François M. M. Morel

François M. M. Morel, the Albert G. Blanke Professor of Geosciences, is a world leader in the chemistry of natural waters and one of the founders of the field of biogeochemistry. His research demonstrated that aquatic chemistry, biochemistry, genetics, and microbiology are critical for understanding the oceans, in the process helping to establish the field of marine biogeochemistry.

Among many contributions, these are some of the most important: First, the "chemical speciation" of a trace element in water is as important as its bulk concentration in determining its availability and/or toxicity to the aquatic biota and its interactions with solid surfaces. Second, organisms have diverse strategies for affecting and responding to speciation. For example, François's work on phytochelatins was a critical predecessor to the study of siderophores, compounds that plankton exude into the environment in order to capture iron, and other metal-binding ligands in the ocean. Third, the physiology of algae and other microbes is a major determinant of their trace metal requirements and sensitivities. For instance, François's "ecumenical hypothesis," that large diatoms are more easily iron-limited than the much smaller cyanobacteria, was subsequently confirmed in several large-scale field experiments. Finally, the metal requirements of algae affect the global distributions of metals and other biologically active and climatically important compounds. François's lab established the roles of Zn- and Cd-carbonic anhydrases in CO_2 acquisition by algae, which in turn determines the trace metal composition of particulate matter in the ocean.

In 1967, after majoring in applied mathematics and hydraulic engineering in Grenoble, France, François earned his Ph.D. at the California Institute of Technology (Caltech) on the chemistry of red blood cells. Having acquired an interest in the application of computers to chemical calculations, he remained at Caltech as a postdoctoral fellow, where, with James Morgan, François developed the first family of computer programs for calculating complex chemical equilibria in natural waters. The original key publications were followed by the adoption of this conceptual approach by virtually every trace metal chemist in the world. These programs and

their descendants (EPA's MINTEQ) are widely used in industry, government, and academia.

As a faculty member in civil and environmental engineering at the Massachusetts Institute of Technology from 1973 to 1994, François's research focused on the interactions between trace chemical species and aquatic microbes, including adsorption of trace elements on minerals, colloid dynamics in natural waters, photochemical transformations, complexation of metals by inorganic and organic compounds, and, most notably, metal requirements and toxicity in marine phytoplankton. After 20 years at MIT, having served as director of the Parsons Laboratory for Hydrology and Environmental Engineering since 1991, François decided in 1994 that it was time for a new challenge and moved to the Department of Geosciences at Princeton.

One of his first great successes at Princeton was the discovery of the first cadmium enzyme, cadmium carbonic anhydrase. Cadmium is a toxic metal and had never been imagined as a requirement for life. The existence of such an enzyme in phytoplankton, however, explains the biogeochemistry and distribution of cadmium in the oceans, with important implications for the controls on phytoplankton growth. François pursued this discovery not only at the environmental scale but also at the biochemical level, exploring the structure of the enzyme and its flexibility to accommodate both cadmium and zinc in its active site. This body of work was central in illustrating to biochemists and oceanographers alike the vast potential of merging findings from molecular and oceanographic scales. As part of this effort, François established the Center for Environmental BioInorganic Chemistry (CEBIC), with major funding from both the National Science Foundation and the Department of Energy. This center, whose motto is "From the molecular to the global," brought together bioinorganic chemists and environmental scientists to investigate, at the molecular level, some of the key processes that control the global cycles of elements. François served as director of CEBIC for its 10-year history and provided critical opportunities for many young scientists entering the field. They now populate the academic departments of the country and world with interdisciplinary environmental scientists of high caliber.

Cadmium carbonic anhydrase catalyzes the interconversion of bicarbonate (HCO_3-) and CO_2 in water or other biological solutions and is central to carbon acquisition by marine phytoplankton. The

connection to carbon acquisition led to the next chapter of François's career, in which he and his students addressed the ocean's chemical response to the fossil fuel-driven rise in atmospheric CO_2 and its effect on ocean life. The increase in atmospheric CO_2 leads to global warming, but much of that industrially produced CO_2 is actually dissolving in the ocean, rather than remaining in the atmosphere. In seawater, the addition of CO_2 decreases the pH, leading to the popular term "ocean acidification." François led a National Academy study on ocean acidification and published several papers on the topic. Both his own research and his National Academy study yield the perspective that the effect of ocean acidification on ocean life may be less and slower than supposed, because of the enzymatic resilience of biological systems.

Mercury is known for its toxicity to humans and other vertebrates. François transformed our understanding of the environmental behavior of this metal, for which speciation largely controls its bioavailability and thus toxicity. This work eventually led François to fish. Fish can be seriously contaminated with mercury, especially freshwater species, to the extent that advisories limiting fish consumption are in place in most states. The source of increasing mercury contamination in freshwater systems derives from power plant and industrial emissions. The situation is quite different in the ocean; based on their data showing no change in mercury concentration in Pacific tuna over 30 years, François's group asserted that methylmercury in the open oceans may be formed at the ocean bottom or in suboxic pelagic environments and may not be influenced by pollution. François's work was the critical factor in a 2006 court decision in California in which it was ruled that most mercury in ocean fish (tuna explicitly) is naturally occurring and therefore not relevant to the case for pollution regulation.

Francois's accomplishments have been recognized with many awards starting early in his career: The Association of Environmental Engineering (AEE) professor-adviser award in 1987 and the AEE outstanding paper award in 1994, endowed chairs (the Doherty Junior Professorship, 1974–1977, and the Turner Professorship, 1993–1994), at MIT; the Blanke Professorship, 1996-present, at Princeton; and chairmanships of the Gordon Conferences (Environmental Sciences in 1986, Chemical Oceanography in 1998). He was elected to the National Academy of Sciences in 2009 and in the same year was awarded the Urey Medal by the European Association for

Geochemistry and the Distinguished Alumni Award from Caltech. Other medals include the C. C. Patterson Medal from the Geochemical Society (2001), the Maurice Ewing from the American Geophysical Union (2005), and the ENI Award from the ENI Foundation (2010).

The American Chemical Society honored him with the Award for Creative Advances in Environmental Science and Technology in 2010 and Carnegie Mellon University awarded him the Dickson Prize in Science in 2012. He was internationally recognized with the Einstein Professorship of the Chinese Academy of Sciences in 2010 and was elected to the Instituto Veneto de Scienze, Lettre ed Arti, in 2011. He is a fellow of the Geochemistry Society and the American Geophysical Union. He has served on numerous national committees, review boards, and steering committees.

In addition to the publication of 260 research papers, François also published two editions of a textbook, *Principles of Aquatic Chemistry*, which remains the standard text for generations of students. It is the basis of François's upper-level course in environmental aqueous geochemistry, which at least once received a perfect 5 evaluation (i.e., every student rated the course a 5 in every category!). He has graduated 33 doctoral students, most of whom are pursuing successful academic careers in fields including oceanography, chemistry, biology, engineering, geosciences, and molecular biology.

At Princeton, François served twice as director of the Princeton Environmental Institute, from 1998–2004, and from 2014–2017. During his first term as PEI director, he oversaw the restructuring of the PEI curriculum, including teaching the first lab sections himself. He also cherished several years of service on the editorial board of Princeton University Press, a task which gave him the opportunity to review book proposals on a wide variety of topics, from Greek poetry to molecular biology, and provided fodder for his voracious appetite for reading and for engaging with unfamiliar ideas.