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ALFRED C. REDFIELD

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A Biographical Memoir by
ROGER REVELLE

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ALFRED CLARENCE REDFIELD was a member of a scientific family. His great grandfather, William C. Redfield, was the first president of the American Association for the Advancement of Science in 1848. Like most scientists in those days, he was an amateur. He made his living as a railroad and canal manager, but he contributed many ideas and observations to the then-infant science of meteorology, and particularly to the understanding of hurricanes, which he showed were giant whirlwinds. Alfred's grandfather was a botanist in the Academy of Natural Sciences in Philadelphia, and his father, Robert Redfield, was a naturalist photographer, whose works are in the Library Company in Philadelphia and at Yale. Alfred's son, Alfred Guillon Redfield, is a physicist and biochemist who is a member of the National Academy of Sciences. His nephew, Donald Griffin, is world famous for his studies of bats and their use of high-frequency acoustics to navigate and to find their prey. One of his two daughters, Elizabeth Marsh, is a member of the Division of Natural Sciences and Mathematics of Stockton State College in New Jersey.

Alfred C. Redfield was born on November 15, 1890, in Philadelphia. He died March 17, 1983, at his home in Woods

Hole, Massachusetts. During his boyhood his family spent their summers in Cape Cod, starting in Falmouth in 1898 when Alfred was seven, and afterwards for many years in Barnstable, on the shores of Cape Cod Bay. The boy was fascinated by natural history, being especially interested in insects and birds. He attended Haverford College for one year, 1909-10, and then entered Harvard University, where he received a bachelor's degree in 1913 and a Ph.D. degree in 1917. After receiving his doctoral degree, Redfield studied at Christ College in Cambridge University and at the University of Munich. He spent a year as assistant professor of physiology at the University of Toronto and then joined the faculty of Harvard University as assistant professor of physiology in 1921. Redfield remained on the Harvard faculty for the rest of his life, as professor of physiology from 1931, director of the Biological Laboratories in 1934, and chairman of the newly consolidated Division of Biology, which united botany, zoology, and physiology, from 1935 to 1938, and finally as professor emeritus after 1956.

Redfield married Elizabeth Pratt in 1913, shortly after receiving his bachelor's degree, but she was a casualty of the 1918 flu epidemic. In 1922 he married Martha Putnam. After more than sixty years together and three children, she outlived him by only a few months.

Redfield's doctoral research dealt with skin coloration in the horned toad, which he found was controlled by adrenalin, the "stress" hormone in mammals. After obtaining his degree, he studied the physiological action of radium radiation and X-rays, demonstrating that the effects on living tissue resulted from ionization caused by the radiation.

During his graduate years, Redfield visited the Marine Biological Laboratory at Woods Hole. In later summers at Woods Hole he became interested in the respiratory functions of the blood in marine invertebrates and made notable discoveries of oxygen binding and physiological behavior of the copper-bearing respiratory compound hemocyanin. This is the blood pigment of Limulus, the horseshoe crab, and several other ancient invertebrate species.

Redfield's life story from 1930 to 1970 was intimately intertwined with the first forty years of the Woods Hole Oceanographic Institution. The "Oceanographic" was founded in 1930 under the leadership of Frank Lillie, director of the Woods Hole Marine Biological Laboratory, with a $3 million endowment from the Rockefeller Foundation and with the marine biologist Henry Bryant Bigelow, a Harvard professor, as director. Following the tradition established by the Marine Biological Laboratory, the small staff gathered at Woods Hole only during the summertime. During the rest of the year they scattered to their respective universities and home institutions. Alfred Redfield was one of the first dozen or so staff members recruited by Bigelow, who was his intimate friend. Others were the meteorologist Carl Gustav Rossby and his students, Ray Montgomery and Athelstan Spilhaus; the bacteriologist Selman Waxman and his assistant, Charles Renn; Bigelow's students, Columbus Iselin, Mary Sears, and George Clark; the chemists Norris Rakestraw from Brown University and Richard Seiwell from the Carnegie Institution; Redfield's student Bostwick Ketchum; and the geologist Henry Stetson from Harvard. There were also Albert Parr, director of the Bingham Oceanographic Foundation at Yale, who used the Woods Hole ship *Atlantis* but was never actually a staff member, and Floyd Soule, physical oceanographer of the International Ice Patrol, which made its headquarters at Woods Hole after the oceanographic institution was founded.

Other than Bigelow, Iselin and Seiwell, none of the rest of the staff had much seagoing experience, let alone oceanographic experience. They had to teach themselves how to be oceanographers. They became seasick when they went out on *Atlantis* into the Gulf of Maine or beyond. Some of them more or less got over it and were able to work on the ship; others were never able to work at sea, though they were very useful in the laboratory. In any case, this small staff produced 260 scientific papers in ten years on a budget of about $80,000 a year. Nowadays the Oceanographic issues about 260 papers a year, but the budget is several hundred times as large.

Some of the research staff doubled as managers. Columbus Iselin was the first captain of *Atlantis.* He took delivery of the ship from her builders, Burmeister and Wain, in Copenhagen and sailed her across the Atlantic with an amateur crew. William Schroeder, an ichthyologist who was Bigelow's collaborator in writing about the fishes of the Gulf of Maine, was the business manager; his father, "Pop" Schroeder, was superintendent of buildings and grounds. The elder Schroeder was a retired plumber; according to Redfield, "he took care of all the problems that you could take care of with a monkey wrench." On the other hand, some of *Atlantis's* crew also did science. Harold Backus, the engineer, started the tradition of keeping records of the different species of land birds that came on board when the ship was at sea. Like the scientists, these birds usually became seasick when they landed on deck. A seagoing technician, Alfred Woodcock, observed and explained many of the essential but previously unobserved features of the ocean-atmosphere circulation in the boundary layer between the two fluids.

In the early 1930s Redfield made the discovery for which he is best known. This is that the atomic ratios between the chemical components of marine plankton, specifically nitrogen, phosphorus, and carbon, are identical with their relative proportions in the open ocean. For every atom of phosphorus there are fifteen atoms of nitrogen and 105 atoms of organic carbon. Usually much more carbon is present in the form of carbonate and bicarbonate ions. But 105 atoms of carbon can be shown to be of biological origin, originating in the “soft parts” of marine organisms.

The content of dissolved oxygen in the open sea is in most regions adequate to account for the oxidation of the phosphorus, nitrogen, and carbon in marine organisms after they die (i.e., about 235 to 270 milligram atoms of oxygen for each milligram atom of phosphorus). In some regions, however, for example, in the Black Sea, in Norwegian fjords, in tidal marshes, and in the interstitial waters of many bottom sediments, the amount of dissolved oxygen is insufficient to oxidize the phosphorus, nitrogen, and carbon, and oxygen must be supplied under anaerobic conditions from the reduction of sulfate ions in the seawater to sulfides. (In a later paper Redfield suggested that oxygen in the earth’s atmosphere may have originated in large part from sulfate reduction and subsequent release of oxygen in photosynthesis.)

The reasons why the proportions of biologically active elements in seawater and in marine plants are virtually identical are by no means clear. Redfield thought that bacterial nitrogen fixation might increase the ratio of nitrate to phosphorus and that somehow denitrifying bacteria operated to limit the increase of nitrate nitrogen in the ocean to the ratio observed in marine plants. He thought also that the total amount of oxygen in the atmosphere and in oxidized sediments was mainly limited by the quantity of organic matter available during the earth’s early history for sulfate reduction and by processes that isolated the sulfide produced—for example, formation of iron sulfide and other insoluble compounds.

In recent years Wallace Broecker and other geochemists have referred to oceans in which there are constant ratios between phosphorus, nitrogen, and carbon as “Redfield Oceans.” They have used these ratios to explain aspects of the carbon cycle in the sea. From Redfield’s point of view the identity of the ratios of biologically active substances in marine organisms and in the ocean waters was one source of his famous aphorism: “Life in the sea cannot be understood without understanding the sea itself.”

With the onset of America’s role in World War II in 1941-42, the Oceanographic underwent a sea change. Alfred Redfield was appointed associate director, and he and Martha moved permanently from Cambridge to Woods Hole. Within a year the staff was multiplied thirtyfold. Research and development on underwater explosives and on many oceanographic problems of military importance was undertaken on a crash basis. Such a large number of people had never lived in Woods Hole during the winter. Most of the houses were not winterized, and it was very cold. I was the Navy’s project officer for the Oceanographic, and I came up from Washington about once a month on a two-day trip. It was my impression that the old New England custom of bundling was widespread just so that people could keep warm.

During this time Redfield concentrated his research in two areas—the problem of fouling of ships’ hulls by various marine invertebrate organisms and protection of submerged submarines from surface ships and aircraft. The former work, carried out in cooperation with Bostwick Ketchum and others, led to the development of antifouling paints, which were said to reduce the costs of ship operation by 10 percent or more.

The work on submarines was an outcome of a study of the behavior of echo-ranging equipment (called ASDIC by the British, and SONAR by the Americans) installed on surface ships to detect and track submerged submarines.

This equipment was observed to behave in a seemingly erratic way. Sometimes an echo could be received from a submarine several thousand yards away; at other times and places an echo would not be returned at a distance of only a few hundred yards. To find a rational explanation for this behavior, Columbus Iselin on *Atlantis* and Commander William Pryor on the U.S. destroyer *Semmes* carried out tests together in the Caribbean Sea. They found that, when there was a temperature gradient in the waters near the surface (e.g., in the afternoon when the surface waters were heated by the sun), echoes were returned only from nearby submarines or not at all, whereas in the morning, when the surface waters had cooled to a uniform temperature with depth, echoes were returned from submarines several thousand yards away. The "afternoon effect" was clearly caused by refraction or downward bending of the sound beam from the sonar, which created a "shadow zone" in the upper-water layers where the sound did not penetrate. Later studies showed that there are large areas in the oceans, particularly in coastal regions, where temperature gradients in the upper layers greatly weaken performance of the sonar gear. Athelstan Spilhaus's invention, the bathythermograph, which accurately and quickly recorded water temperatures in the top 150 meters beneath the sea surface, was refined and mass produced by the navy and installed on all ships used in antisubmarine warfare.

Maurice Ewing and Allyn Vine, two of the wartime recruits at Woods Hole, recognized that knowledge of subsurface ocean temperatures would be equally valuable to submarines in avoiding sonar detection. If a subsurface temperature gradient existed, a submarine could hide in the shadow zone and be immune from sonar. They designed a bathythermograph for submarines, and this was widely installed.

Redfield and Vine devised a completely different method for submarine use of vertical temperature gradients. They realized that a submerged submarine could control its buoyancy with sufficient accuracy to be able to "sit on a layer" (i.e., to remain in the middle of a vertical ocean temperature gradient without moving). The submarine could shut down its motors and remain absolutely quiet for many hours, thus avoiding detection by listening as well as echo ranging. Together with their colleagues Dean Bumpus and William Schevill, they installed submarine bathythermographs and taught this technique with great success to the U.S. fleet submarines in the Pacific. In Washington the oceanographic unit of the Navy Hydrographic Office under Mary Sears (by that time a WAVE lieutenant) and the Sonar Design Division of the Bureau of Ships cooperated with Redfield and Vine in producing training manuals and *Submarine Supplements to the Sailing Directions.* This work was done under the sponsorship of Division Six of the National Defense Research Committee—part of the Office of Scientific Research and Development, led by Vannevar Bush—and the astronomer Lyman Spitzer was very much involved, as was I.

The Woods Hole Oceanographic Institution never returned to its prewar status after World War II. The Navy and the country had learned of the value and importance of oceanographic research. The Bureau of Ships and the Office of Naval Research replaced the National Defense Research Committee in providing generous support for oceanography. But, unlike the war years, that support was given for basic undirected research. After a few years they were joined by the National Science Foundation and to a lesser extent by other federal agencies.

Alfred and Martha remained as residents of Woods Hole, although he retained his Harvard professorship. By this time he was senior oceanographer, as well as associate director of the institution. They purchased 5 acres of land at the corner of Water Street and Maury Lane, built a house on one corner of it, and gave much of the rest of the area away to a church and to the Oceanographic Institution. But they kept enough land to cultivate a vegetable and flower garden, which both Alfred and Martha farmed vigorously and effectively, almost until the end of their lives.

Redfield turned his research interests to the study of tides in coastal waters and the ecology of the salt marshes that characterize the subsiding East Coast of the United States. He concentrated on the marsh near Barnstable on Cape Cod, which he had known since boyhood. He showed that the marsh has developed over the past 3,000 to 5,000 years, as sea level has risen about 15 centimeters per century. The present surface around the edges of the estuary is at high water level and is vegetated with three marine grasses, which form a firm turf, punctuated with pond holes. Beneath the surface are consolidated deposits of peat 5 or more meters thick. Within the estuary there are patches of Spartina alterniflora that catch drifting sand to form small islands with relatively high levees around the edges. These islands are submerged about 30 centimeters below high-tide level. In their origin and behavior they resemble somewhat the "coral heads" on the floor of coral atoll lagoons in the Central Pacific.

The slowly accumulating peat in the salt marsh gave an opportunity to measure the heat flow from the interior of the earth. By measuring summer and winter temperatures at different depths of the peat deposits, it was possible to compute the average temperature gradient with depth. Combining this with the average thermal conductivity, two similar values for the upward heat flow were obtained, averaging 1.47×10^{-6} cal cm^{-2} sec^{-1}, very close to the average continental value of $1.43 \pm 0.57 \times 10^{-6}$ cal cm^{-2} sec^{-1}.

Redfield's last scientific paper, "The Tides of the Waters of New England and New York," was published shortly before his ninetieth birthday. In this treatise he dealt with the predictions of time and height of the tide and the velocity and direction of related tidal currents in the inshore waters of the northeastern United States, where bottom topography and narrow channels result in complex distortions of the tidal wave.

What sort of man was Alfred Redfield? His younger colleague, William S. Von Arx, has described him well:

> Alfred Clarence Redfield was an inherently civilized man: urbane, courtly, gracious, but at the same time forthright, redoubtable and demanding. He was neither modest nor immodest. A man of pure reason, he was thoroughly convinced of his own worth, yet always open to rational improvement and adventure. He enjoyed his mark as a plain-mannered patrician; one who could move as easily in the company of artisans and tradesmen as among scholars. . . . His working methods were honest expressions of his character. He was logical and not above hard work in all he did as a gentleman farmer, sailor, citizen, forester, architect, historian, lecturer, writer, pipe-smoking editor and friend.

Redfield was well appreciated by his peers. He was a fellow of the American Academy of Arts and Sciences and was elected to the National Academy of Sciences in 1958. The National Academy gave him its Agassiz Medal in 1956 for original contributions to oceanography. He became president of the Ecological Society of America in 1946 and president of the American Society of Limnology and Oceanography in 1956, at which time he was largely responsible for establishing the society's publication, *Limnology and Oceanography.* For many years he was also editor of the *Biological Bulletin.* In that capacity he gently improved the scientific writing of a generation of American biologists. He was a trustee of both the Woods Hole Oceanographic Institution and the Marine Biological Laboratory and president of the Bermuda Biological Station for Research in the early 1960s.

Like some other members of the staff of the Oceanographic, Redfield took an active and continuing interest in the village of Woods Hole and the town of Falmouth. He was a member of the Falmouth Town Meeting, the forest and finance committees of the town, president of the Woods Hole Public Library, and a member of the Cape Cod Chamber of Commerce. Laboratory buildings are named for him at both the Oceanographic and the Bermuda Biological Station. In 1960 he obtained a Woods Hole twin-masted "spritsail boat," which was then seventy years old. He restored it and donated it to the Mystic Seaport Museum.

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