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BENO GUTENBERG

1889—1960

A Biographical Memoir by

LEON KNOPOFF

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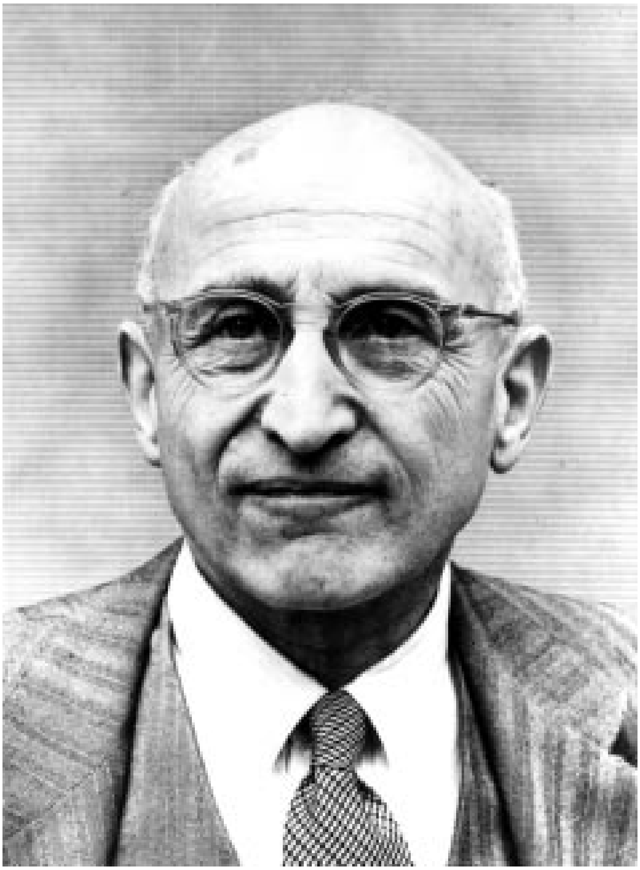

Beno Gutenberg.

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BENO GUTENBERG

June 4, 1889–January 25, 1960

BY LEON KNOPOFF

BENO GUTENBERG WAS THE foremost observational seismologist of the twentieth century. He combined exquisite analysis of seismic records with powerful analytical, interpretive, and modeling skills to contribute many important discoveries of the structure of the solid Earth and its atmosphere. Perhaps his best known contribution was the precise location of the core of the Earth and the identification of its elastic properties. Other major contributions include the travel-time curves; the discovery of very long-period seismic waves with large amplitudes that circle the Earth; the identification of differences in crustal structure between continents and oceans, including the discovery of a significantly thin crust in the Pacific; the discovery of a low-velocity layer in the mantle (which he interpreted as the zone of decoupling of horizontal motions of the surficial parts from the deeper parts of the Earth); the creation of the magnitude scale for earthquakes; the relation between magnitudes and energies for earthquakes; the famous universal magnitude-frequency relation for earthquake distributions; the first density distribution for the mantle; the study of the temperature distribution in the Earth; the understanding of microseisms; and the structure of the atmosphere.

Beno Gutenberg was born in 1889 in Darmstadt, Germany, where his father owned a small soap factory. Beno was the eldest of two sons; his brother Arthur was his junior by four years. Both parents came from merchant families. His father's ambition was that Beno would step into the family business, as would his younger brother, but Beno wanted to study science, having little interest in the business. In the *gymnasium* he became involved in the operation of the meteorological station, and this aroused an interest in weather forecasting and climatology, which led him to undertake meteorological studies at the university.

In the summer of 1907 Gutenberg entered the Technische Hochschule in Darmstadt. He learned that a course on instrumental observations of geophysical phenomena was being offered by Emil Wiechert at the Institute of Geophysics of the University of Göttingen, and he moved there in 1908. Wiechert had a major reputation in both seismology and electromagnetic theory. In the latter area, he is identified with the Liénard-Wiechert potential. He proposed that X rays are electromagnetic waves, and from his measurement of *e/m* for cathode rays, he was the first to announce that cathode rays (electrons) are particles of subatomic mass from 2,000 to 4,000 times less massive than the hydrogen atom shortly before J. J. Thomson took the extra step of identifying the mass precisely. Wiechert was the inventor of a seismograph in widespread use in the first half of the twentieth century, and he had studied the problem of constructing the velocity structure of a spherical Earth from travel-times of seismic impulses, having derived an integral equation also identified with the names of Herglotz and Bateman. Wiechert had also inferred that the Earth must have a central iron core.

The four students in Wiechert's course were introduced into observational methods in meteorology, the handling of seismographs and the reading of seismograms, and the determination of exact (astronomical) time. Gutenberg took lectures from Wiechert on terrestrial magnetism, tides, and geodesy. He took lectures in physics, pure and applied mathematics, elasticity, algebra, and logic from Born, Hilbert, Klein, E. Landau, Madelung, Minkowski, Prandtl, Runge, K. Schwarzschild, Voigt, and Weyl. Gutenberg took a course in geophysics to prepare better for his work in meteorology.

At the end of a course in seismology in Gutenberg's third year, Wiechert told him that he had progressed to the limits of knowledge in seismology and advised him to start his thesis research; Gutenberg selected a study of microseisms. In 1910 Gutenberg made a trip to the coast of Norway, and was able to correlate surf in Norway with microseisms in Göttingen. Microseisms are small disturbances, more or less continuously recorded by sensitive seismometers, and form the background motion upon which earthquake recordings are superimposed. As Gutenberg was later to discover, microseisms are mainly associated with storms in the deep oceans that are at times very distant from the recording station, and less so with surf. Gutenberg's first published paper, which was on microseisms, appeared in 1910. Gutenberg was concerned with the problems of microseisms even at the end of his career.

The possibilities of modern instrumental seismology were not recognized until the end of the nineteenth century. Indeed, the first recording of a distant earthquake was only made on February 25, 1889. So the time was ripe in the first decade of the twentieth century for a bright young investigator to attack the problems of the seismic wave velocity in the Earth's interior through the application of readings of high quality instrumental data. Like many of the prominent seismologists of the first half of the twentieth century, Gutenberg took up the subject without previous intentions. He was attracted by the opportunities for research in a comparatively new subject.

One of Wiechert's assistants, Karl Zöppritz, had been concerned with the calculation of the reflection and transmission coefficients of elastic waves. At about the time of Gutenberg's arrival in Göttingen, Zöppritz died of a massive infection at the age of twenty-seven. Wiechert passed along an unfinished manuscript by Zöppritz on the relation between the amplitudes of seismic waves and velocity variations at depth, with the recommendation that the paper be finished by Gutenberg and Ludwig Geiger, who was Wiechert's other assistant. This event opened the door to a series of studies of the use of amplitudes of seismic waves to determine the structure of the Earth; Gutenberg's interest in amplitudes lasted throughout his career.

Two papers on amplitudes by Geiger and Gutenberg appeared (1912) as part of the series "Über Erdbenwellen" by Wiechert and his students. The two papers presented new results on the structure of the solid Earth determined from the amplitudes and travel-times of seismic waves. Geiger and Gutenberg attempted to determine the amplitude-distance relation for P-waves, but there are enormous fluctuations in the amplitudes from station to station, especially because of differences in instrumentation and in the local geology. Geiger and Gutenberg avoided local influences by taking the ratio of amplitudes of PP/P (i.e., of waves with one bounce off the outer surface of the Earth to waves with no bounce). They observed a large increase in the ratio at about 40° and 95°. The increase at 40° was attributed to a decrease in the amplitude of P; as was to be discovered later, the increase was actually due to an increase in P at 20°, and hence of PP at 40°. An abrupt change of amplitudes with distance is a strong indicator of inhomogeneity in the velocity distribution at depth. Thus, Geiger and

Gutenberg inferred that there was a significant decrease in the velocity gradient at a depth of about 1200 km in the mantle, instead of the more appropriate sharp increase in gradient starting at a depth of around 410 to 440 km. Their model had two additional discontinuous velocity gradients at depths greater than 1200 km. The increases in amplitudes at 20°, called the 20° discontinuity, are today identified with two steps in the properties of the mantle at depths around 410 km and 670 km. The decrease in velocity gradient at about 1200 km and the absence of a sharp increase in velocity at shallower depths persisted in Gutenberg's models to the end of his career (1958), although the depth of the decrease was reduced to about 900 km in the later models. Indeed, Gutenberg (1934) stated, "There is no indication of a discontinuity in the mantle of the Earth at larger depths (than 200 km) . . . and none corresponding to an epicentral distance of about 20°" and again (1953), "There is no evidence of a discontinuity in the mantle between the low-velocity layer and a depth of about 900 km . . . ." Geiger and Gutenberg correctly interpreted the second increase in the ratio as due to a decrease in the amplitude of P. This was the onset of the shadow zone due to the decrease in seismic velocities in the core.

In 1911 Gutenberg submitted his dissertation on microseisms entitled "Die seismische Bodenunruhe" (1912), written under the supervision of Wiechert. The oral examination was held on May 3, 1911, and Gutenberg was awarded the degree of doctor of philosophy *valde laudabili*, with geophysics as his major and geometry and applied mathematics as minor subjects. Wiechert's citation read, "The author has applied extraordinary diligence. About two million facts are used! The discussions are carried out with much skill, and the results are of considerable importance for science."

Gutenberg worked in a postdoctoral capacity at the Institute of Geophysics at Göttingen during the year following the award of his doctoral degree. At that time he began his famous work of the systematic study of seismic waves through the interior of the Earth. From Göttingen recordings, he observed that the seismic phase P´ had an increase of amplitudes at a distance of about 143°. He extended the range of amplitudes to greater distances, which allowed him to interpret the shadow zone between 95° and 143° as cast by a low-velocity core at great depth in the Earth and of considerable contrast to the region above.

In 1897 Wiechert had proposed that the Earth had an iron core starting at a depth of about 1400 km, and in 1906 Oldham had interpreted seismographic data to propose that the core began at a depth of about 3900 km. Gutenberg calculated "the travel-times of waves to be reflected and refracted at the surface of the core, outside as well as inside"; the waves refracted at the core-mantle boundary are the P´ or PKP phases, and the reflected waves are the PcP phases. Gutenberg determined the depth to the top of the core as 2900 km from the surface. He established that the core has a sharp boundary and specified the values of the P-wave velocities in the mantle and in the core (1914).

To do the calculation, Gutenberg developed new, accurate travel-time curves for both P- and S-waves for distances greater than 80°, which allowed him to determine the slope with high accuracy. His velocity distribution for the mantle was similar to the 1912 model. The precision of Gutenberg's determination of the depth to the core is astounding and would be so at any time. More than twenty years later, Gutenberg and Richter (1936) used the times of the reflections PcP from the upper surface of the core and derived the same depth to the core boundary. In 1939 Harold Jeffreys, using his powerful seismological and statistical skills in a calculation with his own travel-time data, derived the result

2898 ± 3 km, which is the value in common use today. Jeffreys also verified that the core-mantle boundary was sharp. Jeffreys noted that, although his and Gutenberg's travel-time curves agree within one second, the first derivatives were significantly different, which was (and is) important, since the ratio of radius to velocity r/v for the ray whose maximum penetration is to radius r is equal to the derivative of the time-angular distance relation. After the monumental discovery of the core, two major seismological plums of deep-earth structure remained to be discovered, namely Lehman's discovery of the inner core and Gutenberg's work on the absence of S-phases in the core.

Gutenberg began a year of military service in October 1912. In October 1913 he started to work as a seismologist with the title of scientific assistant at the Central Bureau of the International Association of Seismology (IAS) at Strassburg, working on microseisms, travel-time curves, and the crustal structure of Europe. His work at Strassburg was interrupted by the outbreak of World War I in August 1914 after only ten months on the job. He was quickly inducted into the German army and served in the infantry. Almost immediately, Gutenberg was wounded in the head by a grenade (his helmet saved his life). Upon recovery, he returned to Strassburg, where he was assigned to the training of officers. In 1916 he volunteered for the weather forecasting service and was sent to the Central Station for Meteorology near Berlin. Gutenberg shuttled between the Russian, French, and Belgian fronts as a meteorologist attached to the chemical warfare engineers, having been assigned the problem of the prediction of the likelihood of backward drift onto the German soldiers of the poison gases that their own army had released. He was also assigned the problem of measurement of the location of cannons from the travel-times of sound transmission, a problem of great similarity to that of the location of earthquake sources. His later work on the structure of the atmosphere (e.g., 1926, 1930) had its genesis at this time.

During the war he spent as much time as possible at Strassburg and worked on routine interpretation of seismograms at the Central Bureau in Strassburg under O. Hecker. The IAS and the Central Bureau were dissolved on March 31, 1916, and Gutenberg became scientific assistant for the Meteorological Service at the German Imperial Station for Earthquake Research at the University of Strassburg. He was concerned with seismological problems during much of the war, meteorological work permitting.

With the return of Alsace to France at the end of World War I, Gutenberg was unemployed, and he returned to Darmstadt. He was an applicant for his old post at the now-French seismic station in Strasbourg, but he was not successful, even though he was soon to be the most famous seismologist in Western Europe.

After the war, the German interior ministry placed Gutenberg in an earthquake research institute that was planned for Jena, but because of the chaos in postwar Germany, the institute existed only on paper. In 1923 Hecker was appointed to the Jena position, but the interior ministry could not (or would not) appoint Gutenberg. (Gutenberg received a letter of greeting on the occasion of the thirtieth anniversary of the Jena Institute addressed to its long-time workers and colleagues that he considered to be a “wry joke.”)

Since he could not find a scientific position after the war, Gutenberg worked in his father’s soap factory in Darmstadt from 1918 to 1930. Arthur had died in the war in 1915, and Beno was under some pressure to help with the family business. After his father’s death in 1927, Beno took over the factory. He met Hertha Dernburg at activities of Jewish sporting and democratic clubs in Darmstadt. They were married on August 14, 1919. Gutenberg continued to be active in local Jewish causes, and was a member and later president of the local chapter of B'nai Brith.

From 1918 Gutenberg worked on geophysical problems at his home in Darmstadt, when he had free time, mainly during evenings and weekends. He used seismographic recordings that were obtained from the institute at Frankfurt—a long tram ride away. He obtained recordings and other information from other observatories by correspondence. Starting in 1923, a steady stream of important papers began to appear from his study in Darmstadt. In *Der Aufbau der Erde* (1925) Gutenberg constructed accurate travel-time curves for seismic waves in which all the important seismic phases were shown to 180°, including some phases triply reflected from the surface.

Gutenberg confirmed and made precise the observations of Tams, Angenheister, and Macelwane in 1921-22, in which the velocities of propagation of surface waves were faster across the oceanic than across the continental portions of the Earth's surface (1924). For this he used measurements of the velocities of both Love and Rayleigh waves at a number of periods from all the prewar seismographic records at Strassburg, from all records at Jena, and selected records from other stations. He proposed a method of inversion of the dispersion of surface waves to determine upper mantle structure that was similar to the method ultimately applied in the late 1950s. His inversion for crustal thickness (he managed to confuse group and phase velocities) gave a thick crust under the continents and a thinner crust under the oceans, with a crustal thickness of only 5 km under the Pacific. The latter was a remarkably foresightful result in view of direct substantiation about thirty years later when exploration of the oceanic crust became possible. From these results, Gutenberg became convinced that there were large structural differences between continents and oceans in the outermost parts of the Earth, a view that was to play a significant part in his model of continental drift (1936). Because of his observation of differences between continental and oceanic upper mantle structure, Gutenberg was convinced of the likelihood of horizontal mobility long before it became fashionable in the geophysical community. He began a study of the rheological problems associated with Wegener's theory of continental drift and developed his own theory of flow in the mantle (1927).

Gutenberg was especially pleased with his calculation of the distribution of the density, and hence the elastic moduli, as a function of depth in the Earth (1923). The calculation may be considered crude by today's standards, since it relied on a linear density-versus-depth model in each of the four layers in the mantle model of 1912, but it is important, because it was the first construction of a density distribution for the mantle. Later, Bullen introduced the constraint of compressibility, and still later the density was obtained by Gilbert and Dziewonski and others from inversion of the free oscillation spectrum. This was the starting point for a new discipline concerned with the chemical composition of the Earth's interior. In his later discussions of composition, Gutenberg relied mainly on the density models of Bullen, Bullard, and Birch, rather than his own.

Gutenberg's unhappy financial situation did not escape the notice of Professor Franz Linke, director of the Institute of Meteorology and Geophysics of the University of Frankfurt. Linke proposed to Gutenberg that he obtain his *Habilitation*, which was awarded at the University of Frankfurt on July 25, 1924, with his book *Die seismische Bodenunruhe* as his *Habilitationsschrift.* Although it had the same title as his thesis, the book presented new results on microseisms and the structure of the Earth. After an introductory lecture with the title “New Results on the Structure of the Earth’s Crust,” he became privat-dozent, the equivalent of an instructor and held lectures in geophysics at the University of Frankfurt from 1924 to 1930. He lectured on seismology, applied geophysics, oceanography, tides, and the structure of the Earth. The salary at Frankfurt was a percentage of the tuition paid by his students, but it was still insufficient to support himself and his family, and now he had the additional workload of his numerous lectures. During this period, Gutenberg and his wife devoted their full efforts to operation of the factory under hardship; in the immediate postwar period they bartered soap both for raw materials for their products and for personal necessities.

His financial situation did not change significantly when, on October 21, 1926, the science faculty of the University of Frankfurt elected him to the position of *ausserordentlicher Professor*, a non-state funded position, which he held from 1926 to 1930. The citation of the faculty in his election read, “It is not consonant with his scientific importance that Dr. Gutenberg has been a merchant-official in his father’s soap factory in Darmstadt since the end of the war in order to support himself. Our faculty has conferred upon him the Habilitation on July 25, 1924. His lectures are delights from semester to semester and attract more and more students. We fear that under this double life as merchant and scholar, his productivity will gradually disappear. It is unlikely that such productive scientific work as has appeared in recent years from Dr. Gutenberg can persist for much longer if he continues to have his full-time merchant’s responsibility.”

Despite these concerns voiced by the faculty, the professorship was poorly funded and Gutenberg’s stipend continued to be derived principally from his position as privat-dozent. Later he added a position as director of the seismological station of the university, located on the Kleine Feldberg in the Taunus mountain range on the opposite side of Frankfurt from Darmstadt. The two scientific positions were still insufficient to support him and his family, which now included two children.

Gutenberg used his stipend as director of the Kleine Feldberg station to start the publication of a bulletin. After working with the Galitzin pendulum seismographs, Gutenberg showed no further direct interest in instrumentation; he was, of course, an avid user of the recordings that could be obtained from the seismographs. Each year he spent two or three periods of one to two weeks each in the Taunus. He enjoyed the quiet, which enabled him to think creatively in solitude on his daily, and occasionally twice daily, walks to the peak. The path is now named “the Benoweg” in his honor. Gutenberg was invited to the dedication of the Benoweg in August 1959, a few months before death, but he did not attend.

A number of well-known seismologists visited the house at Mühlstrasse 6 in Darmstadt, including Inge Lehmann in 1926 and James Macelwane and Perry Byerly in 1929. Although Beno spent his days at the factory, the visitors received his full attention in the evenings, on weekends, and in his spare time. Lehmann has stated that on the occasion of her visit with Gutenberg in 1926, they simply worked together without any communication of a personal nature. She also stated that Gutenberg was a wonderful teacher and that she owed him her excellent introduction to seismology and that he gave of his time unselfishly. Her impression did not change when she visited Gutenberg in Pasadena.

Contrary to the pessimistic forecast of the Frankfurt faculty, Gutenberg continued to turn out many papers and a remarkable series of books. The *Lehrbuch der Geophysik* (1929) was written and compiled in the study of the house on Mühlstrasse. The *Lehrbuch* was a major undertaking that provided a complete description of the understanding of the geophysics of the solid Earth, the oceans, and the atmosphere up to that time. The topics included evolution of the Earth and its geologic structure, volcanoes, mechanics of the atmosphere, and ice ages. There were nine contributors, including Linke and L. Weickmann. Gutenberg wrote a fourth of the volume, whose length exceeded a thousand pages. Interestingly, Gutenberg's bylines for his own chapters in the *Lehrbuch* are "B. Gutenberg, Darmstadt," while the title page and table of contents identify him as "B. Gutenberg, Frankfurt."

It is clear that the massive undertaking of the *Lehrbuch* was a project developed almost completely from his home and that Mühlstrasse 6 had become the center of German seismology and geophysics. Of special note in the *Lehrbuch* are remarks that appear on the concluding pages, in which he speculates about the possibility of earthquake prediction and admits that the density of seismographs at the time was too small to allow for the collection of adequate data to help with this question. Gutenberg's optimism was in sharp contrast to the pessimism of his later colleague Richter.

Wiechert died in March 1928, and Gutenberg was on the list to succeed him at Göttingen. He also had hoped to be the successor to Angenheister at Potsdam. But these hopes were not fulfilled, and he still could not find a permanent, decently paying position, despite his Olympian reputation among geophysicists. There are indications that his Jewish background played a part in all this. Indeed, Max Born remarked, in the case of the rejection of von Karman's candidacy, that there was concern over the number of Jews in the science faculty at Göttingen.

The *Lehrbuch* was a precursor to the even more monumental *Handbuch der Geophysik*, which was planned to be a series of ten volumes. Gutenberg accepted and successfully carried forward the editing of this daunting task. Although the job of editing the encyclopedia was accepted before his departure for Pasadena in 1930, the work continued afterward. The volumes appeared in irregular order; I was unable to locate volume 5, and it may not have been published. Volumes 1, 2, 4, 6, 7, and part of volume 9 appeared between 1931 and 1936. In 1937 the Nazis removed his name from the enterprise. Although the editorship of volume 3 (1940) was given to Weickmann, Gutenberg's chapters on forces in the Earth's crust and geotectonic hypotheses were not removed. Strangely, Gutenberg's bylines for these two sections in volume 3 identify him as being at Frankfurt, even though he had left for Pasadena ten years earlier. Linke's name appears as editor of volume 8.

The last part-volume to appear, volume 8(3), did so in 1955, thirteen years after the appearance of the volume preceding it. It was a slender and poor shadow of the earlier volumes. Clearly, without Gutenberg at the helm, the enthusiasm for the project had dissipated. Gutenberg contributed about 750 pages of text to chapters in volumes 2, 3, 4, and 9 between 1932 and 1940.

In 1921 the Carnegie Institution of Washington initiated studies in seismology at its Mount Wilson Observatory laboratory in Pasadena in cooperation with the California Institute of Technology. Laboratory director H. O. Wood with the concurrence of J. C. Merriam, president of the Carnegie, focused on understanding California earthquakes. Wood's scientific interests were mainly in instrumentation used to locate epicenters of earthquakes in southern California; faults then could be identified and statistics of local earthquakes could be constructed so that they might contribute to the prediction of strong earthquakes. To do this he had constructed a small but effective network of identical seismographs of his own design. The network was inaugurated in 1923 with Pasadena as the focal station.

In 1927 the Carnegie activity in seismology was moved to a new Seismological Laboratory that had been built by Caltech. By 1929 it was clear that the Carnegie program diverged from the directions that R. A. Millikan and the Caltech faculty thought important, which was that seismological studies should address global as well as regional problems. After all, could not the growing collection of records of near and distant earthquakes gathered by the best local network of instruments in the world be applied to the more basic problems of seismic wave propagation and the structure of the Earth?

A meeting of leading seismologists was convened in October 1929 to assess the program, and Gutenberg, Jeffreys, Byerly, and Macelwane attended as external visitors. (This was the first time that the two giants of geophysics and seismology—Jeffreys and Gutenberg—had met.) One of the recommendations was for the establishment of a chair at Caltech. It was clear that the decision to establish the chair had been made before the meeting had convened. As Gutenberg left Pasadena, Millikan remarked significantly that he hoped he would be seeing Gutenberg soon. Gutenberg, reflecting on the arduous sea and land voyage, thought not. Upon hearing the rumor that Harvard was also interested in Gutenberg, Millikan accelerated the process. Millikan's telegram arrived in Darmstadt two months after the meeting, "Could you consider seismological post here if satisfactory arrangements could be made?" Gutenberg's wire, mimicking Millikan's, read, "Would consider post if arrangements satisfactory." Six weeks after the telegram, the official letter arrived in Darmstadt in January 1930, offering him a full professorship in geophysics and meteorology at Caltech, as well as an appointment at the Seismological Laboratory.

Linke and the science faculty at Frankfurt were thus prodded to make a counteroffer. Frankfurt organized a search for a position in Germany for Gutenberg, but the hasty effort was half-hearted and expectedly unsuccessful. After some correspondence, mainly concerning salaries, in which Millikan raised his initial offer by 40%, Gutenberg accepted the position at Caltech (June 4, 1930); the dean of sciences at Frankfurt congratulated him. In September 1930, Beno, Hertha, and their children Arthur and Stephanie came to the United States to start a new life at Caltech. The beginning of the rapid development of the laboratory coincides with Gutenberg's arrival in Pasadena.

In 1936 responsibility for the Seismological Laboratory was transferred from the Carnegie Institution of Washington to the California Institute of Technology. From 1935 onward, Gutenberg was the de facto head of the Seismological Laboratory because of the illness of Wood. Although Wood had resisted the proposal to change the direction of the laboratory away from the phenomenology of earthquake occurrence and toward theory and interpretation, he stated when Gutenberg was appointed that the effort in southern California needed Gutenberg's talents and experience to help in the determination of epicenters and origin times (a misuse of Gutenberg's talents), adding "We need Gutenberg more than Europe does." Wood persisted in his belief that the focus of the laboratory should be on local seismicity and not on global geophysics. Wood remarked in 1938 that the true cost of his illness could be measured by the relentless effort of the Seismological Laboratory on distant earthquakes.

Even in Gutenberg's first year at Pasadena, it was clear that the work of the laboratory was undergoing a revitalization that reflected his presence. At the annual meeting of the Seismological Society of America in 1931, six of the fourteen papers on seismology came from Caltech, and three of these bore Gutenberg's name. In contrast, at the meeting of the society in 1929, there were no contributions from the Seismological Laboratory among the five papers on seismology. Over the years, many students and colleagues came to Pasadena, attracted by the wealth of new ideas and methods of doing earthquake research and by the intellectual power of Gutenberg and his two colleagues Benioff and Richter. The global center of seismological research had shifted from Darmstadt to Pasadena.

Gutenberg had now moved from aseismic Hessen to the active seismic environment of southern California. Having spent his life to that time studying seismic wave propagation from distant earthquakes, his new career allowed him to study earthquakes at close range. He was now able to work on both local and global seismological problems. He could use the records from the Caltech network of Wood-Anderson torsion seismometers, later to be upgraded to the electromagnetic seismographs invented by Benioff. Gutenberg quickly realized that the network could be used for more than the location of local earthquakes. The recordings could be applied not only to the study of local Earth structure in southern California but also to structural issues of a global nature, to Wood's dismay, as remarked. Gutenberg attacked the issues of microseisms in California and those of the structure of the Earth's crust in California. He used the laboratory's archive of seismograms from a number of southern California earthquakes to determine local Earth structure (1943).

Wood retired in 1947, and from that time Gutenberg was the official director as well. While this appointment clarified matters at the laboratory and generated coherence to its work, it had the unavoidable disadvantage of taking much of Gutenberg's research time for administration. He worked hard to stabilize the relationship between the Caltech administration and the laboratory during some difficult times.

On the global stage, Gutenberg and Richter wrote four monumental papers, *On Seismic Waves* (1934, 1935, 1936, 1939), covering the problems of travel-times for the many body waves in the Earth, amplitudes, surface waves, and deep-focus earthquakes. A bible for the observationalist, the papers represent the foundations of modern observational seismology. Although the titles reflect those in the earlier series of the Göttingen school, they are in no sense a revisiting of the older; rather, they are a magnificent original contribution containing all that was known about observations of the propagation of seismic waves through the Earth. The travel-time curves in the first of these papers (1934) were an exhaustive catalog of the properties of most of the identifiable seismic phases, including phases involving many multiple bounces off the surface of the Earth from within; multiple reflections off the core boundary; multiples within the core; and many mixed phases, such as ScSSKP and others. The travel-time curves of the 1934 paper preceded the Jeffreys-Bullen curves by one year, and the two sets of curves were in excellent agreement for the important phases.

The travel-time relations in the Gutenberg-Richter curves for roughly 30 phases are identified only by letters. Of particular interest is the branch labeled "G." This was a long-period wave with strikingly large amplitudes from the Solomon Islands earthquake of October 3, 1931, to which Gutenberg and Richter (1954) assigned magnitude 7.9 (the periods were as long as 135 sec). The large amplitudes were even more striking in view of the short-period pass-band of the seismometers of the time. Gutenberg and Richter identified the G-waves as horizontally polarized shear surface waves, which we now identify as very long-period Love waves. For the Solomon Islands earthquake, two later arrivals of the G-waves, labeled G2 and G3, were observed at some stations of the world. Gutenberg and Richter identified G3 as the G-wave phase, which had traveled one complete circuit of the Earth farther than G1. The observation that surface waves can undergo many circuits of the Earth is an important preliminary to the study of the free oscillations of the Earth that began in the 1960s.

In his work on the core, Gutenberg had noted that the wave motions at sites in the shadow zone did not vanish. He assumed that these waves were the consequence of diffraction by the boundary of the core. In her 1936 paper entitled "*P′*" Lehmann showed that the amplitudes of these waves in part of the shadow zone were too large, and she proposed that they were due to an inner core of the Earth lying within Gutenberg's core. Gutenberg and Richter (1938) reanalyzed the data on *P′* in the shadow zone and, using realistic models for the velocities in the core, concluded that the boundary of the inner core involved a gradual transition over a distance of 300 km starting at a radius that was 100 km less than Lehmann's value. Their P-wave velocity in the inner core of 11.3 km/sec was 2.7 km/sec higher than Lehmann's and was precisely consistent with the current estimate derived from analysis of the free oscillation spectrum of the Earth. The transition zone has disappeared from modern models of the inner core/outer core boundary. In the 1914 paper, the P-wave velocity at the top of the core was 8.5 km/sec. In view of the high velocities in the inner core, this value was lowered in the 1938 paper to 8.0 km/sec, a figure that is the same as the value today.

Jeffreys has described Gutenberg as being hesitant to accept the liquidity of the core. Gutenberg was quite aware of the non-seismological arguments for a liquid core from the tides and from the figure of the Earth. But in Gutenberg's view, a very low but finite velocity for S-waves corresponding to a low rigidity could still imply that the core could be mechanically weak, and there was no way to identify absolutely the absence of S-wave propagation through the core. The absence of observable S-wave propagation in the core could only place an upper bound on the value of the velocity. In the 1914 paper setting forth the discovery of the core, Gutenberg calculated the arrival times of S-phases through the core under the assumption that the Poisson's ratio for the core was 0.27, which would have given velocities around 4.7 km/sec, but he found no arrivals at these times. In the 1923 paper for the elastic constants in the interior, Gutenberg's velocity-depth curves show that the S-wave velocities in the core are less than about 1.2 km/sec. In later papers, the bound is lowered progressively. By 1959 (pp. 277-79), taking the tidal and figure-of-the-Earth issues into account, the velocity for the still unobserved S-waves was "probably less, possible much less than" 0.3 km/sec; the value for velocity is my interpretation of his threshold for the shear modulus.

In work done in Germany, Gutenberg used the variation of amplitudes to deduce the existence of a weak low-velocity zone for P-waves in the upper mantle at a depth of between 70 and 80 km (1932, vol. 4, p. 213). He also speculated that the low-velocity zone might start at the top of the mantle. For more than twenty years, he steadfastly held to his position of the existence of the zone, even though there were times when he was almost alone in this view. In 1949, using southern California data, he lowered the depth to the low-velocity zone to around 100 km below the surface; the zone had a much stronger contrast to the regions above and below than in his earlier study. He identified an additional low-velocity zone in the upper crust of southern California just above the Conrad discontinuity (1934), which was confirmed by showing that the arrivals of P-waves from explosions were earlier than those from earthquakes (1951). Gutenberg also speculated on the possibility that there were also low velocities in the lower crust above the Mohorovičic discontinuity. In the 1950s his tenacious view began to be accepted, especially from the evidence given by Press and Ewing in 1956 and by later authors of dispersion of surface waves by the mantle channel.

Throughout his career, Gutenberg was concerned with the horizontal mobility of the continents. How was horizontal mobility driven? His early models (1930) for continental drift involved centrifugal and nonisostatic forces; forces due to thermal contraction were added later. In September 1950 in Hershey, Pennsylvania, Gutenberg was a co-organizer of and active participant in a conference on flow in the Earth's interior, where much discussion centered on convection (1951). One of the conclusions of the conference was the importance of convection in the mantle of the Earth driven by gravitational instabilities of thermal origin. The proponents of convection David Griggs, Harry Hess, and Felix Vening Meinesz were prominent. The opposite view was represented by Francis Birch. Gutenberg stated, ". . . we observe at the surface, phenomena that are possibly connected with convection currents at spots where the currents are going down (or coming up) and that all such observations refer to belts surrounding the Pacific basin," and that the bottom of the Pacific is moving in the same direction relative to the continents in California, Japan, Philippines, and New Zealand. These may be prescient statements of the present view that the major part of subduction takes place around the rim of the Pacific and about plate motions, although plate tectonics was eighteen years in the future.

Gutenberg's ideas about convection must have been encouraged by the 1950 conference, because convection in the mantle appears as an important component of his thinking. In *Internal Constitution of the Earth* (1951), he suggests that convection may be the most potent of all mechanisms for causing continental drift. He also constructed a temperature profile for the mantle to a depth of 600 km based on the assumption that convection below a depth of 80 km will lower the temperature gradient. The depth of 80 km was chosen to correspond to the depth of his low-velocity zone, a zone that he associated with low strength due to elevated temperature. In today's language, the lithosphere, that is, the uppermost 80 km of the Earth (his value for the thickness) and especially under the oceans, moves as a consequence of mantle convection. The temperatures below 80 km were significantly lower than present estimates. Later, in *Physics of the Earth's Interior* (1959), he extended the temperature curve smoothly to the center of the Earth. In making the extension, Gutenberg relied on estimates of the melting temperature of iron at core and inner core pressures that were considerably lower than present-day estimates, and thus derived rather lower temperatures than present-day estimates.

Gutenberg had never experienced an actual earthquake until a few years after his arrival in Pasadena. The story often has been told that Einstein and Gutenberg were walking across the Caltech campus in the late afternoon of March 9, 1933, so deeply engrossed in their scientific conversation that they failed to notice the shaking of the ground in the disastrous Long Beach earthquake and were only made aware of the earthquake by colleagues shortly thereafter. The story was confirmed by wives of both men, so it must have been true. Gutenberg did feel many of the large aftershocks of the Long Beach earthquake.

The large number of earthquakes in southern California presented a natural challenge to quantify the earthquake process. The start was the construction of a magnitude scale for local earthquakes (M_L) in southern California using the uniformity of the Wood-Anderson seismographs in the local network. Gutenberg had an important influence on Richter's publication in 1935 of the local magnitude scale. Shortly thereafter, Gutenberg and Richter (1936) constructed the surface wave magnitude scale for distant earthquakes (M_S), and the surface wave magnitudes were normalized according to the local scale. For the first time, the magnitudes of the largest earthquakes were identified as having magnitudes from 8 to 8.5. Gutenberg and Richter established the magnitude scale for deep earthquakes, which do not excite surface waves (1945). The magnitude scale for local earthquakes was mainly due to Richter; the magnitude scale for distant earthquakes, with application to the largest earthquakes, was due to both men, with Gutenberg as the prime mover. Some people have expressed unhappiness that the magnitude scale has not been called the Gutenberg-Richter scale.

Magnitudes are of importance in that they provide a unifying parameter about which a variety of properties of earthquakes can be related (1942). The development of the magnitude scale, Gutenberg's calculation of the energies radiated in seismic waves (1956), and Benioff's ideas about strain accumulation and relaxation allowed for the opening of a new science: the study of the Earth's seismicity. This was first explored in the monumental book by Gutenberg and Richter, *The Seismicity of the Earth* (1954), in which the statistics of local earthquakes were described. This was the first major catalog of great earthquakes worldwide, classified not only as to time and location but also as to magnitude. The statistics showed the famous universal, log-linear frequency magnitude relation with a slope close to 1.0. The calculation of energies for selected earthquakes had been done earlier (1929, pp. 187, 296). Gutenberg now embarked on a study to relate the energy released in an earthquake to its magnitude. For the first time the energy flux in earthquakes could be calculated. The energy-frequency relation could now be shown to be a power law with exponent close to –2/3. In later years, the power law relation has been a paradigm for the modeling of seismicity and the earthquake process.

In 1926 the National Research Council appointed a committee to prepare a report entitled *Internal Constitution of the Earth*. Little appears to have been done until 1937, when Gutenberg was appointed to chair the committee and was charged with the task of reorganizing it. With characteristic vigor, the task was completed in short order, and the volume appeared in 1939; the printing was exhausted quickly. In view of the progress made since 1939, a second revised edition appeared in 1951 with major changes from and additions to the first edition. The purpose of the volume was to give a scientific reader outside the field an overview of the status of the field and an identification of the unsolved problems. The volume responded to the original charge, but it was also a resource of great completeness where students could find copious references to additional material. It thus became almost immediately a major and highly cited scientific resource for the evidence and interpretation of the composition, temperature, elastic properties, figure, density, gravity, origin and evolution, and the stress-strain state of the interior. The volume shows that major new results and major new ideas had developed in the years since the *Handbuch*. Gutenberg was no mere managing editor, having written more than half of the volume himself. Where differences of opinion arose among the authors, no effort was made to reach consensus; each author developed his material unrestrained.

Only months before his death, Gutenberg's last book *Physics of the Earth's Interior* (1959) was published. A companion volume on seismology was planned, but death intervened. The book focuses on many of the same subjects as *Internal Constitution*, but this time the exposition is a personal, systematic journey through crust, mantle, and core before attacking the issues of temperature, density, tides, etc. The book is a remarkable summary of the properties of the interior of the Earth and an accounting of the vast number of sources for this information, many of them coming from Gutenberg's own measurements. Gutenberg showed himself to have been a voracious reader of the literature. The book is a deep, thoughtful, and thorough monograph on geophysics and proves that Gutenberg was not merely a great seismologist. Remarkable in his swan song is his prescient identification of topics that shortly would elicit much interest. I mention two such areas.

The first topic was his brief identification of the importance of studies of the resonance spectrum of the Earth. Would not Gutenberg have been excited by the unprecedented observations of the rich resonance spectra that resulted from recordings of the great Chilean earthquake of 1960, which occurred four months after his death? The observations of these spectra triggered a grand flowering of activity in inverse theory and ultra-long period seismology; in particular, density estimates for the Earth's interior could be derived from the spectra without assumptions about compressibility or other properties.

The second topic was Gutenberg's commitment to the ideas of convection and continental drift, although he did not connect the two. That linkage was not to happen for another nine years, with the development of the plate tectonics model. However, he made a definite insightful assertion that convection would be shown to be responsible for mountain building and earthquakes, and from his reconstruction of the continental geometry into an almost single mass in Cretaceous times, that climates on the long-time scale will depend on understanding continental drift.

After the assumption of power by the Nazis, Gutenberg kept his contacts in Germany alive. During these prewar years, he helped many Jewish scientists escape from Germany. Notable among these were Viktor Conrad, editor of *Gerlands Beiträge*, and Helmut Landsberg. Landsberg had been Gutenberg's student and was his successor as director of the earthquake service at the Taunus observatory. In 1934 Landsberg fled to the United States with Gutenberg's help and became professor at Pennsylvania State College in College Park.

Gutenberg returned to the problem of microseisms and their meteorological causes while working on a project for the U.S. Navy during and after World War II. Gutenberg was a valuable World War II consultant to the Navy, applying his knowledge of the structure of the upper atmosphere to the problems of ballistics. He also worked on applications of the observations of microseisms to locate hurricanes in the Caribbean and the western Pacific. Within a few weeks of the war's end, Gutenberg wrote to the Navy stating that for many years he had been suggesting the use of microseisms for forecasting of storms, especially hurricanes. No longer were microseisms associated with surf, he asserted, but now they were associated with differential loading of the ocean bottom by distant storms. The theory was given by M. Longuet-Higgins in 1950. The results that he had obtained in the Caribbean area exceeded by far his most optimistic hopes. In the spring of 1947 the Navy sent Gutenberg to Japan, Guam, and the Philippines to do additional research on microseisms, as well as to consult on the problems of the revival of seismological research in these countries in the wake of the war.

Gutenberg was small of stature, very personable, and lively. He was well organized and kept to a precise daily schedule. Although his scientific demands on himself were rigorous, Gutenberg was gentle and self-effacing in his relationship with others. He was helpful to anyone who asked a question of him and was tolerant of critics. Gutenberg was a man who could give his colleagues and students a liberal education in scientific method, made pleasantly easy by kindness, patience, amazing industry, and a delightful sense of humor. He was a cultured individual, well read, and with wide interests—reflections of his broad European education.

Having inherited his mother's musical talents, Beno learned to play the piano, a skill that was to last him through his entire life. In his earliest years in Darmstadt, Beno sang in the synagogue choir and often played the organ. In the Pasadena years, Einstein played the violin in chamber music events organized at the Gutenberg home. At the end of World War II, in a reprise of the bartering activity of earlier years, Gutenberg collected the accumulated royalties on his publications in Germany by payment in the form of numerous piano scores for two and four hands.

His bookplate shows the Owl of Wisdom with a seismogram in its beak in flight around the Göttingen Institute of Geophysics. The text on the bookplate repeats the motto of the *Lehrbuch*:

Viele Zeichen gibt uns die Natur,
Leitet uns auf der Erkenntnis Spur,
Weist uns ihre wunderbaren Bahnen,
Lässt die Seele uns des Weltalls ahnen!

Frank Press, former president of the National Academy of Sciences, has stated, "Gutenberg was absolutely dedicated to seismology, especially to observational data and their interpretation. His work carries the mark of much self-confidence in his ability to examine data not as a statistician but as a skillful interpreter and synthesizer." Throughout his entire career, Gutenberg's reputation rested on the solid foundation of his own reading with great accuracy and insight of the arrival times and other properties of seismic waves on the seismic records. In contrast to the modus operandi of many modern scientists, Press continues, "Gutenberg could draw conclusions from sparse and noisy data with uncanny insight that" structures such as a core and a low-velocity zone and continent-ocean differences could be stated to exist. Gutenberg's belief in the power of the data to resolve issues of differences in models is given by the penultimate sentence of *Physics of the Earth's Interior*: THE DATA "MUST BE GREATLY AMPLIFIED AND STRENGTHENED" (Gutenberg's capitalization and punctuation). Gutenberg dominated the field of observational seismology as no one before or after. At the time of his death, Byerly remarked, "It is rare that anyone writes a paper in seismology without referring to him."

When one reads the list of Beno Gutenberg's contributions to the full range of seismological studies—spanning seismicity, wave propagation in the Earth, and the physics of the Earth's interior—one must be in awe of his insights, his breadth, his thoroughness, his vigor, and especially his creativity.

I AM MOST GRATEFUL to Caltech for allowing me access to a variety of documents in its archival files of Beno Gutenberg and Charles F. Richter and to a transcript of an oral history interview with Hertha Gutenberg. The history of the Seismological Laboratory as given in

Milikan's School by Judith R. Goodstein (W. W. Norton, New York, 1991) was valuable. I have also found the following biographical articles helpful:

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If it should be perceived that I have appropriated some of the language in the above documents, the accusation is well founded. These authors have been a most valuable resource, not only for their thoughts on the life and science of Beno Gutenberg but also in their admirable choice of words.

HONORS

1945	Member, National Academy of Sciences
	Honorary member, Royal Society of New Zealand
1945-47	President, Seismological Society of America
1947	Foreign member, Academia dei Lincei
	Honorary member, Finnish Geographical Society
1948	Foreign member, Finnish Academy of Letters and Sciences
1949	Foreign member, Royal Swedish Academy of Sciences
	Member, Washington Academy of Sciences
1950	Fellow, American Academy of Arts and Sciences
1951-54	President, International Association of Seismology and the Physics of the Earth's Interior
1952	Prix Lagrange, Royal Belgian Academy of Sciences
1953	Bowie Medal, American Geophysical Union
1954	Foreign Member, Geological Society (London)
1955	Honorary doctorate, University of Uppsala
1956	Emil-Wiechert Medal, German Geophysical Society

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