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CHAPTER 4 The 1940s (1940–1950)

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CHAPTER 4

The 1940s (1940–1950)

4.1. THE LATE 1940s IN CENTRAL EUROPE

Controlled-source seismology investigations of the Earth's crust and the first international cooperations started effectively after 1945. In the first edition of Volume VII of *Physics of the Earth* (edited by B. Gutenberg) on the internal constitution of the Earth in 1939, J.B. Macelwane summarized essentially the seismic studies up to 1939 on 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 and 1939. In the second edition of this volume in 1951 (Macelwane, 1951), he added some results obtained between 1940 and 1949, in particular results from the seismic profiles using the military explosions in Germany, Heligoland in 1947 (Schulze, 1947; British National Committee for Geodesy and Geophysics, 1948; Reich et al., 1951; Mintrop, 1949b), and Haslach (Black Forest, Southwest Germany) in 1948 (Reich et al., 1948; Rothé et al., 1948; Förtsch, 1951) and from some early explosion studies of Tuve et al. (1948) in the United States.

By the early 1950s, the overall picture of the crust had already been established. Reinhardt (1954), in his review of crustal investigations up to 1954, plotted the basic scheme (Fig. 4.1-01). Beneath a layer of sediments, the Earth was divided into an upper crust of granitic composition and a lower crust consisting of gabbroic rocks, underlain by a peridotitic mantle layer, the top of which was determined by the Mohorovičić discontinuity.

Based on the pre-war investigations by Wiechert, Angenheister, and others, such investigations would eventually be continued, after the Second World War had ended. Former friendships between scientists in Britain, France, and Germany could be renewed and so, only one year after the war, the first international scientific cooperations were organized. The very first crustal investigations in central Europe were enabled by using large explosions undertaken by the British and French armies, particularly in Germany, to destroy great quantities of ammunitions, fortifications, and other military objects.

A large explosion of ammunition in 1944 near Burton-on-Trent in England was recorded by many earthquake stations in Europe (Jeffreys, 1947). In 1946, surface detonations of large ammunition reserves were carried out near Soltau in the North German Plain and recorded up to 50 km away (Schulze and Förtsch, 1950; Willmore, 1949). The recorded traveltimes resulted in upper crustal velocities being determined between 5.8 and 6.6 km/s. Of particular interest were the azimuth-dependent variations, evidently caused by salt domes. Other ammunition reserves were detonated in 1946 in Danish waters (Lehmann, 1948). Near Kahla in Thuringia, an underground factory was demolished and the explosions were recorded up to 438 km away (Sponheuer and Gerecke, 1949). The interpretation of the seismograms resulted in a layer with 6.35 km/s velocity being interpreted at 9 km depth. P_n arrivals, however, were not recorded.

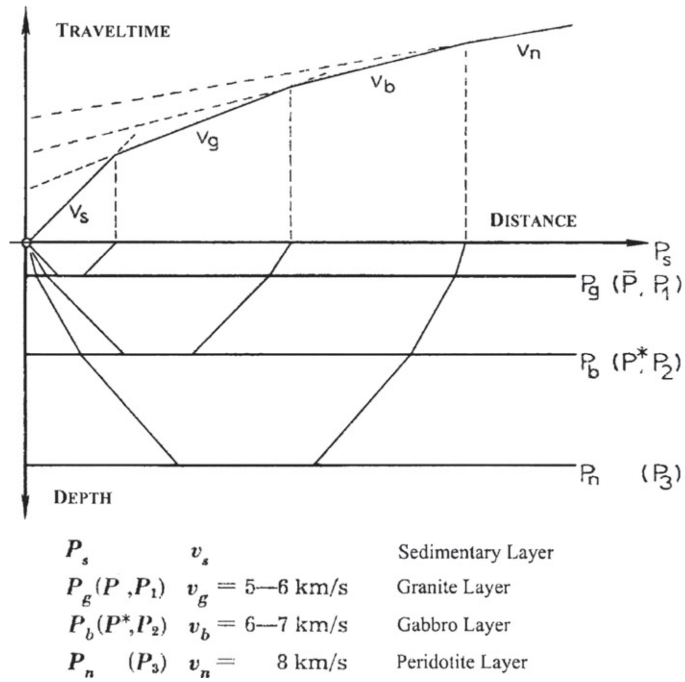

Figure 4.1-01. Schematic division of the Earth's crust due to seismic measurements (from Reinhardt, 1954, fig. 1). [Freiberger Forschungshefte, C15, p. 9–91. Reproduced by permission of TU Freiberg, Germany.]

The very first nuclear explosions in North America, which were recorded by earthquake stations in North America, also have to be mentioned in this context. However, as their origin time had not been announced in advance, the recordings did not supply any new information on the Earth's crustal and upper mantle structure.

The greatest impact on crustal studies at this time was created by the large explosions on Heligoland in 1947 and in the Black Forest in 1948.

In 1947, 4000 metric tons of explosives were detonated instantaneously in fortifications on the island of Heligoland in the North Sea off northern Germany (Charlier, 1947; Willmore, 1949; Engelhard, 1998). This explosion was located 50 m underground.

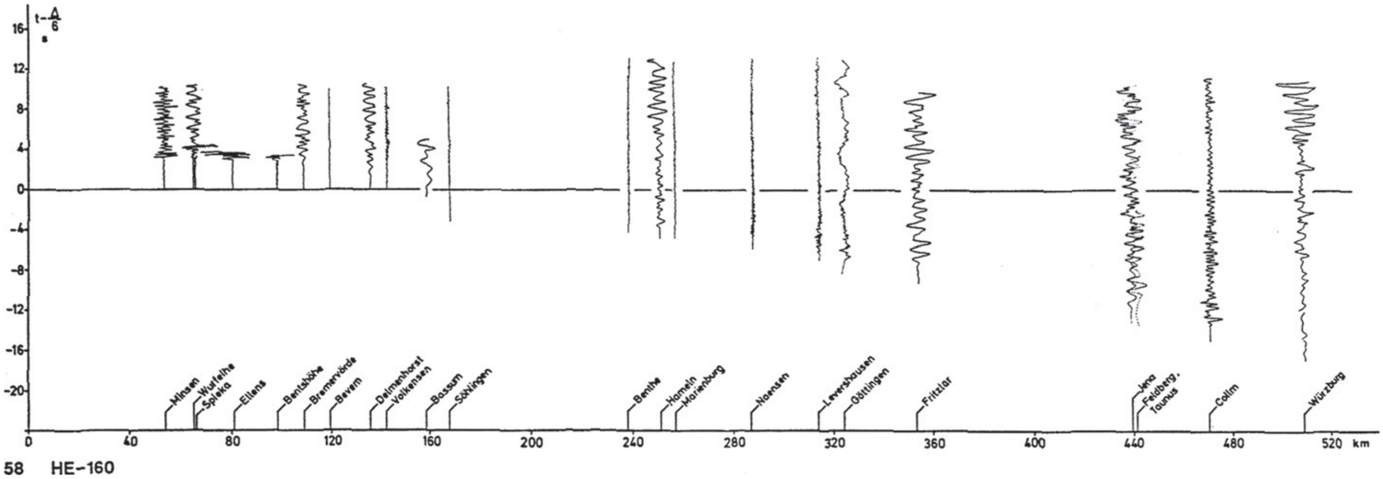

Figure 4.1-02. Seismograms of the Heligoland-explosions of 1947 recorded on a N-S line through Germany (HE-l60), compiled by P. Friese and J. Ansorge (from Giese et al., 1976, map 2, fig. 58, reproduced after Ansorge et al., 1979a, fig. 6). [*In* Giese, P., Prodehl, C., and Stein, A., eds., Explosion seismology in central Europe—data and results: Berlin-Heidelberg-New York, Springer, 429 p. Reproduced with kind permission of Springer Science+Business Media.]

The explosion on the island of Heligoland (Fig. 4.1-02) is the factual beginning of controlled-source seismology in Germany (Schulze, 1974). The use of the explosion on Heligoland for science was enabled by British geophysicists with good army contacts. Engelhard (1998) reviewed this event and its consequences for explosion seismology in Germany. Twenty-four recording stations were arranged along three profiles throughout northern Germany, the recordings being organized by the Geophysical Institute of Goettingen and the State Geological Survey at Hannover. The longest profile extended for more than 300 km and ran through the troop training area of Soltau and farther toward Goettingen. Another profile ran into Schleswig-Holstein across the magnetic high of Husum.

In southwestern Germany in 1948, an underground ammunition factory near Haslach in the Black Forest was destroyed by several very large explosions. The pre-war friendship of E. Peterschmitt (Strasbourg) and W. Hiller (Stuttgart) enabled the use of these subsurface explosions for science and recording along two lines, one toward the WNW across the Rhine valley toward Strasbourg and one toward the ESE into Bavaria (Fig. 4.1-03).

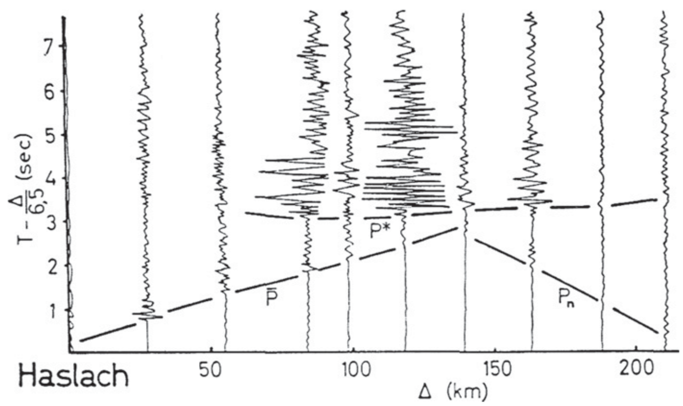

Figure 4.1-03. Seismograms of the Haslach explosion of 1948 (HA-120), recorded on an ESE profile (from Giese et al., 1976, Map 3 fig. 60). [*In* Giese, P., Prodehl, C., and Stein, A., eds., Explosion seismology in central Europe—data and results: Berlin-Heidelberg-New York, Springer, 429 p. Reproduced with kind permission of Springer Science+Business Media.]

Both the Heligoland and the Haslach explosions were recorded mainly by mechanical seismometers with mechanical-optical and mechanical-electrical-optical recording systems on photographic paper. The mechanical-optical system (system of Schulze and Förtsch), for example, had seismometers (Fig. 4.1-04) with an eigenperiod of 1/6 s, an amplification of 1:25,000 for 1 m light path, air damping (could be modified), 1 kg mass, and a total weight of 4.5 kg (Reinhardt, 1954). Effectively a 40,000-fold amplification was reached (Reich et al., 1948). The mechanical-electrical-optical instruments operated with induction and worked usually with electronic amplification which increased the sensitivity but caused complications when amplitudes and/or frequencies were evaluated.

The interpretation of the Heligoland and the Haslach explosions resulted in representative models of crustal structure for Central Europe. From the Heligoland observations (Reich et al., 1951; Schulze and Förtsch, 1950; Willmore, 1949) a depth of 26–30 km was derived for the Mohorovičić discontinuity under northern Germany. The internal crustal structure, however, was interpreted differently by the various authors. Reich et al. (1951) and Schulze and Förtsch (1950) favored two crustal layers underneath the sedimentary cover: a granitic upper crust with 5.34 km/s velocity and an essentially thicker gabbroic lower crust, the velocity of which varied from model to model between 6.19 and 6.60 km/s. Willmore (1949) favored a one-layer crustal model, but also discussed the possibility that the crust may con-

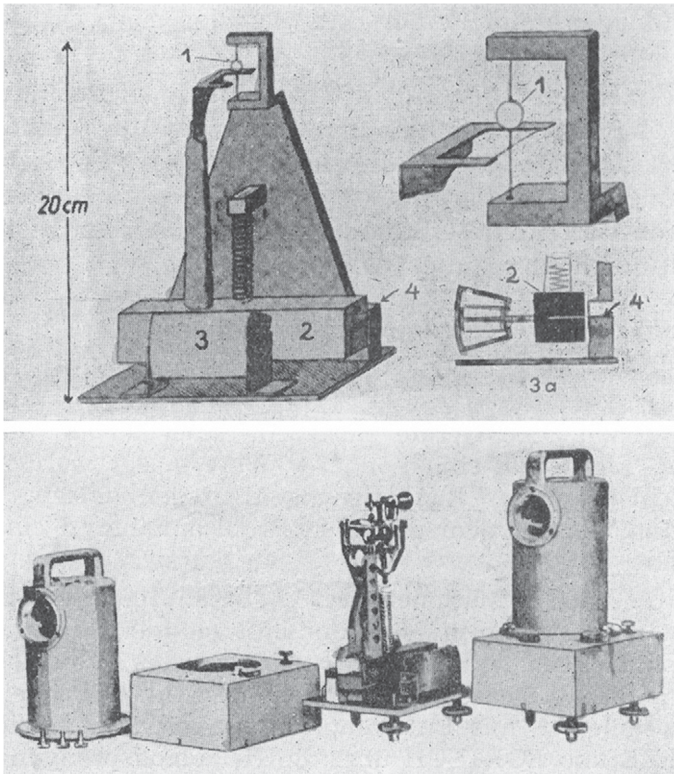

Figure 4.1-04. Mechanical seismometer of Goettingen (from Reinhardt, 1954, fig. 7) for long-range recording after Schulze and Förtsch (1950). Top: Scheme of seismometer: 1—mirror, 2—mass, 3—damping (3a—cross section of damping), 4—plate spring. Bottom: Seismometer closed (right) and opened (left). [Freiberger Forschungshefte, C15, p. 9–91. Reproduced by permission of TU Freiberg, Germany.]

sist of two layers. Mintrop (1949b) considered later arrivals on stations close to Heligoland as possible deep reflections from layers in the upper mantle.

The interpretation of the observations of the Haslach-explosion gave better results than the Heligoland measurements (Reich et al., 1948; Rothé et al., 1948; Rothé and Peterschmitt, 1950; Förtsch, 1951). A 16–21-km-thick granitic upper crust with velocities of 5.9–6.0 km/s is underlain by a 10–12-km-thick gabbroic lower crust with 6.55 km/s velocity, and the Moho is between 30 and 33 km deep. The P_n phase resulted in uppermost mantle velocities of 8.15–8.34 km/s. The nine seismograms, recorded on the profile from Haslach toward the east-southeast (Haslach-120, Fig. 4.1-03), clearly showed the P_MP-reflection and are among the first of many worldwide examples demonstrating that the Mohorovičić-discontinuity, the Moho, is a first-order boundary between Earth's crust and mantle under many regions of the Earth. At that time, however, this phase was not recognized as a wide-angle reflection, but was interpreted as a refracted wave from which the depth to the Conrad-discontinuity was derived. The model of Rothé and Peterschmitt (1950) showed the division of the crust (Fig. 4.1-05) into a granitic layer reaching to a depth of 15–20 km and a basaltic layer of ~10 km thickness, and a crustal thinning from 31 to 32 km under most of SW Germany to 28 km under the Black Forest and 25 km under the Rhinegraben. The Haslach profile into Bavaria furthermore led to the detection of a new discontinuity which later in the literature was named the "Förtsch-discontinuity," a boundary between upper and middle crust at ~10 km depth (Förtsch, 1951). It was also identified later in a statistical evaluation of commercial deep-seismic reflection seismograms recorded throughout Southern Germany (Liebscher, 1962, 1964), but was not regularly observed elsewhere. It was later identified as the top of a low-velocity zone in the upper crust (Giese, 1968a; Landisman and Mueller, 1966; Mueller and Landisman, 1966).

4.2. CRUSTAL STUDY ACTIVITIES IN THE 1940s OUTSIDE CENTRAL EUROPE

4.2.1. Soviet Union

Early crustal studies in the 1940s had also been undertaken in other parts of the world, partly even during World War II. In 1950 Twaltwadzse reported on a series of very large explosions amounting up to 220,000 kg. They had occurred between 1941 and 1945 in the Soviet Republic of Georgia. Twaltwadzse (1950) assumed that the 20-km-thick granitic upper layer with

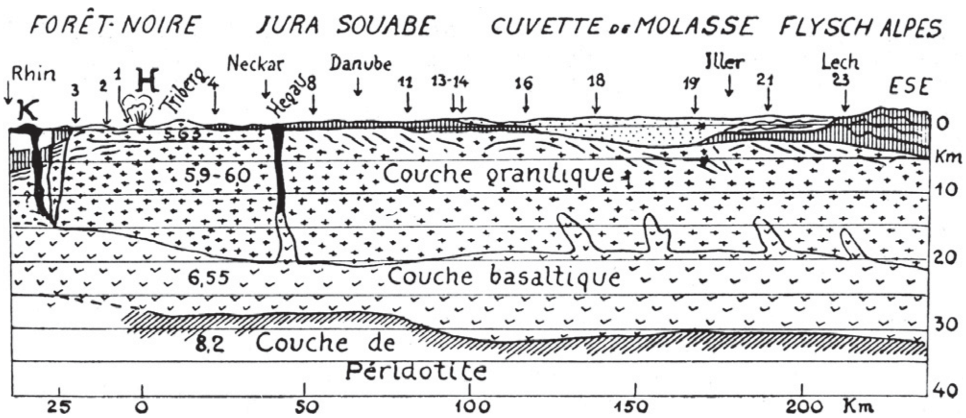

Figure 4.1-05. Seismic-refraction cross section for the ESE-profile from Haslach (after Rothé and Peterschmitt, 1950, fig. 14) (reproduced in Giese et al., 1976, p. 315: fig. 2 of Prodehl et al, 1976a). [*In* Giese, P., Prodehl, C., and Stein, A., eds., Explosion seismology in central Europe—data and results: Berlin-Heidelberg-New York, Springer, 429 p. Reproduced with kind permission of Springer Science+Business Media.]

a velocity of 5.6 km included solidified sediments in its upper part, the physical properties of which are close to those of granite. The existence of a basaltic intermediate layer was also reported, but its lower boundary could not be determined from seismic-refraction data. However, deep reflections indicated a depth to Moho of 48 km. A similar crustal structure was also assumed for other parts of the Caucasus.

Based on the experiments by Gamburtsev and co-workers in 1938–1941 on the European platform of the former USSR in 1938–1941 and on the Aspheron peninsula in 1944, mentioned in Chapter 3, and theoretical work by Riznichenko and Gamburtsev and co-workers during the 1940s, the method of "deep seismic sounding" was developed (for details and references see Steinhart, 1961, Appendix A5-1). A specialty of this method was the use of continuous profile sections of 10–20 km with close geophone spacing, alternating with gaps of 10–30 km.

The deep seismic sounding method was applied in 1949–1950 to investigate the crustal structure under the northern Tien-Shan region (Gamburtsev, 1952). Underwater explosions in the lakes Issyk-Kul and Kara-Kul served as energy sources. As seismic reflection measurements had not given satisfying results, modified refraction instrumentation of the prospecting industry with 0.1 s eigenperiod and increased sensitivity were used to record seismic energy at offsets up to 400 km. Along the profile, specially selected 20–25-km-long stretches were very densely occupied with seismometers. The measurements resulted in the interpretation of a 10–15-km-thick granitic layer which was underlain by a 30–40-km-thick basaltic layer. It was noted in particular that both discontinuities deepened considerably toward the south in the direction of the Kirgisian mountains—an indication of a crustal root?

4.2.2. North America

In Canada, rock bursts occurring between 1938 and 1945 in the mining area near Kirkland Lake, Ontario, were used for the first time for crustal structure studies. Some events were recorded by observatories up to 1000 km distance. The timing of the events was successfully achieved by a geophone set up inside the mine. The interpretation (Hodgson, 1942, 1947) resulted in the interpretation of a depth to Moho of 36 km.

The Canadian investigations of rock bursts in the early 1940s were continued in 1947–1951. In addition, some large explosions in this area were included. Two recording stations were moved regularly to new positions so that finally a complete refraction profile of 174 km length resulted. The data were interpreted by a one-layer 36-km-thick crust with a mean velocity of 6.1 km/s, overlying a mantle with 8.18 km/s velocity. The observed wide-angle reflections indicated that the Moho was a first-order discontinuity. Some later arrivals were recorded from some of the explosions and resulted in a velocity of 7.1 km/s giving hints on the possible existence of an intracrustal discontinuity (Hodgson, 1953).

In the United States, a large explosion of ammunition occurred in 1944 near Port Chicago in California. From records in North America, a velocity of 7.72 km/s was derived, but a depth of only 14 km was deduced (Byerly, 1946). Also recorded in North America were the first nuclear tests: on 16 July 1945 the first test was undertaken in New Mexico (Gutenberg, 1946), a second test followed on the Bikini Island in the Pacific on 24 July 1946 (Gutenberg and Richter, 1946). As the origin times of the detonations were not known, new knowledge on crustal structure was not achieved, however.

Immediately after World War II the Carnegie Institution of Washington undertook a major field program to study the Earth's crust with controlled explosions. In the first years of 1946–1949 optical-mechanical-electrical mobile field stations were developed which were capable of detecting ground motions of the order of 10^{-8} at 4–10 Hz. The detectors used had a resonant frequency of 2 Hz (Steinhart, 1961, see Appendix A5-1).

In the Appalachians, large quarry blasts and shots fired in water in Chesapeake Bay were recorded up to 350 km away (Tuve et al., 1948, Tuve and Tatel, 1950a). From the time-distance curves of the refraction observations Tuve et al. (1948) derived the following model for the region around Washington, D.C.: 0–10 km—6.0–6.17 km/s, 10–24 km—6.7 km/s, 24–42 km—7.05 km/s, 42 km and below—8.15 km/s. When interpreting the data, strong secondary arrivals were detected in the ranges predicted for critical reflections from the Moho and from depths of 90–120 km. The results were consistent with the refraction model, but it also was noted that several models could be deduced that were consistent with the data (Steinhart, 1961). Junger (1951) reported on deep seismic reflections from the basement obtained during commercial seismic prospecting work in Big Horn County, Montana. During experimental seismic work by Shell Company, a number of deep reflections from 7.0 to 8.5 seconds were observed. The reflecting surfaces were flat and were interpreted to come from inside the basement at depths of 18–21 km.

At subsequent recordings of several large shots in Tennessee, seismograms were obtained at distances out to 1200 km at several azimuths, but the arrivals disagreed in different areas by as much as 1 second, indicating some real difference in crustal structure along the various paths. As more measurements were made, Tuve and Tatel (1950a) began to doubt the interpretation of a simply layered crust. They also were concerned about the explanation of "reverberations" on seismic records and the lack of coherence in waves over distances of a few kilometers, leading to new experiments in the 1950s (Steinhart, 1961).

A discussion on the nature of the P_g wave had already started in the early 1940s. In two publications of 1943, Gutenberg (1943a, 1943b) had compared observations of near-earthquakes and quarry blasts in southern California and had concluded that the velocities of 5.5–5.6 km for P_1-waves from earthquakes should not be compared with the 6 km/s-velocity from quarry blasts, because earthquake waves which were generated at greater depths were not influenced by relatively thin sediments on top of the basement. Leet (1946), however, concluded that arrivals with 6 km/s would be strongly limited in their distance range, as the sediments were not very thick and their properties would substantially change locally. Rather he suggested that another phase with 5.9–6.1 km/s determined by Gutenberg and named P_g would better fit with the quarry blast observations. In 1949, the Carnegie Institution of Washington conducted experiments in southern California in an attempt to resolve the apparent discrepancies in the velocities reported for P_1 from earthquakes and from blasts. It could be shown that in fact the traveltimes coincided within the experimental error (Tuve and Tatel, 1950b, Steinhart, 1961).

4.2.3. South Africa

In South Africa, very early seismic investigations were carried out in the mid to late 1940s (Gane et al., 1946; Willmore et al., 1952). These experiments were enabled by the fact that frequent earth tremors occur in the Witwatersrand gold mining area. The first investigation by Gane et al. (1946) had made it clear that many of the tremors were large enough and occurred often enough (about two tremors per working day) to permit observations at relatively large distances (up to 400 km) to be made in a relatively short time using sensitive mobile equipment. This experience was used by Willmore et al. (1952) for more extended seismic field surveys in 1948 and 1949 with recording distances up to 500 km. The data received amounted to ~200 seismograms. Two simple models of crustal structure were deduced assuming flat layering. The first model contained two layers: underneath the Witwatersrand system with 5.65 km/s velocity and 4.5 km thickness the so-called crustal layer 1 of 6.09 km/s P-velocity overlies the mantle with 8.27 km/s P_n velocity, the Moho depth being ~36 km. The second model took into account that a phase corresponding to an intermediate layer is evident and thus contained two crustal layers 1 and 2 underlying the Witwatersrand system giving a Moho depth of ~39 km.

4.3. SEISMIC-REFRACTION WORK AT SEA

During World War II, the techniques of seismic measurements at sea were further developed so that after 1945 the experiments could be extended from shallow coastal waters into the deep ocean basins.

As the method to place geophones on the sea bed, which had been common in the 1930s, restricted the investigations to less than 100 fathoms water depth, after 1945 the hydrophone came into use as sensor for seismic waves. Some of the earliest seismic investigations in the deep ocean were carried out with a single hydrophone suspended from a stationary or slowly drifting vessel (Hersey, 1963; Hersey and Ewing, 1949). Small TNT charges were fired at depths of 1–100 m and a hydrophone suspended 50–300 m below the ship detected echoes from the seabed and reflectors below (Fig. 4.3-01). After amplification and filtering, the hydrophone signals were photographed on an oscilloscope.

The seismic data obtained in the late 1930s were now, after WWII, supplemented by new expeditions, in particular in the

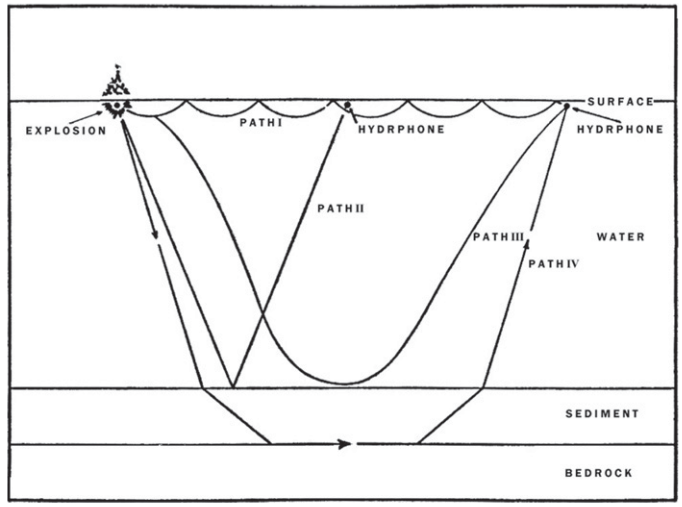

Figure 4.3-01. Sound paths between explosion and hydrophone (from Hersey et al., 1952, fig. 5). [Bulletin of the Geological Society of America, v. 42, p. 291–306. Reproduced by permission of the Geological Society of America.]

northern Atlantic Ocean in 1948 and 1949 (e.g., Drake et al., 1952; Ewing et al., 1950, 1954; Gaskell and Swallow, 1951; Hersey et al., 1952; Hill, 1952; Katz et al., 1953). In general, the seismic-refraction method was applied. Results of these investigations were published since 1949.

Reinhardt (1954, Appendix A4-1) has summarized coordinates, dates, references, some technical details, and main results of selected early offshore experiments in Table VII.

For the work at sea, the seismic refraction method was used at that time. In contrast to land seismics, at sea the shotpoint moved and the recording station remained at a fixed position. Officer et al. (1952) and Hersey et al. (1952) have described the techniques in some detail. Usually two ships were used. One ship would heave to and put the hydrophones over the side. The other ship would proceed away from the first ship and fire 6–20 shots to make up half of the reversed profile. The size of the shots varied from 0.5 to 5 kg for the close shots, fired at 5–15 min intervals, to 25–150 kg for the more distant ones, fired at 30–60 min intervals. The ships were equipped with hydrophones, which were lowered some tens of meters below the effective depth of ocean swell, but usually not exceeding 45 m (Ewing et al., 1950; Galperin and Kosminskaya, 1958; Shor, 1963). The hydrophones had a low-frequency response down to 5 Hz. They detected the seismic signal and fed it into a five-channel amplifier, each channel of which could be filtered in any required manner. Each channel was provided with two output stages at different dynamic levels for recording weak and strong signals on the same record. The amplifier outputs fed a bank of galvanometers, the deflections of which were recorded on photographic paper. One channel was used to record the direct water wave and the bottom-reflected waves. Another galvanometer was connected to a radio receiver to record the shot instant markers from the other ship and one galvanometer finally was connected to a break circuit chronometer to give the time scale.

Profile lengths were between 25 and 100 km and were usually reversed. Some profiles also had intermittent shotpoints or intermittent stations. On a typical record, three types of arrivals were received: the refraction waves from the basement and sediments, the direct wave traveling through the surface sound, and the bottom-reflected waves (Fig. 4.3-02). Before the final traveltime curves could be drawn, numerous corrections had to be applied, for example to account for the speed of the shooting ship, for the time interval between dropping the charge overboard and shooting, or for the depth of the shot and of the hydrophone. For the interpretation the arrivals were plotted on a time-distance graph and connected by straight lines to obtain velocities and then the seismic refraction and reflection formulas were applied for depth determinations. For a geological identification of the layers, most authors compared the obtained seismic velocities with experimental results published, e.g., by Leet (1946) or Birch et al. (1942).

One of the earliest marine surveys in the East Atlantic was undertaken in 1949 in the ocean weather ship *Weather Explorer* by the Department of Geodesy and Geophysics of the University of Cambridge (Hill and Swallow, 1950). The experiments were primarily to test if the method of seismic refraction shooting at sea, which had been developed since 1946, was applicable to deep water. Surface sonobuoys containing radio transmitters for sending hydrophone signals to a recording ship were pioneered by Hill (1952) during these experiments. The sonobuoys were free-floating and held hydrophones on a compliant suspension at depths of 50–150 m to keep ambient noise levels at an acceptable low level.

The area in which the work was undertaken lay within 30 miles of the meteorological position at latitude 53°50′N, 18°40′W, where the water depth was ~1300 fathoms. Depth charges were detonated 30 m deep as sources of the shock waves. They were detected by quartz hydrophones suspended ~45 m below sono-radio buoys which transmitted the information to the recording instruments in the ship. The charges were fired at distances up to 30 km from the buoys, four of which were in use simultaneously spread over a line ~5 km long. The evaluation showed the presence of two interfaces below the sea bed at depths of ~300 m and 500 m. In the surface layer, the velocity was between 1.9 and 2.2 km/s, in the intermediate layer 4.9–5.2 km/s were measured, and the deepest layer showed 6.2 and 6.4 km/s at two different positions.

The majority of investigations in the late 1940s concentrated on the western half of the Atlantic Ocean. Hersey et al. (1952), for example, described an expedition to carry out a series of underwater sound transmission experiments to study the ocean floor north of the Brownson Deep by means of the seismic refraction method. The general area was ~250 km north of Puerto Rico and 100 km north of the axis of the Brownson Deep, at ~21°N, 65°W (Fig. 4.3-03). In this case, two recording vessels and a shooting vessel were used. Shots of 150 kg were fired at a depth of 90 m. Several reversed profiles of up to 50 km distance were recorded. Figure 4.3-02 shows an example of a travel time plot from this experiment.

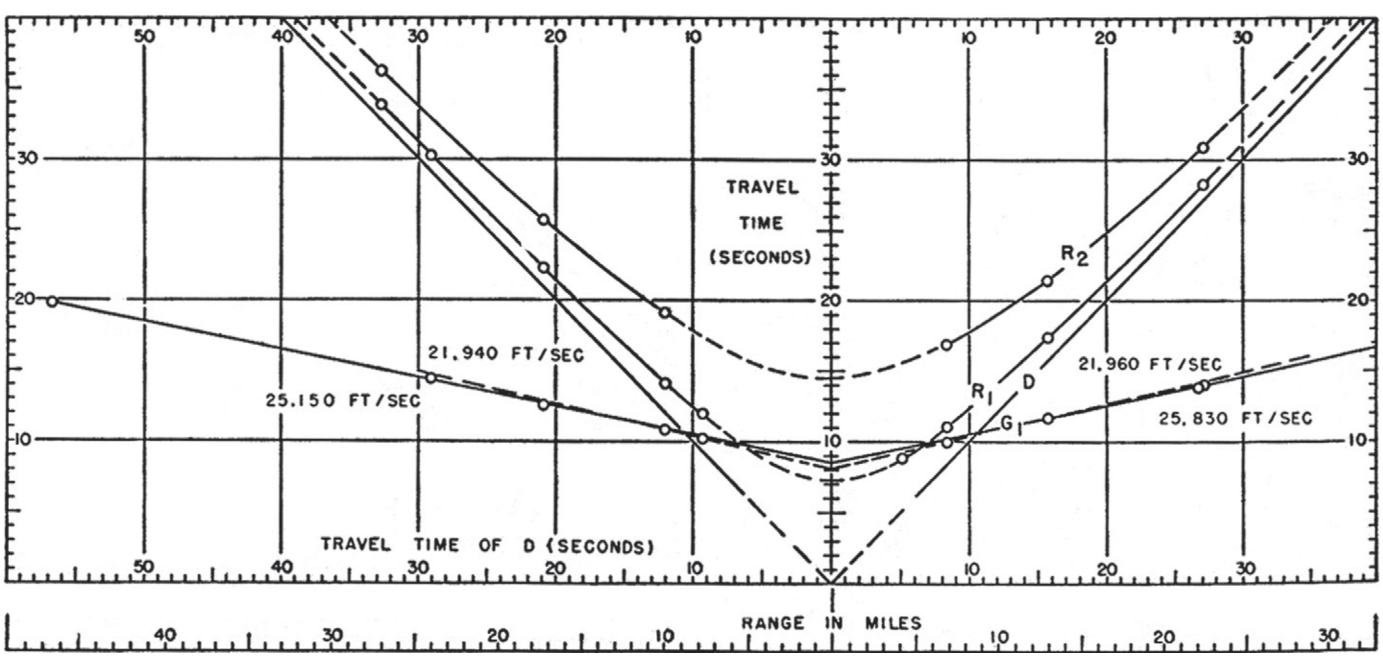

Figure 4.3-02. Traveltime versus distance graph for shots by the moving vessel *Atlantis* received on the stationary vessel *Caryn* (from Hersey et al., 1952, fig. 6). Straight line starting at zero distance and time = travel time curve of direct wave travelling through the surface sound, ellipsoidal curves = bottom-reflected waves, straight line starting at + 9 seconds = refraction wave from the first interface below the sea bed. [Bulletin of the Geological Society of America, v. 42, p. 291–306. Reproduced by permission of the Geological Society of America.]

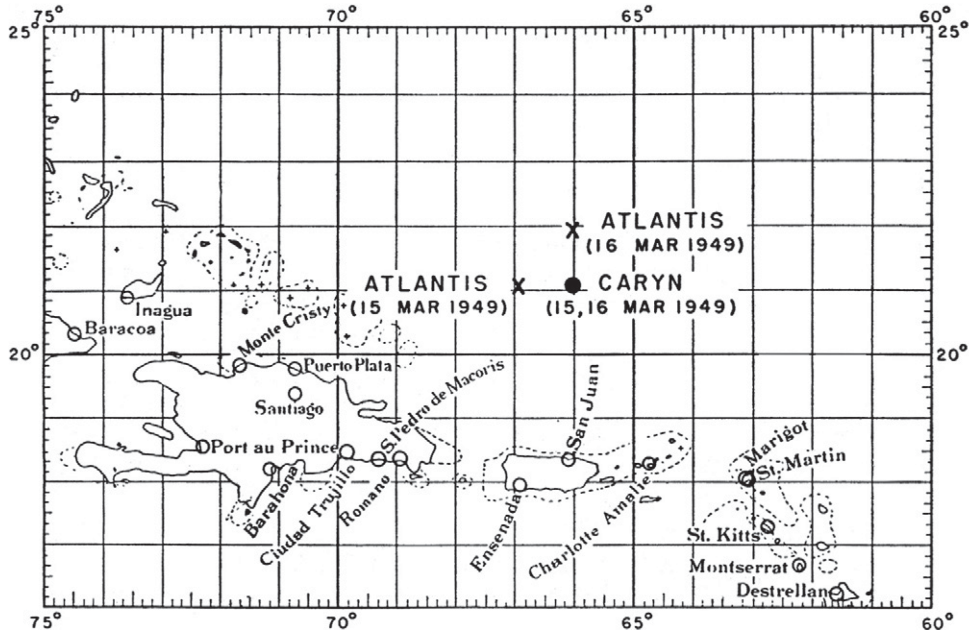

Figure 4.3-03. Location of seismic-refraction profiles shot in 1949 in the area of the Brownson Deep north of Jamaica (from Hersey et al., 1952, fig. 1). [Bulletin of the Geological Society of America, v. 42, p. 291–306. Reproduced by permission of the Geological Society of America.]

Also in the North American basin, northwest and south of Bermuda, Ewing et al. (1952) recorded six reversed seismic refraction profiles of 60–100 km length. Five of these profiles were long enough to record P_n arrivals. Ewing et al. regarded these profiles as typical for the western North Atlantic. For the sedimentary layer, an average thickness of 1.2 km and a velocity of 1.4 km/s were determined; for an intermediate basement layer, a velocity of 6.4 km/s and a thickness of 4.4 km was found, and a velocity of 7.9 km/s started at a depth of 10.3 km below sea level.

Drake et al. (1952) reported on seismic refraction measurements in the Gulf of Maine in 1948 and 1952 as part of a program to investigate the continental margin. During these voyages, they observed sections along the coast of Maine, but they also recorded seismic data along a section from Cape Ann, Massachusetts, to Yarmouth, Nova Scotia. Basement rocks with velocities of 4.95–5.4 km/s pinched out rapidly away from the shore on all sections, and sub-basement rocks with velocities of 5.7–6.3 km/s were found to underlie the entire Gulf of Maine.

In 1949, another marine seismic research project was carried out by Katz et al. (1953) in the Gulf of Maine. A partially reversed refraction profile was shot across the northern Gulf from a point east of Portland eastward beyond Matinicus rock (Fig. 4.3-04). Three portable seismographs were set up at Falmouth near Portland, Maine, on Mount Desert Island, Maine, and at Crowell, Nova Scotia, which recorded shots from 30 positions. The most distant station—Crowell, Nova Scotia—was too far to the east to obtain clear ground arrivals from most of the shots, and an engine failure of the ship stopped the shooting operation beyond shot 30. The distance ranges successfully covered were 36–131 km for Falmouth, 63–158 km for Mount Desert Island, and 116–158 km for Crowell. Interpretation using the standard method, slightly modified for interpreting reversed profiles, found a surface layer at 5.1 km depth east of Falmouth with an unreversed velocity of 5.3 km/s thinning toward east over a distance of 50 km. The underlying material had a velocity of 6.25 km/s (partly reversed), with the interface between the two layers sloping upwards to the east at ~3°.

Moho was not always detected by these marine experiments, but in some areas, velocities between 7 and 7.6 km/s were found, interpreted as a transition zone between basaltic lower crust and peridotitic upper mantle. In the area around the Bermuda islands, a depth range of 8–12 km was reported for the Moho (Ewing et al., 1952; Hersey et al., 1952).

Offshore investigations were also undertaken in the Pacific off California since 1948 (Raitt, 1949). Since 1948, seismic-refraction studies of the Pacific Ocean were made in a region extending from San Diego to the Marshall Islands and south almost to the Tropic of Capricorn (Raitt, 1956). The investigations included three different regions: the deep Pacific basin proper, atolls and islands, and the continental margin of North America and continued into the early 1950s.

Along the continental shelf, the velocity in the basement increased from 4.5 to 6.3 km/s with increasing distance from the coast. In the ocean basin proper, west of San Diego, underneath thin sediments the thickness of the basement was determined to be 5 km and the velocity 6.5 km/s. At the crust-mantle boundary, the Moho, at 9 km depth below sea level, a sudden velocity increase to 8 km/s was determined.

The experiments also included seismic-reflection shooting with 5 kg TNT charges. The charges were fired a few feet (~1–2 m) below the surface of the sea and the low-frequency reflections from the bottom were received on a hydrophone hung below the ship. Among many confusing sub-bottom echoes was

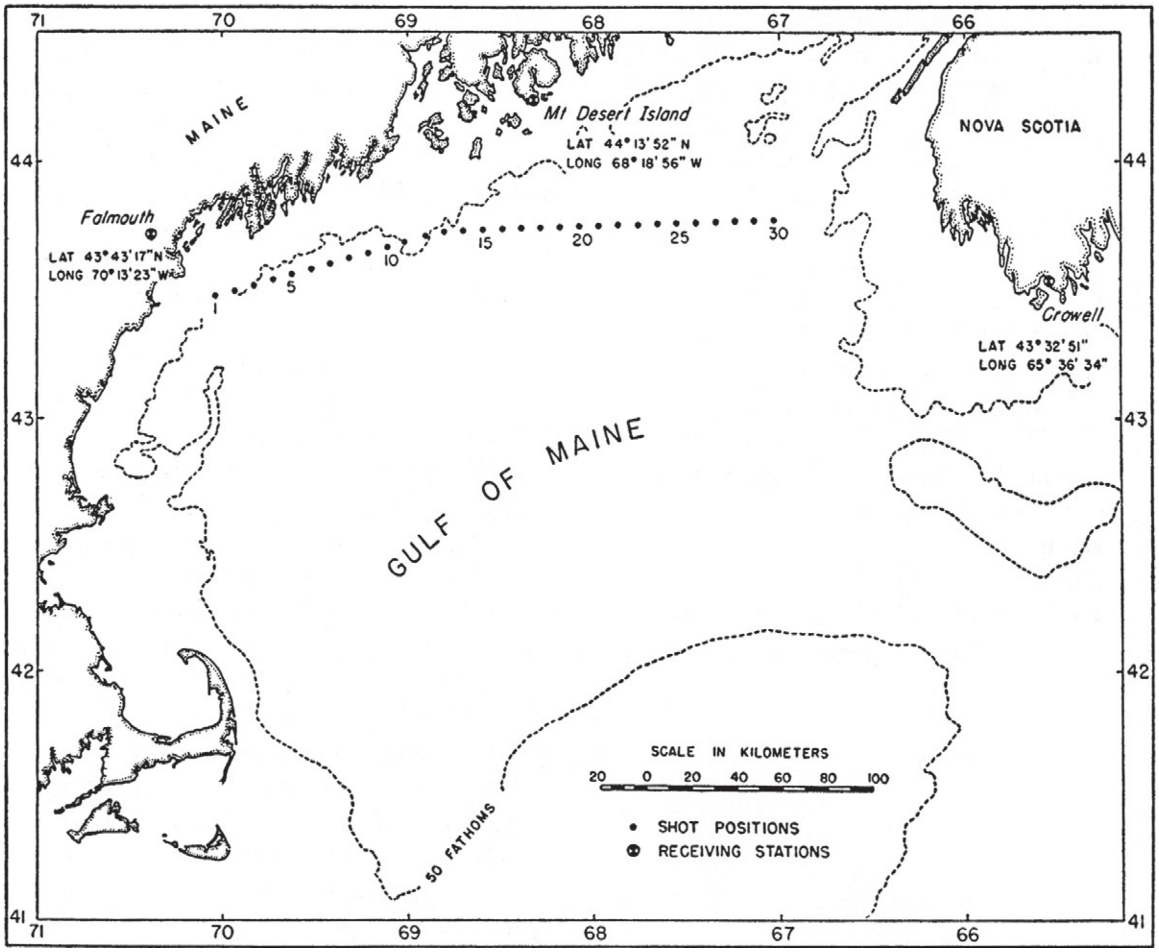

Figure 4.3-04. Seismic-refraction profile across the Gulf of Maine with fixed recording stations on land and a moving shotpoint at sea (from Katz et al., 1953, fig. 1). [Bulletin of the Geological Society of America, v. 64, p. 249–251. Reproduced by permission of the Geological Society of America.]

one persistent reflection from a horizon at a depth of ~600 m below the sea bed (Hill and Swallow, 1950).

The seismic-reflection techniques proved difficult in the beginning. Many hundreds of single-hydrophone observations revealed reflecting horizons at depths greater than 1 km below the ocean floor. However, the echoes between widely spaced stations could not unambiguously be correlated.

4.4. STATE OF THE ART AT THE BEGINNING OF THE 1950s

The philosophy on how to obtain the structure of the crust is based on the assumption that the Earth is divided into more or less flat layers of rocks of different physical properties and that the propagation of seismic waves follows the laws known from optics. This implies that waves are reflected and that beyond the critical distance, head waves develop which follow the discontinuities and produce arrivals aligning on straight lines in a time-distance graph. Thus the methodology to interpret seismograms in the late 1940s to the mid 1960s was to pick arrivals from the seismograms, to plot them into a time-distance graph, and to correlate those arrivals which were identified and assumed to belong to the same phase. Those arrivals were then connected by a number of straight lines with gradients interpreted as the velocity of the corresponding head waves (see, e.g., Fig. 5.2-02).

For a geological identification of the layers, most authors compared the obtained seismic velocities with experimental results published, e.g., by Leet (1946) or in a handbook edited by Birch et al. (1942). In this handbook, various authors had compiled tables summarizing laboratory measurements of densities, velocities, and other physical properties of minerals and rock samples from all over the world under varying pressure and temperature conditions. Amongst others, the information collected by Leet and Birch (1942) on seismic velocities and summarized in tables were of particular importance.

Gutenberg (1951b) summarized what was known on the crustal structure by the end of the 1940s. He concluded that the relatively large phase $\overline{P}$ in records of nearby earthquakes, which

TABLE 4.4-01. VELOCITIES OF LONGITUDINAL WAVES IN CONTINENTAL AREAS FROM ARTIFICIAL EXPLOSIONS (FROM GUTENBERG, 1951B, TABLE 1)

Region	Reference	Depth (km)	Velocity (km/s)	Depth (km)	Velocity (km/s)	Depth (km)	Velocity (km/s)
Northern Germany	Wiechert (1926)	0–?	5.98				
Northern Germany	Brockamp (1931b)	0–8	5.9	8–?	6.7		
Helgoland	Willmore (1949)						
	A	7–27	5.95			27	8.18
	B	6–14	5.57	14–30	6.5	30	8.18
Helgoland	Schulze and Förtsch (1950)	6–11	5.34	11–27	6.2–6.6	27	8.19
Black Forest	Reich et al. (1948)	0–21	5.9–6.0	21–31	6.55	31	8.2
Black Forest	Rothé and Peterschmitt (1950)	2–20	5.97	20–30	6.54	30	8.15
Canadian Shield	Hodgson (1947)	0–17	6.15	17–36	6.45	36	8.20
New England	Leet (1936)	0–23	6.0			23	8
Washington, D.C.	Tuve (1948)	0–10	6.0–6.7	10–42	6.7–7.1	42	8.15
Southern California	Wood and Richter (1931)	0–?	6.0				
Corona, California	Gutenberg (1951a)	0–6	5.7–6.0	10–?	6.5–7	40±	8.1–8.2
Corona, California	Tuve and Tatel (1950b)	3–14	6.3	14–?	6.8		

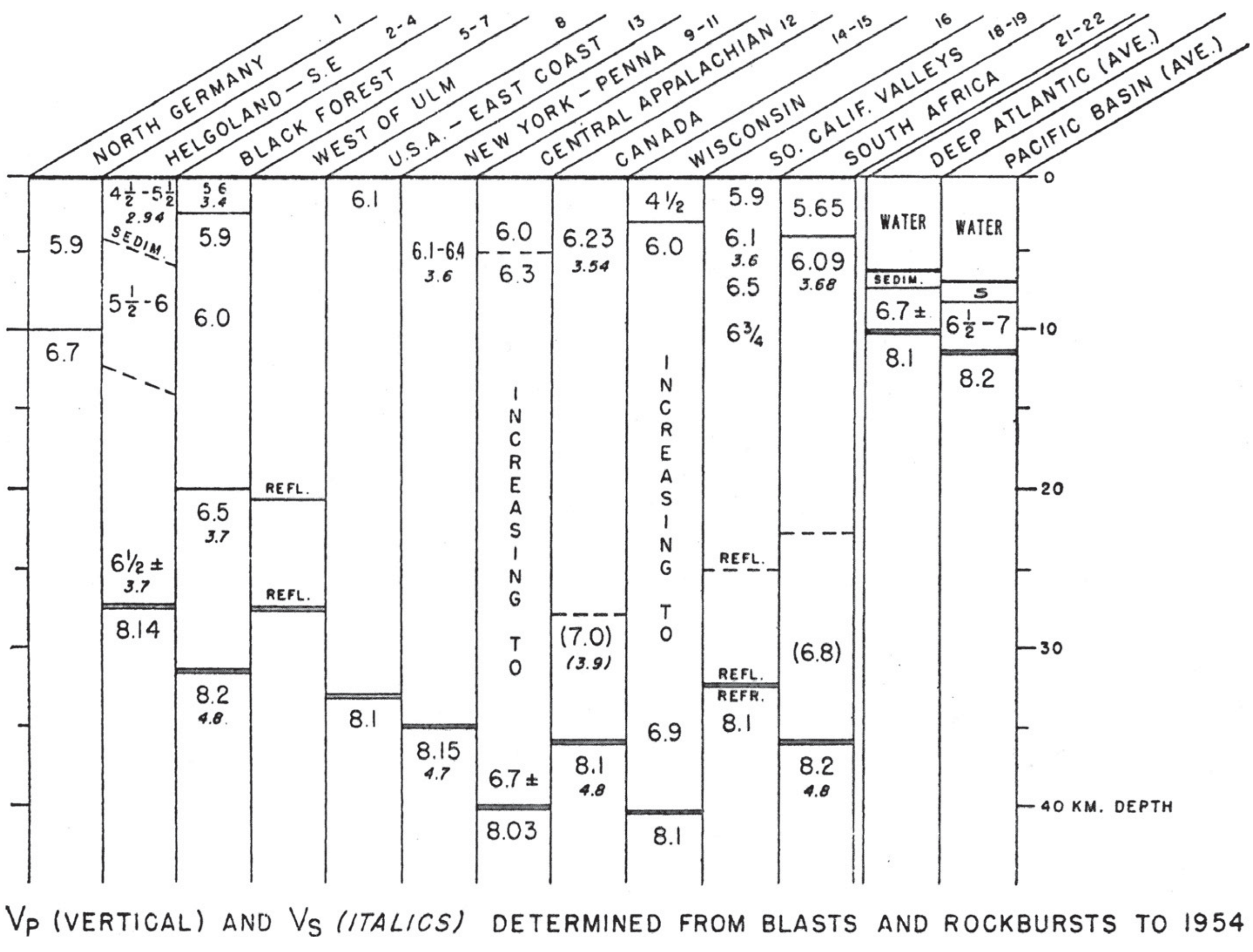

Figure 4.4-01. Average velocities of longitudinal and of transverse waves in the Earth's crust based on explosion records (from Gutenberg, 1955, fig. 1). [Geological Society of America Special Paper 62, p. 19–34. Reproduced by permission of the Geological Society of America.]

TABLE 4.4-02. LOCATIONS OF LARGE EXPLOSION-SEISMIC STUDIES OF THE EARTH'S CRUST AS SHOWN IN FIGURES 4.4-02 AND 4.4-03

No.	Location
1	Oppau, Haslach, Southern Germany, Blaubeuren
2	Göttingen, Kahla (central Germany)
3	La Courtine (France)
4	Burton-on-Trent (England)
5	Soltau, Heligoland (Northern Germany)
6	Denmark
7	Southern California
8	Richmond, Port Chicago (Northern California)
9	New England
10	Kirkland Lake (Eastern Canada)
11	New Mexico
12	Bikini
13	Big Horn County, Montana
14	Pennsylvania, Appalachians
15	Northeastern Japan
16	Western Transvaal (South Africa)
17	Soviet Republic of Georgia
18	Tien-Shan (USSR)
19	Californian coast (East Pacific)
20	Gulf of Maine
21	NW Bermuda, North American Basin (western Atlantic)
22	N Brownson Deep (western Atlantic)
23	Eastern Atlantic
24–26	Atlantic (Martinique, Bermuda), (western Atlantic)
27–31	Northern Atlantic (western Atlantic)
32	Bermuda (western Atlantic)
33–43	Pacific (central Pacific, western Pacific)
44	Newfoundland

hitherto was assumed to be the direct longitudinal wave and corresponded with its velocity of 5.6 km/s to the granitic layer, could not be reconciled with observations of the longitudinal waves from blasts. He stated that the velocity of longitudinal waves below the sediments was likely to be 6 km/s and increases to 6.5 km/s at depths of ~10 km. At greater depths between 10 and 15 km, this velocity might decrease, which was to be expected in rocks with considerable amounts of quartz, based on laboratory experiments (Birch et al., 1942). At the bottom of a deeper layer with higher velocity (7.0–7.5 km/s), he expected the Mohorovičić discontinuity at a depth of 30–40 km, but deeper under some mountain chains, forming the boundary between the simatic lower crust and the ultrabasic material below with P-wave velocities of 8.2 km/s. In a table (Table 4.4-01) he summarized the velocities for P-waves in continental areas from artificial explosions, which corresponds to his results published in 1955 and shown in Figure 4.4-01.

Gutenberg (1951b) also pointed out that there seemed to be a greater difference between the structure of the Pacific Ocean and the surrounding continental areas than between the bottom of the Atlantic or Indian Oceans and their surrounding shelves and continents. In the Pacific, he assumed a crustal thickness of only a few kilometers, while under the Atlantic Ocean, and probably also under the Indian Ocean, he saw a more gradual transition from the continent to the basins and the Mohorovičić

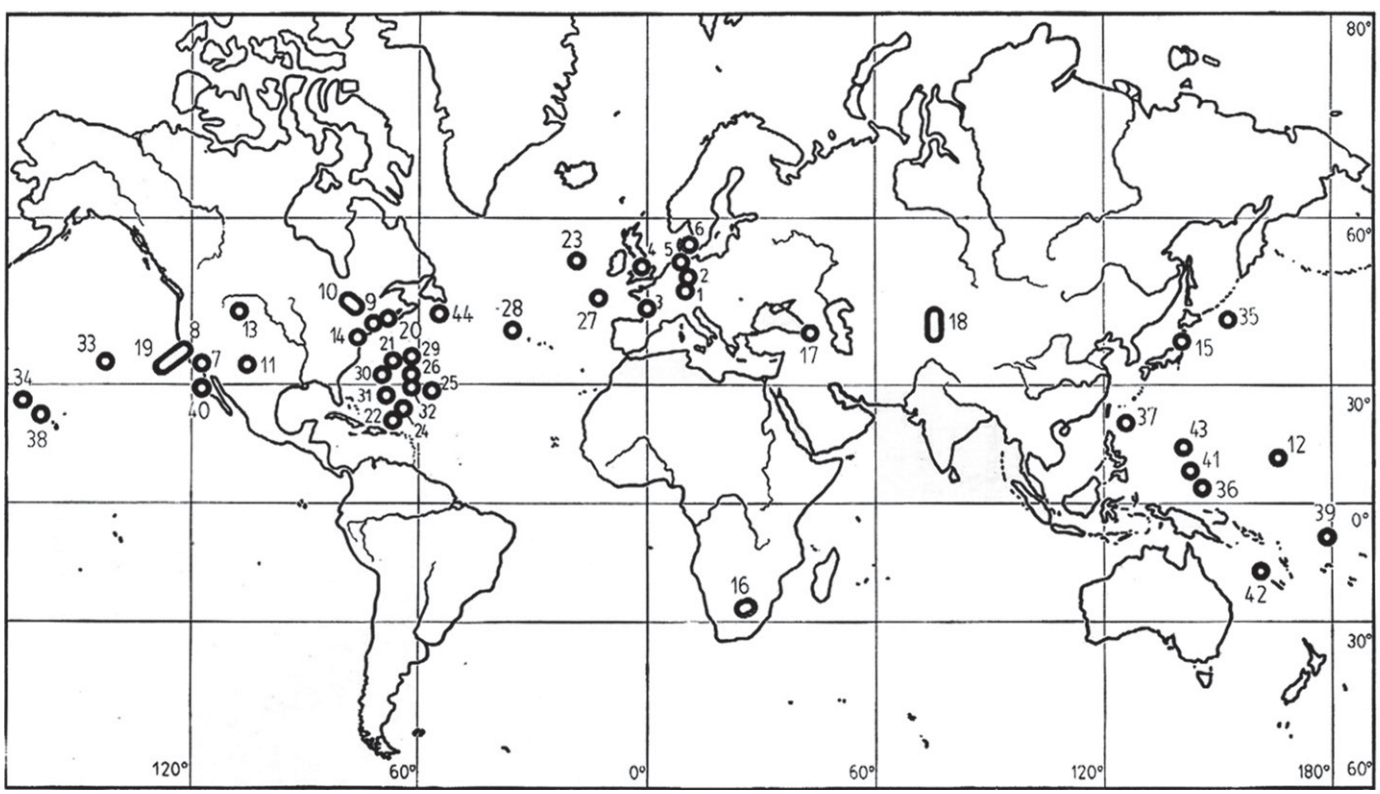

Figure 4.4-02. Location map of large explosion-seismic studies of the Earth's crust (from Reinhardt, 1954, fig. 3). [Freiberger Forschungshefte, C15, p. 9–91. Reproduced by permission of TU Freiberg, Germany.]

discontinuity at greater depths than under the Pacific but much shallower than under continents.

In 1954, a symposium was held at Columbia University ("The Crust of the Earth") where results of earthquake and explosion-seismic studies achieved until 1954 were presented (Poldervaart, 1955). Gutenberg (1955) summarized the velocity values published from earthquake observations from 1948 to 1954 and the corresponding depths for the Conrad and Mohorovičić discontinuities. In addition, he summarized separately apparent wave velocities and depth values obtained from blasts and rock bursts, including some early results from deep ocean basins (Fig. 4.4-01).

Ewing and Press (1955) pointed to the essential difference between oceanic and continental crust, with the silicic crust under ocean basins being no more than one fifth of that under continents. They also saw a remarkable unity of results reported for the oceanic crust: It is a layer of mafic rocks somewhat less than 5 km thick with P-wave velocity of 6.4–6.9 km/s. The Moho is at 10–11 km beneath the sea surface and is underlain by ultramafic rocks with 7.9–8.2 km/s P-wave velocities. They also pointed out that the crust under the Gulf of Mexico, the Caribbean, and the Mediterranean resembles the oceanic type rather than the continental type.

At the same time in the early 1950s, Otto Meisser, head of the Geophysical Institute of the Technical University of Freiberg, East Germany, initiated a diploma thesis to summarize the available knowledge on crustal structure obtained by experimental seismic work based on man-made events with emphasis on quarry blasts. In this thesis, which was published as a monograph in 1954, Reinhardt (1954) compiled all experiments and their main results as far as published until 1952 (Appendix A4-1).

The experiments were summarized in a map and in crustal structure columns, which are reproduced in Table 4.4-02 and Figures 4.4-02 and 4.4-03. The key data (coordinates, dates, references, details of recording equipment, and charges and key results) were compiled by Reinhardt (1954) in a series of tables.

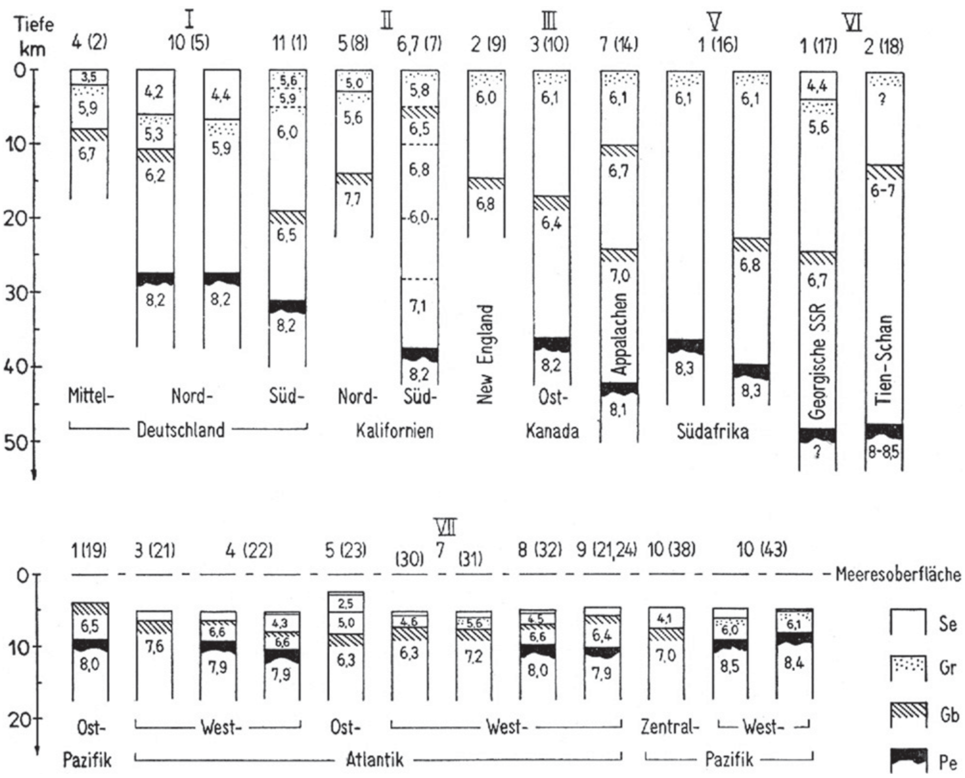

Figure 4.4-03. Crustal structure derived from large explosion-seismic studies (modified from Reinhardt, 1954, fig. 4). Se—sediments, Gr—upper crust (granite), Gb—lower crust (gabbro), Pe—uppermost mantle (peridotite). [Freiberger Forschungshefte, C15, p. 9–91. Reproduced by permission of TU Freiberg, Germany.]