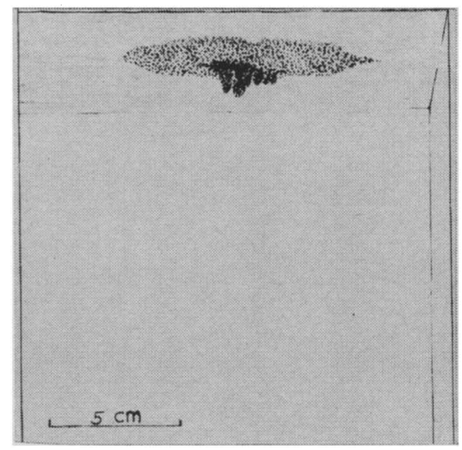

Fig. 2. Several small vertical density currents forming on the underside of a disk of particles suspended for an instant at the interface between dilute saline solution and an overlying layer of distilled water. A moment later these tiny density currents merged into one current, which entrained the remainder of the particles above the chemocline.

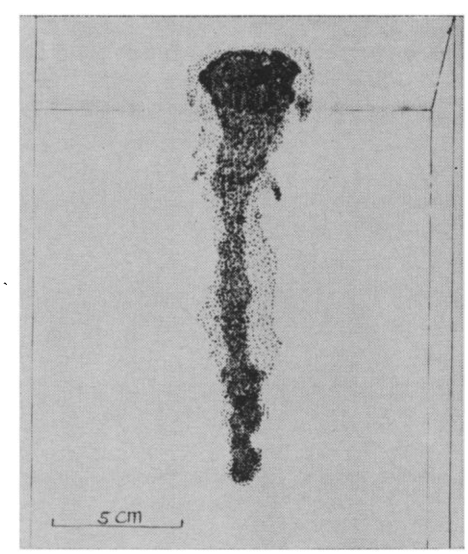

Fig. 3. A later stage of the currents shown in Fig. 2, showing the small vertical density currents merged into a single current, in which some of the original filaments may be seen. The diffused margin of this density current contrasts sharply with the smooth walls of faster-flowing vertical density currents.

A second group of experiments in this first series was made with a stratified water body. The purpose was twofold. First, it seemed desirable to have an upper layer of liquid to serve as a sort of cushion to decrease the velocity that the particles acquired in falling through the air before they entered the water. Second, it seemed that the stratified water body might reveal something of what happens below a chemocline (a zone of gradation between fresh-water and underlying saline water) in a lake. Accordingly, enough $NaHCO_3$ was dissolved in the water to raise its density to 1.060 and its viscosity to 0.0138 at 21.5°C. A layer of tap water about 8 centimeters deep was floated on the saline solution, bringing the water surface nearly up to the sieve.

In the experiments with this layered system the calcite particles were sifted through an opening (3 cm in diameter) in the sieve onto the surface of the fresh-water layer. At the interface between the fresh and the saline water the cloud of particles flattened to a disk more than three times the diameter of the sieve opening. About 1/16 second after this disk formed, several small, fingerlike density currents began to descend from the underside of the disk (Fig. 2). These quickly coalesced into a single, somewhat sinuous density current (Fig. 3).

Density currents that formed below the chemocline behaved much like those that formed in a homogeneous body of distilled water, except that they moved more slowly, because of the density and increased viscosity of the saline solution, and did not have cloudlike heads on their lower ends. By means of a moving-picture film the rate of descent of the tips of one of these currents was found to be 0.95 centimeter per second, which is 36.5 times the calculated rate of fall of individual glass beads (median diameter, 19.9 μ), according to Stokes's law.

As a variant of this experiment with the two layers of fluid in the tank, particles were sifted onto a large part of the area of the fluid. These particles settled through the upper layer and spread as a nearly uniform layer (area, roughly 600 cm^2) at the interface between the two fluids. From the underside of this layer a large number of vertical density currents less than 1 centimeter in diameter immediately began to flow. The flow of these currents could not be followed because there were so many of them, and because they occupied so large a part of the tank area that they quickly forced the static body of fluid into a confused state, in which the orderly pattern of the many parallel, vertical density currents was destroyed. This experiment was made to test the assumption that if particles are distributed over an extensive area of the surface waters of a lake, many vertical density currents will begin to flow, and their spacing will probably reflect local irregularities in the distribution of the particles.

A critical rate of fall, or a critical viscosity, sets a limit to the formation of vertical density currents. In an experiment designed to test this relationship qualitatively, the main body of the fluid was a concentrated sugar solution, whose density and viscosity (not measured) were considerably higher than those of the saline solution used in the earlier group of experiments. On this sugar solution a layer of distilled water about 7 centimeters deep was floated. A dense population of calcite crystals was sifted through an opening (3 cm in diameter) in the sieve into the layer of distilled water; as in previous experiments, the particles settled and spread to an area about 9 centimeters in diameter at the interface between the distilled water and the sugar solution. Particles came through the interface and settled slowly into the sugar solution, but they came down as discrete individuals without forming any density currents.

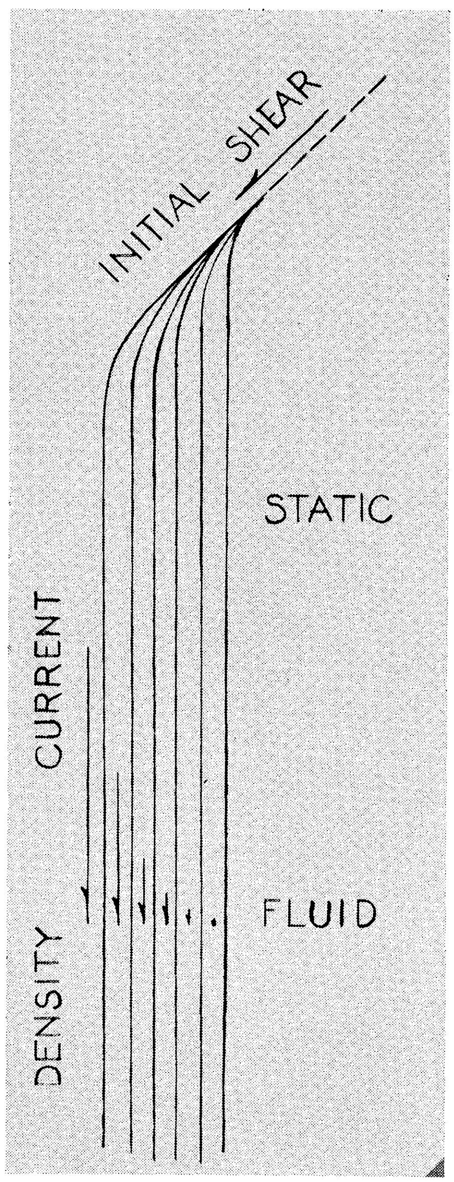

Fig. 4. The inferred angle of initial shear and, greatly enlarged, the structure of the shear wall of a vertical density current. Vertical vectors show, qualitatively, the progressive decrease in velocity across the shear wall.

In all the experiments in which density currents formed, the current continued to flow even when the particle content was clearly less than it was in the leading cloud of particles which had started the current to flow. This raised the question of the source of the flowing fluid and its entrained particles. Was the fluid being entrained from the quiet and denser saline (or sugar) solution through which it flowed, or was it being drawn down from the lighter layer of water that floated on the denser solution? In order to explain what Nipkow observed it was necessary to know, also, whether very much smaller and lighter particles would be entrained in such vertical density currents.

To discover whether they would be, a dye (alizarin red) was put in the layer of distilled water that floated on a dilute sugar solution. In this experiment a dilute slurry of glass beads (median diameter, 19.9 μ) was introduced into the dyed surface layer of the tank through the stilling tube, whose orifice was just above the interface. The usual density current formed in the dilute sugar solution, though it probably started to form in the colored water above. A thin thread of purple-colored water was drawn in from the layer of dyed water and flowed down in the central part of the density current. This experiment showed that both water and its contained particles, including the molecular-sized dye particles, were gathered in from the source area of the vertical density current and flowed along with it as long as suspended particles were available to provide the energy to drive the density current.

An extremely small difference in density will produce a well-defined vertical density current. This was demonstrated by introducing dyed distilled water into a tank of quiet distilled water through the stilling tube. In this experiment a thin, more or less cylindrical current flowed rapidly down through the tank.

Interpretation of Results

The experiments show that vertical density currents do form under the conditions provided in the laboratory, and they reveal something of the behavior of these currents as the conditions are varied. But they tell us little about what made the fluid begin to flow, or about the hydrodynamics once it started to flow.

Before we explore the question of what makes the fluid in a density current begin to flow, I should state that in this article I am dealing only with suspended particles so small that, if they are treated as spheres, their rate of free fall through water comes well within the range where Stokes's law applies: particles whose effective diameters are less than 0.14 millimeter (*4*). Actually, no particles larger than 0.05 millimeter are considered here. As particles in this size range settle through a viscous fluid they reach terminal velocities determined by the internal frictional resistance, or viscous resistance, of the fluid.

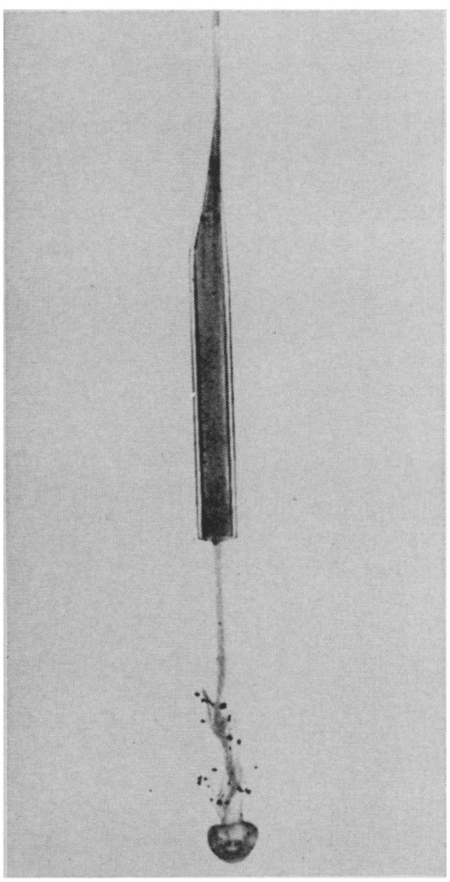

Fig. 5. Vertical density current of freshly precipitated lead chromate particles in dilute lead nitrate solution. The specific gravity of this slurry is considerably greater than that of the dilute lead nitrate solution through which it flows. The impact of the rapidly flowing density current on the static fluid in the tank is shown by the bulbous cap at the lower end. The cap is formed by the flaring and involution of the surface of discontinuity that makes the sheath, or boundary layer, of the stream-tube. The upper, largest, part of the cap is actually a torus.

It is instructive to examine this viscous resistance a little more closely. A spherical particle (less than 0.14 mm in diameter) settling through water crowds the water aside so that streamlines diverge and pass around the particle. Where these streamlines part directly below the center of the sphere, there is a point of stagnation where the fluid moves at essentially the same velocity as the particle. To quote from Furry *et al.* (*5*), "The stagnation pressure at this point exceeds the general pressure in the fluid by the amount $\rho(v^2/2)$, where v is the relative speed of the fluid and body . . ." and ρ is the density of the fluid. The stagnation pressure of a particle falling through water is transmitted to the water and tends to set it in motion in the direction of the falling particle. But this is not the only energy that is transmitted to the water. Water is an associated liquid, in which water molecules are connected to one another by hydrogen bonds; therefore, energy is required to break these bonds when the falling particle forces some of the water to flow around it. In other words, the particle is slowed by the amount of energy required to overcome the viscous resistance to flow, or shearing stress, which causes a drag on the water and tends also to set it in motion in the direction of the falling particle. The sphere falling through a viscous fluid at terminal velocity transmits to the fluid a total amount of energy given by $6\pi r\eta v$, which is equal to the weight of the suspended particle,

$$\frac{4}{3}\pi r^3(\rho_p - \rho_f)g.$$

This is the Stokes equation, which is usually given in terms of the (terminal) velocity

$$v = \frac{2}{9}\, g \left(\frac{\rho_p - \rho_f}{\eta}\right) r^2.$$

As the number of such falling particles per unit volume of water is increased, the stress transmitted to that unit volume of water must also increase. Moreover, the aggregate stress of all these pressure points tends to be distributed uniformly to the whole unit volume of water, because water has, in part, a quasi-crystalline structure—that is, a tetrahedrally coordinated open lattice of water molecules (*6*). As Hutchinson says (*6*, p. 201): "in so far as a lattice exists in liquid water, it consists of branched chains of tetrahedra united corner to corner in such a way as to permit the individual members to rotate freely. These chains form an intermeshed net and run in any direction in the free liquid." One must not, of course, attribute the properties of a solid to liquid water. Its structure is always rapidly changing, and it has progressively less order as its temperature is raised. Nevertheless, energy is required to distort the lattice and to make the liquid flow.

The aggregate amount of energy that the increasing number of falling particles transmits to the unit volume of liquid soon reaches a critical value that exceeds the small amount of energy

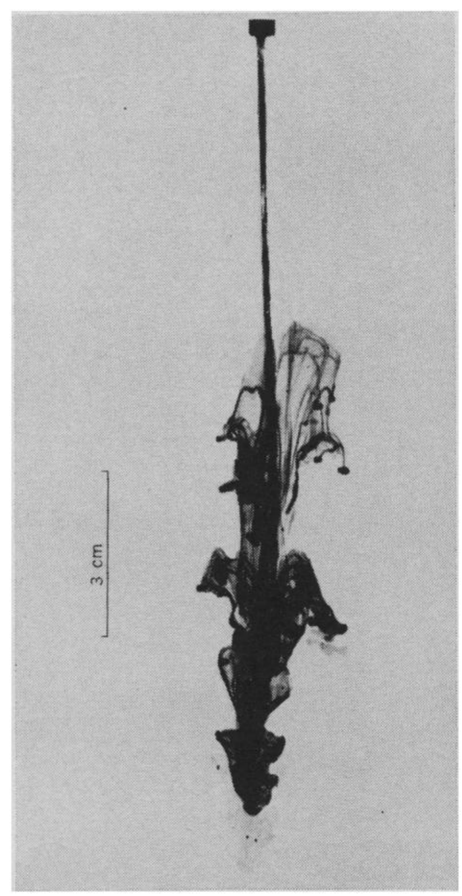

Fig. 6. A later stage of the stream-tube shown in Fig. 5, showing, in the lower part, a succession of caps through which the stream-tube now passes. The confused streamlines and rings on either side arise from the peripheral breakdown of other caps.

required to shear the liquid below. We may think of the unit volume of the liquid as having increased its effective density to the point at which the static water below fails by shear under the imposed load. At first, the shear surface dips inward below the unit volume of liquid with its contained particles, but as the denser fluid begins to flow and its velocity increases, the shear walls steepen until they become vertical. Also, as the flow accelerates, the diameter of the funnel and of the tube below decreases to a constant value at terminal velocity. The downflowing water and its suspended particles are thereafter contained by walls that consist of a cylindrical shear zone, which separates the denser, flowing fluid from the adjacent static water. Despite the fact that the two fluids are completely miscible, the shear walls keep them sharply separated. All the flow considered here is laminar flow. In a vertical density current the flow can be thought of as a series of tubes of decreasing diameter sliding one within the other. Resistance to shear between the sliding tubes determines the terminal velocity of the leading interface of the density current. The experiments described above show that this terminal velocity is, in fact, constant.

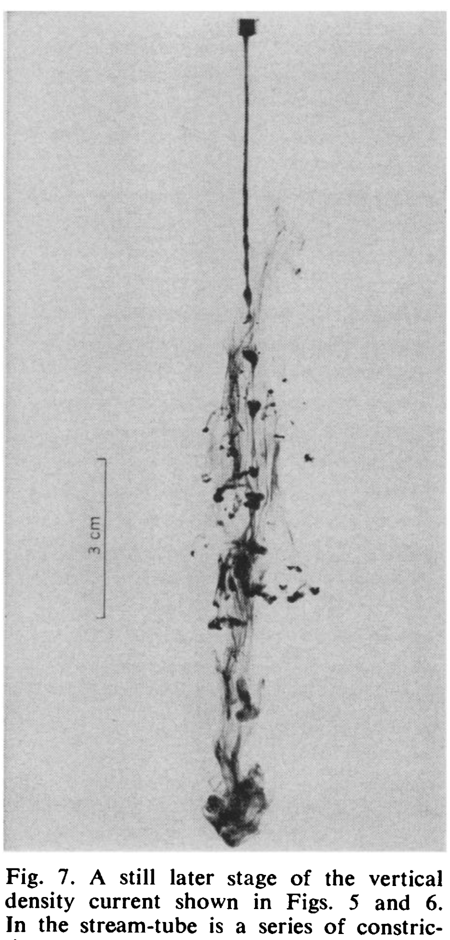

Fig. 7. A still later stage of the vertical density current shown in Figs. 5 and 6. In the stream-tube is a series of constrictions and enlarging nodes, which suggest the behavior of a jet of water in air as it constricts and as the enlarging nodes then separate into globules. But in these stream-tubes the nodes enlarge and become cup-like, and the density current then flows through their centers.

The distribution of velocity across such a stream-tube, or vertical density current, before it reaches terminal velocity is probably much like the distribution in a tube with solid walls—that is, greater along the axis and decreasing toward the walls, where it is considered to be zero. Observation of several of the density currents in my experiments suggests that when the current reaches terminal velocity, differential rates of flow disappear within the body of the stream tube and occur only within the tube walls. In consequence, the leading surface of the density current approximates a paraboloid.

Such stream-tubes, as they are called, are well known to hydrodynamicists. Prandtl (*7*) found that the hydrodynamically important property of continuity holds for flow in stream-tubes, just as it does for flow in a solid tube. The principle of continuity requires that there be no gap and that the fluids shall not mix. It follows from this that the components of velocity at right angles to the boundary surface must be the same on either side of the surface—that is, that the pressure outside the stream-tube must be balanced by the pressure within the stream-tube, that the cross section of the tube be circular, that the velocity of flow be inversely proportional to the cross section, and that the structure of the stream-tube be the structure shown diagrammatically in Fig. 4.

Vertical density currents appear superficially to fit the modern definition (*8*) of stratified flow, but they are a special case not yet treated theoretically. They differ from the general conception of stratified flow (*8*) in being initially inverted, the denser fluid being above the lighter. But from that momentary, unstable state, the actual flow departs still more radically from the accepted concept of stratified flow, because the denser fluid flows in stream-tubes down through the less dense fluid.

A vertical density current will continue to flow under the force of gravity as long as δ_s, the effective specific gravity of the fluid plus its contained particles, is greater than ρ_{H_2O}, the density of the water, regardless of the size and shape of the particles entrained. An additional generalization follows from the experiments conducted thus far; namely, the diameter, *d*, of the stream-tube varies inversely as the difference in specific gravity of the density current and the surrounding water.

$$d \propto \frac{1}{\delta_s - \rho_{H_2O}}$$

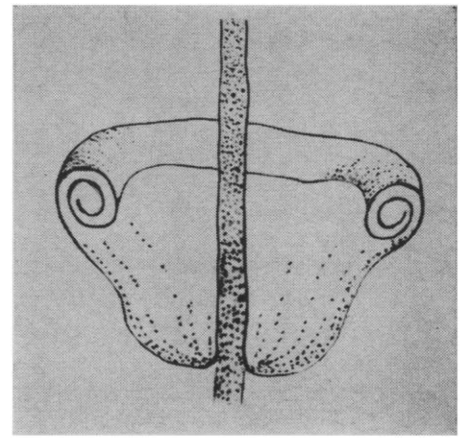

Fig. 8. Internal structure of a terminal cup, shown in transverse section, at the lower end of a vertical density current. The drawing was made from observation of the behavior of very dilute suspensions of freshly precipitated lead chromate.

It seems apparent from the behavior of lead chromate suspensions that if the diameter of the density current is artificially made too high, the stream flows so fast that it mushrooms at the lower end and thereafter divides repeatedly until the resulting streams have a stable diameter (see Figs. 5–9).

Limnological Significance

Vertical density currents should be expected in any lake that produces calcite particles from either photosynthesis of phytoplankton or warming of the surface water, and in any lake that produces dense populations of microorganisms whose dead remains have specific gravities greater than the specific gravity of the water in which they lived. That blooms of diatoms, for example, give rise to such vertical density currents is a conclusion that seems to follow from the fact that Nipkow (*1*) found in the varved sediments of Zürichsee sharply defined microlayers of single species of diatoms, each in its proper seasonal position, despite the fact that the individual frustules have settling rates far too slow to permit them to reach bottom in a fraction of a year. Indeed, the rapidity of their transport to the bottom is further attested by the fact that so many of these

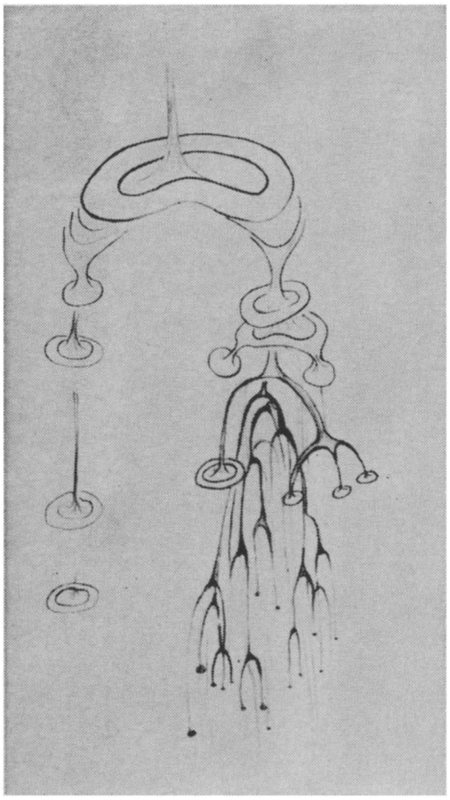

Fig. 9. Diagrammatic sketch showing how a terminal cup, or a simple torus, deforms and gives rise to two, or three, density currents, each of which forms its own terminal torus or cup, which in turn divides again and again.

diatoms retained their cell contents that each of the corresponding microlayers had the characteristic color of that particular diatom.

Presumably such density currents would originate wherever sufficiently large populations of particles come together—for example, along the downflow margins of convection cells or under the convergences of wind-drift helices (*6*).

The turbulent currents of full circulation in the lake may very well have played a significant role in transporting certain microorganisms to great depths in Zürichsee. But another of Nipkow's findings leads one to conclude that the importance of such major circulatory currents is much less than might have been supposed. He found also (*1*, p. 112) that other plankton organisms—for example *Phacotus* and *Codonella*—which are abundant only in the summer, reached the bottom in so brief a time that they, too, took their proper seasonal position in the varve, even though the lake was thermally stratified and the epilimnion no more than 10 to 15 meters thick.

If vertical density currents are responsible for moving particles from the surface waters of lakes to the bottom in relatively brief intervals, as I infer they are, then they should also carry with them an appreciable amount of heat and dissolved oxygen into the deeper parts of a lake. Hutchinson and others (*6*, p. 454) have drawn a similar conclusion concerning other types of density currents formed in other ways. Such a transfer of oxygen could seriously affect calculation of the rate of oxygen consumption in the hypolimnion.

One would not expect to find vertical density currents of the sort described in this article in oligotrophic lakes except in the event of great dust storms or falls of volcanic ash.

Geological Significance

One would expect vertical density currents to form when volcanic ash falls into a lake or other body of relatively quiet water. The rapidity of transport offered by the density currents apparently accounts for the sharply defined lower and, especially, upper boundaries of layers of volcanic ash in sediments. Only very rapid deposition can account for such features, particularly if the particles are very fine. Shards and grains larger than 0.14 millimeter in diameter settle so rapidly that no special process is required to account for the fact that they make sharply defined layers. What is true of sharply defined individual layers of tuff would, of course, be equally true of the clearly defined layers and laminae within thinly banded water-laid tuffs. Had these fine ash particles not been transported rapidly to the bottom they surely would have been mixed with particles of organic matter, clay, silt, and the like.

Fine particles of sediment brought into a lake by great dust storms or by warm muddy water spreading into the surface water should also result in the formation of vertical density currents and in consequent relatively rapid transport of the particles to the bottom.

Because air is a fluid, one would expect also that vertical density currents would form and flow downward from the clouds of volcanic ash thrown out from explosive volcanoes.

Many years ago Grout (*9*), and later Wager and Deer (*10*), proposed that the evidence of flow in certain igneous rocks could be accounted for by initially vertical density currents in the magma, which were set in motion by the growth of crystals and the cooling of the magma. Grout showed that the growth of crystals would have been much more effective than the cooling of magma because the crystals have much greater specific gravities than the melts from which they grow. This proposed process is analogous to the growth of calcite crystals in the surface waters of lakes as carbon dioxide is abstracted from the water either through photosynthesis or through warming of the water.

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