Dr. George Lovell, a Methodist minister who as an engineer had been a colleague of Norman in his aircraft years, gave a moving address at the Memorial Service. They both enjoyed fell walking; in the summer of 1985, they set off to climb a favorite Cumbrian fell. Norman's illness was beginning to take its toll, and he could not make the summit but stopped short at a lower view point. In Lovell's words, he seemed to take in the beauty of the scene silently as if he knew this would be his last sight of it, then said "You know, George, I've achieved most of the work I set out to do 25 years ago and count myself lucky to have had the opportunity to do so."

This tribute was written by David E. Cartwright, *IOS, Wormley, Surrey. He was a friend and laboratory director of the late Dr. Heaps.*

Seismology in the Days of Old

PAGES 33–35

Inge Lehmann
Copenhagen, Denmark

Editor's Note: A related article, entitled "50 Years of Studies on the Inner Core" by Bruce Bolt (Seismographic Station, University of California, Berkeley), will soon follow in *Eos*.

I may have been 15 or 16 years old when, on a Sunday morning, I was sitting at home together with my mother and sister, and the floor began to move under us. The hanging lamp swayed. It was very strange. My father came into the room. "It was an earthquake," he said. The center had evidently been at a considerable distance, for the movement felt slow and not shaky. In spite of a great deal of effort, an accurate epicenter was never found. This was my only experience with an earthquake until I became a seismologist 20 years later.

In the autumn of 1925, I became an assistant to N. E. Nörlund, who shortly before had been appointed director of "Gradmaalingen" (a geodetic institution that was in charge of measuring the meridian arc in Denmark). He had become interested in establishing seismic stations in Denmark and Greenland. He wanted everything done in the best possible way, and much attention was paid to the time service. The best existing seismographs had to be used, and they were to be placed so that they were not strongly affected by disturbing movements, such as traffic, for example. Two solid buildings, part of the fortification system that surrounded Copenhagen, were made available. My first major task was to assist in the installation of the Galitzin-Willip seismographs there. On November 18, 1926, the seismic station was inaugurated. Its standard was high in comparison with existing seismic stations.

I heard for the first time that knowledge of the earth's interior composition could be obtained from the observations of the seismographs. I was strongly interested in this and started reading about it. I got the opportunity to visit some of the best European seismic stations, such as those in Hamburg, Göttingen (both in Germany), De Bilt (the Netherlands), and Strasbourg (France). I stayed for a month in Darmstadt (Germany), where Beno Gutenberg still had his home. With great kindness, he guided my studies excellently.

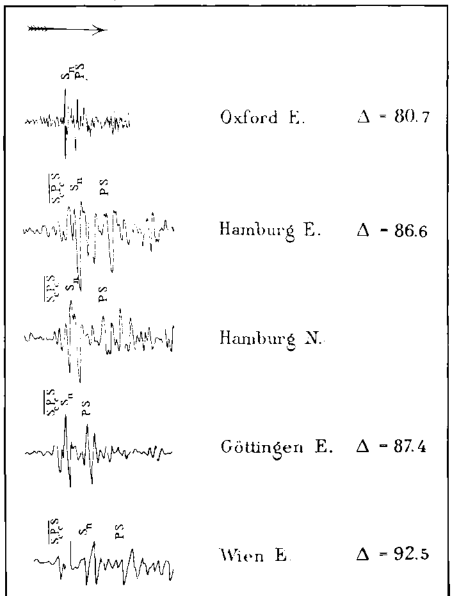

Fig. 1. Seismograms from the Mexican earthquake of March 22, 1928 [*Lehmann*, 1930*a*].

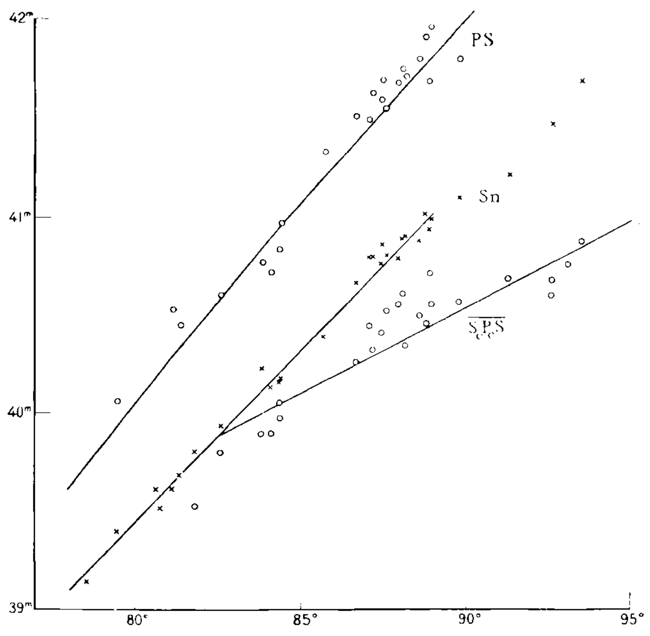

Fig. 2. Time of the phases S_cP_cS, *Sn*, and *PS* (now *SKS*, *S*, and *PS*) versus epicentral distance for the Mexican earthquake of March 22, 1928, as recorded at European stations [*Lehmann*, 1930*a*].

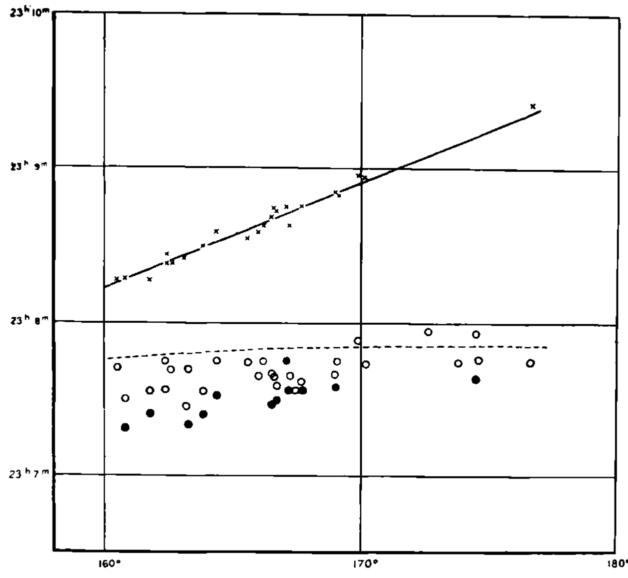

Fig. 3. Time of the two branches of *P'* (now *PKP*) versus epicentral distance for the New Zealand earthquake of June 16, 1929, as recorded at European stations [*Lehmann*, 1930*b*].

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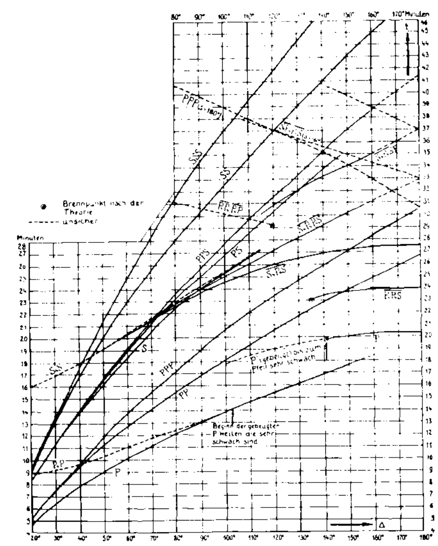

Fig. 4a. Frankfurt travel time curves. The German text connected with curve P' means that the bent P' is weak up to the arrow at the focal point [*Gutenberg*, 1924].

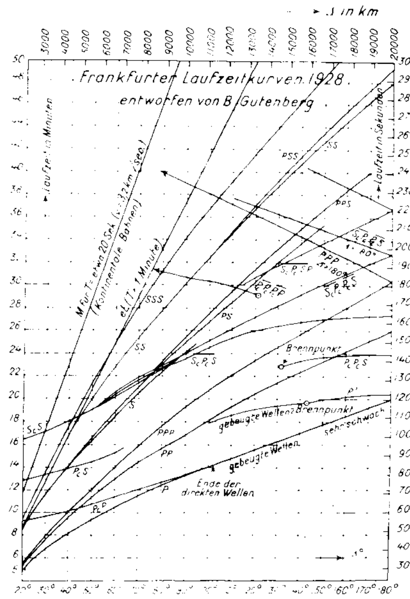

Fig. 4b. "Frankfurtur Laufzeitkurven" 1928 [*Lehmann*, 1931]. The label "gebeugte Wellen" (bent waves) also appears in other versions of these travel time curves [*Gutenberg*, 1925, 1932].

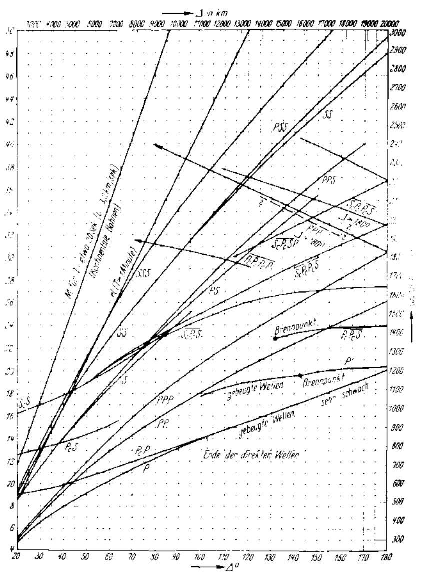

Fig. 4c. Additional Frankfurt travel time curves [*Gutenberg*, 1932].

In the summer of 1927 the International Geodetic and Geophysical Union had a meeting in Prague. I was allowed to attend, although it was not customary for a person in my position. Seismic time curves were discussed. These cause a great deal of difficulty. Time curves had been worked out by various seismologists, and they all differed. How to decide on any particular one? Which one should be preferred? The difficulties were partly due to the fact that the observations used were not very accurate. Many seismographs did not record sufficiently clearly, and the time services were imperfect. On a later occasion, I made an investigation of the accuracy of the stations. The observations from the International Seismological Summary for the 4 years 1930–1933 inclusive were used. Five stations (one of them Copenhagen) were found to be particularly accurate.

There was, in addition, another problem of quite a different kind. We were trying to find how observations vary with epicentral distance. Consequently, we had to determine the epicenters of each earthquake from the observations available. This could not be done with any degree of accuracy unless good observations were well distributed in azimuth around the epicenters, and this was rarely the case. Most European stations formed a group, and there were not a great many stations outside this group. Attention had not been paid to this. It was understood that the time curve could not be determined directly by calculating epicentral distances, so we now had to try to approach the time curve in a different way. As result of many considerations it was found that while the group of stations did not allow travel times to be accurately determined, it was possible to determine the slope of the time curve for the distances covered by the group. This could be done with considerable accuracy if the center was at a fair distance from the group, for a small change of epicenter would affect the travel time of all the stations practically in the same way. In modern terminology it might be said that the European stations were used as an array.

At first, it was chiefly the time curves of the direct longitudinal wave P and the transverse waves S that were considered, along with the time difference $S - P$ as a function of distance. For P a fairly smooth curve was obtained up to about 100°, but for S there were difficulties for distances greater than 85°. The movement following the first onset was complex (Figure 1). Later onsets were more or less clearly indicated. If the first onset was taken to be S, it was no longer possible to derive the distance from $S - P$. Now I studied an earthquake that was well recorded by the European stations at distances from 85° to 95°. It was found that the travel times of the first arriving S wave were on a line parallel to the P curve in the same range, while several of the later onsets were on the continuation of the normal S curve for distances smaller than 85° (Figure 2). It was then understood that the first onset was due to a different wave. It was denoted S_cP_cS (now called *SKS*), for the time was found to fit the travel time calculated for a wave that was transverse in the mantle and transformed into longitudinal where it entered the core and then again transformed into transverse where it left the core. When other earthquakes with good records in the same range were considered, the *SKS* curve was again found, and its slope was well determined. The slope of the time curve was made for other distance ranges in the same way. Use could be made of these results when the complete time curve was constructed. I had a lively correspondence with Harold Jeffreys while he, in cooperation with K. E. Bullen, was calculating the complete time curve at Cambridge University (Cambridge, U.K.).

In the beginning, observations from the International Seismological Summary were used. Later, I preferred to read phases from borrowed records or from copies of records that had been obtained. It meant a lot of work, but the published readings were not always satisfactory, especially when the movement was complex. Some observers read only few very prominent phases, while other read

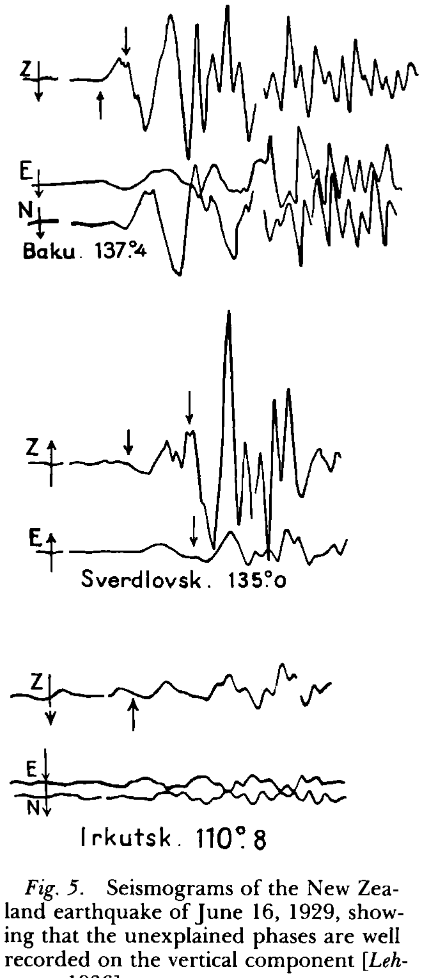

Fig. 5. Seismograms of the New Zealand earthquake of June 16, 1929, showing that the unexplained phases are well recorded on the vertical component [*Lehmann*, 1936].

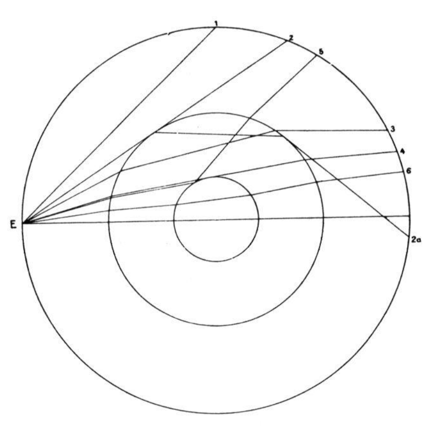

Fig. 6. An earth model with constant velocity in each layer, 10 km/s in the mantle, 8 km/s in the outer core, and 8.6 km/s in the inner core [*Lehmann,* 1936].

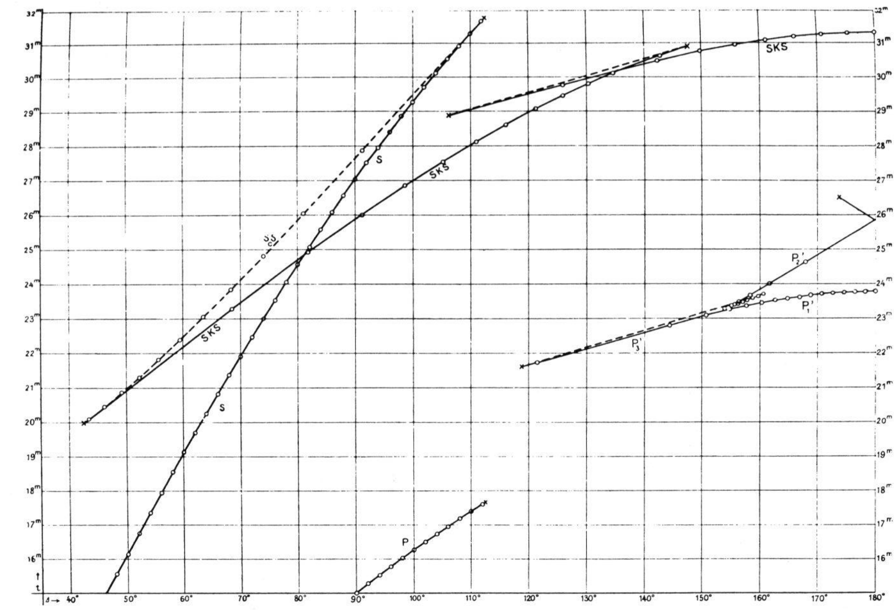

Fig. 7. Travel times for the earth model of Figure 6. The branch labeled P_3' (now *PKIKP*) explains the phases in Figure 5 [*Lehmann,* 1936].

many phases that were not always clearly marked. The best way of reading records was discussed. If the observations of a group of stations were all read by one and the same person who paid attention to the shape of the curves, it might be possible to trace a phase from one station to another and in this way determine a time curve that was not otherwise obtainable. A very critical attitude is required in order to avoid reading phases where they are expected to be. If the readings are adapted to time curves that already exist, they are not very useful.

Among the phases of interest was P', because of the longitudinal waves through the core of the earth. The rays are bent when they leave the mantle and enter the core, in which the velocity is much smaller. Thus the time curve has two branches. The first wave through the core (the one with the smallest angle of incidence) emerges at the surface of the earth at considerably greater epicentral distance and later than the wave that just touches the core. When the angle of incidence increases, the time curve runs backward until it stops at about 143° epicentral distance and runs forward again. Both branches of the time curve are indicated by European observations of the June 16, 1929, New Zealand earthquake (Figure 3). The upper branch had not been indicated in Gutenberg's time curves and does not seem to have been observed before.

At other distances, some P' observations were found that had not been explained. If the earth simply consisted of a hard mantle surrounding a fluid or soft core, we could not have observations recorded between 102°, where the direct P curve ended, and 143°, the smallest epicentral distance for P'. Gutenberg had already published (in 1928) the so-called "Frankfurter Laufzeitkurven," which included a lot of phases (Figure 4). He drew time curves for phases he could not explain, and he labeled them "Gebeugte Wellen." Later on, they were named "diffracted waves," with no explanation given. They were more clearly recorded when better vertical seismographs came into use, and an explanation was required (Figure 5).

Evidently, there was a reflection of the waves in the interior of the earth that caused them to emerge at a shorter epicentral distance. It was shown in a simple example how this could happen. I considered a globe in which a hard mantle surrounded a softer core, the radius of which I took to be five ninths of the surrounding sphere. The velocity of the longitudinal waves was 10 km/s in the mantle and 8 km/s in the core. It was then a simple matter to calculate the time curves arising from an earthquake that took place at the surface of the globe. The P curve that resulted from waves confined to the mantle ended at 112° distance from the epicenter. P' consisted of two branches, as observed in the New Zealand earthquake. When the variation of the travel time was considered in relation to the angle of incidence, an estimate of the intensity could be obtained. In this way it was found that the intensity of the waves corresponding to the upper branch of the P' curve would be small. This was in accordance with the fact that it had been difficult to observe the upper branch.

No rays emerged at epicentral distances between 112° and 154° (Figure 6). I then placed a smaller core inside the first core and let the velocity in it be larger so that a reflection would occur when the rays through the larger core met it. After a choice of velocities in the inner core was made, a time curve was obtained (Figure 7), part of which appeared in the interval where there had not been any rays before. The existence of a small solid core in the innermost part of the earth was seen to result in waves emerging at distances where it had not been possible to predict their presence.

Gutenberg accepted the idea. He and Charles Richter (California Institute of Technology, Pasadena) placed a small core inside the earth and adjusted the radius of this small core until the calculated time curves agreed with the waves observed. Jeffreys was slower to accept the inner core. Jeffreys-Bullen time curves had been completed in 1935. In 1939, a new edition was published in which the inner core had been accepted [*Jeffreys,* 1939].

The first results for the properties of the inner core were naturally approximate. Much has been written about it, but the last word has probably not yet been said.

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Inge Lehmann *was born in 1888 and received her degree in mathematics in 1920. She later became chief of the Seismological Department of the Geodetic Institute of Denmark, which was established in 1928. As described in this article, she aided in setting up seismic stations in Greenland and Copenhagen. Her studies of the travel times of a special phase led to the discovery of the inner core of the earth in 1936. In addition to the other pioneering activities in seismology described in this article, Lehmann has participated in committee work for many scientific societies and had received numerous awards. She was awarded the William Bowie Medal, AGU's highest honor, in 1971.*