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NOTES ON THE EARLY HISTORY OF APPLIED GEOPHYSICS IN THE PETROLEUM INDUSTRY

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The writer first became interested in the possibility of using applied geophysics as an aid to prospecting for petroleum deposits during the summer of 1914 as the result of a conversation in London with the late P. C. A. Stewart, regarding the difficulties of prospecting for new salt domes in the flat Gulf Coastal plain of Texas and Louisiana and in the Isthmus of Tehuantepec, Mexico. Stewart vaguely remembered that some success was said to have been had in determining underground geology by gravity surveys in the great Hungarian Plain. Inquiry was made and we were told that such was indeed the case, that the surveys had been made with a new instrument, the torsion balance, invented by Baron Roland von Eötvös and that the only existing balances were within the territory of the Central Powers. The Great War had just started.

The torsion balance is essentially a development into a comparatively robust field instrument of the more delicate and older Coulomb torsion balance which has been used in physical laboratories since the eighteenth century for investigating and demonstrating the laws of gravitational attraction. In 1888, the eminent Hungarian physicist, Baron Roland von Eötvös, Professor of Physics in the University of Budapest, demonstrated how this balance, which has since been known universally as the Eötvös torsion balance, could be used for more extensive studies of gravity variation than had hitherto been possible by the use of pendulum stations. The first primitive field instrument was completed by 1890. Various determinations were made in the laboratory and in the field, and the instrument was modified and refined both as to mechanical system, insulating housing, and recording until, in 1902, Eötvös introduced the double-beam instrument which is essentially the instrument of today.

The first exhaustive field investigation by Eötvös was carried out in 1901 on the ice of Lake Balaton, in order to avoid the computation of terrain effects, but surveys were soon extended into the Great Hungarian Plain where such corrections were necessary.

Eötvös designed and built his instrument for geodetic research; geodesy and physics being his main interest in the instrument, the methods, and the field surveys throughout his entire life, except that during the first decade of the present century, he demonstrated the possibility of interpreting buried regional geological structure from a consideration of gravity anomalies. He apparently believed that the precision of his instrument was great enough and the gravity expression of smaller structures such as anticlines and domes was sufficiently definite for them to be mapped by torsion balance surveys.

The more definite understanding of the possibilities of the instrument as a geological tool was mainly the realization of the geologist Hugo V. Boeckh who, in 1917, first called attention to the fact that anticlines and domes with light or heavy cores could be located by means of the torsion balance, citing surveys and the existence of such anticlines at Gbely (Egbell). The American geologist, Eugene Wesley Shaw, suggested the possibility of using gravity anomalies in a search for salt domes in the same year. In 1918, Schweydar, with the advice of Boeckh, employed the method to delineate the boundary of an explored German salt deposit.

The possible use of the balance was again discussed in early 1919 with the late Dr. Th. Erb, when in charge of exploration throughout the world for the Dutch-Shell group. Dr. Erb said that his group had investigated the method and that it appeared to be theoretically sound but that they had not yet made a practical test.

In 1920, I learned that one could then purchase or contract for the construction of torsion balances. After lengthy consideration, a joint field research was arranged between the Amerada Petroleum Corporation and the Mexican Eagle Oil Company. Two instruments were contracted with Ferdinand Süss, Budapest, and construction was commenced in August, 1921. Donald C. Barton was sent to Budapest in May, 1922, to receive the finished instruments, which had been standardized by Dr. Pekar of the Eötvös Institute and to be instructed in their operation. The instruments were received in New York on September 5, 1922, and were in Houston in early November. The first survey, one of the Spindletop salt dome, was made in early December, 1922. This was the first or one of the first surveys of an oil pool made by geophysical methods in the United States and appeared to be a brilliant success though it now seems, in the light of our more extensive knowledge of gravity variations, to have been in the nature of a lucky accident, since it was a very definite gravity maximum, one of the very few in the entire coastal regions.

The method was apparently taken up by the petroleum companies in the early 1920s, first by the Anglo-Persian and the Dutch-Shell groups. The *Mexican Financier* for January 1, 1922, contained an advertisement of the Eötvös balance and within the early months of the year the Dutch-Shell group was making a survey of the Hurgada field in Egypt, using Bamberg instruments. By the latter part of the year they were possibly being experimented with in California and a Dutch-Shell instrument was sent to the Gulf Coast about the time that the Amerada-Mexican Eagle instruments arrived and to Mexico within a very short time thereafter.

With the apparently brilliant success of the initial survey in indicating Spindletop as a definite gravity maximum, surveys were extended to other known domes, for the most part with vague and indifferent results. These experimental surveys generally covered only small areas and were entirely inadequate to test the value of the instrument or of the method. Various prospects were surveyed with results none too definite and several of them were drilled and failed.

Just as we were about to abandon the instruments and method, a survey of the Nash area in southern Fort Bend County, Texas, gave a gravity maximum as brilliant and definite as that for Spindletop. A well was drilled in November, 1924, and encountered cap rock at 648 feet and salt at 943 feet. This was the first successful geophysical prospect to be proved in the United States. Oil was discovered on the flank of this dome January 3, 1926, and this was probably the first oil pool to be discovered by geophysical methods in the entire world.

During 1922, as consulting geologist to the Mexican Eagle Oil Company, I had recommended that the company make an attempt to locate the extensions of the buried Tomasopo ridge by the use of refraction seismic surveys. A German crew was engaged from Dr. L. Mintrop of the Seismos Company and it worked without very satisfactory results, attempting to map the extension of the Tomasopo ridge in late 1923.

About the same time, a Mintrop crew was engaged by the Marland Company, as a result of Dr. Van der Gracht's recommendations. Various tries in the Mid Continent from northern Oklahoma to the possible extension of the fault line play north of Mexia gave results of interest but of doubtful value. A discussion in late October, 1923, with F. Park Geyer, then chief geologist of the Marland Company, indicated that the method might be developed into one of usefulness but had not yet been of practical value.

In March, 1924, John F. Weinzierl appeared on the Gulf Coast with the first seismic crew, a Mintrop crew working under Weinzierl and under the general direction of Alexander Deussen for the Marland Company.

A Mintrop crew was also engaged by the Gulf Production Company in 1924 and before the end of the year, the Orchard dome in Fort Bend County, Texas, had been found; the first seismic discovery on the Coast and possibly the first in the world.

In view of my own unconvincing experience with the seismograph in Mexico, and that reported by Geyer, for the Marland Company, in Oklahoma and north Texas, and in view of the recent success of the torsion balance at Nash, I was inclined to be skeptical with regard to the possible value of the seismic method. Repeated successes of the Seismos crews for the Gulf, however, soon convinced me that the method was one to be reckoned with. Its results were positive, the solution obvious, and the speed of coverage very great, in all of which respects it was superior to the torsion balance in a highly competitive search for shallow salt domes.

In searching for some one competent to develop seismic methods, I became acquainted with Dr. J. C. Karcher who, as early as 1919, while a fellow in the Graduate School of the University of Pennsylvania, had applied for patents on the reflection method and who, with the late W. P. Haseman, had been conducting field work in Oklahoma as early as 1921. Karcher was engaged to head the work for a new company, the Geophysical Research Corporation, organized in May, 1925. He designed and built instruments and was in the field with a crew for the Gulf early in 1926. It seems probable that Udden's famous "Suggestions of a New Method for Making Underground Observations," as published in early 1920, Vol. 4, *Bulletin of the American Association of Petroleum Geologists*, was inspired by Karcher's early ideas on the subject since one of Udden's sons was a fellow in physics at the University of Pennsylvania, and a colleague of Karcher, who had communicated ideas on the subject to him.

During 1925, practically all of the commercial work was being done by Seismos. In November of that year three crews were operating for the Gulf and one crew for Marland. The Humble was developing its own instruments and McCollum was in the field during the latter part of the year. The Seismos crews were using mechanical seismographs, surveying positions, and estimating time of shot explosions by sound through the air. Karcher introduced the electrical seismograph, determined the time of shot explosion by radio and used the air sound waves for surveying position, innovations which became standard practice within the year.

The real success of the refraction type of seismic surveys, and one of the most brilliant successes for geophysical prospecting yet scored by any method was the intensive campaign of searching for shallow salt domes which swept the Gulf Coast of Texas and Louisiana from 1924 to 1930. This campaign was initiated with the appearance in the Gulf Coast, in March, 1924, of the Mintrop crew working for the Marland Oil Company. This crew was soon followed by another Mintrop crew for the Gulf Production Corporation under the general direction of L. P. Garret.

Mr. Garret had conceived the idea of using seismic refraction surveys as a tool to prospect for salt domes as early as 1905–06 and together with Mr. Robert Welch of Houston, had made inquiries as to instruments and methods. Instruments were expensive and not really adapted to work on the scale required and so the matter was dropped. When the Mintrop crews appeared in the United States, however, they found in Mr. Garret one who was already quite convinced as to the possible value of the method, and one who was in position to use them broadly and earnestly. The Gulf Coast with its types of rocks-clays, shales, and sands, having a linear velocity of sound transmission of around 6,000 feet per second and rock salt with a corresponding velocity of 15,000–16,000 feet per second, was an ideal region for the method. The outstanding success of the method and indirectly of the introduction of geophysical methods into the oil business, owes much to the peculiar suitability of the area where it was tried and to the vigorous support given by Mr. Garret.

The seismic or sonic method was by no means new. A little less than a century ago, Robert Mallet, one of the fathers, if not *the* father of the modern science of seismology, in a paper delivered before the Royal Irish Academy—*On the Dynamics of Earthquakes: Being an Attempt to Reduce Their Observed Phenomena to the Known Laws of Wave Motion in Solids and Fluids*,[1] said:

> However well modern geologists have surveyed and mapped the formations constituting the land which we can see and handle, of the nature of the bottom of the great ocean we know nothing; no human eye has or ever can behold it; we cannot even reach its deep abysses with the sounding line; yet the ocean covers nearly three-fourths of our entire globe, and of this vast area the geology is an utter blank. If, however, we are enabled hereafter to determine accurately the time of earthquake shocks, in their passage from land to land, under the ocean bed, we shall be enabled almost with certainty to know the sort of rock formation through which they have passed, and hence to trace out at least approximate geological maps of the floor of the ocean. For, knowing the time of transit of the wave, we can find the modulus of elasticity which corresponds to it, and finding this, discover the particular species of rock formation to which this specific elasticity belongs.

After further emphasis on the desirability of acquiring such information, he continued:

> While the facility with which one class of our data may be ascertained will be disputed by none, it may, perhaps, occur to some that, as earthquakes are happily rare, and give no notice of their advent, and moreover, are times of such consternation, so but little accuracy is to be hoped for in observations, as to the speed or circumstances of the shock, made during such visitations. This might be partly true, were we dependent upon the nerve or watchfulness of individual observers; but already attention has been given to the contrivance of self-acting instruments (and instruments, though by no means well devised nor self-registering, have been already in use in Scotland, and perhaps elsewhere) for the registration of earthquake shocks; and there can be no doubt that, by *earthquake observatories* established, with suitable instruments, at distant localities, in South America or Central Asia for instance, where earthquakes, greater or less, are of almost daily occurrence, a very complete knowledge of the time of wave transit, and of the amplitude and altitude of the earth waves for given districts, would be soon obtained. No instruments for ascertaining the latter have been yet proposed, but they do not seem by any means difficult to devise.

He minimized the apparent delays in waiting for natural earthquakes, and suggested a workable substitute as follows:

> But another, and much more rapid, and perhaps even certain,

[1] *Irish Acad. Trans.*, XXI, pp. 50–106, Dublin, 1848.

method, remains to be noticed, for obtaining part of our data as to the *specific period of wave transit*, viz., *by direct experiment*, which in all matters of inductive science may be pronounced, whenever it is possible, better than mere observation.

I have already stated that it is quite immaterial to the truth of my theory of earthquake motion what view be adopted, or what mechanism be assigned to account for the original impulse; so, in the determination of the time of transit of the elastic wave through the earth's crust, if we can only produce a wave, it is wholly immaterial in what way, or by what method, the original impulse be given.

Now the recent improvements in the art of exploding, at a given instant, large masses of gunpowder, at great depths under water, give us the power of producing in fact, an artificial earthquake at pleasure; we can command with facility a sufficient impulse to set in motion an earth wave that shall be rendered evident by suitable instruments at the distance, probably, of many miles, and there is no difficulty in arranging such experiments, so that the explosion shall be produced by the observer of the time of transit himself, though at the distance of twenty or thirty miles, or that the moment of explosion shall be fixed, and the wave period registered by chronometers, at *both* extremities of the line of transit.

In presenting this paper, Mallet stressed the necessity for experiments to determine the time of wave transit through rocks of different type, and three years later we find him giving notice of experiments in progress for the direct measurement of the velocity of transit of earthquake waves. He describes experiments to be carried out over a measured mile with a charge of "a few pounds of gunpowder buried four or five feet in the ground" connected by a wire circuit with a battery so that it could be fired by the experimenter at the other end of the line with his crude seismometer for observing the arrival of the earth wave. A chronograph was to be attached to the battery for determining the time of transit of the wave.

The author stated that if the elasticity of the earth's crust were known, it would be possible to determine the point from which an earthquake shock originated, and also to form an estimate of the nature of the intervening formations— whether solid or plastic— through depths of perhaps hundreds of miles, and even under the ocean.[2]

In 1849, Mallet actually carried out experiments in the field at Killiney Bay on the coast of County Dublin, Ireland, and at the nearby Dalkey Island. At Killiney Bay he had a widely extended

[2] *The Athenium*, Vol. 22, Num. 1144, p. 991, London, Sept. 29, 1849.

beach and attempted to determine the velocity of the transit of elastic waves through sand; at Dalkey Island, velocity in granite. He used a battery circuit for firing black powder, buried half a mile distant from the observers station, and recorded with chronographs at each end of the line. The arrivals of waves through the earth were detected by using a crude seismoscope or seismograph consisting essentially of a tray of mercury from the surface of which was reflected a spot image kept under observation through a small telescope by the observer. Disturbance of the mercury by earth movement destroyed the reflected image.[3]

In 1850, similar observations were made for granite on Dalkey Island over a distance of 1,166 feet.

The results of these experiments were to determine a velocity of transit through sand of 824 feet per second and through granite of 1,306 and 1,664 feet per second.

In 1856 Mallet carried on similar experiments in government quarries at Holyhead in North Wales, determining similar velocities for quartz and slate (metamorphics) of 1,088 feet per second.[4]

The rock velocities observed by Mallet are all extremely low and it is practically certain that he was observing the surface or Rayleigh wave. It is remarkable, however, that in his experiments he was doing essentially what the geophysicist engaged in refraction work does today i.e., discharge an explosive and attempt to determine the time of transit of waves generated by the explosion to points a measured distance away. It is a tribute to his genius that he had so clear a conception of the value of the method as a geologic tool.

On April 2, 1914, Reginald Fessenden filed the original Sonic Sounder application for determining ocean depths, the first and a clear use of the reflection method. The U. S. Hydrographic Bulletin for May 13, 1914, gives an account of the location of an iceberg off the Newfoundland Banks, at a distance of two and one-half miles, by acoustic methods and on January 15, 1917, Fessenden filed his patent application on Methods and Apparatus for Locating Ore

[3] An exceedingly detailed account of these observations is given in Second Report on the Facts of Earthquake Phenomena, Brit. Assoc. for the Advancement of Science, Report of Meetings, 1851, Vol. 21, pp. 272–320.

[4] Account of Experiments made at Holyhead (North Wales) to Ascertain the Transit-Velocity of Waves, Analogous to Earthquake Waves Through the Local Rock Formations. *Phil. Trans. Royal Soc.* of London, Vol. 151, Part 3, pp. 655–679, London, 1861.

Bodies, a division of his original Sonic Sounder application. The claims of this patent cover clearly both refraction and reflection as used to locate geologic formations.

Dr. L. Mintrop in 1919 applied for patents on the refraction seismic method in Germany.

On July 9, 1920, Prof. John William Evans, F.R.S., and Willis Bevan Whitney, applied for British patents on the seismic method.

On August 14, 1922, Burton McCollum applied for the first of a series of patents on the seismic method.

These, in brief, are the outstanding earlier patent applications. Mallet clearly was the discoverer of the refraction method; Fessenden of the reflection method. Mintrop worked with some success on a group of extremely high grade prospects selected by Garret in an area ideally suited to the refraction method, while Karcher improved considerably the technique of the refraction method, and later reduced the reflection method to practice. It should be emphasized that the refraction and reflection methods are quite different. The instrumental technique is different. The field set-up is different. The problem is different. The solution is different and the results secured are different. Mintrop's brief "On the History of the Seismic Method for the Investigation of Underground Formations and Mineral Deposits"[5] avoids this point. He barely mentions reflections in his patent and apparently did not develop nor use the reflection method.

After several years of preliminary experimentation the Geophysical Research Corporation mapped the Maud pool in T. 8 N., R. 5 E., Oklahoma, in 1927, upon which the discovery well was subsequently drilled by the Gypsy Oil Company. In 1928, a supposed structure was drilled in T. 7 N., R. 3 E., Oklahoma, resulting in a small well. In 1930, three geophysical highs, found by the reflection method in the Seminole plateau, Oklahoma, were tested with excellent results. The Edwards area in Sec. 22 and 23, T. 9 N., R. 5 E.; a northwest extension of the Carr City pool, Sec. 3, T. 8 N., R. 5 E.; and the Chase area in Sec. 29, T. 9 N., R. 6 E., were all successfully explored, technically and practically, and established the value of the reflection method as an exploratory tool beyond any doubt.

Late in 1929, the dip method, a gradient method of reflection shooting differing somewhat from the correlation method, was developed by the Geophysical Research Corporation. The Darrow dome, Louisiana, which had previously been discovered by other methods

[5] Publications of the Seismos Company, II., Hannover, Germany, 1930.

was the first to be detailed by this method. The dip method has been used chiefly for detailing known salt domes in the Gulf Coast and is today almost the only method of seismic exploration being used in that area. It is used as an exploratory method in a search for the so-called deep domes. The Valentine or Harang dome, Louisiana, is the only dome actually discovered by the method which has been proved by the drill to be an actual salt dome, though many structures, of the so-called "deep-seated" type have been found by it and, with deeper drilling, the salt cores will probably be found.

Such in brief are the outstanding events in the early history of applied geophysics in the oil industry as they have come to the knowledge of the writer. The technique has developed rapidly and is still being improved substantially. Much remains to be done. It is a notable fact that, since the discovery of the great East Texas field some five years ago, notwithstanding that exploratory drilling of geophysical structures has been at a maximum, actual discovery of oil in the United States has not been able to keep pace with consumption. This condition suggests that, without the aid of geophysics, the industry would have fallen even further in arrears. The aid of the geophysicist is and must be the hope of the future in further search for oil.

ON THE STRATEGY AND TACTICS OF EXPLORATION FOR PETROLEUM[1]

E. E. ROSAIRE[2]

The marked increase in applications of geophysical methods of exploration since 1930 has resulted in the recent grouping of many men relatively unfamiliar with the history of geophysics. Since these men, generally, are specialists in only one exploration method, they are prone to considerable discussion as to the relative merits of various geophysical methods, and too frequently deprecate the value of methods other than their own individual specialty. Pride in, and prejudice for a chosen arm are to be expected of second lieutenants, but are quite unseemly in a chief of staff.

One purpose of this paper is to review the history of the use and development of geophysical methods in the exploration for petroleum as exemplified in one particular, successful strategy. A second purpose is to examine the choice and sequence of methods to be used in an exploration campaign. A third purpose is to determine the relative importance of problems of tactics, such as research in methods of exploration, and problems of strategy, such as the more extended use of the methods already developed. The justification for this paper to the writer at least, has been his own past confusion as to the relative merits of various exploration methods, and his observation that their proper use now is the exception rather than the rule.

The policy of an oil company, at various times, may vary considerably. Shortly after the discovery of the East Texas field, the general policy was to decrease exploration for new fields. Recently, however, the general policy has been that of searching intensively for new fields. Policy, then, may be defined as the recognition and statement of a broad problem intimately associated with the future of the organization.

With the problem recognized and stated, the next question is that of the choice of approach to the solution. Thus, with an oil company committed to a policy of increasing reserves, strategy calls for a choice between the tactics of purchase or discovery, or the use of

[1] Address of Retiring President, presented at the Annual Meeting, Society of Petroleum Geophysicists, March 22, 1935, at Wichita, Kansas.

[2] Independent Exploration Company, Houston, Texas.

both. Purchase may be on a minor scale, such as the acquisition of proved or semi-proved acreage; or on a larger scale, such as the Tide Water Oil Company's recent purchase of the producing properties owned by the Simms Oil Company. Similarly, discovery may be on a minor scale, in the nature of the development of new producing horizons in a field already in production, such as the recent discovery of deeper production (Cockfield) at Raccoon Bend, Austin County, Texas, by the Humble Oil and Refining Company. Discovery may also take the form of improvements in recovery methods, as in the development of the water drive at the Bradford Oil Field in Pennsylvania, and in the use of acid treatment in the producing lime horizons of Michigan. The development of cracking methods in the refining of crude oil is an equivalent of discovery. Finally, discovery may take the form most familiar to the geophysicist, i.e., the search for and development of production on previously dry or undiscovered structures.

Strategy, then, is the approach to the solution of a problem engendered by policy, and tactics is the means of solution.

With a chosen policy of acquiring additional reserves, and a chosen strategy of searching for and developing production on untested structures, the problem of finding these structures is one of tactics.

The strategist, however, may be stalemated, as under conditions where there is no known answer to the problem, or where the only answer is prohibitively expensive. Two such stalemates come to mind: One, the trench deadlock in the World War in 1916; and, the second, the high cost of finding new production in 1914.

These two cases are interesting because of the parallelism in question and answer. In each case, the answer was theoretically attainable, but only at a cost obviously so great that the practical attainment of the solution might well be a Pyrrhic victory. Further, in each case, the tactical means so badly needed had already been conceived, and in one case proposed.

The trench deadlock was solved by the tank. Yet the idea of a mobile fortress was as old as the armored chariots of the Egyptians and the war elephants of the Carthaginians. In 1916, the mechanism required was already at hand in the shape of the caterpillar tractor in use in the grain fields of America. The major credit for the introduction of the tank is generally given to Lloyd George, who, however, did not invent the tank. His contribution was in the field of strategy, and consisted primarily of intangibles. For the successful introduction of the new tactics at hand, the fundamental need was for some strategist of prominence and position to realize that the existing stalemate could not be solved by the tactics then recognized, and who would further cast about for tactics which, even though new and unrecognized, had possibilities of breaking the stalemate. The inertia of accepted thought too frequently exists with discouraging ponderosity.

In the case of the petroleum industry, a somewhat similar situation existed in 1914. New exploration methods had appeared on the scene some time before, primarily those of surface mapping, core drilling and subsurface stratigraphical studies. However, after intensive application of these methods, only marginal prospects remained, for which the cost of development was obviously high in view of the hazard involved.

As a result of the indicated hazard, the strategy of exploration approached a stalemate. New tactics were needed. And yet, in 1896, von Eötvös had developed the torsion balance, and had used it in 1902 to indicate the subsurface extension of the Jura Mountains. Even prior to this development, as far back as 1846, Mallet had proposed the use of artificially excited seismic waves to explore the subsurface of the earth, and had gone so far as to secure field data. He anticipated and used the fundamentals of applied seismology, for he transmitted electrically an instant of explosion, observed the arrival of the resulting seismic wave with an inertia type seismometer, and used a chronometer to indicate the interval of time between. Further than these, little more, fundamentally, is done today.

In neither of these two examples was the development of new tactics required. The fundamental need was that strategy recognize the fact that the law of diminishing returns had run its course in the case of the accepted tactics of the day. Both stalemates were strategical rather than tactical, and the rates with which the newer tactics were applied in both cases are probably good measures of the relative inefficacy of the older competing tactics. Further, the spectacular results which followed strongly suggest the almost complete absence of really long range strategy in the years prior to the development of these stalemates.

Case treatments of all the strategies that blossomed with the advent of geophysical prospecting would be interesting and instructive. The time and detailed information required for such a complete study has not been available. However, the writer's prior and early service with the Geophysical Research Corporation has presented some personal opportunity for observing, in the history, aspirations, and successes of the Geophysical Research Corporation, one particular strategical approach, that of E. L. DeGolyer. His has been chosen, not only because it is more familiar and so more personally interesting to the writer, but also because therein are found excellent examples of effective short and long range strategies.

The chronology that follows is certainly open to the charge of being incomplete, but is not intentionally biased. With apologies for the gaps, and with a premium upon brevity, DeGolyer's strategy appears as follows.

Some time before 1914, study had convinced him that the high cost of crude was fundamentally due to the increasing cost of successful exploration. In that year, in London, he heard of a device which had possibilities of mapping subsurface structure while operating at the surface of the earth. The trail led to two torsion balances, one in Germany, the other in Austria. By that time, the war had intervened, and nothing further could be done. After the cessation of hostilities, arrangements were made with the firm of Ferdinand Süss, at Budapest, for the delivery of two such devices, and for the training of an observer in their manipulation. By arrangement, one was to be used in Mexico by the Mexican Eagle, and the other in the Gulf Coast by the Amerada.

Dr. Donald C. Barton was chosen to receive this training, and on his arrival in Europe, found the delivery dates postponed. This additional time was spent, at DeGolyer's suggestion, in checking into the state of applied geophysics on the Continent. Barton was able to secure some information on the possible use of the refraction seismograph as an exploration instrument. Meanwhile, DeGolyer, through his association with the Mexican Eagle, had witnessed an unsatisfactory demonstration of the seismograph in Mexico.

On his return to the United States, Barton made the first torsion balance survey at Spindletop, in 1922. There he was able to observe a marked anomaly with the torsion balance, but other known domes did not consistently show the same pronounced effects. However, a success was scored with the confirmation by the drill of the gravity anomaly at the Nash salt dome in Fort Bend County, Texas, although at least the next two tries were failures.

About this time (1924), Mintrop appeared on the scene, and under the patronage of the Marland Oil Company and the personal supervision of Alexander Deussen, introduced the refraction seismograph into the Gulf Coast. In the exploration of several prospects recommended by Deussen, the device consistently failed to indicate any marked anomalies. One of the prospects was Sheppards Mott, in Matagorda County, Texas, and another later proved to be the Rabbs Ridge, or Thompson oil field in Fort Bend County. The failures of the device to register then at those two prospects is understandable now that they are recognized as very deep-seated salt domes, but Deussen could not reconcile himself to the possibility that all of his carefully studied and chosen prospects were normal areas. Finally, in desperation, he tried the device out in another area where, unknown to the operators, the shallow salt dome near New Iberia, Louisiana, had recently been discovered as a result of drilling a surface prospect. We can probably appreciate Deussen's sigh of relief when the all too familiar report "No salt dome present" was made.

About this time, a second Mintrop seismograph crew appeared in the Gulf Coast, operating under the auspices of the Gulf Production Company. Possibly, as H. C. Cortes suggests, the experience gained at the cost of the Marland failures had borne fruit by this time, for the method showed positive evidence of shallow salt domes in quick succession on the Gulf's chosen surface prospects at Orchard, Fannett, Hawkinsville, and Starks.

This spectacular performance, together with the quicker and greater operating coverage of the seismograph (as compared with that characteristic of the torsion balance), led DeGolyer to reconsider his former unfavorable opinion of the device and to change his strategy. Investigation showed that Dr. J. C. Karcher alone remained available of four American physicists who had participated in the first seismograph exploration in the United States in 1919. With him as a nucleus, the Geophysical Research Corporation was organized and staffed with men trained in operating electrically rather than mechanically. This organization invaded a field dominated by a successful rival, and quickly set the pace. In less than a year, positive results were registered in the discovery of the Moss Bluff salt dome, Liberty County, Texas, and the Port Barre salt dome, St. Landry Parish, Louisiana, in May and June, 1926.

As a strategist, DeGolyer properly allowed his tacticians a free hand. Rather than a taskmaster, he was a taskmaker. For instance, before his organization had thoroughly mastered the refraction seismograph, he set them the problem of quantitatively anticipating the drill. In little more than two years after the formation of the Geophysical Research Corporation, the answer was provided by the introduction of the reflection method on a commercial basis on the Seminole Plateau, Oklahoma. The solution to this problem, however, was much harder than DeGolyer anticipated, for in 1927 the prevalence and importance of crooked drill holes had not yet been appreciated. The fact that the sub-sea datums available as yardsticks were not infrequently in error by as much as one to three hundred feet was a temporary but serious handicap in the task of establishing this new method as a valuable exploration tool.

DeGolyer's strategy was successful because, first, after realizing and evaluating his existing tactical limitations, and finding one answer (the torsion balance), he arranged for and secured tactics which furnished a better answer to the immediate problem by shifting to the refraction seismograph. Second, not content with tactical developments which were highly successful in answering the immediate problem, he went further and instigated the development of the reflection seismograph, a method which closely approximated his ideal of the basic exploration method, and remains today as the exploration method with a resolving power bettered only by the drill.

This latter point is an example of really long range strategy and undoubtedly eliminated another strategical stalemate. The justification for developing new tactics, rather than switching back to the torsion balance, was that an exploration method with a resolving power uncontrollably greater than the range of exploitation can be economically unsound. The torsion balance lost prestige when, for appreciable periods of time, the gravity predictions at Lost Lake, Roanoke, and Eureka remained unconfirmed and apparently disproved because of the existing limitations on drilling depths. Therefore, DeGolyer was justified in choosing to seek an exploration method with a resolving power which could be set by the operator, and so could keep proper pace with the exploitation methods.

THE CHOICE AND SEQUENCE OF TACTICS

Since 1912, when only surface mapping, core drilling and subsurface studies were available, five new exploration tactics have been developed, i.e., airplane photography, and the recognized methods of exploring by seismic, magnetic, gravimetric and electric methods. Any one of these methods can be used to demonstrate, quite convincingly, the existence of an anomaly at one or more producing fields. In planning a campaign, then, what should be the initial choice and the sequence of tactics?

This is not a simple problem. Thus, in 1923, an examination of the history of the discovery of salt domes in the Gulf Coast would have shown that the exploration method with the greatest record of accomplishment was that attained by drilling prospects resulting from the search for gas seepages, topographic anomalies and paraffin dirt beds. Yet this method had stagnated,[3] and two years later the introduction of geophysical tactics revolutionized the strategy of exploration. In 1929, the refraction seismograph had attained a remarkable record of discoveries in the Salt Dome Provinces of the Gulf Coast Embayment, and yet a year later the method had become practically obsolete. In considering a choice of tactics, the important question is not only whether the method under consideration will reasonably define an anomaly at some known producing field, but also to what extent the law of diminishing returns has run for that particular method in the province under consideration. No matter how strikingly an airplane photograph may show the areal geology, the method will contribute little if the surface geology was carefully, even though laboriously, mapped at an earlier date.

Assuming an ultimate recovery of twenty thousand barrels to the acre, fifty thousand acres, or about two and one-fourth townships would produce one billion barrels of oil. Ten billion barrels of oil, under such conditions, would be recovered from about twenty-five townships, or a square about thirty miles on a side. The area of such a square is negligible in comparison with the thousands of square miles of potential oil-producing territory in the continental United States of America.

Although from an individual operator's standpoint, the problem is that of finding a structure, from the standpoint of an exploration campaign, one major problem is that of eliminating unfavorable areas, or rather, selecting areas where the great odds against random drilling are minimized. Bearing in mind that good strategy requires the use of exploration methods with greater resolving power than those previously used, obviously the preliminary phase of the exploration should be the critical examination of existing sub-marginal prospects.

The resolving power of a given exploration method might be likened to the cone of error for a rifle. As the range increases, the base of the cone of error increases. As long as the target is greater than the base

[3] *Geology of Salt Dome Oil Fields*, DeGolyer *et al.*, p. 776, *Occurrence of Sulphur Waters in the Gulf Coast of Texas and Louisiana, and their Significance in Locating New Domes,* by W. F. Henninger.

of the cone of error, a satisfactory percentage of hits will be registered. However, when the base of the cone of error becomes greater than the target, the percentage of hits can be expected to fall off quite rapidly. At such an extended range the percentage of hits can best be raised by the substitution of another rifle with a smaller cone of error at the range now in question, rather than by trusting wholly to chance and continuing the use of the original rifle.

The primary function of geophysics was the evaluation of existing sub-marginal prospects. The discovery of prospects by these newer tactics was a later function. In the usual course of events, discovery at a premium, i.e., at a minimum cost, is naturally expected to follow from the use of geophysical methods to evaluate existing sub-marginal prospects, rather than in their use to discover as well as to evaluate prospects.

Such was the case for each exploration campaign, except one,[4] in which geophysical methods made spectacular records. The first discovery for the torsion balance was at the Nash salt dome in Fort Bend County, Texas, a sub-marginal surface prospect. The first discoveries of shallow salt domes in the Gulf Coast Province for the refraction seismograph followed in rapid succession as the sub-marginal surface prospects at Orchard, Fannett, Hawkinsville and Starks were examined. In East Texas, most of the refraction discoveries followed the examination of surface prospects, while the early successes of the reflection method on the Seminole Plateau were almost exclusively due to the examination of sub-marginal prospects. And in every case to date, with one exception,[5] the discoveries following the use of the reflection method in the Gulf Coast have been due to the examination of sub-marginal prospects indicated by one or more of the exploration methods in previous use, i.e., surface indications, the refraction seismograph and the torsion balance. Finally, the

[4] This one geophysical exploration campaign attended by discovery at a premium, and unassisted by previous methods, was the refraction seismograph exploration made by the Geophysical Research Corporation for the account of the Louisiana Land and Exploration Company in the lakes and bays of Southern Louisiana. This spectacular success followed the extensive initial use of a method with high resolving power in virgin territory, wherein the number of prospects existing was undoubtedly abnormally high. However, after the discovery of the Lake Barre salt dome, in this same campaign, gas seeps were found to have been known there for many years before.

[5] And in the case of this one (unassisted) discovery by the reflection seismograph, at the Valentine salt dome in LaFourche Parish, Louisiana, favorable surface indications were later found to have been known for several years over the dome itself.

first oil field credited to geophysics in the Rocky Mountain Province resulted from the use of the reflection seismograph at the sub-marginal surface prospect at the Quealy dome, Albany County, Wyoming.

Actual experience shows, then, that the geophysical discoveries at a premium have, in general, been due to the use of these tactics (characterized by a higher resolving power) in the re-examination of sub-marginal prospects carried over from the earlier campaigns with tactics of a lower resolving power. However, this increase in resolving power was attained only at a marked increase in operating cost. Thus, if the recognized methods of exploration are listed (approximately) in order of increasing cost, they are also listed (approximately) in order of resolving power, as follows:

Library methods[6]
Surface geological methods
Airplane photographs
Core drilling (cost listing probably markedly incorrect)
Magnetometer
Gravity meter
Torsion balance
Refraction seismograph
Reflection seismograph
Drill (including subsurface paleontology, subsurface stratigraphy and electrical logging).

From past experience, then, and for an exploration campaign, rather than a prospecting sortie, empirical rules can be drawn, that for the general case of discovery at a minimum cost:

1. Prospects should be first located by the appropriate method of lowest operating cost. These prospects should be evaluated and culled by the successive use of the appropriate methods of higher cost (successive high-grading).
2. Prospect development in a particular area should not be initiated by any given method until the area has been previously explored by the appropriate methods of lower cost.

Thus, if in a given area there are "N" appropriate methods, A, B, C, D, etc., so arranged in order of increasing cost and resolving power, the sequence is:

[6] Including all the ethical and unethical methods of securing and making use of "other peoples' data."

Prospect Development	*Prospect Evaluation and Culling*	*Final Evaluation by Drill Prior to Exploitation*
A	B C D E F · · ·	N
B	C D E F · · ·	N
C	D E F · · ·	N
D	E F · · ·	N
E	F · · ·	N
F	N	
N (Active wildcat drilling)		

The justification for successive prospect evaluation is that the experience gained thereby will be valuable in the later phase of prospect discovery by the same method. Thus, if, in a given area, the appropriate exploration methods are:

Library methods
Surface methods
Torsion balance
Reflection seismograph
Drill

there may be a strong temptation to skip either or both the surface methods and the torsion balance in prospect evaluation, particularly if experience shows that not all prospects shown by the reflection seismograph are indicated by one or both of these methods. However, even if there existed only incomplete correspondence between these methods (i.e., that the torsion balance, say, did not indicate anomalies at all reflection seismograph structures), the method of lower resolving power should be used in sequence for prospect evaluation, not only because of its lower operating cost, but also because the experience and data secured in the course of prospect evaluation by this method of lower resolving power would be useful in the later stage of prospect development by that same method.

These conclusions suggest that an exploration department should be completely integrated, consisting of the use of geological and geophysical methods under the supervision of one head. Also, proficiency in the effective use of one method of exploration should not be considered a valid reason for neglecting the use of other methods, for the result may be either an inherently greater hazard in exploitation, or an inherently greater cost in discovery. Thus, if an exploration department in the Gulf Coast relied wholly upon geological methods, or, perhaps, was satisfied with torsion balance data alone prior to drilling, then prospect exploitation would be burdened with an unduly great hazard. On the other hand, if these methods, of resolving power less than the reflection seismograph, were neglected in prospect discovery, the cost of prospect discovery would probably be unduly great.

EXPLORATION STATUS OF THE VARIOUS PETROLEUM PRODUCING PROVINCES

It may be of interest to examine several petroleum producing provinces from the standpoint of the appropriate methods of exploration and the present exploration practice.

GULF COAST

There has been intensive use of library methods, surface methods, airplane mapping, the refraction seismograph, torsion balance, and the reflection seismograph. At present, the most effective sequence of tactics seems to be, for a company which has recently initiated an exploration campaign,

1. Library methods
2. Torsion balance
3. Reflection seismograph
4. Drill

There is no doubt, however, that the law of diminishing returns is beginning to operate against the present general reliance upon library methods and the torsion balance for prospect discovery, and that the next and rather imminent phase will be prospect discovery and evaluation by the reflection seismograph. This phase, naturally, will be materially more expensive, and will be required when prospect discovery can no longer be made by any of the lower cost methods. There is no doubt but that the prospects now being discovered by the torsion balance are approaching the sub-marginal stage, and the time will soon come when many companies will find it cheaper to discover prospects by simply filling in the gaps between the areas already covered by the reflection seismograph in previous prospect evaluation. At present, the reflection seismograph is mapping at depths from 8,000 feet to 12,000 feet sub-sea, to keep pace with and to reasonably anticipate drilling practice. There is considerable doubt that gravity methods would be materially revived even if deeper objectives were found, for torsion balance data, once properly taken, hardly justifies repetition, and so belongs properly in the past and in the library.

EAST TEXAS

The area has been intensively explored by surface methods, refraction seismograph, the torsion balance, and the reflection seismograph.[7] At present, even this last method yields only marginal prospects. The discovery of a new objective, such as production in the Trinity Sand series, can result only in a revival of deeper exploration by the reflection seismograph, for the results to date of all methods used in that area should now be listed as future library methods.

CENTRAL OKLAHOMA

The appropriate methods in the past have been surface methods, subsurface methods, and the reflection seismograph. The stage of prospect discovery by the reflection seismograph has been current for several years, and is drawing to a close, with the prospects for discovering new objectives rather poor.

EASTERN OKLAHOMA
WEST VIRGINIA
OHIO-INDIANA
ILLINOIS

In all four of these provinces, the use of surface and subsurface methods is generally assumed to have practically exhausted the possibilities prior to the advent of geophysics. Although there is thought to be little hope of new objectives, still geophysical methods have not been intensively applied.

CALIFORNIA

Most of the existing known structures have, in general, been so highly folded that nearly all possibilities appear to have been exhausted prior to the introduction of geophysics. There exists, at present, an almost hysterical exploration activity, based on the use of the reflection seismograph to discover as well as to evaluate deep-seated prospects, with no great encouragement shown to date. Deeper objectives are being discovered with almost monotonous regularity in the known fields, but these newly recognized horizons may be too deeply buried if future discoveries are not as highly folded as the known fields. Perhaps the discovery of the Bosco oil field in South Louisiana will prove to be the result of good strategy on the part of the Superior Oil Company of California.

[7] At least to the Georgetown Limestone.

PERMIAN BASIN

Surface and subsurface methods, the magnetometer, the torsion balance and the refraction seismograph have been used successfully for prospect discovery in this province. The present stage seems to be the early phase of the discovery as well as the evaluation of prospects by the reflection seismograph. An interesting situation prevails in that seismic reflections are not as readily returned from the Big Lime (the present production objective) as they are from a deeper horizon, probably Pennsylvanian in age.

EDWARDS PLATEAU

This province is one of the most intriguing and yet most baffling existing. Discoveries to date have been due to random wildcatting and the use of surface geology. All other recognized exploration methods have been tried and found wanting. Development in the area is attended by an unusually great hazard because of the absence of any method with satisfactory resolving power which is appropriate for use ahead of the drill.

ROCKY MOUNTAIN PROVINCE

The possibilities of surface methods in the area were practically exhausted several years ago. At present the area is yet in the stage of sub-marginal surface prospect evaluation by the reflection seismograph. There have been trials of geophysical methods with resolving powers lower than that of the reflection seismograph, but with little success except for the torsion balance, which has shown possibilities of locating structure, but little possibility of detailing structure. If the present interest in the producing possibilities of the Sundance horizon persists, the reflection seismograph may yet be used intensively to discover as well as to evaluate prospects.

SOUTH TEXAS

Although surface prospects are still being found, the most promising tactics now seem to be prospect discovery by gravity methods, followed by evaluation with the reflection seismograph. Although there is some use of the reflection seismograph to discover prospects, the attempt is probably premature, and so may prove to be unduly expensive.

SOUTHERN OKLAHOMA

Prospect discovery by library methods, surface methods, and perhaps airplane mapping would seem to be the most favorable tactics, for, except in local areas such as near the Fitts Pool, prospect discovery by the reflection seismograph seems to be a little premature.

MICHIGAN

The only appropriate tactics recognized at present seem to be surface and subsurface methods. Due to the thick cover of glacial drift, the resolving powers of those methods are none too high, so that the hazard of exploitation is very real and very great. There is apparently a great need here for some method with a resolving power greater than the geological methods available. Although to date geophysical methods have not proved very successful, this conclusion seems to be based upon rather half-hearted trials, since recent experiments with the reflection seismograph in the area have shown favorable results.

EASTERN COLORADO

The exploration of the Los Animas Arch is an interesting demonstration of the use of methods of varied cost and resolving power. At the southern part of the area, surface geology is the appropriate method of lowest operating cost. To the north, as the Arch plunges, surface geology does not have sufficient resolving power, and core drilling succeeds it as the appropriate method of lowest operating cost. Still farther to the north, however, neither surface geology nor core drilling has sufficient resolving power, and recourse is had to the reflection seismograph as the appropriate method of lowest operating cost. The magnetometer anomalies present seem to result from compositional rather than structural irregularities in the basement.

NEW YORK–PENNSYLVANIA

The spasmodic exploration being carried out seems to consist primarily of prospect discovery by the reflection seismograph and by the drill.

THE GENERAL SITUATION, PRESENT AND FUTURE

In general, then, the petroleum producing areas so far generally considered to have possibilities for discovery, are in, or are being reduced to, the stage of prospect discovery either by the reflection seismograph or by the drill.

However, there are rules for playing football, but no rules for winning. The rules proposed for the choice and sequence of tactics are obviously subject to modification. As principles, however, they appear to the writer to be self-evident. It is somewhat surprising, therefore, to find them more honored in the breach than in the observance.

The usual sequence for initiating exploration in a given province is as follows. A wildcatter drills a well in a geological area not looked on with general favor. His reasons are usually best known to himself, but are frequently based on a minimum expenditure for leases. When the occasional strike is made (and in the case of prospect discovery by the drill, the odds, small as they may be, still favor the discovery of large rather than small features, as in the case of East Texas and Conroe), the oil fraternity moves in, and the exodus is usually proportional to the size of the strike and to the previously existing unfavorable opinion of the area. The exploration chief of staff is swamped (for the time being, at least) with demands for prospects to lease, explore and drill, and since too frequently the larger strikes are made in areas not in favorable regard, he is then in no position to make immediate and well-considered recommendations. In the absence of good strategy, the chiefs of line take over, and the results are frequently expensive and even disastrous. Very often a blanket exploration campaign is prematurely initiated with the method of highest available resolving power, with the average success and cost of a frontal attack in force upon a strong point. Tactics, at best, can hardly substitute effectively for strategy.

And so what of today? In 1912, the problem was one of discovering reserves of potentially high priced crude. In 1935, with East Texas still a market-factor field, the problem is one of locating reserves of potentially low priced crude, with tactics of much higher operating cost. More than ever, the problem is one of strategy. By virtue of past experience, even if not because of continued success, the position of chief of staff or exploration frequently has been assigned to a tactician, whose early experience was generally gained primarily in walking outcrops or piroguing to gas seeps, and whose interest in these newer tactics is academic, or even hostile. Proficiency in tactics is a necessary but not sufficient prerequisite for proficiency in strategy. Now, the problem is one of discovering and evaluating structures at depths of one to three miles. Surface geology and airplane mapping may occasionally be more than good honest fun, but in these days they are sporting and so hardly war. The higher cost of these new tactics (together with the expected low price of the oil that may be produced as a result) puts a premium upon good strategy, and good strategy requires an excellent working knowledge of the newer tactics. Geology remains one of the ends, but no longer the primary means of discovery. In that recent "Stone Age" of optical exploration, strategy and tactics were practically one and the same. The giants of those days were not called on to ride airplanes, have diurnal worries, eliminate temperature coefficients, and see that dynamite was kept harmless. Although the tacticians of today are shouldering these necessary evils, the successful strategist of today must take them in his stride.

And what of tactics in the future? Well, some modern strategists are bound to break with tradition and, disregarding the areal condemnations of Stone Age, optically-minded strategists, subject some of the featureless Tertiary covered areas, now in disfavor, to examination by modern tactics, and thereby enjoy the thrill of organizing a campaign from the library stage on.

In those areas which are as yet unexplored by any geophysical method, and which so have possibilities of shallow production, perhaps the electrical method may some day actually locate petroleum in situ. As long as marginal prospects can still be discovered by the torsion balance, the gravity meter, the magnetometer and the refraction seismograph, the improvement of these methods is justified. Further, as long as prospects remain to be evaluated or discovered by the reflection seismograph, its improvement is justified. Finally, as long as areas remain unexplored because of problems which cannot be solved even by the newer tactics, careful, cautious research on still newer methods is justified.

And beyond that? Well, with hydrogenation of coal in the pilot plant stage, with the development of oil shale refining in its infancy, and with the decrease in the cost of manufacturing alcohol to be expected from probable advances in chemistry, the pessimistic strategist in exploration may be like some other strategist of the not far distant past, who, envisioning faintly the United States of today, but without anticipating the automobile, wondered and worried about the future distribution of corn and wheat between man, mule, and moonshine.