

23. Scientific Background and Economic Seismology

Seismology has become the most incisive tool in petroleum exploration. The seismic method depends fundamentally on measurement and interpretation of travel times of elastic waves through various media. Theoretical basis for the technique was enunciated by Pierre de Fermat of France, who lived from 1601 to 1665.

The most important "law" pertaining to the propagation of elastic waves . . . through solids, liquids, or gases is Fermat's principle. This states that the waves follow a path which makes their travel time between two points a minimum. (Gutenberg, 1960, p. 959.)

A seismograph which could record the arrival of earthquake shock waves was invented in 1841. Robert Mallet of Ireland in 1846 presented a challenging argument for geological application of seismic observations.

When the earth wave passes abruptly from a formation of high elasticity to one of low elasticity, or *vice versa*, it will be partly reflected; a wave will be sent back again, producing a shock in the opposite direction; it will be partly refracted, that is to say, its course onwards will be changed, and the shocks will be felt upwards and downwards, and to the right and left of the original line of transit of the wave. (Mallet, 1846, quoted by Mather and Mason, 1939, p. 387.)

Mallet suggested that if moduli of elasticity and cohesion of various rocks be computed and actual times of transit of earth waves be accurately measured, knowledge of "a wide domain of physical geology" could be acquired. It should be possible to make geologic maps of the floor of the ocean, determine depths at which earthquakes originate, and learn the internal composition of the earth. He recommended that self-registering instruments be perfected and installed in earthquake laboratories at favorable locations. Earthquakes are too infrequent to supply adequate data, so he proposed that artificial earthquakes be initiated by explosives and the action of their waves recorded. In 1851, he reported measurements of velocities of artificially created waves through granite and sand.

Experimental work during the next several decades formed a base for important advances in theory around the turn of the century. Henry L. Abbot of the U.S. Army Engineers positioned several recording instruments to determine the velocity of seismic waves activated by an explosion of 50,000 pounds of dynamite in 1876. He reported (1878) velocities as great as 8,000 feet per second. In 1878, John Milne of England went to Japan, where he and his associates observed natural earthquakes and conducted extensive experiments with waves generated by explosives and by weight of falling objects—precursor of the modern "thumper" method.

In order to find out the nature of the vibrations they recorded the different components of motion of the waves. They sought to discover the effect of irregular terrain by placing the seismographs on steep hills, and by having a pond between the shot and the seismograph. They studied variations in amplitude with distance from the shot.

Milne showed that different materials had different velocities but his values were lower than those of Abbot (5,000 feet per second in schist, 3,500 feet per second in tuff). (Weatherby, 1949a, p. 8, 9.)

Ferdinand Andre Fouqué, professor in the College de France, and Auguste Michel-Levy, a mining engineer, made many important contributions to seismology, volcanology, and igneous petrography. Working together in the late 1880s and using more sensitive instruments, they recorded velocities of 10,000 feet per second in granite and 4,000 feet per second in Permian sandstone. Many other workers could justly claim important accomplishments.

Investigators of several nationalities made giant strides in theoretical and interpretive seismology during the period between 1890 and the outbreak of World War I in 1914. Among the many notables were F. Omori of Japan, Prince B. Galitzin of Russia, and A. Mohorovičić—the Croatian whose enunciation of the "Moho" discontinuity in 1909 gained lasting fame. The most fertile sources of major contributions were the Cavendish Laboratory at Cambridge University, England, where John W. Strutt (the third Lord Rayleigh) and A. E. H. Love were outstanding, and the geophysical

Institute at Göttingen University, Germany, where Emil Wiechert founded an international dynasty of seismologists. Wiechert's students and collaborators included, among many others, L. Mintrop, L. Geiger, and Beno Gutenberg. They, in turn, had distinguished lines of intellectual heirs.

By 1907 Wiechert and Zoeppritz had worked out the theory of seismic wave transmission through the earth, and in a monumental work 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. (Weatherby, 1949a, p. 9-10.)

Further scientific advance was inhibited by inadequate experimental facilities and techniques—deficiencies which were not overcome until industrial deployment of seismic methods provided the impetus and the means for improved technology.

24. Inception of Seismic Prospecting

Various scientists, particularly Belar in 1901, Mintrop in 1910, Galitzin in 1913, and Wilip in 1914, suggested the possible use of seismology to determine local geologic structure, but economic field trials were not undertaken until after the first World War. The method of refraction profiling which was subsequently adopted was outlined by Wiechert in 1910, as described by Weatherby (1949a, p. 10):

The farther from the origin the earthquake waves are observed at the earth's surface, the deeper the rays have penetrated into the earth and the more of the assumed layers they have therefore traversed. If one therefore proceeds from the origin gradually in the distance, then initially only the first, later also the second and then the third, and so on of the layers will come into action. One proceeds correspondingly with the computation. (This and the two preceding Weatherby items are quoted with permission of the Society of Exploration Geophysicists.)

Ludger Mintrop filed on December 7, 1919, for a German patent on the refraction-profiling "method for the determination of rock structures," but the application was not confirmed until 1927—after Mintrop had received a

United States patent on the method. Mintrop was well prepared to exploit the refraction technique commercially. He had received a Ph.D. degree from the University of Göttingen in 1911 after four years of research under Wiechert. Previously, he had attended the Academy of Mines at Berlin and the School of Technology at Aachen, and had practiced mine surveying. He taught part-time in mining and technical schools from 1905 until he joined the German army in 1914. His military service included two years of work constructing seismographs for artillery sound-ranging. Mintrop and K. Lehmann improved the instruments in 1919 and experimented successfully in determining the depth of coal deposits. (Sweet, 1966, 1969.)

Mintrop shot experimental lines during 1920 and 1921 across known salt domes at Sperenberg and Wietze, Germany, and found a new dome in the course of an exploratory profile from the Wietze oil field (Sweet, 1966, 1969). In October 1920, he made a refraction survey around the Neuengamme gas well, near Hamburg, which had been discovered accidentally some years earlier. He indicated a shallow salt plug nearby, but a well drilled to a depth of 436 feet failed to confirm the findings. His location proved later to be a few hundred feet off of the Reitbrook salt dome which had been outlined more accurately by torsion balance in 1918 (Behrmann, 1949). Reitbrook became productive in 1937. Mintrop and associates, with financial backing by five large steel and metallurgical companies, founded Seismos Gesellschaft in April 1921 to do seismic work on a commercial basis (Sweet, 1966, 1969).

Seismos party No. 1 with Otto Geussenhainer, a former student of Wiechert, as party chief, worked for Shell's "Aguila" company in Mexico from March 1923 until the spring of 1924 with indeterminate results. Party No. 2, which Mintrop supervised personally, operated under an exclusive contract with Marland Oil Company from July 1923 to November 1925, first in Oklahoma, later in east Texas, and after March 1924 in the Texas-Louisiana Gulf Coast. The results were wholly unrewarding. Geussenhainer's party No. 1 moved to the Texas Gulf Coast in the spring of 1924 under contract with Gulf Oil Corporation and made the first seismic

discovery of an American salt dome in June. This crew mapped three other Texas domes before returning to Mexico in May 1925. Gulf employed another Seismos party in the Gulf Coast area from 1925 to 1929. Ernst Cloos, who had attended Göttingen and other German universities, was the first chief of this party, which also was successful in finding new domes. Shell's Roxana Petroleum Corporation used two Seismos crews in the Gulf Coast during 1926-1930 and found at least six domes by their work. (Sweet, 1966, 1969.)⁶ One of the most productive discoveries by Seismos was the East Hackberry dome in Louisiana, which was mapped in 1926 for Union Sulphur Company and Calcasieu Oil Company. (Exploration by Seismos in the Gulf Coast is discussed in more detail in Chap. 14.5, 14.10, 14.15.)

The early work by Seismos in the Gulf Coast, including that which resulted in the first few of their salt-dome discoveries, was by profiling. It covered ground slowly, and observations were generally indefinite unless a line happened to cross a shallow salt plug directly, because the stratigraphic section lacked layers with velocity contrasts prominent enough to be easily recognizable by the instrumentation. L. P. Garrett, Gulf's chief geologist, suggested the "fan-shooting" system of rapid reconnaissance, which was adopted in 1925 or early in 1926 (Weatherby, 1949a; Sweet, 1966, 1969). This consisted of placing several recording instruments in a fan-shaped pattern radiating from a single shot point. The relatively high velocity through salt would cause a "time lead" on any line along which the waves penetrated a salt mass.

The diagnostic properties for salt domes were: high absorption, 15,000 feet per second velocity and time leads of from .3 to .5 second. Occasionally anomalous results were being obtained in local areas where none of these conditions were satisfied. These abnormal areas had leads of the order of .1 to .2 second and no amount of profiling revealed a salt velocity. As was right and proper, these anomalies were set aside to await the advent of an exploration method of higher

resolving power. . . (Weatherby, 1949a, p. 14; quoted with permission of the Society of Exploration Geophysicists.)

A small number of shots sufficed to search for salt velocities over a wide area. Seismos did all the effective seismic exploration on the Gulf Coast prior to June 1926 using mechanical seismographs and air-wave determination of the time of explosions.

On account of the limitations of the air-wave determination of the time of the explosion and on account of a belief in a theoretical impossibility of effective work at a distance of more than 3 miles, shot lengths of less than 2½ miles were used and the seismic prospecting was effective down to a depth of 2,500 feet. (Barton, 1930, p. 1119.)

Large parts of coastal southeast Texas and southwest Louisiana were explored for shallow salt domes by the end of 1926. Seismos had inaugurated a revolution in the art of petroleum exploration although, thus far, it had proven able only to locate shallow salt plugs. The sensational technical success and prompt discovery of commercial oil production on some of the new domes attracted competition. The Seismos company was slow to improve its instruments and field procedures and soon lost the leadership to more alert innovators. It discontinued seismograph operations in the United States in 1930 but continued work in Germany and some other countries.

25. American Competition in Refraction Seismology

E. L. DeGolyer organized Geophysical Research Corporation (GRC) as an affiliate of Amerada Petroleum Corporation in 1925 with J. C. Karcher in charge as vice president. GRC designed new equipment in less than a year and put its first two crews in the field in March and April 1926 under contract with Gulf (Sweet, 1966, 1969).

Many changes in both apparatus and field technique were effected from the very beginning. The newly designed electrical detectors and amplifiers were many times more sensitive than the German mechanical seismographs. Radio communication between shot point and detector point permitted the sending of the instant of ex-

⁶ Sweet (1966, 1969), *The History of Geophysical Prospecting*, contains a wealth of biographical information and interesting anecdotes as well as a history of the application of the techniques.

plosion by radio, whereas the Germans estimated this instant by using the air wave and the surveyed distance. Distances between shot and detector were found by the use of the air waves, whereas the Germans used surveyed distances. The above advantages greatly increased the speed of shooting and consequently the cost of coverage was reduced substantially. (Weatherby, 1949a, p. 13; quoted with permission of the Society of Exploration Geophysicists.)

GRC discovered its first salt dome at Moss Bluff in Texas and its second at Port Barre, Louisiana, in June 1926 (*see* Chap. 14.6). Both finds were for Gulf by a crew headed by E. E. Rosaire. Another party, with Eugene McDermott as chief, found ten domes in Louisiana for Gulf during 1926–1928 (Sweet, 1966, 1969). During an early phase of the campaign, these crews learned that lengthening the distance between shot point and recorder to about 5 miles enabled them to obtain salt velocities from domes buried at depths of 4,500 to 5,000 feet (Barton, 1930). Later experience with distances of about 9 miles afforded penetration to much greater depths; consequently many areas were re-shot two or three times in search for deeper structures. GRC quickly attained a pre-eminent position in seismic exploration and secured contracts with several oil companies about as fast as equipment could be assembled and competent personnel employed. One of the most notable achievements was exploration of about 2,000,000 acres of coastal swamps, lakes, and bays for Louisiana Land and Exploration Company (*see* Chap. 14.7). Two parties discovered nine domes in sixteen crew-months between August 1927 and September 1928. Some of these ultimately proved to be exceptionally productive.

All the GRC refraction reconnaissance in the Gulf Coast region was by fan shooting, with occasional profiles to find the form of the time-distance curve and distances from the shot point at which marked changes in the slope of the curve occurred (Weatherby, 1949a). Some of the newly discovered domes were detailed by refraction profiling before the reflection method was adopted for detail work in 1929. GRC refraction surveys also scored important successes outside the Gulf Coast district. While shooting for shallow salt domes in northeast

Texas in 1927, a party under B. B. Weatherby obtained records in an area of interest near Van which lacked salt velocities but appeared anomalous. Further work by profiling outlined a deep-seated structure on which the sensational Van oil field was discovered by Pure Oil Company in 1929 (Liddle, 1936; *see* Chap. 15.15). Refraction profiles proved effective during 1928 and 1929 in locating some of the large subsurface features of southeastern New Mexico, where the Permian stratigraphy afforded substantial velocity contrasts (Innes, 1953).

The initial successes of Seismos and GRC were fortuitous in the sense that they depended on deployment in areas endowed with abundant structures of a type ideally suited to detection by their techniques. Producing salt domes were available for investigation as models. The prospective region was already outlined in a general way, and a few of the local prospects were previously suspected from superficial indications. Most newly discovered seismic anomalies were promptly tested by the drill, and enough of them proved productive to add impetus to the campaign. The greatest triumphs came to those who were first to explore some of the most favorable territory and who had adequate financial support for large-scale operations. Other early entrants in economic seismology lacked this favorable combination of circumstances.

A group of outstanding scientists organized Geological Engineering Company in 1921 and conducted significant field experiments with seismic reflections and refractions in Oklahoma (*see* ¶26 below). Their financial backing by Marland Oil Company was discontinued in 1922, and Burton McCollum took over their patents and other assets and liabilities. McCollum contracted with Atlantic Refining Company in 1923 to make a refraction survey of Atlantic's (Cortez Oil Corporation) extensive wildcat leases southwest of Tampico, Mexico, in search of anticlinal structure on Cretaceous limestone. The field work began in February 1924. J. E. Brantly, who was Atlantic's chief foreign geologist, has recounted (1965) the laborious procedure:

The instruments comprising the seismograph were not in an assembled package but were all

in their separate component parts and when laid out and connected in operating order covered the better part of a flat bed White truck, some 8 feet wide by 20 feet long. . . . The four oscillographs and the camera were mounted in a separate light-proof and sound-proof box. Thus the strip negative carried four traces. This required four "detector" or receptor stations. These were carbon granule instruments built into proper counterweight, air cushion, and spring mounted devices that could be set in motion by the seismic or sound waves to be generated. . . . These detectors were mounted in aluminum cases about 5 inches in diameter and 4 inches high. In order to have four in good operating order, we carried a stock of about twenty. These instruments were set in hand-bored holes about 6 inches deep, at numbered stations, from 50 meters to 200 meters apart, depending upon the apparent depth of the limestone and the structural detail desired. The seismic wave was generated by the explosion of 40 percent dynamite placed and tamped in hand-bored holes from 6 to 15 feet deep and 6 inches in diameter. Quantities of the explosive used varied from a few pounds to as much as one ton on long distant shots. . . . Several shot holes were needed for the larger amounts of dynamite used. Shot points varied from 500 meters to as much as 5,000 meters from the detector stations. . . . All shot points and detector stations were incorporated in precise surveys for distance and elevation. In the early days the detonation of the dynamite and the starting of the camera was done [at pre-arranged times] by stop watches that had been carefully adjusted and coordinated.

Several profile lines some 5 to 10 kilometers in length were shot at right angles to the assumed strike direction of the formations. Two or three 25-kilometer lines were shot also.

The structural relief found on the long 25-kilometer lines was at least 2,500 feet. . . . Lesser highs were found on top of the uplift. There was also a complication of igneous dikes and plugs.

Five or six exploratory holes were drilled behind this and later seismic surveys. All locations were made on apparent anticlinal or high features. Without exception the depths determined by the seismic surveys checked out with remarkable, or at least reasonable accuracy. (p. 4-5.)

Two of the wells found substantial oil showings. One of them, with capacity of 400 barrels per day, may have been the first oil well ever completed on a seismograph location, but it was noncommercial in the contemporary cir-

cumstances of the Mexican oil business. McCollum Geological Exploration Company, which was owned 50/50 by Atlantic and McCollum, did further refraction work in Mexico and Venezuela.

Our geophysical work . . . was quite successful from the standpoint of finding highs or structures but not successful in locating commercial oil fields. (Brantly, 1965, p. 7.)

Atlantic released its interest in the company in 1928 to McCollum, who entered into a new and mutually profitable relationship with The Texas Company.

California was another region in which the first trials of the seismograph in exploration were unrewarding. Frank Rieber, a talented individual inventor, obtained financial support from the General, Standard of California, Associated, and Shell oil companies for experimental surveys in 1925 with a seismograph of his own design (Sweet, 1966, 1969). A refraction profile across the Lost Hills oil field showed general correspondence between the structure of loosely consolidated shallow beds and that of the oil sand (Rieber, 1930). Some other surveys were technically successful but found no new anticlines, and the project was soon discontinued.

One of the pioneer exploration contractors was Petty Geophysical Engineering Company, which was incorporated in October 1925 and set up laboratories in San Antonio, Texas. Four members of the Petty family owned the corporate stock. Dabney E. Petty, an experienced petroleum geologist, first proposed the project in April 1925 while working for the Texas Bureau of Economic Geology under J. A. Udden, who had advocated use of the seismograph for mapping geologic structure since 1919. Dabney Petty and Olive Scott Petty, a professional engineer, did the firm's technical work initially in constructing and operating seismographs. Experimental field operation began in May 1925 and was followed within a few months by successful surveys of Gulf Coast properties owned by members of the family and associates. The first contracts for foreign work were undertaken in 1927 in Venezuela. Conversion from refraction to reflection seismology brought a major expansion of Petty's contracting busi-

ness in the early 1930s, both in the United States and abroad. (O. S. Petty, personal commun.; Sweet 1966, 1969.)

Several major oil companies in the United States established geophysical departments soon after the practicability of the techniques became apparent, but most depended on the commercial contractors for a quick start in seismic exploration. Humble Oil and Refining Company was exceptional in deciding to develop its own capability instead of relying on outsiders—a decision which imposed some delay in entering the field. The company employed Norman Ricker in 1924 as head of a geophysical division under the control of chief geologist Wallace Pratt. Ricker resigned in July 1925 and was succeeded by O. H. Truman after some of the difficulties which seem inherent in team research.

Truman was difficult. He came to us as an instrument maker from the observatory at Flagstaff, Arizona. Ricker, a highly educated, widely experienced physicist from the Bell Telephone companies, had been almost a year trying to design and construct a field seismograph, with no tangible results. Truman, who had reported to Ricker some months previously, appeared at my office, my first real contact with him. He was unhappy. If I would give him *carte blanche* in the shop for 30 days, free of interference from Ricker, he would produce a seismograph, together with a survey of the Pierce Junction dome that would show the salt plug. Otherwise, he was through and would quit. I was impressed and persuaded Ricker to agree. Truman took over and made good his undertaking. Ricker resigned and Truman equipped and trained our first seismic field parties. (Wallace E. Pratt, letter to E. W. Owen, July 15, 1972.)

Subsequently both Truman and Ricker were successful as independent geophysicists. Dave P. Carlton was Humble's co-ordinator of geophysical and geological matters. Humble's refraction parties quickly acquired orientation experience on some of the known salt domes and were competitive in finding new prospects in 1926. The policy of conducting its own geophysical activities proved advantageous in activating a large and effective organization.

Marland Oil Company began using its own personnel and apparatus for seismic explora-

tion on the Gulf Coast, in January 1926, after the termination of its contract with Seismos. At the start of this new endeavor, Marland had the strongest geophysical research department and one of the largest and most experienced geological organizations in the oil industry. These advantages, however, did not bring good fortune to its seismic program. The company which had pioneered exploration seismology in the United States with the Geological Engineering Company in 1921 and the first Seismos party in 1923 had no substantial returns from its geophysical initiative when the Marland company was taken over by Continental Oil Company in 1929.

The refraction method had passed its heyday by 1929 and was rapidly superseded by reflection seismology. However, its usefulness continued for special purposes and in areas where the early reflection technique encountered difficulty in obtaining good records—for instance, in Mississippi, some parts of the Permian basin, and Iraq. It enjoyed another period of popularity and rapid success in the offshore exploration campaign for salt domes in the Gulf of Mexico which began in 1944.

¶ 26. Inauguration of Reflection Seismology¹

The seismic reflection method of determining subsurface structure, which became the most powerful tool in petroleum exploration, originated and received its first effective application in the United States. Reginald Fessenden applied for a patent on "Method and Apparatus for Locating Ore Bodies" by sound waves in 1914. This basic patent was issued in 1917 and was purchased by Geophysical Research Corporation in 1925. William P. Hase-man conceived the method of contouring subsurface structure by reflected waves in 1917 and invited John C. Karcher, E. A. Eckhardt, and Burton McCollum to join with him in activating it. Karcher and McCollum applied for pertinent patents in 1919 while Hase-man organized Geological Engineering Company to un-

¹This section, except portions otherwise attributed, was derived from Schriever (1952) and Sweet (1966, 1969). The former wrote an excellent summary, and the latter provides rich detail.

dertake commercial exploitation. The company was incorporated in April 1920. Frank Buttram, Irving Perrine, and D. W. Ohern—petroleum geologists at Oklahoma City—and some of their associates supplied \$28,000 working capital and participated with Haseman in 85 percent of the stock. Karcher, McCollum, and Eckhardt received 15 percent of the capital stock. The company paid Karcher and McCollum \$6,000 and acquired their patents. Karcher and Eckhardt designed and assembled equipment, which was field-tested in June 1921 near Oklahoma City by Haseman and Karcher with assistance of Perrine and his partner, W. C. "Cap" Kite. Reflections were recorded along several profiles by sequences of shots spaced at 100-foot intervals from the detector.

Karcher, Haseman, Ohern, and Perrine conducted a pilot survey in July 1921 near the Arbuckle Mountains in southern Oklahoma, where the stratigraphic column of Hunton Limestone, Sylvan Shale, and Viola Limestone seemed especially favorable. They shot refractions to determine velocities, which they found to be 11,680 feet per second for the Hunton, 5,780 feet for the Sylvan, and 14,070 feet for Viola. After obtaining these basic data, they shot reflection profiles on the well-known Vines Branch anticline and constructed a cross section showing the structure on top of the Viola. Perrine exhibited these results to E. W. Marland, for whom he had worked formerly as chief geologist. Marland Oil Company agreed to underwrite the bare cost of experimental surveys for two months around Ponca City, Oklahoma. F. P. "Spot" Geyer and Fritz L. Aurin, respectively the chief geologist and assistant chief for Marland, selected known anticlines for the experiment, and the shooting was done in September and October 1921 on the Mervine anticline and other structures. Aurin assisted in contouring structure from the reflection data.

The results were not generally conclusive. . . . However, the Marland Company tried to make a deal with this [Geological Engineering] Company for a continuation of the experimental work and the exclusive use of their services, but no agreement could be worked out. (Fritz Aurin, letter to E. W. Owen, March 23, 1964.)

Additional field work in northern Oklahoma failed to attract further financial backing. Geological Engineering Company assigned its reflection and refraction patents and delivered its instruments to McCollum in 1922.

The Geological Engineering Company was most important to the advance of seismic exploration because of the experience of physicists and geologists working together in applying reflection techniques and instrumentation to problems of petroleum geology. McCollum went ahead with exploration for Atlantic Refining Company in 1923. Haseman went to work for Marland Oil Company, and in 1924 organized the most comprehensive research department that thus far had been established in the producing branch of the oil industry. Eckhardt and other outstanding scientists joined the Marland department.

The major projects of interest were seismic, gravity (pendulum and torsion balance), permeability and other characteristics of formations, especially reservoir rocks, and estimation of oil and gas reserves. (Aurin, letter to E. W. Owen, March 23, 1964.)

In May 1926, Haseman was instrumental in forming a strong petroleum engineering division with E. O. Bennett and K. C. Sclater as chief engineers for Marland's Texas and Oklahoma Companies respectively (E. O. Bennett letter to Fritz Aurin, June 1, 1964). When Marland was being taken over by Continental Oil Company, Eckhardt went to Gulf Research and Development Company as head of its new geophysical division in December 1928, and several of his associates followed. Karcher became the first head of Geophysical Research Corporation when E. L. DeGolyer founded that phenomenal organization in 1925.

Mutual personal acquaintanceships were the matrix of the constellation in which reflection seismology crystallized. Haseman, Eckhardt, and Karcher received their Ph.D. degrees from the University of Pennsylvania, as also did Charles B. Bazzoni who initiated seismograph operations for Sun Oil Company in 1926. Anton Udden, a fellow graduate student with Karcher at Pennsylvania, was responsible for influential contacts in 1919 between Karcher and J. A. Udden, Director of the Texas Bureau

of Economic Geology. Haseman, Karcher, Eckhardt, McCollum, and Bazzoni had been engaged in sound-ranging research for the United States Government during the first World War. Haseman, Karcher, Buttram, Perrine, Ohern, Kite, Geyer, Aurin, and DeGolyer were well known to each other as former teachers and/or students at the University of Oklahoma. None of these lived in an ivory tower.

¶ 27. Reflection Seismology by Geophysical Research Corporation

Development of a reflection technique was one of its principal objectives when GRC was formed in 1925, although the company's first commercial work used the refraction method (Weatherby, 1949a). Efforts directed by J. C. Karcher toward achieving that objective are related interestingly by Henry Salvatori in a letter of September 9, 1948, to C. T. Jones, which is quoted by Sweet (1966, 1969), and in H. B. Peacock's *Reminiscences of a Doodle Bug* (1964). An experimental crew under J. E. Duncan tried unsuccessfully to record reflections near Anthony, Kansas, in the late summer of 1926 before moving to the Gulf Coast. Duncan obtained satisfactory reflections from the caprock of the Nash salt dome in the fall of 1926 (Weatherby, 1949a). Other GRC parties experimented with reflections during the course of refraction surveys, and a crew headed by Salvatori recorded definite reflections in an area south of Shreveport, Louisiana, in February or March 1927. H. B. Peacock was placed in charge of a crew which began work in the Balcones fault zone of Texas in December 1926.

We obtained some good reflections, but could not do so consistently. (Peacock, 1964, p. 4.)

Reflection results in various areas by the several GRC parties were very erratic until 1928.

The equipment of the first "full-fledged" reflection crews consisted of three pickup trucks with box-like cabs built on the back to house the instruments.

The instruments for each truck consisted essentially of one geophone (to distinguish our detectors from competing mechanical seismographs); a one-channel amplifier; and a one-trace, hand cranked camera, which was a commercial mov-

ing picture camera, fitted with a tuning fork mechanism for placing timing lines on the records. The photographic records were on paper about 1½ inches wide with perforations along each edge like moving picture film of that time. Except for the geophones, the instruments were the same as those used in refraction work. The "refraction" geophones were an adaptation of Baldwin loud-speaker units in which a weight suspended on flat springs was attached to the pivoted armature of the Baldwin unit by a slender brass rod. The reflection geophones used the same Baldwin units, but instead of the weight, a thin metal diaphragm, similarly attached to the armature, and forming a part of the geophone case, constituted the vibrating mechanism. . . . The reflection geophones were suspended in water-filled pipes about 2½ feet long, welded to a point at one end for driving into the ground. From the difference between the refraction and the reflection geophones, it is now quite apparent that refracted and reflected waves were considered to be quite different in character. It was only when this belief was dispelled that the reflection method made progress. (Peacock, 1964, p. 3.)

Belief that the reflected waves were more "sonic" than the refractions may have been psychological fall-out from the wartime research in sound-ranging.

Peacock mentions some of the major handicaps inherent in the early procedures.

1. First of all, proof of reflections depended on the correlation of certain events on two or more seismic traces. The fact that the traces were on separate pieces of paper, which were cranked at varying speeds, and [which] tended to roll up at every opportunity, made this very laborious and difficult.
2. The equipment had no filters other than the inherent filtering action of the various components.
3. Shallow holes dug by hand were used exclusively, which made the effectiveness of the shots dependent on the near surface soil conditions.
4. For some time little attention was paid to the polarity of the various traces. Actually, I was unable to find anyone willing to say that the direction of first breaks depended on the polarity of the instruments. (1964, p. 7.)

A favorable turn in the fortunes of the reflection method took place in the Seminole, Okla-

homa, district where Amerada placed four GRC crews in the summer of 1928 in a concerted attempt to find structures which had been missed in the prior oil development. This area had the advantage of the Viola Limestone as an excellent reflecting horizon, although complications arose where good reflections from Hunton and Mayes limestones imposed ambiguous data. Two instrumental changes improved the consistency of reflection results—replacement of the experimental pressure-type geophone by the customary inertia type, and introduction of a more discriminating amplifier (Peacock, 1964; Salvatori, *in* Sweet, 1966, 1968).

Judged by present standards this work was of questionable value. In fact, up until the fall of 1928, it should be considered mainly of an experimental nature although one or two structures had been indicated.

In early 1929 the method was under considerable fire. Seismic predictions made during 1927 and 1928 had been only partially confirmed by the wells drilled on the [Seminole] plateau during this period. Doubt was expressed on a number of occasions whether the recorded pulses actually were reflections and if so whether they could be interpreted. Consequently something had to be done to revive the earlier optimism. Fortunately an opportunity was presented in a program then in progress. (Weatherby, 1949b, p. 286; quoted with permission of the Society of Exploration Geophysicists.)

GRC made a thorough check on the method in the spring of 1929 in central Kansas, where the Cimarron Anhydrite supplied good reflections at depths confirmed by core holes. Adequate evidence substantiated the validity of the reflections and the accuracy of interpretations (Weatherby, 1949b).

The technique improved rapidly with field experience. Short refraction shots were taken at each recording spread to obtain corrections for discrepancies in arrival time of reflected waves, which accrued from irregularities in the low-velocity "weathered zone" near the surface. Record quality was improved by digging shot holes to the water table, and drilling machines were introduced to replace digging by hand. A second galvanometer added to each camera provided two traces on each record; later cam-

eras recorded multiple traces. Explosions were detonated electrically and the "time break" was recorded on the seismogram. Computation methods were formulated and standardized. (Weatherby, 1949b; Peacock, 1964; Sweet, 1966, 1969.)

The first successful mapping by the reflection method depended on data computed from prominent reflections on persistent horizons which could be correlated from one location to another. A GRC party, led by T. I. Harkins under the supervision of Eugene McDermott, found no such persistent correlatable horizons when they were assigned to detail the Darrow salt-dome prospect in the Louisiana Gulf Coast in the summer of 1929. They initiated there the first step in the development of the "dip-shooting" method of reflection surveys, which proved applicable in many difficult areas. They placed sets of detectors first in one direction from the shot point and then in the opposite direction. Difference in arrival time at the opposite sets indicated the presence of steep dips.

An effort was made in this investigation to correlate all reflections obtained with the aid of differential times. (Eby and Harkins, 1949, p. 151.)

The first well drilled on this reflection picture resulted in discovery of the Darrow oil field, and subsequent drilling showed the reflection map to be more accurate than those made from prior refraction and torsion-balance surveys.

GRC re-entered the Seminole, Oklahoma, area for Amerada in the fall of 1929, and mapped several small structures during the next few months. Drilling on three of these discovered substantial oil fields during 1930 (Weatherby, 1949b; *see* Chap. 12.9). Reflection seismology had proved to have such great prospective value that Amerada decided to restrict GRC's employment of the method to exploratory projects in which it was a sole or part-interest owner. The company maintained an imposing record for many years thereafter.

28. Exploration by the Reflection Method, 1930-1945

Competition in the use of reflection seismology for exploration arose during the early years of the great depression, when the world was

plagued also with an oversupply of oil. Most of the men who started new geophysical contracting companies had been officials, supervisors, party chiefs, or instrument makers for GRC. Karcher and McDermott resigned from GRC to organize Geophysical Service, Inc. (GSI) in 1930 with *sub rosa* support from DeGolyer. They designed new instruments, the principal virtue of which was that they were different. Many GRC men joined GSI, which was immediately successful—reputedly because of the excellence of its personnel and despite its instrumentation. Seismograph Service Corporation was founded in 1931 with William Green, a former GRC employee, as president. Independent Exploration Company was incorporated in 1932. All its original stockholders were former GRC men; E. E. Rosaire was the first president. Reginald Sweet and Elliott Sweet, formerly of GRC, formed American Seismograph Company in 1933. These companies, in turn, became the source of key personnel for numerous other competing firms. Henry Salvatore left GSI to organize Western Geophysical Company in 1933, as did Roland Beers to start Geotechnical Corporation in 1936. An exception to the GRC heritage was United Geophysical Company, which Herbert Hoover, Jr., headed in 1935. (Sweet, 1966, 1969.) Petty, Humble, and Shell, who had been experimenting with reflections earlier began systematic field work with this method by their own staffs in 1930 and 1931 (Weatherby, 1949a). Other major oil companies soon formed geophysical departments or adopted the reflection technique in departments already existing.

The question of basic patent rights was not taken too seriously during the early years, as the art was about 80 years old and was thought by many to be in the public domain. The matter became big trouble in 1933, when The Texas Company asked all users of seismic techniques to pay royalties and in 1934 brought suit against Sun Oil Company for infringement of the McCollum and Mintrop patents (Hrdlicka, 1936; Sweet, 1966, 1969). All operators who had employed seismic methods joined forces in defence, but when the oil companies realized potential jeopardy to ownership of many of their properties the litigation was settled out of court in 1937. Several important

patents were held by firms other than The Texas Company, and cross-licensing agreements facilitated further development of the art by making the fundamental patents generally available.

Outstanding accomplishments in several regions brought the reflection method into prominence in the early 1930s, and its prestige continually increased. In the Texas-Louisiana Gulf Coast, the most influential early triumphs were discoveries of important oil fields following reflection dip surveys of prospects which the torsion balance and refraction seismograph had indicated previously with less precision and less assurance. The first sensational cases were the Iowa, Louisiana, oil field in October 1931; and the Tomball, Texas, oil and gas field in 1933 (Rosaire and Ransone, 1936; Eby, 1949a, 1949b). A more convincing demonstration of the value of dip shooting was discovery in 1934 of the giant Anahuac, Texas, oil field on a deep-seated dome in an area which had been shot over several times by refraction fans without finding any anomaly (Bader, 1949). A rapid increase in reflection operations in the Gulf Coast district followed the discovery of Anahuac and was stimulated further by recognition of the importance of faulting (Rosaire and Ransone, 1936). Although the most frequent successes of the reflection method in this district during the 1930s were on prospects where some favorable indications were already known, reconnaissance surveys found new domes at least as early as 1933 (Buchanan, 1934). Rosaire and Adler (1934) published a valuable analysis of the accuracy, limitations, and sources of error in dip shooting.

In the East Texas basin, the Tide Water and Seaboard oil companies, jointly, conducted notably successful exploration during the years 1932–1935, using a GSI crew led by H. B. Peacock and later by Fred Romberg, with Gus Schmidt of Tide Water as the directing geologist. They covered the major part of the basin by reconnaissance and mapped many local structures in some detail. The first two wells drilled as a result of this work were dry holes near Tennessee Colony on structures which remained prospective for many years. The partnership discovered major oil and gas fields at Long Lake in 1933 and Cayuga in 1934 (*see*

Chap. 15.17), and took leases on other structures where important fields were developed later. The reconnaissance coverage comprised depth points spaced about a mile apart. Reflections were obtained from Upper Cretaceous Pecan Gap and Austin Chalks, but the main reliance was on the Lower Cretaceous Buda or Georgetown Limestones which underlie the productive Woodbine Sand.

... our procedure was to shoot in general along roads or trails and watch for anomalous conditions; then to return at a later date and shoot other lines which might confirm the anomaly. We were scouted almost daily and very seldom did we repeat a line. Usually when an anomaly was observed, the crew was moved to another part of the area for a time. In spite of the fact that we were scouted, we had very little competition from other crews. ... We soon recognized a distinguishing character in the Georgetown reflections which enabled us to correlate between lines over considerable distances with some feeling of reliability. (Peacock, 1964, p. 19, 22.)

A strikingly successful reflection campaign in southern Arkansas was responsible for establishing the Jurassic Smackover Limestone as a new producing formation (*see* Chap. 15.7). The first commercial production was found in the Snow Hill sector of the old Smackover shallow field in 1936 on a deep structure mapped by reflections in 1935. Several productive anticlines were found by the reflection method thereafter. Nine Jurassic oil fields were opened in south Arkansas by the end of 1940, the largest being Schuler in 1937 and Magnolia in 1938.

Illinois suddenly became one of the hottest oil districts in the United States in 1936, when Pure Oil Company discovered the large Clay City field on a reflection seismograph prospect mapped in 1935 (*see* Chap. 12.33 and 12.34). Discovery of other major oil fields followed in rapid succession—Loudon in 1937, Salem in 1938, and a multitude of others which brought Illinois production to 147 million barrels in 1940.

The first consistently good reflections in California were obtained in 1932, but only four seismic parties were operating in the state as late as February 1934. Discovery in November 1934 of the small Chowchilla gas field on a re-

flection prospect caused immediate increase in seismic exploration. Spectacular results accrued in 1936 when the major Ten Section oil field was discovered in the San Joaquin Valley and California's largest oil field was discovered at Wilmington in the Los Angeles basin. (Salvatori, 1949.)

The reflection technique was slow to displace refraction and gravity methods as the dominant exploration tool outside the United States. European oil companies appear to have taken little notice of it during the early 1930s, and some European geophysicists and geologists were skeptical of its validity. Reflection surveys were conducted in Venezuela in 1934 (Zuloaga, 1950; Peacock, 1964), but had trouble with record quality. The discovery well of the major Jusepín field, which was completed in October 1938.

... was located on a vaguely defined reflection seismograph high. (Wallis and Renz, 1953, p. 741.)

Discovery of the rich Oficina field in 1937 was based on refraction, gravity, and surface geology, but reflection work there began in 1939 and was used successfully in the later development of Greater Oficina (Hedberg, Sass, and Funkhouser, 1947).

The discovery well of one of the world's most wonderful oil fields—Burgan, in Kuwait—was completed in 1938 at a location based on detailed reflection seismology following reconnaissance by gravimeter and magnetometer (Boots and McKee, 1949; *see* Chap. 20.13).

Use of reflection seismology increased continually from 1931 to 1945, especially in the United States, as its economic impact became apparent in one region after another. About 200 seismograph parties (mostly reflection) were in the field by the end of 1941. The number was about 350 at the close of 1945 and 500 in 1948 in spite of wartime constraint of personnel and equipment (Gilmour, 1950). The method underwent little fundamental change during this period, but instruments were greatly improved. Continuous profiles instead of correlation jump shots were run more commonly as costs were reduced. Skill in contouring a phantom horizon from dip data became more accurate in areas where reflecting

beds were discontinuous. Velocity surveys made from drilled wells afforded more realistic structural pictures; lateral variations in velocity and other sources of serious error were recognized. Experience is a great teacher, and many of the geophysicists acquired much experience.

It is impossible to assay the discovery results of the reflection campaign statistically. A great many discovery wells were drilled at locations which were determined by composite evidence from multiple geophysical investigations and surface and subsurface geology. It is difficult to assign proportionate credit to the various lines of evidence. A great many dry holes were drilled on reflection seismograph prospects and in some areas the success ratio was not much better than that achieved by other prospecting methods. The success ratio would have been very high if only the first class prospects had been drilled, but the quality of prospects varied widely and many wells were drilled at locations for which there was only a scintilla of favorable evidence. There were many districts in which the best obtainable records were poor. Many field parties lacked a full measure of skill and perseverance, especially during periods when rapid expansion caused employment of personnel with inadequate training (Gilmour, 1950). Neither the technique nor the technicians were infallible, but they constituted the most effective exploration instrument that had ever been devised. Confidence in reflection work became so strong that it was most commonly the decisive factor in getting financial support for exploratory wells or in surrendering unpromising leases.

29. Reflection Seismology since 1945

Oil-industry geophysics was too busy tooling up, training personnel, and organizing programs for expanding world-wide exploration during the years immediately after the war to make radical changes in the methods and instrumentation. However, geophysical research increased rapidly in academic and industrial laboratories, at first in response to business opportunities and subsequently stimulated by defense needs to monitor nuclear explosions. New developments began coming in volume from the research laboratories about 1951 and were adapted expeditiously to exploratory opera-

tions. The tempo quickened as each technical innovation entrained multiple consequences, and by 1955 the rate of progress was sensational.

Introduction of magnetic tape initiated a major revolution. By September 1, 1955, 145 magnetic recording units had been delivered (Dobrin and Van Nostrand, 1956) and the rest of the 892 seismic crews in the world-wide field would get theirs in due course. Improvement in presentation of seismic data followed almost immediately. In 1955 the Reynolds plotter was in use; cross sections were prepared from magnetic-tape playback; and experiments were being made with record sections on variable density film (Dobrin and Van Nostrand, 1956). Record sections, incorporating corrections for surface effects and normal moveout, were soon to constitute a whole new show. High-frequency seismic recording obtained finer detail.

Acoustic velocity logging of wells was developed by several companies. By mid-September 1955, oil companies had logged 334 wells with their own instruments and contractors had logged 327 others. Of those, 407 were in the United States and 254 in other countries, mostly Canada. The velocity logs were important to the subsurface geologist and more so to the geophysicist.

The greatest potential usefulness of velocity logs lies, however, in the improved insight they can give us on the origin of seismic reflections. (Dobrin and Van Nostrand, 1956, p. 148.)

A direct offspring of the interval velocity log was the synthetic seismogram.

Magnetic tape supplied a means for economic application of the common-depth-point (CDP) or "horizontal stacking" method of shooting which had been patented previously.

In stacking, several shots with different shooting distances are made over the same subsurface. The records or tapes are then individually corrected for normal moveout and surface effects, after which the corrected tapes are composited. (Van Melle *et al.*, 1963.)

The CDP method discriminated against random noise, attenuated other bothersome phenomena, and contributed a new dimension to record quality. Many companies and contrac-

tors were licensed under Petty's basic patent by 1962, and use increased exponentially thereafter. Levin *et al.* (1966) estimated that the technique in 1965 was in use by 75 percent of seismic crews the world over. Outstanding success was achieved in many areas which were not amenable to previous methods.

Sources of energy for propagation of artificial waves also underwent major changes. Numerous improvements were made in the manner of deployment of conventional explosives. Nonexplosive sources gained popularity. Dobrin and Van Nostrand (1956) stated that at least seven crews were using the "thumper" in 1955. Van Melle *et al.* (1963) reported the weight-dropping method in use by 12 domestic and 3 foreign crews in 1959 and 24 domestic and 20 foreign crews in 1963. Magnetic-tape recording made employment of various mechanical, electrical, and novel explosive sources feasible. The patented VibroSeis method of a vibrating weight had experience of 180 crew-months in May 1961 and 280 crew-months in July 1962, when it became available for license. Electric "sparker" penetration was about 1,000 feet for continuous profiling in 1962, but energy input was increased later. Gas exploders, using a mixture of propane and oxygen, had produced reflections from 8,000 feet by 1962 (Van Melle *et al.*, 1963).

Nonexplosive sources have proliferated like rabbits. Equal ingenuity can be noted in source design and nomenclature. A client can choose among DinoSeis, Dyna-Pulse, Dynaseis, Geosine, Rogacord, and VibroSeis. Some are electric, pneumatic, hydraulic or combinations of these; others explode gaseous mixtures in contained chambers. . . .

Similar development can be noted in marine exploration with continuous seismic profilers. The search for greater penetrations and higher survey speeds has resulted in more powerful sources and efficient detectors. (Levin *et al.*, 1966, p. 322.)

Gas exploders produced more energetic sources. By 1965 the "ping" of gas exploders towed at fixed depths and speeds of several knots for continuous profiles superseded the blasts and geysers that formerly signified individual dynamite explosions in marine exploration. Much to the relief of the company treasur-

ies as well as the fish!

Development of electronic computers revolutionized the recording and processing of seismic data and also implemented many intermediate and ancillary procedures. Analog magnetic recording seemed the last word prior to adoption of digital computers. By 1963, analog-to-digital converters were in use to digitize data from as many as 24 channels, and direct digital recording seemed to have advantages (Van Melle *et al.*, 1963). According to Levin *et al.* (1966), about 15 percent of all seismic crews were recording digitally in the field by 1965.

Regardless of the system used to convert seismograms to digital form, processing is done on a digital computer. (Levin *et al.*, 1966, p. 321; this and preceding item Levin *et al.*, 1966, are quoted with permission of the Society of Exploration Geophysicists.)

A trend toward processing seismic data in large central laboratories containing complicated and expensive equipment, which was apparent in the 1950s, became almost universal in the 1960s. Something may have been lost in detaching the field operator from the interpretation, but results were obtained which were not otherwise attainable.

Seismology had become very big business. Some of the early seismic contractors grew into large manufacturers of electronic equipment as well as researchers and suppliers of services to industry and governments. Others were merged into giant conglomerate corporations or purchased by oil companies in need of their expertise. Most of the major oil companies had sufficient resources to conduct the entire geophysical operation for their own account. There was still a place in the sun for contractors who stuck to the role of explorationist. There arose service companies whose sole function was the processing of geophysical data. Even the little guys were big; it had become an age of the computer, and nobody goes from a large computer to a less powerful one.

¶ 30. Investigation of Gravity

The investigation of gravity as a geophysical phenomenon, as every schoolboy knows, was one of the principal researches of Galileo

