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CHAPTER 3 The First 100 Years (1845–1945)

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CHAPTER 3

The First 100 Years (1845–1945)

3.1. THE BEGINNING OF SEISMOLOGY

Since the beginning of the twentieth century, seismic waves have been used to study the Earth's interior. This concerns both the study of the whole Earth by distant earthquakes and of Earth's crust by local natural and artificial events. The rapid development of this special branch of seismology would not have been possible without the early technical developments of seismographs and sensitive recording devices of the foregoing century. An early historic review was published by Mintrop as early as 1947, describing the history of the first 100 years of earthquake research and explosion seismology (Mintrop, 1947; see also Appendix 3-1).

The first seismoscope is believed to have been constructed by the Chinese philosopher Chang Hêng in 132 A.D. Europeans wrote about earthquake-detecting instruments from the early eighteenth century. Earthquakes in Naples in 1731, the earthquake of Lisbon in 1755, earthquakes in Calabria in 1783, the New Madrid earthquakes of 1811 and 1812 in America, a series of small earthquakes near Comrie in Perthshire, Scotland, in 1839, and others triggered the construction of various seismoscopes. The general interest in recording earthquakes grew systematically.

Physical earthquake research started in 1848 with a publication by Hopkins (1848), who for the first time applied the refraction and reflection laws of optics to the propagation of earthquake waves and who introduced the expressions apparent surface velocity v, volume velocity V and the relation v/V = i, giving the angle at which elastic waves enter the Earth's surface (Fig. 3.1-01; Mintrop, 1947).

The years between 1850 and 1870 saw several significant contributions to seismological instrumentation. These included Palmieri's seismoscope for recording the time of an earthquake, and a suggestion by Zöllner that the horizontal pendulum might be used in a seismometer. Palmieri's *sismografo*, for example, seems to have been an effective earthquake detector for its time and was used by Palmieri on Mount Vesuvius. Later, Palmieri's *sismografo* was used by seismologists in Japan; where, from 1875 to 1885, 565 earthquakes were detected in Tokyo. In 1889, while investigating tidal signals with a horizontal pendulum at the Telegrafenberg in Potsdam, Germany, Ernst von Rebeur-Paschwitz identified, for the very first time, a signal that was caused by seismic waves from an earthquake near Tokyo.

The foregoing work set the stage for the late 1800s and early 1900s, when many fundamental advances in seismology were made. In Japan, three English professors, John Milne, James Ewing, and Thomas Gray, working at the Imperial College of Tokyo, invented the first seismic instruments sensitive enough to be used in the scientific study of earthquakes. They

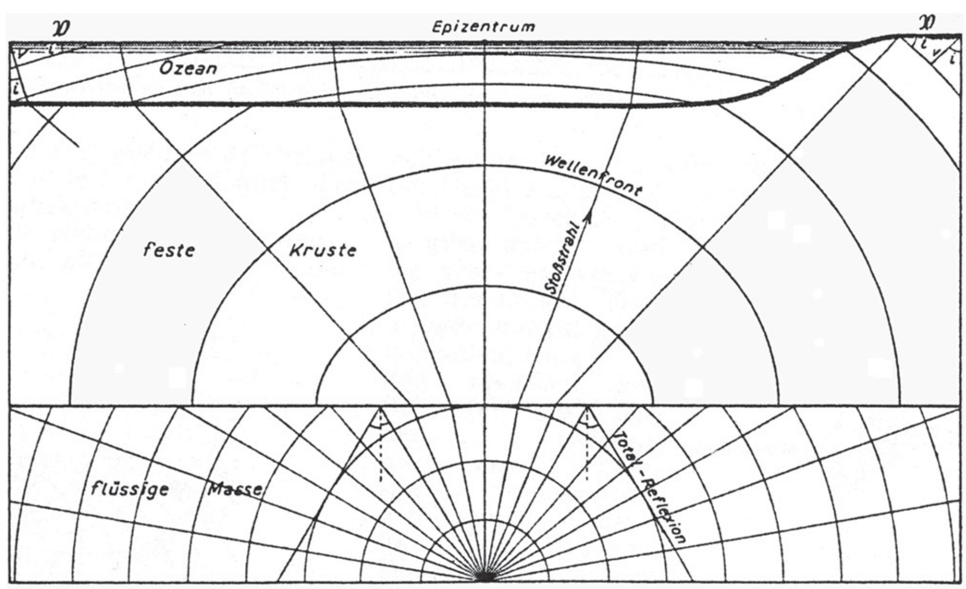

Figure 3.1-01. Wave fronts and rays radiating from an earthquake source according to Hopkins (1848) (from Mintrop, 1947, fig. 1). [Die Naturwissenschaften, v. 34, p. 257–262, 289–295. Published by permission of Springer-Alerts.]

obtained the first known records of ground motion as a function of time, and they learned what such records could reveal about the nature of earthquake motion. They used their instruments to study the propagation of seismic waves, and they used them to study, for engineering purposes, the behavior of the ground in earthquakes. Under the influence of J. Milne, the Seismological Society of Japan was founded in the spring of l880 after a larger earthquake in Yokahama (Milne, 1885). After 1885, routine earthquake recording in Tokyo was started by new seismographs just developed in Japan. Nearly two decades later, Milne was largely responsible for having similar seismographs set up at stations throughout the world, in order to collect data which could be evaluated at a central observatory. In 1882, A.B. Briggs constructed his own seismograph in Launceston, Tasmania, Australia, and made recordings of Tasmania's earthquakes from 1883 to 1885 (D.M. Finlayson, 2010, personal commun.). Ewing's "duplex-pendulum" seismometer, invented in Japan, is of particular interest because in 1887 and 1888, this type of seismometer was placed at ten sites in Northern California and Nevada. In Italy, earthquake research begun by Cavalleri and Palmieri was continued by Italian seismologists in the 1870s. In 1874 the first journal devoted to solid-earth geophysics, the *Bulletino del Vulcanismo Italiano*, was founded and edited by M. De Rossi. In 1869, Zöllner described a horizontal pendulum with the suspension which has since been associated with his name. Horizontal pendulums were to be widely used in seismographs after 1880, because they could be given long periods and could still be compact. The Zöllner suspension was used, e.g., in the Galitzin horizontal seismograph, constructed in 1910 in Russia. A detailed summary of the early history of seismometry has been published by Dewey and Byerly (1969).

3.2. EARLY CRUSTAL STRUCTURE INVESTIGATIONS FROM SEISMOLOGICAL OBSERVATIONS SINCE 1898

During the following decades, earthquake recording stations were established in many countries of the world, in particular in Europe, Japan, and North America, where a high technological standard was available. As an example, the early development of seismology in Germany may be described in some detail.

In Germany, geophysics became a recognized field of science when the University of Goettingen established the Institute for Geophysics in 1898 (for details see Appendix A3-2). Here, Emil Wiechert (1861–1928) was appointed as its director and thus became the first professor of geophysics in Germany. He was one of the first scientists in Germany to study Earth's interior. Wiechert established a working group for seismology which was leading science in this type of research at the beginning of the twentieth century. The most famous co-workers of E. Wiechert were G.H. Angenheister, L. Geiger, B. Gutenberg, G. Herglotz, L. Mintrop, W. Schlüter, G.v.d. Borne, and K. Zoeppritz (Ritter et al., 2000; Ritter, 2001, Appendix A3-2).

The first seismological measurements in Goettingen were made in 1898. In the following years, the theory for seismological instruments was improved and more precise measurements were developed at a new institute on the Hainberg, outside the city to avoid cultural noise (Wiechert, 1903). Modern earthquake recording began in January 1903 (Figure 3.2-01).

Since that time seismicity has been continuously observed in Goettingen, using the famous automatically recording Wiechert-seismographs (Figure 3.2-02) which recorded on smoked paper. From July 1903 onwards, seismic bulletins were published (Linke and Wiechert, 1903). In 1905, this station (GTT) was officially appointed as the main seismic station in Prussia. Additional stations were soon added in the Hartz Mountains (Clausthal) and on the island of Heligoland. The disastrous 1906 earthquake of San Francisco was well recorded in Goettingen (Figure 3.2-03). Worldwide observations were initiated by establishing seismic stations at Tsingtau, China, and on the Samoan archipelago (Apia) in the western Pacific Ocean. In 1909, Father Edward Pigot established the Riverview Observatory, Sydney, Australia, using a system derived from the work of Galitzin in Russia and the seismometers designed by Wiechert (D.M. Finlayson, 2010, personal commun.).

Up to 1914, numerous basic discoveries were made at Goettingen (e.g., Wiechert, 1907), for example, the law for amplitude ratios of reflected, transmitted, and converted waves at discontinuities (Zoeppritz equations; Wiechert and Zoeppritz, 1907), contributions to the existence of Earth's core (Gutenberg, 1914), and an inversion algorithm for determining the depth-dependent distribution of seismic velocity from arrival times (Herglotz-Wiechert method; Herglotz, 1907). During World War I, seismic waves from large guns were detected at arrays of seismic stations and used to pinpoint gun emplacement sites. This basic research laid the foundations for the first experiments with manmade seismic events in the early 1920s after the First World War.

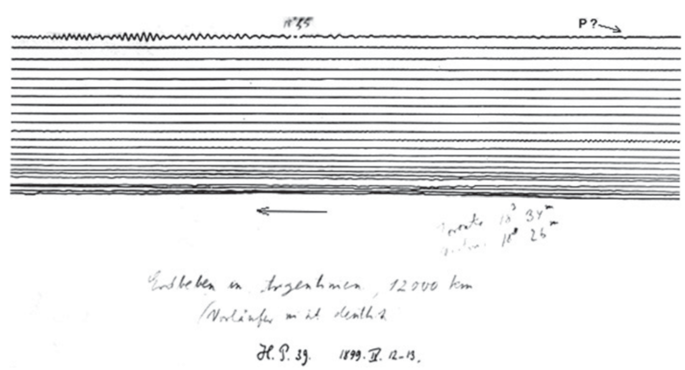

Figure 3.2-01. Example of an early recording on photo-sensitive paper with a horizontal pendulum (from Ritter et al., 2000). The time increases from right to left; one line corresponds to nearly one hour (1 min = 6 mm). On 12 April 1899, a far-distant earthquake from Argentina was recorded. [History of Seismology in Göttingen ("Overview" by Joachim Ritter, fig. 1), unpubl., reproduced in Appendix A3-2. Published by permission of J. Ritter.]

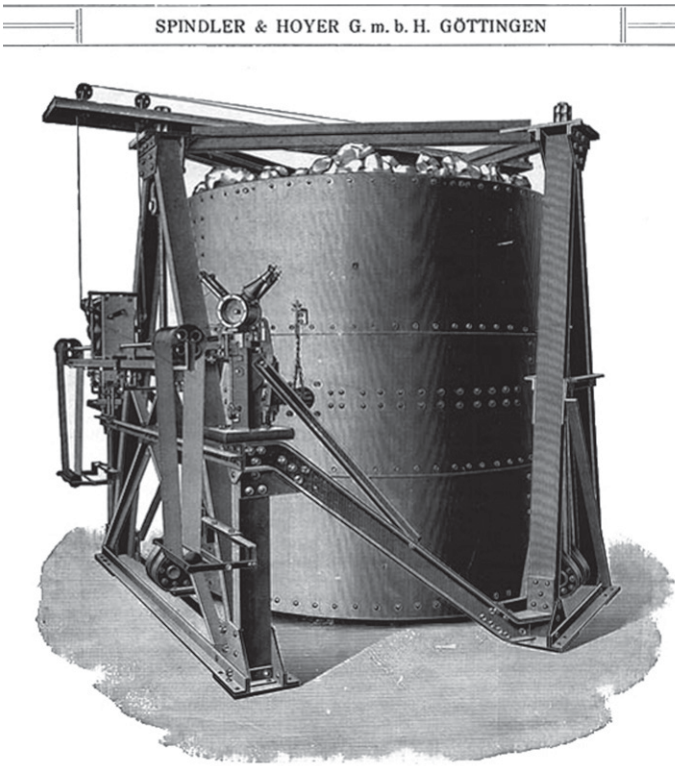

Figure 3.2-02. Drawing of the 17 t horizontal pendulum built by Wiechert in 1904 (from Ritter et al., 2000). [History of Seismology in Göttingen ("Emil Wiechert 1861–1928" by Sebastian Rost, fig. 4), unpubl., reproduced in Appendix A3-2. Published by permission of J. Ritter.]

The very first detection of Earth's crust as a separate unit, however, was detected by the study of local earthquakes in southeastern Europe (Mohorovičić, 1910). Many of the numerous studies of early earthquake records aimed to learn about the structure and physical properties of the Earth. So, in 1909, A. Mohorovičić at Zagreb, during his study of seismograms of a strong local earthquake, constructed a travel-time–distance plot (Figure 3.2-04). This event had occurred on 8 October 1909 in the nearby Kulpa Valley (~40 km south of the observatory) and had many aftershocks recorded throughout central Europe. Mohorovičić noticed that exclusively for distances between 300 km and 720 km, an additional P-wave and a corresponding S-wave could be identified from which he deduced a discontinuity with a velocity jump from 5.68 to 7.75 km/s at a depth which he calculated to be 54 km. He stated, "Since the $\bar{P}$-wave can only reach down to a depth of 50 km, this depth marks the limit of the upper layer of the Earth's crust. At this surface, there must be a sudden change of the material which makes up the interior of the Earth, because there a step in the velocity of the seismic wave must exist" (Mohorovičić, 1910). This boundary, based on the phase $\bar{P}$, later labeled P_n, was shortly thereafter defined as the crust-mantle boundary and was named the Mohorovičić discontinuity (subsequently shortened to "Moho") separating the crust with average velocity of 6.0–6.5 km/s and the uppermost mantle with velocities around 8 km/s.

It took another 15 years before the first fine structure of the Earth's crust was detected. In 1925, when investigating the records of the Tauern earthquake of 20 November 1923, Conrad detected a phase P* and inferred from it an intracrustal

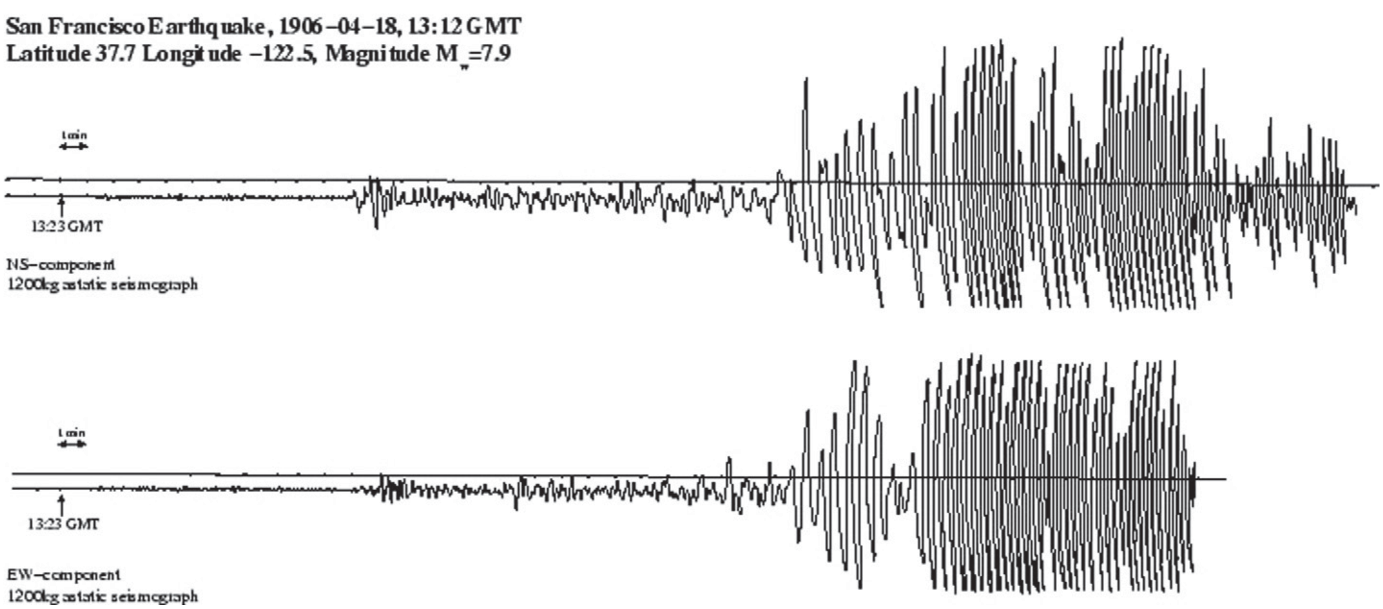

Figure 3.2-03. Recording of the 1906 San Francisco earthquake at Göttingen, (digitized by Elmar Rothert, from Ritter et al., 2000). [History of Seismology in Göttingen (seismogram digitized from original paper record), unpubl., reproduced in Appendix A3-2. Published by permission of J. Ritter.]

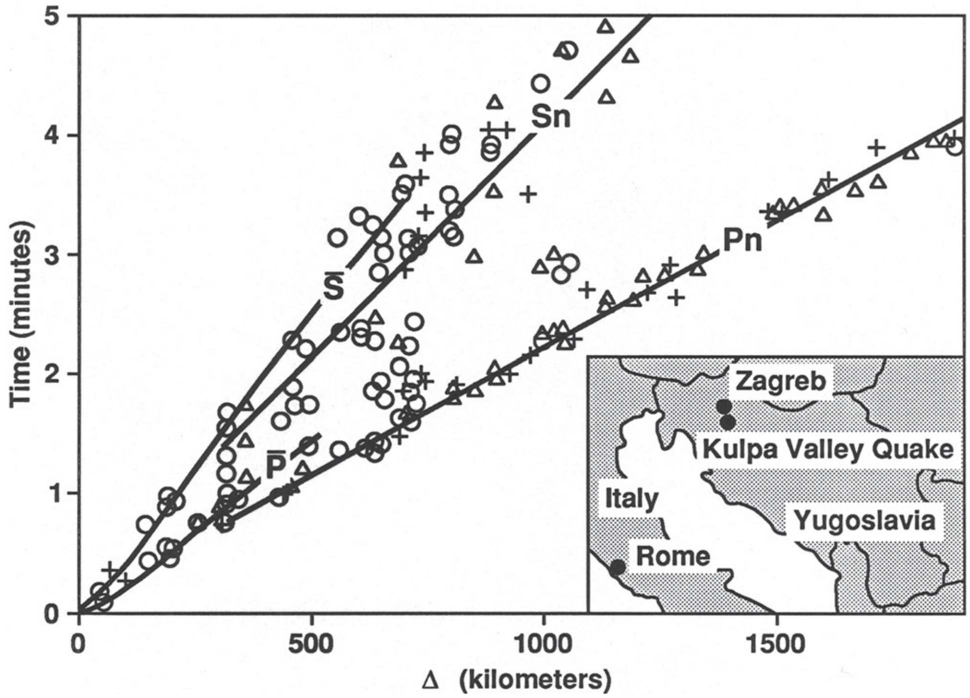

Figure 3.2-04. Mohorovičić's (1910) traveltime versus distance plot for the 8 October 1909 Kulpa Valley earthquake and its aftershocks. After Mohorovičić (1910) and Skoko and Mokrović (1982) and redrawn from Jarchow (1991, ch. 2, fig. 2). [Ph.D. thesis, Department of Geophysics, Stanford University, Stanford, California, ch. 2: The nature of the Mohorovičić discontinuity, p. 2.01–2.53. Published by permission of the author.]

discontinuity (Conrad, 1925). He could establish its existence, but with varying depths, when he investigated a 1927 earthquake (Conrad, 1928). Subsequently, many other investigators worldwide confirmed this discontinuity and it was finally named the Conrad-discontinuity.

In his book *The Earth*, Jeffreys (1929) discussed in much detail the detection of the subdivision of the crust based on near-earthquake observations in continental regions. In his summary on the upper layers of the Earth, he concludes that three layers are concerned: an upper layer, 10 km thick, with P-velocities 5.4–5.6 km/s; an intermediate layer, 20 km thick, with 6.2–6.3 km/s; and a lower layer with 7.8 km/s. Comparing the velocities with laboratory measurements on the compressibility of rocks, he suggested that the three layers are probably composed of granite, tachylyte (glassy basalt) and dunite, and that there is probably no layer of crystalline basalt. Though the conditions below the oceans had been "less thoroughly studied," he saw evidence that the granitic layer there was thin or absent.

Suggestions that the structure of the Earth's crust was even more complicated came from Gutenberg in 1934. He had already used the variation of amplitudes in local earthquake recordings to deduce the existence of a weak low-velocity zone for P-waves in the upper mantle at a depth between 70 and 80 km (Gutenberg, 1932a, vol. 4, p. 213). Now, in 1934, he identified an additional low-velocity zone in the upper crust of southern California just above the Conrad discontinuity (Gutenberg, 1934), which was confirmed by showing that the arrivals of P-waves from explosions were earlier than those from earthquakes (Macelwane, 1951). Gutenberg also speculated on the possibility that there also existed low-velocity zones in the lower crust above the Mohorovičić discontinuity. Also, for oceanic areas, early estimations of crustal thickness were made. For example, Hayes (1936) and Bullen (1939) used records from earthquakes to determine the crustal thickness around New Zealand.

Gutenberg (1924) also acknowledged another fundamental property of the Earth's crust, namely a fundamental difference between continental and oceanic crust. He confirmed observations, which Tams, Angenheister, and Macelwane had made in 1921 and 1922, that the velocities of propagation of surface waves were faster across the oceanic than across the continental portions of the Earth's surface (Gutenberg, 1924; see also tables 54–65 of Macelwane, 1951). He proposed a method of inversion for the dispersion recognized in surface waves to determine upper mantle structure that was similar to the method ultimately applied in the late 1950s. His inversion for crustal thickness 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. 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 (Gutenberg, 1936).

In Volume VII of *Physics of the Earth*, edited by B. Gutenberg, on the internal constitution of the Earth, first published in 1939 and re-published with revisions in 1951, Macelwane (1951) summarized velocity measurements for the entire earth in 38 tables (tables 36–73), based on 244 references. Table 43 of Macelwane (1951) shows the varying velocities of the phase P* defining the Conrad-discontinuity published until 1939, and a summary of P_n-velocities published until 1939 is given by Macelwane (1951) in table 44.

3.3. THE FIRST STEPS INTO CONTROLLED-SOURCE SEISMOLOGY—1851–1945

While the basic structure of the Earth's crust was detected by the detailed study of earthquake records, the accuracy of seismological studies was limited for more refined studies of the Earth's crust because of too many unknown parameters, i.e., the exact time and the exact location of natural earthquakes. In the middle of the nineteenth century, the first studies with controlled events were started. Explosion seismology was born in 1849, when Robert Mallet used dynamite explosions to measure the speed of elastic waves in surface rocks (Mallet, 1852; Mintrop, 1947; Dewey and Byerly, 1969; Jacob et al., 2000). He wished to obtain approximate values for the velocities with which earthquake waves were likely to travel. However, he obtained only 500 m/s in granite, i.e., the energy was not sufficient to observe the first arrivals at his 2 km distant seismoscope even using 5500 kg of black powder. It was Henry Larcon Abbot who, in 1876, for the first time obtained a realistic velocity in gneissic rocks of 6.24 km/s recording several explosions with charges between 11,000 and 2000 kg dynamite with similar instruments to Mallet's, but with much larger amplification (Abbot, 1878; Mintrop, 1947).

The further development of explosion seismology depended largely on the construction of suitable instrumentation. In 1881, with his new 3-component seismic instrument invented in Tokyo, J. Milne described a trial to record an explosion of 1 kg of dynamite at 65 m distance on smoked paper (Milne, 1885). The problem, however, was to detect the short-period P-waves preceding the long-period surface waves. Also Hecker's experiment with 1500 kg of explosives recorded up to 350 m distance gave only weak indications of these preceding short-period arrivals (Hecker, 1900). Slightly more successful were Fouqué and Lévy (1889) experimenting in a mine to obtain the precursors using, for the first time, a photographic recording device when recording charges of 4 kg black powder at 145 m distance. Mintrop (1947) described in detail the first steps of controlled-source seismology.

Many of the explosion seismic experiments had hinted at practical uses of the method. In the late nineteenth century, various publications appeared on the theory of wave propagations. Schmidt (1888) proposed the study of time-distance records of artificial disturbances to determine the variation of the speed of seismic waves with depth (Nettleton, 1940). Knott (1919) published a paper on the propagation of seismic waves and their refraction and reflection at elastic discontinuities. Weatherby (1940) cites the objectives as expressed by Belar in 1901 that "the modern, sensitive instruments may easily be used to special advantage wherever we wish to learn beforehand the composition of the Earth's crust to carry out to advantage, e.g., the construction of a tunnel. A series of tests carried out along the tunnel line on the surface would be sufficient to enable us to form a reliable judgment on the elasticity conditions, or, say, on the rigidity of the ground, of an earth stratum which would not be accessible by other means." A few years later, Wiechert and Zoeppritz (1907) had worked out the theory of seismic wave transmission through the Earth and gave solutions to the problems of seismic wave propagation, refraction and reflection, which placed the theoretical solution of the problem far ahead of the experimental solution (Weatherby, 1940). Finally, Wiechert (1910) expressed what would be the subsequent practice of refraction profiling, that the farther away from the source seismic waves are observed, the deeper they penetrate into the Earth and the more of the assumed layers they will have traversed. Correspondingly, one can compute the paths of all rays through these layers.

The final instrumental progression to record artificial earthquakes was when, in 1906, E. Wiechert in Goettingen constructed a transportable seismograph which amplified the horizontal component of the ground movements by 50,000. In 1908, active seismological experiments started in Goettingen in the garden of the institute where Ludger Mintrop made the first experiments to investigate the uppermost sedimentary layers using a weight drop and recording with Wiechert's portable seismographs (Figure 3.3-01).

To examine the effect of a falling weight, he built a mechanism to drop a 4000 kg iron ball from a height of 14 m. In this way, Mintrop recorded the first seismograms including the fine details of precursor waves (now called P and S body waves) from a controlled source (Figure 3.3-02).

As mentioned above, during World War I, seismic waves were recorded to compute the position of large guns. The British

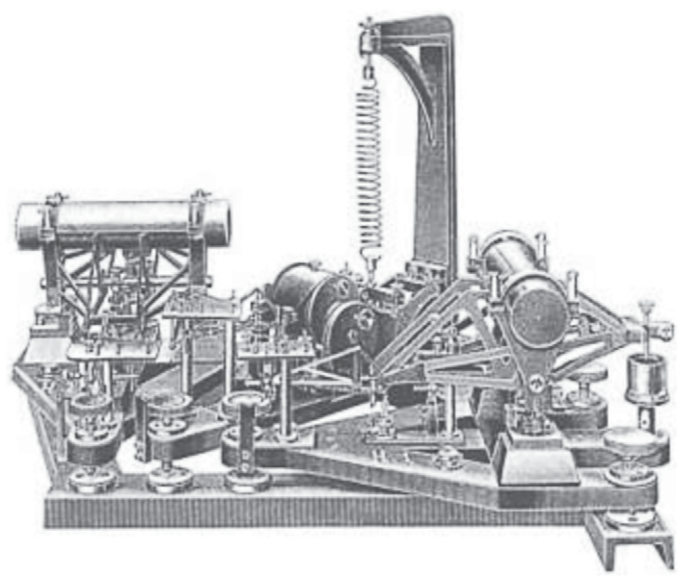

Figure 3.3-01. Drawing of Mintrop/Wiechert mobile seismometers built to observe higher frequencies in all three components (after Galitzin, 1914) (from Schweitzer and Lee, 2003). [*In* Lee, W., Kanamori, H., Jennings, P.C., and Kisslinger, C., eds., International Handbook of Earthquake and Engineering Seismology, Part B: Amsterdam, Academic Press. Copyright Elsevier.]

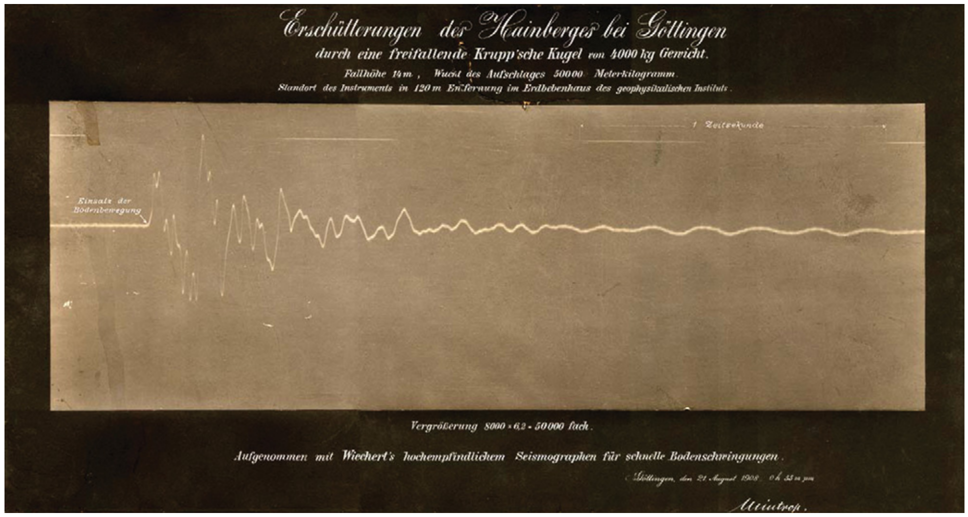

Figure 3.3-02. Recording of the wavelet generated by the drop of the 4000 kg ironball by the Wiechert-seismograph on 21.08.1908 (from Ritter et al., 2000). [History of Seismology in Göttingen ('L. Mintrop' by Andreas Barth, fig. 1), unpubl., reproduced in Appendix A3-2. Published by permission of J. Ritter.]

army used a 6-channel Eindhoven string galvanometer system, tuning fork timing and an array of carbon microphones to record the seismic energy (D.M. Finlayson, 2010, personal commun.).

The Canadian inventor Reginald Fessenden was the first to conceive of using reflected seismic waves to infer geology. In 1913, he had worked in the United States and had conducted various experiments. On the basis this research, he obtained "patents (Fessenden, 1917) on a method of exploration that involved the principle of the seismic method" (Nettleton, 1940). Due to World War I, however, he was unable to follow up on the idea, but worked on methods of detecting submarines.

In the United States, John Clarence Karcher discovered seismic reflections independently while working for the U.S. Bureau of Standards (now the National Institute of Standards and Technology). John Clarence Karcher had entered the University of Oklahoma (OU) in the autumn of 1912 to study electrical engineering, but later changed his major to physics. Contacts he made in both departments become an important part of the story. Karcher graduated from OU in 1916 with a B.S. in physics and started graduate work at the University of Pennsylvania. Unfortunately, World War I began and Karcher went to the U.S. Bureau of Standards. William P. Haseman, who was the head of the Physics Department at OU responsible for getting Karcher into the University of Pennsylvania, took a temporary leave and also went to work during the war at the U.S. Bureau of Standards, where scientists were engaged in the development of sound-ranging equipment to be used in locating the enemy artillery. During this work, seismic energy as well as the air waves were studied. When Karcher tried to observe artillery via ground waves, he noticed some extra waves that seemed to be reflections from layers of rock inside the Earth. It occurred to him that by means of reflected energy, geological structures could be mapped. When he showed these reflections to Haseman, it was Haseman who suggested they form a company to use these reflected waves to find oil and gas. They agreed to form this company after the war. Karcher went back to the University of Pennsylvania to finish his education before starting on his big venture with Haseman. In 1919, they started experimental work. After numerous tests in many areas, a two-trace record was obtained that positively indicated a shallow reflection. In 1920, they finally organized the Geological Engineering Company and began field operations in Oklahoma (Musgrave, 1967). The first field tests were conducted near Oklahoma City, Oklahoma, in 1921.

The company soon folded due to a drop in the price of oil. In 1925, oil prices had rebounded, and Karcher helped to form Geophysical Research Corporation (GRC) as part of the oil company Amerada. In 1930, Karcher left GRC and helped to found Geophysical Service Incorporated (GSI). GSI was one of the most successful seismic contracting companies for the following 50 years and was the parent of an even more successful company, Texas Instruments (see Chapter 10.8). Early GSI employee Henry Salvatori left that company in 1933 to found another major seismic contractor, Western Geophysical.

In Germany, Mintrop had developed a method to estimate the distance to cannons by using seismic and sonic signals. He also developed a portable vertical seismograph with a photographic device. His interpretation of travel-time curves of seismic waves was based on the methods developed by Wiechert and Zoeppritz for global seismology. In particular, he made use of the seismic head waves (Mintrop, 1930, 1947). In 1919, he finally applied for a patent for a "method to investigate geological structures" (Figure 3.3-03).

In the period up to 1921 Mintrop (1930, 1947, 1949a) had developed seismic prospecting methods, the refraction and reflection methods, for which, in 1921, he obtained the exclusive rights (German Patent no. 371,973, 7 December 1919) without indicating how the method worked. In the same year, 1921, L. Mintrop founded an exploration company in Germany, SEISMOS, which started with successful seismic measurements on oil, coal, ore, and quartzite. In 1923, a team was sent overseas to Mexico and later on to Oklahoma and Texas where the application of the seismic-refraction method led to good results. Nettleton (1940)

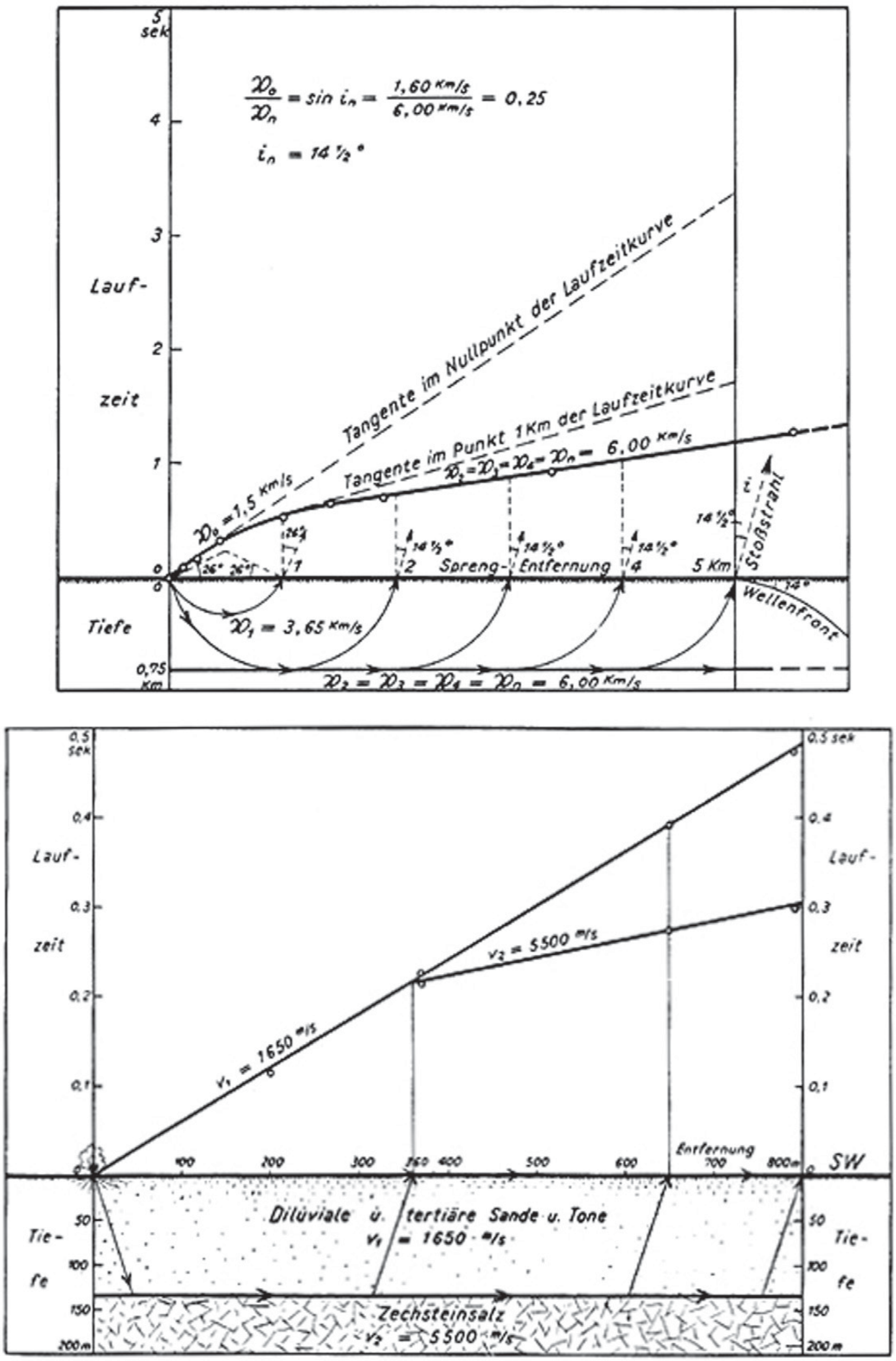

Figure 3.3-03. Two traveltime curves, which were used by Mintrop in 1919 and 1920 (from Ritter et al., 2000). [History of Seismology in Göttingen ('L. Mintrop' by Andreas Barth, fig. 2), unpubl., reproduced in Appendix A3-2. Published by permission of J. Ritter.]

and Weatherby (1940) have described in detail the further development of applied seismic refraction work by various companies in the Gulf Coast area in the 1920s.

The development of near-vertical reflection seismics in Germany was described by Köhler (1974). In 1925, the first electronic amplifier was constructed at the Geophysical Research Corporation which allowed the passing of relatively low-frequency reflected waves. This enabled the development of a central recording unit, i.e., the recording of several traces side by side on one seismogram, and thus allowed recognition of impulses by eye occurring on all traces at the same time and correlating them as reflections.

These achievements enabled new scientific research on shallow geological structures. As suggested by Wiechert in 1926, Mothes (1929) carried out seismic-reflection measurements by detonating dynamite charges in ice to study a glacier in the Alps. A few years later similar measurements were carried out on other European glaciers and in Greenland to measure the thickness of the ice cap (Brockamp, 1931a).

In ca. 1930, the seismic refraction method started to find natural limitations in the Gulf Coast. At the same time, the successful application of the seismic-reflection method started in Oklahoma. Two years later, the reflection method had almost completely replaced the refraction method and was applied in all parts of the world where extensive geologic exploration for oil was conducted (Barton, 1929; Nettleton, 1940). Weatherby (1940) described this development in some more detail.

In the period 1929–1931 the Imperial Geophysical Experimental Survey (IGES) in Australia again used the system that had been used by the British army in World War I to record shots buried at 4 m depth. The whole system was housed in a portable hut that could be moved in about one hour from site to site. Work was conducted at Gulgong and Tallong ~150 km north of Canberra (D.M. Finlayson, 2010, personal commun.).

In Germany, the first seismic reflections were recorded in 1933 with mechanical seismographs. The clear recognition of reflections, however, was only enabled by introducing central recording, for which electronic amplifiers, electrical seismographs, and recording with galvanometers were essential. In 1933, the first German seismic-reflection instrument was built and in 1934 was successfully used for the first time. The first useful field seismometer was built in 1936 in the lab of SEISMOS (Fig. 3.3-04). As energy sources, explosions in boreholes were used exclusively. The number of traces of a reflection-seismic instrumentation increased with time. In the beginning, only 4–6 channels were available, increasing to 12–14 channels during the years. Also, in the beginning, in order to increase the distance to the individual seismograph from the shot hole when working with a fixed pre-set amplification, the charge had to be increased and the shot repeated. Only in the early 1940s did the techniques advance such as to allow regulation of the amplification per individual trace (Köhler, 1974). This regulation of arriving seismic amplitudes varying as much as 10^5 was a precondition for later deep crustal studies (Meissner, 2010, personal commun.).

This technical achievement enabled the successful application of the seismic-reflection method in Germany. Mintrop (1947) discussed, with the aid of various figures and corresponding references, how the refraction and reflection method gradually developed and how it was used for commercial applications both in Germany and in the United States from 1920 on. The

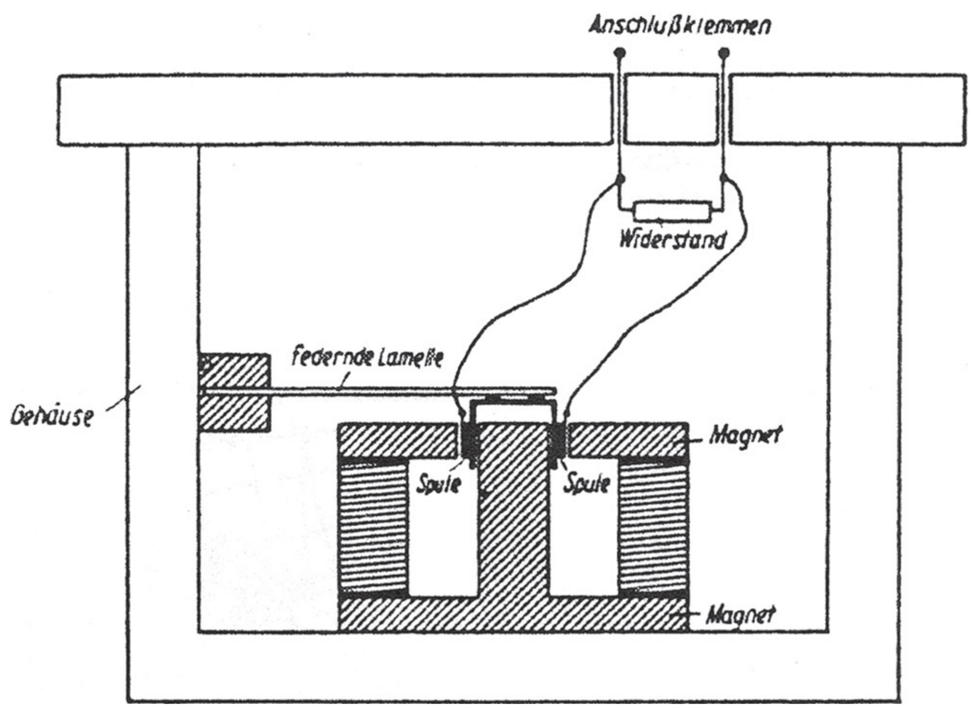

Figure 3.3-04. Electrical seismometer developed by Trappe and Zettel in 1936 (from Mintrop, 1947, fig. 33). [Die Naturwissenschaften, v. 34, p. 257–262, 289–295. Published by permission of Springer-Alerts.]

technical development of the seismic method (Barsch and Reich, 1930) was also stimulated by the fact that from 1934 on, the whole area of Germany was systematically being investigated for useful oil and mineral resources by refraction-seismic (mainly fan-shooting), magnetic and gravimetric measurements (Reich, 1937; Closs, 1974). This so-called "Reichsvermessung" was a unique cooperation of geologists and geophysicists from universities and industry. However, mainly data were collected but not simultaneously interpreted at that time.

In the United States, contrary to Europe, with improved instrumentation, the success of the reflection method was so immediate and pronounced that it gave rise to a phenomenal growth in seismic activity. By 1937, there were between 225 and 250 crews working in the country compared to four in 1929. In the 1930s, substantial improvements in instruments and techniques had been made. Automatically controlled amplifiers became general; their sensitivity was either a function of time or of amplitude and they were adjusted so that the early part of the record was compressed and made readable. Narrower band pass filters were used to eliminate extraneous energy from the record. Also, some overlap was already applied, feeding the output of each detector into two or more recording channels. Because of the better control of amplitudes, more seismic traces could be recorded on a given width paper. Near the end of the 1930s, as many as 10 traces could be recorded on the same paper. Some companies even made trials with up to 20 traces on wider paper. More attention was also paid to the depth of shot holes. For example, it was recognized that better energy was provided by placing the charges below the groundwater table (Weatherby, 1940).

The early worldwide state-of-the-art techniques for seismograph prospecting for oil were first summarized in a symposium of the American Institute of Mining and Metallurgical Engineers in Los Angeles in 1938 with contributions by W.H. Tracy (theory of seismic reflection prospecting), A. Nomann (instruments for reflection seismograph prospecting), F. Ittner (seismograph field operations), and P.C. Kelly (determining geologic structure from seismograph records), edited by English (1939). In his textbook *Seismograph Prospecting for Oil*, Nettleton (1940) describes in great detail instrumentation, data collection, theory, and interpretation methods available at the end of the 1930s.

The worldwide history of exploration geophysics, however, will not be the subject of this publication. Rather, the reader is referred to Lawyer et al. (2001), who have written a personalized history on the commercial application of controlled-source seismology starting at the time of World War I. This work was first published under a similar title in 1982, but was thoroughly revised and updated, carrying the story into the new millennium.

For academic crustal structure research, it was not until 1923 that "artificial earthquakes" were introduced by the use of large explosions. Reinhardt (1954) researched the use of quarry blasts for crustal studies up to 1954 and has published a historical review of early explosion seismology work up to the early 1950s.

The artificial event which started detailed investigations using blasts was a large catastrophic explosion near Oppau, Germany, in 1921, which was recorded by earthquake stations up to 307 km distance (e.g., Hecker, 1922). Wiechert (1923) noticed that elastic waves produced by large quarry blasts could be detected by stationary vertical seismographs with 2-million-fold amplification at distances of several hundred kilometers. This fact caused him to name such events "artificial earthquakes" and to treat them as such. He organized the construction of portable recording units and recorded the vibrations from these explosions along profiles. In addition, equipment development enabled the exact explosion time to be transmitted and recorded by the recording stations. Compared to natural earthquakes, the artificial ones have the advantage that both time and location were known exactly. The so-called Goettingen travel-time curves for longitudinal and transversal precursors from far explosions by Wiechert (1929) and their depth interpretation by Brockamp (1931b) are shown in Figure 3.3-05. However, in spite of recording distances up to 230 km, signals from the Mohorovičić discontinuity could not be detected, most probably due to low energy at the source and to insufficient sensitivity of the recording devices. Despite many publications (Wiechert 1923, 1926, 1929) and oral reports, Wiechert tried without success to obtain support from other geophysical institutes in Germany (see also Schulze, 1974).

After Wiechert's death in 1928, G.H. Angenheister continued the observation of quarry blasts and sound transmission, as well as the study of the Earth's interior and the application of the seismic method for the geophysical exploration of the uppermost layer of the Earth's crust, drawing attention to their practical importance (e.g., Angenheister, 1927, 1928, 1935, 1942; Brockamp 1931b). For example, he developed the theory to determine boundaries by using traveltimes of seismic waves and incidence angles. The portable seismic recording instruments were improved as well as the recording of time signals via radio broadcasting. By 1929, recordings were obtained at distances beyond 50 km. Angenheister plotted all arrival times of seismic longitudinal waves from explosions in a diagram, using the same procedure as used for local earthquakes, but the values scattered considerably. For the time being, the only conclusion deduced was that the Eurasian continent does not possess flat discontinuities with interlayering of homogeneous rock sequences (Angenheister, 1950). These investigations were fundamental for subsequent seismic-refraction investigations in Western Germany after World War II (Engelhard, 1998).

At the beginning of the 1930s, the principle of seismic head wave propagation was still not totally accepted in Germany. In his textbook on applied geophysics, Haalk (1934) mentioned that there are three competing models of head wave propagation. The differences occur in the spreading wavefront between the surface and the boundary layer: (a) a totally vertical ray path, (b) a diagonal ray path according to Fermat's law of shortest traveltimes, and (c) a curved ray path similar to version b, but with a sharp refracted wave instead of a real head wave (Figure 3.3-06). Indeed the author preferred the second (correct) model, but obviously the opinions varied. Using seismic measurements on the Rhône glacier in 1931 and 1932, Gerecke (1933) could prove that, according

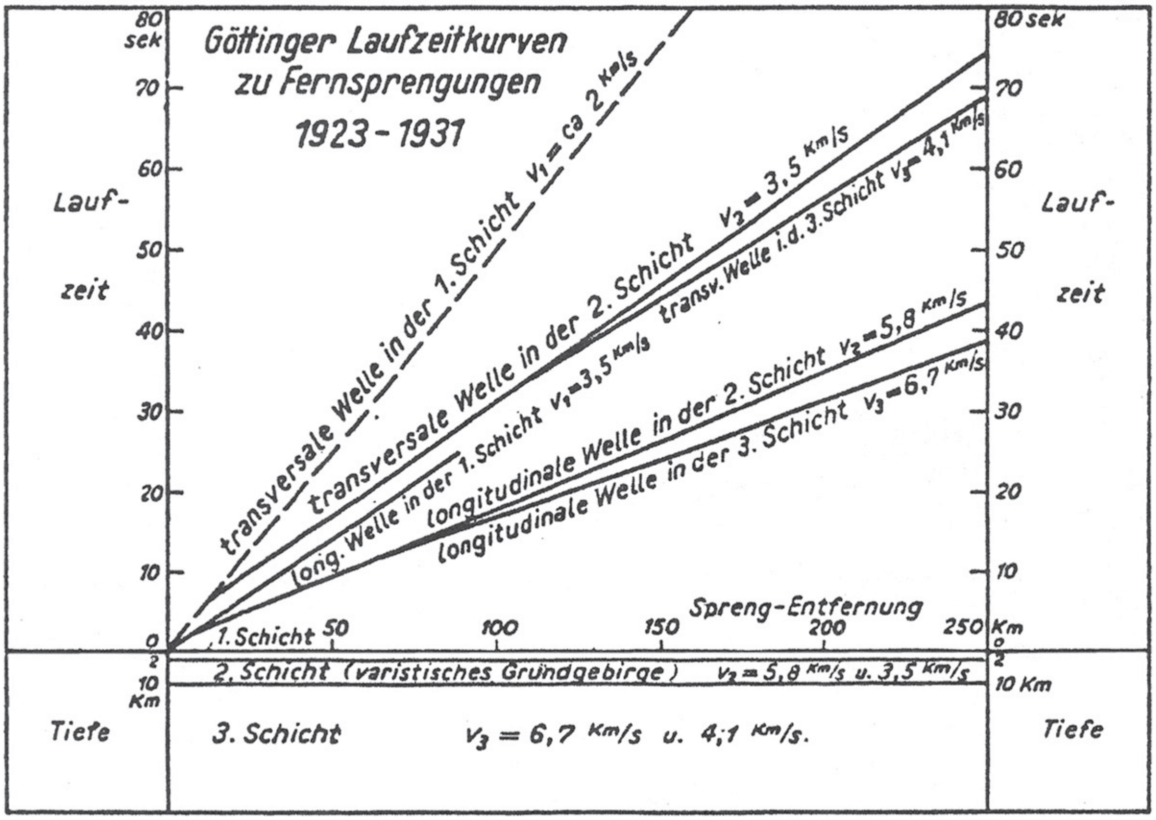

Figure 3.3-05. Traveltime curves of Göttingen of longitudinal and transversal precursors from far explosions and their depth interpretation by Wiechert and Brockamp (from Mintrop, 1947, fig. 38). [Die Naturwissenschaften, v. 34, p. 257–262, 289–295. Published by permission of Springer-Alerts.]

to Fermat's principle, the seismic waves followed the inclined ray path based on the calculated traveltimes of refracted waves.

Not only had large explosions been recorded in Germany. In France, results of the investigation of large surface explosions in 1924 near La Courtine had been reported upon (Maurain et al., 1925; Rothé et al., 1924). Here only the direct waves with an average velocity of 5.5 km/s had been recorded and later arrivals with 2.8 km/s had been interpreted as "long waves."

In California, seismic investigations using quarry blasts had been undertaken (e.g., Wood and Richter, 1931, 1933). A successful interpretation failed, however, due to the fact that the time of the explosion was not exactly known. More detailed velocity-depth models were given by Byerly and co-workers who investigated quarry blasts at Richmond (e.g., Byerly and Wilson, 1935b) and suggested a 3-layer crust of 31 km thickness beneath northern California (Table 3.3-01). Based on near-earthquake recordings, Gutenberg (1932b) derived a 39-km-thick 4-layer crust for southern California (Table 3.3-01).

For the purpose of oil prospecting in the 1930s, the principles of close station spacing were employed at the same time in west Texas and elsewhere in the oil industry (Ewing et al., 1939).

In the eastern United States, several quarry blast studies were reported. In Pennsylvania, Ewing et al. (1934) recorded surface velocities of 6.4 km/s and interpreted them as wave propagation in limestones. The first blast measurement of crustal thickness seems to have been that of Leet (1936) from a study of quarry blast recordings on station seismographs in New England. His tentative depth was 23 km (Steinhart, 1961). Numerous quarry blasts were recorded in the following years by the Harvard observatory (Leet, 1936, 1938) from which a 14.5-km-thick granitic upper crustal layer was deduced overlying an intracrustal layer with 6.77 km/s velocity. Later, Leet (1941) added observations of near-earthquakes to his data set from various permanent stations in northeastern America up to 10° distance and obtained another intracrustal layer with 7.17 km/s velocity, which was underlain by the Moho at 35–36 km depth with an upper-mantle velocity of 8.43 km/s.

In reviewing the studies of the crust by explosions before World War II, Steinhart (1961; see Appendix A5-1) concluded that a number of seismologists recognized the potential value of explosion studies, but instrumentation was inadequate, the theoretical basis of the refraction methods used in geophysical prospecting was suspect, and financial support for large field experiments was not available. The interpretations of seismic data concerning the structure of the crust followed the ideas of Daly (1914), who postulated a "granitic" layer overlying a "basaltic"

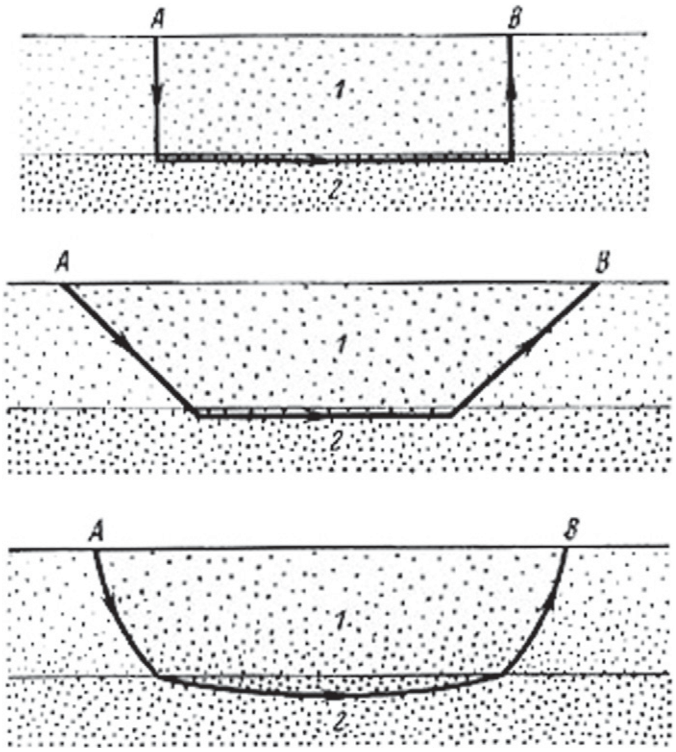

Figure 3.3-06. Ray paths after Haalk, 1934 (from Ritter et al., 2000). [History of Seismology in Göttingen ('L. Mintrop' by Andreas Barth, fig. 3), unpubl., reproduced in Appendix A3-2. Published by permission of J. Ritter.]

substratum that was of no great strength, and Jeffreys (1926) who designated P_1 as P_g and referred to P_b as a wave traveling in the basaltic layer (Steinhart, 1961) and explained the recorded waves as head waves from the top of the two layers superimposed on the mantle.

Early investigations using explosion data were also made in the former USSR just before World War II. Koridalin, from commercial blasts in 1939, divided the crust near the Ural Mountains into nine layers. At the Institute of Terrestrial Physics in Moscow, experiments were carried out from 1938 to 1940 by Gamburtsev and co-workers for the improvement of refraction prospecting methods. The principle suggested close spacings of seismometers, so that wave groups and individual phases may be traced for as long a distance as possible. Experiments to test these methods were performed on the European platform of the USSR from 1938 to 1941 and on the Aspheron peninsula in 1944 (for references see Steinhart, 1961, Appendix A5-1).

Seismic-refraction techniques were also developed to investigate shallow sea and coastal areas. Reflection and refraction measurements in water-covered areas were made as early as 1927 for the purpose of locating oil-baring structures (Rosaire and Lester, 1932). For various areas the thickness of sediments and the velocity at the top of the underlying basement was determined both on land and at sea (e.g., Ewing et al., 1937, 1939,

TABLE 3.3-01. DEPTH-VELOCITY STRUCTURE DEDUCED FOR CALIFORNIA BY GUTENBERG (1932B) AND BYERLY AND WILSON (1935A)

Southern California (Gutenberg, 1932b)		Northern and central California (Byerly and Wilson, 1935a)	
Depth of layer (km)	P-velocity (km/s)	Depth of layer (km)	P-velocity (km/s)
00–14	5.55	01–13	5.6
14–26	6.05	13–25	6.6
26–30	6.83	25–31	7.3
30–39	7.60	>31	8.0
>39	7.94		

1940). The first tests were made in 1935 in the vicinity of a deep borehole; the next tests were made on board of a ship. Both the charge and the geophones were placed on the ocean floor; otherwise, the method was similar as used on land. Both reflection and refraction measurements were successfully applied, but Ewing et al. (1937) stated that the refraction method gave more important results.

At that stage of development, the method was not applicable for water depths exceeding 100 fathoms, i.e., beyond the edge of the continental shelf, though successful tests were made to place both charges and recording system on the bottom of the ocean. Already in 1937 and 1938, tests were made in which seismographs were placed on the ocean floor at depths exceeding 2000 m in several attempts. In these experiments, an automatic oscillograph, four geophones, and four bombs, all distributed along an electric cable ~1 km long, had been lowered to the sea floor, laid down to form a straight line, and left undisturbed for 15 minutes while the profile was shot and recorded automatically. In 1939 and 1940, a new wireless system was developed and a small amount of data successfully recorded at two positions, one at 2600 m near Cape Cod, Massachusetts, and one at 4500 m water depth 550 km NW of Bermuda (Ewing and Vine, 1938; Ewing et al., 1946). These instruments were allowed to drop to the bottom under ballast which was detached automatically to allow them float to the surface after the tests were completed (Ewing and Ewing, 1961).

In general, however, the work was restricted to shallow waters, as hydrophones were not yet invented. Ewing et al. (1937) have described in much detail the experiment and the interpretation methodology both for land and for sea stations. As a result of their onshore and offshore experiments in Massachusetts and in Virginia, Ewing et al. (1937) could determine the configuration of the surface of the crystalline basement from the foot of the Piedmont Plateau to the edge of the continental shelf. The thickness of the unconsolidated and semi-consolidated material (P-wave velocity ~2.4 km/s) near the edge of the continental shelf was ~3600 m. In 1938, Woollard and Ewing (1939) applied the refraction method to the investigation of the Bermudas. They were probably the first to investigate the structure of an atoll using seismic methods. They found that on Bermuda calcareous sediments were underlain by presumably volcanic rocks with a relatively low velocity of ~4.9 km/s. Later measurements by Officer et al. (1952) showed that the velocity of the volcanic cone of Bermuda is 5.05–5.35 km/s without changing the simple model proposed by Woollard and Ewing (1939). Similar work at sea around Britain at the end of the 1930s was also reported upon by British scientists (Bullard and Gaskell, 1941; Bullard et al., 1940). Bullard et al. (1940) found velocities close to 5 km/s for rocks of the Paleozoic floor in southeastern England.

In tables 36–50, Macelwane (1951) has summarized velocities for the outer surface layers of the earth, i.e., for sediments and crustal crystalline rocks, obtained from quarry blast and near earthquake recordings between 1900 (e.g., Hecker, 1900) and 1939 with a few additions of results from 1940 to 1949. Tables 42–47 concentrate on P- and S-velocities in the crust for different depth ranges: P_g, P*, P_n, and S_g, S*, and S_n respectively, and in table 48, velocities of other seismic phases from near earthquakes are cited. Table 41 of Macelwane (1951) (Table 3.3-02) concentrates on P and S velocities of waves caused by explosions and blasts measured in France (Maurain et al., 1925; Rothé et al., 1924), Germany (Müller, 1934; Wrinch and Jeffreys, 1923; Hecker, 1922), Italy (Agamemnone, 1937; de Quervain, 1931), Switzerland (de Quervain, 1931), California (Gutenberg et al., 1932; Byerly and Wilson, 1935b; Wood and Richter, 1931, 1933) and New England (Leet, 1938). With a few exceptions, explosion seismology recordings up until 1939 only resulted in velocities being determined for sedimentary layers and the uppermost crystalline crust, the so-called granitic layer. In Macelwane's table 41 (Table 3.3-02) only one value is given for a P_2-phase of 6.77 km/s, based on quarry blast observations by Leet (1938). Also, the interpretation of Brockamp, 1931b, Figure 3.3-05) shows a third layer with P-velocity of 6.7 km/s, which, however, is not listed in Macelwane's table 41.

TABLE 3.3-02. VELOCITIES OF WAVES RECORDED BETWEEN 1921 AND 1938 CAUSED BY EXPLOSIONS AND BLASTS

Location	Wave type	Velocity (km/s)	Authority
Europe			
France:			
La Courtine	P	4.9	Maurain et al. (1925)
	P	5.3	Maurain et al. (1925)
	P	5.5	Maurain et al. (1925)
	P	5.6	Maurain et al. (1925)
	P	6.2	Maurain et al. (1925)
	P	5.5	Rothe et al. (1924)
Germany:			
Hainberg	P	3.36	Müller (1934)
Oppau	P_g	5.53	Jeffreys (1937)
	P	5.4	Wrinch and Jeffreys (1923)
	P	5.73	Hecker (1922)
	P	5.4–5.6	Gutenberg (1926)
Italy:			
Carrara	P	4.6	Agamemnone (1937)
	S	3.0	Agamemnone (1937)
Falconara	P	6.2–6.4	de Quervain (1931)
	S	3.64	de Quervain (1931)
Switzerland:			
Alpnach	P	4.7	de Quervain (1931)
Grenchen	P	5.1–5.25	de Quervain (1931)
North America			
United States			
California:			
Los Angeles basin	P	2.9–3.5	Gutenberg et al. (1932)
Richmond	P_1	4.3	Byerly and Wilson (1935b)
	P_2	5.4	Byerly and Wilson (1935b)
	S_1	2.4	Byerly and Wilson (1935b)
	S_2	3.1	Byerly and Wilson (1935b)
	S_3	3.8	Byerly and Wilson (1935b)
San Gabriel	P	5.5	Wood and Richter (1931)
Southern California	P	4.1	Wood and Richter (1931)
	P	5.0	Wood and Richter (1931)
	P	5.4	Wood and Richter (1931)
	P	5.55	Wood and Richter (1931)
	P	5.9	Wood and Richter (1931)
	P	6.0	Wood and Richter (1931)
	S	2.7	Wood and Richter (1931)
	S	3.0	Wood and Richter (1931)
	S	3.15	Wood and Richter (1931)
	S	3.21	Wood and Richter (1931)
	S	3.25	Wood and Richter (1931)
	S	3.4	Wood and Richter (1931)
	S	3.5	Wood and Richter (1931)
Ventura basin	P	2.9–3.5	Gutenberg et al. (1932)
Victorville	P	5.5	Wood and Richter (1931)
New England	P	6.0	Leet (1936)
	P	8.0	Leet (1936)
	S	3.5	Leet (1936)
	S	4.6	Leet (1936)
	P_1	6.01	Leet (1938)
	P_2	6.77	Leet (1938)
	S_1	3.45	Leet (1938)
	S_2	3.93	Leet (1938)

Note: From Macelwane (1951, table 41).