changes in location are mediated by the element.

Insertion of movable elements can also disrupt the normal course of development in the fruit fly, according to Welcome Bender, who originally worked with Hogness, but who is now at Harvard Medical School. He has shown that two spontaneous mutations, which cause severe abnormalities in the development of the segmented *Drosophila* body, are caused by the insertion of fairly long DNA segments containing about 10,000 base pairs each. A reversion of one of the mutations is accompanied by the loss of the insert. Benders says, "We see striking developmental effects of apparently simply mutations."

The hybrid offspring of certain matings of wild-type fruit flies with laboratory strains are characterized by a complex of abnormalities, including frequent and unstable mutations, chromosomal rearrangements, and sterility. This mating incompatibility is called hybrid dysgenesis, and it, too, appears to involve the activities of movable elements. For example, one type of hybrid dysgenesis occurs when males of one strain, designated P, mate with females of another strain, designated M. Production of the abnormalities in the hybrids requires the interaction of a chromosomal factor contributed by the males with a cytoplasmic factor contributed by the females. According to William Engels of the University of Wisconsin, the P factor has all the attributes of a movable element, and the abnormalities seen are consistent with this being the case.

Just because movable elements have been firmly implicated as generators of mutations, however, it does not necessarily follow that they are important for evolution. In fact, some investigators, including W. Ford Doolittle and Carmen Sapienza of Dalhousie University in Halifax, Nova Scotia, and Lesley Orgel and Francis Crick of the Salk Institute, have proposed that movable elements may have no such function at all*. The idea is that DNA segments, which are present in the genome in multiple copies and which furthermore can move about, will be just about impossible to lose. Provided their presence does not impose too high a drain on the cell's energy production, the cells bearing them will survive, and the DNA segments will be perpetuated as parasitic DNA molecules.

—JEAN L. MARX

*See *Nature*, 17 April 1980, p. 601; 26 June 1980, p. 617; and 18/25 December, p. 645.

Fingers of Salt Help Mix the Sea

Once ridiculed as imaginary, tiny salt fingers are helping to explain how extremes of temperature and salinity mix in the sea

Sandy Williams was becoming just a bit discouraged. Here, in the Atlantic beyond Gibraltar, was the fourth part of the world that he had searched, as yet with no success. If he was ever going to find salt fingers, the layers of fingerlike, interwoven protrusions of water predicted by some theorists, this should be the place.

Twelve hundred meters below his ship's deck, a huge tongue of warm, salty water, which had slipped out of the Straits of Gibraltar and down into the depths of the Atlantic, was mixing with the cooler, less salty water of the Atlantic. Those conditions seemed ideal for salt fingering, the special kind of mixing in which large bodies of water are supposed to mingle through centimeter-wide, vertical columns of flowing water. Williams, from the Woods Hole Oceanographic Institution, had looked in other likely places but found nothing to convince his colleagues that he had seen salt fingers.

As Williams rolled the wet, freshly developed film exposed by his deep-diving camera package onto a reel, the chief scientist of the cruise, a chemist, happened by and asked "Where are these salt fingers of yours?" Without having inspected a single frame, Williams grabbed a handful of wet film from the tank, held it up, and said "Right there." To the surprise of both of them, the shimmering images of salt fingers were there, as clear as they ever would be seen.

With those observations in 1973, salt fingering, initially only a theoretical and laboratory curiosity, took a big step toward being regarded as a significant mechanism for oceanic mixing. Impressed by these and other observations, oceanographers now accept salt fingering as a common, efficient mixing process in polar waters where water masses having different temperatures and salt contents meet to form fronts, much as warm and cold air masses collide to form weather fronts. Still controversial is salt fingering's role in determining the distribution of heat and salt over large areas of the tropical and subtropical oceans. Several recent studies suggest to some researchers that salt fingers help to mix these warm, salty surface waters with the cooler, fresher waters beneath them. Such mixing would be of particular interest because salt fingers, which are driven by molecular processes, have the unique ability to transport salt more efficiently than heat.

The molecular nature of salt fingering was a major obstacle to its acceptance as a possible mixing process. According to David Evans of the University of Rhode Island and others, many physical oceanographers clung to the philosophy that such interactions between molecules could not affect a body of water tens or even thousands of kilometers across. The ocean, they said, is simply too turbulent to allow it. Considering that kind of resistance, it is not surprising that salt fingers were for some time viewed as a mere theoretical oddity. Their history is usually traced back to a thought experiment presented in 1956 by Henry Stommel, Duncan Blanchard, and Arnold Arons in which they envisioned a "perpetual salt fountain" formed by sticking an aluminum pipe down into the sea. The pipe walls would allow heat but not salt to pass into the pipe. Once "the pump" was primed, seawater would be driven up the pipe by the differences in the distribution with depth of temperature and salinity.

In 1960, Melvin Stern of the University of Rhode Island pointed out that a pipe was not necessary to separate the heat and salt—nature can discriminate between heat and salt on the basis of the speed with which they diffuse through seawater. The 100-fold higher rate of molecular diffusion of heat over that of salt

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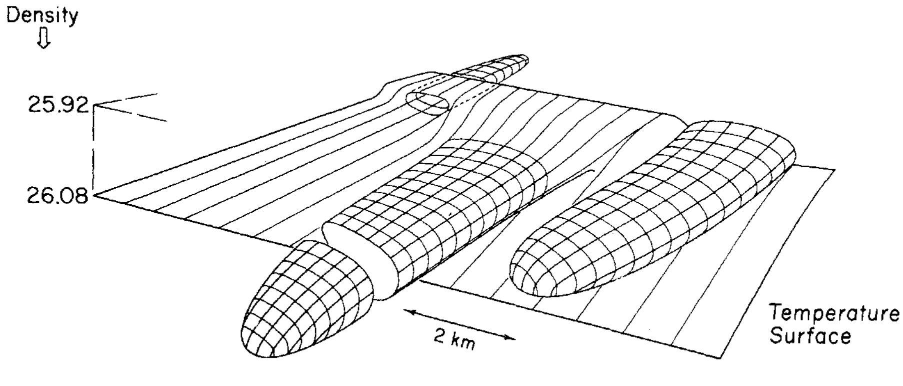


Frontal Intrusions

A schematic representation of cooler, fresher tongues of water crossing a front into warmer, saltier water. Salt fingering was assumed to be occurring along their upper surfaces because the intrusions were becoming more dense and sinking, especially at their tips. [From M. C. Gregg, Journal of Physical Oceanography, ***10****, 1468 (1980). © American Meteorological Society, 1980]*

will produce salt fingers, he said. On the underside of the Mediterranean outflow, for example, warm, salty water lies on top of cooler, less salty water. The saltier water stays on top because its higher temperature more than compensates for the water's higher load of salt, leaving its density slightly lower than that of the water below.

But if the interface between the two layers is disturbed, a nearly imperceptible dimple of cooler water can rise above the boundary. It will quickly warm as heat diffuses, molecule by molecule, across the stretched boundary. However, because of salt's slower rate of diffusion, the dimple will gain little salt. As a result of these unequal transfers, the dimple will be warmer but not much saltier than it was at the start. Lightened by the heat, it will begin to rise, forming a column of rising water. A descending finger can form beside it in the same way by losing heat to the ascending cooler water but retaining its higher salt content. The result is much like a nest of vertical heat exchanger tubes that pick up the heat from descending water and return it to the upper layer but allow the salt to pass through. The "tubes" extend only a few tens of centimeters before they break down and steadily mix their flows into the layers above and below the band of fingers.

Although Williams's pictures proved that salt fingers exist in the ocean, it was not until the late 1970's that oceanographers convinced themselves that salt fingering makes any difference. What changed researchers' minds was the behavior of tongues of water intruding across oceanic fronts, the tongues being smaller versions of the Mediterranean outflow. Michael Gregg and J. H. McKenzie of the University of Washington came across such intrusions in the far northeast Pacific (50° N, 145° W) at a front between two patches of surface water. These tongues of cooler, fresher water, measuring up to 8 kilometers long, 2 kilometers wide, and 7 to 15 meters thick, poked into the warmer, saltier water on the opposite side of the front.

The peculiar thing about these intrusions was that they refused to behave according to conventional rules. Normally as a water mass having a particular temperature and salinity, and thus a set density, slides between layers of water, its density does not change. Floating in between, it remains slightly denser than the water above it and less dense than that below it, even though some water may mix into the intruding layer from above or below.

Instead of maintaining a constant density, the cold intrusions found by Gregg and McKenzie became heavier and sank down into water on which they should have been able to float. Although they never directly observed any salt fingers, Gregg and McKenzie concluded that no process other than the unequal mixing of salt and heat could make these intrusions sink. Salt fingering on the top of the cold intrusion would allow salt to enter unaccompanied by most of the heat that made the overlying layer lighter. With the additional salt but little additional heat to compensate for it, the intrusion would become denser and sink. This behavior is consistent with predictions made by Stern on purely theoretical grounds and by Stewart Turner of the Australian National University on the basis of laboratory experiments.

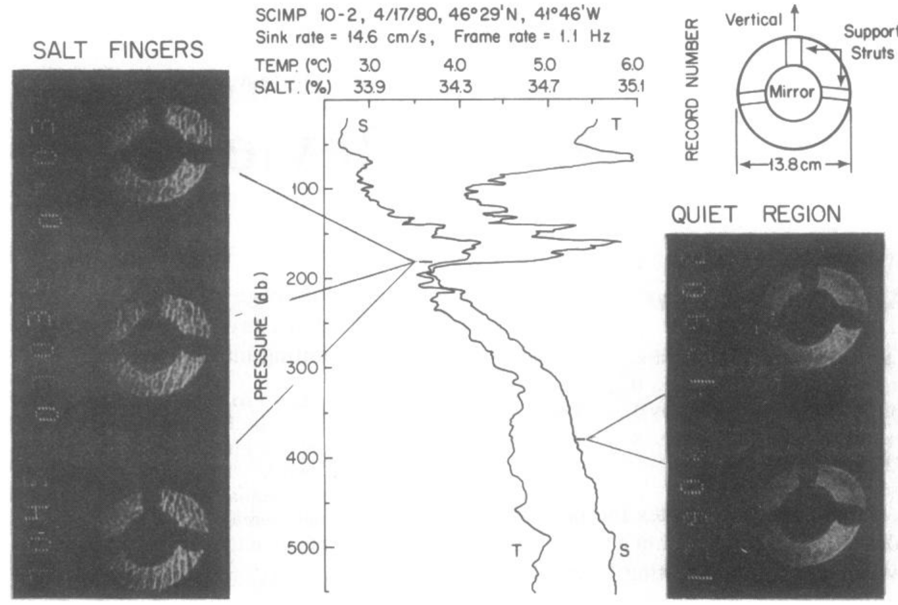
Terrence Joyce and a group at Woods Hole, the first workers to observe any intrusion density changes, found that 50-to 100-meter thick, cold intrusions across the Antarctic Polar Front also become denser as they take on more salt from the saltier water above them. In addition, they found warm intrusions that were becoming lighter, presumably because they were losing more salt than heat through salt fingering. Only cold, fresher intrusions sank, and only warm, saltier intrusions rose. The only known process that could cause that, Joyce says, is salt fingering.

Until recently, the salt fingers that were supposedly mixing salt in and out of frontal intrusions had not been seen. Raymond Schmitt and Daniel Georgi of Woods Hole caught them in the act east of Newfoundland on the edge of the North Atlantic Current, which is thought by some to be an extension of the Gulf Stream. As they reported at the December meeting of the American Geophysical Union (AGU), they used Williams's instrument package, the self-contained imaging micro-profiler (SCIMP), which includes a camera for making laser shadowgraphs of the fingers and precise salinity and temperature detectors. They found salt fingers on the lower surface of warm, salty water intruding from the Gulf Stream-like water on the south of the front into the colder, fresher water from the Labrador Sea on the north. The shadowgraph images showing centimeter-sized vertical bands not only looked like laboratory salt fingers, but they showed up most often when theory indicated that conditions most favored their formation. Not all intrusions showed changing densities, but the ones that did had the greatest salt fingering activity. From all of this, Schmitt and Georgi conclude that salt fingering did more to mix the intrusions with surrounding water than any other process.

Now that salt fingers are accepted as a mixing process to be reckoned with at fronts, some oceanographers are suggesting that salt fingering may have a significant effect on huge areas of tropical and subtropical oceans. There, the sun warms the surface water and concentrates its salt through evaporation, just as it does to the water that forms the Mediterranean outflow. This warmer, saltier surface water lies over colder, fresher water, but the transition between them, called the thermocline, is a gradual one, spanning hundreds of meters.

There is no generally accepted explanation of how the ocean manages to mix this excess heat and salt back into the rest of its water, creating the observed thermocline. One theory holds that turbulent mixing carries the salt and heat downward across the thermocline while the deep, cold, fresher water upwells in various spots around the ocean. How this theory of the thermocline, or any other, might be tested has not been obvious. As a result, oceanographers have tried to measure directly the turbulence itself.

So far, it seems all too quiet in the thermocline for turbulent mixing to be the whole answer. Using a freely falling temperature sensor accurate to a few microdegrees, Gregg has looked for the tiny variations that would be caused by the hypothesized turbulence. Wherever he looked, he saw a tenth to a hundreth of the turbulence that was predicted by the theory. Others have had the same experience. Most researchers agree that, at least within 30° of the equator where the search has been most thorough, there is not enough turbulence to carry the excess heat and salt downward.



Shadowgraphs of salt fingers

The photographs on the left were made at the bottom of a warm, salty intrusion in the North Atlantic Current. A laser and a mirror system were used to visualize the differences in temperature and salinity between the individual fingers. The field of view (partially obstructed by a mirror and its supports) is 13.8 centimeters wide. The photos on the right were made well below the intrusion. [*Source: Raymond Schmitt and Daniel Georgi, Woods Hole Oceanographic Institution*]

The alternative to moving salt and heat vertically across the thermocline is to slide it horizontally, or at least nearly so, between the polar and equatorial regions. According to this theory, a patch of surface water in the Antarctic polar region might cool to the point where it would sink and slip beneath less dense water to the north. As it moved northward, its density, as set when it left the surface, would determine the depth at which it moved. The farther north it went, the deeper it would fall as the near-surface water becomes warmer and lighter. Warm equatorial water would move horizontally in the opposite direction. As one oceanographer puts it, water "just sloshing around horizontally" would create the thermocline while requiring little or no mixing. Although these movements have not been directly observed, the lack of turbulence and the resemblance of deep thermocline water to some surface waters have prompted some researchers to lean toward this explanation.

Proponents of a major role of salt fingering agree that something like this probably happens, but they argue that the salinity and temperature of thermocline waters cannot be explained entirely unless salt fingering modifies them. One basis for the argument is usually visualized as a plot of temperature versus salinity at various points in the upper thermocline or "central waters." The points from the central water at any one location fall roughly on a straight line. A perfectly straight line would suggest that the central waters result from turbulent mixing across the thermocline. But Schmitt argues that the best line through the points is actually a curve, the one that would be produced if salt fingering were moving salt down more efficiently than heat. The points fit the temperature-salinity curve so closely, he says, because any water entering the thermocline, whether from the surface, a front, or a large eddy, would move vertically under the influence of salt fingering until its salt and heat content matched the curve.

Schmitt's proposition is only beginning to be closely examined by oceanographers, but evidence has recently appeared supporting one essential of his hypothesis—the existence of salt fingering in the subtropical thermocline. Like others who have found evidence of salt fingers, Ann Gargett of the Ocean Sciences Institute, Sidney, British Columbia, was not looking for them in particular. In fact, after she made her temperature observations east of the island of Hawaii in 1973, she put some of them aside as being too odd to decipher—"maybe some noise," she thought—and forgot them.

Recently, Gargett was reading a paper by Schmitt and Evans on salt fingering that described the type of observations that would help resolve the thermocline problem. "Oh, I have those," she recalls thinking. Looking at the "noise" in her old data, she became "absolutely convinced that they're salt fingers. There is an extremely clear-cut signature." In her talk at the AGU meeting, she noted that her record of tiny, regular temperature variations, obtained far from any front, closely match those predicted by Schmitt's simple model of salt fingering. Her apparent success where others have failed might be attributed in part to her having towed the temperature sensor horizontally, cutting through whole patches of fingers, rather than dropping it vertically, as is usually done. If salt fingers have indeed been found by such an undirected search in the vastness of the Pacific, most researchers agree, then salt fingering could be ubiquitous in the thermocline.

Salt fingering is only one way that the large water masses of the ocean, which are initially created by the sun's energy, are mixed together again. But its ability to mix salt more efficiently than heat has not been taken into account in the standard theories of ocean mixing. Fronts, where salt fingering obviously is important, are showing up more often than most oceanographers would have thought a few years ago. And mixing is central to more practical matters, such as the dispersion of chemical pollutants, the fate of the man-made carbon dioxide that threatens to change Earth's climate, and the recycling of the nutrients that support all marine life.

—RICHARD A. KERR

Additional Readings

1. J. S. Turner, *Buoyancy Effects in Fluids* (Cambridge Univ. Press, New York, 1973).
2. B. A. Warren and C. Wunsch, Eds., *Evolution of Physical Oceanography* (MIT Press, Cambridge, Mass., 1981).