Richard R. Doell

1923–2008

BIOGRAPHICAL *Memoirs*

A Biographical Memoir by
G. Brent Dalrymple

NATIONAL ACADEMY OF SCIENCES

RICHARD RAYMAN **DOELL**

June 28, 1923–March 6, 2008

Elected to the NAS, 1969

Photograph courtesy Janet Doell.

By G. Brent Dalrymple

Richard Doell was a kind and gentle man of many talents. He earned a bachelor's degree in 1952 and a doctorate in 1955, both of them in geophysics, from the University of California, Berkeley. Introduced to paleomagnetism by his mentor, John Verhoogen, Richard went on to become a pioneer in that discipline. With his close colleague Allan Cox he founded the Rock Magnetics Laboratory (RML) at the U.S. Geological Survey in Menlo Park, CA, and he published many seminal papers on geomagnetic reversals, field intensity, behavior of the non-dipole field, and rock magnetism. A veritable genius at mechanical design, Richard invented most of the new and novel equipment and techniques that were critical to the success of the RML.

Richard, Allan, and their colleague Brent Dalrymple proved conclusively that Earth's magnetic field had reversed in the past, and they determined the time scale of geomagnetic reversals for the last four million years. This time scale helped prove sea-floor spreading, which led to the theory of plate tectonics and revolutionized our knowledge of how the planet works. For his important work, Richard was elected to the NAS in 1969 and received the Vetlesen Prize in 1971.

In retirement, much of Richard's focus was on MUAV, a 38-foot sloop that he built and then cruised to many and diverse destinations, including the South Pacific, the Galapagos Islands, Alaska, the Panama Canal, the east and west coasts of the United States, Iceland, Europe, and Russia.

Early life

Richard[1] was born in Oakland, CA, to Raymond A. and Mable L. Doell, and raised in Carpenteria and Santa Barbara, CA. He graduated from high school in 1940 with a good background and aptitude in mathematics and drafting—skills that would serve him well

1 Throughout his career, Richard Doell's friends and colleagues knew him by the nickname "Dick." But during the last few decades of his life, he requested that people call him by his given name. In deference to his later wishes, I have referred to him as Richard throughout.

Richard was interviewed in 1950 for readmission to UC Berkeley by geophysics professor Perry Byerly, who examined his prior academic record and advised him that, "you have a good job; keep it."

throughout his career. Richard enrolled at UCLA but proved to be a poor student, more interested in social activities than academics. He dropped out and applied to the Navy to become an aviator, but was refused for medical reasons. In 1942, Richard was drafted into the U.S. Army and served in Europe during World War II. Discharged from the Army in November 1945, he was admitted to UC Berkeley as a physics major, but he again proved to be a poor student and left. Richard worked for a short time as a draftsman for a construction company before answering an ad by United Geophysical Company for someone with drafting ability and a bit of knowledge of physics and math.

He worked for United Geophysical for two and a half years, much of which was spent in the Persian Gulf, and he was then sent to Calgary, Canada, to measure the thickness of glacial deposits using seismic reflection methods. Although he found this particular assignment rather boring, his work with United Geophysical had kindled an interest in geology, and he decided to pursue a bachelor's degree in the subject; United Geophysical gave him a leave of absence to do so. Richard was interviewed in 1950 for readmission to UC Berkeley by geophysics professor Perry Byerly, who examined his prior academic record and advised him that, "you have a good job; keep it." Undeterred, Richard again enrolled at Berkeley and declared a major in geophysics, given that he already had completed much of the required course work.

In Richard's junior year he married Ruth Jones (1926–2013), a biochemistry student who ultimately earned her Ph.D. and enjoyed a long and successful teaching career at San Francisco State University. Richard received his B.A. in 1952 and enrolled in graduate school, at UC Berkeley, at the urging of Byerly and John Verhoogen, who had been impressed with his more recent, and outstanding, academic performance. Introduced to paleomagnetism during a seminar taught by Verhoogen that year, Richard became hooked on the subject and decided to do graduate work under Verhoogen. This was a bold and risky decision on Richard's part because it was unclear, at the time, if there was any future in paleomagnetism. Indeed, most geologists, geophysicists, and physicists were unconvinced that the study of magnetism in rocks could provide any useful information about Earth. There were, at the time, far more serious questions about paleomagnetism than answers, but Richard was undaunted and forged ahead.

Although originally a Stanford-and Berkeley-trained volcanologist, Verhoogen had become primarily a theoretician and had little interest in doing laboratory or field work. As a result, Berkeley had no lab for measuring and testing the magnetism of rocks; so Richard had to build one from scratch, and quickly. He borrowed a spinner magnetometer from the Stanolind Oil and Gas Company and, using funds from a grant to Verhoogen from the Office of Naval Research to study metamorphic rocks, he constructed an alternating-current demagnetizer to test magnetic stability. William Glen (1982) recalled that when Richard invited Verhoogen to inspect the finished laboratory, Verhoogen opened its door, briefly looked around, then turned to Richard and said, "Let's get some coffee."

Photo 2. Richard Doell (left) visited his mentor, John Verhoogen, at UC Berkeley, December 1962. (USGS photo.)

Richard's thesis was on the paleomagnetism of sedimentary rocks in the Grand Canyon Series and the Neroly Formation near Livermore, CA. For the Grand Canyon samples he found that only those from two units, the Supai Group (late Paleozoic in age) and the Hakatai Shale (Precambrian), had retained their depositional magnetism, from which ancient pole positions could be calculated. He also found that the magnetic directions determined from samples of the Neroly Formation, of Miocene age, had been acquired in the Pleistocene, well after folding had deformed the formation. Thus most of his thesis work did not result in reliable magnetic pole positions. These disappointing results most likely discouraged Richard from further work on sedimentary rocks, and from then on he focused entirely on volcanic rocks, which were much more reliable for paleomagnetic research.

It was while he was a graduate student at Berkeley that Richard met Allan Cox, a senior majoring in geology who would pursue a doctorate in geophysics under John Verhoogen too. Richard and Allan, seemingly destined to become lifelong colleagues and friends, often discussed building a paleomagnetics laboratory and conducting a research program together.

Shortly after Richard was awarded his Ph.D., in 1955, he was hired by J. Tuzo Wilson as a lecturer in geophysics at the University of Toronto, where he again built a paleomagnetics laboratory and began to develop a teaching and research program. But soon after committing himself to Toronto, Robert Shrock, chair of the Department of Geology and Geophysics at the Massachusetts Institute of Technology, offered Richard an assistant professorship there; and Shrock agreed to hold the position open for him until he finished his obligation at Toronto. Thus in the Fall of 1956 Richard moved to MIT, where he taught courses in geophysics, including a seminar on the then-heated question of geomagnetic polarity reversals.

In 1959 Richard was diagnosed with melanoma in his right leg. He underwent a surgical procedure that removed the cancerous tissue as well as all of the associated lymph nodes, but he was given little hope of living for more than a few years, if that. Preferring to be near their families, he and Ruth decided to move back to the West Coast.

Richard had taught a summer session at UC Berkeley in 1958, and while there he was briefly reunited with Allan Cox. They again ruminated about designing a paleomagnetics research program and began work on a comprehensive review of paleomagnetism intended for eventual publication. After receiving his Ph.D., in 1959, Allan was hired by James Balsley, chief of the Geophysics Branch, into a position at the U.S. Geological Survey (USGS) in Menlo Park, CA. Balsley himself had ventured into rock magnetism as part of his research, in which he used aerial magnetic surveys, and he thought that both theoretical and experimental paleomagnetism would be good areas for the USGS to pursue. Learning that Richard wanted to return to the West Coast, Allan approached Balsley with the proposal that a Cox/Doell collaboration could underpin such a USGS program. Knowing Richard and familiar with his work, Balsley readily agreed to hire him and fund the proposed joint research. Thus Richard became a USGS research geophysicist in 1959, joining Allan in Menlo Park to pursue their dream of working together.

Funding in hand, what Richard and Allan needed next was space for a laboratory. There was not sufficient space in the two principal USGS office/lab buildings at Menlo Park, but there was a little-used building that had been part of the Dibble Army Hospital for returning soldiers injured in World War II. Built during the war, the building had concrete floors, walls, and ceilings and a roof framed with 1” x 4” studs sheathed in gypsum board with a black tarpaper covering. Officially known as Building 9B on the USGS campus, this "tarpaper shack," as it became affectionately called, was perfect for the new paleomagnetics laboratory because it was made almost entirely of nonmagnetic materials, it was large, and its fate was of little concern to USGS administrators, though over the ensuing years the tarpaper shack was improved somewhat and expanded with a minimum of paperwork and expense.[2] Thus began the Rock Magnetics Laboratory (RML) at Menlo Park, with Richard as the project chief.

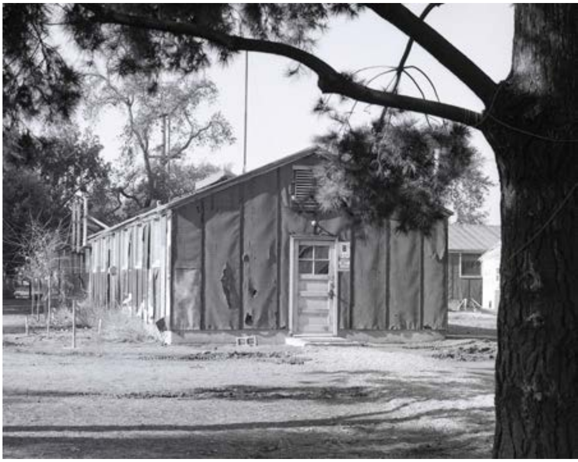

Photo 3. The RML "tarpaper shack," officially Building 9B, as it looked in 1963. The building was designated a National Historic Landmark in 1994 but demolished in 1996 after it had been thoroughly documented. (USGS photo.)

The Rock Magnetics Laboratory

Jim Balsley was generous in funding the RML. For example, he encouraged Richard and Allan to hire technicians to do routine work, and he arranged for Major Lillard, a skilled instrument maker, to transfer from Washington, DC, to Menlo Park to assist in building the necessary instruments, which Richard designed. When I joined the RML in 1963, it was a going concern with a well-defined research program, a first-rate paleomagnetics laboratory, several laboratory technicians, a well-equipped machine shop for Lillard, and an electronics technician.

While the laboratory was being built, Richard and Allan completed their review of paleomagnetism. The resulting paper (Cox and Doell 1960) was comprehensive, including thorough discussions of theory, methods, techniques, and results, as well as a table that

2 The RML tarpaper shack was put on the national register of historic places (#94001647) on October 12, 1994. It was demolished in 1996, after the building and the paleomagnetic work that went on there in the 1960s had been documented to the National Park Service's satisfaction. The new paleomagnetics lab that replaced it contains displays about the historic nature of the building and the research done within it. Numerous photos of the outside and inside, taken by the National Park Service in 1995, are archived in the U.S. Library of Congress and can be accessed at URL http://www.loc.gov./pictures/search/?q=Rock+Magnetics+Laboratory&sp=1.

contained all paleomagnetic data extant through 1959. The review became an instant classic and established their reputation as important players in the field.

Most of the paper's discussion of results concerned pole positions and their relation, or lack thereof, to continental drift. There was some discussion of reversed magnetism in rocks, which the authors attributed partly to self-reversal and partly to reversal of the geomagnetic dipole field. They also pointed out that in order to prove that field reversal had not happened, it would be necessary to show that all reversed rocks were due to self-reversal—a difficult if not impossible task. Their review concluded with a short section suggesting directions for future research in paleomagnetism but, curiously, it made no mention of geomagnetic reversals. Perhaps the authors didn't want to give anyone ideas!

During this early period, Richard and Allan also began several experiments, using volcanic rocks, designed to further test the dipole theory[3] of the geomagnetic field and investigate the secular variation (short-term pole movements) and non-dipole components (deviations from an ideal dipole field) of the field over time. Richard also developed better equipment and methods to test the stability and reliability of thermoremanent magnetism (or TRM—the component that records the geomagnetic field when the rock forms).[4] Several investigators, including Richard, had built three-axis tumblers to use in the progressive a.c. demagnetization of rocks, but such tumblers repeated the sample position much too frequently, leaving a magnetic artifact. To solve this problem, Richard designed, and Major Lillard built, a four-axis tumbler that repeated position fewer than once every 10,000 revolutions—a significant improvement.

Richard and Allan also began collecting precisely oriented cores from young volcanic rocks, over a wide geographic area, for research on reversals, secular variation, and geomagnetic field intensity. Richard focused on Iceland and the Hawaiian Islands; Allan

3 The present geomagnetic field, to a first approximation, is the same shape as if a giant bar magnet were located at Earth's center. The dipole theory postulates that it has been so for all or most of geologic time. In the 1950s, that was a working hypothesis. Paleomagnetic research has now shown it to be true, thereby allowing one to calculate a magnetic pole position from a single well-located sample anywhere on Earth. In practice, however, many samples are used.

4 TRM is acquired within a few tens of degrees below the Curie temperature(s) of the minerals in the rock, but lightning, chemical changes, and other factors can cause magnetic imprints that postdate and interfere with the TRM. In most rocks, these undesirable overprints can be erased and separated from the TRM by progressively demagnetizing the rock either in an a.c. field or thermally.

Photo 4. Richard Doell taking an oriented core from a basalt lava flow in the Hawaiian Islands, February 1967. (USGS photo.)

on Alaska, the Galapagos Islands, and Antarctica. Both of them collected from many areas in the western U.S. By the time I arrived at the USGS in 1963, there was already a fair quantity of material with which to start the isotopic dating, but the collecting continued throughout the 1960s. I had the good fortune to accompany Richard on many trips to the Hawaiian Islands, including the leeward islands of Nihoa and Necker, and to join both Richard and Allan in collecting samples from various places in the western United States. We all got along well; and those trips, which were very productive, provided opportunities to plan future research and to take a break from the more intense laboratory work.

The Rock Magnetics Laboratory during the early and mid-1960s was a gathering place for visiting geophysicists interested in paleomagnetism and rock magnetism, and Richard knew them all. They came to see recent improvements in laboratory equipment and to discuss the latest findings and ideas. Richard kept a Polaroid camera in his desk so that he could record these visits and post them on the RML office's bulletin board. This "rogues gallery" of notable visitors included Keith Runcorn, Patrick Blackett, Ken Creer, Edward Bullard (who vigorously entreated the three of us to stop varying the authorship of our papers on geomagnetic reversals because he found the lack of consistency confusing), Fred Vine, Ted Irving, Naoto Kawai, Takeshi Nagata, Seiya Uyeda, James Hall, John Graham, Thorbjorn Sigurgeirsson, Jim Heirtzler, and Neil Opdyke, to name just a few. The RML was an exciting place to work for all of us, given the pervasive sense of mission, purpose, and promise.

The reversal experiment

At the time the RML was founded, several research groups, such as Keith Runcorn and his students at Cambridge, were heavily involved in the application of paleomagnetism to the problems of continental drift and polar wandering, but the reversal question was being largely ignored. So although there were a number of research possibilities for the new lab, Richard and Allan decided to focus mainly on geomagnetic reversals. In addition, the West had no shortage of young lava flows, both on the continent and on islands in the Pacific, which were perfect for the study of reversals and other attributes of Earth's ancient magnetic field.

During the 1950s and early 1960s it was not clear whether reversed magnetism in rocks was due to reversals of the geomagnetic field or to self-reversal. On the one hand, there seemed to be periods of time when the polarity of the field, as determined by paleomagnetic data, was the same. On the other hand, several physicists, most notably Louis Néel of the National Center for Scientific Research in France, proposed mechanisms whereby rocks might be self-reversing. Néel won the Nobel Prize in physics in 1970 for his work on the magnetic properties of solids, and the geophysics community took his proposed mechanisms seriously. To compound the difficulty, in 1951 Seiya Uyeda and Takesi Nagata, of Tokyo University, found that samples of dacite pumice erupted from Haruna Volcano in the sixth century self-reversed when they were heated and then cooled in a magnetic field.

Richard and Allan were cognizant of Patrick Blackett's 1954 Weizmann Memorial Lectures in Israel, in which the Nobel laureate delineated the three possible hypotheses to explain reversely magnetized rocks: field reversal, self-reversal, or a combination of the two. Blackett also emphasized the near impossibility of performing laboratory tests that would definitely rule out self-reversal. But he was thinking primarily of the physics laboratory, while Richard and Allan decided on a more straightforward geological experiment. They proposed to sample young volcanic rocks of different ages from a wide geographic area. If the geomagnetic field had reversed in the past and self-reversal was rare, then the polarities would fall into definite time periods. If reversed magnetism were instead due to self-reversal or a combination of field reversal and self-reversal, then the polarities would show a random scatter. Martin Rutten, of the Mineralogic-Geologic Institute at Utrecht University (The Netherlands), first tried this method in 1959 using only three published data sources, but he was a paleontologist and did not have the means to proceed.

The RML was perfectly equipped to measure the magnetic polarities of volcanic rocks, but Richard and Allan had neither the expertise nor the equipment for the necessary age measurements. They initially approached Garniss Curtis and Jack Evernden at UC Berkeley, who were pioneering the application of the K-Ar isotopic technique to the dating of young volcanic rocks. However, Curtis and Evernden were fully engaged in the important work of dating the geologic time scale and the fossil hominids then being discovered in Africa, and they declined to get involved.

Enter yours truly. I first encountered Richard and Allan at an informal two-day field trip to Owens Valley, CA, organized in the summer of 1961 by King Huber, a distinguished USGS geologist. I was invited because Curtis, who also attended, was my thesis advisor, and even though I had just completed my second year at Berkeley, I already had become one of the very few who could determine the ages of young volcanic rocks using the K-Ar method. I met Richard the first evening and took an immediate liking to this knowledgeable but quiet and humble man. Allan spent several hours after dinner talking to me about the geomagnetic-reversal problem while sitting around a campfire and having a few beers. I didn't realize it then, but I was being recruited.

Over the next two days, Richard, Allan, and I discussed reversals a lot, and I was sold on the idea as a research project. I had my thesis study well underway, however, and was in no position to start something new, but we agreed to cooperate on the reversal experiment whenever possible. Our first paper, which used published data and a few suitable ages from my thesis work, was written shortly thereafter and published just before I graduated (Cox, Doell, and Dalrymple 1963a). Aside from Rutten's minimal effort, it was the very first polarity time scale using precise radiometric ages. Having only nine data points spread over the past 3.2 million years, we proposed two possible time scales, both with equal intervals of normal and reversed polarity. But not surprisingly, both were wrong.

It was Richard, at a December 1962 regional meeting of the American Geophysical Union held at Stanford University, who offered me a job working with him and Allan on reversals. At the time, we were sitting in his VW minibus in the Stanford parking lot, having just returned from lunch. I jumped at the offer and joined the RML right after receiving my Ph.D. in June 1963.

We built a K-Ar lab in a small spare room in the tarpaper shack. We bought a Reynolds-designed rare-gas mass spectrometer tube from the physics department at Berkeley, but everything else, including the electronics and magnet, had to be made from scratch. Richard and I built the tables that held the ultra-high-vacuum argon-extraction lines at night in his garage; he was a skilled woodworker and had the needed tools. In six months we were off and running, ours being the only magnetics laboratory on the planet that included an isotopic dating facility devoted entirely to paleomagnetism. The next three years were hectic and tense, but fun.

From June 1963 to May 1966, Richard, Allan, and I published a total of seven geomagnetic polarity time scales, each refining the previous one. In 1963 and 1964 we had some competition from Ian McDougall and Don Tarling of the Australian National University, but after April 1964 the stage was all ours. We discovered early on that the times of reversed and normal magnetism were not periodic at all but contained longer periods of one polarity punctuated by shorter periods of the opposite polarity. In order to avoid the confusion inherent in numbering schemes, which we initially used, in 1964 we named the features "polarity intervals" (now called "polarity chrons") after famous and deceased geophysicists who had been pioneers in the study of the magnetic field. Polarity events, which occurred within polarity intervals, were named after the localities at which they had been discovered.

By this time it was obvious that the vast majority of reversed magnetism in volcanic rocks was due to geomagnetic field reversals and that self-reversal was exceedingly rare.[5] Under Richard's leadership, we had proved conclusively that Earth's magnetic field had reversed polarity numerous times.

The most important reversal time scale, based on 62 lava flows, was published in May 1966 (Doell and Dalrymple 1966). This effort had taken three years of work—at that time, both paleomagnetic measurements and isotopic age analyses were very labor-intensive and time-consuming. Why was the 1966 time scale important? In 1962, Harry Hess of Princeton University had proposed that the sea floor was spreading outward from the mid-ocean ridges as new molten crustal material was injected there. Magnetic surveys over these oceanic ridges had revealed a series of enigmatic magnetic stripes of positive and "negative"—i.e., reversed—magnetism, a pattern never seen in the magnetic mapping of the continents. In 1963, Fred Vine and Drummond Matthews of Cambridge University suggested that these magnetic stripes recorded normal and reversed states of Earth's magnetic field as the new crust formed at the ridges and spread

5 Only a handful of self-reversing rocks have ever been found.

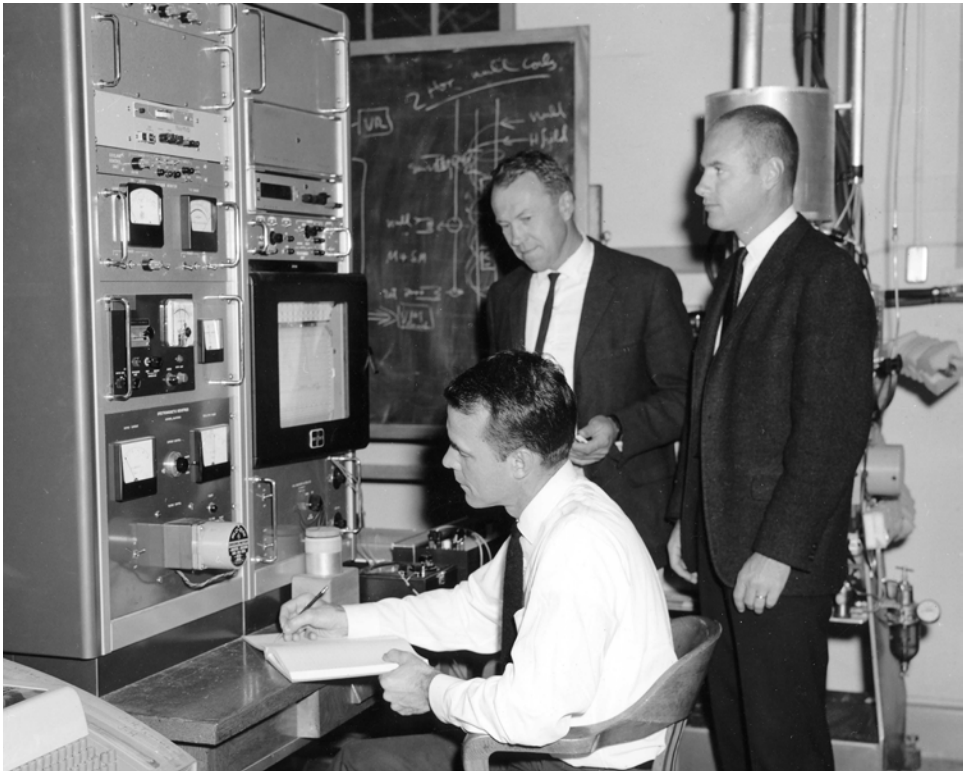

Photo 5. From left to right: Allan Cox, Richard Doell, and Brent Dalrymple, at the Curie balance in the Rock Magnetics Lab of the USGS in Menlo Park, CA, about 1965. (USGS photo courtesy of the School of Earth, Energy, and Environmental Sciences, Stanford University.)

outward on either side.[6] The problem was that the pattern of magnetic stripes did not perfectly match our quantitative land-based reversal time scale.

But the May 1966 time scale published by Richard and me fixed that inconsistency with the discovery of the Jaramillo Event, named after samples we had collected from

6 The Vine and Wilson (1963) paper was published in the September 7 issue of *Nature*. In February of that same year, Lawrence Morley, of the Geological Survey of Canada, submitted a paper to *Nature* proposing the same hypothesis, but the paper was rejected. Morley then submitted the paper to the *Journal of Geophysical Research* in April, but the paper was again rejected. The hypothesis is now sometimes called the Vine-Matthews-Morley hypothesis, but Morley was certainly ill served by the editors of these two scientific journals (Glen 1982).

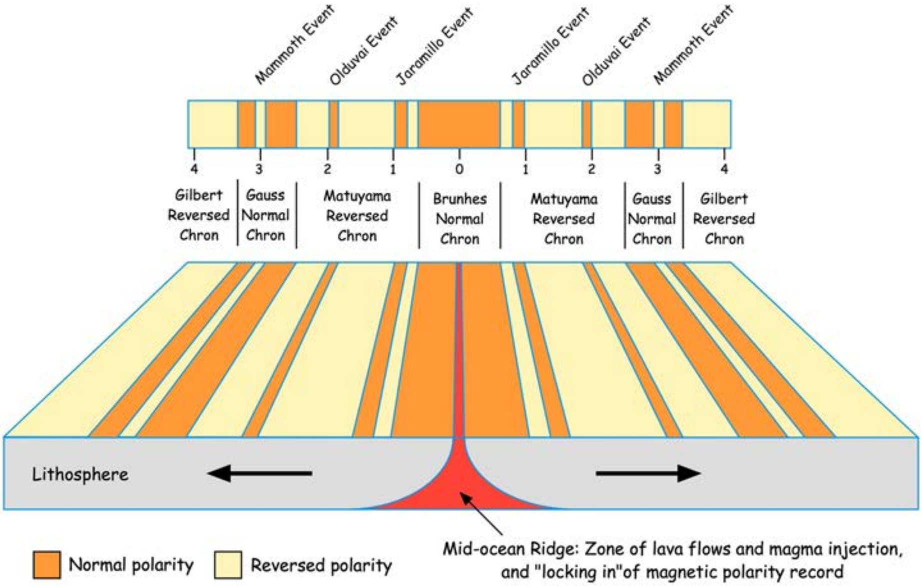

Figure 1.The geomagnetic reversal time scale as it was known after the discovery of the Jaramillo normal event by Doell and Dalrymple (1996), and its correlation with the normal and reversed magnetic stripes on the ocean floor at mid-ocean ridges. After Kious and Tilling (1996).

the Valles Caldera in New Mexico. The magnetic stripes on either side of the mid-ocean ridges exactly matched our land-based time scale, proving sea-floor spreading and leading directly to the theory of plate tectonics (Figure 1). For this reason, the geomagnetic reversal time scale has been called the Rosetta Stone of the theory of plate tectonics, which revolutionized the study of planet Earth.

Numerous versions of the reversal time scale followed, but they were only refinements and extensions. It was the 1966 scale that really tipped the balance. Glen (1982, p. 353) expressed it this way: “Had there been no potassium-argon/polarity-reversal time scale, how and when might seafloor spreading have been confirmed?”

Life after reversals

Photo 6. From left to right: Allan Cox, Richard Doell, and Keith Runcorn receiving the Vetlesen Prize from Maurice Ewing, April 8, 1971. (Photo courtesy of University Archives, Rare Book and Manuscript Library, Columbia University in the City of New York.)

Richard continued doing paleomagnetic research on reversals, secular variation, magnetic stability in rocks, and geomagnetic field intensity. In 1965 he spent a year in Paris working with Émile Thellier on ancient geomagnetic field intensity and returned to Menlo Park to build an astatic magnetometer, which is much more sensitive than a spinner but not as suitable for high sample throughput. He served as chief of the Branch of Theoretical Geophysics from 1967 to 1971. He was a NASA principal investigator for the Apollo 11–13 missions, and he designed an ingenious flux-gate magnetic gradiometer that could be sterilized for use in the vacuum chamber of the Lunar Receiving Laboratory to make initial estimates of the induced and remanent magnetism in the lunar rocks. After he returned from France, Richard and I designed and built a novel instrument to measure thermoluminescence (TL) in volcanic rocks; our hope was to use the stored energy due to radiation in order to date very young rocks, as was done with pottery artifacts, but it didn't work too well on volcanic rocks. We did use it to make TL measurements on Apollo 11 and Apollo 12 lunar soils to get some understanding of how frequently the soils had been "gardened" by meteoritic impacts.

In recognition of their many accomplishments, but primarily their work on the reversal time scale, Richard and Allan were elected to the National Academy of Sciences in 1969 and were awarded the Vetlesen Prize, which they shared with Keith Runcorn, in 1971.[7]

7 We never discussed it directly, but I had the impression that Richard and Allan were a little bit embarrassed that I had been left out of the Vetlesen Prize—a conclusion on which William Glen concurred, based on the interviews he conducted for his book (Glen 2015). But it is a fact of scientific life that big awards are rarely given to scientists at the beginning of their careers. I just had to wait.

In 1970 Richard left the RML (Allan had departed for Stanford University in 1967) and spent a year at the University of Wisconsin at Madison in an attempt to retrain for environmental work, which he considered important. He returned to the USGS and spent several years working on the cost/benefit of recycling. By then, I think, he had lost most of his drive to do science, and his contributions to environmental research were minimal. Richard was looking for something else—a larger sailboat.

One of Richard's cousins was Gary Mull, a well-known naval architect. Richard and Ruth had purchased a Santana 22—a Mull design—in the 1960s and enjoyed sailing it on San Francisco Bay and along the northern California coast. A desire to cruise more widely led Richard and Ruth to ask Mull to design for them a fast and sleek 38-foot sloop, to be named MUAV, after the Muav limestone in the Grand Canyon. Their plan was to have the hull and deck built professionally and for Richard to finish it. While the hull was being built at a boatyard in Redwood City, Richard and I would hop on our motorcycles at least once a week, ride a few miles up the freeway to check on progress, and then have lunch at the nearby marina. The hull and deck were finished in 1974, moved to a boatyard in Half Moon Bay near where the Doells lived, and Richard began the lengthy task of finishing the sloop. This increased my ride considerably, but I managed to visit Richard and MUAV every few weeks. We both looked forward to those visits and to abalone sandwiches at a restaurant nearby.

In 1978 Richard retired from the USGS to finish MUAV, and she was launched that same year. MUAV was a beauty, inside and out, and a fine display of Richard's craftsmanship and attention to detail. The inaugural long-distance cruise, also in 1978, with his daughter Kerstin was to Hawaii, Sitka, Glacier Bay, and back to San Francisco.

Richard and Ruth had divorced in 1975 and separated permanently in 1978. In 1984, he married Janet Hoare, the widow of a USGS geologist and someone whom Richard had known for decades. Janet immediately began to learn to sail and became a vital member of MUAV's crew, aboard for all subsequent voyages. Together with friends or Richard's daughter Shirley, they sailed to Alaska and French Polynesia; and in 1988 they departed for an ambitious four-year voyage to Europe, visiting 23 countries. The unusual route included a detour to the Galapagos Islands, through the Panama Canal, up the East Coast of North America, north around Iceland, through the North Sea, and east into the Baltic in the summer of 1990. MUAV was the first private US-registered yacht to enter St. Petersburg (then Leningrad) during the last days of the Soviet Union.

Janet was an amateur lichenologist, and she shared with Richard an appreciation of lichens much as he shared with her his love of sailing. In 1987, wanting to come up to speed quickly, he took a course in lichenology at San Francisco State University. Richard and Janet were founding members of the California Lichen Society in 1994, and together they wrote two miniguides to California lichens, published by the society. Richard had always been an avid photographer, so Janet wrote the text and Richard took the photos. He was also the producer of the Society's bulletin for six years.

After thoroughly enjoying 30 years in retirement, Richard died in his sleep at his home in Point Richmond, CA, on March 6, 2008, after several serious illnesses.

Some personal observations

Over the years, Richard, Allan, and I were repeatedly asked if any of us realized from the start how important the reversal time scale would be. The answer is no. We thought that solving the field reversal/self-reversal conundrum was exciting enough, and that if the geomagnetic field had reversed, then a time scale of the reversals might prove useful to Pleistocene stratigraphy. It was shortly after the 1963 Vine and Matthews paper, suggesting that the sea floor magnetic stripes were caused by reversals of the geomagnetic field, that the three of us simultaneously had an "aha" moment. When everything—reversals recorded in terrestrial lava flows, oceanic sediment cores, and magnetic stripes on the ocean floors due to sea-floor spreading, transform faults, oceanic trenches, lithospheric plates, and Eulerian geometry on a sphere—was integrated in the theory of plate tectonics in 1968, we didn't have to be convinced.

Richard was a superb designer and craftsman, comfortable at the drafting table, in the machine shop, and with woodworking tools. Whether it was elegant furniture for his house, innovative instruments for the laboratory, or practical and beautiful fittings for his yacht, everything he designed and made was functional without compromise, and a thing of beauty. Much of his physical legacy is still admired and in use every day.

Richard had many admirable qualities, but his modesty was particularly notable. He rarely, if ever, called attention to his accomplishments unless asked, and then usually minimized them. A glance at his bibliography shows that he was not first author as frequently as one might suppose. This is not because he didn't take the lead in the scientific work or because he couldn't write well—he was actually quite a good writer—but because he cared little about "first authorship," and if he could talk either Allan (usually) or me (sometimes) into doing most of the writing, all the better. Richard much preferred to be doing the fun stuff—i.e., designing and testing equipment, and doing scientific experiments. Credit was near the bottom of his priority list.

Richard was a mentor, colleague, and good friend for many years, and he was one of the most even-tempered and kindest individuals I have ever known. I don't recall ever seeing him really angry with anyone or anything, and I never heard him raise his voice to anyone. Very little disturbed him outwardly. He and I spend many weeks drilling cores and sampling on tropical islands and elsewhere, sometimes camping in heat and humidity. He took it all in stride and could usually find something amusing in any unusual situation. One example was our new red tent that was turned completely white by bird droppings within two days on Nihoa Island. That gave us both a good laugh. As a result of having no lymph nodes in his leg, he had always to wear a heavy, full-length compression stocking during the daytime. I know it was uncomfortable, particularly in the heat and humidity, but I never heard him complain.

I once asked him about his thoughts and emotions when he found out in the late 1950s that he had cancer and might not live long. His reply was typical Richard: "You suck it up and carry on. There's no point in getting frantic and emotional about it." Fortunately, he lived a long and productive life. He is greatly missed by all those whose lives he touched and enriched.

ACKNOWLEDGMENTS

William Glen (1982) wrote an excellent book on the discovery of the geomagnetic reversal time scale and its importance to the theory of plate tectonics. This book includes considerable information about the life and career of Richard and his colleagues, and I have relied heavily on Glen's scholarship.

I also thank Edward Mankinen, Jack Hillhouse, Kerstin Doell, and Shirley Doell for their thoughtful reviews, which added information I did not have and improved the manuscript considerably.

REFERENCES

Glen, W. 2015. Personal (written) communication to the author.

Glen, W. 1982. *The road to Jaramillo: Critical years of the revolution in earth science.* Stanford, CA: Stanford University Press.

Kious, W. J., and R. I. Tilling. 1996. *This dynamic Earth: The story of plate tectonics.* Washington, DC: US Government Printing Office.

Vine, F. J., and D. H. Matthews. 1963. Magnetic anomalies over ocean ridges. *Nature* 199:947–949.

SELECTED BIBLIOGRAPHY

1957 Crystallization magnetization. *Phil. Mag. Suppl.* 6:327–332.

1960 With A. Cox. Review of paleomagnetism. *Geol. Soc. Amer. Bull.* 71:645–768.

1961 With A. Cox. Paleomagnetic evidence relevant to a change in the Earth's radius. *Nature* 189:45–47.

Paleomagnetism. In *Advances in geophysics.* 8:221–313. New York: Academic Press.

1963 a. With A. Cox and G. B. Dalrymple. Geomagnetic polarity epochs and Pleistocene geochronometry. *Nature* 198:1049–1051.

b. With A. Cox and G. B. Dalrymple. Radiometric dating of geomagnetic field reversals. *Science* 140:1021–1023.

c. With A. Cox and G. B. Dalrymple. Geomagnetic polarity epochs—Sierra Nevada II. *Science* 142:382–385.

With A. Cox. The accuracy of the paleomagnetic method as evaluated from historic Hawaiian lava flows. *Jour. Geophys. Res.* 68:1997–2009.

1964 With A. Cox. Long period variations of the geomagnetic field. *Seismol. Soc. Amer. Bull.* 54B(6):2243–2270.

With A. Cox and G. B. Dalrymple. Reversals of the Earth's magnetic field. *Science* 144:1537–1543.

1965 With G. B. Dalrymple and A. Cox. Potassium-argon age and paleomagnetism of the Bishop Tuff, California. *Geol. Soc. Amer. Bull.* 76:665–673.

With A. Cox. Measurement of the remanent magnetization of igneous rocks. *U. S. Geol. Surv. Bull.* 1203A:1–32.

With A. Cox. Paleomagnetism of Hawaiian lava flows. *Jour. Geophys Res.* 70: 3377–3405.

1966 With G. B. Dalrymple. Geomagnetic polarity epochs: A new polarity event and the age of the Brunhes-Matuyama boundary. *Science* 152:1060–1061.

With G. B. Dalrymple and A. Cox. Geomagnetic polarity epochs: Sierra Nevada data 3. *Jour. Geophys. Res.* 71:531–541.

1967 With A. Cox. A spinner magnetometer for igneous rocks. In *Methods in paleomagnetism*. Edited by D. W. Collinson, K. M. Creer, and S. K. Runcorn. pp. 136-141. Amsterdam: Elsevier.

With A. Cox. Analysis of alternating field demagnetization equipment. In *Methods in paleomagnetism*. Edited by D. W. Collinson, K. M. Creer, and S. K. Runcorn. pp.241-253. Amsterdam: Elsevier.

With G. B. Dalrymple and A. Cox. Reversals of the Earth's magnetic field. *Sci. Amer.* 216:44–54.

1968 With A. Cox and G. B. Dalrymple. Radiometric time scale for geomagnetic reversals. *Geol. Soc. London Quart. Jour.* 124(493):53–66.

With G. B. Dalrymple, R. L. Smith, and R. A. Bailey. Paleomagnetism, potassium-argon ages, and geology of the rhyolitic and associated rocks of the Valles Caldera, New Mexico. In *Studies in volcanology: A Memoir in honor of Howell Williams*. Edited by R. R. Coats, R. L. Hay, and C. A. Anderson. *Geol. Soc. Amer. Mem*. 116:211–248.

1970 With G. B. Dalrymple. Thermoluminescence of lunar samples from Apollo 11. *Geochim. et Cosmochim. Acta Suppl. I.* 3:2081–2092.

1972 Paleomagnetism of volcanic rocks from Niihau, Nihoa, and Necker Islands, Hawaii. *Jour. Geophys. Res.* 77:3725–3730.

1973 With G. B. Dalrymple. Potassium-argon age and paleomagnetism of the Waianae and Koolau Volcanic Series, Oahu, Hawaii. *Geol. Soc. Amer. Bull.* 84:1217–1242.