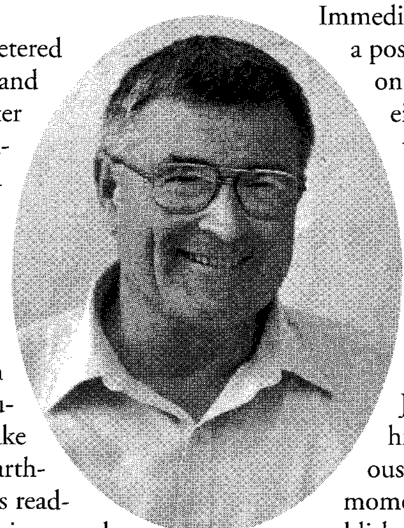
## Jerry P. Eaton (1926–2004)



Jerry P. Eaton, the legendary pioneer of telemetered seismic networks for monitoring volcanoes and active earthquake faults, died 2 April 2004 after a long battle with cancer. His friends and colleagues knew Jerry as a dedicated scientist and resourceful inventor who was unfailingly generous in providing help and encouragement to younger scientists.

Jerry's impact on seismology, volcanology, and the programs of the U.S. Geological Survey (USGS) was enormous. More than anyone else, his pioneering vision of instrumental networks advanced microearthquake seismology to the forefront in studies of earthquake tectonics and volcanology. Through his reading knowledge of French, German, Russian, and Spanish, he was familiar with seismological research published in these languages as well as that published in English. His knowledge of early seismology papers was encyclopedic, and he could recall details of observations he had made a half-century ago. Less than a week before his death, he was at his workstation in his office at the USGS, Menlo Park, timing earthquakes, as he had done virtually every day since his retirement in 1995.

### Background and Education

Jerry was born on 11 December 1926 on a Central Valley farm near Fresno, California. When Jerry was about five years old, his father responded to the bad economic times by building a well rig from salvaged materials and moving it and his family to Woodland, near Sacramento, where he eked out a living drilling water wells. Jerry's mother, a former school teacher, was the bookkeeper for the business. On occasion, Jerry would tell his colleagues of his early life in the farming area, a time when he and his brothers learned to be self-reliant in solving problems as they arose.

Jerry attended the University of California at Berkeley, earning a B.A. with honors in physics (1949) and a Ph.D. in geophysics (1953). An early indication of his ability and resourcefulness was that he completed his Ph.D. thesis while his professor, Perry Byerly, was on sabbatical leave. At Berkeley, Jerry met his wife Nancy, a fellow student studying zoology. Nancy remarked later that, "We were both kind of shy people, and we just fit perfectly." They have four children: Marian, Jeffrey, Dana, and Carol.

### At the Hawaiian Volcano Observatory (HVO)

Immediately after receiving his Ph.D., Jerry accepted a position with USGS and was stationed at HVO on the island of Hawaii, where he spent the next eight years developing the modern science of volcano monitoring. He designed and installed a telemetered, electronic seismic network that improved earthquake detection by a hundredfold and location accuracy to more than mere guesswork on the island of Hawaii, as compared to the previous methods of analyzing seismic data from mechanical seismographs. As T. Asada in Japan and P. G. Gane in South Africa before him, Jerry realized that to capture the numerous, smaller earthquakes, a dense array of seismometers of high magnification was required. To establish a common timing reference for individual seismometers in the 1950's, signals from these seismometers in the field had to be telemetered to a central recording site.

At this time seismic equipment was quite costly, so Jerry and a machinist at HVO built their own seismometers, amplifiers, recorders, and timing systems. Jerry was able to raise the peak magnification to 40,000 at 5 Hz, an order of magnitude higher than other recording systems available at that time. Because radio telemetry was still in its infancy, Jerry solved the telemetry problem by laying out miles of wires, which he obtained free as military surplus. Because these wires had been previously used, relatively short lengths of them first had to be stretched out and spliced together. Jerry then laid them out by hand in rough volcanic terrain to relay seismic signals from the seismometers in the field to HVO headquarters.

Jerry developed methods for calibrating the seismometers with Perry Byerly and for locating the earthquakes, which sometimes occur at Kilauea and Mauna Loa by the hundreds per day. He soon defined the primary regions where earthquakes occur throughout the island of Hawaii, outlined the basic plumbing system of Kilauea volcano, and, based on travel times of seismic waves, showed that the crust bends downward under the island, apparently due to the load of the volcanic pile.

In addition, Jerry recognized the importance of ongoing ground-surface deformation associated with the slow inflation of Kilauea Volcano's summit region between eruptions and its rapid deflation during flank eruptions. To document these inflation/deflation episodes accurately, he designed, built, and deployed a network of water-tube tiltmeters around the summit of Kilauea that are sensitive to changes of 0.3 microradians. To ensure the uniformity of environmental conditions under which the measurements were taken, Jerry and his colleagues took their readings late at night, often in pouring rain.

In 1960, Eaton and Murata published a classic paper describing how Kilauea Volcano works: Magma from 50 to 60 km depth is fed to a shallow magma reservoir. When the magma pressure in this reservoir exceeds the strength of the volcano, a fracture breaks upward to feed a summit intrusion or eruption, or sideways to feed a flank intrusion or eruption. This conclusion was based on eight years of study on earthquakes, deformation, and the eruptive behavior of the volcano, including close monitoring of a major eruption in 1959. The model presented in Eaton and Murata continues to play a central role in the study and understanding of volcanism in Hawaii. Jerry set a standard for volcano monitoring that has been followed and refined by volcanologists worldwide. He also became a skillful photographer. The films and slides taken by Jerry and his HVO colleagues to document the course of the 1954–1955 and 1959–1960 Kilauea eruptions are still among the best shown today.

Jerry left many handwritten notes concerning seismic and tilt data processing that were used in daily operations at HVO for many years after he left Hawaii. In addition to his volcano research, Jerry also addressed the tsunami hazard in Hawaii. He and his colleagues witnessed the destruction of a large part of Hilo, Hawaii by the tsunami generated by the great 1960 Chilean earthquake. They were particularly distressed by the deaths of more than 60 people in Hilo, because timely interpretation of widely available seismic and wave-height data and implementation of simple but effective protective measures could have saved them. Subsequently, long-period seismographs were installed and an effective tsunami warning program has since been in operation.

Although he left Hawaii in 1961, Jerry maintained an active interest in volcanology throughout his career. In 1987, he and colleagues (Don Richter and Harold Krivoy) published a new paper on the cycling of magma between Kilauea's summit reservoir and the Kilauea Iki lava lake based on data they had collected during the 1959 Kilauea eruption. It was published in a collection that marked the 75th anniversary of the founding of the Hawaii Volcano Observatory.

### At USGS, Denver

In 1961, Jerry Eaton joined the USGS Crustal Studies Branch in Denver, Colorado led by Lou Pakiser. There he contributed to the development of new, long-range, seismic refraction instrumentation and took the lead in running a seismic-refraction profile from the Bay Area across the Sierra Nevada into central Nevada. His analysis of that profile provided clear evidence for the existence of an asymmetrical crustal root that extends to at least 50 km beneath the high crest of the range.

Mindful of the severe earthquake threat posed by the San Andreas Fault system, Jerry was an articulate opponent of siting a nuclear power plant on the California coast about 2 km from the 1906 fault rupture. In evaluating the hazard to a proposed plant 75 km north of San Francisco, he argued, "Acceptance of Bodega Head as a safe reactor site will establish a precedent that will make it exceedingly difficult to reject any proposed future site on the grounds of extreme earthquake risk." In a preface to his review, Jerry eloquently stated the delicate relationship between scientists and engineers engaged in the siting and design of critical facilities. Although humbly honest in his assessment of the state of scientific knowledge, Jerry did not shrink from offering his best scientific "judgment" to safeguard the public from harm.

### At USGS, Menlo Park

In 1965, following the great Alaskan earthquake of 1964, Jerry moved to Menlo Park, California, where he became a key player in the group led by Lou Pakiser that laid the groundwork for establishing the USGS' National Center for Earthquake Research (NCER) and the National Earthquake Hazards Reduction Program (NEHRP). Jerry's greatest contributions stem from his conviction that measurements of signals from the Earth's crust are best done with many instruments of acceptable quality, rather than a few instruments of outstanding quality, as are typically used to study the Earth's interior. He continually promoted the development of better and cheaper seismic instruments, always mindful of the scientific objectives and of the need for careful calibration in order to advance the understanding of Earth processes. The importance of dense networks of instruments is widely understood today, but Jerry was the first person to see their importance and to deploy them within a limited budget. In this way, he set the foundation in the 1960's for subsequent evolution of techniques and instrumentation for studies of local seismicity, regional strain, and seismic refraction applied to studies of crustal structure.

Jerry's classic study of the aftershocks of the Parkfield earthquake of 1966 was a startling demonstration of the value of dense networks. Applying his HYPOLAYR earthquake location program to the Parkfield data, he demonstrated the power of high-precision studies of microearthquake locations and established definitively that earthquakes occur on faults. By precisely locating the aftershocks, Jerry Eaton, M. E. O'Neill, and J. N. Murdock showed that the slippage had occurred along a 30-km segment of the near-vertical fault to a depth of 12 km. This study led the way to identifying seismic gaps along strike-slip faults and other key concepts at the center of studies of earthquake hazards today. His study of the 1983 Coalinga earthquake demonstrated the existence of a shallow, blind thrust fault within the predominantly strike-slip environment near the San Andreas Fault.

### Real-time Seismology

In the early days of NCER, the research staff ate lunch together every Friday. One day in 1968, Lou Pakiser, head of NCER, read a memo from an assistant to the President of the United States to the Director of the USGS inquiring how long it would take to detect and locate an earthquake. Rapid detection of nuclear explosions was then a national issue because

China had become the fifth country possessing nuclear bombs in 1964. Jerry suggested that the reply should be one minute, although at that time, a routine earthquake location took more than one hour. A few weeks later, the same Presidential assistant ordered that this capability be demonstrated. At that time most of the staff favored an analog electronic circuit approach for the demonstration, using the signals telemetered from the local seismic clusters that had just been installed. Willie Lee proposed that it might also be possible to use a computer simulation to produce the demonstration. Pakiser cautiously decided to pursue both approaches. He instructed Willie to visit Jerry at Stanford University Hospital, where he was recovering from a back operation.

Although confined to his bed and in obvious pain, Jerry outlined a scheme for doing real-time earthquake detection and location. Using the IBM 360-67 mainframe computer at Stanford University, Willie quickly wrote a computer program demonstrating that Jerry's scheme worked and that an earthquake could indeed be detected and located about 30 seconds after its occurrence inside a local seismic network. Soon thereafter, Sam Stewart joined in the effort. The three of them wrote an unpublished report to the Defense Advanced Research Projects Agency and obtained funding to implement a real-time seismic system for local networks using a CDC 1700 mini computer.

It would be hard to find three more different personalities than Eaton, Lee, and Stewart, but they managed to work together in 1968–1969. Jerry's vision and optimism, Willie's experience from having worked in a computer center, and Sam's meticulousness and perseverance all contributed to the success of the project that ushered in the era of real-time seismology.

### Jerry Eaton's Calnet

Jerry frequently stressed the importance of observing Earth processes at their noise levels, of making continuous recordings, and of systematically cataloguing earthquakes and volcanic phenomena. His goal for NCER was not just to study choice parts of the San Andreas Fault, but rather to monitor the system as a whole. To do so, he not only had to create a modern, regional seismic network (with Wayne Jackson, Willie Lee, John Roller, Sam Stewart, Jack Van Schaack, and many others) by using telephone and radio telemetry to carry signals from many remote stations to a central site for recording and analysis, but also had to find the funds to underwrite it. Beginning with the first two clusters of about eight stations each in 1967, Calnet grew outward from its initial South Bay and Hollister regions to cover all of California by 1986. As it grew, Jerry made many largely unsung contributions to the high instrumentation standards that the network maintained. Jerry also had the foresight and patience to back the development of the automatic seismic processing systems that we sometimes take for granted today. Jerry summarized his vision and contributions to local seismic networks in his memoir.

Jerry's many scientific contributions include studies of numerous important California earthquakes, including Kern County, Parkfield, Coalinga, Morgan Hill, and Eureka, to name some notable ones. In all of these papers his goal was to use seismicity to elucidate tectonic processes by revealing the structural elements, crustal structure, and stress fields. One of Jerry's contributions was his refinement of duration and amplitude magnitude scales for short-period stations operating in Northern California. This development provides the magnitude of reference for tens of thousands of earthquakes smaller than $M_w$ 3.5 that occur annually and allows seismologists to investigate the statistical properties of earthquake occurrence.

Jerry also contributed greatly to the careers of a generation of young scientists who worked at USGS in Menlo Park. Whether they were postdocs, new staff, students, or short-term visitors, he was ever eager to hear their ideas and encourage them. He also helped set the standard for sharing of seismic data, which today we take for granted.

### A Career of Leadership

Besides his extraordinary personal contributions to understanding the structure and dynamics of the Earth's crust, Jerry also held important leadership positions in which he coordinated the efforts of many investigators. He was the Scientist in Charge of the Hawaiian Volcano Observatory (1955–1958, 1960, 1961), Chief of the Office of Earthquake Research and Crustal Studies (1971–1973), Chief of the Branch of Seismology (1973–1975), and Acting Chief of Branch of Network Operations (1978–1982). He played a major role over many years in defining and defending the National Earthquake Hazards Reduction Program and its predecessors.

Jerry was a Fellow of the American Geophysical Union, President of the Seismological Society of America (1966), a member of the California Governor's Earthquake Prediction Evaluation Committee (1972–1992), and Chairman of the Earthquake Prediction Commission of the International Association of Seismology and Physics of the Earth's Interior (1975–1979).

Jerry Eaton was truly a pioneer, for he went where there was no path. He left a trail for others to follow and encouraged many colleagues to excel. He was a dedicated scientist and a wonderful colleague, and he leaves a rich legacy for future generations of seismologists.

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