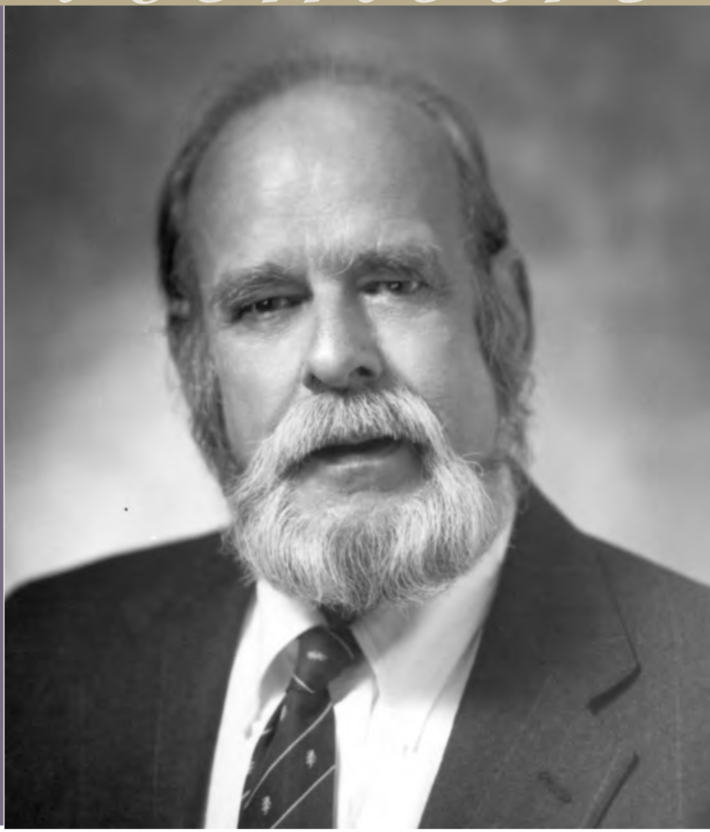
Francis R. Boyd Jr.

1926–2004

BIOGRAPHICAL *Memoirs*



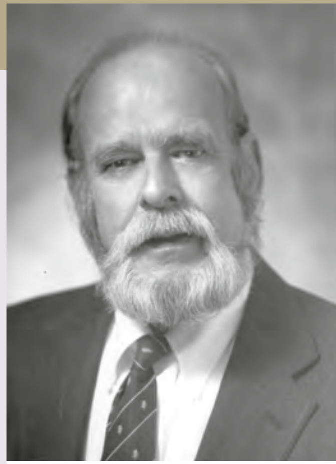
A Biographical Memoir by
W. G. Ernst
and Russell J. Hemeley

NATIONAL ACADEMY OF SCIENCES

FRANCIS RAYMOND **BOYD** JR.

January 30, 1926–January 12, 2004

Elected to the NAS, 1974



Carnegie Institution Archives.

By W. G. Ernst
and Russell J. Hemeley

Francis Raymond Boyd Jr., known to his friends and colleagues worldwide as Joe, was born in Boston, Massachusetts, on January 30, 1926. He received an AB degree in 1949, an MS in 1951, and a PhD in 1958, all in geology from Harvard. He also was awarded an MS in geology from Stanford in 1950. His doctoral study, working under the supervision of George C. Kennedy, was entitled: "Geology of the Yellowstone Rhyolite Plateau." This field-based geologic research (Boyd 1961) was featured in the 1998 IMAX film "Yellowstone."

In 1953, Joe Boyd accepted an appointment at the Geophysical Laboratory of the Carnegie Institution of Washington, and from that supporting foundation, he carried out mineralogic phase equilibrium and petrochemical research throughout his long and remarkably fruitful career. After retirement in 1996, Joe continued his scientific research and remained a widely recognized contributor to the understanding of mantle geochemistry and geophysics, as well as the geologic structure and evolution of the Earth's lithosphere, until his death on January 12, 2004.

An insightful scholar and innovator, Joe Boyd was a world-class Earth scientist, a warm, fun-loving human being, and an especially generous, gentle soul. He was a leader in the revolution that took place during the 1950s and 1960s in experimental high-pressure techniques for understanding the nature of the Earth's deep interior, work that had implications well beyond the geosciences. One of us knew him for forty-nine years, the other for twenty years, as a laid-back and informal, but insightful, mentor and colleague. Joe led by example, rather than by direction. His love of life was expressed in his joyful dedication to research at the Geophysical Laboratory, as well as his enthusiastic extracurricular pursuits involving fast cars, sailing, skiing, fishing, gardening, and the arts.

From field to lab

As a Harvard undergraduate, Joe developed an interest in geology from his professor, George Kennedy. Inspired by summer geologic fieldwork in Yellowstone National Park with Kennedy, he began a lifelong pursuit to understand the Earth's interior through its high-pressure minerals. (See Robert M. Hazen's book, *The Diamond Makers*, published by Cambridge University Press in 1999.) Joe was part of a group of experimental Earth scientists who advanced the frontier of laboratory-based studies of the Earth's deep interior through the 1950s and 1960s. He was inspired by the advances of Loring Coes and others, who demonstrated high-pressure minerals could be synthesized using novel laboratory techniques. Joe went on to develop and exploit many techniques for generating high Pressure-Temperature (P-T) conditions in the laboratory and characterizing the high-pressure phases produced in those experiments.

> After an eventful series of unanticipated laboratory floods and explosive disintegration of pressure vessels and their confining jackets, the vastly improved, widely copied instrument, more massive than its predecessors, could simultaneously reach pressures of 3 gigapascals or more at temperatures exceeding 1600 degrees Celsius.

Joe began his early work at the Geophysical Laboratory studying the P-T phase equilibrium relationships of some complex rock-forming chain silicates, the hydroxyl-bearing calcic amphiboles. Thermal stability limits of two end-members, tremolite and pargasite, were detailed in several annual reports of the Geophysical Laboratory. A summary paper dealing with relatively low-pressure phase relations of these minerals and solid solutions toward other amphibole end-members was included in *Researches in Geochemistry*, a discipline-setting volume edited by Philip H. Abelson (Boyd 1959). Joe's pioneering investigations employed conventional hydrothermal autoclaves—the so-called "cold-seal" pressure vessels—that were largely developed by Geophysical Laboratory staff scientists, notably O. Frank Tuttle. Such equipment could only reach hydrostatic confining pressures of about 200 or 300 megapascals (2 or 3 kilobars), pressures appropriate for rocky depths of about 10–12 kilometers, a mere fraction of the thickness of the continental crust (25-40 kilometers), never mind the underlying mantle. While completing his innovative studies on the P-T stabilities of tremolite and pargasite, Boyd passed on the hydrothermal investigation of amphiboles to a new doctoral candidate (WGE).

Recognizing a promising intellectual frontier, Joe was determined to delve much more deeply into the largely unknown interior of the Earth. Joining forces with Geophysical Laboratory engineer Joseph England, he began designing what was termed the single-stage (and the multi-stage) piston-cylinder apparatus, soon to be known as the Boyd-England press. After an eventful series of unanticipated laboratory floods and explosive disintegration of pressure vessels and their confining jackets, the vastly improved, widely copied instrument, more massive than its predecessors, could simultaneously reach pressures of 3 gigapascals or more at temperatures exceeding 1600 degrees Celsius, and it routinely and safely maintained P-T conditions for days, or ultimately, for weeks. This seminal achievement took place in steps during the late 1950s (Boyd and England 1960).

Figure 1. Joe Boyd with his piston-cylinder press, about 1975.
(Courtesy Geophysical Laboratory Archives.)

The piston-cylinder apparatus (Figure 1) has since been used by hundreds of materials scientists and solid-state physicists around the world in their efforts to create synthetic materials that are stable only at the great confining pressures appropriate to mantle depths. Perhaps most famous among these high-pressure phases is the dense cubic form of carbon, diamond. Boyd and England synthesized their first black diamonds in 1960 as a successful proof of the design concept for the piston-cylinder press, but also an effort largely done for fun. (See Robert M. Hazen's *The Diamond Makers* for additional stories associated with early syntheses of diamond.)

The piston-cylinder press allowed Joe to turn his attention to the phase-equilibrium relationships of chief minerals comprising the rocks of the upper mantle, especially the pyroxene and garnet groups. Working first at relatively low pressures with colleague

Frank Schairer, and then at high pressures with several Geophysical Laboratory staff scientists, a series of landmark phase-equilibrium investigations were published (Boyd and Schairer 1964, Davis and Boyd 1966, Boyd 1970). The research on the diopside-enstatite miscibility gap, or solvus, coupled with analytical data on the Al_2O_3 solubility in enstatite coexisting with magnesium-rich garnet studied at high pressures by colleague Ian MacGregor, led to the formulation of a geothermobarometer. Soon thereafter, this new geothermobarometer provided important constraints on the P-T structure of the mantle lithosphere and its underlying asthenosphere.

Figure 2. Joe Boyd in the electron microprobe laboratory, about 1968.
(Courtesy Geophysical Laboratory Archives.)

In the mid-1960s, a large crystal fragment, or megacryst, of subcalcic diopside had drawn Joe's attention to rocks from deeper portions of the Earth's mantle. Such pyroxenes have very high calculated temperatures—up to more than 1400 degrees Celsius—based on coexisting minerals lying along the diopside-enstatite solvus. Although these calcium-poor diopside analyses were previously known from the literature dealing with mantle minerals, they were largely ignored as inaccurate or representing multiphase mixtures. However, after the installation of an automated electron microprobe at the Geophysical Laboratory, and with the technical assistance of scientific associates Larry Finger and Chris Hadidiacos, Joe was able to accurately analyze these deep mantle samples, as well as phases from lunar rocks being investigated by Steve Haggerty and coworkers. The electron microprobe thereby became a critical analytical tool for quantifying the chemical compositions of coexisting minerals—a preliminary step required for the revolution in petrologic investigations of terrestrial and lunar materials during the 1970s (Figure 2).

Kimberlites and the lithosphere

Joe's deep interest in mantle rocks including peridotites and eclogites, and especially in mantle fragments, or xenoliths, entrained in ascending magmas, led to his involvement in the studies of kimberlites, funnel- and pipe-like bodies consisting of mantle-derived magmas fluidized by H_2O and CO_2. Such geological features rapidly transport mantle xenoliths, nodules, and megacrysts toward the surface. Some xenoliths famously contain diamonds, suggesting sources deeper than 100 kilometers. In the early 1970s, Boyd began a fruitful collaboration with Peter Nixon, who was then collecting and studying the kimberlites of Lesotho, Africa. Based on Boyd's P-T phase-equilibrium studies on the diopside–enstatite miscibility gap, coupled with analytical data on Al_2O_3 solubility in magnesium-rich enstatite, Joe demonstrated that the compositions of coexisting magnesian pyroxenes and garnets in these rocks could be used to calculate their physical conditions of equilibration, and therefore that of the host rock. Such experimental results were initially applied to Nixon's xenoliths and megacrysts from the Lesotho kimberlites.

Joe's seminal paper in *Geochemica et Cosmochimica Acta* was an instantly recognized classic (Boyd 1973). It provided a new method of determining the thermal structure of the upper mantle based on equilibrated phase assemblages. Xenoliths that were chaotically mixed within single kimberlite pipes, such as those from Kimberley and Lesotho, now could be reordered in terms of mantle depth of formation attending Cretaceous annealing, and their P-T values of equilibration plotted as "paleo-geothermal gradients" down to depths of approximately 200 kilometers (Boyd and Nixon 1975, Boyd and Nixon 1978). The petrochemical results confirmed the continental geotherm proposed by Sidney Clark and A. E. Ringwood based on heat-flow measurements combined with the known thermal properties of mantle materials.

Reflecting the insistent urgings of Joe and colleague Henry Meyer, the First International Kimberlite Conference (IKC) was held in 1973 in Cape Town, South Africa, organized by John Gurney in cooperation with Barry Hawthorne. Joe and Nixon presented research that spawned the new field of paleo-geothermobarometry and introduced unfamiliar mantle concepts, such as kinked geothermal gradient, sheared nodule, and fertile versus barren mantle. These seminal ideas evoked widespread interest and a flood of controversy, especially with regard to the origin and significance of kinked geotherms. The heightened understanding generated by Boyd's ideas, coupled with new research tools, stimulated a wide spectrum of further experimental and geochemical analytical studies of the upper mantle.

Boyd's solid foundation in field geology, classical thermodynamics, mantle architecture, and experimental phase equilibria at high pressures ensured for him a universally recognized leadership role and his insightful involvement in the seven subsequent IKC conferences that were held worldwide through 2003. The unqualified success of the first conference resulted in Joe and Meyer being asked to organize a second one in the general vicinity of Santa Fe, New Mexico. This, too, was memorable, and involved field trips both before and after five fully packed days of technical sessions. Earth scientists presented the results of work undertaken on mantle materials collected from around the world, as well as on field trips associated with the First IKC, thereby setting a very high bar for all subsequent kimberlite conferences. His scientific knowledge and judgment in this field were universally recognized, and Joe remained an active member of the advisory committee for kimberlite conferences for the rest of his life. Because of his wide-ranging studies in this area, Joe also developed interests in the mantle root beneath the Kaapvaal craton in southern Africa, as well as in the Siberian platform and the northern Andes (Boyd and Gurney 1986, Boyd and Mertzman 1987, Boyd 1989, Boyd et al. 1997).

On July 4, at the time of a celebration observed by the entire international group of kimberlite and diamonds experts, an unpredicted, heavy snowstorm blew in and covered the tents with 20 centimeters of snow, but failed to dampen the enthusiasm of the field trip participants, who included several Americans.

Joe investigated a number of Siberian kimberlites during two especially memorable international field trips organized by Nick Sobolev on behalf of the Siberian Branch of Russian Academy of Sciences, Novosibirsk, jointly with the State Diamond Company (now ALROSA). The first trip took place in July 1985 in an exceedingly remote area of northern Siberia in order to study several Mesozoic kimberlites, including the famous Obnazhennaya pipe, that were exposed in a 10-meter cliff of Precambrian dolomites along a tributary of the Olenek River. This pipe and several others were visited at the end of June and in early July, within the brief time available between arctic winters. Like Greenland, this region lies north of 70° N latitude. On July 4, at the time of a celebration observed by the entire international group of kimberlite and diamonds experts, an unpredicted, heavy snowstorm blew in and covered the tents with 20 centimeters of snow, but failed to dampen the enthusiasm of the field trip participants, who included several Americans. Fortunately, everyone was well prepared with appropriate clothing and

Figure 3. Nick Sobolev (left), Joe Boyd (center), and Russian colleagues along the Olenek River, Siberia, 1995.
(Photo courtesy Professor N. V. Sobolev.)

"Russian antifreeze" for such unseasonable weather, as is evident in photographs of the expedition (Figure 3) that show Joe and his Russian colleagues wearing warm jackets. Two days later, this severe winter weather was replaced by a heat wave that approached 30 degrees Celsius. The trip members started from Yakutsk, transported by fixed-wing aircraft to the frontier town of Zhigansk on the Arctic Circle (mid-stream of the Lena River). The field party then changed to a pair of helicopters, which carried them down the Lena River, then west to the Olenek River area, where a supporting group from Novosibirsk had prepared camp. All daily field trips involved caravanning participants in a number of rubber boats led by small motor boats about 150 kilometers down river (Figure 4). At the conclusion of the field investigations, the group was again conveyed by the helicopters to Zhigansk, and then flown back to Yakutsk.

Figure 4. Expedition to study field occurrences of diamond-bearing kimberlite pipes along the Olenek River, Siberia, 1985.
(Photo courtesy Professor N. V. Sobolev.)

The second international field trip was organized in August 1990 to visit and study the world-famous diamond mines of Mir, Udachnaya, Yubilee, and others as far north as the Arctic Circle. Living conditions were considerably more civilized, inasmuch as accommodations were in local hotels of the diamond mine towns Mirny, Udachnaya, and Aikhal. Most of the regions investigated lie farther south compared with those of the more arduous first trip. Joe was very happy to collect fresh, deep-seated xenoliths at the bottom of Udachnaya open pit, which was only 300 meters deep that time and is now about 650 meters deep. Field trips such as these are crucial because they provide a geologic reality check on laboratory experiments and theoretical calculations made in the comfort of the office.

Back in the lab

Joe continued his interest and support of laboratory experiments at the Geophysical Laboratory throughout his career. In 1990, when the Geophysical Laboratory moved from its original site at Upton Street, where it had been for eighty-five years, to co-locate with Carnegie's Department of Terrestrial Magnetism on Broad Branch Road, Joe helped design a state-of-the-art, high-pressure laboratory for the new building. During this time (1990–2001), under its director Charles Prewitt, the Geophysical Laboratory became a leading part of the Center for High Pressure Research,a Science and Technology Center supported by the National Science Foundation. Not wishing to become a part of major programs, Joe nevertheless supported the center, especially with his mentoring of staff scientist Yingwei Fei in the design and construction of a cubic-anvil, very-high-pressure apparatus. The instrument they perfected, and their laboratory as a whole, allowed scientists at the Geophysical Laboratory and its many visitors to conduct even higher pressure phase-equilibrium studies, providing data that aid in illuminating the processes of the Earth's formation and its subsequent petrochemical evolution, including that of the planet's core. Under Fei's leadership, the laboratory has also been the site of important discoveries of unusual materials formed at high pressure, such as new superhard, mesoporous, and electronic materials that may have important implications for modern technology.

Legacy

Mineralogists, petrologists, geochemists, and geophysicists are the fortunate beneficiaries of Joe's career-long field and laboratory investigations of mantle rocks. He will be remembered as one of the greatest contributors to a fuller understanding of the evolution of the Earth's upper mantle. His work on high-pressure phases of silica involved the seminal study of the quartz-coesite transition, and he played a key role in the discovery by E.C.T. Chao of the mineral stishovite, the dense, rutile-structured form of SiO_2. This phase was synthesized experimentally first by Sergé Stishov, resulting in a discovery that revolutionized our understanding of minerals of the lower mantle. (See the 1995 article by Sergé M. Stishov, "Memoir on the discovery of high-density silica," in *High Pressure Research* 13:245-280.)

Joe's pioneering field and laboratory work on the Earth's mantle spurred the development of a plethora of career paths for scientists, many of whom were and are pursuing investigations in mineral physics, mantle geophysics, diamond exploration, and solid-state physics. Equally important, research conducted by geochemists studying the isotopic and trace element constitution of the mantle has been substantially advanced due to Joe's generosity in making available to the scientific community his substantial collection of xenoliths. Over the past forty years, his original contributions have been further refined and substantiated, but never disproven, by a subsequent generation of mantle petrologists, geochemists, and geophysicists. Fulfilling Joe's wishes, his world-class collection of peridotites and eclogites is now housed and curated in the Smithsonian Institution's National Museum of Natural History, available for continued research.

To recognize Joe's contributions, the Geophysical Laboratory hosted a workshop on mantle petrology in his honor on the Broad Branch Road campus (Washington, DC, 1996) that was attended by many of his friends and colleagues. In 1999, "A Tribute to Francis R. (Joe) Boyd" was published in the Geochemical Society's *Mantle Petrology: Field Observations and High-Pressure Experimentation*, Special Publication 6, edited by Yingwei Fei, Constance M. Bertka, and Bjorn O. Mysen.

Many institutions called upon Joe to lecture on the numerous subjects for which he became especially well known. He traveled widely pursuing his investigations, and he collaborated internationally with a host of Earth scientists. Cooperative projects were undertaken globally, including, for instance, several studies in the Gondwana continental assembly (India, Brazil), the diatremes of northern Montana (Carter Hearn), and the Premier kimberlite and diamond fields of Angola (Bobby Danchin). Major collaborations included investigations with petrologists and geochemists including Nick Sobolev at the Institute of Mineralogy and Petrology, Novosibirsk, and Barry Dawson and Wes Stephens at the Department of Earth Sciences, the University of Leeds. Presented at the Fifth IKC in 1991, this latter research was co-authored with a group of international authorities on mantle petrology, geochemistry and mantle geophysics who focused on similarities and differences between the lithospheres forming the Siberian platform and the Kaapvaal craton. Not including Geophysical Laboratory annual reports, Boyd authored or co-authored more than seventy-five research papers. Perhaps even more important, he was remarkably generous in sharing information with fellow Earth scientists.

In 1974, Joe was elected to the National Academy of Sciences. Elected president of the Geological Society of Washington in 1977, he presented several lectures to that learned society over his lifetime. In 1982, he received a medal of honor from the city of Clermont-Ferrand, France, while attending the third IKC. He was elected fellow of the Mineralogical Society of America and received its highest honor, the Roebling Medal, in 2004. Boyd was also a fellow of the Geological Society of America and of the American Geophysical Union. He served first as secretary, then as president, of the Geochemical Society. Joe's presidential address to the Geochemical Society, "A pyroxene geotherm," was published in *Geochemica et Cosmochimica Acta*. As noted earlier, it was a blockbuster because it provided a method of illuminating the P-T structure of the upper mantle by utilizing phase-equilibrium relations of chemically analyzed calcic + magnesian pyroxenes and garnets.

Family life

When Joe passed away on January 13, 2004, he left two children, Duncan and Hadley, from a first marriage, and three stepchildren, Vincent, Suzanne, and Siobhan, of his second wife, Marguerite (Margo) Kingston. She is a fellow geologist and the hostess of memorable gatherings at their home in Chevy Chase, Maryland, where raw oysters professionally shucked by Joe were typically on the menu. Margo provided tremendous support for Joe, tempered with uniformly good humor, and she found time to accompany him in the global hunt for mantle rocks.

Joe was an avid gardener and a talented landscape architect. After work, he relaxed by planning, planting, and gleaning in his gardens, and most of his beautiful plantings continue to thrive to this day. He particularly liked rhododendrons and camellias. The latter had to be coaxed to withstand the cold Maryland winters. His whole family profited from the wonderful vegetables he grew, with peppers being a specialty. Traveling in Mexico, Spain, or Provence, if Joe saw an interesting pepper, he would collect it for the seeds that ended up in his garden. Like one of his mentors, George Kennedy, he also sought out and grew orchids—the more rare, the better—and he maintained indoor and outdoor spaces for their proper care during each season. When the Geophysical Laboratory was moved to its present location on Broad Branch Road, Joe found it difficult to say goodbye to the huge, proud, and graceful tulip poplar tree he had planted on the great front lawn at Upton Street. This magnificent fifty-foot tree began its life as a seedling in a paper cup presented to him by one of his children. It remains there still, as vigorous and graceful as ever.

Music was another important part of Joe's life. He particularly enjoyed opera, and he knew the genre well. His home was filled with the music of Verdi, Puccini, Mozart, and the great singing voices of the twentieth century. He and Margo never missed an opening night of the Washington Opera, and as a special treat, they occasionally went to New York City for a Metropolitan Opera production. Classical jazz was a musical favorite, as well. Joe and Margo's perfect New York trip generally included a late night visit to the 7th Avenue jazz clubs, as well as to a performance of the Met.

Joe loved art, particularly the German Expressionist movement, and he collected a few paintings, woodcuts, and lithographs. He also collected primitive art, initially pre-Columbian and African, but later he moved on to Inuit works, which he found in tiny shops in New York and San Francisco. He and Margo seldom visited any city without exploring their art museums, spending many happy hours especially in New York's many museums, but also Harvard's Fogg Art Museum and the St. Louis Museum of Art, as well as their local National Gallery of Art in Washington, DC.

Joe was a strong supporter of environmental conservation, as well as an enthusiastic and knowledgeable birder. Not an early riser, Joe nevertheless would eagerly rise at dawn to catch a glimpse of some new birds or old favorites. A pair of binoculars was usually included in his field pack for work, or for hiking vacations in Australia, Brazil, Botswana, Mexico, and Europe.

Margo and he enjoyed traveling and often tacked a few days of vacation onto the end of their scientific fieldwork. After one of Joe's trips to Siberia (the arduous Yakutsk/Olenek River trip in 1985), they met in Granada, where Margo had just finished geologic field investigations in southwestern Spain. The magnificent Alhambra and its gardens could not have been a more beautiful and peaceful place for the reunion. But, during their first meal there, Margo suggested that Joe order the excellent local specialty, the sopa de pescado, and her suggestion was met with a forceful, "No." Apparently, the major part of his diet in Siberia had been fish soup (plus mosquitos), and that experience had satisfied for life his appetite for this particular dish.

EPILOGUE

It was in the field, foraging on mine dumps for mantle samples, that Joe's former students, colleagues, and recipients of his unhesitatingly generous help cherish their memories of him. Joe will surely be recognized by Earth science historians as one of the great contributors to the development of our knowledge of the petrochemical evolution of the upper mantle. All of us who are privileged to have known this remarkable gentleman and insightful Earth scientist remain grateful for our association. We all thank him for his exemplary feedback and support, and we deeply regret his passing. Joe will forever be remembered by his family and friends as an unusually approachable, generous person; a remarkably versatile, accomplished scientist; and a warm human being.

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