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ALBERT FRANCIS BIRCH
1903–1992

A Biographical Memoir by
THOMAS J. AHRENS

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Francis Birch

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BY THOMAS J. AHRENS

FRANCIS BIRCH WAS a founder of the science of solid earth geophysics. He demonstrated how study of the physics of minerals and rocks could lead, in conjunction with knowledge of seismic structure and geochemical abundances, to an understanding of the constitution of the Earth. Birch obtained, in his Harvard University laboratory, some of the first reliable data for the elasticity (especially at high pressures and temperatures), thermal expansion, and thermal conductivity of rocks and minerals. Based on his own and other experimental results and his analytical perception, he pioneered our understanding of the composition, structure, and temperature of the Earth's interior and developed models of the Earth's initial differentiation. Francis Birch was fascinated by the Earth and worked his whole life refining his analysis of it.

At Los Alamos National Laboratory during World War II, Birch played a crucial role in translating his considerable Harvard experience in the high pressure and temperature mechanics of materials to developing a gun-type device that evolved into the first of the two atomic bombs produced by the Manhattan Project. Although the decision for their deployment is still controversial, it is clear that these explosions decisively ended World War II in August 1945. Francis

Birch returned to Harvard and remained continuously on the faculty until his death in January 1992. Birch had a remarkable and extremely productive scientific career that spanned some sixty years.

LIFE IN WASHINGTON D.C. AND AS A HARVARD UNDERGRADUATE

Francis Birch was the eldest son of George Albert Birch and Mary Hemmick Birch, who resided in Chevy Chase, Maryland. His father hailed from Falls Church, Virginia, and was in the banking and real estate business. His mother was a homemaker and participated in choir singing, notably as soloist at St. Matthew's Cathedral in Washington, D.C. Young Francis attended D.C. public schools, and on entering Western High School in 1916, he enrolled in the High School Cadets, or what we call today the Junior Army Reserve Officer Training Corps.

The United States was just plunging into World War I. In high school Francis was an excellent student and participated in track, boxing, and gymnastics. Francis had three younger brothers who pursued varying careers. Next oldest David Birch, like his father, went into banking. John Birch was a diplomat with the U.S. Department of State, and Robert Birch, the youngest, became a composer of songs.

In 1920 Francis Birch entered Harvard supported by a scholarship and majored in electrical engineering. He also continued his military commitment and joined Harvard's Army ROTC Field Artillery Battalion. At that time artillery pieces were horse drawn. Francis spent several hours a week removing manure and grooming the horses maintained by the Harvard ROTC contingent in a large barn-like structure, which was later converted to the Gordon McKay Laboratory of Applied Physics.

Francis Birch received his bachelor of science degree in electrical engineering magna cum laude in 1924. This was followed by two years (1924-26) in the engineering department of the New York Telephone Company.

Francis became restive and applied for an American Field Service Fellowship. The fellowship supported Francis Birch's research visit from 1926 to 1928 to the Institut de Physique at the University of Strasbourg in France in the laboratory of Professor Pierre Weiss. Weiss was a pioneer in the modern sub-field of the magnetic properties of matter. At the time of Birch's visit, the laboratory contained one of the world's highest strength steady magnetic field devices (10 kilogauss in a volume of several cubic centimeters).

Birch rolled up his sleeves and managed to be involved with this group in his first four research papers–all first rate and written in French. He reported for the first time the paramagnetic properties of potassium cyanide, and in a paper first-authored by Weiss, Birch provided initial data for the magnetic saturation field value for metallic Co-Ni alloys. A separate paper on the magnetic moment of Cu^{++} ions was solely authored by Birch. Birch's appetite for research had been awakened by this interlude in Strasbourg, and he later wrote that the experience resulted in his decision to become a research scholar.[1]

FRANCIS BIRCH AND PERCY BRIDGMAN

Recognizing that some of the world's most exciting new research on materials was being conducted in the physics department at Harvard by the already well-known Hollis Professor of Mathematics and Natural Philosophy Percy Bridgman, Francis applied to the graduate school at Harvard. On acceptance as an assistant in physics, Francis immediately started to work in Bridgman's pioneering high-pressure laboratory. Work was supported in this laboratory by grants of only a few hundred dollars from the Sanford and Bache funds of the American Academy of Arts and Sciences and the National Academy of Sciences. This laboratory, which produced a 1946 Nobel Prize in physics for Bridgman, was old-fashioned even by the standards of the 1930s. Francis adapted Bridgman's pressure system by adding a small metal chamber fitted with tiny metal tubes and wires and instrumented with Wheatstone bridges, long slide-wire variable resisters, galvanometers, and dial gauges. Thousands of measurements were read by eye, recorded by hand in notebooks, plotted, and smoothed graphically.

On starting graduate school, Francis traveled to the office of Arthur L. Day, director of the Geophysical Laboratory of the Carnegie Institution of Washington. Although Day undoubtedly suggested that Birch should conduct research on geophysical problems at the Geophysical Laboratory, Birch instead followed the advice of his mentor Bridgman, who suggested that he should measure for the first time the liquid-vapor critical point of mercury. Unsuccessful previous measurements for the critical point indicated conditions above 500 bars and 1000° C were required to obtain such data for mercury. Pressure apparatus to reach 10 kilobars were available in the 1930s in Bridgman's laboratory, but the expected temperature requirements for achieving mercury's critical point was a formidable 1400° C, well above Bridgman's normal range. Birch obtained technical advice from the Geophysical Laboratory staff's pioneering researchers F. H. Smyth, Leason Adams, Ralph Gibson, and Roy Goranson. He very carefully machined his own high-pressure chambers in Jefferson Laboratory in the physics department. The advice proffered both by the Geophysical Laboratory and Bridgman was well taken, and Birch's fifth paper reported the results of his Ph.D. thesis project. This was a measurement of the critical point of mercury. He obtained the values 1460 ± 20° C and 1610 ± 50 bars and solely authored this work in *Physical Review* in 1932. This was a scientific home run! Some thirty years later several groups repeated these measurements and newer data agreed closely with Birch's original study.

In 1930, during the period that Birch was working on his Ph.D., the Committee for Experimental Geology and Geophysics was formed at Harvard. This effort was led by Reginald A. Daly, a leading Harvard geologist, and included physicist Percy Bridgman, astronomer Harlow Shapely, geologists L. C. Graton and D. H. McLaughlin, and chemist G. P. Baxter. This committee, empowered to raise funds and advance the field of experimental geology and geophysics, exists to this day. In 1931 geophysics at Harvard thus began with the appointment of Professor Don L. Leet as director of the Seismological Station at Harvard. A second appointment went to W. A. Zisman, another Bridgman student. Zisman was appointed to study the elastic properties of rocks. Their complexity, however, was not to Zisman's liking, and he resigned in 1932. At the depths of the American and European economic depression, the position of research assistant in geophysics was offered to Birch, who readily accepted the job. This occurred several weeks after another graduate of Harvard, Franklin D. Roosevelt, began twelve years of service as President of the United States.

In 1933, having accumulated laboratory experience under Percy Bridgman, one of America's premier experimentalists, Francis Birch was asked to lead the geophysics program at Harvard. In retrospect, Harvard's geology department at that time was one of the most forward looking in North America.

Francis Birch married Miss Barbara Channing of Cambridge, Massachusetts. She was a collateral descendant of the American theologian William Ellery Channing. She brought a sense of warmth, family, and intellectual and cultural affairs to the household. She was Birch's lifelong mate.

They lived in Cambridge. The Birches had three children, Anne Birch (now Mrs. Harry Hughes) and Mary Birch who both reside in Cambridge. Their son Francis (Frank) S. Birch is professor of geophysics at the University of New Hampshire.

GEOPHYSICS AT HARVARD

Birch's first geophysics papers coauthored with R. R. Law and R. B. Dow, dealt with the compressibility of rocks and glasses. They used the apparatus from Birch's Ph.D. thesis project on mercury and adapted Bridgman's slide-wire method to measure length changes to 10 kilobars and 400° C simultaneously.

Soon after, Birch broke new ground in his study of the shear velocities of rocks as a function of temperature and pressure. All previous shear moduli measurements at high pressure employed measurement of angular strain of samples wound into the shape of helical springs. This technique was clearly impossible to apply to rock.

Assisted by J. Ide and D. Bancroft, Birch[2] developed a new type of torsional-bar resonance experiment that, for the first time, resulted in the determination of the shear modulus and quality factor in a wide range of rocks and glasses within a 4-kilobar gas apparatus that could also be heated to 100° C. This was no trivial experiment to operate in the 1930s. It would be a difficult experiment even today, and was state of the art in the 1936-37 time frame, when pressure was measured with manganin coils insulated with silk fiber.

Birch then constructed the first theoretical mineral physics models of the lower crust and compared these with velocity models from crustal refraction seismology. Birch found that the lower crust's elastic properties were compatible with several granites and gabbros he had tested.[3] This work probably demonstrated to Birch a serious deficiency in definitive information on the actual temperature at crustal depths. It probably was obvious to Birch that the near surface thermal gradients, which Birch and Clark[4] measured before the war, but published after World War II, were too high (50° C/km). Such values would suggest implausibly high temperatures deep in the Earth.

The clouds of war were ominous and it turned out that Birch did not seriously grapple with the question of the thermal state of the Earth until much later. In 1937 Francis Birch was promoted to assistant professor of geophysics at Harvard.

Birch obviously was concerned about how one could extrapolate data taken to a few kilobars to the millions of bars in the Earth's interior. He discovered the then recent theory of finite strain compression developed by applied mathematician F. D. Murnaghan, which was published in the *American Journal of Mathematics* in 1937. This theory appeared to provide a route to extrapolating low-pressure compression data to high pressure. Much of these data had been produced by Bridgman in a long series of papers starting in 1909. In a brilliant paper published in the *Bulletin of the Seismological Society of America* in 1937, using the framework of Murnaghan's finite strain theory, Birch derived equations for the extrapolation of seismic velocity into the upper and lower mantle; he found such models agreed closely with seismically determined compressional and shear velocity versus depth data recently obtained by Bullen, Jeffreys, and Gutenberg. Although Birch assumed a primitive isothermal Earth model, this promising paper provided the first complete, self-consistent, elastic and density model of the Earth's mantle.

Before the United States became engaged in World War II, Birch and Clark[5] published the first careful, definitive study of the thermal conductivity of a wide range of igneous rocks. They found striking differences in the thermal behavior of the thermal conductivity of feldspar-bearing rocks, which increased in conductivity with temperature. This contrasted with the usual decreases in conductivity with temperature found in many other rock types. They then went on to calculate the heat flow from continental regions and obtained a value close to modern averages. All this work and virtually all of his measurements on the elastic properties of rocks, and all the other then existing physical properties of Earth materials were reported in a 21-chapter data collection, the first edition of the *Handbook of Physical Constants* published by the Geological Society of America in 1942.[6] Birch was the principal editor of this remarkable data collection, and he himself wrote contributions to eight of the twenty-one chapters. This handbook was the first collection of mineral physics data and it is still being used, although later versions have been published.

WORLD WAR II AND LITTLE BOY

In 1942 Francis Birch took a leave of absence to contribute his experimental talents to developing proximity fuses at the Radiation Laboratory at the Massachusetts Institute of Technology. He remained in Cambridge only a year. On the basis of prior ROTC training at Harvard and his promotion to associate professor in 1943, he accepted a commission in the U.S. Navy as a lieutenant commander. His first assignment was at the Bureau of Ships in Washington, D.C., where he spent only ten months. To his great surprise, and probably because of his research experience with Percy Bridgman and his friendship with J. Robert Oppenheimer, who knew Francis from his Harvard years, he was assigned to the Manhattan Project. This was an Army Corps of Engineers project formed in June 1942, and was designated as a special district with initial headquarters in New York City. The Corps of Engineers, Manhattan District, evolved into the Manhattan Project, which encompassed all aspects of the United States's secret effort to build atomic weapons: all research and development programs, processing of materials, and fabrication of components in localities all over the United States, as well as assembly and delivery of the military weapons to the Army Air Force.

Francis Birch was ordered to report to the Los Alamos Ranch School some 30 miles northwest of Santa Fe, New Mexico. In 1943 he packed his spouse Barbara, his three children, and himself into the family car and drove from Washington to Los Alamos.

Francis Birch was assigned to a gun development group in 1943. Initially, he worked under the leadership of Navy Captain W. S. Parsons to develop a fission device. This device conceptually would launch a projectile made of some tens of kilograms of ^{239}Pu into a ^{239}Pu target at the end of a 2-meter-long gun. The goal was to achieve projectile velocities in excess of 1 km/sec. This simple gun concept of mechanically and rapidly assembling a greater than critical mass of fissionable ^{239}Pu was considered more likely to succeed than the then untested concept of explosively imploding an assembly of ^{239}Pu to greater than critical densities. This later led to the atomic device named Fatman, first demonstrated at the New Mexico Trinity Test of July 16, 1945. Most of the research and development at Los Alamos was directed not toward gun assembly, but to design and building of implosive devices. The coterie of famous physicists, mathematicians, and chemists-many émigrés from Europe assembled from all over the United States-was concentrating on the implosive plutonium design. The gun concept was considered less difficult to design and construct.

The goal of the Ordinance Division Section to which Birch was assigned was the development of a gun that would weigh only 1 ton and have a muzzle energy that was comparable to then existing guns having five times more mass. Thus, special high-strength alloy steels were used to fabricate barrels to test ordinary uranium dummy projectiles and targets as mechanical proxies for enriched ^{239}Pu and ^{235}U.

In the period April-July 1944 the very high neutron emission rate of the first reactor-produced ^{239}Pu was discovered and the 1-km/sec gun method was discovered to be unworkable and was abandoned for use in developing a plutonium bomb in favor of the implosion Fatman design. At that point, all the gun development activities were redirected towards a ^{235}U-fission bomb. The revised uranium gun program (code name Little Boy), started in February 1944, was now led by newly promoted Commander Francis Birch. Testing began in March 1944.

Before the guns for the uranium bomb arrived in Los Alamos in October 1944, Birch continued to use unenriched uranium for tests, first on a subscale. In December 1944 high-strength alloy-steel gun tubes constructed by the Navy were delivered and test fired several times. After each gun test was fired at Los Alamos, the uranium gun required massive force for disassembly. A D-8 Caterpillar bulldozer was used to pull the gun apart. Birch actually used the Los Alamos gun device that went into the Hiroshima bomb in four previous tests at Los Alamos.

In February 1945 the amount of ^{235}U required to produce excess of a critical mass was determined and the actual first bomb began to be fabricated. It was composed of the entire supply of enriched ^{235}U in the United States. Thus, *all* the ^{235}U produced in the United States (64.1 kilograms) was used in the ^{235}U Little Boy bomb. There would be no test prior to combat!

The components were cast between June 15 and July 3, 1945, under Francis Birch's watchful eye. The Little Boy bomb case and projectile were shipped to Tinian Island in the Marianas on the U.S. Navy cruiser *Indianapolis*. Birch accompanied the ^{235}U target, which for safety reasons was flown in three parts from Kirtland Air Force Base, New Mexico, to Tinian; it arrived on July 28, 1945. On August 5 Francis Birch supervised the assembly of the Little Boy device and loaded it into the specially outfitted B-29 heavy bomber named Enola Gay. On August 6, 1945, this bomb was dropped on Hiroshima. It was hoped by many that Japan would immediately surrender. A blood bath was expected if the Allies were forced to invade the Japanese islands. Japan did not surrender. On August 9 Fatman, the ^{239}Pu bomb, was dropped on Nagasaki. The second explosion proved decisive to the military leadership in Tokyo and Japan surrendered within a week. World War II ended. After receiving the Legion of Merit from the U.S. Navy, Birch was mustered out of the Navy, and he returned to Harvard in late 1945. He was promoted to full professor in 1946.

HEAT FLOW AND RADIOACTIVITY OF THE EARTH

Birch's objective was to understand how the temperature versus depth in the Earth was controlled by radioactivity and thermal conductivity. In the post-World War II years, Francis Birch supervised a comprehensive program to understand the thermal regime of the continental crust of the Earth. Boreholes were drilled specifically for heat flow measurements. Measurements of the in-situ radioactivity of rocks, the Earth's thermal gradient as sampled within boreholes, and thermal conductivities in which a large number of rock samples in the laboratory (taken from these same boreholes) were undertaken. This campaign had its roots in the pre-war thermal conductivity technique development of Francis Birch and Harry Clark. Temperatures versus depth data were initially supplied to Birch by the Gulf Oil Company from its wells in the West Texas Permian Basin. Taken with conductivity data measured on samples, also supplied by Gulf, heat flow for that region was reported by Birch and Clark.[4]

In 1949 Birch was promoted to Sturgis Hooper professor of geology, a chair that was formerly held by Reginald A. Daly, the geologic mentor of high-pressure research at Harvard. The following year, 1950, Birch was elected to the National Academy of Sciences.

Later, with the help of Harvard postdoctoral fellows and students Robert F. Roy, Henry Pollack, David D. Blackwell, Edward R. Decker, W. H. Diment, Arthur Lachenbrook, and major National Science Foundation support, Birch and his coworkers discovered that various broad geological provinces (e.g., Eastern United States; Basin and Range; Northern Rocky Mountain – Columbia Plateau, Southern Rocky Mountain, Sierra Nevada; Colorado Plateau – Wyoming Basin – Middle Rocky Mountains; and the Pacific Coast) had heat flows that were uniquely described in a province by a relation that was simply given as

$$Q = a + bA$$

Where Q is the surface heat flow, A is heat production per unit volume in the surface rocks, and a and b were parameters characteristic of the geological province. This simple empirical result implied a decreasing radioactivity in rocks downward into the crust. Because the radiogenic elements U and Th are also “incompatible,” meaning that they have large ions that are not easily taken into major rock-forming silicate mineral lattices, the radioactivity of the crust is concentrated upward. This concept was accepted by the Earth science community. Moreover, Roy et al.,[7] in a publication celebrating Francis Birch’s accomplishments upon his retirement from active teaching, showed that the measured radioactivity per unit volume correlated with the depth that crustal igneous rock masses had been eroded in a given region.

ELASTICITY AND CONSTITUTION OF THE EARTH'S INTERIOR

Francis Birch's most important paper (1952) appeared in a 57-page article in the *Journal of Geophysical Research* in 1952 and contained an enormous quantity of new material and analyses, as well as several predictions on the nature of the Earth's interior. Birch wrote easily and well, reflecting his undergraduate stint as a contributor to of the *Harvard Crimson.*

Birch first generalized the Williamson-Adams[8] equation, which relates compressional and shear velocity profiles to density for a uniform phase adiabatic region within a planet. Birch showed how this relation could account for differences between the actual thermal gradient (increase in temperature with depth) versus that expected upon adiabatic compression of rock in a self-gravitating field. He derived a new form of the finite-strain, pressure-density equation of state following the ideas of Murnaghan. This equation is now widely used in Earth and planetary science, as well as in material science, and is referred to as the Birch-Murnaghan equation of state. Birch showed that this equation described the compression behavior of a wide range of materials reported earlier by Bridgman. Moreover, for the first time, he used the Debye theory to estimate the thermal expansion coefficient of materials at high pressure, a quantity very difficult to actually measure, and then derived complete equations of states specifying density as a function of pressure and temperature, and the internal gravitational acceleration in the Earth from the seismic velocity profiles versus radius. New seismic profiles had been recently refined by K. Bullen, B. Gutenberg, and H. Jeffreys for both the mantle and the core. The paper came to a number of conclusions and inferences, all of which appear to have been basically correct. These were:

1. The Earth's mantle between the depths of 900 and 2900 km is uniform in phase and composition with elastic properties similar to that of the close-packed oxides. Except for the close-packed oxides Al_2O_3 (corundum) and MgO (periclase) at the time of Birch's paper, virtually nothing was specifically known about the silicate phases of the lower mantle. Moreover, Birch suggested that the incompatible elements (e.g., Th, K, and Ca budget of the Earth) were concentrated upward in the crust and in an upper mantle eclogite layer.

2. The liquid outer core of the Earth was less dense (by about 10%) than expected for pure liquid iron at the pressures and temperatures of the liquid core, and he suggested that the liquid core contained lighter alloying elements (S, C, Si, or O) in addition to molten iron.

3. The inner core was solid, nearly pure iron. The solidity of the inner core was confirmed by A. M. Dziewonski and J. F. Gilbert[9] and Anderson et al.,[10] using the free-oscillation frequencies of the Earth.

It is interesting in spite of the fact that most colleagues and students considered Birch to be a very serious man, he started the introduction of the seminal 1952 paper with a little joke describing the way he felt about the magnitude of unknowns with regard to the nature of the materials under high pressure and temperature in the Earth's interior:

> Unwary readers should take warning that ordinary language undergoes modification to a high-pressure form when applied to the interior of the Earth. A few examples of equivalents follow:

High Pressure Form	*Ordinary Meaning*
Certain	Dubious
Undoubtedly	Perhaps
Positive proof	Vague suggestion
Unanswerable argument	Trivial objection
Pure iron	Uncertain mixture of all the elements

A. E. Ringwood, later at Australian National University, spent several months of 1957 visiting Birch's laboratory. This visit motivated him to conduct his first experiments demonstrating that the transition from olivine to spinel structure occurred at relatively low pressure in Fe_2SiO_4.[11] Later, Ringwood spent much of his career working on the phase transitions of the mantle, first at lower pressures using analog germanates and subsequently exploring phase transitions in silicates.

Birch continued his research over the next twenty years and produced seminal papers on the energetics of core formation and the Earth's thermal state. He conducted laboratory and field work on thermal gradients and conductivity measurements in crustal rocks. He also performed elastic constant measurements on important rock-forming minerals and carried out an extensive series of measurements on rocks with the assistance of several graduate students, including Gene Simmons, who studied the systematics of shear-wave velocities using ultrasonic methods.[12]

Birch's two papers on compressional wave velocities in rocks, published in 1960 and 1961 in the *Journal of Geophysical Research*, are landmark works, and they resulted in a second linear relation now called Birch's law. This describes the variation of compressional wave velocity V_p of rocks and minerals of a constant average atomic weight with density *r* as:

$$V_p = a + b$$

The success of this simple formula was later explained theoretically by Birch's graduate student Thomas J. Shankland[13] and independently by Don L. Anderson.[14]

Geologist William Brace was another visitor who learned static high-pressure methods from Francis Birch in the early 1960s. Brace went on to study rock failure and other physical properties of rocks in a laboratory he later established at MIT. Another student, Peter Bell, established (with colleague David Mao) the world's premier diamond cell high-pressure laboratory at the Carnegie Institution of Washington in the late 1960s.

Birch became interested in the theory of Ramsey,[15] who suggested that the core-mantle boundary of the Earth was not due to compositional differences between a rocky mantle and a metallic core, but resulted from metalization *and melting* of mantle silicates *at the same pressure*. Birch found this implausible and was thus motivated to get involved in the explosive shock compression measurements then being conducted on a wide range of materials at Los Alamos National Laboratory. Birch supplied mineral and rock samples and sample analyses, as well as much encouragement, to Robert G. McQueen and his coworkers at Los Alamos in the 1960s in their application of shock studies to Earth materials. McQueen demonstrated decisively that all silicates underwent major shock-induced phase changes. Later, these were demonstrated to be accounted for by transition from tetrahedrally to octahedrally coordinated silicon with oxygen. Moreover, he showed that silicates emphatically *did not* transform from a density of approximately 5.8 to 10 g/cm^3 at a pressure of 133 GPa (which corresponds to the core-mantle boundary pressure) as Ramsey's theory required. The shock-wave data also supported the conclusions Birch had reached earlier in his 1952 paper about the nature of the lower mantle and the outer and inner cores of the Earth. Birch encouraged me to conduct shock-wave experiments, although, in spite of his experience developing the Hiroshima gun bomb, he did not immediately grasp how useful light-gas guns could become in shock-wave research.

As a member of the Harvard faculty and chairman of the Experimental Geology Committee, Birch sponsored and supported many graduate students, who later made important contributions to Earth science. Early in his Harvard career, Birch supported two students, David T. Griggs and George F. Kennedy, who were doing research as members of the Society of Harvard Fellows. Before World War II Griggs worked on the deformation of rocks under pressure in Bridgman's laboratory, and after the war he continued these studies at the University of California, Los Angeles. Just after the war, Kennedy worked on moderate pressure geochemical research, including the high-pressure and temperature properties of water and CO_2. Kennedy later joined Griggs and moved to UCLA.

After the war, Birch lectured in several courses in geophysics. He was an extremely effective teacher. One year at his last lecture on "Physics of the Earth," he summed up the topics covered so well that the class gave him a standing ovation.

During his career, Birch supervised the doctoral thesis of some fifty graduate students. As might be expected, the theses covered all aspects of the physical properties structure and processes in the Earth. Contributions to his retirement Festschrift and symposium "The Nature of the Solid Earth" included papers from his former graduate students D. D. Blackwell, S. P. Clark, E. C. Decker, W. H. Diment, E.

Herrin, R. F. Roy, and E. C. Robertson. Robertson was the principal editor of the Festschrift book.

PROFESSIONAL SERVICE AND RECOGNITION

Birch officially retired from Harvard in 1974, but he continued to conduct research. He spent more of his time with his family and took summer vacations at his farm in nearby Kensington, New Hampshire.

He received the Geological Society of America's Arthur L. Day Medal and Penrose Medal in 1950 and 1969, respectively, and served as president of the society in 1963-64. The American Geophysical Union honored him with its highest award, the William Bowie Medal, in 1960. President Lyndon Johnson presented him with the National Medal of Science in 1967. In 1968 he shared the Vetlesen Prize with Sir Edward Bullard. This prize was highly symbolic, as Bullard pioneered the measurement of Earth heat flow beneath the oceans, whereas Birch pioneered heat flow measurements on the continents. The University of Chicago and Harvard conferred honorary degrees to Birch in 1970 and 1971, respectively. The Royal Astronomical Society's Gold Medal was awarded to Birch in 1973. Birch received his last major award, ironically named the Bridgman Medal, from the International Association for the Advancement of High Pressure Research in 1983.

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