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DAVID TRESSEL GRIGGS

1911—1974

A Biographical Memoir by

IVAN A. GETTING AND JOHN M. CHRISTIE

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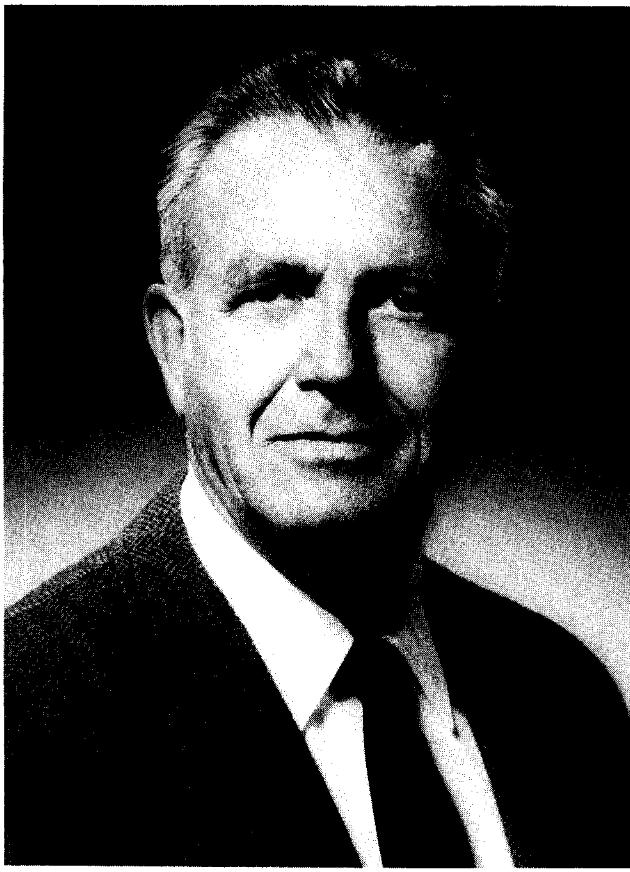
Biographical Memoir



David T. Griggs

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October 6, 1911–December 31, 1974

BY IVAN A. GETTING AND JOHN M. CHRISTIE

LIKE MANY CONTEMPORARY scientists, David T. Griggs became enmeshed in a dual career: (1) scientific research and teaching in the field of geophysics and (2) the application of science to national defense.

David Griggs was born October 6, 1911, in Columbus, Ohio, the son of Robert Fiske Griggs and Laura Amelia Tressel Griggs. The ancestors of both parents derived from English immigrants who came to America prior to the American Revolution.[1] Robert stemmed from a long line of Congregationalists and Quakers; Laura was from a Methodist and Lutheran line—in fact, her father had been a minister. David had a younger brother and two sisters.[2] His parental home was a citadel of Christian values, based on love, fidelity, and truth.

While his early childhood was spent in Ohio, Dave's high school days were spent in Washington, D.C., where his father had become the first professor of botany at the George Washington University. In the early part of the twentieth century, botany in the United States had not reached a high scientific level, and Dave's father was instrumental in bringing it into the science realm. His research included expeditions to Puerto Rico, Guatemala, Texas, and Alaska. It was during one of these expeditions to Alaska, in 1916, supported by the National Geographic Society, that near Mount Katmai he discovered the Valley of Ten Thousand Smokes. The highest mountain in the area was subsequently officially named Mount Griggs.

It was natural for Dave to spend his first year of college (1928–29) at the George Washington University. His interests were in things mechanical and in physics. His next three years of undergraduate work were at Ohio State University (1929–32). In the summer of 1930 he persuaded his father to take him on one of his expeditions to the Valley of Ten Thousand Smokes. "This Alaskan experience and the encouragement he received from a gifted and enthusiastic teacher, Professor Edmund M. Spieker, led him to choose for his life work the application of physics to the problems of the earth."[3]

Before going on to a year of graduate work at Ohio State, Dave was elected to Phi Beta Kappa, the Mathematics Honor Society, and Sigma Xi. The next year (1933), he served as an assistant in the Geology Department at Harvard, and the following year he was appointed a junior fellow of the recently created Society of Fellows.

The Society of Fellows at Harvard University began operating in 1933, just one year before Dave's appointment. "The concept of the Society was largely the creation of two men: Lawrence Joseph Henderson, then professor of biological chemistry, and Abbott Lawrence Lowell of the old Boston family, president of Harvard. They sought a solution to the problem of advanced studies and research opportunities for young men at the university without the often debilitating requirements of formally proceeding to a doctor's degree."[4] Dave was reappointed after the first term of three years and served the following two years until he was called to support the war effort against Nazi Germany. Among his colleagues in the society were to be found many scholars who continued to distinguish themselves in later years: James Baker, renowned astronomer and optical designer; John Bardeen, twice Nobel prize winner in physics (transistors and theory of superconductivity); James Fisk, president of Bell Telephone Laboratories; Henry Guerlac, historian of science; Paul Samuelson, Nobel prize winner in economics; Stanislaw Ulam, mathematician and coinventor of the hydrogen bomb; Robert Woodward, chemist and Nobel prize winner (synthesis of quinine); Willard Van Quine, mathematical logician; Fred Skinner, psychologist; Garrett Birkhoff, mathematician; E. Bright Wilson, chemist; and others.[5] Dave Griggs's scientific contributions to geophysics during his tenure as a junior fellow are described in the next section—but here a few words about Dave as a person.

A single junior fellow was assigned to one of the houses where he lived with resident students and dined with distinguished faculty members who were also assigned to houses as tutors. Thus, Dave Griggs and one of the authors (I.A.G.) were assigned to Leverett House. There were four suites on each floor, and Dave and I found ourselves neighbors. While Dave's principal experimental research work was done at the Jefferson Physical Laboratory (his laboratory was flanked by Professor Bridgman's laboratory on one side and my laboratory on the other), his living room at Leverett House was always crammed with experiments: long-term deformation (creep) of rocks under applied loads, mountain-building models, and related experiments. Every opportunity that offered itself for mountain climbing (or skiing for that matter) was seized. Another resident on "our floor" was Agnew Bahnson, a well-to-do (by our standards) student who owned a Buick roadster. In the summer of 1936, Agnew and Dave set out to go mountain climbing in the Caucasus Mountains, a mountain chain linking the Caspian Sea and the Black Sea—a new range to climb and study. The trip is worth mentioning in this biography because it tells a lot about Dave and because the accompanying events had a profound impact on the rest of his life.

> The road stretches straight ahead, a long ribbon of concrete, the artery of the North Hungarian plain. We are heading eastward to Bucharest, Odessa, Tiflis, and the mysteries of the Caucasus. We stretch out to make up some of the time we have lost. The cyclist appears from nowhere, immediately ahead of us. Bon (Agnew) swings the wheel quick as light for the bare chance that we can swerve enough to miss him. We almost miss him and then I see the tree looming up. There is nothing more—all is quiet. Bon is no longer in the seat beside me. I see him stretched out in the middle of the road beside the car. Then I became conscious of a searing pain in my legs. They are caught between the seat and the radio as the body of the car telescoped. I can't even move my feet. Then I see the blood everywhere. No wonder I can't move them. My legs are like sacks of flour. Those legs that served so well going up the Matterhorn only a few weeks ago—are they no longer mine?[6]

After many delays and hardships, Dave and Agnew were transported to Budapest. Agnew had brain concussions and hemorrhages from which he fully recovered. Dave had compound fractures in both legs, the left knee was dislocated, and he had serious lacerations on both elbows. The Budapest surgeons recommended amputation. Dave would not accept the advice. He was moved to Vienna, where the same recommendations were repeated. Finally, his mother, Laura, brought him back to the United States on the *Queen Mary.* Dr. Smith-Peterson, at the Massachusetts General Hospital, performed innumerable operations, and much time elapsed. Dave's indomitable spirit prevailed, and in a few years he was not only walking but skiing in the mountains he loved so much. These characteristics of courage, faith, and endurance were his hallmark. To these must be added a disregard for personal risks. Nevertheless, when the United States entered World War II, Dave was found physically unfit to serve his country in uniform!

The automobile accident had another critical impact on Dave's career. Agnew's father had carried special insurance because of the hazardous nature of the contemplated trip to the Caucasus in the southern USSR. The insurance company awarded $15,000 to Dave as compensation for his suffering. With this money he purchased a Luscumbe airplane and became a pilot. So while at first he could not climb his mountains, now he could fly around and over them. And it was this situation that brought Dave, as pilot and owner of the Luscumbe, into the war effort.

As a junior fellow at Harvard, Dave adapted high-pressure techniques developed by Nobel laureate Percy Bridgman and began his systematic experimental studies of the mechanical properties of rocks and the effects of environmental factors, such as increased pressure and the presence of fluids, on the mechanics of deformation of mineral crystals and rocks. He designed and built new apparatus for long "creep" experiments at room temperature and pressure and in the presence of fluids. He improved apparatus for deformation experiments at high pressures, of the type pioneered by Th. von Karman (1911). He also devised ingenious scale models to investigate the possibility that mountain-building processes might be driven by thermal convection currents in the solid but deformable rocks of the earth's mantle ("substratum"), as was advocated by Arthur Holmes, C. L. Pekeris, F. A. Vening Meinesz, and H. H. Hess.

About a dozen important papers published between 1934 and 1941 established the relevance of experimental rock deformation and scale model studies in geology and geophysics. Most notable among these were Dave's papers on the creep of rocks, which provided a remarkably modern insight into the physics of slow deformations and of the effects of confining pressure, stress, time, and the presence of solutions on the solid-state flow of rocks. In his paper, "A Theory of Mountain-Building" (1939), Dave argued, on the basis of his experimental data and scale models, that thermal convection currents in the earth's mantle were responsible for the distribution, structure, and periodicity of mountain-building episodes in the earth's crust. This was a very controversial idea at the time, opposed vigorously by Harold Jeffreys and other geophysicists. The development of the unifying theory of plate tectonics in the 1960s has shown that Dave's visionary model was well conceived in principle, if not in detail, and has certainly vindicated his position in the controversy with advocates of a "strong" earth. This very fruitful period of research was terminated in 1941 when Dave left Harvard to apply his effort fully to national defense.

Dave Griggs's contributions to national defense in World War II were manifold: first at the MIT Radiation Laboratory and then as expert consultant to the Secretary of War. The Radiation Laboratory at MIT was established by the National Defense Research Committee (NDRC) in the fall of 1940 to develop microwave radar. One of the three start-up programs was the demonstration of automatic radar tracking of airplanes. If such a capability could be demonstrated and then put into production, it would be possible to fire at enemy airplanes, day and night, in clouds or clear weather. The development of such a capability required the use of airborne targets. However, in 1940 the Army Air Corps had no planes to spare for experiments, and there were then no commercial flights of opportunity. In addition, attempts to use hydrogen-filled balloons had ended in near disaster. "I then remembered my best friend, Dave Griggs, from the Society of Fellows. So Dave was cleared for access to radar and for ten dollars an hour flew his plane over Boston and Cambridge as a target for our tracking experiments."[4]

Dave became immersed in the possible contributions of radar in air warfare, and in June 1941 took leave from Harvard to join the staff of the Radiation Laboratory. Automatic radar tracking turned out to be practical indeed. The first application was to ground-based anti-aircraft fire, and the resulting system became known as the SCR-584. Because of Dave's special interest in aircraft, he was appointed program manager of the airborne version, which went into production as the AGL-1. Dave's penetrating mind plus his insatiable drive impelled him to participate in the larger framework of the war as seen from the Office of the Secretary of War.

Having established a firm understanding of all the systems at the Radiation Laboratory, he transferred in July 1942 to Washington as an expert consultant to the Secretary of War—operating through a special office that had been established by Secretary Stimson under the leadership of Edward Bowles. Dave's assignment from Dr. Bowles was to do whatever was necessary to further the introduction and effect the most efficient use of radar in the war against the enemies of the United States.

He applied himself wholeheartedly to the end of the war, November 1945, starting in the European War and transferring to the Pacific as the tides of war demanded. Dave spent most of his time with the operational commands, at first with the Strategic Air Forces in Europe. While working directly with the commanders, such as General Pete Quesada, Jimmie Doolittle, and Tooey Spatz, he flew both training and combat missions introducing airborne bombing radar systems. In one flight over Bremen, the bomb-bay doors stuck. With usual disregard for his own safety, Dave kicked them open and in the process fell through the doors as they suddenly let go. He caught himself with one hand and was pulled back into the plane by the crew. The commanding general ordered him "grounded"; Dave was too valuable for such operational risks. Nevertheless, in a later tactical mission over northern Italy, he was hit by a 20-millimeter shell from an enemy plane; and for this he received the Purple Heart Medal—though a noncombatant.

In the words of General Doolittle, commander of the 8th Air Force, "Dave did the only thing that could have straightened out the equipment. He became one of the boys; he flew on combat missions and demonstrated the use of the equipment under combat conditions. Dave took some 'flak' in the leg, and I had to take him off flying. Dave had an unusual capability of dealing in an understandable way with operational people; and, when he left, the operators carried on in the image established by Dave." Dave then went to the 15th Air Force under General Nate Twining, where, as the general stated, "He did the same thing, changing from no success to full success."

In the 1944–45 period, following the invasion of the continent, Dave turned his attention also to the Tactical Air Forces, particularly the IXth, and in that connection became involved in the overall tactical use of radar and electronic control of toss bombing as well as radar control of fighters using the Radiation Laboratory-developed microwave ground radars: the MEW and SCR-584.

While he was in the European theater, Dave established the role of critical communications link and personal emissary between the theater commanders, such as Doolittle, Vandenberg, Twining, Spatz, and the leaders back at home such as General Arnold, Secretary Stimson, Dr. Bowles, Assistant Secretary for Air Bob Lovett, Dr. Vannevar Bush (head of the Office of Scientific Research and Development [OSRD]), and others. When the war in Europe came to an end, the war in the Pacific heated up. Here Dave played two major roles: (1) establishing working relations between

General MacArthur and his staff on the one hand and OSRD on the other (in this effort he was joined by Allan Waterman) and (2) making preparations for the A-bomb drop on Hiroshima.

For his working contributions, President Truman, on April 15, 1946, presented Dave Griggs with the Medal for Merit—the highest award of the nation given to a civilian for service during a declared war. The citation read:

> DR. DAVID GRIGGS, For exceptionally meritorious conduct in the performance of outstanding services as H2X Project Officer in the Eighth Air Force during the period 1 May 1943 to 1 April 1944. Dr. Griggs rendered invaluable service in connection with H2X equipment and instructing personnel to operate this equipment. Through his tireless efforts and outstanding leadership he made a substantial contribution to the heavy bombardment operations performed by the Eighth Air Force. The professional skill and the devotion to duty displayed by Dr. Griggs reflect the highest credit upon himself and the Armed Forces of the United States (signed HARRY TRUMAN, COMMANDER-IN-CHIEF).

In a more personal letter, Edward Bowles wrote to Dave (11 August 1947), "Your drive and determination, along with your brilliance, have been sources of both inspiration and joy to me. Your selflessness and your innate desire to give everything you had for the nation have given those who know you a great respect for your courage and idealism."

Dr. Bowles had a stable of scientific experts supporting his activities in the Office of the Secretary of War, including Julius Stratton, Louis Ridenour, William Shockley, Maurice E. Strieby, Norman Ramsey, Dale Corson, and Ivan A. Getting.[7] To support these operations required a staff of secretaries. One of these was a pretty young brunette from Iowa, Helen Avery. She and Dave fell in love, and on May 4, 1946, they were married.

Dave's postwar contributions to national defense continued to the day of his death, December 31, 1974. Although his principal interests were in support of the Air Force, he also contributed to the work of the Atomic Energy Commission, the Army, and to many other government agencies. In 1947 he was instrumental in setting up the RAND Corporation and became the first head of the Physics Department. As a member of the Air Force Scientific Advisory Board and as chief scientist of the Air Force (1951–52), he labored for a better understanding of the effects of nuclear weapons, development of the hydrogen bomb, and establishment of underground testing of nuclear weapons.

The early 1950s were characterized by the great debate as to whether the United States should develop thermonuclear weapons. President Truman had announced on January 31, 1950, that the United States would proceed with the thermonuclear (or fusion) bomb. However, the General Advisory Committee of the AEC, led by J. Robert Oppenheimer (October 29–30, 1949, et sequitur) opposed the development. Other scientists, such as Edward Teller and Luis Alvarez, supported it. The details of the debate are voluminous, but it is clear that Dave Griggs, while chief scientist of the Air Force, projected the official position of the Air Force in support of such a development, including the establishment of a second AEC laboratory, the Lawrence Radiation Laboratory at Livermore, California.

Oppie's opposition to the development of a hydrogen bomb, combined with his long record of association with liberals and communists, led Secretary Finletter by early 1951 to deny Air Force classified information to Oppie.[4] While Oppie's outward opposition to the hydrogen bomb decreased during Dave's tenure as chief scientist of the Air Force, Oppie became involved in an Army-contracted study, Project Vista, at the California Institute of Technology (1951–52). Here he advocated the development of small tactical nuclear weapons. The leadership of the Air Force looked upon this as an end run designed to delay the hydrogen bomb and reduce the availability of fissile material for use in hydrogen bombs. Secretary Finletter forbade the release of the section of the Project Vista report written by Oppie.[8]

From April 12, 1954, through May 6, 1954, a series of hearings were held in Washington under the auspices of the AEC entitled "In the Matter of J. Robert Oppenheimer." The issue at stake was whether Oppenheimer's clearance for access to classified AEC information should be reinstated. After some thousand pages of testimony, including testimony by Dave, the Personal Security Board voted to support the suspension of Oppenheimer's security clearance.

J. Robert Oppenheimer was a brilliant theoretical physicist. He led the successful wartime effort in the development of the atomic bomb. He was admired, if not worshiped, by many of his physicist colleagues. In the hearings, Dave accurately reported the official Air Force position; and though his evidence was not pivotal, Dave, in the minds of some physicists, became the Judas who had betrayed their god.

During the postwar period, efforts were made by a number of scientists, notably Dr. Eleanora B. Knopf and Professor Frank Turner, to persuade Griggs to resume his experimental studies of the mechanical properties of rocks. In 1948 he was induced by Professor Louis B. Slichter, director of the Institute of Geophysics at the University of California, Los Angeles, to accept an appointment as professor of geophysics at the institute, a position he held, except for relatively short leaves of absence, until his death.

At UCLA Dave Griggs established a new laboratory for experimental deformation of rocks that was productive in terms of both scientific papers and well-trained scientists. At UCLA he designed and supervised the building of improved high-pressure equipment for obtaining precise mechanical properties at high temperatures in gas pressure vessels. With Frank Turner and graduate students at Berkeley and associates and students at UCLA he undertook an exhaustive and valuable study of the mechanical properties of calcite crystals, limestone, marble, and other carbonate rocks. This research had immediate application to the interpretation of naturally deformed rock microstructures, as well as being at the cutting edge of materials science research on the development of "texture" or "preferred orientation" in crystal aggregates.

Application of the experimental data to the interpretation of geological processes was at least as important to Dave as acquisition of the data. One of his major interests was extrapolation of laboratory results to the conditions and time spans of deformation in the earth's crust and mantle and application of the data in modeling of dynamical processes in the earth by experiment and with the computer. His research had great scope and originality, encompassing fracture and seismicity, flow of rocks in mountain building, the global motions of the lithospheric plates, and, at the opposite extreme of the scale, the submicroscopic dislocation processes that are fundamentally responsible for the solid-state flow of rocks. In recent years he worked extensively on problems of earthquake mechanisms and played a significant role in establishing programs to investigate prediction and possible control of earthquakes.

Griggs's ability as an experimentalist was unique and deserves special mention. What he called his "gift for gadgets" was, in fact, an extraordinary genius for design and successful operation of apparatus of all kinds. In the difficult and sometimes dangerous practice of deformation at high temperatures and pressures, his inventions have had tremendous impact. The greatest range of experimental conditions consistent with safe operation of the equipment and the best attainable precision in measurement of stress and strain were the goals he aimed for and consistently achieved. The several generations of apparatus of his design that employed gaseous confining media have provided much of the basic mechanical data on the weaker rock types. Recent developments and improvements rely generally on the availability of superior engineering materials and improved ancillary instrumentation. In 1956 Griggs's introduction (with G. C. Kennedy) of the "simple squeezer" provided an extremely versatile exploration tool for both phase equilibrium and deformation studies over an extended range of experimental conditions and portended the development of a variety of modern anvil devices. In an effort to attain pressures and temperatures high enough to induce plasticity in the strongest silicates, Griggs designed (about 1960) the first "cubic apparatus" based on the principles of the tetrahedral presses then in operation, employing weak solids as confining media. This equipment achieved pressures up to 50 kilobars and temperatures up to the melting points of silicates, and its geometry permitted controlled deformation of prismatic samples. Extensive plastic flow of quartz crystals and many silicates was first obtained in this apparatus. Encouraged by the potential of this equipment for providing much-needed data on the flow laws of important crustal and mantle rocks, Griggs then developed devices with cylindrical geometry, also with solid confining media. They provided more reliable and continuous data on the temperatures and flow parameters of the samples over long periods of time (the longest tests lasted up to nine months). These devices, the DT apparatus and its larger successor, the GB apparatus, have provided much of the information currently available on the flow mechanisms and flow laws of minerals and rocks.

In 1965 Griggs discovered the phenomenon of "hydrolytic weakening" in quartz and silicate crystals: the addition of very small amounts (<<1 percent by weight) of water dissolved in quartz and silicate crystals has a spectacular effect on reducing their strength and promoting plasticity. The phenomenon was first observed in experiments on synthetic quartz crystals (with J. D. Blacic) and subsequently demonstrated in dry natural crystals (and silicates) into which small amounts of water were diffused. The recognition of this effect is probably the most significant step in our understanding of the mechanisms by which quartz and silicates deform at moderate to high pressures and temperatures present in the earth's crust and mantle. This may, in the future, be judged Griggs's most significant contribution to earth and materials science. The microscopic mechanism is still under vigorous study; it is still not fully understood.

As a teacher, Dave Griggs was tremendously effective. He was an intellectual father to a long line of students and implanted in them his high intellectual standards, scientific insight, and curiosity. He was impatient with incompetence and more so with carelessness or negligence, and his students quickly became aware of these traits. He had an uncanny insight and a critical ability that enabled him to detect flaws in a scientific argument or theory with ease; students and colleagues alike have seen their theories devastated under his critical examination. But this critical ability and insight were more frequently employed constructively with students in getting to the heart of a problem and suggesting a solution. Dave's relationship with his students was permeated by warmth, good humor, and mutual respect, and he always showed a deep concern for their personal and scientific welfare. Many of his students have made important contributions to geology and geophysics and are now in positions of professional eminence.

While continuing his research in geophysics, Dave continued to support the defense of his country; and in 1967, a quarter of a century after his departure from the Air Force as chief scientist, he again donned fatigues to help the fighting American soldier—this time in the national commitment in Vietnam. He made three extended trips to the theater. He helped General Westmoreland design an organizational structure to provide competent scientific support to the component commands with an information focal point at MACV Headquarters. During the Tet offensive he and an associate developed on-the-spot software that markedly improved the performance of the newly introduced sensor equipment system in use for the interdiction of enemy supply lines.

As many as have been Dave's technical contributions to military science and technology, perhaps his greatest contribution came from recognizing critical problem areas and calling upon his prodigious memory and his acquaintance with other scientists whom he marshaled in support. Throughout he was motivated by a strong feeling of patriotism and devotion to his country, always guided by a strict adherence to accuracy and truth.

On December 31, 1974, Dave had returned to his beloved mountains at Snowmass, Colorado, and to his favorite sport—skiing. He was with his friends Robert McNamara, former secretary of defense, and Richard Hodgson, a colleague from the MIT Radiation Laboratory. Dave was aware of a precedent heart attack, but with typical disregard for his own safety, he was not deterred from vigorous skiing. On the slopes he had a massive heart attack and died.

Years before, he had climbed Mt. Griggs in Alaska and at the peak buried the ashes of his parents and emplaced there a monument. His daughter, Nicola Andron, died in 1975 while giving birth to his granddaughter, Hilary. Now it was Stephen's, his son's, turn to climb the mountain with the ashes of Dave and Nicola.

NOTES

1. Robert F. Griggs, *We Two Together* (Pacific Grove, Calif.: Boxwood Press, 1961).

2. Brother and sister: Ruth Higbie, born June 25, 1909 (Ibid., p. 246), died 1990, author of *A Classful of Gods and Goddesses in Nepal* (Pacific Grove, Calif.: Boxwood Press, 1988); Julian Griggs, born April 21, 1917, died 1982, (Ibid., p. 260).

3. W. W. Rubey, "Foreword," in *Flow and Fracture of Rocks,* Monograph 16 (Washington, D.C.: Geophysical Union, 1972).

4. I. A. Getting, *All in a Lifetime* (New York: Vantage Press, 1989).

5. Crane Brinton, *The Society of Fellows* (Cambridge, Mass.: Harvard University Press, 1959).

6. Unpublished notes of David T. Griggs.

7. Unpublished activities of Edward L. Bowles, April 6, 1942, to August 13, 1947 (177 pp.).

8. David C. Elliot, *Project Vista and Nuclear Weapons in Europe* (*International Security,* Summer 1986, Vol. 11, No. 1, c. Harvard and MIT); also David C. Elliot, *Project Vista: An Early Study of Nuclear Weapons in Europe* (Santa Monica, Calif.: The California Seminar on International Security and Foreign Policy, 1987).

SELECTED BIBLIOGRAPHY

1935

The strain ellipsoid as a theory of rupture. *Am. J. Sci.* 30:121–37.

1936

The factor of fatigue in rock exfoliation. *J. Geol.* 44:783–96.

Deformation of rocks under high confining pressures. *J. Geol.* 44:541–77.

1938

Deformation of single calcite crystals under high confining pressures. *Am. Mineral.* 23:28–33.

With J. F. Bell. Experiments bearing on the orientation of quartz in deformed rocks. *Bull. Geol. Soc. Am.* 49:1723–46.

1939

Creep of rocks. *J. Geol.* 47:225–51.

With C. S. Hurlburt, Jr. Structure and mechanism of intrusions, igneous rocks of the Highwood Mountains, Montana, Pt. 1: The laccoliths. *Bull. Geol. Soc. Am.* 50:1089–1107.

A theory of mountain-building. *Am. J. Sci.* 237:611–50.

1940

Experimental flow of rocks under conditions favoring recrystallization. *Geol. Soc. Am. Bull.* 51:1001–22.

1941

An experimental approach to dynamic metamorphism. *American Geophysical Union Transactions,* 22nd Annual Meeting, Pt. 2, p. 526.

1951

Some experiments bearing on plasticity of rocks in the earth. In *Colloquium on Plastic Flow and Deformation Within the Earth. American Geophysical Union Transactions,* vol. 32, pp. 505–8.

Summary of convection-current hypotheses of mountain-building. In *Colloquium on Plastic Flow and Deformation Within the Earth. American Geophysical Union Transactions,* vol. 32, pp. 527–28.

With W. B. Miller and others. Deformation of Yule marble. Pt. I:

Compression and extension experiments on dry Yule marble at 10,000 atmospheres confining pressure, room temperature. *Bull. Geol. Soc. Am.* 62:853–62.

With J. Handlin. Deformation of Yule marble. Pt. II: Predicted fabric changes. *Bull. Geol. Soc. Am.* 62:863–86.

With I. Borg, J. Sosoka, and F. J. Turner. Deformation of Yule marble. Pt. IV: Effects at 150°C. *Bull. Geol. Soc. Am.* 62:1385–1406.

1953

With I. Borg, J. Sosoka, and F. J. Turner. Deformation of Yule marble. Pt. V: *Geol. Soc. Am. Bull.* 64:1327–42.

1954

With H. C. Heard and F. J. Turner. Experimental deformation of calcite crystals. *Geol. Soc. Am. Bull.* 65:883–934.

With F. J. Turner, H. C. Heard, and L. W. Weiss. Plastic deformation of dolomite rock at 380°C. *Am. J. Sci.* 252:477–88.

High-pressure phenomena with applications to geophysics. In *Modern Physics for the Engineer,* ed. L. N. Ridenour, pp. 272–305. New York: McGraw-Hill.

With N. E. Coles. Creep of Single Crystals of Ice. SIPRE Report II, U.S. Army, Corps of Engineers.

The earth's mantle. Symposium discussion. *American Geophysical Union Transactions,* vol. 35, pp. 93–96.

1956

With F. J. Turner, R. H. Clark, and R. H. Dixon. Deformation of Yule marble. Pt. VII: Development of oriented fabrics at 300–500°C. *Geol. Soc. Am. Bull.* 67:1259–93.

With G. C. Kennedy. A simple apparatus for high pressures and temperatures. *Am. J. Sci.* 254:722–35.

1958

Surface motion from deep nuclear shots. Lawrence Radiation Laboratory Report UCRL–5253.

With W. G. McMillan, E. D. Michael, and C. P. Nash. Lack of metallic transition in LiH and $LiAlH_4$ under static pressure. *Phys. Rev.* 109:1858–59.

1960

With M. S. Paterson, H. C. Heard, and F. J. Turner. Annealing recrystallization in calcite crystals and aggregates. In *Symposium on Rock Deformation,* eds. D. T. Griggs and J. Handlin, pp. 21–37. Geological Society of America.

With F. J. Turner and H. C. Heard. Deformation of rocks at 500 to 800°C. In *Symposium on Rock Deformation,* eds. D. T. Griggs and J. Handlin, pp. 39–104. Geological Society of America.

With J. Handin. Observations on fracture and a hypothesis of earthquakes. In *Symposium on Rock Deformation,* eds. D. T. Griggs and J. Handlin, pp. 347–64. Geological Society of America.

With F. J. Turner and H. C. Heard. Experimental deformation of enstatite and accompanying inversion to clinoenstatite. Twenty-first International Geolology Congress, Copenhagen, 1960, Pt. 18, pp. 399–408.

1961

With F. Press. Probing the earth with nuclear explosions. *J. Geophys. Res.* 66:237–58.

With E. C. Bullard. The nature of the Mohorovicic discontinuity. *R. Astron. Soc. Geophys. J.* 6:118–23.

1963

With C. B. Raleigh. Effect of the toe in the mechanics of overthrust faulting. *Geol. Soc. Am. Bull.* 74:819–40.

1964

With N. L. Carter and J. M. Christie. Experimental deformation and recrystallization of quartz. *J. Geol.* 72:687–733.

With J. M. Christie and N. L. Carter. Experimental evidence of basal slip in quartz. *J. Geol.* 72:734–56.

1965

With J. D. Blacic. Quartz: Anomalous weakness of synthetic crystals. *Science* 147:292–95.

1966

With J. M. Christie and N. L. Carter. Discussion of experimental deformation and recrystallization of quartz and experimental evidence of basal slip in quartz—Authors' reply. *J. Geol.* 74:368–71.

1967

Hydrolytic weakening of quartz and other silicates. *R. Astron. Soc. Geophys. J.* 14:19–31.

With A. C. McLaren, J. A. Retchford, and J. M. Christie. Transmission electron microscope study of Brazil twins and dislocations experimentally produced in natural quartz. *Phys. Stat. Sol.* 19:631–44.

With H. R. Wenk and D. W. Baker. X-ray fabric analysis of hot-worked and annealed flint. *Science* 157:1447–49.

1968

With J. H. Healy, W. W. Rubey, and C. B. Raleigh. The Denver earthquakes. *Science* 161:1301–10.

1969

With D. W. Baker. The origin of deep-focus earthquakes. In *Properties of Matter Under Unusual Conditions,* eds. H. Mark and S. Fernbach, pp. 23–42. New York: Interscience.

1970

With J. M. Christie, R. M. Fisher, A. H. Heuer, and S. Radcliffe. High voltage (800 kv) electron petrography of type B rock from Apollo 11. *Apollo 11 Lunar Science Conference, Proceedings,* vol. 1, pp. 731–48.

With H. W. Green and J. M. Christie. Syntectonic and annealing recrystallization of fine-grained quartz aggregates. In *Symposium on Experimental and Natural Rock Deformation,* ed. P. Paulitsch, pp. 272–335. Berlin: Springer-Verlag.

With S. Radcliffe, A. H. Heuer, R. M. Fisher, and J. M. Christie. High voltage "electron petrography" of lunar minerals. In *Proceedings of the 28th Annual Meeting of the Electron Microscopy Society of America,* ed. C. J. Arceneaux, pp. 24–25.

With S. Radcliffe, A. H. Heuer, R. M. Fisher, and J. M. Christie. HV transmission EM study of lunar surface material. *Science* 167:638–40.

1971

With J. M. Christie, R. M. Fisher, A. H. Heuer, J. S. Lally, and S. Radcliffe. Comparative electron petrography of Apollo 11, Apollo 12, and terrestrial rocks. In *Proceedings of the Second Lunar Science Conference. Geochim. Cosmochim. Acta* 1:69–90.

1972

The sinking lithosphere and the focal mechanism of deep earthquakes. In *Nature of the Solid Earth*, ed. E. C. Robertson, pp. 361–84. New York: McGraw-Hill.

With J. M. Christie, R. M. Fisher, J. S. Lally, A. H. Heuer, and S. Radcliffe. Deformation of lunar and terrestrial minerals. In *Electron Microscopy and Structure of Materials*, eds. G. Thomas, R. M. Fulrath, and R. M. Fisher, pp. 1234–44. University of California Press.

With J. M. Christie, R. M. Fisher, A. H. Heuer, J. S. Lally, G. L. Nord, and S. Radcliffe. Electron petrography of Apollo 14 and 15 rocks. In *Proceedings of the Third Lunar Science Conference. Geochim. Cosmochim. Acta* 1:401–22.

1973

With J. A. Tullis and J. M. Christie. Microstructures and preferred orientations of experimentally deformed quartzites. *Geol. Soc. Am. Bull.* 84:297–314.

With R. L. Post, Jr. The earth's mantle: Evidence of non-Newtonian flow. *Science* 181:1242–44.

With J. M. Christie, R. M. Fisher, A. H. Heuer, J. S. Lally, G. L. Nord, and S. Radcliffe. Electron petrography of Apollo 14 and 15 breccias and shock-produced analogs. In *Proceedings of the Fourth Lunar Science Conference. Geochim. Cosmochim. Acta* 1:365–82.

With J. M. Christie, R. M. Fisher, A. H. Heuer, J. S. Lally, G. L. Nord, and S. Radcliffe. Petrologic study of igneous and metaigneous rocks from Apollo 15 and 16 using high voltage electron microscopy. In *Proceedings of the Fourth Lunar Science Conference. Geochim. Cosmochim. Acta.* 1:953–70.

1974

A model of hydrolytic weakening in quartz. *J. Geophys. Res.* 79:1653–61.

1975

With David D. Jackson, Leon Knopoff, and Ronald L. Shreve. Earthquake prediction: Modeling the anomalous Vp/Vs source region. *Science* 187:537–39.