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ON THE HISTORY OF THE SEISMIC METHOD FOR THE INVESTIGATION OF UNDERGROUND FORMATIONS AND MINERAL DEPOSITS

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PREFACE.

The economic history of the method for the investigation of underground formations and mineral deposits by means of elastic waves begins with the patent application of Reginald A. Fessenden, of Boston, U. S. A., on April 2nd, 1914, referring to „*Method and Apparatus for Locating Ore-Bodies*". Fessenden mentions in the patent description that by means of his method he succeeded in determining the position of a hidden ore-body.

Fessenden's method may be described as follows: Bore-holes are sunk and filled with water in the area which is to be investigated for the occurrence of hidden ore-bodies. A submarine sound transmitter will be lowered into one bore-hole while in a second, sunk in some distance from the first one, a sound receiver is placed. Sender and receiver are connected with one another by cables. Fessenden now observes the time which elapses between the emission of the sound impulse in the first bore hole and the arrival of the sound wave in the second. The distance between the two bore-holes being known, the average velocity of the sound waves in the area between the two bore-holes is obtained. So far it remains unknown whether an ore-body exists in this area, as only the average velocity of the waves along the whole path between the two bore-holes is determined. Fessenden therefore drills two more bore-holes, in such a way that all those now brought down form the corners of a quadrangle. Sound receivers are also placed in the two new bore-holes and they are connected with the sound transmitter. This enables Fessenden to determine the travelling time and the velocity of the sound waves in the connecting lines between the various bore-holes. As long as equal velocities so result it can be assumed thar the formations occurring between the bore-holes are homogeneous. Should the formations, however, contain inclusions of different elasticity, for instance, ore-bodies, then there will result unequal wave velocities along the connecting lines of two bore-holes each. In a first approximation the location of the ore-bodies can be so determined. For a more accurate location Fessenden lowers both a submarine sound transmitter and a sound receiver into one of the four bore-holes, which allows to observe the reflexions of the sound waves on the ore-body. The directions of the emitted and reflected waves are determined, the intersection of the wave rays then allows to determine the location of the reflecting ore-body. By changing the vertical distance between sender and receiver there can also be determined the angle of total reflection. This angle, the vertical distance of sender and receiver, and the normal velocity of the sound waves in the area under investigation, allow to determine the lateral distance of the ore-body from the bore-hole. In certain cases Fessenden believes it necessary to sink an additional bore-hole closer to the ore body assumed.

Fessenden's method has not obtained any economic importance, primarily due to the fact that the sinking of bore-holes is very expensive and requires much time.

Another epoch in the economic history of the method of elastic waves begins with the application of the author, on December 7th, 1919, for German Reich Patent No. 371 963 referring to „*Verfahren zur Er-*

mittlung des Aufbaues von Gebirgsschichten".[1]) The patent description mentions two instances of the application of the method, in one instance a hard formation was determined under a top layer of loose sands which was 9 m thick.

The method may be described as follows. In the area the geological underground of which is to be explored seismic waves are generated at the surface, f. i. by an explosition. At various distances from this explosion the waves are recorded by means of a seismograph. The times used by the waves for the bridging of the distances are taken from the seismograms. Distances and respective times are plotted in a rectangular coordinate system, and furnish the „time-distance graph". The velocities of those formations which are visible at the surface, as well as the velocities of the invisible subsurface formations, are taken from the time-distance curve. As each geologicial formation has an individual and characteristic velocity, the character of the subsurface formation can be found out by means of the wave velocity. Furthermore the time-distance curve allows to calculate the depth of the hard formation underground. The time-distance curve also allows to determine the character and to calculate the depth of a succession of layers of different elasticity. The author here follows the theory of the propagation of seismic waves and its application on the time-distance curves of natural earth quakes as first developed by Wiechert in 1907.

Contrary to Fessenden, the author avoids the sinking of boreholes. For this reason the new method has had a far greater success than the method of Fessenden. The progress brought about by the method of the author was reported on by the American geologist Donald C. Barton in the book "Geophysical Prospecting", 1929, published by the American Institute of Mining and Metallurgical Engineers in New York. Among other things Barton mentioned, that the introduction of the seismic method has thrown forward the exploitation of the salt-dome district of Texas and Louisiana by 75 years. 765 wildcat wells had been sunk in this area between the years 1919 and 1924, costing about 20 million Dollars. Only one salt-dome was so found. On the other hand, since the introduction of the seismic method by the Seismos Company in 1924, about 60 new salt domes were found in depths going down to 2000 m. American professional publications estimated the cost of this seismic exploration work to be about 30 million Dollars. To explore by wildcat drilling the area seismically investigated (about 300 000 squ. km) would have required at least 30 000 wells, costing about 1 billion Dollars.

In consideration of the world wide economic importance of the seismic method, which is protected in 26 countries, and in view of the attacks made by German scientists on the German patent, it appears necessary to give an account of the development of the method; and to quote the remarks of scientists and practical men, both before and after the application for patent, as they appeared in professional publications. The account begins with suggestions for measuring seismic velocities, made by Mallet in 1846/48, and considers all professional publications until today. Furthermore some letters to the author are published, as they constitute a material contribution to the history of the seismic method. An alphabetic list of all authors mentioned precedes the text.

Hannover, Germany, October 25, 1929.

Mintrop.

[1]) Method for the determination of the structure of rock-strata.

LIST OF AUTHORS

The problem to draw conclusions on the structure of the earth's crust from observations of earthquake waves has long moved the thoughts of seismologists and geologists. Robert Mallet already suggested *(session of the Royal Irish Academy, February 9 th, 1846)* to equip the numerous already existing magnetic observatories with suitable instruments for the observation of earthquakes. At the same time he suggested to cause to detonate large quantities of powder under water, and to observe the so created tremor with suitable instruments at distances of many miles from the explosion point. The following is an abstract of the *Transactions of the Royal Irish Academy, Vol XXI, 1848, pag. 96:* Mallet 1846/1848

"It would, therefore, seem very desirable that suitable instruments for earthquake registration were, at least, added to all the magnetic observatories now so widely extended over the earth, accompanied by proper instructions to the observers, unless, indeed, separate geological observatories be established in favourable localities for taking cognizance of all movements of the earth's crust.

But another, and much more rapid, and perhaps even certain, 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 for transit.

For this alone very moderate charges of powder will answer, but if the explosion be made out at sea with sufficient energy, there will not only be produced the transit of the earth wave and the sound waves through the sea and air, but the accumulation and subsequent coming in of the great sea wave, so that all the phenomena of the natural earthquake are thus placed within our power of production, observation, and control.

These are experiments, the value of which, to general physics as well as to geology, will be admitted; but they cannot be made without the aid and appliances which our Government can afford, through the Admiralty and Royal Engineer departments. It cannot be doubted, but that application made for such assistance, through the Royal Irish Academy, or some other of our learned bodies, to the proper authorities, would meet with a favourable reception.

It is to be remembered, however, that these direct experiments can only give the time of wave transit for the substances forming the very uppermost crust of the earth. That earthquake shocks often come from profound depths is in a high degree probable; and while down to a certain depth we may expect to find the density and elasticity of the earth's crust continually increasing, below this again, we must suppose the mineral masses in a more and more softened or even party condition, as they approach the lower fluid region, and hence possessed of lower elasticity. While, therefore, we cannot draw direct conclusions as to the time of transit of the wave in the rocks thus circumstanced at profound depths, from its time of transit in the solid rocks or superficial deposits of the surface, we may reasonable expect to derive information as to some of the physical characters and molecular condition of the deep rocks themselves, by comparing observations of the actual time of wave transit of natural shocks, coming from great depths, with that of natural or artificial shocks traversing at the surface or near it."

Mallet discussed in this first paper his plans with artificially produced earthquakes and emphasized that no information about the condition of deeper layers could be expected from velocity measurements of superficially produced and observed earthquakes. However, Mallet expected some information about subsurface rocks by comparing those waves which are artificially produced at the surface and travel only through the upper layers, with those which emerge from the depths during natural earthquakes. This shows that Mallet had not yet recognized the essence of Wiechert's method of calculating character and depth of layers from observations of natural earthquakes alone, nor did he conceive Mintrop's method of artificial earthquakes.

Mallet 1850

In a second paper by Mallet, in 1859, the results of velocity measurements in sandstone and granite are given. The velocity in sand was 825′ (about 250 m/sec), in weathered granite 1306′ or 398 m/sec, in solid granite 1665′ (510 m/sec), furthermore an average value of 1320′ or 402 m/sec was obtained in the quarries near Holyhood. These values are extraordinarily low and certainly do not refer to the first impeti of longitudinal waves which penetrate into the depth, but refer to surface waves, as we know today.

Pfaff 1873

In 1873 Dr. Fr. Pfaff, Professor at the university of Erlangen, took up Mallet's investigations in so far as they dealt with the determination of the depth of the focus of an earthquake. He did not take up Mallet's measurements of velocities. Concerning the latter Pfaff merely said: "The velocity of propagation (of the earthquake waves) corresponds exactly to the one calculated from the elasticity of the rocks, 1600–2000′ per second, i. e., the amount corresponds with the one that could be determined by experiment if tremors were produced in a rock by a violent concussion." Nothing was said neither by Pfaff nor by Mallet about an application of velocity measurements on the determination of formations deep under the surface, nor was anything said about a method which would have allowed this determination. May it be added that the velocity values given by Mallet as well as by Pfaff do not in any way check with the correct values, which are up to ten times greater.

Abbot 1878

In 1878 Abbot published a paper "*On the Velocity of Transmission* *of Earth Waves", American Journal of Science and Arts, Vol. XV, 1878.* He reported on velocity measurements made at the occasion of a dynamite explosion of 50 000 lbs = 23 000 kg, on September 24th, 1876, near Hallet's Point, New York. A wave velocity of 2500 m/sec was observed at a distance of 13 km and a velocity of 1600 m/sec was observed at a distance of 22 km.

Attacks made by Mallet in *"Philosophical Magazine, London, Edinburgh and Dublin,"* October 1878, doubting the results of Abbot's observations near Hallet's Point, caused Abbot to arrange detailed experiments in the vicinity of Willet's Point, which covered distances of 2—20 km and powder charges ranging from 30 to 180 kg.

Using 15 different measurements an average velocity of 5900' = 1800 m/sec was obtained. The lowest velocity amounted to 380 m, the highest to 2700 m/sec. Though these values appear to be quite plausible, their spread is such that its cause was sought in the varying character and size of the charge. Abbot did not draw any conclusions from his measurements as to the condition of the subsoil.

None of the authors, neither Mallet nor Abbot, referred even casually to an intention to determine unknown formations in the subsoil by means of the various velocities. The observations rather referred to determinations of velocities in known beds, in the case of Mallet f. i. sand and granite are determined separately. In no case was granite covered up by sand in such a way that it was found by Mallet's shooting. As a comparison of the results of Mallet and Abbot, and as the conclusions of Abbot show, not even the problem was solved to determine accurate velocities in known formations. The attempt to a solution failed in its very beginnings.

Milne 1885

In 1885 Milne published the results of velocity measurements from altogether 17 explosions in the *"Transactions of the Seismological Society of Japan, Vol. VIII"*. At three explosions the ground consisted of black mud with a one foot covering of earth; the velocity was 105 m/sec. At a second experiment the ground was composed of 5—6 feet of reddish earth with boulders, underlain by hard blackish clay. From the average of 7 detonations there resulted a velocity of 83 m/sec; a repetition gave a value of 91 m/sec. Milne described in detail the constitution of the ground formations, but he did not distinguish between upper and lower stratum, he merely gave an average velocity for both strata. Nothing was said about a differentiation of the layers by means of seismic measurements.

A. Schmidt 1888

In 1888 there appeared a paper by Professor A. Schmidt in Stuttgart on *"Wave propagation and earthquakes", a contribution to the dynamics of earthquakes.* It was published in *"Jahreshefte des Vereins für vaterländische Naturkunde in Württemberg" (Annual publications of the association for natural science, of Wuerttemberg), E. Schweizerbarth, publisher, Stuttgart.* In this publication the theory of the propagation of earthquake waves was developed, which was later on dealt with by Rudski and Benndorf, and especially in 1907, much more in detail, by Wiechert and Zoeppritz. Schmidt already distinguished between velocities in the depth, velocities in space, and apparent surface velocities, and discussed in detail the construction and interpretation of hodographs (time-distance curves). The data of ~~three~~ two typical cases were calculated; the first case referred to the Central German earthquake of March 6th, 1872, with focal distances of 30 to 500 km, and a calculated focal depth of at least 40 km; while the second case referred to the earthquake of Herzogenrath, October 22nd, 1873, with focal distances between 3 and 150 km and a maximum of depth of the hypocentrum of 3 km.

The publication of Schmidt abandoned the idea, so far considered valid, of a concentric propagation of earthquake waves with straight rays of propulsion, it abandoned the conception of a hyperbolic shape of the hodograph and deduced a velocity of propagation of the earthquake waves that increased with the depth, the rays of propulsion being convex towards below. This new conception explained, as Schmidt elaborated, the great difference in the experimental results of Pfaff, Mallet and Abbot. Schmidt wrote as follows: "Another circumstance that renders the determination of the focal depth difficult is the lack of information on the true (not the apparent) surface velocity, certainly the latter must be smaller than resulted from the smallest powder charges in the experiments of Pfaff, Mallet and Abbot, because, as already shown, these must give greater results the farther away from the centrum the measurement is made."

With regard to experiments which might be made in the future Schmidt wrote: „Let us hope that the increasing interest in the earthquake problem of large sections of the public may provide us with plenty and reliable observations, that sensitive seismographs in connection with accurate chronometers may give us in the future a precise determination of the arrival of impeti, including the shock directions and intensities, in order to approach, by such observations, a law that connects the velocity changes with the depth, a law that certainly exists. Particularly much could be gained for the finding of this law by the repetition of artificial experiments, because the best information about the different velocities appertaining to the individual depth sections might be obtained from hodographs of a superficial hypocentrum".

A. Schmidt said here, that, though the law of change in velocity with the depth was still unknown, information about the velocity of propagation in the different depth sections would be obtained from hodographs of artificial earthquakes. However, Schmidt did not construct any hodographs of artificially produced earthquakes, and did not say either that he hoped to be able to determine the various rocks in the depth by this means. In this respect it must be assumed from the paper of Schmidt that he did not believe in this possibility, because on another page (pag. 249) he said:

"Though now the propagation of energy from one point in the interior of the earth's crust will be irregular in detail,[1] on account of the many ways of stratification and cleavage, it may yet be expected that by the combined action of the elementary waves the smaller irregularities will be balanced out, while those repeating themselves in the same trend will combine obeying to special rules, in such a way that a regular feature, interrupted only by minor disturbances, can be found in the propagation of the total wave, quite similar to the propagation of a wave in homogeneous material."

It may be taken from these remarks that A. Schmidt did not think it possible to explore individual rock formations, he merely expected average values as the result of observations which he proposed.

Fouqué, Lévy 1889

Much more likely results than those of Mallet, Abbot and Milne were obtained by *Fouqué and Lévy, Memoires de l'Académie des Sciences, T. XXX, Nr. 2, 1889.* They made their velocity measurements both on the surface and in a mine 143 m deep, employing automatic registration of the waves produced by explosions. Fouqué and Lévy

1) following many ways, due to the change in minerals, also . . .

did not conceive the idea to determine the velocities of deep formations by observations on the surface, as it would have been possible by using the time-distance curve method; instead of this they determined the velocities separately at and below the surface, even in rocks already known. At the close of their publication they thus represent the results of their work:

"Summing up, these experiments seem to indicate that the propagation of the vibrations does not evolve itself in the same way at the surface of the earth, and by avoidance of the surface way. In the first case, a series of maxima follows upon one another and the phenomenon keeps on for a long time.

In the second case there is only one observable maximum, and the vibrations extenuate rapidly.

In one word, the records obtained at distant points in a mine are similar to those which are obtained at the surface near the mercury mirror. The different geological formations give very variable velocities, here it may be interesting to list and compare the principal velocities which we have obtained. In granite velocities of 2450 to 3141 m/sec. In Permian sandstone (little compact) 1190 m/sec. In compact sandstones (charbon-sandstone) 2000 to 2526 m/sec. In Cambrian marble 632 m/sec. In the sands of Fontainebleau about 300 m/sec. The values which we obtained from our experiments approach very closely those calculated by Abbot, but they differ greatly from those which we owe to other observers. The results which are obtained by an analysis of the phenomenon partly explain the differences, because they show the complication of the problem and cause us to understand that only one single shock generates vibrations of equal intensity which propagate in the ground with different velocities."

From the works of M. P. Rudski which appeared 10 years after the publication of A. Schmidt it may be seen that Rudski excluded the possibility that individual rock formations might be determined. These papers are: *"On the apparent velocity of the propagation of earthquakes"* and *"On the form of elastic waves in rocks", Gerlands Beiträge zur Geophysik, Band III, 1898.* The purpose of the first publication of Rudski was the mathematical treatment of Schmidt's theory of curvilinear earthquake rays. On page 517 Rudski wrote: "It appears to be somewhat delicate that no account can be taken of the notorious irregularity of the construction of the upper layers, and that it is impossible to account for it. As for the rest, we believe that the time has not yet arrived to attempt a determination of the function n (= index of refraction) for the interior of the earth, based on available observations". At the close of the second publication, on page 540, it may be read: "Let us say concludingly, that the purpose of this treatise consists only in the investigation of a certain aspect of the theories of earthquakes. Consequently the reader should not think that the author considers the ideal medium investigated here to be a model perfect in all respects." Rudski 1898

Twice, nine and eleven years respectively after the publication of the treatise of A. Schmidt on wave propagation and earthquakes, O. Hecker made velocity measurements with the aid of artificially produced earthquakes. The results of the observation of the first detonation, which was made at Kummersdorff on May 6, 1897, with 1500 kg dynamite, are reported in *"Gerlands Beiträge zur Geophysik", 1900, Vol. IV.* Hecker had nine horizontal seismographs placed in line, 70 m apart from one another; the moment of detonation was electri- Hecker 1897/1900 cally transmitted to all recording apparatus. The velocity of the longitudinal main wave was found to be 205 m/sec. No change in velocity with increasing distance could be found out, as not all time marks were clear. Hecker remarks that the main waves were preceded by very small vibrations, which were, however, too weak to be reproduced in the reproductions of the seismograms.

The change observed in the character of the main wave with increasing distance from the point of detonation was discussed by Hecker as follows: "If this dismemberment of the main wave into minor ones is due to heterogeneity of the ground — in the vicinity of the line in which the instruments were placed there was a short ditch about 2 m deep and a small elevation about 3—4 m high – then this will prove that the longitudinal tremor wave goes only into very shallow depths in the case of explosions in the surface, otherwise the main wave could not have changed so much by diffraction, interference etc." It may be inferred from this that Hecker did not think it possible that "longitudinal tremor waves" might give information about the character of formations in the depth, for the reason that they do not penetrate into the depths, but remain at the surface.

Apart from the measurement of the main wave in the vicinity of the detonation point up to a distance of 631 m, a mercury mirror was observed by the Japanese Omori in a distance of 6200 m; there resulted a velocity of 1430 m/sec, calculated from the time difference between detonation and first tremor, and from the distance of 6200 m. With regard to this Hecker remarks: "These observations prove again, how extraordinarily different the velocities of propagation of the various wave forms are, and how diverging results are obtained depending upon whether the apparatus used is sensitive for this or that wave form of ground movement." All in all it may be taken from Hecker's work that the ideas about the propagation of artificially produced earthquake waves were still quite vague in 1900. It is especially important to note that an effect of the detonation into the depth, that is, a propagation of the earth vibration produced by the detonation into great depths, was not believed in.

Hecker 1899/1904

On October 12th, 1899, also in Kummersdorf, Hecker observed a detonation of 1500 kg gelatin-dynamite with horizontal and vertical component seismographs observing in 5 different distances of 70 to 350 m from the point of detonation. These observations were reported on in 1904 in *„Gerlands Beiträge zur Geophysik"*, *Vol VI.* The velocity of propagation of the "main wave" was found to be 238 m/sec as against 205 m/sec at the first detonation on May 6th, 1897. Before the arrival of the main wave minor waves appeared which could be recognized on some records, which, however, could not be reproduced on the copies of the seismograms on account of their diminutiveness. Their speed of propagation could not be deduced, because their beginning could not be discerned clearly enough. It could only be said that the velocity of these waves was much greater than the one of the main waves. The time of one period was very short. In about 500 m distance from the point of detonation the retardation of the main wave against the minor waves was well noticeable. Immediately after the flashing of the explosives there occurred the characteristic trembling of the ground, marking the passage of waves of short period through the ground, then the hollow report in the air caused by the explosion was heard, and not until then was the large movement of the ground felt.

Hecker now supposed that the forerunning waves were compression waves, while the main waves were displacement waves. "In order to obtain conclusive evidence that the first wave of the record of seismic instruments in the case of distant earthquakes consists of compression waves and that the second, or, as it is now commonly called, the third phase represents displacement waves, this experiment is of the greatest importance. With the aid of improved instruments which are now at the disposition of seismic research such investigations should be carried out in places with as much homogeneity of the upper layers of the earth's crust as is possible. If it could be proved with certainty that the first phase of the wave motion is formed by compression waves, as it seems, then a good step ahead in the enlargement of our knowledge of the interior of the earth has been made. Should the observation show that the velocity of propagation of the displacement waves measured along the greatest arc is constant or at least very nearly so — actual constancy cannot exist, because the velocity must be essentially influenced by the different geological constitution of the layers passed through — then it would follow that the displacement waves propagate only in the upper layers of the earth's crust, if one does not want to introduce quite unlikely assumptions. The compression waves, however, will always pass through a part of the interior of the earth, may it be solid or fluid, and further they will, in general, not propagate in the direct connecting line between the focus and the place of observation, but will choose another path, the course of which will depend upon the ratio of elasticity and density in the different depths of the interior of the earth. Investigations made by various research workers already reveal with some certainty that the velocity of propagation of the first phase of the earthquake movement increases considerably with the distance from the focus. Should the constant velocity of the displacement waves, which apparently exists, now be found out with certainty, we would have one proof that the interior of the earth is not solid. This proof, however, can only be made in case the globe is enclosed with a network of observation stations, all equipped with standardized instruments as sensitive as possible, which furnish a record material that can be compared, a thing which is only attained to a very small measure up till now."

Compared with the first treatise of Hecker which appeared in 1900 those results which were published in 1904 denoted a progress in so far, as the problem to explore the interior of the earth with the aid of seismic waves was much clearer conceived. On the other hand Hecker failed both times to construct a time-distance curve of those compression waves which penetrate into the depth. Accordingly nothing was mentioned, so far, pertaining to an exploration of the constitution of the subterranean formations.

Belar 1901

Between both treatises of Hecker in the years 1900 and 1904 there appeared a note from A. Belar in 1901 *"On a new practical application of seismometers"* in the periodical *"Die Erdbebenwarte" (The earthquake station), 1st annual volume, monthly paper 4/5, page 59.* The note says: "It is a well known fact in the case of local tremors, that under otherwise equal conditions those edifices which stand on loose ground, be it broken stones or clayey soil, have much more to suffer than those structures which are on rocky ground. Also during the strong earthquakes in Laibach it was noticeable that the houses standing on rock ground — for instance on the slope of the Schlossberg — were in general much less shaken than those located in the plain on the boulder field. The observations made during the earth tremors by persons being on the one or the other kind of ground differed just as much. In general, one and the same tremor was characterized either as a short trembling or as a swinging and rocking, depending upon whether the observer stood on rock ground or, in the latter case, on loose terrain. Now, the difference in the character of the movement is inherent in the nature of the ground waves, which propagate quite differently in rocks than in loose ground; or in other words: form and character of the ground vibrations depend upon the elastic properties of the medium which is traversed by the ground waves.

At the present time where a beginning has been made to record in detail by means of extremely sensitive instruments the faintest tremors of the ground as well as slow changes of the level, which might be compared with pulse beats, it has already been found out that ground movements give an unequal record on identical instruments located at different points of the globe, and it has been found that the underground on which the instruments are placed influences to a large degree the character of the record. In this connection, experiences were gathered with one and the same instrument which had been mounted in Padua for testing, and was then transferred to Laibach. At this occassion it was found out that the manyfold artificial ground tremors caused by traffic in the town of Padua affected the instrument in a quite different way as compared with identical movements in Laibach. Even in one and the same locality different seismograms might be obtained, if one instrument were placed on boulder fields and another one on rock ground. Without great difficulty it would then be possible to determine by means of seismometers the type and composition of the ground on which the instrument is located. Based on these facts we can now derive a practical advantage from these modern sensitive instruments, especially where we want to know, right in the beginning, the composition of the earth's crust in order to undertake advantageously a tunnel boring. A series of experiments conducted along the surface following the projection of the tunnel path would be sufficient to form at once an opinion on the elasticity conditions or, let us say, on the ground stability of a certain underground way which is not otherwise accessible. The experiments could be carried out easily, by placing suitable instruments — sensitive, transportable seismometers — at the different points to be investigated. At the same time artificial explosions would have to be caused, preferably by mines, which would have to detonate in a certain required depth. Now, the ground tremors caused by an explosion will be recorded — according to time and character — by the instruments located on the surface, and from the records, and some material for comparison, it will be possible to draw a conclusion as to the ground condition of those places which were traversed by these artificially produced tremor waves. Today, where experimental seismology is endeavouring to explore the interior of the earth beyond those boundaries which exist since time unknown, it may no longer be doubted that it is possible to classify the composition of the earth's crust by means of instruments at the surface. Just now the good opportunity offered by the construction of tunnels along the Tauern Railroad should not be allowed to escape, and the authorities concerned should earnestly consider these very promising experiments."

Belar's proposition is the first concrete literary hint at the possibility of application of artificial earthquakes and seismographs to the exploration of the geological underground of a certain area, in this case the profile through a tunnel axis. Belar supposed that the tremor waves caused by an explosion would give a different record on the seismographs, according to time and character, with changing geological underground. Belar does not say in what the difference is to consist. He intends to compare the times which are required by the waves in order to travel from the detonation point to the various observation points, and very probably he will assume that in the case of loose rocks these times will be longer than in the case of solid ones. Such conclusions with regard to deep layers, which are important in the case of tunnelling, are not possible without the construction and the interpretation of a time-distance graph. The latter is not mentioned in Belar's paper; furthermore Belar proposes detonations in "a desired depth", that is, not in the surface; only the instruments are to be placed on the surface. As will be seen from the treatises of Hecker, the latter did not succeed in constructing a time distance graph in spite of the use of 1500 kg explosives for distances of 70—350 m and 70—631 m resp. There existed quite vague ideas in 1904 regarding the course of depth waves, as Hecker says, so that the suggestions of Belar did not have any practical consequence. The question remains: What did Belar intend with his proposition? That he did not intend the construction of the time distance graph and especially not its use for the determination of the depth and character of formations, follows without further explanation from Belar's deductions. An expert living today who is informed of the Mintrop Method and who kept his eyes open in the last years when the Mintrop Method became the common property of the professional world, could read the contents of the Mintrop Method into Belar's deductions, while the contemporaries of Belar and those experts following him for 18 years did not read it. In the end Belar has never carried out his proposition.

In his "*Handbuch der Erdbebenkunde*" *(Textbook of Seismology)* Sieberg 1904
A. Sieberg printed, in 1904, more or less the whole of Belar's publication of 1901. He wrote the following in the chapter "*Angewandte Seismologie, Untersuchung des Baugrundes und der Erdbeschaffenheit*" *(Applied seismology, investigations of construction grounds and ground conditions)* page 333 and following: "Let us begin with the well known thesis of experience, that, other conditions equal, those structures which stand on loose ground, be it boulders or clayey soil, suffer more than those structures which stand on rock ground (let us remember the so called "earthquake insulas") then we may say, in other words: the type and character of the ground oscillations depends upon the elasticity conditions of the medium which the earthquake waves traverse. Consequently the same seismometers, placed at different points of unequal geological ground condition, will give quake records which are accordingly unequally influenced. Consequently it is possible to determine, by means of seismometers, the composition of the ground that supports the instruments. The case may be, for instance, to form in advance an opinion on the solidity of the ground of an underground way not otherwise accessible, say a tunnel boring. It is only necessary then to place transportable and suitably adjusted seismometers at the various points to be investigated and to produce artificial earth concussions, preferably by mines which are exploded at a desired depth. Then the ground oscillations will record individually according to time and character, at the various points to be investigated, and given some material for comparison, conclusions can easily be drawn now

on the geological condition of those places which were traversed by these artificially released concussion waves.

Still farther reaching and at the same time of the greatest importance for the perception of the dynamic events at the focus are the views opened by G. Tammann. The latter described the "diagram of state" of an ideal body, which is, so to say, the average of a number of real bodies; he first described it for a spherical body, for which, similar to our earth, the pressure increases with the depth. At the end of his treatise he derives the following conclusion: "If the diagrams of state of numerous bodies with high melting point were known, and if the position of the earthquake center were further known, from which there would follow the pressure and temperature of change, then in many cases the data would be given from which a determination of the type of body, the transformation of which caused the quake, could be made. From accompanying geological phenomena a conclusion might eventually be drawn on the energy and changes in volume of the transformation. A partial analysis of those earth formations which are not accessible, based on comprehensive seismic observations and the working out of diagrams of state of all those bodies that enter the proplem, is a task the solution of which should not encounter unsurpassable difficulties. So it does hardly have to be doubted anymore today that it will be possible, in the course of time, to determine the composition and condition not only of the earth's crust but also of the interior of the earth by means of seismometers working at the surface."

Nagaoka 1900

On page 74 Sieberg lists the theoretically calculated results of the velocity measurements of H. Nagaoka which are reproduced below: *H. Nagaoka: "Elastic constants of Rocks and the Velocity of Seismic Waves". No. 4 of the publications of the Earthquake Investigation Committee in Foreign Languages, Tokyo 1900.*

Type of Rock	Formation	Density	Velocity of propagation in km/sec
Perodite-Serpentine	Paleozoic	2.786	5.86
Marble	,,	2.654	4.09
Clayey shale, decomposed	,,	2.490	2.25
Idzumi-sandstone	Mesozoic	2.236	2.93
Idzumi-sandstone	,,	2.223	2.76
Tuff-sandstone	Tertiary	2.321	3.35
Rhyolite-Tuff	,,	2.316	3.18
Rhyolite	,,	2.454	2.78
Tuff	Pleistocene	2.557	4.44
Andesite	,,	2.397	3.06
Tuff	,,	1.838	2.75
Andesite-Tuff	,,	1.400	2.50
Andesite	,,	2.022	2.21

Kusakabe 1903

In 1903 there appeared a paper by *Kusakabe: "On the Modulus of Rigidity of Rocks and an Explanation of the wide Difference between the Velocities of Propagation of the Tremors and principal Shocks in seismic Waves", No. 14 of the Publications of the Earthquake Investigation Committee in Foreign Languages, Tokyo 1903.* The velocities found by torsion tests in the laboratory fluctuate between 430 m/sec in sandstone and 2580 m/sec in eruptive granite.

Sieberg 1904

On page 75 of his book *"Erdbebenkunde" (Seismology) Sieberg* brought a comparative list of the results of the velocity measurements of Pfaff, Mallet, Milne, Fouqué and Lévy.

Velocities of Propagation at Ground Detonations.

Type of Rock	Velocity of propagation in m/sec, as found by			
	F. Pfaff	R. Mallet	J. Milne	F. Fouqué and M. Lévy
Granite	539	398 — 507	800 — 1400	2450 — 3140
Limestone	547	—	900 — 1260	—
Shale	737	331	1000 — 1600	—
Sand	—	250	—	300

In connection herewith Sieberg wrote: "Those values calculated from artificial earthquakes usually remain far below those theoretically calculated. That the force of the concussion should have such a great influence on the velocity of propagation would only be possible, if with each individual propagation of a concussion wave the velocity would decrease proportional to the decreasing intensity from the center to the periphery, however, such a decrease in velocity has never been observed at an actual earthquake. As it is seen, artificial earthquakes do not give us satisfactory insight, mainly for the reason that the source of agitation of the ground oscillations is situated too near to the surface.

The safest means for the determination of the velocity of propagation are the immediate earthquake observations; the matter thus observed are the long transverse surface waves."

It follows that Sieberg did not doubt in 1904, three years after Belar's publication, that it would be possible "in the course of time" to determine the condition of the earth's crust, but he did not expect satisfactory insight from the observation of artificial ground waves.

The attainments of seismic ground exploration have been very sharply characterized 13 years later by A. Sieberg in the chapter *"Methoden der Erdbebenforschung" (Methods of Seismology) of the Lehrbuch der praktischen Geologie (Text book of practical geology)* written by Privy Mining Councillor Professor Dr. Keilhack, department chief of the R. Prussian Geological Survey, Professor at the R. Technological College at Charlottenburg, and published in 1917. Sieberg assigned 55 pages of the book to seismology and wrote the following remarkable lines on pages 54/55:

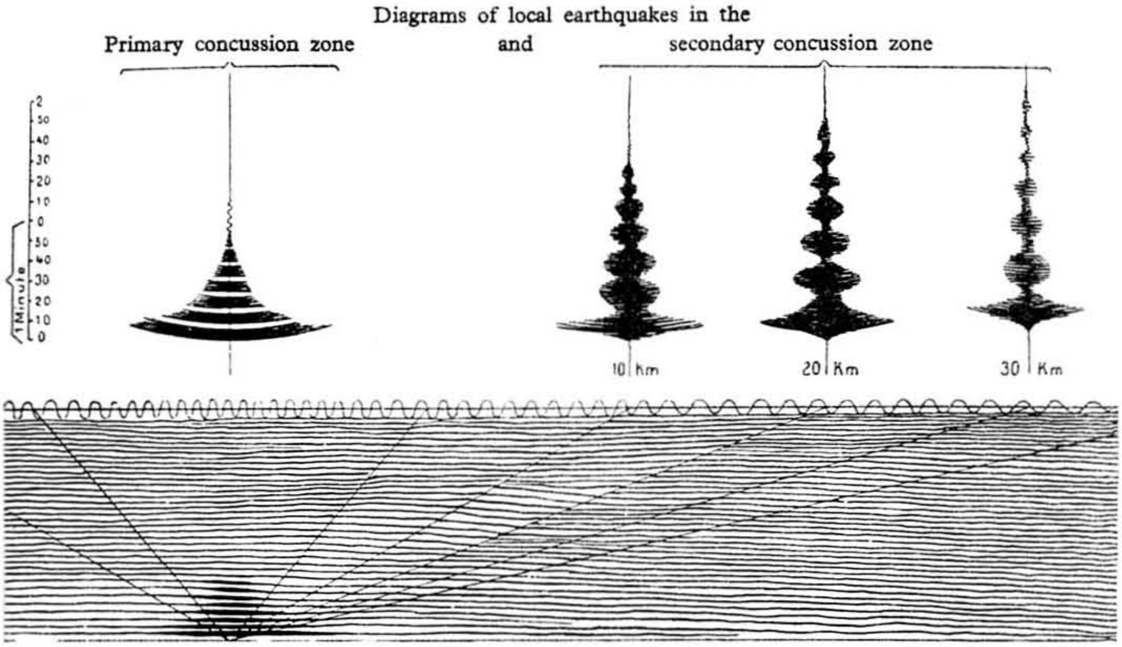
„It cannot be our task here to discuss the very difficult and still quite unexplored methods of the determination of the travelling times on the ray of propagation of the forerunners which traverse the interior of the earth, nor can we discuss the coordinated calculations of the 'true velocity of propagation'. Work in this department must remain the privilege of the mathematician and physicist. Whoever is somewhat interested in this may read the respective publications. This will obviate a discussion of the methods proposed for the calculation of the focal depth, as these are based on the aforementioned problems. While we are still groping in the dark concerning the physical conditions in the depths of the earth and the further influencing of the propagation of seismic energy by the geologic-tectonic construction of the earth's crust, we are not in a position to pass a fair judgment on the said methods concerning their value or demerits." Comparing these negative statements with the positive ones in *Sieberg's "Geologische Einführung in die Geophysik" (Geological Introduction into Geophysics)* in 1927, it can clearly be seen what progress was brought by Mintrop to practical geology.

Belar
1906/1907

Six years after his first note Belar gives some more information about the then existing attainments of science and technique, especially in so far as his own knowledge is concerned; in an extensive treatise about *"Was erzählen uns die Erdbebenmesser von den Erdbeben?" (What do seismometers tell us about earthquakes?)* in *"Gerlands Beiträge zur Geophysik", Vol. VI, 1906/07.* The introduction reads „Aided by the newest attainments of this science and further helped by the experiences gathered by him on the classical earthquake ground of Laibach and in cooperating with railroads, mines and other industrial undertakings, the author will endeavour to explain in as plain and easy to be understood terms as possible that which the observer must know of the mechanical relations of an earthquake in order to become a good earthquake observer who forwards this science." Among other things Belar then tried to explain the different phases of a seismogram, aided by illustrations, writing on page 108: "It has already been remarked previously what explanation might be given to the regular attenuation of the shock groups in mining, by using simultaneous observations. Even though this hypothetical presumption of the origin of the shock groups by successive breaking of individual earth layers, may be sufficiently supported in mining observations, the author believes he should mention here another possible interpretation. At the occasion of the powder explosion in the Laibacher Felde, which occurred on June 27th, 1906, and left distinct traces on all our earthquake recorders, the records allowed to identify a regularly decreasing series of shock groups, which however was not as distinct as on an earthquake record. Now shock groups were recorded on the instrumental records of the concussion due to the explosion, which were on the other hand opposed by the statements of hundreds of observers, who all stated that the explosion did not occur in several sections, but that only one single detonation comparable to the report of a gun was heard. As an explanation of the earthquake-like explosion record it could be said that the elastic waves which at the time of the explosion start from the surface and propagate towards the interior, are reflected from several depths in such a way that these regularly attenuating shock series would constitute an echo of the explosion at the surface from various depths of the earth. We must leave open the possibility that the original idea about the inception of the shock series will have to be changed in this direction, also for earthquakes. In any case this would lead the way to approach this problem, and it is certain that artificially produced earthquakes, by means of mines or explosions, are qualified to finally solve this problem."

"Investigating the seismograms which were gathered in the area which is immediately adjoining the zone of main concussion, it will be found that first of all the habitus of the diagram shows much similarity to the seismogram of the primary concussion zone; it only strikes at first view that the whole record appears to be drawn lengthwise; quite similar as if the picture of the primary concussion zone were drawn on a rubber band and then stretched in longitudinal direction.

The farther away from the focus the observations are made, the more stretched the quake record appears, as the sample diagrams for 10, 20 and 30 km show (Table 1). Another thing will be noticed when comparing the diagrams, namely, that with increase in distance from the focus the short periodic movements appear especially in the first shock groups, even before the first shock group, initiating the latter ones as so called forerunners. These forerunners are the impulses of the quicker propagating waves which are at first longitudinal, and which radiate directly from the focus to all points of the surface. They are intermingled with just such surface waves (already previously called compression waves) which will arrive nearly simultaneously in the immediate vicinity of the main concussion zone, which the author called secondary concussion zone."



A. Belar: What do seismometers tell about earthquakes?

It follows from the preceding text that Belar in 1906 had no clear conceptions of the individual phases of a seismogram, especially whether reflexions existed or not. Belar also had absolutely wrong ideas about the propagation of the forerunners, which he believed propagating directly from the focus to all points of the earthquake area. In the accompanying illustrations Belar draws the rays straight from around the focus to the surface, while in reality these rays are curved, as had already been theoretically deduced by A. Schmidt in 1888. Considering the picture of the course of the rays drawn by Belar it will now appear clearly what he intended to say with his remarks in 1901. It is now certain, that in 1901 Belar did not know that waves generated at the surface penetrate into the depth and are refracted at planes of discontinuity there, and then return to the surface where they can be recorded by seismograph, as Mintrop showed for the first time. On account of his being unaware of this fact (which was first discovered by Mintrop) Belar requested in his suggestion of 1901, that the artificial earthquakes were to be produced in a "desired" depth, while the seismographs were to be located at the surface. Nothing, however, indicated in Belar's note of 1901, that he intended the construction of a time-distance curve, nor that he conceived its importance for the determination of the depth and constitution of the rock formations.

The journal *"Die Erdbebenwarte" (The Earthquake Station) 2nd annual volume, 1902,* the editor of which is Belar, carried the following note on page 39 under the heading: *"Seismometers working for mining":* "On April 15th and 16th there was in session in Oberleutersdorf

(North Bohemia) a joint commission of mining experts, architects and earthquake experts, which was called in by the mining office of Brix, in order to find out whether and if, to what a degree, concussions due to coal mining had affected a factory building there. The I. a. R. District Mining Office invited Professor A. Belar as earthquake expert, while a German seismologist, Dr. O. Hecker, cooperator of the Royal Prussian Geodetic Institute, participated in the commission as a private expert in the same field. As observations with a mechanically recording seismometer had already been made for years in this locality, it was the task of the seismological experts to determine first of all the instrumental records, and to find out what influence had been exerted on the factory building by these disturbances of the ground unrest."

From this note it may be seen that Hecker was already in immediate touch with Belar in 1902. Therefore Belar's suggestion of 1901 should not have remained unknown to him, all the more as it was published in the *"Erdbebenwarte"*. (Belar's periodic publication). In spite of this Hecker did not draw any conclusions as to the geological subsurface from the velocity measurements in Kummersdorf which he made in 1902, and did not publish until 1904. It may be taken from this that neither Hecker nor Belar conceived the means and ways necessary for such a conclusion. This perception was still far away at that time and not until 25 years later did Prof. Angenheister determine the geology of the subsurface in the vicinity of Kummersdorf with the Mintrop Method, publishing the results in the *"Zeitschrift für Geophysik", No. 1, annual volume 1927*. Likewise not before this year, did Schweydar and Reich determine the velocity of the longitudinal forerunners in Kummersdorf to 1000 m/sec (see *Gerlands Beiträge zur Geophysik, Vol. VXII, 1927, pag. 121 foll.)*

In view of Belar's suggestion in 1901, to predetermine seismically the formations along a tunnel axis, the following letter from Prof. R. v. Klebelsberg, director of the geological institute of the University of Innsbruck, dated Nov. 9th, 1922 and addressed to the Seismos Company headed by Dr. L. Mintrop, is of special interest. The letter reads: "With the greatest interest I have taken cognizance of your communication 'Exploration of strata and mineral deposits by the seismic method'. Considering the very good experiences you gathered with the new method in plains and hilly country, the question comes up in how far the same can also be applied in mountainous regions, f. i. in our Alps, namely, for practical as well as for theoretical geological questions. Among the problems which offer themselves to the investigation by the seismic method there is one of special interest that could be solved without difficulty, according to the impressions gained from your communication. The question is how deep the large valleys in the alps are buried. The solution of this problem would not only have great theoretical importance but practical importance just as well; it is only necessary to remember the disaster at the construction of the Loetschberg Tunnel.

A second doubtless more difficult problem refers to the tectonic structure of mountains; the question is whether the new method would allow to find out over- and underbedding of such rock-complexes which do not differ very much in density; f. i. the underbedding of a mass of 1000 m thickness of cristalline silicate rocks by carbonate rocks.

In our mutual interest — the proof that your method could also be employed in these cases would figuratively speaking crown the present experiences — I would like to ask you whether you are inclined to try a couple of tests in this direction."

This letter is remarkable for the reason that the geological institute at Innsbruck also considered the Mintrop Method new in 1922, that is, 20 years after Belar, and that it considered the method suitable to obtain the required information on rocks to be expected in tunnel borings, information which was never gained following the suggestion of Belar in 1901.

In 1905 there appeared an extensive theoretical treatise by Lieutenant-Colonel Harboe on *"The velocities of propagation of earthquake waves" in "Gerlands Beiträge zur Geophysik", Vol. VII.* About those observations of artificial earthquakes carried out up to this year Harboe wrote: Harboe 1905

„Considering the observations of Robert Mallet, H. Abbot, F. Fouqué and Michel Lévy, John Milne, O. Hecker and F. Omori, which were carried out with detonations, it can at once clearly be seen that the velocities found for the first waves rely for the major part on the condition of the apparatus used for the observations.

The observations of Fouqué and Lévy at detonations in Montvicy and Commenty showed that the waves with small velocities of propagation belonged to the upper layers while those with greater ones belonged to deeper layers, because the main range of waves with a velocity of less than about 1000 m — which occur at detonations in the surface – do not occur in a depth of 142,79 m. One item checks completely, which was encountered in the investigations of Abbot, and which was also confirmed by the observations of Milne, as well as by a comparison of the latter with the observations of Hecker, also by a comparison of the observations of Fouqué and Lévy with the above mentioned observation of Omori (at the former ones detonative charges of less than 15 kg of dynamite were used, but at the latter 1500 kg of gelatin dynamite was used) that is to say, that the amount of the velocity of propagation varies with the charge. It will appeal at once that the effect of the strong charge will reach into greater depths of the ground than the one of a weaker charge, for which reason the deeper, hurriedly traversing waves will grow stronger with stronger detonations than with the weaker ones."

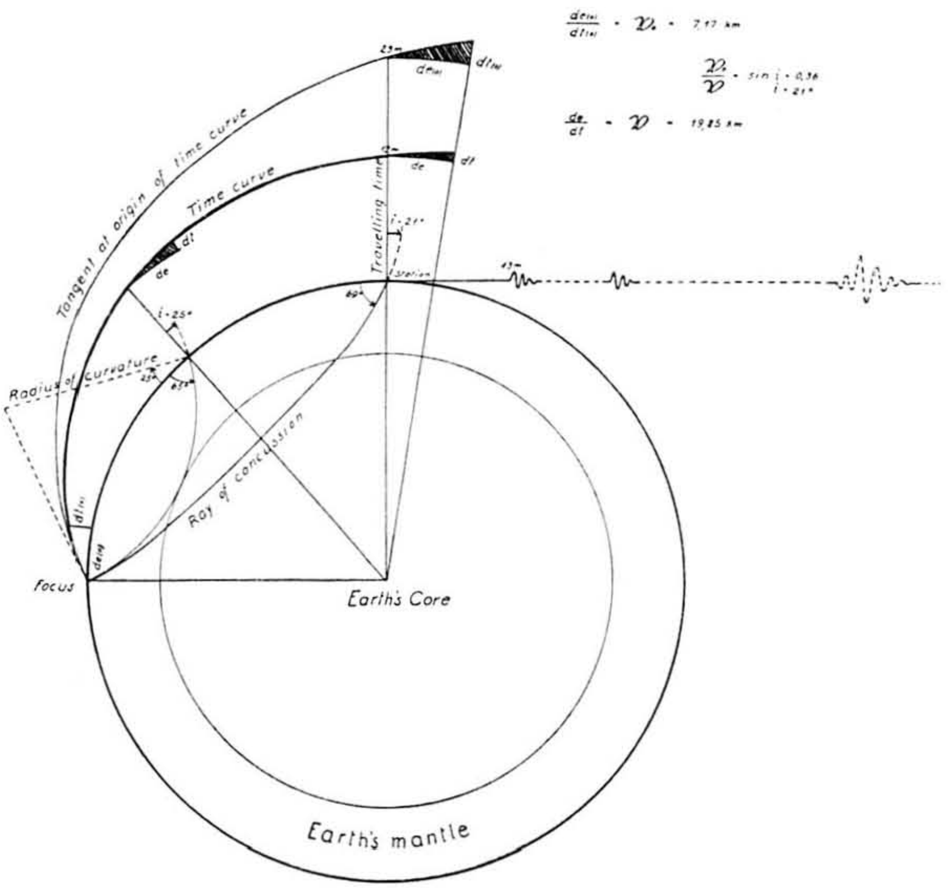
Harboe, in 1905, already calculated with an increase of the wave velocity with the depth, without discerning the law of this increase, to say nothing of using it for the determination of the formations occurring in the depth. Harboe merely explained the fact that former authors obtained different velocities with different charges, by stating that the velocity will increase due to the greater depth penetrated on account of the stronger charges.

In the years 1905/1906 there appeared two publications by *H. Benndorf in Graz "On the character of the propagation of earthquake waves in the interior of the earth"*. These were followed in 1907 by the classical book of *E. Wiechert and K. Zoeppritz "Ueber Erdbebenwellen" (On Earthquake Waves), Nachrichten der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse.* For the first time these publications led to a clear perception of the path of earthquake waves in the interior of the earth. Benndorf 1905/1906

Benndorf also proposed an experimental determination of the angles of emergence, "because these on the one hand give a good check on the time-distance graph, and on the other hand they render possible the calculation of the velocity of propagation of longitudinal waves in the outer crust of the earth, at the same time affording a means to find out geological anomalies in the vicinity of the surface of the earth". However, Benndorf spoke only of the time-distance graph of natural earthquakes.

Wiechert 1907 On the strength of time-distance graphs based on observations of natural earthquakes Wiechert determined the depth of the earth's crust to 1500 km, and below it he found a solid core. Supplementary observations in the following years led to the conception that the earth's crust is 1200 km thick and that an intermediate layer follows, while the core of the earth should not begin before a depth of 2900 km.

The publication of Wiechert's book in 1907 initiated a new epoch in scientific seismology in so far as therein the arrangement of strata in the earth is for the first time determined, based on a time-distance graph plotted from observations of natural earthquakes. While in the crust there is found a rapid and steady increase, from above to below, in the velocity of the earthquake waves, from 7—12 km/sec, the velocity increases only slowly to 13 km/sec in the intermediate (depth 1200—2900 km) layer, in order to decrease abruptly to 8 km/sec in a depth of 2900 km.



Concerning the difficulty of the construction and interpretation of a time-distance graph K. Zöppritz wrote the following on page 126 of Wiechert's book: "The time-distance curve therefore must have a point of inflexion right close the origin. The relation between this point of inflexion and the focal depth has often been discussed, as so far no one has succeeded to fix the turning of the time-distance curve by means of (actual) observations, free from objections." (The observations of Schmidt in 1888 on the hodograph of the earthquake of Herzogenrath, with a focus close to the surface, are still ambiguous, as Schmidt himself wrote).

On the probable influence of dissimilarities of the outer layers of the earth[4] Zoeppritz wrote on page 129: "One item will be of importance here, i. e., that the earth is presumably homogeneous not in concentric spheres, but in concentric ellipsoid shells. On the other hand this modified law will not be fully complied with, especially not in the outermost layers; local deviations, changes in elasticity within one shell, from place to place, will maintain their influence. However, the deviations so caused, after all, will be extremely insignificant and will probably be smaller than those errors in earthquake observations which are still unavoidable at this time. Consequently it will be a long time until a much more refined earthquake observation service will clarify such details. In the meantime we must be content to use the seismic observations for conclusions which refer to the earth as a whole, in which connection it must surprise that, evidently, our assumption of homogeneity in concentric spheric layers proves true to a very far reaching degree, which is very useful for the purpose in mind."

From the deductions of Zoeppritz it may be taken that according to the attainments of science and technique in 1907, at the time of the publication of Wiechert's book which is so fundamental for the development of seismology, there was no thought of a construction of time-distance graphs for the determination of the structure of the outermost layers of the earth. Nothing was said in Wiechert and Zoeppritz' book about the time-distance curves of artificially produced earthquakes, which are even more difficult to construct and to interpret. On page 42 and following Wiechert merely discusses that it is possible to determine the thickness of a self-oscillating surface layer by determining the period of oscillation, presuming that the velocity of propagation of the surface waves is known. By no means does this suggestion of Wiechert refer to velocity measurements, nor does it refer to the time-distance curve method.

Coincidently with the publication of the book "On earthquake waves" by Wiechert-Zoeppritz, Prof. Haussmann published an article in *"Glückauf", 1907, No. 26* entitled *"On the seismograph station of the Technische Hochschule Aachen"*. Haussmann wrote: "My assistant, mining surveyor Mintrop, was instructed to call for the instruments in Göttingen, to study the arrangements of the Göttingen seismograph station and then to instal the Aachen station. Mintrop eagerly took care of this task and carried it out with ability; he became quickly familiar with the matter formerly quite unknown to him, he put up the instruments within a short time and set them going". The purpose of the station, "which is a seismograph station, built for the Rhenish-Westphalian College of Technology in Aachen from donations of Mr. Moritz Honigmann in behalf of the pit Nordstern near Herzogenrath, and of the Vereinigungsgesellschaft für Steinkohlenbergbau im Wurmrevier, is to serve the mining industry" and is characterized by Haussmann (after extensive remarks about arrangement of the station):

Haussmann 1907

"Not infrequently earthquakes occur in Germany, which according to magnitude and duration as well as due to the varying type of their occurrence, are quite capable of causing damage. These earthquakes are not felt and they would remain unnoticed in practical life if they

4) on the compilation of the time distance curves

were not recorded by seismograph instruments. The seismograph station of the College of Technology in Aix-la-Chapelle (Aachen) has undertaken the investigation of these earthquakes and their effects for the benefit of technical establishments. The basis for this exploration shall be made by an arrangement whereby the station reports the major earthquakes that occur in Germany to the authorities and industrial concerns, and asks for a report on damages perceived".

It is interesting that this seismograph station which was donated by the mining industry did not yet know, in 1907, the seismic method for the exploration of strata and mineral deposits.

von dem Borne 1907

In 1907 there also appeared an article in the *"Zeitschrift des Oberschlesischen Berg- und Hüttenmännischen Vereins", Kattowitz, (Journal of the Upper Silesian Mining and Metallurgical Association)*, describing the Silesian Main Station for Seismology at Krietern, near Breslau, written by Lecturer Dr. Georg von dem Borne. v. d. Borne wrote: "What is our aim in recording the movements of the ground simultaneously at numerous points? We aim at the solution of geophysical, geological and technical problems. Other geological conclusions of extraordinary importance will probably be drawn from a study of certain details of the seismograms. Though an earthquake from a certain place of origin, say the East Indies, gives a nearly corresponding record at different European stations, some characteristic divergencies occur, for instance between a seismogram recorded in Göttingen and one recorded in Leipzig. Similar to the recording of a given type of ground movement by a certain apparatus (which may look different from the record of another apparatus), the subsurface — of different geological composition, i. e. mechanically different — responds in different ways to the same seismic agitation. There is still a lack of methodic exploration of these dissimilarities in recording. However, in my opinion, there can be no doubt that we shall gain a means here to draw conclusions, from the manner in which a certain rock complex reacts on a certain seismic agitation, on its geological structure, f. i. on the condition of the rocks, or on the direction of the strike, or on the presence and the character of dislocations of the layers."

Von dem Borne listed the individual problems to be worked out by the Silesian Seismograph Station:

1. The precise investigation of form and composition of seismograms,
2. The dependence of the variations of these seismograms from the geological structure of the observation point,
3. The investigation of the seismic properties of artificial structures, f. i. buildings, or mining workings, and the study of artificial concussions.

Though von dem Borne touches the scope of the Mintrop Method in this treatise, he does not yet perceive it, but merely confines himself to the general allusion that conclusions as to the tectonics might be drawn from the manner in which a certain complex of rocks reacts on a certain seismic agitation.

von dem Borne 1908

Also, von dem Borne confined himself to the following general remarks, in 1908, in his article in *"Gerlands Beiträge zur Geophysik", Vol. IX, Leipzig: "The physical foundations of tectonic theories", page 403,* published after the publication of the Wiechert book:

"Just as the observations of the seismic occurrences give us some information about the mechanic relations of the entire globe, they will also give us similar information about those tectonically important parts of it which are close to the surface. This will have to be done through the instrumental study of ~~the coda of~~ earthquakes, of artificial disturbances, and of ground movements due to meteorological actions".

Von dem Borne did not answer the question of how this could be done, nor did he solve the problem himself.

In 1909 Mintrop wrote a very comprehensive article in the *Mining* Mintrop 1909
and Metallurgical Journal "Glückauf" on the seismograph station in Bochum, bringing numerous observations of artificial earthquakes, and discussing the purposes of the seismograph station which is maintained by the Rhenish-Westphalian mining industry, without, however, mentioning the possibility of the exploration of strata. As there is also mentioned in this article the publication of von dem Borne (1907) and Wiechert's book, it will be seen that Mintrop did not at that time perceive the possibility of applying Wiechert's law of the propagation of natural earthquakes to artificial earthquakes. Also, in the description
of the same seismograph station in *"Gerland's Beiträge zur Geophysik"* Mintrop 1912
1912, in which Mintrop said that the main task of the station would be the observation of artificial earthquakes, nothing was said of the exploration of strata and mineral deposits, nor of the later Mintrop Method. Mintrop, however, approaches the matter in his publication "On
artificial earthquakes", Reports of the International Congress of Min- Mintrop 1910
ing, Metallurgy, Applied Mechanics and Practical Geology, at Düsseldorf, 1910, wherein numerous seismic records of artificial earthquakes were published and analysed.

On page 111 of this report may be read: "If the relatively quick progress of such an 'artificial earthquake' is left out of consideration, it looks quite similar to a natural earthquake that came to us from a distance of several thousand kilometers. The ground consists of diluvial clay, sand and glacial drift with boulders, in varying thickness from 1—10 m. Below it there occurs in a shallow trough a clay bed with spherosiderite about 3 m thick, on which water pools often stagnate."

The summarizing conclusion of the treatise reads: „Seismic science, and geology too, consider as very important the investigations of the propagation of impulses in the earth's crust, where intensity and time of arrivial can freely be selected, if reliable data on velocity of propagation and absorption can so be gained, which will in turn give information on the elasticity of the matter penetrated. Furthermore there are of interest the reproductions of the individual phases of the movements as a function of the distance from the place of origin of the concussion, and the reflexions of the various types of waves. Observations of artificial earthquakes close the chain of investigations on the propagation of earthquakes. The purpose of this treatise is attained if it has given a general conception of the character of the propagation of artificial concussions of the ground, and if it has encouraged further efforts."

As the report was printed not only in German, but also in English and French, one might assume that, if not in this country, scientists in foreign countries might have been induced to strive at a solution of this problem which forms the contents of the later Mintrop patent. Foreign countries, as will be explained in detail later, did not make use of the method until 13 years later, and it was Mintrop himself who used it abroad for the first time. It is noteworthy that in the discussion of the Düsseldorf lecture, which was held before several hundred mining experts and geologists of this country and from abroad, nobody pointed at the possibility of such a method though the geological conditions under which the observations took place were communicated;

this fact proves that the solution, after all, was not so obvious. Moreover, during the lecture Mintrop showed the instruments which are also described in the publication, and with which it was for the first time possible to obtain a very distinct record of all phases of the seismogram of an artificial earthquake, that is, longitudinal, transverse and surface waves up to 700 m distance. The solution of the instrument problem so necessary for the future successful application of the Mintrop Method was therefore already accomplished at that time.

Hennig 1909

How unfamiliar theoretically orientated geologists were with the later Mintrop method, follows also from the book, published in 1909, *„Seismology, a review of the present attainments of seismography, of the more important earthquake hypotheses and of the international earthquake observation service" by Dr. Edwin Hennig,* Assistant at the Geological-Paleontological Institute and Museum of the University of Berlin. Hennig wrote in the chapter *"Seismophysics"*, page 127 and the following pages: "If we now want to comprehend the true velocity of propagation, the problem is found to branch out into several questions. First of all this velocity is not a homogeneous one, it depends upon the condition (material and constitution) of the media to be penetrated. Further it is not homogeneous in so far as movements of quite different character come into existence through the concussion, each one of which, as already said, has a velocity which differs considerably from the other ones. Furthermore the velocity stands in relation to the intensity of the shock. Finally the focus is never confined to a point, there are many starting-points, not only this, but each particle of the earth partaking of the commotion radiates again waves of its own, from which, however, only a few are of importance to us. Hoernes and Sieberg compiled the results of the investigations on the velocities of propagation made by several parties in various types of rocks. There only follows from the widely diverging data what might have been expected, namely that denser media conduct the energy faster than looser ones. The discrepancies in the results are ascribed by *Hoernes (Seismology, Leipzig 1893)* to the force of concussion applied in each case. It has further to be considered, if conditions are to be transferred to the surface crust of rocks, that resistances will oppose a movement vertical to the strike of the layers, resistances which do not exist in the direction parallel to the strike; that areas with tectonic disturbances will impede the velocity more than it would be the case with undisturbed stratification and so on. This is only offered as an explanation that it must be impossible in an individual case to calculate the distance of the epicentre from the time of arrival of the ground movement, especially if the intermediate geological areas are not, or poorly, known. Even then the reading of the apparatus (seismograph) allows a determination of the epicentral distance with sufficient accuracy, in such a way that, given a knowledge of the seismic active areas, the zone of concussion can usually be surmised with great probability."

In these remarks not even a possibility has been mentioned of exploring by means of artificially generated seismic waves "the geologically unknown or poorly known areas", though Wiechert's work, which Hennig calls full of genius, is already two years old.

A. Mohorovičić 1910

In 1910 there appeared in the *Year Book of the Meteorological Observatory at Zagreb (Agram)* a paper from Dr. A. Mohorovičić on the earthquake of October 8th, 1909. In this paper Mohorovičić distinguishes two kinds of forerunners: the normal primae P and the individual primae $\overline{P}$. He found the first ones at focal distances of 300—400 km, while up to this distance there were only found the individual primae, which in their turn could only be observed up to a focal distance of 700 km, from where on only the normal primae appeared. Mohorovičić explained this phenomenon by saying that the individual primae only traversed the upper crust of the earth, while the normal primae found an abrupt change in material at an approximate depth of 50 km, as at this depth there must occur an abrupt change of the velocity of propagation of the seismic waves. The time-distance curve of the normal primae is (as Mohorovičić states) nearly straight, up to 1650 km, then it suddenly turns downward. "The break is probably still more pronounced than it can be shown in the curve, however, the data between 1000 and 2000 km were not satisfactory enough in order to draw the curve still more downward."

The normal primae correspond to the depth waves, while the individual primae correspond to the waves which expand in the upper layers of the earth. The proof, or the explanation, given by Mohorovičić of these two wave forms occurring in natural earthquakes, has either not been understood by seismologists for a long time, or no attention has been paid to it. At artifical earthquakes these two wave forms exactly correspond to the surface and depth waves which Mintrop describes in his patent application of December 7th, 1919, and the velocity of which he measured. With regard to the observations and explanations of Mohorovičić on normal and individual primae Dr. E. Tams, Professor of the Hamburg Seismograph Station, wrote in the **Tams 1913** *Transactions of the NaturhistorischerVerein* under the heading: "Recent *developments in the science of seismology*", in 1913: "Endeavours have also been made which aim at an exploration of the outer crust of the earth and the proving of a magmatic zone which might possibly exist in such crust. These considerations, however, are yet of a preliminary character so that a discussion of these may be omitted here. In spite of much uncertainty in the results there already exists many a general agreement between the different investigations and it should be borne in mind that the science of seismophysics, due to its youth, still has to create its own methods, or has to develop and to test them."

In 1910 there appeared the enlarged edition, in German translation, **Hobbs 1910** of the book *"Earthquakes, an introduction to Seismology" by William Herbert Hobbs*, Professor of Geology at the University of Ann Arbor, Michigan, U. S. A., a friend of Professor Mainka, who contributed a chapter to the book of Hobbs. In the first chapter *"Modern Seismology, Robert Mallet"*, which comprises 21 pages, Hobbs reproduced in two illustrations (in the paragraph *"The New Seismology")* the focal theory of Mallet, from which follows that Mallet still assumed spherical propagation of the vibratory energy. With this type of propagation the determination of deep layers is excluded. The final sentence of the chapter which bears the heading "The New Seismology" reads: "The term new seismology refers to the transformation of this science through the possibility of distant observation. In this meaning it does not draw enough attention to the great changes through which this science is now passing. Our time is a very remarkable period of transition in seismology, and evolution points into two directions. On the one hand the geologists recognize more and more that an important part of their own domain of research has been given back to them, which offers at the same time the possibility to push the limits of the unknown farther and farther back by direct application of geological observation methods; this is the modern study of earthquakes in the field. On the other hand the new instrumental methods introduced into science require men who are experienced in the manipulation of the instruments, and who are trained as physicists. The researches carried out by seismologists of this school lead to far reaching conclusions as to the condition of the interior of the earth; the phenomena studied by them are essentially astronomical, their subject is the physics of the earth considered as a whole, that is, the study of earthquakes by distant observations.

Unfortunately there is great danger that the two classes of scientific workers, geologists and geophysicists, follow diverging paths. For that reason nobody can do the best work alone, and the specific interpretation of the instrumental records is rendered difficult or even impossible if the information is missing which has to be gained by direct observation in the field."

These remarks show very clearly the "new seismology" as it was in 1910. On the one hand purely geological study of the effects of earthquakes in the field, and on the other hand a study of the "astronomical phenomena", that is, the study of earthquakes by distant observations. Not even a word was said about the application of artificial earthquakes, neither in the extensive chapter "The study of earthquakes in the field", where it would have fitted in particularly well, nor in the equally comprehensive chapter "The analysis of the earthquake autograms".

It is remarkable that the book of Hobbs had the cooperation of Mainka, three years after the appearance of the fundamental work of Wiechert-Zoeppritz "On earthquake waves".

Löwy 1911

One year after Mintrop's lecture at the International Congress, Dr. Löwy, one of the founders of the "Erda Gesellschaft zur physikalischen Erderforschung" (Erda-Corporation for the physical exploration of the earth, chartered in Göttingen in 1910) lectured at the annual meeting of the Association of German Mining Surveyors in Essen-Ruhr on *"Application of electric waves for the exploration of the interior of the earth with special consideration of the mining industry"*

Mintrop 1911

(Mitteilungen aus dem Markscheidewesen, dritte Folge, 1911, Heft IX). At the same meeting Mintrop reported on Wiechert's seismic method for the exploration of the interior of the earth. It is now very interesting to note that neither Mintrop nor Löwy conceived the idea at that time to use the Wiechert method for the determination of the constitution of the uppermost strata which are of importance to the mining industry and to practical geology. The audience to which the lectures were read were conceivably the most suitable one, all the more as the meeting was held in the center of the Ruhr mining industry, and in the presence of representatives of the Prussian Geological Survey.

In 1911 *Mintrop's thesis* was presented in Göttingen: *"On the propagation of the oscillations of the ground produced by the pressures of the mass of a large gas engine"*, in which is also reproduced the seismogram of an artificial earthquake produced by the striking upon the ground of a steel globe dropping from a height of 14 m on rock. In this seismogram there can already be discerned the same wave types as in natural earthquakes. At that time neither Mintrop nor Wiechert knew what to do with this seismogram. This can be understood, because it was the first ever obtained and published complete seismogram of an artificial earthquake.

In 1912 there appeared in Petersburg the book *"Lectures on seismometry" by Prince Galitzin* which was published in *German translation by O. Hecker* in 1914. Among other things Galitzin published illustrations of the seismographs for the recording of artificial ground vibrations shown by Mintrop at the International Congress at Düsseldorf and wrote on page 153 in the chapter *"The main problems of seismometry":* "For the investigation of the velocity of propagation of the longitudinal and transverse waves in the uppermost layers of the earth as well as for the study of their individual pecularities, it would be very important and interesting to arrange accurate measurements with suitable seismographs at artificial earthquakes, as, for instance, detonations by means of larger amounts of dynamite; it would be necessary to place suitable instruments in different distances around the point of detonation. Doubtless the velocities of propagation of the longitudinal and transverse waves must depend in a high degree on the physical properties of the upper layers of the earth; for instance, these velocities must have quite different values in igneous rocks as compared against sand or alluvial soil. By such experiments these data could easily be ascertained. Some experiments in this direction were formerly already made, which, however, do not satisfy, especially on account of the use of insufficient instrumental means which alone were available at that time. It would be worth while to carry out systematic and rational investigations of this kind. That such observations are indeed possible is confirmed by the fact that a very sensitive seismograph set up in Göttingen with a normal amplification of 2000 times, recorded an explosion which occurred in Besançon, that is, in a distance of 600 km."

Galitzin 1912

Galitzin, who, together with Wiechert, is regarded as one of the most eminent seismologists, confined himself, still in 1912, to the general proposition to measure velocities in various rocks, as had already been done before with unsatisfactory results by Mallet, Abbot, Fouqué and Lévy, Hecker and others. Galitzin, however, did not draw the conclusion that such measurements, if the results are assembled in a time distance graph, enable the determination of the tectonics and the indication of mineral resources. Galitzin in no way solved this problem, which is so important for technics.

Galitzin not even made those velocity measurements which he considered so appropriate, as will be seen from a publication of his assistant J. Wilip in Petersburg (now in Dorpat), in 1914 *"On an artificial earthquake recorded in Pulkow"*. Wilip wrote on page 173: "The properties of the elastic waves in the uppermost layers of the earth are very little explored. In the vicinity of the focus such waves are indeed caused by earthquakes and for the investigation of such movements local earthquakes, the focus of which should not be located too deep, would be most suitable. However, two facts, very troublesome, have to be considered, which also influence the obtaining of accurate results in seismometry, that is, the great extension of the epicentral area, which may attain several thousand square kilometers in some cases, and the depth of the focus, the determination of which is still very unsafe.

Wilip 1914

With artificial earthquakes, i. e., concussions caused by some kind of explosive or through the dropping of a heavy weight, the epicentral area might be considered a point, and this would very much simplify the investigation of the movements of the uppermost layers. Unfortunately such experiments are very expensive, and it has not been attained so far to determine the hodograph (time-distance curve) of the seismic rays for shorter distances and for the uppermost layers of the earth's crust. But just the properties of the vibrations in the uppermost layers of the earth might become of great practical importance, by giving us information on those regions of the earth's crust where mines operate. It may be pointed out here that in 1897 and 1899 Professor Hecker carried out experiments on the artillery range of Kummersdorf, where in the latter case 1500 kg nitrogelatin were brought to explosion. The records were taken with comparatively simple and sensitive instruments and in rather short distances (about 0,5 km). In 1910 Mintrop carried out experiments of somewhat different type in Göttingen. He caused a weight of 4000 kg to drop from a height of 14 m on rock ground and took photographic records of the concussion up to distances of 2½ km by means of a very sensitive seismograph. The magnification of the apparatus was up to 50 000 times."

On page 180 it goes on: "With regard to the uppermost layers of the earth's crust the prospects of seismology are not so good at present. It can only be supposed, that the seismic energy in the longitudinal waves also suffers an absorption similar to the surface waves. There is hardly a trace of numerical data in the professional literature." On page 182: "It will be seen from this that for these cases the energy of the explosion should be a couple of thousand times greater (than 4900 kg as with the casual observation of an explosion) in order to render visible the ingress of longitudinal waves. If this enormous charge is considered, it seems as if the experiment would require several million rubles worth of explosives to enable the construction of time-distance curves up to 1000 km, which implies that it is absolutely useless to consider such expensive experiments, the results of which, after all, would be a few data on velocities of propagation, coefficients of absorption of the seismic waves a. s. o. As at all times, the experimenter will endeavour to avoid expenses which are too high. It may be noted here, first, that, for such experiments old remainders of explosives might be made use of which are no longer used in the technique of blasting and which cannot be used anywhere else; second, it is known from the practice of seismometric observations, that a strong resistance will considerably increase the effect — which is quite plausible per se. Volcanic eruptions are very often preceded by strong earthquakes, while during the eruption the concussions are of less catastrophic effect. The earthquake swarms of Alaska in 1912, for instance, ceased after the tremendous volcanic eruptions in the Aleutian Islands. It will therefore be endeavoured to bury the charge as deep as possible, by choosing a suitable location, where the earthworks can easily be carried out. Thirdly, there is nothing to prevent us from increasing the sensitivity of the apparatus as far as possible. When there are no continuous seismic registrations to make, as in this instance, one could easily increase, in such exceptional cases, the ratio of magnification to a million by means of mechanical and long optical levers. In this way it could be attained that these seismographs would already show the first prephase with a charge of 5000 kg of artillery powder, up to distances of 1000 km. It can therefore be supposed that the above mentioned quantity of explosive energy will suffice for the determination of the distance curves, by an artificial earthquake, up to distances of 1000 km."

According to the above Wilip proposed in 1914 — on the occasion of the casual observation by the seismograph station of Pulow of an explosion of 4900 kg artillery powder — to construct the time-distance graph up to 1000 km by the seismic observation of detonations, a method that has first been partially applied by Wiechert, not before 1926. *Wiechert, in Geologische Rundschau, No. 5, Vol. XVII, 1926,* wrote that he had been encouraged to make these experiments by the successes of Mintrop with time-distance graphs for very short distances. While Wiechert wants to investigate the depth and the character of the formations, it follows from Wilip's allusions that he intended to determine the velocities of the different wave forms, longitudinal and transverse waves; he did not intend the determination of the structure and the composition of the underground rocks. Besides, a time-distance graph of 1000 km gives already information about depths of at least 100 km, thus naturally passing over all details in the first few kilometers, which alone are of importance to mining and practical geology. Wilip's idea that great expenses would be necessary for the carrying out of his proposition, with only a few data on velocities of propagation, coefficient of absorption, and so on, resulting, shows the attainments of science and technique at that time.

S. Mohorovičić 1914

In 1914 there was published by S. Mohorovičić — a son of A. Mohorovičić whose paper from 1910 was already mentioned — a treatise in *Volume XIII of "Gerland's Beiträge zur Geophysik"* on *"The reduced time-distance curve and the dependence of the depth of the focus of an earthquake from the distance of the inflexion point of the primary time-distance graph"*. It reads on page 231:

"It might be reproached to me that my work is based on the individual primae $\overline{P}$ which were first discovered by my father. He tried to explain this type of rays in a very simple manner by assuming that there exists an interface of strong discontinuity in a depth of about 50 km below the surface, where the velocity of the longitudinal waves is suddenly increased. The individual primae $\overline{P}$ are longitudinal waves, which expand only into the uppermost layers from the focus, while the normal primae P are those longitudinal waves which penetrate from the focus through the uppermost layer to the interface of discontinuity, then travel part of their way in the lower layer, and finally reach the surface by way of the interface of discontinuity and the uppermost layer. As the normal primae P undergo a twofold refraction they reach the surface much attenuated. From this we can see that in a certain area around the epicentre no normal primae can reach the surface. In a farther distance both types of waves reach the surface, first the normal primae P as a series of very weak waves, then the strong impetus of the individual waves or upper primae $\overline{P}$ follows. The diagrams of the South German earthquake which were gathered by my father confirm this statement. Up to an epicentral distance of about 180 km the begin of the quake is seen at all stations as a strong impetus. Munich is the first station which shows the normal primae P as a weak emersio whereupon after a few seconds the first impulse of the upper primae $\overline{P}$ follows. All following stations show very nicely this bipartition of the longitudinal waves.

If, however, the individual primae according to this conception should not exist, if they should be a type of rays of their own, this would not change anything in the matter, the calculation of the focal depth based on them would remain correct, only the interface of discontinuity would not exist.'

From the exposition of S. Mohorovičić there will be seen the uncertainty which still existed in 1914 as to the character and the meaning of the normal and individual primae, i. e., the depth and surface waves observed by A. Mohorovičić in 1910.

Leimbach 1915 In 1915 there appeared, in the *Mining and Metallurgical Journal "Glückauf" No. 14,* an article from Dr. Gotthelf Leimbach, then director of the Erda G. m. b. H. for the exploration of the interior of the earth, in Göttingen, on "Physical methods of exploration in mining", which does not mention the seismic method, though one chapter is entitled "Old and new physical methods for the exploration of the interior of the earth". Only the methods are dealt with applying electrical currents and radioactive measurements, gravity measurements not being mentioned, because these were not introduced by Schweydar into the geophysical subsurface investigation of Northern Germany before 1918 (see *Zeitschrift für praktische Geologie, 1918, No. 11).*

Keilhack & Krusch 1916 In the *Lehrbuch der praktischen Geologie (text book on Practical Geology) by Keilhack, 3rd edition, 1916,* the well known geologist Krusch, at that time department chief, now president of the Prussian Geological Survey, described magnetic prospecting and prospecting by means of electrical waves in the chapter "The finding and investigation of minerals used in technology" but he did not mention seismic exploration and did not even indicate the possibility of a future development.

Mintrop 1917 In 1917 the *German Reich Patent No. 303 344* on a *"vibration indicator"* was granted to Mintrop, and the *German Gebrauchsmuster (protected design) No. 670 330 "Field seismograph",* and also the *German Reich procedure patent No. 304 317 "Method for the determination of the location of artificial concussions".*

Fessenden 1917 In the same year the *U. S. Patent No. 1 240 328* was granted to *Reginald A. Fessenden,* referring to *"Method and Apparatus for Locating Ore-Bodies",* in which the finding of ore-bodies and similar objects in the subsurface is proposed by means of the observation of acoustic waves. According to this patent, the full text of which follows below, bore-holes are sunk in the four corners of a quadrangle in the area to be investigated and filled with water. Sound transmitters and sound receivers are then placed into these bore-holes and the travelling times of the sound are measured between the various bore-holes, as well as the reflexions that occur on ore-bodies that might be hidden within the area. These measurements are made in the horizontal plane through the four bore-holes, and in the vertical plane through one bore-hole and the reflecting ore-body. In this latter bore-hole one transmitter and one receiver are vertically moved against each other until the angle of total reflexion is reached. The so determined approximate position of the ore-body is then reexamined by a new well, and the measurement is repeated from this hole, if the body should not have been encountered by the first hole.

Fessenden was the first one who developed a method for the determination of strata by means of the generation and observation of elastic waves. To be sure, the method still depended upon bore-holes. Following there is given the text of the patent, which, by the way, became publicly known in Germany, due to the blockade, not until several years after the war.

UNITED STATES PATENT OFFICE.

Reginald A. Fessenden, of Brookline, Massachusetts, Assignor to Submarine Signal Company, of Waterville, Maine, a Corporation of Maine.

Method and Apparatus for Locating Ore-Bodies.

1,240,328. Specification of Letters Patent. Patented Sept. 18, 1917.

Original application filed April 2, 1914, Serial No. 828,972. Divided and this application filed January 15, 1917. Serial No. 142,421.

To all whom it may concern:

Be it known that I, Reginald A. Fessenden, of Brookline, in the county of Norfolk and State of Massachusetts, a citizen of the United States, have invented a new and useful Improvement in Methods and Apparatus for Locating Ore-Bodies, of which the following is a specification.

This application is a division of my United States application Serial No. 828,972 filed April 2, 1914.

The invention described herein relates to methods and apparatus whereby, being given or having ascertained, two or more of the following quantities, i. e., time, distance, intensity and medium, one or more of the remaining quantities may be determined.

For example, being given the distance between two points in a mine, and having determined the time taken by a sound wave to travel between the two points, it is possible to draw conclusions in regard to the probable nature of the rock between the two points, or if an echo be observed, or a refraction of the sound, it is possible to estimate the distance of the reflecting or refracting vein.

Heretofore only such ore bodies have been discovered as have had an edge of the mineral vein extending to the surface of the earth and not covered by debris to such an extent as to be hidden, or such as have been reached by drill holes sunk at random in locations where minerals were suspected. The ore bodies so discovered must form an extremely small fraction of the total of such bodies and it is the object of the present invention to disclose methods and apparatus for discovering such hidden ore bodies by means of measurements made on the velocity, direction, reflection, refraction, absorption and other phenomena, of sounds transmitted through the medium containing the ore bodies, i. e., the earth.

By the method herein described I have been able to detect and determine the location of a body of mineral, invisible to the eye, at a distance of two and a half miles, and farther, the test being witnessed and verified by a number of skilled engineers.

In the drawings accompanying and forming a part of this specification,

Figure 1 is a diagrammatic plan, and

Fig. 2 an illustrative section showing also a different source of energy,

Fig. 3 is a modification of the receiver, these views being in part diagrammatical and showing apparatus and methods suitable for carrying out my invention.

In Figs. 1 and 2, 50 represents a territory, which may be assumed to have an area of 25 square miles, within which it is desired to determine the presence or absence of mineral veins.

Four drill holes, 11, 12, 13, 14, shown in plan in Fig. 1 and two of them in section in Fig. 2, are first drilled at the four corners of the territory, approximately five miles apart, and of a depth sufficient to secure the desired results. These holes are filled with water 51, 52, Fig. 2. Sound detective devices, 15, 16, 17, 18, such as microphones or preferably small oscillators, as described in United States Patent No. 1,167,366, January 4, 1916, are suspended in these holes below the water line.

These sound receiving devices are connected by the pairs of leads, 19, 20, 21, 22, 23, 24, 25, 26, to the secondaries 31, 33, 35, 37, of transformers, as shown, and to oscillographs of the usual photographic recording type, but preferably with the galvanometer elements of the quartz fiber, described by applicant at the American Association for the Advancement of Science, 1894, and commonly known as Einthoven galvanometers.

49 is a sound producing apparatus, preferably of the said oscillator type, connected by its leads, 39, 40, to the primaries 32, 34, 36, 38, of the transformers in the oscillograph circuits, and to the alternating current dynamo 42, when the key 41 is depressed. 43, 44 are ore bodies.

The primaries 32, 34, 36 and 38 of the transformers are adjustable with reference to the secondaries, as shown, and are so adjusted that when the key 41 is depressed a moderately strong indication is produced on the photographic records of the oscillographs 27, 28, 29, 30, which fixes on the photographic records the instant at which the key is depressed, and at the same time a sound is send out from the oscillator 49, which after being reflected as at 45 by the ore body 43, or reflected back as from 55, Fig. 2, by the ore body 44, or reflected as from 46 by the ore body 44, or refracted as at 47, 48, by the ore body 44, or proceeding directly through the earth, as shown by the dotted lines 56, 59, reaches the indicators 17, 18, 16, 15, and is recorded on the oscillographs 29, 30, 28,27.

Since the oscillograph photographic strip moves with a regular and known velocity, determined in the manner well known in the art, the distance on the strips between the records produced through the transformers when the key 41 was pressed down, and the records made by the sounds received whether direct, or by reflection or refraction or by the echo, will indicate the distance between the drill holes and the ore bodies.

For example, if the distance between the record made on the oscillograph 30 by the transformer 37, 38 on depressing the key 41, and the record made by the arrival of the sound directly along the line 59 (which would be easily identified, being the first sound to record itself after the depression of the key), is five inches, then one inch on the record corresponds to one mile in distance, since 11 is five miles from 14. This establishes the standard of measurement on the oscillograph.

If, then, the length between the key depression record and the record made at 30 by the sound reflected at 46 is 9 inches, it is evident that the sound proceeding out from 49 and reflected at 46 and finally reaching 14, has traveled 9 miles. If, again, the length between the key depression record on the oscillograph 27 and the record made by the sound sent out from 49 and reflected back from 55, Fig. 2, is eight inches, then it follows that the ore body 44 is approximately 4 miles from the point 11. The ore body therefore lies at the intersection of the sphere described about 49 with radius 4 miles, with the sphere described about 18 with radius 9 minus 4, i. e., 5 miles.

The exact point on the line of intersection may be found in a number of ways. For example:

1. By placing 49 in the drill holes 12 or 13 or 14 and taking other sets of records another line of intersections may be found. The point of intersection of the two lines of intersection will give the point at which the ore body is, or sufficiently close thereto.

2. By determining, by means of the apparatus of applicant's United States application Serial No. 54,556, filed October 7, 1915, shown diagrammatically in Fig. 3, and referred to below, the exact direction of the reflection points 46 of Fig. 1 and 55 of Fig. 2, thus knowing the directions and the distances obtained as given above, the ore body is located.

3. By drilling a test hole, passing near but on the far side of the line of intersection obtained as above.

Other modifications of applicant's method may be used. In fact, the mere determination of the time elapsing between the key depression record and the echo record made by reflection at 55, Fig. 2, together with a determination of the direction from which the echo is received is sufficient.

The extent of the ore body can be obtained by readings made by transferring 49 to the drill holes 12, 13, 14, and taking readings on the oscillographs on sending out sounds at these drill holes; or it may be determined by the refraction of the sound sent out from 49 and received at 16, or by the echo obtained at 16 when the sounder 49 is operated at the drill hole 12.

In place of using an alternator 42, a condenser discharge may be used to actuate the sounder 49, as shown in Fig. 2. Here the condenser key 66, on being depressed, charges the condenser 67 from the battery 68 and on the key being released and coming up against the top key contact, discharges the condenser through the transformer secondary 32 and sounder 49, thus making a single sound impulse, or a rapidly oscillating one, if the discharge is an oscillatory one.

The vertical angle of reflection may be determined by hauling the transmitter 49 or the receivers 18, 15, up or down in the drill holes.

In Fig. 3 is shown the apparatus for determining the direction of the sound received. Here 15, 15′, are two sound receivers, preferably small oscillators, connected in series preferably, their leads being the conductors 19, 20, connected to the oscillograph 27.

53 is a rod supporting the two receivers, 15, 15′, by which they may be turned in any direction. On turning them, the sound will be a maximum if they are connected so as to assist each other, when they are in a plane at right angles to the direction of the received sound. If they are connected so as to oppose each other, the sound will be a minimum when they are in this plane. In this way by drawing a perpendicular to the plane so determined, the direction from which the sound comes may be determined.

By the term "sound inflection" I mean bending of the line of sound propagation, either by reflection, or by refraction.

What I claim is:

1. That method of determining the location of ore bodies which consists in generating sound waves and observing their inflection.

R. A. FESSENDEN.
METHOD AND APPARATUS FOR LOCATING ORE BODIES.
APPLICATION FILED JAN. 15, 1917.

1,240,328. **Patented Sept. 18, 1917.**

Fig. 1.

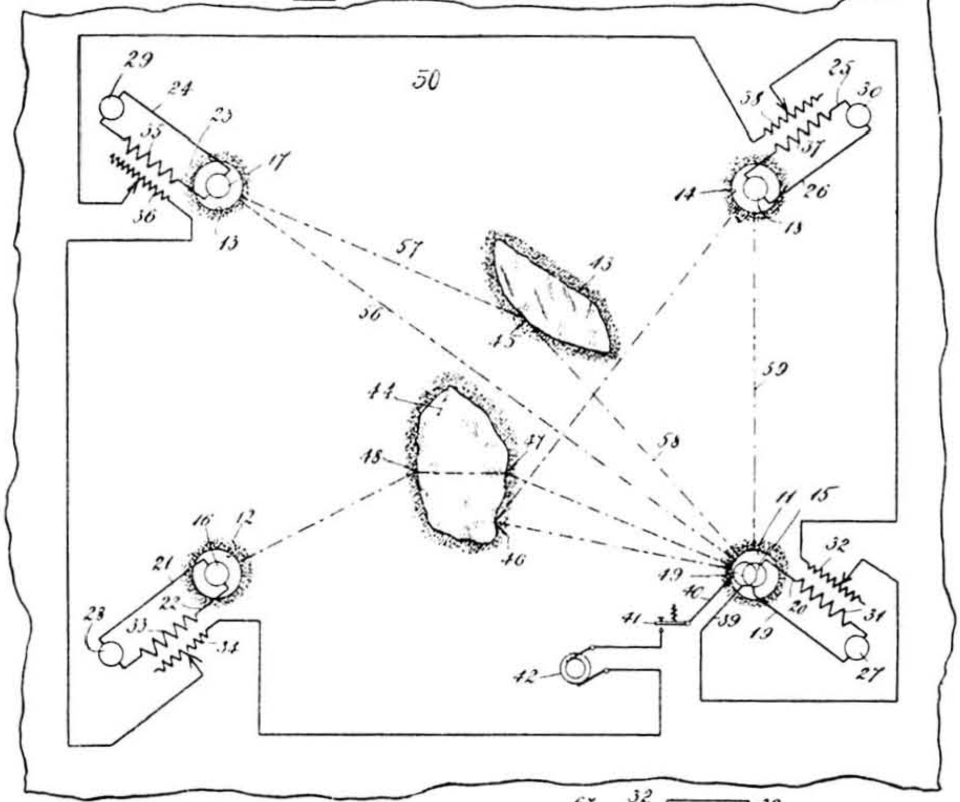


Fig. 2.

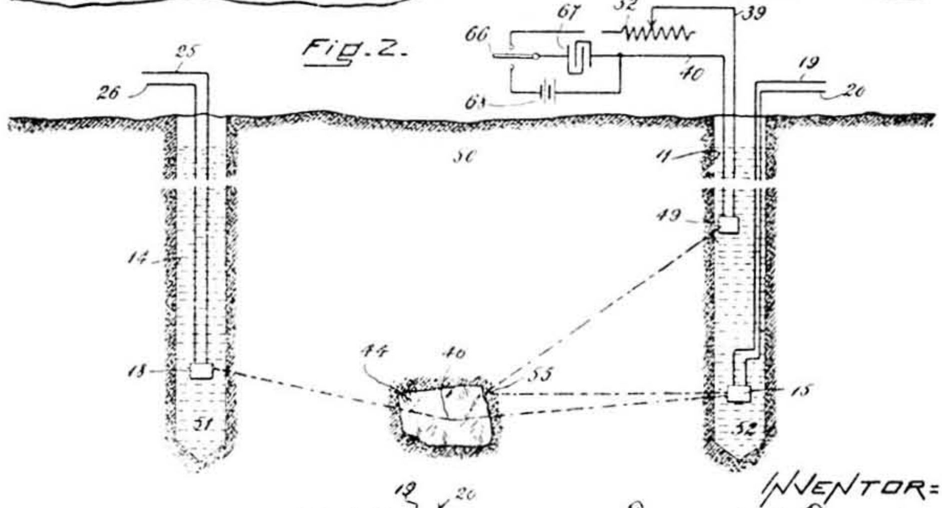
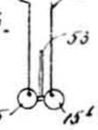


Fig. 3.



INVENTOR:
Reginald A. Fessenden

By [signature]
HIS ATTORNEYS.

2. That method of determining the location of ore bodies by generating s o u n d s and o b s e r v i n g t h e i r i n f l e c t i o n by the ore bodies, and t h e i r v e l o c i t i e s.
Reginald A. Fessenden.

Copies of this patent may be obtained for five cents each, by addressing the „Commissioner of Patents, Washington, D. C."

Sieberg 1917

In 1917 Sieberg expressed his opinion as appended below, in the *Lehrbuch der praktischen Geologie (Text book of Practical Geology)*, published by Privy Mining Councillor Dr. Keilhack, Department Chief at the R. Prussian Survey in Berlin, and Lecturer of the R. College of Technology in Charlottenburg: "It cannot be our task here to discuss the very difficult and still quite unexplored methods of the determination of the travelling times on the ray of propagation of the forerunners, which traverse the interior of the earth, nor can we discuss the coordinated calculations of the true velocity of propagation. Work in this department must remain the privilege of the mathematician and physicist. Whoever is somewhat interested in this may read the respective publications. This will obviate a discussion of the methods proposed for the calculation of the depth of the focus, as this is based on the aforementioned problems. While we are still groping in the dark concerning the physical conditions in the depths of the earth, and the further influencing of the propagation of seismic energy by the geologic-tectonic construction of the earth's crust, we are not in a position to pass a fair judgment on the said methods concerning their values or demerits."

Kayser 1918

In 1918 Professor E. Kaiser, in the 5th edition of his well known text book *Allgemeine Geologie (General Geology)*, given to the press in September 1918, also described the results of observations of the velocity of propagation of artificially generated earthquake waves, without drawing any further conclusions (see the extensive chapter *"Earthquakes and Seismic Phenomena")*. It reads, in part: "The velocity of propagation depends in the first case on the petrographic condition of the rocks in the area of concussion. The denser the rocks are and the freer they are of crevices and cavities the quicker the propagation will progress. R. Mallet determined the velocity of propagation of the concussion for wet sand to 250.5 m/sec. for creviced granite to 395 m/sec. for solid granite to 507.5 m/sec. Similar but somewhat higher values were obtained by Pfaff. New experiments very carefully carried out by Fouqué and Lévy in French mines resulted in: 646 m/sec for Cambrian marble, 1190 m/sec for Permian sandstone, for solid carboniferous sandstone 2000—2526 m/sec, for solid granite 2450—3141 m/sec. The last mentioned data approach those of the long superficially propagated earthquake waves, which have a rather uniform velocity of 3.5 km/sec. as before mentioned."

Kayser in 1918 confined himself, as we saw, to the quotation of results of velocity measurements in known rocks, partly 70 years old, without drawing any attention to the determination of the tectonics.

Evans 1919

On October 2nd, 1919 there appeared in the English Journal *"Nature" (contained in the Report of the 87th Meeting of the British Association)* the Opening Address by J. W. Evans D. Sc. L. B. F. R. S., President of the section. Among other things it reads:

"It deserves consideration, however, as to how far it may be possible to add to our knowledge of the earth's crust by experimental work with a view of the determination of surfaces of discontinuity by their action in reflecting vibrations from artificial explosions, a procedure similar to that by means of which the presence of vessels at distance can be detected by the reflection of submarine sound waves. The ordinary seismographs are not suited for this purpose, the scale of their record, both of amplitude and of time, is too small for the minute and rapid vibrations which would be expected to reach an instrument situated several miles from an explosion as to distinguish between direct vibrations and those that may arrive a second or two later after reflection at a surface of discontinuity. As the cylinder on which the record is made would be only in motion while the experiment was in progress, there would be no difficulty in arranging for a much more rapid movement. At the same time it would be desirable to dispense with any arrangement for damping the swing of the pendulum which would be unnecessary with small and rapid vibrations and would tend to suppress them. It is possible that it might be better to employ a seismograph which records, like that described by Galitzin shortly before his death, variations of pressure expressing terrestric acceleration, instead of one which records directly the movements of the ground. It would, however, probably be found desirable to substitute for the piezo electric record of pressure employed by Galitzin a record founded on the affect of pressure in varying the resistance in an electric circuit. This is, in fact, the principle of the microphone and most modern telephone receivers, not matter so much for the present purpose, where the time of transmission is the most important feature in the evidence, but satisfactory results even in this respect appear to be given by Brown's liquid microphone, from which the record could be taken, if desired, by means of the reflection of a mirror, attached to the needle of the galvanometer."

"In this review of some of the possibilities of geological research I cannot claim to have done more than touch the fringe of the subject. In every direction there is room for the development of fresh line of investigation, as well as for renewed activity along paths already trodden. Whether my particular suggestion proves fruitful or not, they will have served their purpose if they have stimulated anyone to look for new fields of work."

The above suggestions of the well known English geologist Evans show that the problem of the seismic investigation of the subsurface was not yet solved in 1919.

On December 7th, 1919, Mintrop applied for the German Reich patent No. 371 963 "Method for the exploration of strata and mineral deposits", the text of which follows here: Mintrop 1919

GERMAN REICH, REICH PATENT OFFICE.

Patent No. 371 963, class 42 l, group 13.

Dr. Ludger M i n t r o p of Bochum.

Method for the determination of rock structures.

Patented in the German Reich since December 7th, 1919.

In order to accurately determine the structure of the rocks of a certain area it is necessary to resort to the drilling of bore-holes if there are no natural exposures: the sinking of bore-holes, however, always means an expensive and elaborate work, which all the more cannot be carried out everywhere. Where the problem is to obtain at first preliminary information of the approximate composition of the strata, the divining rod has been used as is well known. However, according to "Glückauf", 1919, page 893 and following ones, it has not yet been possible to ascertain a connection of unique meaning between the indication of the divining rod and the geological particularities of the subsoil. Another working procedure for the similar purpose of approximate information exists in the use of electric waves, from the behaviour of which certain conclusions can be drawn as to the tectonics and as to the characteristics of the formations.

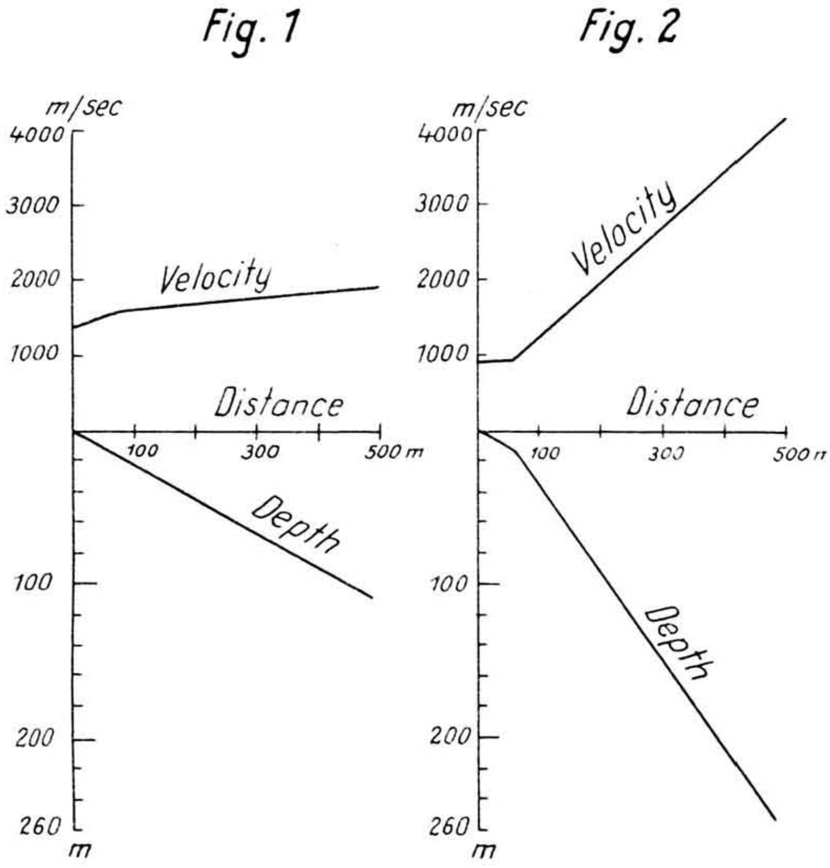
According to my invention waves are also to be used for the determination of the tectonics of the formations, not electrical waves, but mechanically generated elastic waves based on the conception that the connection of mechanical waves with the characteristic properties of the strata is ~~much more~~ immediate and therefore much closer than the interconnection with electrical waves. For this purpose mechanical waves are artificially generated at a suitable place in the area to be examined, — for instance by detonating a certain amount of explosives — their elastic propagation through the various formations is recorded by a seismometer located at a suitable distance. These diagrams are used, as this is known in the science of seismology, in order to construct the so called time-distance graph and in order to calculate the velocity of the waves in the various depths; in the science of seismology it was already tried to draw certain conclusions on the general construction of the earth as a whole. In the case to be treated here it is of importance that the observer is not compelled to wait for the occurrence of natural earthquakes, but that he can at will cause earth concussions, which circumstance alone gives the possibility to make such measurements in a specified place and at a specified time. The fact that we now have a means for convenient comparative measurements for the determination of the propagation of the elastic waves within the formation and of their time of arrival at the seismograph respectively, is of essential importance, by using for the determination of the moment of the generation of the elastic waves either the sound waves which are produced in any case with the blasting of the detonative charge, or a transmission by means of light, electric current or electric waves.

Conclusions can be drawn as to the elastic properties of the formations traversed by the waves, from the so determined surface and space velocities of the waves, as well as from the depths into which the waves have penetrated the formations, and also from the ratio of velocity of the longitudinal and transverse waves. In particular, discontinuities in the elastic properties of the ~~waves~~, as well as diffractions, refractions and reflexions can be found from the points of inflexion and breaks in the time-distance curve. Thus, for different localities, the graphs result as shown in the appended illustrations No. 1. and 2. The different development of the velocities and also their relation to the depth can be seen here. By comparisons carried out with such time-distance curves and velocities gained in localities of known geological structure a valuable check is obtained on the reliability of the conclusions drawn with regard to the sequence of layers and their thickness, as the different types of rock show very different elastic properties. For instance, the pronounced break in the velocity curve in fig. 2 obviously allows to recognize, that a change in the formations must occur in a depth so determined at the same time. As a matter of fact borings show diluvial sands for the total length in fig. No. 1, whereas in the case of fig. 2 hard marl follows below a bed of 9 m of loose sands. By a suitable arrangement of the measurement of the artificially produced elastic waves, the direction of the strike and dip and dislocations of the strata can also be determined.

Even if this will not always enable a determination of the particular kind of rocks, it often suffices to know into what depth visibly exposed formations reach, and in what thickness harder or looser formations follow underneath, or whether the succession of beds follows the normal geological structure. This is very important in supplementing the geological mapping if sites are to be selected for bore holes and shafts in a certain area. Then again, ~~rock salt~~, brown coal and rocksalt deposits show such characteristic elastic properties that, with the use of other observations, such deposits can be directly found by the new method. The method itself is extraordinary simple and cheap, as only a few kilograms of explosives are required for a measurement, and the seismometer to be used can be constructed as a simple, light and handy instrument; nor is it necessary that scientifically trained persons be present when the records are taken, as the scientific interpretation of the measurements can be done afterwards.

Patent Claim:

Method for the determination of the structure of geological formations, characterized as follows: In the area to be investigated elastic waves are artificially produced, for instance by the blasting of an explosive charge, these are recorded by a seismometer placed at a suitable distance; from the records of the latter the velocities of the various waves and the depth to which they penetrated can be determined, which allows conclusions as to the succession, thickness, density as well as the direction of the strike and dip of rock formations, especially by comparisons with measurements in places of known geological structure.



Nine months after his paper appeared in "*Nature*" and seven months after Mintrop's application for patent, Evans applied for the *British patent No. 174 095: "Improvements in and relating to Means for Investigating the Interior of the Earth's Crust"*. The following is the text of the Evans patent: Evans 1920

PATENT SPECIFICATION. 174,095

Application Date: July 9, 1920. No. 20,225/20. Complete Left: May 9, 1921. Complete Accepted: Jan. 9, 1922. Provisional Specification.

Improvements in and relating to Means for Investigating the Interior of the Earth's Crust.

We, John William Evans, of the Imperial College of Science and Technology, South Kensington, S. W., Fellow of the Royal Society, a British subject, and Willis Bevan Whitney, of 21, Victoria Road, Surbiton, Surrey, Associate Member of the Institute of Civil Engineers, a naturalised British subject, do hereby declare the nature of this invention to be as follows: —

This invention relates to means for investigating the interior of the earth's crust and consists in novel combinations of apparatus (said apparatus per se being either new or old) and in the new apparatus per se for carrying out a method of investigating the interior of the earth's crust by which it is possible, without making extensive excavations or borings, to determine the nature and position of hidden strata such as coal, oil shale, water, petroleum, surfaces of rock and other strata or deposits or surfaces of discontinuity in the earth's crust.

The invention has for its object to facilitate the exploitation of mineral wealth, engineering operations, the investigation of the available supply of water, petroleum, and the like.

The method is based on the moulding and modifying influence which strata or surfaces of discontinuity in the earth's crust exert upon waves or vibrations, which pass through them or are reflected by them.

The novel combinations of apparatus according to the present invention comprise means for generating the waves or vibrations, at least two and preferably three or more apparatus for receiving the vibrations and one or more apparatus for recording the vibrations when received, the said receiving apparatus being in electrical or other suitable form of connection or communication with the generating means and with the recording apparatus.

The aforesaid combinations of apparatus may be employed in various ways of which the following are examples : —

1. Waves or vibrations are generated by the generating means at or near the surface of the earth and are automatically received at a plurality of stations and recorded. The receiving apparatus is placed in such positions at or near the surface of the earth that some of the waves are received after and others before they have traversed the stratum under examination, or they may all be received after they have traversed the stratum.

2. Waves are generated as before and having travelled downward to the surface of the stratum to be examined they are in part refracted and in part reflected back (owing to the properties possessed by surfaces of discontinuity between media of different densities and elastic moduli). The reflected waves, which may comprise both distortional and longitudinal waves are received at a plurality of stations and recorded.

3. The waves are generated below the stratum to be examined and having travelled upward to the stratum they are, as in the second case, in part reflected and in part refracted. The refracted waves are then received at a plurality of stations and recorded.

4. The waves are generated at or near the surface of the earth and are received at a plurality of stations and recorded after having been reflected and refracted a number of times between the stratum under examination and the surface of the earth.

In employing the aforesaid combinations of apparatus in the manner described the receiving apparatus of which, as stated, there should be at least two, are preferably so placed that they lie approximately on lines radiating from the generating apparatus as centre and between 90 and 120 degrees apart and are in electrical or other suitable form of connection with the said generating apparatus. It is not necessary that there should be three or more recording apparatus as the receiving apparatus may be connected electrically or by other suitable means with one recording instrument placed in any convenient position. Records of the vibrations at the generating station and at the various receiving stations are obtained and a comparison of these records enables the observer to distinguish between the different reflections and ascertain the time intervals between them even when they are so close together as to form composite waves and, owing to the different properties of reflection, refraction and absorption possessed by various media from the nature of the vibrations recorded and the time intervals between them the nature and position of the media under examination is determined.

For generating the waves the following means or means capable of generating the following kinds of vibrations may be employed :—

Vibrations generated by means of sound for instance, explosives, blows struck by hand or mechanical means and the like.

For receiving the vibrations the following instruments, for example, may be employed according to circumstances :—

Microphone-carbon, liquid or jet:

The following are examples of recording apparatus that may be used according to circumstances:

Telephone receivers in combination if necessary with automatic make and break device such as a commutator. Einthoven String Galvanometer fitted with automatic photographic recording device.

Apparatus based on the piezo-electric properties of quartz, stethoscope, oscillograph and the like in combination with automatic recording devices.

Instead of the above mentioned known apparatus a new receiving apparatus hereinafter described may be employed.

The new apparatus, according to the present invention, comprises essentially a casing which can be firmly embedded in the ground, a mass resiliently supported or suspended within said casing in such a manner that when the portion of the stratum in which the casing is fixed is set in motion by the passage of a vibration from the generator there will be relative motion and variation in pressure between the casing and the mass, and means whereby said relative movement or variation in pressure may be detected.

The apparatus may be constructed in several forms.

In one preferred embodiment it comprises a heavy mass, for example, a hollow steel sphere filled with lead. Said mass is surrounded on all sides by a close fitting rubber envelope having a thickness of say two centimetres. It must be thicker below unless the mass is partly supported by a spring or springs. The rubber envelope is enclosed in a cast-iron or steel casing with a hollow spherical interior. This casing is fixed in a large and solid block of concrete firmly embedded in the ground both vertically and laterally at a depth where it is compact and undisturbed.

The rubber envelope and casing are divided into hemispheres or smaller segments which can be fixed together over the sphere by screws working in flanges so as to exert everywhere a gentle pressure upon it.

Passing through cylindrical holes in the casing and envelope are one or more short cylindrical steel rods, say three millimetres in diameter and five centimetres in length. These fit loosely in the holes in the casing and envelope. On the outer side the surface is flat while on the inner it has the same curvature as the sphere. The inner end of these pins presses lightly against the sphere, and the outer end against the diaphragm of a sensitive microphone so adjusted that a very slight variation in the pressure between the pin and the diaphragm will cause a sensible variation in the current passing through the circuit of the microphone, and these variations are recorded on a rotating drum. The microphone is rigidly fixed in the same concrete block as the casing of the sphere.

If there is only one pin, it should be vertically above or below the centre of the sphere. If there are three, the other two will be horizontal and at right angles to each other, and all three are connected with different microphones.

It may be convenient to have pins in pairs opposite each other so that there will be two or six in the cases described above. The microphones associated with the opposite pins may then have a common circuit so arranged that an increase of pressure on the diaphragm of one microphone will cause the current to flow in the same direction as a decrease in the other. Alternatively they may be independent, furnishing a check on one another. For some purposes, and especially for the observation of vibrations arising from points at horizontal distances similar to the vertical distance at which reflections takes place, it will be convenient to have either in place of or in addition to the pins already described, four or eight pins at the points which would be in the same position as the angles of a cube with the centres of its faces opposite the first mentioned pins. The heavy mass may have different forms. Instead of being spherical it may have the shape of a regular polyhedron with envelopes and casing of corresponding form. The octahedron will be that most suited for the purpose, but the triangular triakis octahedron and the cube may also be employed. In this case the pins will be at the angles of the polyhedron which will be truncated so that the pins may be in complete contact with them. Springs may be substituted wholly or partially for rubber for keeping the mass in position especially vertically where a suspending spring is advantageous. Lateral variations of pressure may also be recorded even if the mass be suspended by an inextensible cord.

Any charcoal microphone may be employed and some forms of relay are also suitable for the purpose. Also a liquid microphone which acts by the varying resistance at a minute hole in a diaphragm in an electrolytic fluid such as copper sulphate or the piezo electric properties of quartz may also be employed for the purpose.

In a second embodiment of the invention the apparatus consists of a brass or gunmetal casing made in two parts and provided with circular flanges and bolt holes, so that the upper and lower portions may be drawn tightly together by means of bolts. These flanges when drawn together grip a mica, or insulated steel diaphragm which has a weight of at least eight ounces firmly attached to its centre. To this weight are attached two platino-iridium or other metallic points, one on the upper side and one on the lower, said points are connected to a conductor which passes out of the casing along the surface of the diaphragm and completes the circuit. of the telephone or other recording instrument. Through threaded holes in the centres of the upper and lower faces of the casing adjustable screws pass, these carry at their ends carbon or metallic shoes which are connected by conductors through a primary battery and if desired through a commutator arrangement to the remaining terminal of a telephone, Einthoven string galvanometer or other suitable receiving or recording device.

In one method of employing this apparatus it is placed in rigid connection with the surface of the stratum to be investigated upon one of the lines radiating from the generating apparatus as hereinbefore described. The screws are adjusted so that the faces of the shoes are just out of contact with the tops of the pins, in this state of affairs the circuit will be incomplete and no effect will be registered on the recording instrument.

When however the portion of the stratum to which the casing is attached, is set in motion by the passage of a wave from the generator, the vertical component of the motion will cause the casing to move bodily upwards or downwards while the mass owing to its inertia will remain fixed in space and will not move appreciably with the casing. As a result there will be relative motion between the casing and the mass and one of the shoes will come in contact with one of the platino-iridium points completing the circuit in the recording apparatus.

The make-and-break or commutator device is not essential to the circuit when single isolated waves are being detected. It is however essential when the generator is sending out waves at regular intervals of time. In one method of using the commutator device under such circumstances it is arranged automatically to break contact at intervals co-inciding with the arrival of say that portion of the wave travelling along the surface so that the arrival of this wave produces no effect on the recording apparatus, the reflected portion on the other hand of the wave which has travelled downwards and upwards and therefore by a longer path will arrive after contact has been made again and will therefore leave its record on the recording instrument. Thus by adjusting the speed of the commutator wheel or the make-and-break device a very accurate determination of the interval between the arrival of the direct and reflected wave can be obtained and thus the depth of the reflecting surface determined.

In another method of using the apparatus, the screws may be so adjusted that when no wave is passing one of the shoes is in contact with one of the platino-iridium points while the other is out of contact, the arrival of the wave will then be shown by a complete break of contact in the circuit.

In a modification of this second form of receiving apparatus the casing and the diaphragm are similar to that already described above, the platino-iridium points and the lower adjusting screw are however omitted. In place of the upper point a hemispherical elastic body is firmly attached to the inertia mass. The spherical surface of this elastic body may—if the body itself is not of the required resistance—be coated with a layer of conducting substance of high specific electric resistance. In the same way the shoe of the upper adjusting screw may be provided with a flat or spherical surface of similarly high resistance.

In one method of using this form of receiving apparatus the adjusting screw is screwed down until the surface of the shoe is in sufficient contact with the hemispherical elastic body to distort the diaphragm to such an extent that whatever the motion of the casing the surface of the hemisphere will always be in contact with the shoe. Upon the arrival of a wave, there will be relative motion between the shoe and the inertia mass but owing to the adjustment already made this will not cause break of contact but only variation of pressure. This variation of pressure will cause a flattening or bellying of the surface of the hemispherical elastic body resulting in a considerable change in the area of contact between it and the shoe and causing considerable variation in the resistance. Since the resistance will under these circumstances be a function of the area of contact and thus of the pressure and motion of the ground, this form of receiver may be used to obtain quantitative results.

Dated this 7th day of July, 1920.

Clement Lean, B.Sc.,
Chartered Patent Agent, Thanet House, Temple Bar, 231 & 232, Strand, London, W. C. 2.

COMPLETE SPECIFICATION.

Improvements in and relating to Means for Investigating the Interior of the Earth's Crust.

We, John William Evans, of the Imperial College of Science and Technology, South Kensington, Fellow of the Royal Society, a British subject, and Willis Bevan Whitney, B. Sc., A. M. Inst. C. E., of "Glen Doon", Bull Lane, Gerrards Gross, Bucks, formerly of 21, Victoria Road, Surbiton, Surrey, a naturalised British subject, do hereby declare the nature of this invention and in what manner the same is to be performed to be particularly described and ascertained in and by the following statement: —

This invention relates to a method of and means for investigating the interior of the earth's crust and consists in novel combinations of apparatus (said apparatus per se being either new or old) and in the new apparatus per se for carrying out a method of investigating the interior of the earth's crust by which it is possible, without making extensive excavations or borings, to determine the nature and position of hidden strata such as coal, oil shale, water, petroleum, surfaces of rock and other strata or deposits or surfaces of discontinuity in the earth's crust.

An object of the invention is to facilitate the exploitation of mineral wealth, engineering operations, the investigation of the available supply of water, petroleum and the like.

The method is based on the moulding and modifying influence which strata or surfaces of discontinuity in the earth's crust exert upon sound waves or like pressure vibrations which pass through them or are reflected by them.

According to a previous method of this nature, in order to investigate the interior of the earth, a sound is emitted from a suitable source and its echo or return or the sound which arrives at a distant point is observed by a receiving mechanism and the time elapsing between the emission of the sound and the reception of the echo or between the emission of the sound and its arrival at the distant point is also measured, the sound producer and the receiver being electrically interconnected for this purpose.

From the observation obtained conclusions are drawn as to the probable nature of the medium which has been traversed by the wave.

Now the method to which the present invention relates as distinguished from the method heretofore proposed, is characterized in that the sound waves, after having been modified by the medium under examination are received simultaneously or approximately so at a plurality (at least two and preferably three or more) of receiving stations placed at a distance from the transmitting station, and the novel combinations of apparatus, in accordance with the present invention, comprise means for generating the waves or vibrations, a plurality of apparatus for receiving the waves and one or more apparatus in connection with said receiving apparatus and in connection, preferably electrically, with the generating means for recording said waves or vibrations when received and their times of transmission and reception.

The use of at least two receiving apparatus by which the waves are received approximately simultaneously is essential for the following reasons :—

Even in the simplest case when it is known that the stratum to be examined is horizontal there are two unknown quantities namely (1) the average velocity of the reflected wave (which is not the same as that of a surface wave) and (2) the depth of the reflecting stratum and therefore two equations connecting them are required and two observations are consequently necessary. These two observations are made simultaneously in accordance with the present invention and must be so made because, as is wellknown, the surface of the earth, when examined by delicate recording instruments is found to be in a constant state of movement, for example, the condition of the surface layers of the earth's crust varies with difference of temperature and barometric pressure, the strains in the rocks vary with the tides in the earth's crust and in the neighbourhood of the coast they vary with the marine tides as well, there are also diurnal changes of unknown origin of even greater magnitude, the earth's crust is continuously traversed by microseisms of varying intensity, vibrations are also constantly being caused by local traffic, slight landslips and distant earthquakes. The presence of these phenomena, therefore, makes it essential that the arrival of the waves should be recorded simultaneously and preferably on the same drum if the artificial vibrations from the transmitting station are to be clearly distinguished from the natural vibrations of the earth's crust.

Further, especially when the waves are generated by means of explosives, the conditions vary considerably with each experiment and this also makes it essential that there should be at least two receiving stations at which records are obtained simultaneously.

In more general cases when the strata are not horizontal, there will be more unknown quantities and further receiving stations will be required.

The employment of a plurality of receiving stations, therefore, has the advantages that the nature and position of the underground strata or media under examination can be determined with greater certainty than has heretofore been possible and there is a great saving of time since the records are obtained simultaneously.

The aforesaid combinations of apparatus may be employed in various ways of which the following are examples:—

1. Waves or vibrations are generated by the generating means at or near the surface of the earth and are automatically received at a plurality of stations and recorded. The receiving apparatus is placed in such positions at or near the surface of the earth that some of the waves are received after and others before they have traversed the stratum under examination, or they may all be received after they have traversed the stratum.

2. Waves are generated as before and having travelled downward to the surface of the stratum to be examined they are in part refracted and in part reflected back (owing to the properties possessed by surfaces of discontinuity between media of different densities and elastic moduli). The reflected waves, which may comprise both distortional and longitudinal waves, are received at a plurality of stations and recorded.

3. The waves are generated below the stratum to be examined and having travelled upward to the stratum they are, as in the second case, in part reflected and in part refracted. The refracted waves are then received at a plurality of stations and recorded.

4. The waves are generated at or near the surface of the earth and are received at a plurality of stations and recorded after having been reflected and refracted a number of times between the stratum under examination and the surface of the earth.

These methods are illustrated diagrammatically in Figs. 1—4 of the accompanying drawings.

In these figures A—B represents the surface of the earth and C—D the stratum under examination, G represents the generating station and R^1, R^2, receiving stations, which are suitably connected with the generating and recording stations. For the sake of simplicity only two receiving stations are shown in the diagrams.

Referring to Fig. 1, which illustrates method 1 hereinbefore described, waves or vibrations are generated at G and received at the receiving stations R^1, R^2 on either side of the stratum C—D which is under examination.

In the second method illustrated in Fig. 2, the waves or vibrations are received at the receiving station R^1, R^2 after having been reflected from the surface of the stratum C—D.

In the third method, illustrated in Fig. 3, the waves or vibrations are generated below the stratum C—D and are received at the stations R^1, R^2 after having passed through the stratum and having been refracted by it.

Fig. 1.

Fig. 2.

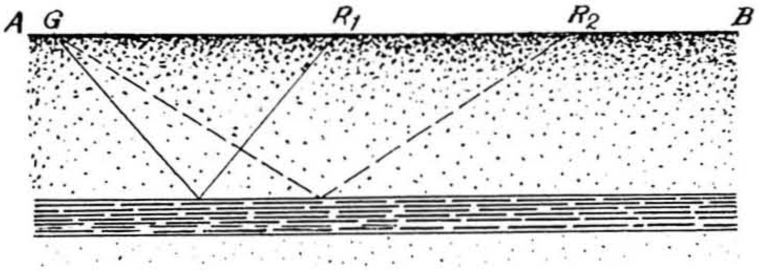


Fig. 3.

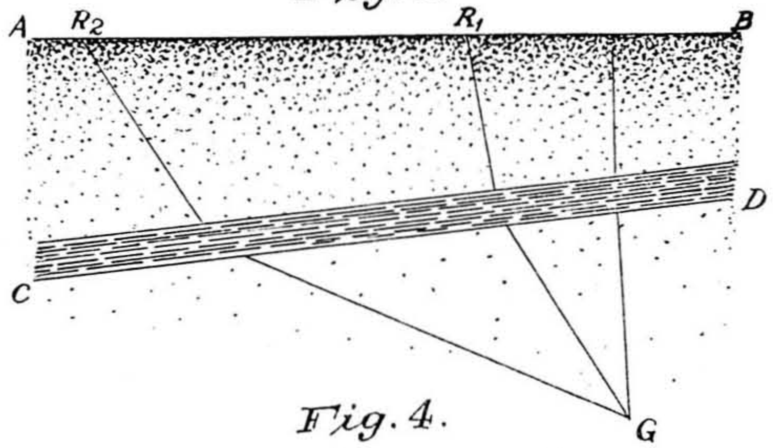


Fig. 4.

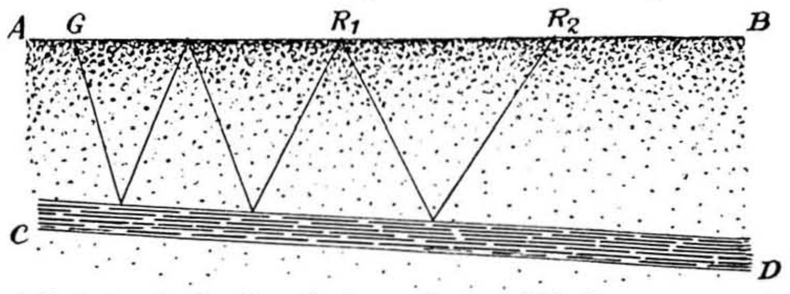


Fig. 4 illustrates the fourth method according to which the waves generated at G are received at R^1, R^2 after having been reflected between the stratum under examination and the surface of the earth a number of times.

It will be understood that the waves may comprise both longitudinal and distortional waves, but as they are generally close together, they are represented as single lines on the diagram.

The distance apart of the generating and receiving stations will generally be considerable, say one mile, but may be greater or less, depending upon the nature of the earth's crust which is under examination.

In employing the aforesaid combinations of apparatus in the manner described the receiving apparatus of which, as stated, there must be at least two, are preferably so placed that they lie approximately on lines radiating from the generating apparatus as centre and between 90 and 120 degrees apart. It is not necessary that there should be three or more recording apparatus as the receiving apparatus may be connected, for example, electrically with one recording instrument, which is in connection, preferably electrically, with the generating apparatus, and may be placed in any convenient position. Records of the vibrations at the generating station and at the various receiving stations are obtained and a comparison of these records enables the observer to distinguish between the different reflections and ascertain the time intervals between them, even when they are so close together as to form composite waves and, owing to the different velocities in different media and the differences in reflection, refraction and absorption, the nature of the vibrations recorded and the time intervals between them will enable the probable nature and position of the media under examination to be determined, (provided there are a sufficient number of stations) for example, in the following manner:—

The time of arrival of the waves at each receiving station will be recorded and on the same record the time of generation of the wave at the transmitting station will be recorded by direct telegraphy automatically from the transmitting station. If the instrument at the receiving station records the actual wave shapes, these can be resolved by harmonic analysis into their components and the time of arrival of the different types of waves sorted out. The "sharpness" of the reflected waves will give information regarding the nature of the reflecting surface and comparison of velocities and times of arrival will give information relating the nature of the medium traversed.

For generating the waves, the following means or means capable of generating the following kinds of vibrations or oscillations may be employed—vibrations generated by means of sound, for instance, explosives, blows struck by hand or mechanical means and the like.

For receiving the vibrations the following instruments for example, may be employed according to circumstances:—

Microphone, -carbon, liquid or jet.

Telephone receivers, in combination if necessary with automatic make and break device such as a commutator.

The following are examples of recording apparatus that may be used according to circumstances:—

Einthoven string galvanometer fitted with automatic photographic recording device.

Apparatus based on the piezo-electric properties of quartz, stethoscope, oscillograph and the like in combination with automatic recording devices.

Instead of the above mentioned known apparatus a new receiving apparatus hereinafter described may be employed.

The new apparatus, according to the present invention, comprises essentially a casing which can be firmly embedded in the ground, a mass resiliently supported or suspended within said casing and one or more pins or the like inserted in an electrical circuit between the mass and a microphone or other apparatus whereby the relative movement between the casing and the mass, which occurs when the portion of the stratum in which the casing is fixed, and therefore the casing itself, is set in motion by the passage of a vibration from the generator while the mass owing to its inertia tends to remain fixed in space, may be detected. Instead of pins a hemispherical elastic body, as hereinafter described, may be employed.

The apparatus may be constructed in several forms.

In one preferred embodiment it comprises a heavy mass, for example, a hollow steel sphere filled with lead. Said mass is surrounded on all sides by a close fitting rubber envelope having a thickness of say two centimetres. It must be thicker below unless the mass is partly supported by a spring or springs. The rubber envelope is enclosed in a cast-iron or steel casing with a hollow spherical interior. This casing is fixed in a large and solid block of concrete firmly embedded in the ground both vertically and laterally at a depth where it is compact and undisturbed.

The rubber envelope and casing are divided into hemispheres or smaller segments which can be fixed together over the sphere by screws working in flanges so as to exert everywhere a gentle pressure upon it.

Passing through cylindrical holes in the casing and envelope are one or more short cylindrical steel rods, say three millimetres in diameter and five centimetres in length. These fit loosely in the holes in the casing and envelope. On the outer side the surface is flat while on the inner it has the same curvature as the sphere. The inner end of these pins presses lightly against the sphere, and the outer end against the diaphragm of a sensitive microphone so adjusted that a very slight variation in the pressure between the pin and the diaphragm will cause a sensible variation in the current passing through the circuit of the microphone, and these variations are recorded on a rotating drum. The microphone is rigidly fixed in the same concrete block as the casing of the sphere.

If there is only one pin, it should be vertically above or below the centre of the sphere. If there are three, the other two will be horizontal and at right angles to each other, and all three are connected with different microphones.

It may be convenient to have pins in pairs opposite each other so that there will be two or six in the cases described above. The microphones associated with the opposite pins may then have a common circuit so arranged that an increase of pressure on the diaphragm of one microphone will cause the current to flow in the same direction as a decrease in the other. Alternatively they may be independent, furnishing a check on one another. For some purposes, and especially for the observation of vibrations arising from points at horizontal distances similar to the vertical distances at which reflection takes place, it will be convenient to have either in place of or in addition to the pins already described, four or eight pins at the points which would be in the same position as the angles of a cube with the centres of its faces opposite the first mentioned pins. The heavy mass may have different forms. Instead of being spherical, it may have the shape of a regular polyhedron with envelopes and casing of corresponding form. The octahedron will be that most suited for the purpose, but the triangular triakis octahedron and the cube may be employed. In this case the pins will be at the angles of the polyhedron which will be truncated so that the pins may be in complete contact with them. Springs may be substituted wholly or partially for rubber for keeping the mass in position especially vertically where a suspending spring is advantageous. Lateral variations of pressure may also be recorded even if the mass be suspended by an inextensible cord.

Any charcoal microphone may be employed and some forms of relay are also suitable for the purpose. Also a liquid microphone which acts by the varying resistance at a minute hole in a diaphragm in an electrolytic fluid such as copper sulphate or the piezo electric properties of quartz may also be employed for the purpose.

A preferred embodiment of an apparatus of the aforesaid type is illustrated by way of example, in Fig. 5, which represents a sectional diagram of the apparatus.

Referring to Fig. 5, 1 is a solid sphere of lead enclosed in a steel casing 2. The casing 2 is surrounded by a rubber envelope 3 which is enclosed by the two hemispherical steel casings 4, having flanges 5 by means of which they are bolted together. The whole is enclosed in a concrete block 6 which is embedded in the ground. The casing 4 and rubber envelope 3 are provided with circular holes 7 in which the steel rods 8 fit loosely. The inner ends of the rods 8 are rounded to the same curvature as the sphere and press lightly against the casing 2, while the outer ends are flat and in connection with the diaphragm or a microphone or with a piezo-electric apparatus which is fitted in suitable openings 9 left in the concrete block, whereby slight variation in pressure may be measured.

A second preferred embodiment is illustrated diagrammatically by way of example in Fig. 6. The apparatus consists of a brass or gun metal casing a made in two parts and provided with circular flanges and bolt holes, so that the upper and lower portions may be drawn tightly together by means of bolts f. These flanges when drawn together grip a mica, or insulated steel diaphragm b which has a weight c of at least eight ounces firmly attached to its centre. To this weight c are attached two, platino-iridium or other metallic points g one on the upper side and one on the lower, said points are connected to a conductor h which passes out of the casing a along the surface of the diaphragm and completes the circuit of the telephone or other recording instrument j. Through threaded holes in the centres of the upper and lower faces of the casing a adjustable screws k pass, these carry at their ends carbon or metallic shoes n which are connected by conductors l through a primary battery p and if desired through a commutator arrangement e to the remaining terminal of a telephone, Einthoven string galvanometer or other suitable receiving or recording device.

In one method of employing this apparatus, it is placed in rigid connection with the surface of the stratum to be investigated upon one of the lines radiating from the generating apparatus as hereinbefore described. The screws k are adjusted so that the faces of the shoes n are just out of contact with the tops of the pins g, in this state of affairs the circuit l—j—h—g—n will be incomplete and no effect will be registered on the recording instrument at j.

When however the portion of the stratum to which the casing a is attached, is set in motion by the passage of a wave from the generator, the vertical component of the motion will cause the casing to move bodily upwards or downwards while the mass

Fig. 5

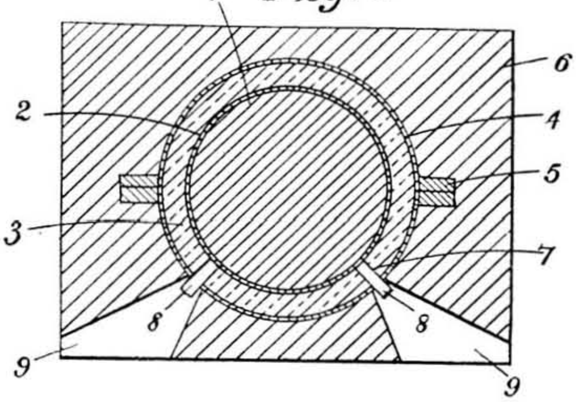


Fig. 6.

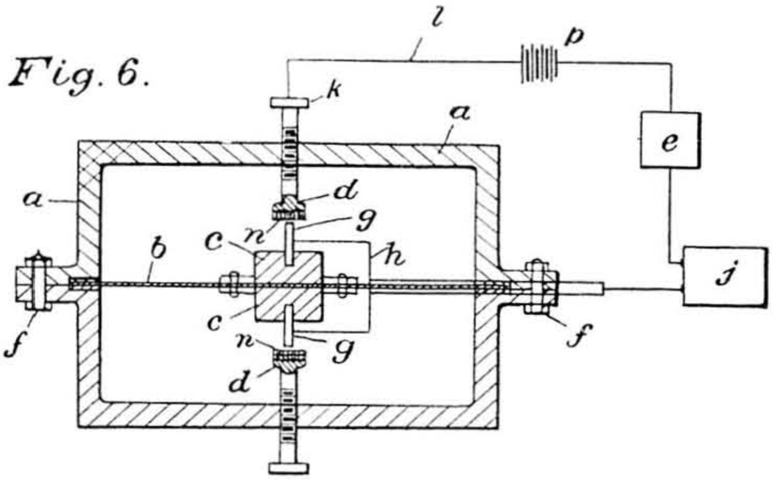
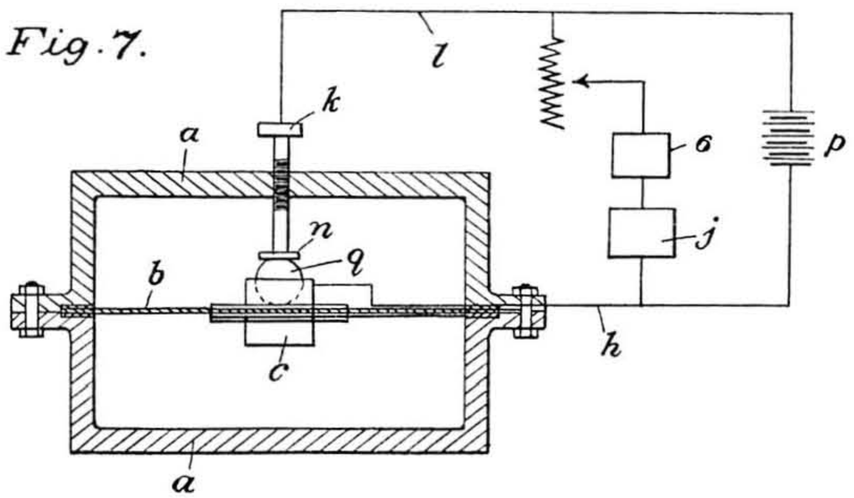


Fig. 7.



"c" owing to its inertia will remain fixed in space and will not move appreciably with the casing. As a result there will be relative motion between the casing a and the mass c and one of the shoes n will come in contact with one of the platino-iridium points g completing the circuit in the recording apparatus j.

The make-and-break or commutator device e is not essential to the circuit when single isolated waves are being detected. It is however essential when the generator is sending out waves at regular intervals of time. In one method of using the commutator device under such circumstances it is arranged automatically to break contact at intervals coinciding with the arrival of say that portion of the wave travelling along the surface so that the arrival of this wave produces no effect on the recording apparatus, the reflected portion on the other hand of the wave which has travelled downwards and upwards and therefore by a longer path will arrive after contact has been made again and will therefore leave its record on the recording instrument. Thus by adjusting the speed of the commutator wheel or the make-and-break device a very accurate determination of the interval between the arrival of the direct and reflected wave can be obtained and thus the depth of the reflecting surface determined.

In another method of using the apparatus, the screws k may be so adjusted that when no wave is passing one of the shoes n is in contact with one of the platino-iridium points g while the other is out of contact, the arrival of the wave will then be shown by a complete break of contact in the circuit.

A modification of this second form of receiving apparatus is illustrated diagrammatically by way of example in Fig. 7. In this apparatus the casing a and the diaphragm b are similar to that already described above, the platino-iridium points g and the lower adjusting screw k are however omitted. In place of the upper point a hemispherical elastic body q is firmly attached to the inertia mass c. The spherical surface of this elastic body may—if the body itself is not of the required resistance—be coated with a layer of conducting substance of high specific electric resistance. In the same way the shoe n of the upper adjusting screw k may be provided with a flat or spherical surface of similarly high resistance.

In one method of using this form of receiving apparatus the adjusting screw k is screwed down until the surface of the shoe n is in sufficient contact with the hemispherical elastic body q to distort the diaphragm b to such an extent that whatever the motion of the casing a the surface of the hemisphere q will always be in contact with the shoe n. Upon the arrival of a wave, there will be relative motion between the shoe n and the inertia mass c but owing to the adjustment already made this will not cause break of contact but only variation of pressure. This variation of pressure will cause a flattening or bellying of the surface of the hemispherical elastic body q resulting in a considerable change in the area of contact between it and the shoe n and causing considerable variation in the resistance. Since the resistance will under these circumstances be a function of the area of contact and thus of the pressure and motion of the ground, this form of receiver may be used to obtain quantitative results.

We are aware that, for the purpose of detecting sounds by means of ground vibrations, it has hitherto been proposed to employ various devices of the microphone type. such as, a casing adapted to be fixed or embedded in the ground and containing two electrodes one of which is fixed and the other is attached to a diaphragm or supported by means of springs so as to be capable of vibration. The vibrating electrode is set in motion by the ground vibrations and varies the resistance in a hearing circuit in the usual manner.

Having now particularly described and ascertained the nature of our said invention and in what manner the same is to be performed, we declare that what we claim is : —

1. Means for carrying out a method of investigating the interior of the earth's crust based on the moulding or modifying influence which strata or surface of discontinuity in the earth's crust exert upon sound waves or like pressure vibrations which pass through them or are reflected by them comprising in combination means for generating the said waves or vibrations, a plurality of apparatus whereby said waves or vibrations are received simultaneously or approximately so, and one or more apparatus in connection with said receiving apparatus and in connection, preferably electrically, with the generating apparatus for recording said waves or vibrations when received and their times of transmission and reception, substantially as described.

2. A combination in accordance with Claim 1, in which the receiving apparatus comprises a casing which can be firmly embedded in the ground, a mass resiliently supported or suspended within said casing, and pins or the like inserted between the mass and the sensitive portion of a microphone or other apparatus, whereby relative motion or variation in pressure between the casing and the mass may be detected.

3. A combination in accordance with Claim 1, in which the receiving apparatus comprises a heavy mass, a close-fitting envelope of elastic material, such as rubber, surrounding said mass, a casing enclosing said envelope, a concrete block or the like adapted to be embedded in the ground in which said casing is enclosed, and means whereby relative motion between the mass and the concrete block may be detected.

4. In apparatus in accordance with Claim 2, the feature that pins are arranged in pairs opposite each other, for the purpose specified.

5. A combination in accordance with Claim 1, in which the receiving apparatus is substantially as described with reference to Fig. 5 of the accompanying drawings.

6. A combination in accordance with Claim 1, in which the receiving apparatus is substantially as described with reference to Fig. 6 of the accompanying drawings.

7. A combination in accordance with Claim 1, in which the receiving apparatus is substantially as described with reference to Fig. 7 of the accompanying drawings.

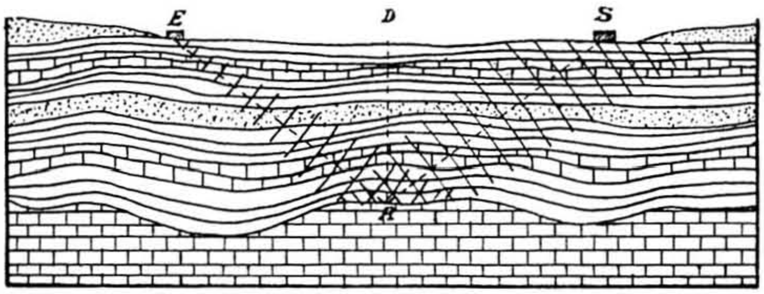
Dated this 20 th day of December, 1921.

Clement Lean, B. Sc., A. M. I. Mech. E.,
Chartered Patent Agent,
Thanet House, 231, Strand, W. C. 2.

One year after the patent application of Mintrop and three years after the publication of the Fessenden patent the well known American geologist and Professor at the University of Texas in Austin, J. A. Udden, Director of the Bureau of Economic Geology and Technology, published a paper in the *Bulletin of the American Association of Petroleum Geologists, Vol. 4, 1920, No. 1*, on *"Suggestions of a new Method of making Underground Observations"*. Herein he proposed to make a detonation at the surface and to set up a seismograph which should register in certain petroliferous areas the waves which would be reflected by limestone covered with soft beds and which would then return to the surface. Udden thought it would be possible by this method to determine the depth of the limestone at various places of the area, thus plotting lines of equal depth on the surface of the limestone. Udden wrote: "It has suggested itself to the writer that it ought to be possible with present refinements in physical apparatus and their use, to construct an instrument that would record the reflections of earth waves started at the surface, as they encounter such a well-marked plane of difference in hardness and elasticity as that separating the Bend and the Ellenburger formations. Some such instrument as a seismograph, especially constructed to be sensitive to vertical waves, possibly a slight adaptation of some of the present seismographs would be ample suitable for the purpose. A seismic wave might be started by an explosion at the surface of the earth, and a record of the emerged reflection of this wave from the upper surface of the Ellenburger limestone might be registered on an instrument placed at some distance from the point of explosion. The record would, of course, be a component of the direct and the reflected waves. It ought to be possible to notice the point at which the first reflection from the Ellenburger appears on a continuous record. The time of the record being known, it ought to be possible to figure the depth to the plane of reflection. It seems to me that by making a number of observations at points where the distance to the upper surface of the Ellenburger is known, it would be possible to learn to interpret the record correctly. It might be found necessary to make new adaptations on the working parts of the instrument. The difficulties ought not to be insurmountable. After these are once mastered, observations could be made anywhere, probably with quite rapid progress, and the entire upper surface of the Ellenburger might be mapped over wide areas with relatively small effort. The topography of the Ellenburger could, so to speak, be contoured directly by any number of observations desired. With such a topographic map of the surface of the Ellenburger, it seems to me that millions of dollars worth of drilling could be eliminated, which will otherwise have to be done before all of the pools in the Bend shall have been located. Udden 1920

Why not pay twenty thousand dollars for 'theoretical' experiments, if by so doing a million in expenses on 'practical' work can be saved?"

The publication of Udden, illustrated by the figure here also reproduced, is remarkable in several respects. Udden gives a complete rule for technical action and explains at the same time the economic advantage that the application of this rule would bring; contrary to Belar, von dem Borne, Galitzin and Wilip, who confine themselves to



general allusions which were not understood by their contemporaries, without showing the way to the solution of the problem. Furthermore Udden explains unmistakably the purpose of the method. However, Udden did not solve the problem.

Udden's paper proves that Fessenden's method, published three years before, did not meet the practical requirements, because Udden emphasizes that by using detonations and seismographs at the surface millions of dollars, otherwise spent for wells, could be saved, while Fessenden's method is compelled to use bore-holes. The importance of a method that avoids bore-holes follows from a paper of *E. Bowles in "The Oil and Gas Journal", November 19th, 1925, on "Economic significance of new Wells"*. According to this paper 302,541 wells had been brought down in the United States for the purpose of oil exploration in the twelve years between 1913—1925, costing 4,910,500,000 Dollars. Of this number 65,564 were dry holes, that is, useless, and the expenses of 719,300,000 Dollars were fruitless.

Krusch 1920

In the 3rd edition of his book *"Die Untersuchung und Bewertung von Erzlagerstätten" (Investigation and Valuation of Ore Deposits)* given to the press in October 1920, Privy Councillor Krusch, then department chief, and now President of the Prussian Geological Survey, assigned extensive space to the magnetic and electric methods of prospection, to the prospection by means of wireless telegraphy, to the "Eötvös Torsion Balance" and to the divining rod, but did not mention the seismic method, which proves that the Mintrop Method was not known in 1920. On the other hand the mentioning of the use of the torsion balance — which was not introduced into Germany until 1917 by Professor Schweydar, at the suggestion of the Director of the Deutsche Bank, von Stauss — proves that Krusch included the newest publications in his considerations.

Heise/Herbst 1920

The *"Lehrbuch der Bergbaukunde" (Text book on Mining Engineering)* by Heise and Herbst, which is well known in Germany and abroad, does not mention the seismic method in its 4th edition, completed in September 1920, while the magnetic and electric methods of prospecting are mentioned. In contrast to this the 5th edition, published in 1923, contains a remark referring to the seismic method.

Mainka 1919

On December 15th, 1919, Professor Mainka wrote in the *"Physikalische Zeitschrift"* a paper on: *„Angle of emergence of seismic rays and Poisson's constant in the uppermost layers of the earth"*; which reads in part: "From laboratory experiments and from the ratio of longitudinal and transverse waves approximate values for T (Poisson's constant) are known which are in the neighbourhood of 0.26. In any case T will depend upon the geological condition of the subsurface of the upper layers of the earth, at the locality of observation." "According to the experiences gathered up to now all ground movements of artificial or seismic nature seem to have a vertical component, in so far as concussions of short period are concerned. In experimenting with artificial concussions (tests with falling weights and detonations) on rock ground of uniform type the experiment should be made to determine *Vlong* and *Vtrans* as the elastic properties of different rocks could then be determined with the dynamic method. According to the above, purely seismic observations could then be used for purposes of physics".

At the time of the application for the Mintrop patent, Professor Mainka still discussed the possibility to determine the velocities of longitudinal and transverse waves on rock ground of uniform type in case of artificial concussions, in order to determine the physical constants of various rock types, whereas Mintrop had not only already measured these velocities, but had made a technical use of them by determining the various underground formations of the subsurface.

Mintrop's patent application is dated December 7th, 1919, it was made accessible to the public in November 1920; however, *Mintrop read a public lecture on his method on August 15th, 1920, before the Main Meeting of the German Geological Society.* It is therefore quite instructive to review the publications of experts before and after the publication of the method, that is before the 15th of August 1920 and after such date.

Ambronn 1920

On April 30th, 1920, Dr. Richard Ambronn, later on Director of the Erda G. m. b. H. and Erda A. G. respectively (Corporation for the physical exploration of the earth) wrote a paper in the "*Zeitschrift der Bauingenieure*" *(Journal of construction engineers),* under the title "*The investigation of the subsurface by means of physical measurements*". In this paper the seismic exploration of the subsurface was not mentioned, though it appears obvious, that this method deserves first consideration for the judging of the construction ground, because it permits to determine the elasticity of the underground layers.

Mainka 1920

In August 1920 Professor Mainka wrote the following in his pamphlet "*Short demonstration of the necessity of the erection of a seismograph station in the Upper-Silesian Industrial District*":

"In the course of the last two decades it has repeatedly been pointed out in the publications of the mining and metallurgical industry, that it is necessary to accurately and continuously observe the various ground movements occurring in the mining and metallurgical districts, as well as to introduce the recording of distant and local earthquakes, or of the elastic waves radiating from them. The publications coming from the practical field therefore show that in such areas the presence of such a place of observation — seismograph station or geophysical observatory — is required for practical as well as for scientific reasons. Such an establishment is certainly not a superfluous one, the results of which are coveted only by a limited number of persons. In such areas, the scientist, the mining engineer and the industrial producer are very much interested in the records mentioned.

Naturally the instruments must be correctly constructed and set up, and they must daily be controlled by an expert. If such an establishment is not to become illusory in its results, then certainly the discussion and interpretation of the records can only be entrusted to an expert scientist trained in this work, and cannot be given to somebody who for certain reasons made himself familiar with such observations only shortly before.

As will be seen from the above lines, not only mining and industrial, but scientific points of view have to be considered, which however are all closely interconnected. Without claiming a complete listing, some departments shall be referred to here. Detonations in shafts, sudden rock slides in mines, cave-ins, subsidences, engine and steam hammer works and still other causes of mining or industrial origin cause movements of the ground which may be large enough to endanger structures above or below the surface. But not every movement of the ground is damaging in its effect. Sometimes certain plants are unjustly made responsible for damages the cause of which must be looked for in quite another place. A safe collection of evidence, however, can only be made by an expert by means of apparatus similar to seismographs, more or less sensitive, according to the specific purposes.

Very slowly progressing inclinations, which are often a consequence of subsidences, can also be determined by means of instruments. This will be quite welcome in many cases.

Other useful investigations can also be made by means of instruments which are similar to the seismograph. For instance, the oscillations of a chimney 160 m high, caused by the wind, were investigated recently. Investigations of bridges and running rail road cars also belong to this department, and the oscillations of engine foundations and of the supporting ground must not be forgotten either.

The short-periodic shock-like concussions, caused by daily traffic, especially on bad roads, very much influence the buildings located on traffic bearing roads. In mining and industrial areas more attention should be paid to these ground oscillations, by means of suitable observation.

The elastic movements released by an earthquake in the interior of the earth's crust propagate through the layers of the earth and along the surface and cause movements of the ground, the amplitudes and periods of which depend, among other causes, on the distance and bring about corresponding accelerations. Mining interests especially pointed at the effect of such movements on mining. It has to be borne in mind here that the effect does not have to take place immediately, but may do so some time later. Special consideration must be given to natural earthquakes that have occurred in mining areas or their vicinity; and the case may have happened that strong artificial concussions occurred nearly simultaneously, damages being then attributed to the latter which were actually due to the former. In such cases the claim question comes up and the establishment of a seismic observatory would be of great use and importance.

Observations which are coincidently made in the mine, and in the seismic observatory above, are of special interest. The results of such comparative measurements may also be of advantage to the practical man.

Due to meteorological actions seismic movements often occur, which last some time, though their presence can only be indicated by instruments. This is the so called microseismic agitation. This also has received attention by the mining industry, as many events, for instance choke damp and sudden rock slides are said to be connected with it. So far the interrelation has not been thoroughly dealt with. Regular indisputable observations at a seismic observatory in the mining district and their correct interpretation should furnish the foundation for further researches in this direction.

In this case, as well as with regard to the registrations of the earthquakes, the graphical records of other observatories outside the Upper Silesian Mining District must be used for comparison; though special attention must be paid to the correct and unobjectionable working of the instruments of such observatories.

The seismic observatory can also undertake other measurements which are useful for the Upper Silesian Mining District, for instance meteorological observations and those on terrestrial magnetism, without first requiring a greater number of observers.

In Bochum and Aix-la-Chapelle there exist such seismic observatories which do not only serve scientific interests, but just as much those of the mining and industrial plants.

As will have been seen, the program of a seismic observatory in the Upper Silesian Mining District is very comprehensive and will certainly be of great use".

Mainka lists everything in this memorandum that could conceivably be done by a seismic observatory in a mining district. However, the most important field of action, that is, the exploration of strata and mineral deposits, is not mentioned at all by Mainka. The reason for this is that Mainka did not know the method at that time, in August 1920. The application for the Mintrop patent was not yet publicly displayed.

On August 15th, 1920, at the occasion of the main meeting of the German Geological Society, Mintrop, in a lecture with photographic slides, reported in detail on his method: *"Determination of the structure of geological formations by means of seismic observations."* Mintrop 1920

In his lecture Mintrop showed the following photographic slides:

1) Horizontal component seismograph by Wiechert (1200 kg pendulum).
2) Seismogram of a natural earthquake in a distance of 2500 km.
3) Time-distance graphs of natural earthquakes.
4) Path of the first forerunner (longitudinal) under the assumption of a homogeneous and of a heterogeneous interior of the earth.
5) Different wave forms in the earth, longitudinal, transverse and surface waves.
6) Paths of the first forerunners up to a focal distance of 5400 km and 10 000 km.
7) Schematic sketch of the operation of the Mintrop pendulum D. R. P. 303 344.
8) Cross section and perspective view of the Mintrop pendulum.
9) Photographic recorder of Mintrop, in perspective view, opened.
10) Field seismograph consisting of pendulum and photographic recorder, in opened tent.
11) Field seismograph on transport (2 men carrying the apparatus).
12) Seismograms of an artificial earthquake caused by a falling weight in a distance of 1300 m.
13) Seismograms of artificial earthquakes caused by falling weights in distances of 1300, 1600 and 2000 m.
14) Apparatus for the transmission of time by means of electric current.
15) Seismogram with forerunner of an artificial earthquake caused by a detonation.

16) Complete seismogram of an artificial earthquake produced by a detonation at a distance of 900 m.
17) Time-distance curve in diluvial sand.
18) Time-distance curve in tertiary clay.
19) Time-distance curves in diluvial sand and tertiary clay, compared.
20) Time-distance curve in triassic sandstone (Buntsandstein).
21) Time-distance curve in rock salt.
22) Time-distance curves in tertiary and rock salt, drawn on one slide.
23) Path of the rays of concussion in diluvial sand and tertiary clay, shown in contrast to each other.
24) Path of the rays of concussion in tertiary clay, in Buntsandstein, and in rock salt, comparatively demonstrated.
25) Ground-plan and profile of a salt-dome.
26) Determination of a buried salt dome.
27) Time-distance curve with at first increasing and then decreasing velocity.
28) Time-distance curve with abrupt changes in velocity.
29) Time-distance curve with at first increasing and then decreasing velocity, as well as with abrupt changes in velocity.
30) Path of the rays of concussion in a buried saltdome.
31) Path of the rays of concussion in the case of at first increasing, then decreasing velocity.

A short abstract from this lecture is published in the *Zeitschrift der Deutschen Geologischen Gesellschaft (Journal of the German Geological Society), Vol. 72, 1920.* The lecture caused an extraordinary sensation. Unfortunately no minutes of the discussion are kept at the main meetings of the German Geological Society, but it can be taken from the newspapers of those days and from the well known Mining and Metallurgical Journal "Glückauf" that the lecture actually brought something new. *"Glückauf", on August 18, 1920,* brought the following lines by Privy Councillor Keilhack, of the Prussian Geological Survey: "Then Dr. Mintrop (Bochum) read an extraordinary interesting lecture on the determination of the tectonics of geological formations from seismic observations. Beginning with the theory of seismic waves in the interior of the earth as it had been developed by Wiechert especially, the lecturer explained a method developed by him, which renders it possible with simple means to draw conclusions from the records of tremor waves produced by small detonations at the surface, on the type and structure of the formations in the depth. According to the entire design of the method and the results already attained it can be accepted that a valuable aid for the search for and investigation of mineral deposits has been gained".

The *"Hannoverscher Kurier" (newspaper), August 16th, 1920* reports on the geologist's meeting, in part: "Then followed what we consider the most interesting lecture of the meeting, read by Mr. Mintrop (Bochum) on the determination of the tectonics of formations from observations of earth concussions. In the researches of A. Schmidt and Wiechert the natural earthquake waves had already been used for the exploration of the interior of the earth. — Professor Salomon (University of Heidelberg) said that much is expected of this new method. The representative of a mining company said that he had seen the experiments in the field, adding that the results were still more astonishing than had been said in the lecture. If the method would be further developed it would certainly bring surprises. Professor Pompecki (University of Berlin, at that time president of the German

Geological Society) reported that he witnessed the first experiments in Göttingen, he could not but offer his sincerest congratulations to the inventor for his successes in the field".

Soon after the first public lecture of Mintrop on his method the Physikalische Werkstätten A. G. in Göttingen – active in the field of exploration of the subsurface — wrote the following letter to Dr. Mintrop, dated September 13th, 1920: Ambronn, Leimbach 1920

Dr. L. Mintrop, Hannover.

Dear Sir:— Please find enclosed a letter which was delivered to us due to incorrect address. We kindly beg you to excuse that it was not given to the mails earlier. This was due to the absence of Dr. Ambronn on an exploration trip.

We take this opportunity to inform you that we were very much interested in your expositions at the meeting of the Geological Society in Hannover, which were brought to our notice, regretting that none of our representatives could attend there. We would be very pleased to occasionally hear directly on the progress of your work, because, in view of the great extension which the application of our methods has taken in the present year, we would frequently have an opportunity to recommend the application of your method, or to work out clearer, by a suitable combination of preferably different methods, the geologic conditions which are often difficult to analyze, especially in the finding of rock salt potash domes. Due to the great extension which our work has gained in consequence of the introduction of several new physical methods of exploration which are very efficient, we are just now transforming the former department for the exploration of the earth of the Physikalische Werkstätten, Aktiengesellschaft, into a separate company which is to be equipped with very considerable funds, in order to embrace the application of the physical methods in as great a number as possible, methods which will be of very great importance for the solution of problems which are becoming more and more difficult. By suitable combination of the methods to be applied in each individual case their value will be even more increased. As physical methods of prospection will always remain an indirect course only for the finding of such objects as the mining engineer is interested in, the treatment of a problem from different approaches by the combination of several independent methods will, in our opinion, be connected with an especially great promotion of the knowledge to be gained. Physikalische Werkstätten (signed: Dr. Leimbach, Dr. Ambronn)".

On May 21st, 1921, Dr. R. Ambronn, Göttingen, wrote the following on the use of elastic waves, in his paper *"Physical methods of exploration as an aid to geological research"*, in the *Mining and Metallurgical Journal "Glückauf"*: "From observations of the path of earthquake waves it has for a long time been known that the waves propagate in the rocks with different velocities according to their elasticity. From phenomena observed on the occasion of great earthquakes the existence of a core of the earth was followed, which is sharply defined against the shell, and the elasticity of which may be compared to that of steel. Following a proposition of von dem Borne these determinations of elasticity are applied to smaller proportions by means of artificial elastic waves and from the velocity of propagation of artificial earthquake waves — produced by Mintrop by means of the falling of heavy masses, or by means of dynamite explosions which were already extensively used for this purpose formerly — conclusions are drawn on the distribution of elasticity and thereby, on the tectonics of deeper layers. Ambronn 1921

Extremely sensitive autorecording seismometers of various design may be used as recording apparatus for the concussion waves".

It may be added to Ambronn's account of the development of the seismic method that the Erda G. m. b. H. for the Exploration of the Interior of the Earth, founded in the meantime, and headed by Dr. Ambronn, had lodged a protest against the taking out of the Mintrop patent.

Seismos 1921

In cooperation with Phoenix, A. G. for Mining and Metallurgical Works in Hoerde, now Düsseldorf, Gelsenkirchener Bergwerks A. G. in Gelsenkirchen (now Essen-Ruhr), Deutsch-Luxemburgische Bergwerks- und Hütten A. G. in Bochum (now taken over by the Gelsenkirchener A. G.), Eisen- and Stahlwerk Hoesch in Dortmund, Rheinische Stahlwerke A. G. in Duisburg-Meiderich (now in Essen-Ruhr), Mintrop, for the purpose of economic exploitation, on April 4, 1921 founded the Seismos, Limited, for the Exploration of Geological Strata and Mineral Deposits, in Hannover. This is the first company in the world to organize for the purpose of the application of the seismic method. From the fact that the move to this foundation came from the largest German mining concerns, with concerns of international interests endeavouring to obtain the method simultaneously, conclusions can be drawn on the originality and on the economic value of the Mintrop Method.

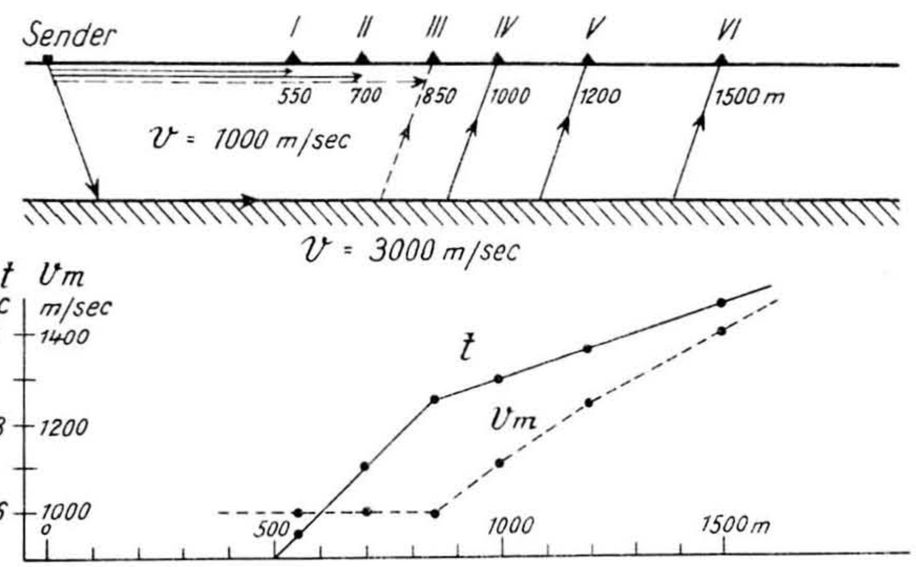
After the great economic advantage of the method was proven, other geophysical companies sprang up in Germany and abroad, who made use of the method. The success of Mintrop has also been the cause for the inclusion of "practical seismology" into the research and teaching curriculum of the respective scientific institutes and professorial chairs, as was mentioned by Wiechert and others, l. c. Since the publication of the Mintrop Method a new period of development of applied seismology has started.

Ambronn 1921

In the June number (No. 12), 1921, of the review "Kali" Dr. R. Ambronn, Göttingen, among other things, said the following on the seismic method in his paper: *"On the use of physical methods of investigation for prospecting in potash mines"*. "The difference in elasticity and consequently also in the amount of sound velocity of hard salt against the frequently much softer sand and clay beds of the younger formations is often very considerable, especially where the salt penetrated the harder sandstones and limestones of the trias and where a cap rock was formed from the debris of younger rocks, gypsum and so on. This difference is used by the Mintrop method *(L. Mintrop, Determination of the tectonics of geological formations from seismic observations, lecture read at the 59th main meeting of the German Geological Society, "Glückauf", 1920, p. 752)*, following a suggestion of von dem Borne *(Von dem Borne, the physical foundations of tectonic theories, Beiträge zur Geophysik IX, page 403, 1908)* by drawing conclusions on the distribution of elasticity from the character and the type of propagation of artificial earthquake waves underground, caused by dynamite explosions which are in use for this purpose (compare *Fouqué and Lévy, Expériences sur la vitesse de propagation des secousses dans les sols divers. Memoires de l'Académie des sciences de France, Tome XXX, 2, Paris, 1889, II. page 57—77). (Experiments on the velocity of propagation of concussions in various kinds of ground).* Mintrop's conclusions are drawn in just the same way which Wiechert and Zoeppritz *(Wiechert und Zoeppritz: On earthquake waves, Göttinger Nachrichten 1907, page 533 and following)*, used for the determination of the distribution of rigidity in the whole globe, that is, by means of a discussion of the propagation of the waves emanating from strong natural earthquakes. Thus the existence and the approximate depth of salt bodies can be ascertained, in case it is known geologically that the hard layers cannot consist of sandstones, limestone banks or heavily calcified or silicated sands".

In this article Ambronn justly traces the method back to the researches of Wiechert and Zoeppritz, without however having understood the essential points of the Wiechert method. This follows from Ambronn's exposition on *"The application of physical methods of exploration to mining engineering, underground workings and hydraulic engineering"* a lecture at a meeting of the members of the *"Association for the Exploration and Utilisation of Central German subsurface deposits", Halle, Province of Saxony,* on March 19th, 1921, issued in print 1922. Ambronn explains the propagation of elastic waves in a loose overlayer and in the harder underlying formation in the following way, in which case the loose formation would correspond to the shell of the earth, while the hard formation would correspond to the core of the earth: "The energy which closely clings to the elastic medium arrives at the receiver quicker than the one which remained in the upper layer. If with each consecutive test the distance between sender and receiver is increased, as indicated in the illustration for points I and II, and if further the distance is divided by the running time of the energy wave as measured in each individual case, whereby an average velocity of propagation of the elastic waves in the intermediate medium is obtained, the latter remains constant and dependent upon the distance, just as long as the energy which first arrives runs only in the upper layer.

Receiving stations.



Just as soon, however, as the circuitous route through the layer of greater velocity of propagation is more quickly traversed than the direct route, the average wave velocity as above calculated, increases abruptly, until, when the distance between the stations is very great compared with the thickness of the top layers, it approaches the sound velocity in the lower harder medium, as the short stretches from the stations through the softer overlayer to the lower layer can be neglected towards the long way in the hard underlying rocks." Ambronn then brings a numerical example, assuming that the velocity of the elastic waves in the soft overlayer amounts to 1000 m/sec, in the hard underlayer to 3000 m/sec and that the upper layer has a thickness of 300 m. Ambronn then remarks: "At a distance of 10 km between the stations the average velocity would be calculated to be 2570 m/sec, that is, it would already approach the value of 3000 m/sec assumed as characteristic for the deep rocks". The fact that the velocity of propagation of elastic waves in a certain area depends upon the distance of sender and receiver carries as a consequence that a layer of different elasticity must exist under the superficial cover of the surface, if the surface layer does not change its structure between these points. If the sound velocities in the layers are already known from preliminary geological work, then the depth of the interface can be calculated. It is evident that these conditions do already essentially limit the applicability of the method."

With these remarks, which, in 1922, were in all essential points repeated in the *"Zeitschrift für angewandte Geophysik" (Journal of applied geophysics)* Ambronn, who had not yet occupied himself with seismology, proved that he did not understand the essential features of a time-distance graph. For instance, he drew the part of the time-distance curve representing the deep formation as a straight line, and then he calculated the average velocity *Vm* instead of using the velocity given by the time-distance curve itself. Consequently he gained the above mentioned wrong conception on the very limited applicability of the method. The knowledge of the essential features of the time-distance curve is a preliminary condition to the understanding of Mintrop's patent description and can be expected from every expert.

Mainka 1921 In March/April 1921 Professor Mainka wrote an extensive article in the review *"Kohle und Erz" (Transl. Coal and Ore)* on *"Some chapters on seismology, with its relations to mining and industrial work."* Though Mainka discussed in detail the methods of seismology, especially the time-distance graphs, in this article, he did not mention the possibility to use these methods of scientific seismology for mining purposes.

On page 154 of this publication Mainka wrote: "In explosions, which in some regards form also a part of this (i. e., disturbing concussions) a distinction must be made between effects of the explosion wave and actual concussions of the ground. We are only interested in the latter ones here. Again nothing is known about how far such concussions penetrate into the depths. Information about this would be valuable in some problems."

It follows that Mainka did not know the seismic method for the exploration of geological formations and mineral deposits at that time. This also follows from his letter to Mintrop, dated August 3rd, 1921. His letter reads: "When I was asked at that time regarding your plans, I reserved my opinion, as I do not know any details about these, and as I do not have experiences of my own which would enable me to form my own objective judgment. Could'nt you write me about the working procedure of your method in more than 2 or 3 lines? Everything is covered by patent, that conforms to modern usage. I am thinking of the possibility to obtain a representation in Silesia, Upper-Silesia and, if you agree, in the Polish Industrial District, which is larger than our own. What about the protection of your matter abroad? You cannot do anything against an exploitation of your idea there, I guess, you know that, be it that you have other tricks. It would be necessary for me to get acquainted with your method in order to be able to represent it."

Notwithstanding that Mainka emphasized in this letter that he did not yet know the Mintrop Method in August 1921, he doubted the method in his expositions in *"Kohle und Erz" (Coal and Ore), Dec. 5th, 1921.* Here he wrote:

"The artificial concussions, as we are going to call them in order to define their origin, have a very short period, their amplitudes decrease with the distance. It still appears necessary to carry out suitable investigations, free from objections, on the exact amount of their velocity of propagation. Other questions of a pure physical nature have also to be answered with a higher degree of certainty, questions which are also of interest for the practical man, on the type of the waves, whether dilatational or torsional, calculation of the elastic constants of the material forming the construction ground by this, i. e., the dynamical method". "In the case of explosions, which in certain respects belong to this department, there must be distinguished between effects of the explosion wave, and the actual concussions of the ground. Only the latter ones are of interest here. Also, in the case of these ground concussions nothing is known about how far they penetrate into the depth, which, however, would be valuable to know for a good many questions. Concluding, two possibilities of using seismometers shall be touched. It has already been reported above on the use of ground oscillations, caused by artificial concussions, detonations, explosions on and below the surface, for the determination of the physical properties of the ground. In case of explosions on the surface or especially under the surface we can also think of an exploration of the layers located between place of explosion (sending station) and place of apparatus (receiving station). An analogous case is found in potash mining, with physical exploration methods for the determination whether lye or water is adjacent to the workings, by means of electric waves and oscillations. In our case where elastic oscillations are to be used experiments must still be made in order to become acquainted with the accuracy of these methods. Not every theoretically possible experiment is applicable to practice. It would be good to be more careful in this respect, especially in recent times."

The comparison between the use of electric and elastic waves is quite interesting here, the use of the former ones being considered as fully developed, while the latter were still considered to be in an experimental stage, so that caution was recommended.

In spite of these doubts regarding the applicability of the Mintrop Method, or its usefulness, *Professor Mainka rendered an extensive professional opinion on "Is the application of Dr. L. Mintrop, method for the determination of the tectonics of geological formations, qualified to be patented?"* under date of November 25th, 1921, in a patent fight brought up by the "Erda" against Mintrop. Even in this professional opinion, which represented the method as being known a long time, Mainka doubted that the method could actually be carried out, by writing: "The use of artificially produced elastic waves for the mapping of the tectonic structure of the earth's crust in major and minor scale is not without doubts and difficulties. Dr. Mintrop does not seem to find any adverse features in the application of artificial seismic waves. In general, one does not think so. For that reason recourse has been taken for the geological exploration of smaller areas to those elastic waves which are, so to say, produced the natural way, i. e., seismic waves."

"Once more examining the possibility that Mintrop's application might be qualified for patent", Mainka continues, "the result is obtained that it is not the application of artificially produced elastic waves, nor the possibility to study the stratification of the earth's crust by means of other geological knowledge, but the method to discover discontinuities of some kind in the earth's crust by means of the time-distance graph. This working procedure, however, is taken from seismology, as will be seen from Wiechert's work ("Earthquake waves"), already cited by Mr. H. Wagner who is protesting against the application. Also, with regard to the application of artificial waves, experiments have already been made prior to Mintrop with several (nine) receiving stations, as cited above; however, the construction of time-distance graphs based on the time-data directly furnished by the individual instruments was not mentioned.

The qualification for patent of Mintrop's claim is at the best a very restricted one, based on this line of thought, which goes a long way to meet him, a qualification that refers solely to the application of time-distance curves (time curves, hodographs). According to this, Dr. Mintrop would have to change somewhat the wording of his patent claim".

Mainka, Patent-application 1921

It follows that Professor Mainka had fully understood the essential features of the Mintrop patent in November 1921. Nevertheless he hesitated to apply it in practice. A clearer acknowledgment of the newness of the method than by Mainka's own expositions is hardly conceivable.

Four days before Mainka rendered the above professional opinion the *application No. E 27 359/42 1 was submitted to the German Patent Office*, referring to: *"Method for the determination of the three dimensional distribution of the elastic properties in the uppermost layers of the earth"*. The application was filed by the Erda A. G. and Prof. Mainka, the latter in his capacity as inventor. The patent claim runs:

"Method for the determination of the distribution according to three dimensions of the elastic properties in the uppermost layers of the earth, by means of artificially produced elastic waves, the elastic waves, expanding into three dimensions from the place of agitation, being recorded in one or more places of observation by ~~one or more~~ suitable receiving instruments, characterized in such a way that from the records of the components of displacement of the ground particles measured in three directions preferably perpendicular to one another, at the place of reception, or places of reception respectively, the corresponding angles of incidence of the wave rays are calculated."

The description of this claim reads: "An elastic wave artificially generated in or below the surface propagates, similar to the elastic waves created by earthquakes, into all directions in the subsurface. From the distribution of the wave rays in space, especially from the angle of incidence of the rays at several points of reception, a conclusion can then be drawn on the distribution of elastic properties, according to three coordinates, in the subsurface. Instead of emitting elastic waves only in one place, observations can be combined with one another which are made on waves which have been emitted from different points suitably distributed. By such a procedure all time measurements whatsoever are avoided, requiring neither the time of beginning of the disturbance, or of the disturbances, nor the time differences between the begin of the disturbance, or of the disturbances, and the time of arrival at the place of observation. For the reception of the waves and for the determination of (their) position in space apparatus are necessary which resemble seismographs, allowing to measure the displacements of the ground occurring in the direction of the wave rays at the place of observation. Such apparatus which allows to determine quantitatively the direction and the amount of the ground displacements, consists of preferably uniformly constructed individual instruments receiving one each of the linear components of the ground displacement, which are preferably selected in three directions perpendicular to each other. As directions for the three components there are suitably chosen the NS, the EW and the vertical component of the ground movement, which are then recorded by the three instruments in proportion to their true amounts. From the amplitudes of the ground displacements so obtained at the individual instruments the different angles of incidence for the various points to be examined then result according to known rules of calculation. The quantities called angles of apparent emergence in seismology are then deduced from these, without any measurements whatsoever of time quantities having been necessary. From the distribution in space of these angles of emergence there can then be concluded at once on the distribution of elastic properties in the subsurface."

The Reich Patent Office rejected this application in its pre-examination procedure, in view of the application of the Mintrop patent No. 371 963, two years older. The Erda was successful in protesting against this rejection, as the following decision of the department for appeals of the Patent Office shows, dated October 9th, 1924: Reasons for the decision: Subject of Patent No. 371 963 is a method for the determination of the tectonics of the upper layers of the earth, based on the measurement of the velocity with which elastic waves propagate in these layers. The arrival of the series of waves is recorded at the place of observation by means of seismometers, and from the time-distance curves obtained conclusions are drawn on changes in the elastic properties of the formations passed through and on deflections, refractions and reflections of the waves at interfaces of various layers traversed by them. The applicant has found out that important conclusions can be drawn on the structure of formations encountered by the waves, not only from the velocity of propagation of elastic waves in the subsurface, but also, independently, from the deflection of the waves from the straight direction. For this purpose, according to the invention, the displacement of the ground particle is measured in three directions orthogonal to each other by means of suitable instruments, and from these data the angle of incidence of the wave rays is calculated. This method is neither the subject of Patent No. 371 963, nor is it described in the American Patent Description 1 240 328 (Fessenden), nor in the review "Glückauf" of the years 1920 and 1921, nor has it been mentioned elsewhere. In all these cases the use of velocities of propagation of artificially produced waves for the purpose mentioned is dealt with. The objections raised in the decisions of March 2nd, 1923 and April 19th, 1923 have to be supported in so far, that the method claimed was not sufficiently described in the first papers submitted. The extensive delineation of the method contained in the description received here on July 5th, 1923, however corrected this deficiency, without changing the features of the invention announced, which were already discernible to the expert from the first papers submitted. According to paragraph 20 of the Patent Law the invention was already made known on November 22nd, 1921, from which such day follows as the day of announcement."

Mainka, Patent-application 1922

On October 30th, 1922, the Erda A. G. filed a *patent application* for another seismic method worked out by Professor Mainka, *under No. E 28 652/42.* The claims of the latter are:

1) Method for the determination of discontinuities in those portions of the earth's crust which are close to the surface, characterized in such a way, that displacements of the ground of a periodic or unperiodic nature are simultaneously artificially generated at two places, thus influencing simple receiving instruments, located on the lines that perpendicularly bisect the connecting line of the places where the disturbances occur, which are then suitably observed.

2) Method according to claim No. 1, characterized in such a way, that the receiving instruments are aligned on both sides of the prolongation of the line connecting the localities of disturbance, and allow a determination of the disturbances arriving.

3) Method according to 1 and 2, characterized in such a way that the instruments are located at will, but in such a manner that to each observation point another one is coordinated symmetrical to the line perpendicularly bisecting the connecting line and another one symmetrical to the connecting line, and that both can simultaneously or successively be adapted for the observation of the disturbances arriving."

The introduction to the description of these claims reads: "For the finding of discontinuities in the uppermost crust of the earth various working procedures have been selected in recent times, which, for instance, are commercially used for the determination of deposits in the ground, that is, for example, for the location of deposits of ores of any kind in ordinary layers, faults which contain water and the location of which is therefore important for fresh water supply, coal deposits in otherwise sterile areas and so on. For such determinations, ground movements i. a. were generated at certain points in the field, for instance by detonations, the time of arrival of which was observed at points located farther away, equipped with suitable receiving instruments, vibration meters, or similar apparatus. From time observations of this kind a time-distance curve was then constructed, from the further interpretation of which the indications for the location of the discontinuities in the earth's crust were obtained. However, the interpretation of the time-distance graph is connected with many troublesome and uncertain details, and in addition to this the exact arrival of the disturbance must be observed at the place of disturbance. The points raised against such a procedure and especially the use of a time-distance graph shall be eliminated by the new method which introduces an advantageous working procedure. Just as the application of the time-distance curve is taken from the physics of earthquake waves, so the time difference method applied below is taken from the same branch of science."

In this application of Erda-Mainka the statement is quite remarkable that the time-distance curve method has been introduced "in recent times", though connected with troublesome details and uncertainties, and that it is therefore objectionable. Mainka's statement in the present patent dispute, that the Mintrop Method had already been known 25 years ago, does not conform with his own exposition in his own patent application.

Against this patent application the Seismos G. m. b. H. in Hannover appealed for the reason that the subject of the application had already been previously submitted as Mintrop Patent No. 371 963, and for the further reason that the application in question refers to the use of abstract geometrical rules for an individual case, a matter that is not qualified for patent. Apart from the Seismos Company, the "Gesellschaft für praktische Geophysik", (Practical Geophysics, Limited), Freiburg, had lodged an appeal against the application of the Erda claiming that her own previously submitted application K 80 369 IX/ 42 1 contain claims, equivalent to those of the Erda. The Pre-Examiner rejected both appeals and granted a patent on the application of the Erda. The protest lodged by the Seismos Company against this decision was not carried out.

In the "Zeitschrift für Geophysik", 1926, page 141, Professor Mainka wrote that the above mentioned patent applications of the Erda A.G. "cover everything outside the time-distance curve."

While the group Ambronn-Mainka on one side tried to have the Mintrop patent application cancelled, it endeavoured on the other hand to obtain patents in the same branch, to be safe in all cases. In the meantime the work of Mintrop and his priority were generally recognized in the professional papers.

Wiechert himself, to whom the credit for the seismic method for the exploration of the interior of the earth goes, even according to the statement of Mainka, Gutenberg and others, said the following in a meeting of the *Committee on Ores of the "Verein Deutscher Eisenhüttenleute" (German Metallurgical Association), on December 15th, 1921* (see report in the review *"Stahl und Eisen")*, speaking after lectures of Dipl.-Bergingenieur Gornick on the torsion balance and of Dr. Mintrop on the seismic method: Wiechert 1921

"For 25 years I have occupied myself with the application of physics on the exploration of the interior of the earth. During this time two methods were used in my researches, one using gravity and one using seismology. I was using the same phenomena which are now used by technology! Strange to say, it was a much easier problem to ascertain the conditions of the earth at great depth. But now the physics of the earth, which I represent, must give its consideration to the crust. We are preparing to investigate the crust from our point of view. You see, to what a high degree our science is interested in the researches which are made here. It would indeed be our greatest joy if those methods which we have partly prepared and partly executed for the aims of pure science and which we applied to the physics of the earth, could now be put to the use of technology. That would be a new justification of our researches. In the reverse order it is quite safe to assume that the results of the gentlemen from technology will be of great value for our scientific researches. I am speaking of matters which are just as important for science as for technology. I would be more than glad if technology would continue to work in this direction and if a little of that which we created would be of use for technology.

I would like to say one more thing: Both methods, the one using gravity and the one using seismology, have their advantages and their disadvantages, both can be applied. I may be allowed to compare seismology with the application of X rays. The X rays made our body transparent, they show its bones, tissues, and foreign bodies. Seismology is qualified to make the body of the earth transparent. It has already now been made possible to look through the depths of the earth. I hope that it may be equally possible to obtain a detailed view of the crust with earthquake rays."

From these remarks of Wiechert in 1921 it can be seen that he did not think of the Mintrop Method in 1907 when publishing the book *"On earthquake waves"*. As will be seen from the exposition of Zoeppritz on page 22 the method was considered to be far out of reach of technical possibilities at that time. Zoeppritz even welcomes the so caused simplification in the construction of the time-distance graph, as at least the major features of the structure of the earth could now be deduced.

The construction of the time-distance graph at places where the succession, depth, and thickness of the various layers is accurately known, as this can be attained by observing artificially generated concussions in areas known to geology and mining engineering, gives a firm foundation to the theory of the propagation of the earthquake waves. Such a foundation is found lacking in the theories advanced by A. Schmidt, Rudski, Benndorf, Wiechert and various others, as it is not possible to explore the actual structure of the deeper interior of the earth by means of wells and shafts, which would give immediate information. The experimental check is lacking in the theory of earthquake waves. Mintrop for the first time applied the theory to a succession of layers known to geology and mining engineering and so made a check possible. That such a check is absolutely necessary follows most clearly from the dissenting results obtained by a great many scientists in the construction and interpretation of the time-distance curves of natural earthquakes. Schmidt already regretted in his paper in 1888 on *"Wave movement and earthquakes"* that the law of increase in velocity with the depth was not known. Wiechert and Zoeppritz in 1907 determined the depth of the core of the earth under the outer shell to 1500 km, while two years later Zoeppritz and Geiger assumed a first surface of discontinuity in a depth of only 1200 km, with a second surface of discontinuity following in a depth of 2900 km. Another two less pronounced surfaces of discontinuity were said to occur in a depth of 1700 km and 2450 km. The idea of a bipartite earth of 1907 had already been changed, two years later, to a tri- or quadripartite earth respectively. What is right now? The application of Wiechert's theories on formations known to geology and mining engineering enables pure science to check these theories, as may be seen from the many scientific papers which followed after the publication of Mintrop's researches. To say that these researches have caused a revival of the entire science of seismology is not claiming to much. Mintrop's method, apart from bringing great engineering and economic progress, has also brought great profit to pure science, which is pointed out by many authors.

Baum 1921

The economic importance of a method that does not need any bore holes also follows from the remarks of Bergassessor Baum, president of the Committee on Ores of the German Metallurgical Association, at the meeting in Düsseldorf on December 15th, 1921 *(also see report in the review "Stahl und Eisen" ("Steel and Iron")*. He said: "May I add to the remarks of Mining Councillor Bartsch that the exploration of the overlying formations caused great expenses to all companies who own mines on the left bank of the Rhine. The great number of borings which had to be made by these companies in order to arrive at an unobjectionable decision about where to sink shafts, caused very great expenses. Not until quite recently we found out that for instance my company, which sunk about 20 wells on the left bank of the Rhine in order to obtain information for the selection of one shaft site, would only have to use about one hundredths of the expenses by employing the methods which have just been explained by the lecturers."

The reporter for geophysical methods of prospecting at the Prussian Geological Survey, District-Geologist Dr. H. Reich, wrote the following concerning the Mintrop Method: in the *Annual Review of the Survey, 1921*, in his *"Attempt at an application of seismometry on geology"*: Reich 1921

"Not only for these problems which are of more scientific interest but also for practical work, a combination of geological and geophysical methods has great importance. For such short stretches which we are concerned with in practice, artificial earthquakes can be produced by means of detonations, as Mintrop showed, and seismometric determinations can be applied to these. Here also we are at a very promising beginning. It is only necessary to imagine what prospects, for instance, are opened for our North-German Plain. Geology and geophysics combined will some day solve its enigmas and open its mineral deposits."

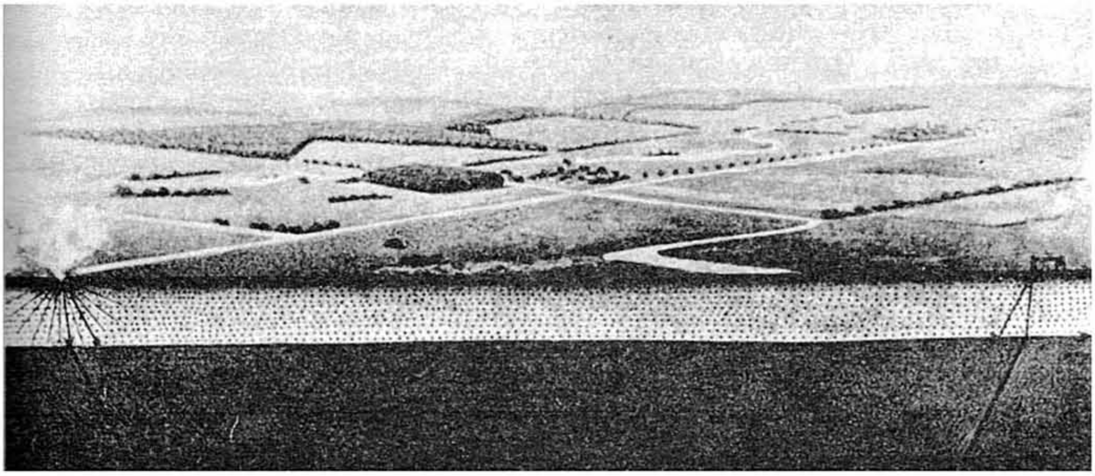
In the *Publications of the R. Academy of Sciences of Göttingen, Department of Mathematics and Physics, 1921*, Reich published a paper on *"The intensity of the main phase of an earthquake in its relation to tectonics"*, the concluding words of which are: „The further development of these seismometrical and geological methods promises great advantage to both the geophysicist and geologist. The geophysicist will more and more approach the problem of elastic ground waves considering geological details, and the geologist will receive information on areas which would always remain hidden to him, be it that they are covered by the sea, or that they are covered up with recent formations; he will also be able to express in exact physical terms such important theoretical conceptions as quantitative figures etc. Finally these things are also of great practical value, as Mintrop's experiments with artificial tremors prove (see Mintrop's lecture at the meeting of the German Geological Society, 1920)."

In the review *"Stahl und Eisen", April 21st, 1921*, Reich wrote on *"Elastic ground waves as an aid in the search for mineral deposits"*:

"It has for a long time been known that the distribution of intensity of an earthquake depends very much on the geological qualities of the subsoil. With great advantage to geology, observations on the intensity of the occurrence of individual earthquakes in various places were therefore gathered and made use of, especially in areas which are frequently disturbed by earthquakes. As only estimates (macroseismic methods) are concerned here, the dependence of the distribution of intensity from geological conditions could only be ascertained in its major features. Details which are important for mining could not be found out. The possibility to do this exists only since instrumental registrations of earthquakes (seismograms) are organized in a larger degree, which is especially due to Wiechert's fundamental researches and constructions of instruments. On account of this it has further become possible to carry out such measurements in areas where earthquakes are not felt, be it by the observation of distant natural quakes or by the observation of artificially produced quakes. It was found that the elastic ground waves caused by an earthquake are of a very complicated nature, which renders very difficult their analysis. In the first instance one succeeded in determining more closely the velocities of propagation and thereby the angles under which the earthquake rays hit the surface. In scientific geophysics very interesting information about the construction of the interior of the earth was so obtained. For this reason a great deal of attention was paid to the matter. The influence of the uppermost layers of the earth which alone are of importance to mining was again and again ascertained, but was not investigated in details. It is Mintrop's merit to have first applied the so gained knowledge to practice. He reported on his so far obtained results in a lecture at the meeting of the German Geological Society in Hannover *(Zeitschrift der Deutschen Geologischen Gesellschaft 1920, monthly reports, page 269).* The elastic waves which Mintrop uses for his measurements are artificially produced by detonations, a procedure which has already been used by Milne, Mallet, Fouqué, Hecker, Wiechert and others for the measurement of the velocity of propagation etc. in the uppermost layers of the earth. Mintrop's method is principally based on velocity measurements and on determinations of the angle of incidence of the longitudinal waves which first arrive. The applicability of Mintrop's method will at first extend to the exploration of such deposits which are connected with a pronounced change of rocks, and where the essential features of the tectonic and geologic construction are known and relatively simple: For instance it will be possible, as was already proven in practice, to determine the extension and the depth of salt domes; the method will also be successfully tried in the exploration and investigation of sedimentary ore deposits of the type of the lias and cretaceous ores of Northern Germany. The method will also be suitable to determine the depth of the older formations in the subsurface of the North German Plain, which would be important for the discovery of new coal fields etc. Apart from these problems of a general nature questions which daily arise in mining could also be solved in this way, if the assumptions given above are complied with. There are now in a seismogram quite a few quantities — apart from those interpreted by Mintrop — that could be used, which, if duly considered, would essentially supplement our conception of the condition and of the structural position of the uppermost layers of the earth. To be sure, artificial quakes are at present less suitable for a close investigation of these quantities, because the various types of waves too quickly follow upon one another and the intensity is so weak that the area shaken up is not extensive enough. For that reason such researches had at first to begin by utilizing natural quakes. This problem has been followed up by the author in the last two years and quite remarkable results were obtained." Reich then discussed extensive measurements of the intensity of natural earthquakes and continues:

"Naturally the results gained with natural earthquakes would have to be checked and continued with artificial ones. In my opinion there is no doubt that in such a way a method will be found in time, which will constitute an extremely valuable supplement to the knowledge gained in deep borings, especially if a combination with other physical methods is considered. In such a way the applicability of the method worked out by Mintrop will be essentially enlarged, as it will then also be possible to approach deposits with smaller differences in rock and complicated structure and composition. It will further be advisable not to neglect the observations of natural quakes, as with one glance they give us information on large areas for which individual investigations with artificial quakes would be prohibitive. Many promising outlooks are now opened for the investigation of large areas, the deeper subsurface of which is unknown to us on account of the covering with recent sediments, as this is the case in the larger part of Northern Germany."

In July 1922, still before the granting of the Mintrop patent, there appeared the *"Mitteilungen I" der Seismos-Gesellschaft "Erforschung von Gebirgsschichten und nutzbaren Lagerstätten" (Publications, Part I, of the Seismos Company, on Exploration of geological formations and mineral deposits.)* In this publication the paths of rays for the normal



Excitation, propagation and seismographic registration of concussion waves.

and individual primae (Mohorovičić) are shown for artificial earthquakes, as well as the results of the application of the method on nine different objects, with the name of the location and the name of the companies for which the investigations were carried out.

Privy Councillor Beyschlag, at that time president of the Prussian Geological Survey, wrote an article in the *Mining and Metallurgical Review "Glückauf"*, under date of *September 9th, 1922, on "The present attainments of the exploration of German underground deposits"*, page 1090. "The elasticity of the formations, i. e., the graduated propagation of elastic waves according to intensity and velocity, as it has for instance been discerned in concussions by earthquakes, is just as successfully used by Dr. Mintrop (as the torsion balance is used by Eötvös). Mintrop determines artificially (i. e. by detonations) produced elastic waves according to velocity of propagation and intensity and then draws conclusions on the location of boundaries of the rocks and on dislocations, based on a graphic representation of the differences in velocity of the media traversed." Beyschlag 1922

Writing in the *"Zeitschrift für praktische Geologie" 30th annual volume, 1922, No. 3*, Professor Königsberger said the following on the method of elastic waves in his paper: *"The application of physical methods to practical geology":* "Not considering older experiments, L. Mintrop was the first to work out a useful practical method. From the time records of concussion waves, which, produced by detonations at a point of the surface of the earth, propagate in the subsurface, he draws conclusions on the condition and extension of rock formations in the depth. The method is based on the theories worked out in seismology. The instruments, protected by German Reich Patent, are suitably adjusted to the recording of artificial concussions of short Königsberger 1922 periods. Mintrop says little about the character of the method and about the calculations. He only says that, with the most recent procedures, it was possible to find buried salt domes in a very short time, and that their depth and extension could be determined etc."

Heiland 1923

The following was written by *C. A. Heiland in his thesis at the University of Hamburg: "The natural gas occurrence at Neuengamme, in the light of geological and geophysical science, a contribution to a critical study of geophysical methods of exploration in the North German Plain.*" "It appears that the microseismic investigations according to the Mintrop method determined the existence of a salt dome of hercynian strike with a maximum depth of 50 m, about 500 m southwest of the well. The so-called Mintrop well, started on the strength of this at the location indicated, showed only a normal sequence of layers down to a depth of 125 m. However, while the well was brought down, Mintrop arrived at the result that the study of the curves also allowed the interpretation that the salt dome might be hit in several hundred meters. The author does not know what caused this failure, or the wrong interpretation of the seismogram; in other places he had however an opportunity to convince himself that the method furnishes results which in part contradict the already known geological conditions. In the prospectus issued by the Seismos Company the statement is also found, that a subsurface connection has been determined, by means of the seismic method, between the saltdomes of Wietze and Hambühren, in a depth of about 100 m. According to kind information from Dr. Monke, who was in charge of the geological mapping of the area, a deep well, which was apparently not known to the Seismos Company, proved that the two salt domes are not connected under the surface, at least not in the depth determined by the Seismos Company.[1]) On the other hand it must be emphasized that in other localities the method worked with excellent result, as the prospectus of the Seismos shows."

"If the question is to be answered where an uplift of the gas bearing formations is to be expected according to the geophysical methods of exploration, the results of radioactivity, and of micro- and macro-seismic investigations must be eliminated, as they do not give any results that could be used." In a general review of the seismic method Heiland wrote:

"The distinction between surface waves and depth waves is without sense in view of the ever changing elastic properties of the upper crust of the earth. It will hardly be possible to determine such a clear sequence of longitudinal and transverse depth waves and of the transverse surface waves as in the seismogram of a distant earthquake. In any case the longitudinal waves radiating from the center of concussion will be first to arrive at the receiver, the time of arrival obtained from these will be used to construct the time distance curve."

In 1923 C. A. Heiland still considered it senseless to distinguish between surface waves and depth waves, while four years earlier, Mintrop had based his seismic method on this difference and had applied it with increasing success.

Quiring 1923

In *No. 17 of "Glückauf", April 20, 1923, Dr. Ing. H. Quiring*, of the Geological Survey, wrote an article on *„The torsion balance as an aid to mining prospecting in the Siegerland"*, dealing with the seismic

[1]) Geology has now accepted as correct the seismic determination of the subsurface connection between the salt domes of Wietze and Hambühren.

method as follows: "The seismic method of Dr. Mintrop has been used with considerable success in parts of Germany which are geologically simpler. Coal seams on the Lower Rhine, brown coal seams, salt domes and oil deposits, iron ores in jurassic and cretaceous formations and tertiary deposits of quartzite were investigated as to position, extension and thickness under younger covering. It was further possible to determine thickness and form of deposit of younger transgressing and folded formations f. i. of tertiary or diluvial age, overlying older rocks. In how far, however, it will be possible to determine by seismic measurements lodes and deposits occurring in old paleozoic rocks, strongly folded and fissured, must be shown by the further development of the method. Perhaps some day this will be possible, but, according to my opinion not until the geology of the area concerned has been so clearly understood that it will be possible at all to interpret the picture obtained by the seismic determination."

In the *"Handbuch der geologischen Arbeitsmethoden" Abt. X, No. 4, (Encyclopedia of geological working procedures), Prof. H. Philipp (Greifswald)* wrote the following, in the section *"Methods of geological surveys"*, published 1923: Philipp 1923

"Seismic surveying method (Mintrop Method): The method is based on the physical fact that rocks transmit earthquake waves with different velocity according to their elasticity. For instance, the velocity of the elastic waves in rock salt is a multiple of the one in tertiary sands. For the determination of the character and depth of a rock formation underground the following method is used: At one end of the profile line to be investigated a light field seismograph is set up; at various distances from this instrument small detonations are then successively made in the profile line. These are made in the surface, that is, without borings. The so produced concussion waves traverse the ~~surface~~ in all directions and are also recorded by the seismograph. The travelling times of the waves pertaining to the various distances from the detonation point to the instrument are then plotted as a time-distance curve. In the case of uniform elastic condition of the rocks the time-distance curve is nearly a straight line. However, if, at a certain depth, a change occurs in rocks, for instance from tertiary to cretaceous or salt, such change will be found as an inflexion point in the time-distance graph. This inflexion point is brought about in the following way: Similar to the optic waves, the elastic waves do not propagate along the geometrically shortest path, but along the path of the shortest time. Coincidently with the waves arriving from, say, tertiary beds, waves appear, beyond a certain distance from the detonation point, which first penetrated into the depth, traversed the fast conducting layers found there, and then returned to the surface. Inspite of the circuitous way through which they have passed, they arrive coincidently with the surface waves, because they gained time on the quicker path through the solid rocks. From the inflexion point on, the depth waves arrive first with further increasing distance, the surface waves following later. From the shape of the time-distance curves the velocities of the surface waves and depth waves can be taken, and the depth can further be calculated in which the transition from one layer to another occurs. A thoroughly substantiated theory of this method applied to the earth as a whole may be found in the treatise of Wiechert and Zoeppritz *"On earthquake waves", Nachr. d. Ges. d. Wiss. Math.-phys. Klasse 1907.* (The author owes this information to Dr. L. Mintrop, Director of the Seismos G. m. b. H. for the exploration of rock strata and mineral deposits, Hannover.)

Also see *R. Ambronn, Jahrbuch des Halleschen Verbandes für die Erforschung der mitteldeutschen Bodenschätze usw., Vol. III, page 39—41.* While the present paper was printed a description appeared with good illustrations: *Exploration of rock strata and mineral deposits by the seismic method, published by Seismos G. m. b. H. Hannover 1922.*"

Petraschek 1923

In the *Zeitschrift des Internationalen Vereins der Bohringenieure und Bohrtechniker (Journal of the international association of drilling engineers and technicians),* Dec. 15, 1923, Prof. W. Petraschek, Leoben, discussed "*Experiences with physical methods of prospecting*". He wrote: "Seismic investigations made by the Mintrop Method show plausible results in the Fohnsdorf district, in the Mürztal their error was not great, but they failed totally near Leoben. It appears that the elasticity of the rocks was not always correctly estimated."

Sieberg 1923

The progress attained by Mintrop's researches in the theoretical knowledge of the propagation of earthquake waves, and in the technical application of this knowledge, is strikingly reflected in the books of A. Sieberg. While Sieberg, as already said, did not yet know the seismic method in 1904 and 1917, he was very uncommunicative about his opinion in 1923, at a time when the Mintrop Method had still to fight its way in industry, and when numerous scientists thought very sceptical about it. In the book, 500 pages thick, "*Geologische, physikalische und angewandte Erdbebenkunde*" *(Geological, physical and applied seismology)* which appeared in 1923, nothing is contained that refers to the seismic method for the exploration of rock strata and mineral deposits, except the two sentences: "The seismometric method alone led to satisfactory results in the course of time, and these did not only benefit the calculation of the epicentre, but they also make it possible to throw light on the inner construction of the globe. Simultaneously endeavours are made to solve problems with the seismometric method which are of importance to mining." In comparison to this, Sieberg's book in its 1927 edition contains a whole chapter on the seismic method.

Gutenberg 1923

Benno Gutenberg, Sieberg's cooperator in the 1923 edition of the book, confined himself to the two sentences (in the chapter "*The surface waves in local earthquakes*"): "Artificial concussions (detonations) were also used for the determination of Vm, the results, however, were mostly kept secret (Mintrop). Older observations are available from Hecker and E. Wiechert, who in the sands of the artillery ranges of Kummersdorf found Vm = 238 m/sec and at Meppen Vm = 240 m/sec." Compared to this, 30 pages in a special chapter are devoted in Gutenberg's text book on geophysics, which appeared in 1926, to the application of elastic waves for the exploration of the uppermost layers of the earth.

Wiechert 1923

Wiechert was the first one who recognized the great importance of the Mintrop method for science. Already in 1921 (see page 63) he called attention to the great value of the method, and two years later the first scientific publication on "*Investigation of the earth's crust with the seismometer, using artificial earthquakes*", appeared, *(Nachr. d. Ges. d. Wiss. zu Göttingen).*

Wiechert 1924/25

A second publication of Wiechert's followed in *Vol. I* of the *Zeitschrift für Geophysik, annual volume 1924/25, No. 1/2,* in which attention was drawn to the particular difficulties which Mintrop had to overcome in the development of this method. Wiechert wrote: "While seismology succeeded to obtain far reaching information on the condition of the deep interior of the earth, not so favorable results were obtained in the seismic exploration of the earth's crust. Here it is necessary to observe local quakes. If natural earthquakes are used, all those difficulties have to be dealt with which are given by the uncertainty of the focus and the focal time. The artificial concussions caused by explosions offer better conditions in many respects, but even the greatest explosions are such minor events against natural earthquakes, that the seismographs in use are mostly insufficient. Accordingly it cannot be surprising that seismology furnished but few reliable data on the stratification of the earth's crust, and still this involves a problem, which is of great importance for the physics of the earth. In view of this I asked myself in 1905 whether it would be possible to achieve progress by the use of artificial earthquakes, if extraordinary sensitive instruments were to be used. I constructed a horizontal seismometer with a magnification of 50 000 and used it in 1906 to detect concussions of the ground due to gunshots at a distance of 16 km, on the artillery range in Meppen, but the reception of the concussions was already near the limit of the observable, although conditions were unusually favorable. The sandy water-soaked subsoil near Meppen was a much better conductor to ground concussions than rock ground. After this the instrument was used by Mr. L. Mintrop for the investigation of earth concussions due to engines, or due to the fall of weights etc., but no appreciable information on the geological depths of the earth's crust was so obtained. Later on Mr. Mintrop constructed vertical seismometers, easily portable and suitable for field use, and he succeeded in using these instruments for the investigation of the layers of the earth down to a depth of 1 km, with the help of detonations. The result for mining purposes must be estimated very highly, even today, concerning as it does an application of seismology of far reaching importance. Through the successes of Mintrop I was called forth to resume my former researches. I now saw clearly that my aim, the seismic exploration of those depths of the earth's crust which are of importance to geology, could only be attained by increasing the sensitivity of the instruments to the uppermost possible limit."

In *No. 4 of the first annual volume (1924/25)* of the *"Zeitschrift für Geophysik" F. Hubert* (assistant at the geophysical institute of the University of Göttingen) published a treatise on *"The recording of oscillations of the ground produced by falling weights, by means of Wiechert's vertical seismometer of a magnification of 2 million"*. The introduction is quite interesting as it refers to the history of the Mintrop Method. It reads, in part: "In the year 1921/22 a vertical seismometer was built with an amplification of 2 million in the Göttingen Geophysical Institute, for the purpose of recording fast oscillations of the ground. Funds for this purpose were furnished by the Emergency Committee of German Science. With this seismometer I undertook the investigation of the concussions of the ground produced by free falling weights. The results so obtained are to be reported on in the following paragraphs. Two reports on the seismometer and a number of experiments have already been published. *(E. Wiechert "Investigation of the earth's crust with a seismometer with special consideration of artificial earthquakes") (Nachr. d. Ges. d. Wiss. zu Göttingen, Math. Phys. Kl. 1923).* The same: *"Observations on air-concussions in Göttingen at the occasion of detonations in Jüterbog. (Seismic investigations, first communication) Zeitschrift für Geophysik, 1924/25).* The experi- Hubert 1924/25 ments consisted in the registration of concussions of the ground, caused by detonations in a basalt quarry 17 km away, and in the registrations of sound waves of a detonation in Jüterbog."

"Similar experiments with a horizontal seismometer amplifying 50 000 times were already made by Privy Councillor Wiechert in 1906 on the artillery range in Meppen for the investigation of concussions of the ground caused by naval guns. *(The same: On earthquake waves I, Page 53, Nachr. d. Ges. d. Wiss. zu Göttingen, Math. Phys. Klasse, 1907.)* With the same seismometer L. Mintrop investigated the oscillations of the ground which were caused by the large gas engines of the Göttingen electric power station *(L. Mintrop, thesis: On the propagation of the oscillations of the ground caused by the pressures of the masses of a large gas engine).* In this thesis the diagram of an artificial earthquake caused by the fall of a steel ball weighting 4000 kg from a height of 14 meters will also be found. On further experiments with falls of the same type recorded at various distances, on microseismic unrest of the ground, caused by carriages, railroads and the various activities of a large city, on concussions of the ground caused by ram blocks, blasting of rocks and similar causes, Mintrop read a lecture at a meeting in Düsseldorf *(L. Mintrop: "On artificial earthquakes", International congress of mining, metallurgy, applied mechanics and practical geology, Düsseldorf 1910, Reports of the Department of Practical Geology).* Similar experiments of Mintrop's are also mentioned in his report on the seismograph station at Bochum. *(The same: The earthquake station of the Westphalian Berggewerkschaftskasse at Bochum. "Glückauf", Mining and Metallurgical Journal, 45th annual volume, Essen-Ruhr, 1909).* Later on Mintrop assembled one vertical seismometer, as counterpart to this horizontal seismometer of Wiechert's, and two horizontal seismometers in such a way, that the registration of the three components could be done on one recording strip. Illustrations of these instruments and of the registrations obtained may be found — apart from the treatises referred to — in *Galitzin "Vorlesungen über Seismometrie" (Lectures on Seismometry)* page 205 and following. Mintrop then designed easily portable seismometers which are successfully used for purposes of practical geology of mining by the Seismos Company, Hannover, of which Mintrop is director. (Exploration of rock strata and mineral deposits, by the seismic method. Publications of the Seismos Company, Hannover, 1922. Published by Seismos Co.) Photographic recorders for the registration according to Mintrop were lent to the Institute by the Seismos Company, Hannover."

Deubel 1924

In the *Publications of the Geological Institute of the University of Greifswald, Vol. V, 1924* Dr. Deubel wrote the following on page 17 of his paper on *"New methods for the exploration of the subsoil and their importance for the province of Pomerania":*

"For conditions in Northern Germany Dr. Mintrop's seismic method has recently been adapted to the application in field practice, and it is of considerable more importance (than the electrical methods). It is based on the results of modern seismology, with the exception that the natural earthquake waves are substituted by artificial concussion waves, which are produced by means of detonations or falling weights. The velocity of propagation of concussion waves depends in an extraordinary degree on the condition of the underground. It amounts to several hundred meters in loose masses (gravels and the like), it may however reach many kilometers in hard and dense rocks (eruptive rocks). The registrations are made by instruments especially designed for this purpose, particularly with the Mintrop field seismograph.

Concerning the difficulties in the way of a successful application of the seismic method, Dr. H. Reich wrote in the *Zeitschrift für Geophysik, No. 3, 1924/25, page 121,* in a report on his lecture: *"Seismic instruments and geology":* "One aim of the application of seismic instruments must be to make clear the connections between geology and seismology which have again and again been pointed out by A. Sieberg, and to apply the results to the uppermost layers of the earth. The Seismos-Method of Dr. Mintrop represents already one application of seismometric observations on geological problems which has been carried out in practice with much success. The method uses chiefly time-distance curves of artificially produced waves. Not only discontinuities parallel to the surface of the earth must be considered, as in case of the interior, but, due to the complicated structure of the uppermost portions of the earth there are faults and bedding planes, overthrusts and similar planes which may have very different inclinations towards the surface of the earth. Structural positions parallel and vertical to the surface must only be considered as extreme cases, with all possible transitions between them. This results in a great multiplicity in the shape of the time-distance graphs, which however, by a certain arrangement in the experiments, admits of a unique interpretation. Such investigations can mainly be applied to the determination of the depth of certain layers, to the tracing of faults, to the delineation of synclines and anticlines in folded rocks, provided always that sufficiently great differences in the elastic properties of the various strata exist." Reich 1924/25

C. A. Heiland, who judged the seismic method so sceptically in 1923, (see page 68), wrote in an extensive publication on *"Instruments and methods for the finding of useful deposits" (Zeitschrift für Instrumentenkunde, 1925, page 427 and foll.):* Heiland 1925

"Passing on now to the second great group of geophysical methods of investigation, which deal with the properties of deposits in artificially produced fields, it will be necessary to begin with the discussion of those measurements, which make use of the observation of elastic waves. There either may be used acoustic waves here, as proposed by the American Fessenden, or seismic waves as suggested by Mintrop. The Mintrop Method is more in connection with the working procedures familiar to seismology, but does not depend upon the sinking of bore-holes in the area to be investigated, in contrast to Fessenden's method. The Mintrop Method works very rapidly, and has a very comprehensive field of application, nearly all problems occurring in practical geology can be solved with it."

During the *Cologne Exhibition* in the autumn of 1925 *(Kölner Herbstmesse)* scientific lectures were read and later on published by the exhibition office (Messeamt Köln). Dr. Ritter, of the Reich Bureau of Chemistry and Technology, contributed a paper on *"Measurements of explosions and application to mining"*, of which the following is a part. "The seismograms allow to determine the depths of the planes of discontinuity and the physical constants of the layers traversed, according to Wiechert's theories. The method was first practically used by Dr. Mintrop, in order to determine at the surface depth, character and thickness as well as strike and dip of layers and deposits. It has proven a valuable aid to practical geology and mining, that gives information on structural conditions quickly and inexpensively and which efficiently helps in geological projections. E. Wiechert used the Ritter 1925 method for the scientific exploration of the earth's crust and constructed for this purpose a vertical seismometer with a magnification of 1½ million."

Wiechert 1926

The priority of the seismic method for the exploration of strata and mineral deposits was awarded to Mintrop by E. Wiechert in the latter's paper on *"Investigation of the earth's crust by means of detonations"* in the *Geologische Rundschau, No. 5, Vol. XVII, annual vol. 1926.* This paper is the printed report of a lecture held at the Natural Scientist's Association in Düsseldorf, in September 1926. Wiechert emphasized the great difficulties which had to be overcome in the application of the method and wrote: "Seismology succeeded in obtaining far reaching information on the condition of the deeper part of the interior of the earth, making the earth transparent. It might be thought now, that by using the same methods it would be especially easy to examine the condition of the crust of the earth, on which we walk. Strange to say, this is not the case. Two difficulties are in the way. In the first line the earth's crust is much more complicated than the deep interior. The earth as a whole showed two planes of division to seismology, one in a depth of about 1200 km, the other in a depth of about 2900 km, planes which divide the earth in regular arrangement into three parts: a shell of rocks, an intermediate layer, and a metallic core. Much more complicated is the construction of the outer crust of the earth which surrounds the body of the earth as a comparably thin skin of 100 or 200 km thickness. Continents and oceans, mountains and plains indicate the heterogeneity of its construction, geological and geophysical insights intensify this opinion.

The fact that natural earthquakes occur only very infrequently, is another reason which makes it difficult for seismology to explore the earth's crust. So it is equally impossible to care for the maintenance of a sufficient number of seismograph stations and to find enough earthquakes in order to study the details of the condition of the earth's crust. – Already in the beginning of my seismic researches I realized these difficulties. For this reason I constructed, in 1906, a seismometer with a magnification of 50 000, but I was very much disappointed when applying it to the observation of gunshots at the artillery range of Meppen and on the island of Heligoland, because I realized that the resources at my disposition were not sufficient for an investigation of the earth's crust. Later on one of my students, L. Mintrop, who was associated with the mining industry, and who made his thesis using the highly sensitive instruments, had the lucky idea the seismic methods might be capable, with suitable adjustment and arrangement, to investigate those layers of the earth's crust which are near the surface, and in which practical mining is interested. It is known that Dr. Mintrop achieved great successes. In particular, it was possible to determine extent and depth of salt bodies which are often connected with the occurrence of oil. Mintrop's successes and deliberations of my own caused me to come back to the problem of "minor seismology" or "experimental seismology" as we might call it. I now knew that it would be necessary to give a much higher sensitivity to the instruments than I had anticipated. After some experiences gained in the meantime this necessity did not frighten me at all. The wonderful results which had been gained by the cooperation of geology and geophysics, with gravity particularly leading, gave me a new impulse. To the scientific considerations the thought was added, that these researches might become valuable to economic problems. Indeed, I had to consider, that long and expensive researches might be necessary, but here, in an ideal way, I found the help of the Emergency Committee of German Science, with its leader, Dr. F. Schmidt-Ott."

After extended and very remarkable notes on the difficulty of constructing and interpreting a time-distance graph, Wiechert wrote: "It appears as an aim of experimental seismology, worth attaining and quite within reach, to explain each dent and each wave of a seismogram, and to use it in clearing up the condition of the earth's crust." Wiechert concluded his lecture with the following words: "Gentlemen, I regret very much to say that I could bring only so little today. Again and again I had to acknowledge that we have only insignificant observations and that I could not answer obvious questions. Please consider, that we are still in the beginning of the work in spite of all endeavours already made. We are still fighting for a suitable arrangement of the apparatus and of the methods. What is required is learnt step by step, during the work itself! Consider how much human work is necessary to bring a single well down to a depth of 1 or even 2 kilometers; consider to what an enormous amount of details geology owes its proud achievement! I must consider that my task today has been done, if my audience understand that this is a scientific method rich in prospects. Mentally I see seismic surveying developing to an aid which will lead geology and geophysics to new great successes. We beginners must be content to do the preliminary work, laboriously, but full of hope."

In annual volume 1926 of the Zeitschrift für Geophysik, No. 8, B. Kühn, department chief at the Prussian Geological Survey, published an extended treatise on *"The bearing of geophysical methods on geology and mining"*. It reads, in part: Kühn 1926

"Now geophysical methods can also pass beyond the field where geological methods can be applied, and certainly we shall not value them less because — theoretically expressed — we can no longer check them with a hammer in our hand; all the more as we ourselves, as scientific argumentation shows, do not always pass beyond a certain degree of probability in our opinon on the structure of areas which are in a high degree accessible to immediate geological observation, and which are even opened up by bore-holes. A special position under the geophysical methods, it might even be said a position of preference, is occupied by the seismic method. This method, which is able to furnish data on depths which cannot be reached by drilling tools, by measuring the velocity of the propagating movement of elastic waves, should be best qualified to give fairly reliable information about conditions in the depths. For instance, it appears promising to obtain gradually, following this method, a comprehensive picture of the depth of the cristalline base rocks rising to the surface in individual blocks, or of the more or less metamorphic old paleozoic in those areas of Germany which are covered by mesozoic stratified rocks. This would be of very great importance to our knowledge of the laws which govern the process of mountain building. However, we are already entering the domain of theoretical geology, the relations of which to geophysics go beyond the scope set for this paper."

"It will not indicate any depreciation of the value of geophysical methods, if, in the preceding remarks on its application to problems of geology, unforeseen difficulties were emphasized, and if the limits of its capacity were stressed. There remains a wide and appreciative field of activity for them. Numerous problems remain, to the solution of which a geologist capable of a critical estimation of their faculties and results can use it. Pure geophysics has already given to theoretical geology a safe foundation for the conception of the laws governing the formation and transformation of the earth's crust, and a later historian of geology may find a characteristic feature of its present phase in the fact that now applied geophysics becomes an aid to mapping and practical geology, with torsion balance and magnetical variometer, vibration meter and electrical instruments of many kinds being added to its so far available tools."

Reich 1926 On the occasion of the main meeting of the Association of German Metallurgical and Mining Engineers in Heidelberg, Dr. H. Reich published a paper, in June 1926, in the review *"Metall und Erz"* on *"The present attainments and the prospects of further development of the geophysical exploration of the underground"*. His lecture at the meeting was also based on this paper. Concerning the Mintrop Method he wrote: "The last of the more important great groups of geophysical methods is the seismic method, on which Professor Weigelt will report more in detail. This method has been used least of all in ore mining. Unfortunately only very little is known about results in this department, because the Seismos Company, which so far nearly exclusively occupied itself with it, is extraordinarily reserved. After all that leaked out it can, however, hardly be doubted that the attempts to directly locate ore deposits with the seismic method have not succeeded so far, or, in any case, have not succeeded in such a way that the second requisite advanced in the beginning, namely to delineate ore deposits by the direct method, is complied with. In contrast to this the method scored well in problems where the thickness of overlayers is concerned, and cannot be surpassed in this respect. In the Swedish publication *(K. Sundberg, H. Lundberg and J. Eklund, Electrical prospecting in Sweden, Sver. Geol. Unders. Ser. C. Nr. 327, Arsbok 17, No. 8. Stockholm, 1925)* already so often referred to, it is reported that the method allowed to determine the thickness of the diluvium above the base rocks with an accuracy of 1 m; it is also mentioned by Sundberg that the investigations were carried out in January and February 1923 by the Seismos Company, or rather personally by Dr. Mintrop. (The snow lying 1—2 meters high, with temperatures of 30—40 centi-degrees below zero). The same favorable opinions are heard from the Aix-la-Chapelle and Limburg coal districts. Quite a number of experimental and theoretical researches in this discipline were carried out and published recently. Among Wiechert's students I especially mention F. Hubert, J. Brand and G. Krumbach. Besides, F. Ritter dealt with these things comprehensively. The Mintrop Method, so far exclusively employed, uses the velocity of elastic waves for the required determinations. The latter depends upon the density and the elasticity constants of a rock. If these change considerably along a preferably regular plane (interface between layers, base of transgression, fault, overthrust etc.), then it is possible to delineate these planes of discontinuity; it is, however, a condition that the elastic waves traverse a not too small fraction of their total path in each of the various media which are different from one another, and that the velocity increases with the depth, which is generally the case. With ore deposits in a more or less vertical position this path will usually be too short in relation to the measurements at the surface. In addition to this the constant of elasticity and the density may change in such a way, that both increase in the same degree. Then the velocity of the seismic waves remains the same inspite of the change in structure.

Another procedure seems to be feasible here. With each refraction or reflection which the elastic waves suffer at the dividing plane of two different media, a loss in energy occurs, which is in part due to the fact that f. i. a longitudinal wave, both through refraction and reflection, is divided into one longitudinal and one transverse part each, with different velocities. Therefore, observations of intensity must also allow to determine the location of planes of discontinuity. This is a fact which is known and has also been applied in seismology for a long time. That it may also have a practical value has been pointed out by Reich in a short paper in "*Stahl und Eisen*", in 1921. 'Recently this method is said to have been put into practice by a newly founded company *(Prospection, Göttingen).* I regret to say that no data on investigations already carried out are available, which makes it impossible for me to say to what a degree these endeavours were successful. Theory and practice have often gone a long way until they met. In any case I would like to point out that the seismic method in the last form mentioned has at least a chance also to accomplish something in ore mining. The method can at any time be carried out under the surface without any difficulties, so that it bids fair in this direction. As the investigations of elastic constants of rocks and ores are only known to the public to a very small extent, it is hardly possible to form an opinion on the possibility of these methods and it will be necessary to wait for the results."

The general impression to be gained from the preceding remarks of Reich is, without doubt, that the seismic method represents a new domain in the exploration of strata and deposits, which was opened by Mintrop.

In his book "*Methoden der angewandten Geophysik*" *(Methods of applied geophysics), Vol. XV of the series Wissenschaftliche Forschungsberichte,* which appeared in 1926, Ambronn described the time-distance curve method correctly in the chapter "*The investigation of the structure of the subsurface by means of elastic [seismic] waves*". However, he did not mention that his presentation of the matter in the Halle publication in 1921 (see page 57) was wrong. In particular Ambronn understood in 1926, that the velocities of the deep layers can be taken from the time-distance curve, while in 1921 he thought that the time-distance curve would furnish an average value between surface and depth velocities. About the origins of the method Ambronn writes on page 181 and following: "Earthquake waves artificially produced were first used by Mallet in order to measure the velocity of propagation of elastic waves in various types of rock and ground. Abbot worked in the same direction with very large charges, Milne produced concussions by means of falling weights; extensive investigations of this kind were also carried out by Fouqué, Lévy and Nogués. The results of these older researches, however, allow ambiguous interpretations, not enough distinction seems to have been drawn between the longitudinal forerunner waves and the later following and usually much stronger acting surface waves. The measurements of reception are usually carried out with a mercury mirror microscope. The time of sending was calculated by merely counting back from the time of arrival of the sound, which naturally will never satisfy exact requirements. Nogués also used detonations underground and determined differences in the velocities parallel and perpendicular to an ore vein. He then referred to various

Ambronn 1926

items which are of influence to the wave velocity in the subsurface: The individual character and the composition of the rocks, their molecular condition, the orientation of the mineral masses, the manner of deposition, their density, their water contents, the position of the wave planes in space and the type of concussion itself. Careful investigations on the velocity of propagation of elastic ground waves which are caused by detonations, have been carried out by Hecker in the sands of the artillery range at Kummersdorf. Pendulums with a mass of 2 kg, which recorded on sooted glass panes, were used as receiving instruments. He found 1430 m/sec as the velocity of propagation of the (longitudinal) waves which cause the first impetus, for the surface waves of greatest amplitude he found 238 m/sec. Attention was also paid to the influences of the geological structure of the subsurface. Wiechert reported that the velocity of the main (surface) waves in the sands of the artillery range near Meppen was found to be 240 m/sec. The measurements were made with a vibration meter amplifying 50 000 times, which allowed to record the step of a person in 100 m, a flock of sheep in 500 m, and a railroad train in a distance of 10 km.

From the theoretical side von dem Borne showed the great importance of seismic investigations by artificial elastic waves for geologic exploration of the uppermost formations of the earth, writing: "As the observations of seismic phenomena afford us some indications regarding the mechanical relations of the earth and, it is true, first on the geologically speaking deep-lying portions of the same, so they will also give us corresponding explanations on the tectonically more important portions near the surface. Above all, the instrumental study of slight local quakes, of artificial disturbances and ground movements of meteorological origin, will have to intervene. Galitzin also emphasizes in his "*Lectures on Seismometry*" the practical importance of investigations on the propagation of artificially produced waves in the underground.

Mintrop then sought to apply the method which determines the focus of earthquakes from the time path of earthquake waves, in order to ascertain the place of artificially excited tremors, for instance of field gun locations. For this purpose he constructed his tremor meter described on page 176. However, the practical execution of this method failed, for the reason that the shots must fall very sporadically in order not to make the general ground unrest too great, and that the discharge of a modern gun with recoil chambers transmits a much slighter amount of energy into the subsoil than the impact of a projectile, especially one with a delayed fuse. The principal obstruction to this method, however, is the very great difference in velocity of propagation of the elastic waves in different ground, which varies from several hundred to about 6000 m per sec. This hindrance is changed into just as great an advantage if the problem is reversed and if now, according to Fessenden, Mintrop and others, the observed wave velocities at known distances between places of explosion and recording apparatus are used, in a suitable way, to determine the unknown geological structure of the underground.

Fessenden used submarine sound transmitters as the exciters of the tremor waves, which, dependent on events (*"dependent on events" or "evtl. auch" in German, was added by Ambronn, Fessenden does not use this term*[1]), he also sinks in bore-holes to the desired depth. Sound receivers are arranged as receivers, and can also be lowered

[1]) Author's annotation.

into bore-holes to the required depth. The registration of the incoming tremor waves as well as the registration of the time of sending of the waves are made by means of string galvanometers. The use of membrane sound transmitters and tuned submarine sound receivers, on the principle of the telephone, has the added disadvantage that the onsets are more or less sharp depending upon the damping of the systems of the instruments. How far his methods can actually be carried out in practice must remain undecided."

Concerning the Mintrop Method Ambronn wrote: "In close connection with the researches of Wiechert and his students, on the relations existing between the formational structure of the interior of the earth and the form of the time-distance curve, Mintrop, for instance, applies the time-distance curve method with use of artificial waves to the analysis of the structure of the layers of the uppermost crust of the earth. It comes in very favorably here that, in the majority of cases, the boundaries of formations are evidently very sharply defined in nature, in such a way that frequently extended layers with very different wave velocities bound one another, while within these formations — due to the long times in which the conditions of sedimentation were apparently essentially the same — the wave velocity remains nearly constant."

In an extended paragraph which begins with the words: "The seismic methods are especially qualified to investigate the tectonic structure of a stratified subsurface" Ambronn discusses the various possibilities for applications, using specimen cases, which he bases in the main on the *Seismos publication of 1922, "Exploration of rock strata and mineral deposits with the seismic method."*

Dr. H. Reich, district geologist with the Prussian Geological Survey, discussing Ambronn's book in the *Zeitschrift für praktische Geologie, 1926, No. 11,* said that Ambronn did not duly appreciate the researches of Mintrop. Reich wrote: "Apart from a general introduction into the essential features of each method the contents of the book represent a report, without special valuation, of all the researches in this discipline which became known to the author. Only those methods are not dealt with which are obviously speculative. It has, however, an unpleasant effect that the certainly existing merits of the author in many of these methods are put into the foreground very much, while other personalities, who, it seems, are inopportune to the author, are either not appreciated as they should be due to their actual importance (f. i. Mintrop), or are sharply criticised (f. i. Krahmann) in a way which is otherwise not customary."

In his *Lehrbuch der Geophysik (Text book of Geophysics)* which appeared in 1926, Gutenberg wrote regarding the Mintrop Method: Gutenberg 1926

"While the acoustic methods (of the American Fessenden) for the investigation of the structure of the uppermost layers of the earth have not been further developed, the seismic methods have been developed more and more. The first one to point at their application, I believe, was von dem Borne. The first practical application appears to be due to Dr. Mintrop." On page 500/01 of the same book Professor Ansel wrote: "As an equivalent (to the investigation of the gravity field or of the magnetic field of the earth) the method of Dr. Mintrop must be added, the elements of which have partly been prepared by seismology. In Dr. Mintrop's method concussions produced by the detonation of small amounts of explosives are transmitted to the surface and further to the sequence of layers below, propagating according to the laws of Ansel 1926 elastic wave propagation. From the time values measured at the surface depth, type of deposit, as well as faults in the layers of various elasticity which were agitated, can then be calculated. Though simple in principle, the method requires a complicated apparatus and much experience in the field, if the results are to be reliable."

On page 596 Gutenberg wrote: "Nothing became known so far as to the practical execution of the methods; in the method patented by Mintrop the use of time-distance graphs is only spoken about in general terms. In the following paragraphs we shall therefore try to discuss individual cases somewhat more in detail."

Regarding the application of the method Gutenberg wrote on page 609: "As each use of time-distance graphs comes under the Mintrop patent, there can at present only be considered, for a practical application, the determination of the onset of reflected waves (echo sounding method). — Usually time-distance curves must be constructed from earthquake registrations, that is, the procedure called "Mintrop Method" must be applied. The accuracy attained with the Mintrop Method is said to average (according to Ambronn) 2—4 % in depth data and ½% in angles of incidence. However, two cases were published by Heiland, in which profiles calculated by Mintrop were proven to be wrong by actual drilling. Unfortunately material that could be checked is hardly published at all."

On page 616 it goes on: "In actual practice the exploration work is carried out by several companies, who are unfortunately, but quite naturally, more interested in the realization of rational management than in the promotion of science. Though they certainly have gathered special experiences with their specific methods, it must be considered, in judging the results published by them, that prospectuses are usually written in an especially optimistic way. It would certainly constitute a progress if experiences, also unfavorable ones, would be exchanged between the individual companies and science. The then developing greater certainty of results would certainly raise the prestige of the methods as well as the number of interested parties, with practice and science stimulating one another, as, for instance, this is the case in meteorology.

The geophysical methods of exploration are also of manyfold importance for purely scientific investigations. Reference is made to the determination of buried tectonics by means of seismograph registrations (§ 332), and to the conclusions which can be drawn from magnetical anomalies on the geological structure. Furthermore E. Wiechert (compare page 602/03) began to determine the formational structure near Goettingen by means of time-distance graphs which had been constructed from registrations of detonations in distances up to about 200 km from Goettingen. He found that the velocity of the longitudinal waves increases to 5.9 km/sec in a depth of about 2—3 km, and further, that another plane exists between the said plane and the layer boundary in a depth of 60 km, in which the wave velocity increases by a small amount. Whether the varistic base rock begins in a depth of 2–3 km, as Stille assumed, and what importance must be assigned to the other surface of discontinuity, can only be found out by further investigations. In any case it can now be expected that the tectonic structure of the continents will be elucidated by these means down to the Sima limit, while earthquakes will give us information on the deeper layers."

Gutenberg's statement concerning the almost total lack of publications of material that could be checked can hardly be admitted, because, in 1922, in the publication of the Seismos Company, not less than 9 different specimen cases were included, all of them being explained by illustrations.

Koenigsberger 1926

Regarding the reserve exercised by mining and exploration companies in respect to publications, Professor Koenigsberger wrote in the *Zeitschrift fuer praktische Geologie, No. 5, annual volume 1926*, discussing the limits of the applicability of geophysical methods: "It would be interesting to learn on what experiences and studies the opinions of Mr. Z. on geophysical methods are based, which were published in this scientific journal. This would be especially valuable in regard to seismic methods, because nothing has been published by Mintrop on his seismic method, apart from two short papers right in the beginning. We have nothing to rely upon but vague reports from hearsay. Other seismic methods, on the other hand, have not yet been tested out according to my information. Various reasons allow to understand that Mintrop did not publish anything from the beginning, and Schlumberger not since 6 years. One reason for non-publication might also be that following this mode the scientific and practical geophysicist does not waste his time in answering critiques, which have often been written without expert knowledge, without participation in the research work, from personal motives and not from objective ones, which are however written with so much more positiveness."

Angenheister 1926

In the *"Korrespondenzblatt der Deutschen Wissenschaft und Technik, Forschungen und Fortschritte" No. 14, July 15, 1926*, Professor Angenheister reports on *"Geophysics at the 14th meeting of the International Congress of Geologists at Madrid"*, writing: "The great German mining concerns founded geophysical research companies which today are working in the important mining and ore areas of the world. Among these must especially be mentioned the "Seismos", which was founded due to the energetic initiative of Dr. Mintrop, who was the first one to utilize the seismic method employing artificial tremors for exploration work."

In the *Zeitschrift fuer Geophysik, annual volume 1927, No. 1*, Professor Angenheister published a paper on *"Observations of detonations"* (This paper belongs to the series of detonation researches which are subsidized by the Emergency Committee of German Science). He wrote: "Seismograms of detonations were recorded up to a distance of 1500 m. From the records time distance curves are deduced for various phases, their interpretation is attempted. Artificial explosions cause elastic vibrations of the underground, which can be recorded by suitable seismographs. The diagrams of this experimental seismology show quite distinguishable onsets, similar to earthquake diagrams. In considering such individual seismograms it is very natural to call these onsets longitudinal, transverse and surface waves, analogous to earthquake diagrams. However, in comparing the records taken within the various distances of several hundred meters, considerable difficulties arise, as, for instance, if it is attempted to identify the various corresponding onsets, and in increasing measure, if a physical interpretation of the nature of the waves is attempted. This is especially the case if records of one component only are available, much is then left to arbitrary choice. If the experiments are made on a subsoil which already shows pronounced stratification in the depths traversed by the waves recorded, the onsets multiply, and consequently there is increasing difficulty in their interpretation. Certainly the so far used time distance curve of the first impetus already affords a very important clue to the stratification of the subsoil. If it should be possible, however, to interpret the nature of the waves of further onsets and to recognize and identify the corresponding onsets in the records taken at various distances, then new ways for the seismic exploration of the underground are opened. To study the above problem, it is necessary to systematically investigate the registrations, i. e., the movement at various distances from the point of detonation, a three component record being necessary at each place. Experimental researches of this type are of great importance to the theory of earthquake waves, because the physical nature of earthquake waves has by no means been determined with certainty for all onsets.

The practical value of the seismic method of exploration for mining does not have to be emphasized any more. It is sufficiently known due to the fine results of Dr. Mintrop.

A part of the elastic waves which can be recorded at detonations penetrates still deeper than the formations that can be opened through mining. This is suggested by the researches which have been carried out in the last years by the Geophysical Institute in Goettingen, directed by Professor Wiechert, on which comprehensive reports have been made by the latter. Consequently there is good reason to expect that the seismic method as an aid to geological exploration will help to solve the great problems of the tectonics and of the formational structure of the earth's crust."

These remarks of Angenheister's are quite interesting in so far as the scientists express the hope that the experiments subsidized by the Emergency Committee might help to develop the seismic method to become an aid to geological research work for the great problems of the tectonics. Simultaneously reference was made to the successes already gained by Mintrop. Therefore Mintrop was also leading science in the field of the application of artificially produced earthquakes.

Schweydar and Reich 1926

In 1926 Professor Schweydar began working with the Mintrop Method. At first he undertook experiments with detonations, together with H. Reich and the Prussian Geological Survey. A report on the first results is published in *No. 8 of the Annual Volume 1926 of the Zeitschrift fuer Geophysik*, under the heading: *"Registration of artificial earthquakes."* The report reads, in part: "The experiments were at first made in Kummersdorf, on loose sands. The surprising result was found that at the short distance of 200 m the waves already came from below. The same phenomenon was found in Ruedersdorf in limestone, and also in Sperenberg in gypsum. In Sperenberg the shortest focal distance was 5.2 m, the first shock being inclined about 76° against the surface. The waves arriving at short distances are either not pure longitudinal waves, or the uppermost layer does not participate in the oscillation, from which would follow that refracted waves are already observed at the shortest distances. In Kummersdorf the period of the ground waves was 0.06 sec, their velocity of propagation was about 1000 m/sec; in Ruedersdorf the period amounted to 0.02 sec, and the velocity of propagation was 4100 m/sec."

Schweydar and Reich 1927

A comprehensive report of Schweydar and Reich on their experimental work appeared in *Vol. XVII, No. 1 of Gerland's Beitraege zur Geophysik, annual volume 1927*, under the heading: *"Artificial elastic waves as an aid to geological exploration"*. Regarding the origin of the seismic method the authors say in the introduction: "The English seismologists Mallet and Abbot have first suggested to use artificial earthquakes for the study of the velocity of elastic waves in the uppermost layers of the earth. Linking up with their researches, A. Schmidt suggested to construct time-distance graphs of artificial earthquakes, in order to study the law of change in velocity of propagation with the depth. Belar intended to utilize such investigations for practical purposes, for instance in order to find out at the very beginning the composition of the earth formations in tunnel boring. He suggested to set up transportable, sensitive seismographs for (the recording of) artificial explosions, hoping to be able to draw conclusions on the geological condition from the records. Among other seismologists, for instance Benndorf, von dem Borne, Mintrop and others it is especially Galitzin who has repeatedly suggested artificial earthquakes by explosions in order to study the velocity of propagation of the longitudinal and transverse waves in the uppermost layers of the earth. He points out that these velocities depend in a high degree upon the physical properties of the upper layers of the earth, and that conclusions as to the composition of these layers could be drawn from the variations of the velocities. Measurements of velocities of artificial earthquakes were carried out in recent times by E. Wiechert and his students, especially by Mintrop. Nothing became known as to the results of the work of the last named." The last statement is not correct, in view of *Mintrop's* already mentioned *lecture at the Main Meeting of the German Geological Society in 1920*, in view of the *report* (also published) *before the Committee on Ores of the German Metallurgical Association* in Duesseldorf, 1921, and, finally, of the *publication of the Seismos Company in 1922*, which contains many specimen cases of application of the method. It is further incorrect to say that Galitzin pointed out that conclusions as to the composition of the layers might be drawn from changes in velocities. Galitzin (see page 29) merely speaks of the determination of velocities in eruptive rocks on the one hand, and in sand and alluvial soil on the other hand, whereas he does not speak of the determination of a rock formation that is covered by another kind of rock. This determination is the object of the Mintrop Method.

In Mintrop's patent description of 1919 depth waves were already mentioned. If, seven years later, Schweydar and Reich determine experimentally that the waves come almost perpendicularly from below, then this can only prove that, in 1919, Mintrop conceived ideas which were unknown to other experts.

As a matter of fact, for years Schweydar did not believe in the applicability of the Mintrop Method, which follows from a letter of the Exploration, dated August 29, 1929, which is published below:

Exploration
Boden-Untersuchungs- und Verwertungs-Gesellschaft mit beschränkter Haftung
(Exploration, Limited, for the exploration and exploitation of the subsurface)

Hannover, August 29, 1929.
Koenigshof.

Prof. Dr. L. Mintrop,
Hannover.

Dear Sir,

In view of the charges made by Professor Dr. Mainka against the patent covering your seismic method, we would like to give you some information which we think would be of importance for the judgment of the position of this branch of science at the time of your application for patent.

Before the shares of this company were transferred to the Seismos, which took place in November 1927, we tried to take up the seismic investigation of the subsurface, apart from our main work, which consisted in gravimetric methods for the exploration of the subsoil. Our scientific adviser for gravimetric work was, until 1924, Professor Dr. Schweydar in Potsdam, who became known on account of the Schweydar-Eötvös torsion balance and on account of other researches. At first Mr. Schweydar, with whom we discussed our seismic plans, dissuaded us from this on account of the difficulties, both theoretical and practical, which would be in the way of an application of the seismic method. In particular Mr. Schweydar told the undersigned literally:

"I do not think that Mr. Mintrop receives the waves which he believes to receive."

However, Mr. Schweydar made up his mind to go to see Privy Councillor Wiechert in Goettingen, in order to hear the latter's opinion on the possibilities of the seismic method. On the result of his trip to Goettingen Mr. Schweydar reported to the undersigned in approximately the following words:

"Wiechert has outlived himself, his opinions can no longer be considered authoritative."

This pessimistic point of view taken by Professor Schweydar, who is also well acquainted with seismology, essentially contributed to our decision not to include the seismic exploration of the subsurface into the range of our activities. Not until after the resignation of our scientific adviser, Mr. Schweydar, and after the results of your method became known in the North German Potash District and especially in the Gulf Coast of the United States, did we consider the seismic field again.

Mr. Schweydar later on went into seismic exploration of the subsurface himself, his first report in the matter appearing in the Zeitschrift fuer Geophysik, in joint authorship with Dr. Reich.

Very sincerely yours
"Exploration"
Boden-Untersuchungs- und Verwertungs-Gesellschaft
mit beschränkter Haftung
(signed) Gornick.

The sentence "I do not think that Mintrop receives the waves which he believes to receive" is easy to understand in view of the first experimental results of Schweydar and Reich in 1926. As a matter of fact Schweydar up to that time did not believe that the depth waves referred to in Mintrop's patent description actually existed. Schweydar, who became quite known in the field of the application of the Eötvös Torsion Balance for the exploration of the geological subsurface, especially in petroliferous areas, only turned to the seismic method when the latter threatened to displace the torsion balance.

Laska 1927

Professor V. Laska, Prag, writes *"On the importance of recent seismometry for the geology of oil"* on *July 1st, 1927, in "Petroleum", Vol. XXIII:*

"The determination of a horizontal discordance, i. e., of a layer in which the velocity of seismic waves is discontinuous, without doubt belongs to the most difficult as well as to the most important problems of practical geophysics. Recently a paper appeared in the *Geologische Rundschau, 1926, No. 5,* which brings us much nearer to the practical solution of the problem. It is written by the well known geophysicist Professor E. Wiechert. It is also known that L. Mintrop achieved considerable results with the seismic method, by successfully determining the extension of salt domes."

Mueller 1927

In the *Mining and Metallurgical Journal "Glueckauf"* of January 8, 1927, Dr. M. Mueller wrote on *"Geophysical methods of prospecting" (subtitle: Communications of the Geological-Mineralogical Institute of the University of Cologne):* "In close connection with the results of Wiechert's researches a method was developed by Mintrop for the seismic exploration of the subsurface, which was applied with much success. He chiefly uses the already mentioned time-distance graphs of artificial earthquakes, the release of which is caused by explosions or by the falling of weights, with place of origin, time and force of the released quake being accurately known. The Mintrop Method is primarily used for the investigation of the tectonics of a stratified subsurface. The seismic investigations are of a most simple nature in such cases where the layers which are to be investigated are parallel to the surface. They become more difficult as soon as the position of the planes of the various layers assumes any angle against the surface. For reasons that can be understood Mintrop has published very little about his method. As the main field of application we must consider the determination of faults and overthrusts, as well as the determination of synclines and anticlines in folded rocks."

In Sieberg's book *"Geologische Einfuehrung in die Geophysik" (Geological introduction to geophysics),* which appeared in 1927, the author discussed "the seismic exploration of local deep geology" in the chapter "Some working procedures in seismology". He recognizes the merits of Mintrop with the sentences: "L. Mintrop's method which was protected by German Patent in 1919, became especially known on account of its successes. Enlarging E. Wiechert's researches, artificial earthquakes are here produced by means of detonations, falling weights and the like." **Sieberg 1927**

Figure No. 235 in Sieberg's book is in all essential features identical to Fig. No. 1 of the Seismos publication of 1922 on *"Exploration of rock strata and useful deposits by the seismic method."* Sieberg also uses the same title "Excitation, propagation and seismographical recording of tremor waves" which is used under the Seismos figure.

While Sieberg (Jena) admits Mintrop's successes, O. Meisser and H. Martin (Jena) do not mention Mintrop's researches in their paper: *"On experimental seismology, I", Zeitschrift fuer Geophysik, 3rd volume, 1927.* The director of the Reich Institute for Earthquake Researches in Jena, O. Hecker, writes in the preface to the paper of Meisser and Martin: "In 1915 I made the first experiments to use seismic-acoustic apparatus for the measurement of ground tremors instead of the usual tremor meters. However, the lack of means during the war and in the post war period did not allow the continuation of these much promising experiments. Now it has become possible, due to support from the Emergency Committee of German Science, to work out the seismic-acoustic method in a systematic way." **Hecker, Meißer, Martin 1927**

Mintrop and the Seismos Company respectively financed Hecker's post war researches for years, before the Emergency Committee of German Science came to the aid. Then, for a time, the Reich Institute for Earthquake Researches, directed by Hecker, received funds from the Emergency Committee as well as from the Seismos Company. **Mintrop 1925**

The method called seismic-acoustic method for the exploration of rock strata by Hecker, Meisser and Martin in 1927 was already patented by Mintrop in 1925, with priority going back to November 2, 1920, as *German Reich patent No. 417 010.* The text follows:

GERMAN REICH, REICH PATENT OFFICE.

Patent description No. 417 010 Class 42 l, Group 13.

Dr. Ludger Mintrop in Hannover. Method for the determination of the structure of rock strata. Addition to patent 371 963. Patented in the German Reich since Nov. 2, 1920. Longest duration: Dec. 6, 1937.

The invention refers to a further development of the method for the determination of rock strata according to patent 371 963, the elastic waves artificially produced in the area to be investigated, being received by a microphone, which makes these audible in a telephone or similar appliance by means of electric current; from the pitch of the tune and from characteristic by-noises the requisite conclusions are then drawn as to the formational structure of the area under investigation. This arrangement is especially suitable, due to its simplicity, to check the investigations which are made according to the main patent, and for preliminary investigations respectively, in order to obtain the required general reconnaissance survey for the subsequent individual investigations by means of the working procedure of the main patent.

The oscillations of current generated in the microphone may also be recorded by means of an oscillograph or similar appliance, while the telephone is only used for listening purposes.

The use of a microphone allows, at the same time, to determine the beginning of the artificial tremors, which is, for instance, calculated from the sound waves transmitted through the air. If a microphone is used which responds to the sound transmitted through the ground as well as to the one transmitted through the air, then two onsets succeeding one another are found in the curve recorded, which easily allow to calculate the exact instant of occurrence. Of course two microphones can also be connected to the oscillograph or to the recording device respectively, one for the sound transmitted through the ground, and one for the sound transmitted through the air. By means of this arrangement a working procedure is obtained which is equivalent to the procedure of patent 371 963, with respect to the accuracy of the measurements, while the arrangement here used is still simpler and lighter in weight.

Patent-Claims:

1) Method for the determination of the structure of rock strata according to patent 371 963, characterized in such a way, that the artificially produced elastic waves are received by a microphone, and are made audible by means of a telephone, with the requisite conclusions being made from the pitch of the tune and from characteristic by-noises.

2) Method according to Claim 1, characterized in such a way that the artificially produced elastic waves received by a microphone are photographically recorded as current oscillations by an oscillograph or similar device.

3) Method according to Claims 1 and 2, characterized in such a way that simultaneously with the recording of the sound transmitted through the ground, the sound transmitted through the air which is due to the blasting charge, is also recorded in the curve, in such a way that either one microphone responding to the ground sound ~~and one microphone responding~~ to the air-sound ~~are~~ used, or two microphones connected with the same oscillograph, one being used for the ground sound, and one being used for the air-sound.

Deubel 1924 F. Deubel, the geological cooperator mentioned in the publication of Hecker, Meisser and Martin, fully recognized the priority of Mintrop in his paper on "*New Methods for the investigation of the subsurface and their importance for the Province of Pomerania*" which appeared in 1924 in the series "*Communications of the Geological Institute of the University of Greifswald*".

Meisser 1929 Quite recently Meisser also emphasized the priority of Mintrop. The reader is referred to Meisser's paper on "*Notes on experimental seismology*", which appeared in the "*Publications of the Reich Institute for Earthquake Researches in Jena, 1929*". On page 62 Meisser wrote: "Another method, which is formed after the working procedures of the seismology of the earth, and which was first systematically applied to experimental investigations by Mintrop[1]) consists in the shooting of time-distance graphs."

Sieberg 1928 Professor Dr. A. Sieberg wrote in the journal "*Steinbruch und Sandgrube*" *(Rock quarry and sand-pit), June 15, 1928: "Prospecting by geophysical methods, with special consideration of the seismic method*": "The seismic exploration of local deep geology in those portions of the earth's crust which are close to the surface is based on the intelligent application of the working procedures in use with instrumental seismology. — The whole range of ideas was already clearly developed by A. Belar in Laibach in the beginning of 1901, in so far as this was possible at all, considering the theoretical knowledge existing at that time. By means of self-constructed special instruments he made the first groping experiments for a practical application. Not until 1914

[1]) Mintrop, L. D.R.P. 304 317, dated May 17, 1917. The same: Exploration of rock strata and mineral deposits, by the seismic method, Hannover, 1922. Note: Meisser refers to the wrong patent description, as also does Gutenberg in his "Lehrbuch der Geophysik".

was the idea successfully transformed into practice, through the American patent of R. Fessenden. Submarine sound transmitters are used as exciters, while various electro-acoustical receivers in connection with photographically recording string galvanometers or the like are used as receiving device. Sender as well as receiver are contained in more or less deep bore holes which are filled with water. Through the tracing of the sound waves, which can be exactly determined as to the moment of their excitation, and from possible reflections, refractions and absorptions, conclusions are drawn on the structural position and condition of the conducting medium. In 1915 Hecker began his experiments which were later on successful, using an acoustic-seismic apparatus instead of the usual tremor meters. The method of L. Mintrop (Seismos, Hannover), protected by German patent of 1919, became especially known on account of its successes in nearly all parts of the globe. Enlarging E. Wiechert's (Goettingen) researches on the inner structure of the earth, artificial earthquakes are here produced by detonations, falling weights and the like. Tremor meters are used as receivers. The travelling times (similar to Fessenden) of elastic waves in the subsoil are measured, with the velocities of propagation resulting from these. The time-distance curve for some special cases was drawn by B. Gutenberg. Deduction and discussion of the formulae are found especially in the papers of O. Meisser and H. Martin and of W. Schweydar and H. Reich, who are systematically carrying out detonation experiments, just as E. Wiechert and his students. Meisser and Martin work at the Reich Institute for Earthquake Researches in Jena, developing E. Hecker's acoustic-seismic method; Schweydar and Reich are also investigating the angles of emergence of the rays. Besides, faults so far unknown were already determined in 1912 by micro-seismic methods applied by Sieberg and Lais to the investigation of the Central German earthquake of November 16, 1911; it might be worth while also to exploit this principle for prospecting, by the development of suitable instrumental means. The practical exploitation of the seismic method for the exploration of mineral deposits is protected by patent to L. Mintrop (Seismos, Hannover). However, a number of research institutes and scientists are also working with these methods, because the latter may also be expected to render information of particular bearing for the theory of earthquakes and related natural phenomena."

In the review *"Metall und Erz"*, July 1928, Dr. H. Reich wrote on *"Notes regarding the further development of applied geophysics"*: "Nothing else became known to us during the last year about seismic investigations in ore mining, except that renewed experiments on certain known ore bodies were made without anything regarding the results being made public. Reich 1928

The conditions of stratification as well as the physical properties of most ores are not favorable to the application of this method, which, for the time being, can be of use to the mining engineer essentially only for the determination of the thickness of loose overlayers over solid rock. In this respect the method cannot so far be surpassed. It has had its main and so far unique successes, suitably acknowledged by Weigelt, Barton and others, in petroliferous areas and the latter will remain its main field of application for the present. The further development of this method in the theoretical and instrumental field is quite interesting. While so far the Seismos Company in Hannover occupied a monopoly in this branch of geophysics, quite a number of new instruments and methods were worked out in Germany and America within the past year and, in part, were also published. Barton reports briefly on the American innovations: The apparatus there invented are said to be in no way inferior to Mintrop's. New instruments in Germany are described by Meisser in Jena and Schweydar in Potsdam. Both, and also Angenheister outline the main features of the application of the method. Quite recently Ambronn came out with a new seismic apparatus. Practice will show which of these apparatus will conquer the market. To explain the advantages and disadvantages of each method here would lead too far."

The chief witness for the priority of Mintrop in the field of seismic exploration of the subsurface, Privy Councillor Wiechert, died in March 1928. In his place his disciples Angenheister, Gutenberg and Lincke testify to the history of the seismic method.

Angenheister 1928

In the obituary to Emil Wiechert in the *"Zeitschrift fuer Geophysik" 1928, No. 3,* Angenheister wrote: "Already in 1905 Wiechert began with experimental seismic researches, with tremor meters. Transportable, highly sensitive seismographs for photographical recording were built. But not until after the war did seismology become an experimental science. Artificial earthquakes were produced by detonations; ground and air concussions were to be measured up to great distances. This advanced new instrumental requirements; a vertical seismograph with photographical registration magnifying 2 million times was set up, light transportable seismographs were constructed; sound receivers were built for soot and photographical registration, they were highly sensitive to sound pressure and indifferent against gusts of wind; flying observation stations were assembled for seismic and sound observations, equipped with wireless time control. Made possible by large-scale support of the Emergency Committee of German Science, a systematic investigation of great extent came into existence.

Great success favored these experimental researches of the last years. Ground movements caused by detonations could be observed more than 200 km distant, the air sound could be followed up to a distance of 400 km. Here also time distance curves were deduced, the velocity at the highest point and the height of the latter were determined, discontinuities were discovered, both in the subsurface and in the air. New ideas on the structure of the upper atmosphere and on the condition of the masses in the ground resulted. In an elevation between 30 and 40 km a warm layer begins which returns the sound to the earth. Possibly a new independent cycle begins there. A new aid to meteorology and geology was called into life, with great practical importance, as the results of Mintrop show."

Linke 1928

Professor F. Linke, Director of the Geophysical Institute of the University of Frankfort on the Main, in his obituary to Wiechert in *Gerland's Beiträgen zur Geophysik, Vol. XIX, No. 4, 1928,* said: "It is good to realize the position of seismology at the close of the last century, when Science tried to bring some clearness into the chaos of seismic registrations, by means of statistical investigations. Seismology was mainly a geographical discipline. What important discoveries on the constitution of the interior of the earth and – of main interest to Wiechert — on the elastic properties of matter under the high pressure and under the high temperatures of the interior of the earth turned out well to Wiechert and to the students whom he inspired: His theory of automatic seismographs created the instrumental foundations. New methods of registration, to the development of which he devoted much time and consideration, came out of his institute. Through the foundation of the Samoa observatory by the Goettingen Academy of Science, of which Wiechert was a member, he obtained access to important observation material from the seismically especially interesting areas of the South Seas, enabling him to crown his researches by the finding of the path which the earthquake waves take in the interior of the earth. Former investigations on the form of the earth, the subdivision of which he had at first theoretically deduced, were confirmed. Then he transferred his activity to the investigation of the movements of the outer crust of the earth, by producing artificial earthquakes. He therefore became the father of applied seismology, which cannot be dispensed with today in the finding of mineral resources, and which his student Mintrop was called to develop further."

In B. Gutenberg's obituary to Wiechert in the "*Meteorologische Zeitschrift*" of May 1928 we read: "It would lead too far to enter into all the successes which he (Wiechert) gained or inspired in the field of seismology. Of predominant importance became his idea to study the oscillations of the uppermost layers of the earth by means of artificial detonations. Under his direction Mintrop began to put this idea into practice at the Goettingen Institute, with the seismic method of exploration developing from this, and Wiechert cooperating in the perfection of the latter." Gutenberg 1928

As in Germany, Mintrop is also regarded abroad as the originator of the seismic method for the exploration of rock strata and useful deposits. In Germany no case of denying Mintrop's priority became known, not even on the part of the geophysicists Mainka, Gutenberg and Reich, at least not in publications. Indeed, these authors declare for Mintrop's priority in their papers, or they divide priority between Wiechert and Mintrop respectively. The geologists and the mining engineers recognize without exception that Mintrop was the first one to develop the method and to apply it. Still quite recently Professor Dr. J. Stoller, of the Prussian Geological Survey, wrote a paper on "*Exploration of German petroleum deposits by means of deep wells*" in the *1929 Almanac of the German National Committee for the International Drilling Congresses*. It reads, in part: "Here Dr. Mintrop's seismic method, which uses artificially produced earth tremors for the determination of the depth, character and thickness of rock strata and useful deposits, may come to the rescue, aiding and supporting. Besides, this method by itself can show good results in the finding and outlining of salt domes." Stoller 1929

The Mintrop Method also came to assume great practical importance abroad, especially in the United States of America. In American professional and scientific publications and in the United States Patent Office the priority of Mintrop is unreservedly recognized.

The first report on the new method to appear in America was contained in the "*National Petroleum News*", April 11, 1923, written by the reporter of this paper, P. Wagner, under the title: "*Seismographic system for exploration of underground formations*". It reads: „Petroleum" 1923

"Germans using Seismograph. In the last ten years, extensive experiments have been made in Europe, especially by the industrial branches of geology in Germany, for the determination and location of coal, oil and other mineral deposits without going to the expense of drilling test holes. For the purpose of an accurate survey of the subterranean folds and formations, the seismographic method has been developed by Dr. Mintrop, an eminent scientist; this seismograph records photographically the wave lengths caused by artificial disturbances of the earth's crust and from these wave lengths the nature, density and distance of the different formations reached by the waves are accurately determined through the use of formulas developed for this purpose."

The Oil Weekly of December 29, 1923 wrote, under the headline "*Extensive Explorations Made in Eastern Texas*":

"The Marland Oil Company, through its operating subsidiary, the Alcorn Oil Company, has been the most aggressive in the geological work that has taken place in the above mentioned counties during the past five months and has used the core drill extensively, besides having a squad of eight Germans imported from Germany on a year's contract to do subsurface work with an instrument somewhat like a seismograph. Prior to coming to Texas, these Germans were engaged by Marland in doing subsurface work in Oklahoma, and are contracted for until May, 1924. These Germans are considered authorities on the use of the seismograph's recording waves in determining the approximate depth, thickness and nature of formations underlaying the earth surface when a large charge of dynamite or other explosive is fired off near the location of the instrument."

Literary Digest 1925

In the *Literary Digest*, April 25, 1925 we read in the article: "*Finding Oil with Earthquakes*": "Dr. L. Mintrop, a German seismologist, is the originator of the method."

Scientific American 1925

"*Scientific American*" of December 1925 referred to the seismic method in the article: "*Buried Treasures*", subtitle "*Apparatus for Locating Underground Minerals*", and wrote: "This method was invented by Dr. L. Mintrop, a German seismologist."

Engineering and Mining Journal 1926

In "*Engineering and Mining Journal Press*" of January 9, 1926 Dr. C. A. Heiland, now Professor at the Colorado School of Mines, wrote under the heading: "*Instruments and Methods for the Discovery of Useful Mineral Deposits*": "Acoustic waves can be used, as suggested by Fessenden, or else seismic waves, as recommended by Mintrop. Mintrop's method partakes more of the practice which is usual in seismology and does not necessitate boring in the area prospected." "Mintrop's method has a wide field of application; almost every kind of stratified deposit occurring in practical geology can be defined by its means."

Wroblewski 1926

In "*The Oil Weekly*" of June 11, 1926 Adam Wroblewski wrote under the heading: "*Geophysical Methods Used in Location of Oil and Other Minerals*": "Fessenden's acoustic method requires sinking or boring of shafts in the area to be investigated, therefore it is expensive and not in general use. The photo-type of the seismoscope was built in China 1790 years ago; the first to apply it in prospecting was Dr. L. Mintrop, director of the Seismos Company Ltd., Hannover, Germany."

Weinzierl 1927

In "*The Oil Weekly*" of Sept. 2, 1927 John F. Weinzierl discussed the introduction of the German geophysical methods in the great petroliferous areas of Texas and Louisiana, under the heading: "*Development of Geophysical Science in Gulf Coast Exploration.*" In the chapter "*The Seismic and later Geophone Methods*" we read: "Notwithstanding the fact that the torsion balance preceded the seismograph on the Gulf Coast, the seismograph and the geophone were really the instruments to bring the greatest results. Contrary to the general belief, the seismograph was first applied on very difficult structural country instead of the more or less easily found shallow salt domes. Also in about 1922 microphone experiments were being tried out by Dr. Haseman for the Marland Oil Company and were successful on the Hewington limestone in the Mervine field in Oklahoma, but not so in the Wellington shales in this vicinity.

It was probably due to Dr. van der Gracht's activities more than anyone else that the Marland employed a scientific crew brought over from the "Seismos" Company in Hannover, Germany, by Dr. Mintrop, its director. This company has had success on different kinds of structural work in Europe and especially on salt domes in Poland. In July 1923, upon arrival of Dr. Mintrop, the writer, at that time an employee of the Marland, was put in charge of this work. After various moves about the Mid-Continent from northern Oklahoma down into North Central Texas and various results encouraging and otherwise had been obtained, it was finally decided to try the seismic method on the Gulf Coast in the search of Salt Domes."

In the article *"Science Taking Hold of Oil Finding"* by F. C. Brown, of the Bureau of Standards, see *Oil and Gas Journal of Jan. 7, 1926,* we read in the discussion of an acoustic method: "This method is rather an improvement over the Mintrop seismic system (Germany)." Brown 1926

On the great successes of the Mintrop seismic method information can readily be obtained by reading the numerous articles in *"The Oil Weekly"* and in *"The Oil and Gas Journal"*. It may be added that none of these articles were inspired by Mintrop, nor by associated parties. The first dome was found by the Seismos Company, near Orchard, Ford Bend County, Texas, in September 1924. (Sometimes referred to as Moore's Field). It was confirmed by a test well in November of the same year. *The Oil Weekly of Nov. 21, 1924,* refers to this in the article: *"Seismograph Proves Succesful on Coast"*. "Previous to drilling this hole (on Orchard) existence of the dome was indicated through experiments with the seismograph, which has acquired the popular title of blasting throughout the coastal counties." Oil Weekly 1924

The Orchard Dome was the first dome to be discovered in America with the seismic method. In the first three years about 20 other domes followed. This is reported in detail by Logan in an article in *The Oil Weekly of Oct. 21, 1927,* entitled: *"Coastal Operations Center on Determined Domes, Volume of drilling now under way is result of discoveries made by geophysical exploration."* Logan 1927

In *The Oil Weekly of Sept. 4, 1925* we read: "The first salt dome located in the Gulf coast by the seismograph was Orchard dome, in Fort Bend County, which was discovered by the Gulf Production Company's Moore Nr. 1, December 21, 1924." Oil Weekly 1925

Already one year after the discovery of the Orchard Dome an article appeared in *The Oil Weekly: "Finding salt domes that formerly took years of drilling"* in which we read: "All in all the coming of recent geophysical methods of finding salt domes has practically brought about a reawakening in the [oil] industry." And the *American Institute of Mining and Metallurgical Engineers* wrote in 1926, under *"Development of the Gulf Coastal Area during 1925":* "Geophysical exploratory work has practically displaced wildcat-well drilling in the search for new salt domes in this area. The new scientific methods have proved much more efficient there than the slow process of drilling." Mining and Metallurgical Engineers 1926

How much the seismic method brought to America by Mintrop in 1923 surprised the experts there, may be seen, among other things, from an article by the well known geologist of the Standard Oil, Wallace E. Pratt, in the *Bulletin of the American Association of Petroleum Geologists in 1926,* in which we read: "Two new salt domes in Pratt 1926

Texas. There is something new under the sun." "For the first time in the history of the Gulf Coast Oil industry it is possible to announce, with absolutely no risk that any informed student of the salt-dome area will question the accuracy of the announcement, that a new salt dome has actually been discovered, without any well having been drilled to prove the discovery or even to test the area. This is tantamount to the assertion that our confidence in the seismograph (by means of which this discovery was made) in geophysical exploration has already come to be perfect. In other words, wherever the seismograph registers the presence of a buried salt dome, Gulf coast operators generally are now willing to accept the verdict just as confidently as though a well had actually been drilled into dome material."

Davis 1927

The extremely great importance of the seismic method for the finding of new salt domes also follows from an article on "*Seismograph Dome Discoveries come with rush*" by Wallace Davis in *The Oil Weekly of April 15, 1927*, which reads in part:

"Through a recent campaign of seismograph exploration, four major companies got results which stand unparalleled in the history of the search for new potential productive spots by bringing to light six new salt domes and indications of two others within a radius of 60 miles in Southern Louisiana during a period of a few weeks. By this unprecedented rush of discoveries the potential oil reserve of Coastal Louisiana is augmented 36 per cent, considering nonproductive domes already known on proven fields, while the new domes raise the percentage of previously discovered domes which are yet non-productive, 72 per cent. The statement concerning the territory's possible oil reserve is of course an estimate arrived at on a basis of all domes having the same production possibilities.

The area of the new discoveries borders in a general trend along the Mississippi River, five of them lying on the west, one on the east side and a probable additional dome on each side. One point of great significance in the new finds is that they extend the possibility of major production further eastward, marking the first coastal salt dome discovery east of the Mississippi. Another point outstanding in the discovery is the value of geophysical instruments in locating production spots; knowledge of the presence of domes which before the coming of geophysics were found and outlined after vast expenditures in rank wildcatting over periods of several years."

Barton 1927

In the *November number of "Economic Geology", 1927*, Donald C. Barton, the well known American geologist, wrote on "*Applied Geophysical methods in America*" (Page 650):

"Seismic Method. — The application of the seismic (or sonic) method to the determination of local geologic structure was first worked out in 1913 by Fessenden, who in a series of field experiments near Framingham, Mass., developed the instruments and technique to the point where he was able to make practical application of the method. He tried to interest some mining companies in the method, but being unsuccessful, he dropped work with the seismic (or sonic) method for other lines of invention, and no practical application of his results seems to have been made. Eckhart, Haseman, Karcher, and McCollom in 1921 experimented in Oklahoma with a seismic method. Their results at the time seemed rather negative but very recent work shows that the apparent failure at that time was due largely to lack of encouragement and to limited financial resources. The initial impetus to the present extensive use of the seismic (or sonic) method is due very largely to L. Mintrop, and his "Seismos" Company of Hannover, Germany. Working as a junior colleague of Wiechert of Göttingen, he developed his instruments and technique during the war, and by 1921 had demonstrated the potentiality of the method, but apparently had not done much actual surveying of geologic structure. Late in 1923 his method was introduced into Mexico by the Royal Dutch Shell, and about the same time he got the Marland Oil Company to try out his method in the Mid-Continent area, and slightly later, the Gulf Production Company to try out the method on the Gulf Coast salt domes. The success of the method in the Gulf Coast is due in very considerable part to the encouragement and support given to it from the start by L. P. Garret of the Gulf Production Company, who previously had imaginatively foreseen the possibilities of the method in reconnaissance for new salt domes. The discovery by the seismograph of several salt domes late in 1924 gave great impetus to the use of the method. By the spring of 1926, Ricker, Eckhart, McCollom, Rieber and Karcher, all Americans, had perfected seismographs, some of them radically different from Mintrop's seismograph, and had radically improved some of the instrumental technique of the method, and during the year several additional seismographs of American design were tried out in the field. The best American method is probably somewhat superior to Mintrop's. Up to 1926, the "refraction" method was the only in practical use, although there had been some experimentation in the attempt to perfect a method of using waves directly reflected back at a high angle. During 1926 the Geophysical Research Corporation perfected the instruments and technique of a reflection method to the point of practical applicability."

The *Saturday Evening Post of March 3, 1928*, contained a long article by *Isaac F. Marcosson* on "*After Petroleum — What?*" in which a survey of the whole oil industry was given. The chapter on the finding of new oil deposits contains the following passage, under the title: "*Artificial Earthquakes*": "Baron Mintrop, a German nobleman, is largely responsible for the development of the standard oilfields apparatus now in use. His war experiences equipped him to employ it in geological formations. He made the first survey in this country, with his own staff of operators and instruments. Thus indirectly the great conflict has made a valuable contribution to the petroleum industry." Marcosson 1928

In *The Oil Weekly of Jan. 18, 1929 Mark C. Malamphy* discussed "*The Seismograph in the Gulf Coast*" in a comprehensive article, writing: "While the seismograph has been used for many years in the study of earthquakes, only recently has the portable type of field instrument been built and adapted to the study of subsurface strata in the search for potential oil producing structures. In 1923, Mintrop, a German scientist, first introduced the instrument to the oil fraternity on the American continent. There had been a considerable amount of preliminary work done by American scientists prior to this time but no commercial work had been attempted. Working under contract with the Gulf Production Company, Mintrop was successful in locating several salt domes in the Gulf Coast in the ensuing year. These discoveries gave considerable impetus to the development of seismograph equipment, and in a few years many of the major companies had developed instruments of their own." Malamphy 1929

This paper was discussed in the *Information Circular, Geophysical Abstracts No. 1 of May 1929* (issued by the Department of Commerce, Bureau of Mines 1929

Bureau of Mines): "A brief review of the history of seismographic exploration in Texas is followed by an elementary description of the fundamental ideas involved in the method, the principles on which the different types of seismographs are based, on a statement of the main physical facts which determine the velocity and path of an explosion wave through the ground. This is followed by an outline of the method of working and of interpreting the results, illustrated by a diagram and graphs of the time-distance curve. These graphs are entirely imaginary and represent what the writer thinks should happen under the assumed conditions according to the still popular "Mintrop theory"; no other method of interpretation is mentioned, so that the reader is left to infer that these ideas are universally accepted." With the last sentence the Bureau of Mines alludes to recent improvements of the seismic method.

Logan 1929

In *The Oil Weekly of June 26, 1929 Jack Logan* wrote an article on "*Discovery of deep domes revises Gulf Coast Potentialities*", which gives a very comprehensive description of the historic and economic development of the oil fields of Texas and Louisiana, due to the application of geophysical methods of investigation, especially of the seismic method. With reference to the last Logan wrote: "The first seismograph crew was brought to the Gulf Coast for the Marland Oil Company. Soon afterwards Gulf Production Company had three troops working in the Gulf Coast. A monopoly on the seismic work was held at that time by the 'Seismos' G. m. b. H. of Hannover, Germany, directed by Dr. L. Mintrop. The Marland Oil Company and Gulf Production Company employed the 'Seismos' troops for the early work. Moore's field (Orchard dome), found the latter part of 1924, is the first discovery credited to the seismograph. Long Point and Moore's field were the only geophysical discoveries in 1924 in the Gulf Coast."

It may be mentioned here that the Seismos Company enjoyed the monopoly by no means on account of a patent, because the latter one was not awarded until 1926. It possessed the monopoly because the seismic method was new.

Barton 1929

In 1929 *The American Institute of Mining and Metallurgical Engineers, New York*, published a book on "*Geophysical Prospecting*". Donald C. Barton contributed the part on "*The Seismic Method of Mapping Geological Structure*" and reported on the history of the seismic method. He emphasized that he chiefly followed a presentation of the history by Schweydar and Reich. The passage in Barton's article reads: "The first proposals for the use of artificial earthquakes in the study of velocity of elastic waves in the surface formations of the earth's crust were made before 1888 by the English seismologists Mallet and Abbot. Partly on the basis of their work A. Schmidt in 1888 proposed the use of time distance graphs of artificial earthquakes to study the variation of velocity with depth. Belar in 1902 proposed the practical application of such investigation in connection with boring tunnels. Galitzin repeatedly (1912, 1913) proposed the use of explosions to study the velocity of the longitudinal and transverse waves in the uppermost formations and pointed out that the velocity depended in a high degree on the physical character of the beds and that from changes in the velocity, conclusions could be drawn in regard to the composition of the beds. Somewhat the same thought was proposed by von dem Borne (1908), by Benndorf, Udden and others. The first application of the use of artificially excited elastic earth waves to the determination of local structure was worked out by Fessenden, who in 1913 in a series of field experiments near Framingham, Mass., developed the instruments and technique to a point of practical applicability and patented his method. He used an adaptation of sonic sounding for depth in water; a sonic sounder, immersed in water in a bore hole, was used to set up a controlled series of compression waves in the water, which in turn set up elastic earth waves in the surrounding ground; sonic receivers were immersed in water in other bore holes and connected with photographically recording galvanometers; from the reflection, refraction, and absorption of the waves, conclusions were drawn in regard to the character of the intervening ground.

L. Mintrop and O. Hecker started experimenting early during the Great War, Mintrop with a mechanical seismograph and Hecker with a microphone and recording galvanometer. Working as a junior collegue of Wiechert of Göttingen, Mintrop perfected his instruments and technique to the point of practicability and in 1919 received a basic patent, since revoked (Note: Barton mentioned here the German working-procedure patent), on the application of the seismic method to the working of local geologic structure. By 1921, he had demonstrated the potentiality of the method but apparently had not done much actual field surveying of geologic structure.

In this country, Eckhart, Haseman, Karcher, and McCollom experimented with a seismic method in Oklahoma in 1921. Their results then seemed rather negative but the apparent failure at that time was due largely to lack of encouragement, to limited financial resources, and to the attempted application of the method in an area of slightly too complicated geology.

In the early summer of 1923, Mintrop's method was introduced in Mexico by the Royal Dutch Shell. In the late summer or autumn of the same year, his method was introduced by the Marland Oil Company in Oklahoma and in the fault line district north of Powell, Texas, and in the spring of the following year in the Gulf Coast Salt dome district of Texas. The discovery of several salt domes late in 1924 by a troop of Mintrop's 'Seismos' Company, working for the Gulf Production Co., gave great impetus to the use of the method.

By the spring of 1926, Andersen, Eckhart, Karcher, McCollom, Ricker, Rieber and Trueman in this country had perfected seismographs of varying degrees of fieldworthiness and of varying types, some of them radically different from Mintrop's seismograph, and some of the instrumental technique of the method being radically improved."

In the same article Barton wrote on the success of the method introduced by Mintrop: "In the discovery of salt domes in the Gulf Coastal Plain region of Texas and Louisiana, the seismic method has scored the most brillant success. The general effect of the introduction of the seismic method into the salt dome area of Texas and Louisiana has been to speed up the discovery of salt domes about 75 years."

The Italian Professor Arnaldo Belluigi wrote the following about the Mintrop Method in *Echi e Comenti, on July 5, 1927:* **Belluigi 1927**

" It is known how petroleum is searched for today, indirectly with the torsion balance, and in some cases with special seismographs, which are particularly sensitive. Seismic investigation has already made remarkable progress in the field of time registration by Mintrop. It is, however, necessary, if the method is to be successful, that the tectonics be simple enough; otherwise it would be difficult (we prefer to avoid the word impossible) to find one's bearing in the seismograms, which show a very complicated way of acting of the elastic waves in the subsurface."

In the same journal Belluigi, on Oct. 5, 1927, wrote: "Mechanical waves produced by artificial explosions in the field, waves, which are sometimes called pseudoseismic, are used for investigations as an aid to mining, as is well known. The seismic method has already had successes (however, not as many as the gravimetric method), and its actual successes were obtained by Dr. Mintrop in the outlining of large salt domes. We would like to point out that the method under Dr. Mintrop, the director of the Seismos Company, and a distinguished seismologist, only had successes because Mintrop worked with the seismograph for more than ten years and commands an experience which cannot be extemporized. However, the results which are known only refer to the determination of salt domes or of bedding planes in general, which simply throw back the mechanical waves. Nothing can be said about results in other cases, for instance of investigations of discordant, or in some way disturbed, areas."

Haddock 1927

The British also acknowledge Mintrop's priority. For instance M. H. Haddock, F. G. S., A. M. I. M. E. wrote in *"The Colliery Guardian" of Aug. 5, 1927:* "Dr. Mintrop has undertaken observations collecting and developing usable methods of investigation through the firm "Seismos" Ltd., in Hannover. All workers in this field are indebted to the pioneering work of Wiechert and his able pupil Gutenberg, the result of whose labours, combined with the very extensive experimental material of many earthquake observations, have brought about practical conclusions upon which modern methods of location by means of time travel curves or course time curves depend."

Rankine 1929

The problem which was solved by the Mintrop method was very clearly characterized by the British Professor A. O. Rankine, O. B. E. D. Sc. Rankine wrote in *"Nature" May 4/11, 1929:* "The phenomenon with which we are dealing is the same as that which has recently been recognized as operative in natural earthquakes. Even in near earthquakes, where the curvature of the earth plays no important part, the records of seismographs show preliminary displacements which apparently correspond to "rays" from the earthquake source which pass from an upper stratum (of low propagation velocity) at the critical angle into a lower stratum (of higher propagation velocity), run parallel to the interface and eventually emerge again at the critical angle to reach the seismograph on the surface. This is, of course, an "optical path" of an extreme character according to the ordinary laws of refraction, but since the initial incidence is at the critical angle, total reflection would occur according to the same laws, and no energy at all would be associated with the path in question. *Dr. Jeffreys (On Compressional Waves in Two Superposed Layers, Publications Cambridge Philosophical Society vol. 23. p. 472, 1926)* has however shown that if the problem be treated as one of diffraction instead of simple refraction, the rather curious result emerges that a finite fraction of the initial energy may be expected to reach the seismograph (as in fact found in practice) at a time which is the same as that obtained by considering the extreme optical path above described. This applies to longitudinal disturbances. There are in solids, of course, transverse disturbances as well, but these travel more slowly, and need not concern us here, since, as has been already stressed, the question is one of first arrivals.

Prof. Mintrop was the first to recognize the applicability of this phenomenon to the smaller scale problem of the relatively shallow formations in the earth, using artificial explosions instead of natural earthquakes. As a result he has initiated a practical system which has been widely and successfully used to determine the depths of such formations."

The recognition of the Mintrop Method is quite general. Neither in German nor in foreign publications can any passage be found that denies the priority of the seismic method to Mintrop. The method mentioned in the preface and described on page 33 (Fessenden Method) is not mentioned in any publication, exept in "*Economic Geology*" and in "*Geophysical Prospecting*", where Barton reports that Fessenden in vain tried to interest mining companies in the method. In view of the fact that the Fessenden Method uses bore holes, the rejection of this method by industry can be understood.

The United States Patent Office recognizes the difference in principle between the methods of Fessenden and Mintrop, by granting to the last mentioned the *seismic patent No. 1,599,538, under date of Sept. 14, 1926* with priority of the German application of December 6, 1919. The patent is called "*Geological Testing Method*". Its text is appended: **Mintrop 1926**

Patented Sept. 14, 1926. **1,599,538.**

UNITED STATES PATENT OFFICE.

Ludger Mintrop, of Bochum, Germany.

Geological Testing Method.

Application filed December 13, 1920, Serial No. 430,432, and in Germany December 6, 1919.

(Granted under the provisions of the Act of March 3, 1921, 41 Stat. L., 1313.)

My invention relates to a method of ascertaining the geological structure of the strata appertaining to a particular region such method being useful in particular for mining operations when developing a lode or opening a seam. Up till now in all those cases where the natural formation of the ground does not throw light upon the subject, recourse must be had to borings. However, the sinking of bore holes regularly constitutes a tedious and expensive operation which moreover cannot even be employed in all cases. Again, whenever it has been merely a question of primarily obtaining an idea of the approximate composition of the strata, the divining-rod has been, as may be well known, experimented with. Notwithstanding, as is well known to those skilled in the art, it has been so far impossible to establish an indisputable connection between the action of the divining rod and the geological peculiarities of the subsoil. A second method of working and serving the same end of securing merely approximate data, consists in the application of electric waves from the action of which certain definite inferences are then drawn as to the arrangement and the peculiar nature of the strata.

Now in accordance with my invention it is likewise intended that waves per se shall be employed for the purpose of ascertaining the arrangement of the strata, however, not electric waves but elastic waves, produced by mechanical means. I employ these waves in appreciation of the fact that the connection of such mechanically generated waves with the properties of the strata, such as density and elasticity, will be far more direct and therewith far more intimate than the correlation to electric waves. To this end, there are generated in accordance with my invention within the measuring area and at a suitable point thereof, artificial mechanical waves, say, for instance, by the detonation of a certain quantity of explosives, the elastic propagation of these mechanical waves through the different beds being recorded by a seismograph set up at a suitable distance remote therefrom. The records thus obtained are then made use of in exactly the same manner customary in seismology for the purpose of setting up the so-called "travelling time curve" and in order to compute the velocity of the waves at the various depths. I am aware that in seismology, attempts have already been made to arrive at certain conclusions relatively to the general geological formation of the earth as a whole.

For general information on this comparatively recent art reference is made, especially with regard to the use of "travelling time curves" or sometimes shortly called "time curves", to "Modern Seismology" by G. W. Walker, published in 1913 by Longmans, Green & Company, New York and London, where on page 53 and following, the function and use of travelling time curves in seismology is dealt with in detail. For the present purposes the use of these curves will be shortly explained hereinafter.

Thus far, however, the investigators were able by such observations to only draw approximate and general conclusions as to the structure of the entire earth, and at that with observations based only on accidental natural earth shocks of uncontrollable duration and origin.

On the other hand, in the present instance, the noteworthy feature is that the observation to be effected does not rely upon the uncertain occurrence of natural earthquakes, but that there are produced, purposely and by special means, artificial earth shocks, in consequence of which alone the possibility is created of carrying out observations of this character for a particular locality and for a definite period of time. Of essential importance in this connection is moreover the fact that by means of my improved method there is now also provided a convenient form of comparative measurement for the purpose of determining the propagation of the elastic waves within the strata and of their time of arrival at the seismometer, respectively, by employing, for the purpose of ascertaining the moment when the elastic oscillations are excited, either the sound waves created in any case on the detonation of the explosive charge, or else by effecting a transmission by means of light, electric current or electric waves, respectively.

From the surface speed and the three dimensional speed of the waves, as also from the depths down to which the waves have penetrated the strata, but in particular, from the mutual relation of the velocities of the longitudinal and transversal waves, inferences may be drawn respecting the elastic properties of the strata traversed by the waves. It will thus be found that especially from the points of inflection and the bends in the "travelling time curve", there may always be inferred that there exist fissures in the elastic properties of the strata, as also inflections, refractions, and reflections at the marginal levels thereof.

The manner in which my novel method is employed is illustrated in the accompanying diagrams in which:

Figure 1 diagrammatically represents the set-up of the apparatus preparatory to making the observation;

Figure 2 represents a portion of the recording tape on which an observation of the artificially produced earth shock and its traveling time has been recorded;

Figure 3 is a straight line traveling time curve composed from a plurality of individual observations such as are recorded on the tape shown in Figure 2;

Figure 4 represents a straight line velocity curve resulting from the traveling time curve in Figure 3;

Figure 5 represents a bent traveling time curve as a resultant of increasing density of the ground under observation;

Figure 6 represents a velocity and a depth curve obtained from the traveling time curve in Figure 5;

Figure 7 represents diagrammatically a traveling time curve with bends in it as a result of a sudden change in the character of the underlying strata; and

Figure 8 represents the velocity and depth curves obtained from the observations plotted in the traveling time curve Figure 7.

Referring to Figure 1, 1 represents a recording field seismograph for the purposes of the present invention and of a construction and character described and illustrated in my U. S. Patent No. 1,451,080, dated April 10th, 1923. The recording seismograph shown in Figure 6 of that patent consists of a pendulum device and a photographic recorder, both of which instrumentalities may be assumed to cooperate in the present case as described in the aforementioned patent, the pendulum device being denoted in the present Figure 1 with 2 and the photographic recording device being diagrammatically indicated at 3. At a suitable distance from the seismograph 1 a cartridge 4 filled with suitable explosives is located and an electric circuit 6 is established between the cartridge and the recording device 3, including the battery 5, of such character that when the cartridge is exploded the circuit is interrupted and thus, by suitable means described in the aforementioned patent, a mark 9 is made on the recording tape illustrated in present Figure 2.

Referring to Figure 2 a tape portion is shown at 7 and assumed to continuously travel at a certain rate of speed, means being provided in the recording apparatus to make recording marks at stated equal time intervals, for instance in seconds, as shown at the lower tape edge in Figure 2. So long as no shocks arrive at the seismograph a straight central line 8 is recorded on the tape by the means provided in the aforementioned apparatus. As soon as a shock disturbs the equilibrium of the seismograph pendulum, the mirror of the instrument oscillates and instead of making a

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Geological Testing Method.

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Fig. 1.

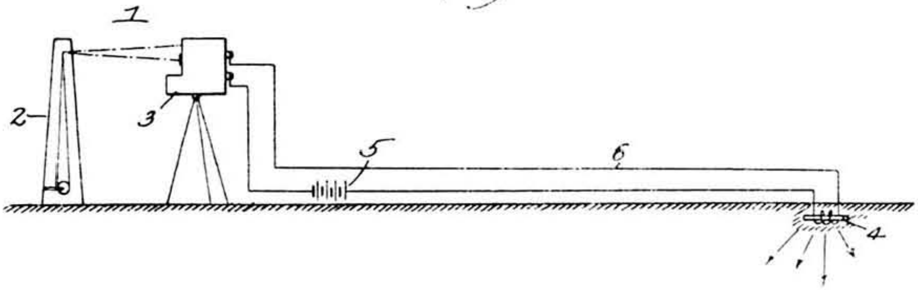


Fig. 2.

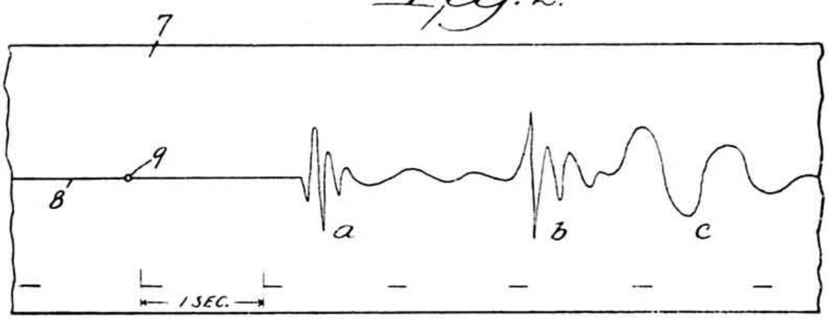


Fig. 3.

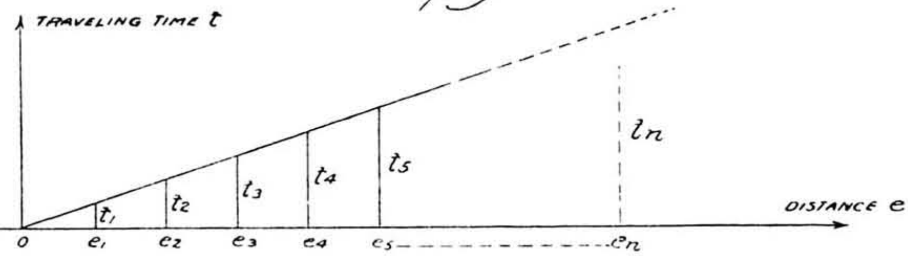
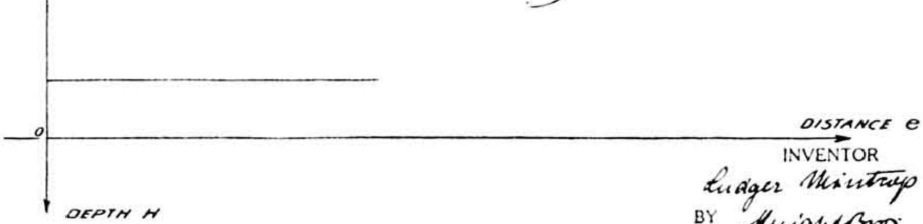


Fig. 4.



INVENTOR
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his ATTORNEYS.

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Fig. 5.

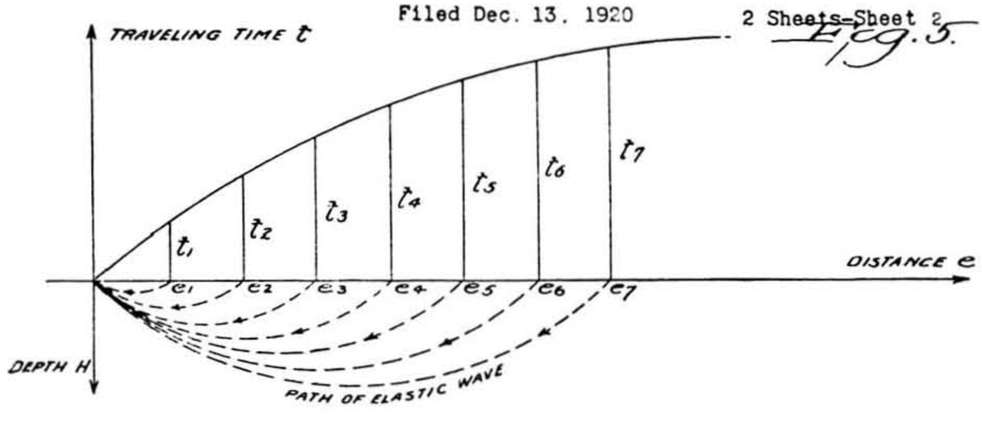


Fig. 6.

Fig. 7.

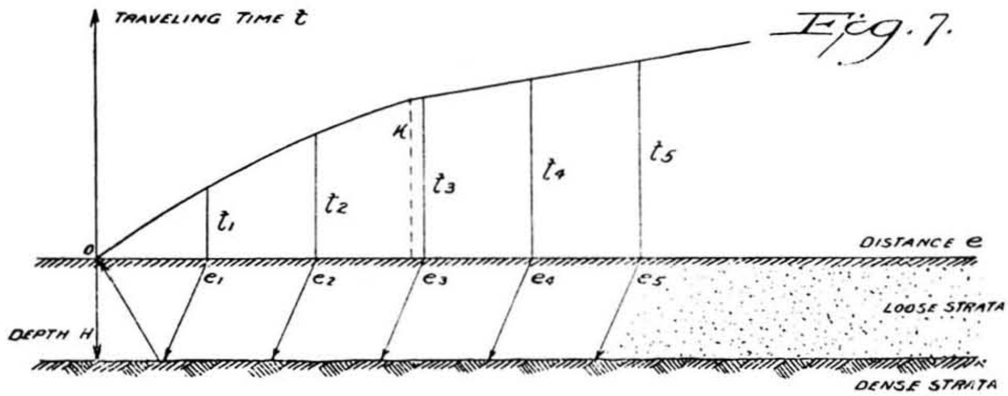
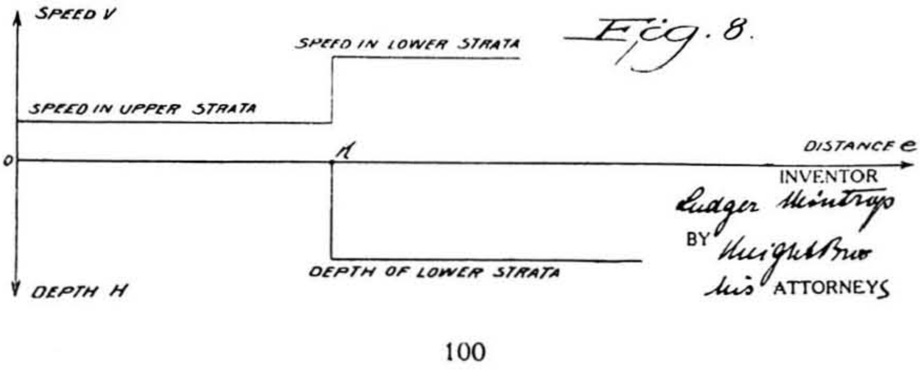


Fig. 8.



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straight line record on the tape, oscillations such as are shown at a or b or c are recorded.

By other suitable means shown and described in aforementioned patent, the interruption of the circuit 6 on the explosion of the cartridge records the vertical mark 9, above referred to, on the tape shown in present Figure 2. The time which has elapsed between the initial mark 9 and the appearance of the first oscillation a is called the "traveling time" of the elastic wave. A number of separate subsequent waves or oscillations are generally recorded on the tape due to the same explosion or shock. The first oscillations a are due to the elastic waves traveling through the ground, the second oscillations b are air waves and the third oscillations c are usually due to very long ground waves.

For the present explanation it is sufficient to receive the first sharply defined short ground waves noted by the oscillations a. The traveling time t thus recorded constitutes the time which these waves consumed in traveling from the point of origin to the seismograph.

This time will be the greater the further the seismograph is removed from the origin of the shock. Thus if the recording apparatus be assumed to remain stationary in one certain place and if successively a number of cartridges are exploded along a straight line further away from the seismograph, but at equal distances from each other, the traveling time increases in homogeneous ground proportionate to these distances. Such a straight line traveling time curve is shown in Figure 3 in which the ordinates represent the traveling times t and the abscissae represent the distances e from the seismograph, at which the shocks have been produced. In the example given the shocks are produced at the distances $e_1, e_2, e_3, \cdots e_n$ and accordingly the values of the traveling times $t_1, t_2, t_3 \cdots t_n$, have been observed at the seismograph, the soil conditions in the present example being assumed to be of such character that a straight line traveling time graph is obtained. From the measured distances and the observed traveling times the speeds or velocities of the wave for the different distances are obtained as:

$$v_1 = \frac{e_1}{t_1};\ v_2 = \frac{e_2}{t_2};\ v_3 = \frac{e_3}{t_3};\ \cdots\ v_n = \frac{e_n}{t_n}$$

Being assumed that:

$$\frac{e_1}{t_1} = \frac{e_2}{t_2} = \frac{e_3}{t_3};\ \cdots = \frac{e_n}{t_n}$$

It follows that:

$$v_1 = v_2 = v_3 \cdots = v_n$$

In other words, the speed of the waves is constant, and therefore, this explains why the traveling time curve is a straight line. Thus in the graph shown in Figure 4 in which the speed of the waves is plotted against the increasing distances e, the speed curve is a straight line in parallel to abscissae line of the graph. Since the speed curve shows a constant speed, the corresponding depth curve would also show a constant depth and would accordingly be represented as a straight line coinciding with the abscissae line, which shows that the depth is zero. In other words, this indicates that the waves have traveled along the surface of the ground in the example assumed in Figures 3 and 4.

In Figures 5 and 6 are illustrated graphs which more closely resemble actual observations, even though it is assumed in this example, that only one strata is observed. The observations represented in Figure 5 are again assumed to have been made with shocks produced at different distances $e_1, e_2 \cdots e_n$ from the point of observation. It will be noted, however, from the uniformly curved character of the traveling time curve that the traveling time does not increase proportionately with the distance. In this graph the approximate paths of the elastic waves are indicated by lines provided with arrows, and it will be noted that the deeper the shocks penetrate into the ground the shorter becomes their traveling time, i. e., the more their speed increases. The corresponding traveling speed curve is shown in Figure 6. Such an increase in speed with increase in distance between the point of shock origin and the point of observation would be caused for instance in sandy soil by the fact that quite naturally the sand is comparatively loose at and near the surface, whereas it increases in density with the depth owing to the increased pressure of the upper layers of sand. Thus the curved paths of the elastic waves shown in Figure 5 are produced, penetrating deeper and deeper into the ground as the distance is increased, whereas in Figure 4, which assumes theoretically uniformly loose soil, the shocks would only travel along the surface of the ground. It thus follows that the traveling time curve will be curved the more, the more the density of the sub-surface increases, in other words, the more the traveling speed of the waves increases with the depth.

Inversely a definite increase in speed observed corresponds with a definite increase in depth which the traveling waves have attained on their way from the point of origin to the point of observation. Figure 6 illustrates the depth curve corresponding with the speed curve plotted from the observations. The different speeds observed at the different distances are easily calculated from the traveling time curve originally obtained from the observations and shown in Figure 5 as follows:

$$v_1 = \frac{e_1}{t_1}; v_2 = \frac{e_2 - e_1}{t_2 - t_1}; \cdots\cdots v_n = \frac{e_n - e_{n-1}}{t_n - t_{n-1}} \text{ or } v_1 = \frac{\Delta e_1}{\Delta t_1}; v_2 = \frac{\Delta e_2}{\Delta t_2}; \cdots\cdots v_n = \frac{\Delta e_n}{\Delta t_n}$$

In the examples represented by the combined graph and subsoil diagram Figure 7 and the graph Figure 8, the case is assumed that a strata of considerable density, for instance limestone, underlies a comparatively soft upper strata, for instance loose sand. When observations are made in such a case the traveling speeds, instead of gradually and uniformly increasing with the distance as shown in Figure 5, increase abruptly from the point at which the elastic waves, heretofore traveling in loose sand, enter the dense limestone. At such a point the traveling time curve suddenly shows a sharp bend (at k in Figure 7). While thus the speed derived from the first part of the curve shows the traveling speed in the upper loose strata, the portion of the curve following the bend gives an indication of the propagation speed in the lower denser strata. Such observations result then in a speed curve as shown in Figure 8 which shows a sudden increase in speed when the waves enter the denser strata, and correspondingly the depth curve assumes a sudden downward path at this point.

These simple examples given, plainly demonstrate that by thus observing on the surface of the ground the varying speeds of the elastic waves in underlying strata, the desired information as to the condition of the subsoil may be ascertained without physically examining the different strata, such for instance as by bore holes. Such seismic observations give the very definite information that in a certain depth a strata of different character underlies the strata visible at the surface. As explained hereinbefore, the character of such an underlying strata, whether dense or loose, is ascertained from the traveling speed, obtained indirectly from the traveling time curve, since the speed is the greater the greater the density of the strata. For instance limestone propagates elastic waves at a much greater speed than sandstone and in turn, sandstone propagates at a much greater speed than for instance clay.

In turn, the foregoing clearly shows that thus also the depth of the strata can be indirectly ascertained from the observed traveling time curve.

For example, referring to Figures 7 and 8, let v_1 and v_2 represent respectively the speeds of the elastic waves in the upper and in the lower strata and let k be the distance of the bend in the traveling time curve from the starting point of the traveling time curve (O), then the depth H of the lower strata is calculated from the equation:

$$H = \frac{v_1}{v_2} \cdot k \cdot c$$

wherein c represents a function depending upon the relation $\frac{v_1}{v_2}$ and which is known to all those skilled from the well known mathematical development of the earthquake theories.

For instance if v_1 is calculated from the observation as $= 1000$ m/sec; $v_2 = 2500$ m/sec, and thus

$$\frac{v_1}{v_2} = 0.4$$

the value of c would be calculated as 0.32 according to well known formulae. If now the point k at which the traveling time curve bends is measured as 100 meters, the depth of the denser strata would be 32 meters.

For general information to those skilled in the art attention has already been called hereinbefore to the book entitled "Modern Seismology" by G. W. Walker, which contains all information necessary to make the required calculations referred to hereinbefore, the present method being a novel embodiment and novel practical use of the seismic theories earlier developed.

However, the factor c may in practice also be determined empirically by recording traveling time curves in a territory which has been completely explored as to its geological character by actual drilling operations. Such empirical methods would obviate making use of many of the formulae used in natural seismological observations and calculations.

Observations of the above mentioned character also enable the ascertaining of the presence of a number of different layers of different density. In the same manner as explained hereinbefore the character and depth of the individual layers may be ascertained by observing the different bends in the traveling time curve.

Even though by these means it will not in all cases be always possible to exactly determine the particular species of mineral per se, yet it will in general suffice to ascertain to what depth the strata visibly appearing on the surface extend and what is the thickness of the more solid or looser layers following thereunder, respectively, whether the manner in which the layers succeed each other corresponds to the normal geological formation of the region or not. This point is of paramount importance in filling-in geological maps or when it becomes a question of fixing the spots in a certain region where bore-holes and shafts are to be sunk. Then again, for instance, deposits of lignite and rock-salt evince such a characteristic elastic reaction that deposits of this nature may be directly ascertained — while making due use of other observations — by means of my improved method. At the same time, the said improved method itself is extraordinarily cheap and simple, since only a few pounds of explosives are all that is required for each observation, while the seismometer employed in connection therewith is so constructed as to constitute a simple, light and handy instrument. Besides, the persons required to carry out the field operations need by no means be scientifically trained, as the computation of the results obtained by the observations may be carried out along scientific lines subsequently. In this manner the sub-surface conditions of several square miles of territory may be ascertained in a few weeks, in other words, at an extremely small fraction of time and cost required for the sinking of a single bore hole. The improved method may also be made use of, when sinking shafts in quicksand, by means of the freezing process, thus enabling the observers to ascertain to what extent the soil has already become solidly frozen.

In the place of the seismometer proper, which mechanically indicates the shocks produced and records them by the aid of a heliograph, use may likewise be made of a microphone adapted to render the shocks audible by means of an electric current in a telephone or in a galvanometer. This is based on an appreciation of the fact that, according to the elastic properties of the subsoil, the pitch of the waves produced by artificial shocks will vary, for instance more nearly resembling a "ring" than a "thud" in which case frequently characteristic accessory sounds will in addition make themselves heard. By comparison with the data obtained by means of a seismograph, or by direct reference to spots the geological structure of which is known, the true inferences may then be drawn.

To this end, acoustic appliances known as terrestrial listening devices and which have been widely employed during the late war for the purpose of determining mining operations on the part of the enemy, may be directly made use of, since devices of this kind are already suitably designed or else may be easily adapted to the purpose had in view. It will thus be understood that in the place of the pendulum use is made of a microphone, placed face down on the ground or slightly buried therein, and, instead of a photographic recorder, a telephone or galvanometer or the like is employed. I may however also record the "travelling time curve" by photographically recording the fluctuations of current arising within the microphone by means of an oscillograph or a like apparatus, the telephone being merely employed for the reception by sound. The use of a microphone further permits of ascertaining the moment at which the artificial concussions take place. By employing a microphone influenced both by the terrestrial and by the air waves one obtains two marks, one succeeding the other, in the curve recorded and which allow of easily computing the said moment. I may however also employ two separate microphones, one for the terrestrial and one for the air sounds and connect them with the oscillograph or the photographic recorder.

A device of this sort is fully equivalent, as far as accuracy of measurement is concerned, to the seismographic apparatus, but exceeds this latter in point of simplicity and light weight.

The methods hereinbefore described may however also be employed in combination, the acoustic receiver being for instance made use of in carrying out certain preliminary tests furnishing general data as to the geological character of a region, whereupon more exact special investigations are carried out with the aid of the seismometer.

I claim:

1. The method of ascertaining geological tectonic formations which comprises generating artificial seismic waves so as to cause them to be transmitted through the ground from a point selected at will and detecting the characteristics of said waves at a determinable distance from said point.

2. The method of ascertaining geological tectonic formations comprising generating artificial seismic waves so as to cause them to be transmitted through the ground from a point selected at will, detecting the characteristics of said waves and from said detected characteristics determining subsurface strata.

3. The method of ascertaining geological tectonic formations which comprises causing an explosive charge to detonate substantially at the surface of the earth so as to transmit artificially generated seismic waves through the ground from a point selected at will and detecting the characteristics of said waves.

4. The method of ascertaining geological tectonic formations which comprises generating artificial seismic waves so as to cause them to be transmitted through the ground from a point selected at will and ascertaining the travelling speed of said waves by observations at several distances from said point.

5. The method ascertaining geological tectonic formations which comprises generating from a point selected at will and substantially at the surface of the earth artificial seismic waves through the ground and ascertaining the travelling speed of said waves so as to cause them to be transmitted by means of a seismograph set up at a distance from said point.

6. The method of ascertaining geological formations which comprises causing an explosive charge to detonate at a point substantially at the surface of the earth so as to transmit seismic waves through the ground and ascertaining the travelling speed of said waves by means of a seismograph set up at a distance from said generating point.

7. The method of ascertaining geological formations which comprises causing an explosive charge to detonate at a point substantially at the surface of the earth so as to transmit seismic waves through the ground and receiving at a measurable distance from said point those seismic waves which precede the sound waves due to said detonation.

8. The method of ascertaining geological formations which comprises causing an explosive charge to detonate so as to transmit seismic waves through the ground from a point selected at will and detecting the characteristics of said seismic waves as well as of the sound waves generated by said detonation.

9. The method of ascertaining geological formations which comprises causing an explosive charge to detonate so as to transmit seismic and sound waves through the ground from a point selected at will and detecting the characteristics of said seismic waves as well as of the sound waves generated in the ground by said detonation.

10. The method of ascertaining geological formations which comprises causing an explosive charge to detonate so as to transmit seismic und sound waves through the ground from a point selected at will and ascertaining the travelling speed of said seismic waves as well as the character of the sound waves generated in the ground by said detonation.

11. The method of determining subsurface strata which comprises generating artificial seismic waves so as to cause them to be transmitted through the ground from a point selected at will and ascertaining the travelling speed of said waves in the different underground beds.

12. The method of determining subsurface strata which comprises generating artificial seismic waves so as to cause them to be transmitted through the ground from a point selected at will and ascertaining the travelling speeds of said waves in the different underground beds by noting the distance between the generating point and the point of observation and by observing the running time of said waves between said points.

13. The method of determining subsurface strata which comprises generating artificial seismic waves so as to cause them to be transmitted through the ground and observing the travelling speed of said waves for a plurality of known distances of travel measured at the surface.

14. The method of determining subsurface strata which comprises generating artificial seismic waves so as to cause them to be transmitted through the ground and observing the travelling speed of said waves over graduated known distances of travel measured at the surface.

15. The method of determining subsurface strata which comprises causing a plurality of explosive charges to detonate so as to transmit artificial seismic waves through the ground from points selected at will at a plurality of distances from the detecting point and ascertaining the travelling speed of said waves by recording the running times of said waves on a seismograph at detecting point.

16. The method of determining the depth of subsurface strata which comprises causing an explosive charge to detonate so as to transmit artificial seismic waves through the ground from a point selected at will and ascertaining the running time and the travelling speed of said waves by recording on a seismograph.

In testimony whereof I affix my signature.

Dr. LUDGER MINTROP.

On June 5, 1928 the appended U. S. Patent No. 1,672,495, with priority of August 14, 1922, was awarded to Burton McCollum: McCollum 1928

Patented June 5, 1928. 1,672,495.

UNITED STATES PATENT OFFICE.

Burton McCollum, of Chevy Chase, Maryland.

Method and Apparatus for Determining the Contour of Subterranean Strata.

Application filed August 14, 1922, Serial No. 581,866. Renewed March 5, 1928.

My invention relates to methods of determining the contour of subterranean strata or boundaries of geologic formations, and has among its objects the study of the geological conditions at depths that cannot be conveniently and economically reached by ordinary means. In particular, I have found that by the use of my invention it is possible to determine the location of deposits of various ores, mineral oils, and other valuable materials. My invention depends on the well known principle that if a sound wave be transmitted through the earth partial reflection of the wave takes place at the boundary between any two masses which differ in respect to certain of their physical properties. By properly utilizing the transmitted and reflected waves I am able to determine accurately the location, shape, and extent of such boundaries, which information is of great value for the purposes stated above. My invention is further described in the following specification, reference being made to the accompanying drawings.

Of the drawings:

Fig. 1 is a diagram showing the relation between the contour of subsurface strata and the occurrence of certain valuable mineral deposits.

Fig. 2 shows the principle of methods that have heretofore been unsuccessfully tried to accomplish the object here sought.

Figs. 3 and 4 are typical examples of records showing difficulties confronting previous attempts to accomplish the results obtained by my invention.

Fig. 5 shows in diagrammatic form a practical embodiment of my invention.

Fig. 6 shows a typical record obtainable through the use of my invention.

Fig. 7 shows in diagrammatic form the principle of an acoustic shield which I use to improve the character of the graphic records obtained in connection with the application of my invention.

Fig. 8 shows a combination of sound receiving devices which I have found particularly valuable.

Fig. 9 shows an arrangement of portions of the apparatus for determining the velocity of sound in the earth.

Fig. 10 shows a preferred method of fixing the sound receiving device in contact with the earth.

Fig. 11 shows an improved form of a sound receiving device which is useful in connection with my invention.

Figs. 12 and 13 show diagrammatic arrangements of microphonic devices which I have found useful in connection with my invention.

For the sake of clearness and brevity my invention is described below with particular reference to but one of its practical applications, namely, the location of deposits of mineral oils and natural gases. It will readily be seen however, that the method may be applied to determining the location of many other kinds of mineral deposits.

It is well known that in regions where deposits of oil or gas may be encountered the deposits are not distributed generally throughout the area, but are highly localized in pools occupying a relatively small portion of the total potential oil bearing area. The location of these pools is governed by a well known principle illustrated in Fig. 1. In this figure, (1) is the surface of the ground and (2) a dense subterranean stratum of irregular contour concave upward at (3) giving a synclinal fold, and convex upward at (4) giving an anticlinal fold. It is well known that in a potential oil bearing region the oil and gas accumulate locally at (5) under the anticlinal fold (4), it being forced upward into this position by the heavier salt water stratum (5a) beneath it. The problem of locating a pool of oil in a potential oil bearing region is therefore, one of determining the location of these anticlinal folds in the subterranean rocks. This latter, as stated above, is one of the objects of my invention.

Heretofore, numerous investigators have endeavored to determine the contour of subterranean strata by the use of sound waves reflected from them, but up to the present time none of these methods has been successful. Fig. 2 illustrates some of the fundamental difficulties that have confronted all these previous attempts and prevented their successful application.

B. McCOLLUM

Method and apparatus for determining the contour of subterranean strata.

Original Filed Aug. 14, 1922.

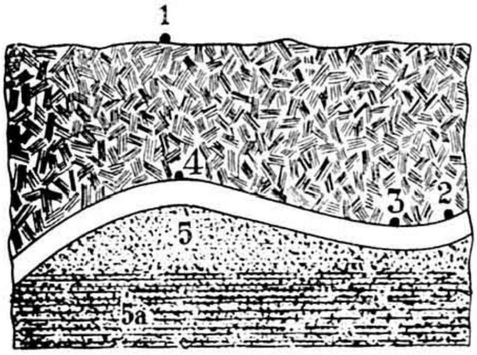

FIG. 1.

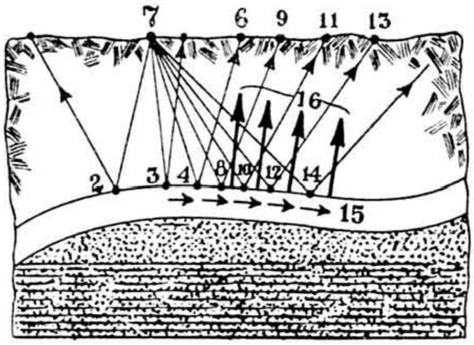

FIG. 2.

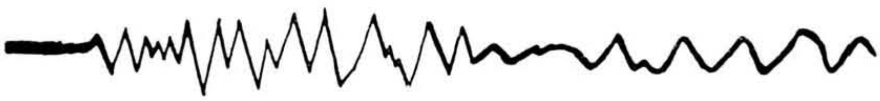

FIG. 3.

FIG. 4.

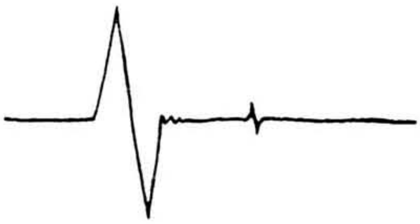

FIG. 6.

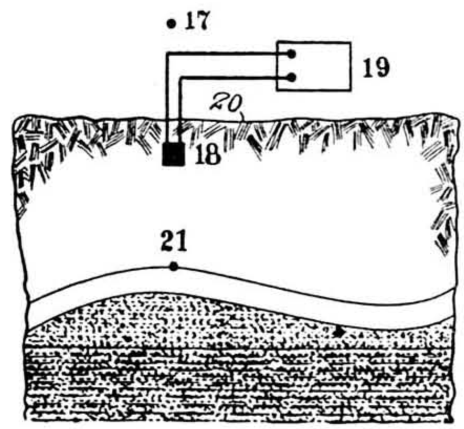

FIG. 5.

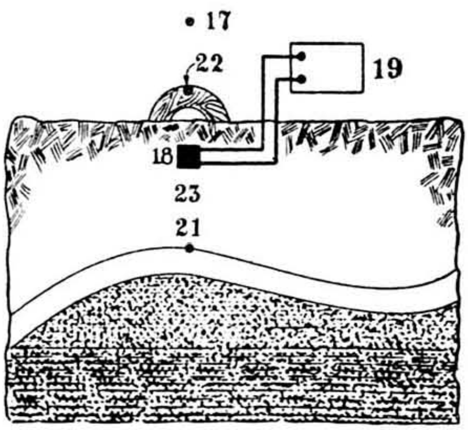

FIG. 7.

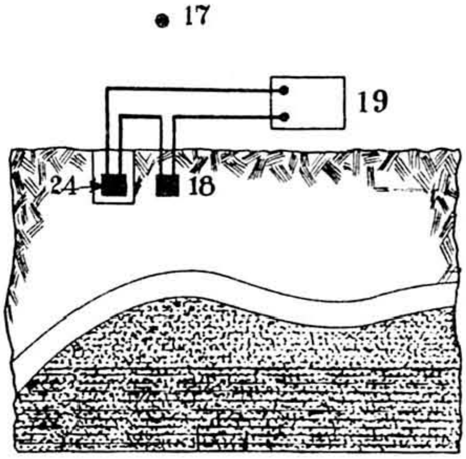

FIG. 8.

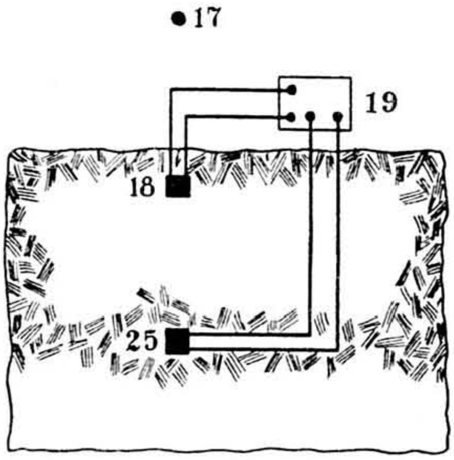

FIG. 9.

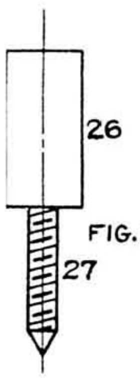

FIG. 10

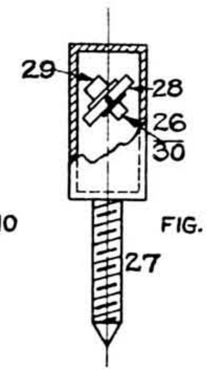

FIG. 11

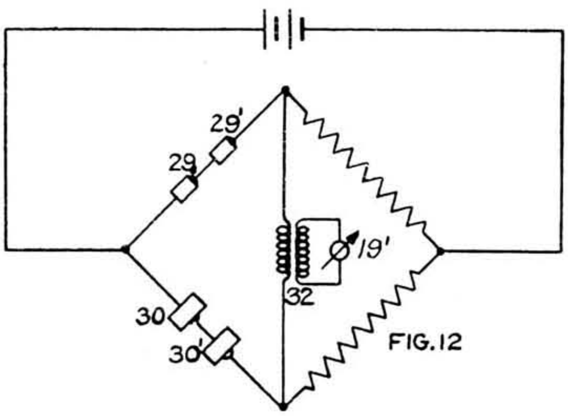

FIG. 12

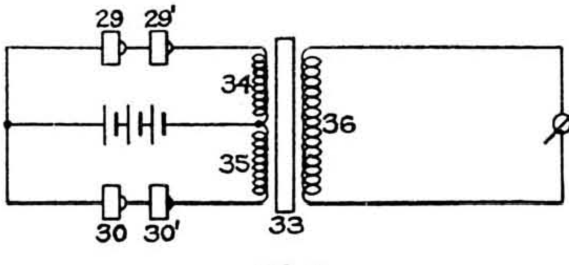

FIG. 13

Inventor
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In their fundamental principles these methods have all comprised a source of sound (7) which has heretofore always been placed either on or below the surface of the earth. The theory is that sound travels out radially in all directions and is in part reflected from the boundary 2, 3, 4, 8, 10, and 12, the part of the wave incident at the point (8) being reflected to the point (9), that part incident at (10) being reflected to the point (11), and so on, the angle of reflection being equal to the angle of incidence. It is evident that if only this simple condition existed and if we could clearly distinguish at any point of known position such as at (11) for example, between the direct transmitted wave (14) which goes either directly or through shallow sub-surface strata to the point (11), and the wave reflected to the point (11) from the point (10), we could by well known means calculate the depth of the point (10) on the reflecting surface. Serious difficulties of a practical nature prevent the realization of this simple set of conditions. In the first place, the velocity of sound in the rock layer (2) is practically always much greater than in the surface strata. On this account when the slowly travelling sound wave reaches the nearest point, as at (3), of the reflecting rock layer, a sound wave of relatively high velocity moves along the rock layer as shown by the arrows (15), and all the while a portion of the energy of the wave is being diffracted upward into the overlying strata as indicated by the arrows (16), and this diffracted energy moves upward and may reach the point (11) before the arrival of the true reflected wave from the point (10), since this latter, although travelling by a somewhat shorter path, must travel all the way through the medium of low velocity. Furthermore, it will be seen that this initial diffracted disturbance arriving at (11) will be immediately followed by others caused by the transmitted wave striking portions of the rock layer (2) at (8) and other points intermediate between (12) and (10), to that a continuous train of diffracted disturbances will be detected at (11) which will completely obscure the arrival of the true reflected wave.

Fig. 3 shows a typical record which reveals clearly the seriousness of this difficulty in practice. This is a record of disturbances received at the detector placed at a point corresponding to the point (11) due to a single quick pulse of sound sent out from the source at the point (7). In consequence of the combined effect of the direct transmitted waves, of which there are three distinct types, namely, a compression wave, a transverse wave, and a surface or Rayleigh wave, all of which travel at different velocities and therefore reach the detector at different times, and further, the innumerable diffracted waves due to the reaction on the two former by the subterranean reflecting surfaces as described above, the record becomes so complex that the effect of the arrival of any pure reflected wave is entirely obscured so that the record is entirely worthless for the purpose desired.

It will be evident that this difficulty will be the greater the more remote is the detector at the point (11) from the source (7), and that it can be diminished by placing the detector close to the source. This is shown by comparing Figs. 3 and 4. These two records are the result of the same source of sound at (7) but in Fig. 3 the receiver was 150 feet from the source, while in Fig. 4 it was but 50 feet away. Interchanging receivers give identical effects showing that the difference in form is not due to the influence of the receivers. The sensitivity of the recording instrument was, of course, adjusted to give suitable sensitivity in the two cases.

Although these diffraction effects may be thus diminished by bringing the detector closer to the source, the disturbances produced by the direct transmitted waves mentioned above become much more violent in comparison with the reflected waves so that if the distance is made short enough to substantially eliminate diffraction effects the transmitted waves completely obscure the advent of any reflected waves. It is evident, therefore, that no location of the detector can be found that will permit it to distinguish definitely between the true reflected wave and disturbances due to diffraction and direct transmission. Similar disturbances result in the case wave trains are used in lieu of single pulses.

I have now invented a very simple expedient whereby the foregoing troubles can be entirely obviated. I accomplish this end by placing the detector or the source, preferably the latter, high up in the air and so arrange the two that the direction of the reflected waves reaching the detector makes only a very small angle with the direction of the transmitted waves, preferably not more than a few degrees. This angle is made small, as in the arrangements hereinafter described, by causing the distance, measured vertically between the shot or sound wave source and the detector, great as compared with the horizontal distance between the detector and the sound wave source or shot. By keeping this angle small the diffraction disturbances are avoided and by placing the source at a considerable elevation above the surface of the earth the difficulties due to the direct transmitted wave are not only eliminated, but this wave becomes very useful as will appear from the following detailed description of the essential features of my invention.

My invention will be clearly understood by reference to Fig. 5. The source of sound (17) is placed high up in the air. This source may be of any suitable kind, but I prefer to use a short abrupt sound such as that produced by firing a charge of explosive or by the sudden release of gas under pressure. Approximately below the source (17) and either on or slightly below the surface of the earth, I place a detector (18) which may be of any type, such as a microphone, piezo-electric crystal, or electromagnetic detector. Wires extend from this detector to a recording device (19) of a type to record the difference in time between two or more events. The well known oscillograph having constants adapting it to this particular work is typical of the recording devices which I have found suitable. It will be evident that if a sudden sound be produced at the source (17) the wave will travel downward and strike the surface of the earth (20) where a considerable part of the energy will be reflected and pass off into space. A part, however, will be transmitted to the earth and this portion immediately produces an effect on the detector (18) which is near the surface and this effect is recorded on the recorder (19). This point on the record is then used as the zero of time to which subsequent recorded events are referred. The wave then travels downward until it strikes the first reflecting surface (21) where a part of its energy is reflected upward to the surface, where it again affects the detector, and the time elapsing between the arrival of the reflected wave and the arrival of the transmitted wave will be determined. The velocity of sound in the overlying stratum can be determined and the depth of the surface from which reflection takes place can be readily calculated from this velocity and the measured time interval between the arrival of the direct transmitted wave and the reflected wave. It will be evident that if the depth of the reflecting surface be determined at a sufficient number of points the contour of this surface will be known.

It will be quite evident that with this arrangement of apparatus the effects on the detector of both the Rayleigh wave and the transverse wave in the earth will be eliminated, and only those effects due to the compression wave will be recorded in either the transmitted or reflected wave, thereby greatly simplifying the record. It will also be very evident that all diffraction effects, such as those described above, will not affect the detector. In consequence of this a very simple form of record, like that shown in Fig. 6 is obtained where the different events can be clearly distinguished and the time intervals accurately measured.

A further consideration of very great practical importance has to do with the relative intensity as shown by the record of the direct wave, actuating the receiving device, and of the reflected wave coming back from the surface under investigation. It will be seen that the sound wave emanating from the source (17) travels out spherically in all directions, and the intensity of the wave at any point is governed by the inverse square law. Suppose, for example, that the height of the source (17) above the detector (18) is equal to the depth of the reflecting surface (21). In that event when the sound wave reaches the detector (18) it has a certain intensity. Suppose now that 100% of the energy of the wave is reflected from the surface (21). It will be evident that when the reflected wave front has travelled back again to the detector (18) the total distance which it will have traversed from the source (17) will be three times as great as the distance traversed by the direct wave in going from the source (17) to the detector (18). The intensity of the reflected wave when it reaches the detector would therefore be only one-ninth of the intensity of the direct wave. If, as is usually the case in practice, only a fraction of the energy is reflected from the surface (21), the intensity of the reflected wave becomes still further reduced. If now the sensitivity of the arrangement is made great enough to give a sufficiently large effect due to the reflected wave, the disturbances due to the direct wave will be so great that they may interfere seriously with the proper interpretation of the records. It will be evident, therefore, that in general it will be necessary to take steps to increase the amplitude of the reflected wave, relative to that of the direct wave. I have devised several means of accomplishing this result, each and all of which comprise a part of my invention.

One of the means whereby I increase the intensity of the reflected wave relative to that of the direct wave, is by putting a source of sound very high up in the air as compared to the stratum under investigation. As seen from the example given above, if the depth of the stratum is substantially equal to the height of the source, then assuming 100% reflection the intensity of the reflected wave at the receiver will be only one-ninth of the intensity of the direct wave. Suppose, however, that the source be put to a height above the detector of say five times the depth of the reflecting stratum under study. In that case the reflected wave travelling back to the detector will have travelled about 40% farther from the source than the direct wave, when the two pass the detector. Applying the inverse square law it will be seen that in this case, assuming 100% reflection, as before, the intensity of the reflected wave at the detector will be 1/1.96, or approximately one-half of that of the direct wave, as compared with the ratio one-ninth, when the source is placed at the lesser elevation. It will therefore be seen that by putting the source very high in the air in comparison with the depth of the stratum under investigation, it is possible, because of the inverse square law of propagation of sound waves, to greatly increase the intensity of the reflected wave in comparison with that of the direct wave. In practice I prefer to elevate the source to height at least as great as the depth of the reflecting stratum, and preferably to several times this height.

It is not to be understood that there is a critical height of the source 17 of the sound energy utilized which under all circumstances is to be exceeded, nor is it necessary to know either the height of the source 17 nor the depth of the reflecting stratum. In actual practice the procedure is substantially as follows:

A sound wave is produced at any convenient height, as by a charge exploded, say, 1,000 or 2,000 feet above the earth's surface, and a suitable record, as photographic, is taken of the waves actuating or influencing the detector. If upon examination of the record so taken there is revealed a reflected event clearly distinguishable from the after effects of the direct wave, it shows that the explosion occurred at a sufficient height. The significant fact is the time interval between the arrival at the detector of the direct and reflected waves, and it is only necessary to know this time interval, which, when multiplied by the velocity of sound in the overlying medium, gives a distance which is twice the depth of the reflecting stratum. If, on the other hand, the record shows no reflected event clearly distinguishable from the after effects of the direct wave, it is proof that the source of the sound energy was not sufficiently high above the detector, and in such case it is only necessary to take another record with the source of sound at a greater elevation.

A second means whereby I secure an increased ratio of the intensity of the reflected and direct waves, is by the use of an acoustic shield interposed between a source and the detector. One form of this is shown in Fig. 7. The acoustic shield (22) which can be made up in any form to be substantially sound proof, is placed between the source (17) and the detector (18) and preferably close to the latter. In practice I prefer to put the shield (22) near or on the surface of the earth, as shown in Fig. 7. It will now be seen that the sound energy travelling downward from the source (17) strikes the shield and the earth all around it. The shield (22) may be designed either to reflect or absorb the energy striking it, in which event it will be seen that no sound energy travels directly into the earth at the detector (18). However, in the region all around the shield, the energy passes downward into the earth as will readily be seen, and is gradually diffracted inward underneath the shield into the region (23). By the time the reflected wave from the surface (21) reaches the detector (18) the diffraction will have been sufficient to give nearly a uniform distribution of energy in the reflected wave, and the detector will therefore be actuated by the reflected wave with nearly as much intensity as if the acoustic shield (22) did not exist. At the same time there will be very little effect due to the direct wave, since only a very small amount of the energy of the direct wave will be diffracted directly from the edges of the acoustic shield to the source (18). I have found that in this way I can reduce the intensity of the direct wave at the receiver to a small fraction of what it would be without the shield, and at the same time secure nearly as much effect on the detector from the reflected wave as if the shield did not exist.

A third method which I have devised for reducing the amplitude of the direct wave in comparison with that of the reflected wave is shown in Fig. 8. It is well known that because of the very great difference in the acoustic properties of the earth and air, a sound wave travelling either in the air or in the earth reaching the surface of the earth will be nearly all reflected back into the medium in which it is travelling, thus, as pointed out above, the wave coming from the source (17) up in the air, has most of its energy reflected at the surface of the earth back again into the air and off into the atmosphere. Similarly, that part of the energy which goes into the earth and is reflected back toward the surface from the reflecting surface (21), will on arrival at the surface be again reflected downward, only a small fraction of its energy returning again to the air. By taking advantage of this principle I am able to reduce the intensity of the effect of the direct wave on the detector to any desired degree without materially reducing the intensity of the reflected disturbance which it is desired to record. This is accomplished by the use of two receiving devices as shown in Fig. 8. Here one receiving device (18) is placed in the earth as previously described, in which case it is actuated only by that part of the sound energy passing into the earth. The second receiving device (24) is placed to be responsive to the direct air wave to a much greater degree than to the reflected ground wave, and very close to the detector (18). In order to make clear the method of functioning of this agreement, let us assume that the sensitivity of the detector (24) bears to the sensitivity of the detector (18) the same numerical ratio as the sound energy transmitted to the earth bears to the total sound energy incident on the surface of the earth from the source (17). In that case it is obvious that the total effect produced on the detector (24) will be just equal to the total effect produced on the detector (18), due to the direct wave coming from the source (17). Consider now what happens when the reflected wave arrives again at the surface after having been reflected from the subsurface (21). This wave travelling in the earth gives full effect on the detector (18) embedded in the earth, but on reaching the surface nearly all of its energy is again turned back in a downward direction, only a small fraction of it being transmitted to the air where it can affect the detector (24). It will be seen, therefore, that the effect of the reflected wave will be enormously greater on the detector (18) than it is on the detector (24), whereas the effect of the direct wave on the two detectors will be substantially equal. If now the two detectors (18) and (24) are coupled together in such manner that they tend to neutralize each other as regards their effect on the recording device, then the direct wave will produce no effect on the records provided the two detectors are adjusted to give equal and opposite impulses, whereas the reflected wave will be recorded through the detector (18) at almost its full value. In practice I prefer not to completely eliminate the direct wave on the record so that I do not adjust the detectors (18) and (24) so that they exactly neutralize each other. I prefer to adjust them so that the resultant effect of the two, due to the direct wave, is only a small fraction of the effect produced on either instrument alone, as this gives an indication on the record showing the time of arrival of the direct wave, which is useful as a basis of reference for the time scale. It will be seen, therefore, that by proper adjustment of the relative sensitivity of the two detectors in Fig. 8, the relative intensity as shown on the record of the direct and reflected waves can be controlled to any desired extent. In practice any one of the above described means for controlling the relative intensity of the effects of the direct and reflected waves may be used, or any two or all of them may be used in combination if desired.

In order to measure the velocity of sound in the stratum between the surface of the earth and the reflecting surface under investigation I place two receiving devices in the earth as shown in Fig. 9, one (18) at a suitable distance below the surface, and the second (25) a known distance below it, substantially in line with the direction of propagation of the sound wave. The difference in time of arrival of the sound wave at the two receivers is measured by means of a recorder from which, and the known distance between the receivers, the velocity is readily obtainable. In some cases where there is reason to believe that the velocity of sound in the overlying stratum may vary with depth, several indicating devices may be placed at various depths in order that the law of variation of velocity with depth may be determined.

I have found that in order to secure a good sensitivity in the indicating devices and also in order to eliminate spurious disturbances due to vibrations of receiving devices themselves, it is desirable to have the microphones very firmly fixed in contact with the earth. This can be done by making a hole, placing the microphone in it filled either with earth or other suitable binding material and thoroughly tamping the filling material in place around and above the detector. This procedure, however, is difficult and time consuming and renders very difficult the recovery of the indicating device, especially when buried to a considerable depth, after the records have been taken.

I have devised a very simple and convenient means of firmly attaching the receiving device to the earth which eliminates these troubles. This is shown in Fig. 10, where the receiving device is mounted inside of a rigid case (26) which may be of metal or other suitable material. In the base of this case is firmly attached a large screw (27), suitable for screwing into the earth. To place a receiving device in position I first bore a small hole, large enough to accommodate the receiver and extending to the desired depth, after which the receiver is placed down in the hole with the screw downward and by means of a suitable long handled wrench the receiver case is turned so as to drive the screw firmly into the earth. After the records have been taken the receiver can readily be unscrewed from its position and brought to the surface. As stated above, any one of the usual types of receiving devices may be used. I have found, however, that instead of using a single receiving element it is often desirable to use a considerable number of such elements grouped in a single unit in order to increase the sensitivity and reliability of the receiving apparatus. This is particularly true in case carbon microphones are used as receiving devices. These microphones, when used singly exhibit certain inherent instabilities frequently called frying, which gives rise to more or less erratic pulsations of current flowing in the microphone, which in turn produces disturbances on the record, especially where a very sensitive recorder is used. This trouble is especially serious if one attempts to use a very large current in the microphone in order to increase the sensitivity. This difficulty can be greatly minimized by using a large number of microphone elements connected in parallel, but such a simple arrangement cannot be used in practice. It is well known that in order to use a microphone successfully and secure good sensitivity in detecting disturbances of relatively low frequencies, it is necessary to use it in conjunction with a mutual inductance having an iron core, and further, that the current flowing through the primary of this mutual inductance, which of course is the current flowing through the microphone, must be kept small enough so as not to produce saturation in the iron core. This fact places a limit on the number of microphones that can be used in parallel on a single mutual inductance, and with the usual forms of inductance practically nothing is gained by the use of more than one or two microphones in this way. I have, however, devised an arrangement whereby the ordinary forms of iron core mutual inductance may be used effectively with a large number of microphone elements in proper combination.

The essential elements are shown in Fig. 11. Inside the receiver case (26) is mounted a rigid plate (28), preferably tilted at an angle with respect to the axis of the case (26). I prefer to make this angle between 30° and 60°, but larger or smaller angles may be used if desired. A terminal of each of the microphone elements (29) and (30) is generally attached to the plate (28), and interposed between this plate and the other terminal of each microphone is placed a cushion of suitable fabric, such as cloth or other material, to serve as a damping agent to prevent vibrations in the microphone when it is actuated. Any desired number of such pairs of microphone elements may be mounted inside the case (26). The receiver case is fixed to the ground with its axis in the direction of the earth displacement which it is sought to record, in this case being vertical. It will be evident that when the earth vibrates due to the passage of a sound wave or pulse, the receiver case is moved up and down with the earth while the heavy case of the microphone elements (29) and (30) tend to stand practically stationary. In consequence of this, it will be seen that the pressure on the microphone elements (29) and (30) will vary as the wave passes, thus causing vibrations in their resistance. It will be noted that when the pressure on the microphone element (29) is increased due to the downward movement of the case (26), the microphone (30) will decrease so that the pulsations of resistance on the two microphone elements will be opposite. In order to make the effects of the two groups cumulative on the recording instrument, either of two arrangements may be used, one of which is shown in Fig. 12. Here all of the microphone elements (29), (29′) etc., which are similarly mounted with respect to the plate (28), are placed in one arm of a Wheatstone bridge while all those (30), (30′), etc., which are so mounted as to give resistance variations opposite to the ones in group (29), (29′), etc., are placed in the adjacent arm of the bridge. It will be obvious that as the resistance of one group increases and that of the other decreases, the two effects are cumulative in disturbing the balance of the bridge, and therefore in effecting the indications of the oscillograph or other instrument (19′) coupled across the diagonal of the bridge. The mutual inductance (32) may or may not be used, as desired. The second arrangement and the one which I prefer to use, is shown in Fig. 13. Here a mutual inductance is used, preferably one having an iron core (33) provided with two primary windings (34) and (35) differentially connected, the winding (34) being in series with the group of microphone elements (29), (29′), etc., and the winding (35) being in series with the group (30), (30′), etc. With this arrangement a large number of microphone elements may be used in each group, and correspondingly large currents sent through the two differentially wound primary coils (34) and (35) without danger of saturating the magnetic circuit. When the current in one circuit increases while that in the other decreases, the effects are cumulative in causing changes in the magnetization of the iron core (33), and hence in actuating the oscillograph (19′), which is connected to the single secondary coil (36). As here shown, the microphone elements (29), (29′), etc., are grouped in series. It will be evident that parallel or series multiple grouping may be used with equal effect, provided the number of turns in the primary coils (34) and (35) of the mutual inductance are made to correspond to the number of microphone elements in series.

A careful consideration of the foregoing discussion reveals that one of the fundamental features of my invention comprises the placing of a source of sound and a receiver in such relation to each other and to the reflecting surface, the depth or contour of which is to be studied, that the angle between the direct transmitted and the reflected waves affecting the receiver is small, whereby the disturbance due to the surface waves, transverse waves, and the innumerable diffraction effects above discussed, are made to disappear. This might, of course, be done by placing both source and receiver in the earth, provided one is placed at a considerable depth, in order to have the receiver remote from the source. It is, however, very difficult, expensive, and time consuming to place the instruments at a great enough depth to be effective. Furthermore, experience has shown that if the source be placed in the earth the available sources of a quick, sharp pulse, such as the firing of a charge of explosive, produce a violent disruptive effect in the earth immediately surrounding it, which in turn tends to change the character of the disturbance from a quick, simple pulse to a complex and greatly prolonged disturbance, thus defeating the object of the arrangement. I have found, however, that if the source of sound be placed high up in the air, preferably high enough so that the wave front striking the earth will be practically a plane wave, this difficulty will be entirely avoided. If the wave front striking the earth be nearly plane, the subsequent diminution of intensity with distance, both before and after reflection, will be relatively slight so that the ratio of the intensity of the transmitted and of the reflected waves will be much smaller than if the wave front striking the earth has a small radius of curvature. For this reason if the source be placed high up in the air, the intensity of the shock imparted to the earth at any point may be very slight, and nowhere sufficient to cause permanent deformation of the medium, and still give a reflected wave of ample intensity for detection. On the other hand, if the source be placed on the surface or imbedded within the earth, the intensity of the shock at points very close to the source must be very great in order that the reflected wave may be of sufficient intensity, and in practice it is found that permanent deformation of the earth very close to the source always occurs, thus giving rise to the increased complexity and prolongation of the wave above described. It will therefore be apparent that the placing of the source up in the air at a considerable distance from the earth, as hereinabove described, is of fundamental importance in eliminating certain of the practical difficulties that have heretofore been encountered in attempting to explore subterranean strata through the medium of sound waves. Any suitable means may be used for placing the source at a proper elevation. Where circumstances are such that a height of not more than about 100 feet is sufficient, a light telescoping pole or tower can be used successfully. As a rule, however, I have found that it is desirable to place the source at a considerably greater elevation, and when this is desired some other means can be conveniently used for putting the source up in the air. Any one of a number of devices may be used if desired, such as a captive balloon, a kite, an airplane, or recourse may be had to projecting a charge of explosive into the air, the same being fired by a time fuse in accordance with principles well known to military ballistics.

For the sake of brevity in the appended claims, the term "aperiodic" as applied to the sound produced by the source includes an abrupt sound wave or a sound wave impulse or rapidly decadent sound waves, produced by a shot, explosion or equivalent means herein described, as distinguished from sustained, continuous or undamped sound waves.

I claim:

1. The method of determining the contour of a subterranean stratum which consists of sending out a sound wave from a source of sound, causing the said sound wave to be transmitted through the earth to the said subterranean stratum and reflected therefrom, measuring the time interval elapsing between the passage of the said sound wave over a known point at a distance from said source and the passage of the reflected wave over the same point, measuring the velocity of sound in the medium between the said known point and the said subterranean stratum and calculating the distance between the said known point and the said subterranean stratum from the said time interval and the said velocity, the said source and the said known point being so placed with respect to the said subterranean stratum tnat the path traversed by the direct wave is substantially identical with the path traversed by the reflected wave.

2. The method of locating a subterranean stratum, which comprises producing an aperiodic sound wave, causing said wave to be transmitted through the earth to the subterranean stratum and to be reflected therefrom, measuring the time interval elapsing between the passage of said wave past a known point and the passage of the reflected wave past the same point, determining the velocity of sound in the medium between said known point and said stratum, and determining the distance between said known point and said stratum from said time interval and said velocity, the place of production of said sound wave and said known point being so positioned with respect to said stratum that the paths traversed by the direct and reflected waves are substantially identical.

3. In the art of exploring subterranean regions, the method which comprises producing sound at a distance above the surface of the earth, and detecting, and whose distance horizontally from the source of said sound is small compared with its distance vertically therefrom the sound reflected from a subterranean formation.

4. In the art of exploring subterranean regions, the method which comprises producing sound at a substantial distance above the surface of the earth, and detecting the sound reflected from a subterranean formation at a point through which both the direct and reflected waves pass.

5. In the art of exploring subterranean regions, the method which comprises producing sound at a distance above the surface of the earth, and detecting, at a point adjacent the earth's surface and whose distance horizontally from the source of said sound is small compared with its distance vertically therefrom the sound reflected from a subterranean formation.

6. In the art of exploring subterranean regions, the method which comprises producing sound at a distance above the surface of the earth, and detecting at a point adjacent the earth's surface the sound reflected from a subterranean formation, said point being located adjacent substantially identical paths in which the direct and reflected waves are transmitted.

7. In the art of exploring subterranean regions, the method which comprises producing an aperiodic sound wave at a distance above the surface of the earth, and detecting, and whose distance horizontally from the source of said sound is small compared with its distance vertically therefrom the sound reflected from a subterranean formation.

8. In the art of exploring subterranean regions, the method which comprises producing an aperiodic sound wave at a distance above the surface of the earth, and detecting, at a point adjacent the earth's surface and whose distance horizontally from the source of said sound is small compared with its distance vertically therefrom the sound reflected from a subterranean formation.

9. In the art of exploring subterranean regions, the method which comprises producing sound at a distance above the surface of the earth, and detecting, and whose distance horizontally from the source of said sound is small compared with its distance vertically therefrom the sound transmitted to and reflected from a subterranean formation.

10. In the art of exploring subterranean regions, the method which comprises producing sound at a distance above the surface of the earth, and detecting the sound transmitted to and reflected from a subterranean formation at a point adjacent substantially identical paths over which the direct and reflected waves are transmitted.

11. In the art of exploring subterranean regions, the method which comprises producing an aperiodic sound wave at a distance above the surface of the earth, and detecting, and whose distance horizontally from the source of said sound is small compared with its distance vertically therefrom the sound transmitted to and reflected from a subterranean formation.

12. In the art of exploring subterranean regions, the method which comprises producing an aperiodic sound wave at a distance above the surface of the earth, and detecting the sound transmitted to and reflected from a subterranean formation at a point adjacent substantially identical paths over which the direct and reflected waves are transmitted.

13. In the art of exploring subterranean regions, the method which comprises transmitting sound from a source to a subterranean formation and reflecting it therefrom, producing an effect by the direct sound wave, producing a second effect by the reflected sound wave at a point whose distance horizontally from said source is small compared with its distance vertically therefrom, and producing a composite indication by said effects.

14. In the art of exploring subterranean regions, the method which comprises transmitting sound originating at a distance above the earth to a subterranean formation to be reflected therefrom, producing a plurality of effects by the direct and reflected sounds, and producing a composite indication by said effects, said effects being produced at points adjacent substantially identical paths over which the direct and reflected sounds are transmitted.

15. In a system of the character described, means for transmitting sound through the earth to a subterranean formation to be reflected therefrom, a plurality of detectors affected to greater extents, respectively, by direct and reflected sound, indicating means, and means for causing said detectors to affect said indicating means in opposite senses.

16. In a system of the character described, means for transmitting sound through the earth to a subterranean formation to be reflected therefrom, a plurality of detectors affected to greater extents, respectively, by direct and reflected sound, indicating means, and means for causing said detectors to affect said indicating means in opposite senses, said detectors disposed adjacent substantially identical paths over which the direct and reflected sound is transmitted.

17. In a system of the character described, means for transmitting sound through the earth to a subterranean formation to be reflected therefrom, a plurality of detectors affected to greater extents, respectively, by the direct and reflected sound, and indicating means controlled by said detectors, the source of said sound disposed at a distance above the surface of the earth.

18. In a system of the character described, means for transmitting sound through the earth to a subterranean formation to be reflected therefrom, a plurality of detectors affected to greater extents, respectively, by direct and reflected sound, indicating means, and means for causing said detectors to affect said indicating means in opposite senses, the source of said sound disposed at a distance above the surface of the earth.

19. In a system of the character described, means for transmitting sound through the earth to a subterranean formation to be reflected therefrom, a plurality of detectors affected to greater extents, respectively, by the direct and reflected sound, and indicating means controlled by said detectors, the sound produced by said means consisting of an aperiodic sound wave.

20. In a system of the character described, means for transmitting sound through the earth to a subterranean formation to be reflected therefrom, a plurality of detectors affected to greater extents, respectively, by the direct and reflected sound, indicating means, and means for causing said detectors to affect said indicating means in opposite senses, the sound produced by said means consisting of an aperiodic sound wave.

21. In a system of the character described, means for transmitting sound through the earth to and causing reflection of sound from a subterranean formation, a plurality of sound detectors respectively influenced principally by the direct and reflected sound, a time-indicating device, a transformer in whose secondary circuit said device is connected, and said detectors connected in circuit with the primary windings of said transformer, said primaries being differentially related.

22. In a system comprising a device for determining the contour of a subterranean stratum and comprising a source of sound, sound detectors, and a sound measuring device, the method which comprises placing said source in the air above the surface of the earth, disposing certain of the sound detectors in contact with the earth at points intermediate said sound source and the subterranean stratum, and substantially in line with the normal extending from the subterranean stratum through said source, and placing other of the sound detectors so as to be actuated substantially only by an air wave, and so associated that its effect is opposed to that of sound detectors in contact with the earth, and coupling the time measuring device to said detectors in such manner as to measure the time interval elapsing between the arrival of a direct sound wave at the detectors in earth and air, and of one or more reflected sound waves at the detectors in earth.

23. In a system for determining the contour of a subterranean stratum and comprising a source of sound, sound detectors, and a time measuring device, the method which comprises placing the source of sound in the air above the surface of the earth at a distance greater than the depth of the subterranean stratum, placing the detectors in contact with the earth substantially in line with the normal extending from the subterranean stratum through said source, and coupling the time measuring device to said detectors to measure the time interval elapsing between the arrival of successive sound waves at said detectors.

24. A system for determining the contour of a subterranean stratum comprising a source of sound, a time recording device, microphonic devices, and means for mounting said microphonic devices to effect opposite phase relation of pulsating change of their resistances in their effect upon said recording device.

25. A system for determining the contour of a subterranean stratum comprising a source of sound, a time recording device, microphonic devices electrically connected in parallel, a differentially wound transformer having primary coils connected respectively in series with said microphonic devices and a secondary connected to the time recording device, and means for mounting said microphonic devices to effect opposite phase relation of the pulsations of their resistances in their effect upon said recording device.

26. In the art of exploring subterranean regions, the method which comprises transmitting sound to a subterranean formation to effect reflection therefrom, producing a plurality of effects at points adjacent substantially identical paths over which the direct and reflected sounds are transmitted, and producing a composite indication by said effects.

In testimony whereof, I affix my signature.

BURTON McCOLLUM.

Karcher 1929

The United States Patent Office further granted the appended patent No. 1,706,066, under date of March 19, 1929, with priority of March 30, 1926, to John Clarence Karcher:

Patented Mar. 19, 1929. **1,706,066.**

UNITED STATES PATENT OFFICE.

John Clarence Karcher, of Montclair, New Jersey, Assignor to Geophysical Research Corporation, of New York, N. Y., a Corporation of New Jersey.

Method and Apparatus for Locating Geological Formations.

Application filed March. 30, 1926. Serial No. 29,428.

This invention relates to methods of and apparatus for determining the character, location and depth of geological formations beneath the surface of the earth and particularly to the locating of formations having sound transmitting characteristics differing from those of the surrounding terrain. The invention has special application to the location of salt domes, anticlines and others structures favorable to the accumulation of petroleum under the earth's surface.

It has heretofore been recognized that subsurface formations may be investigated by observing the velocity of sound waves transmitted through the same from sending to receiving stations where one or more of the stations are located in deep borings in the earth and the stations are approximately on opposite sides of the formation under examination. In my present invention I make use of sound waves transmitted through the earth, but I have discovered that by a novel arrangement and combination of sending and receiving devices I am able to take advantage of principles of sound propagation not heretofore used in this or similar connections, so far as I am aware, with the result that I obviate the necessity of deep borings and by a series of observations made at stations located substantially at the surface of the earth I am able to determine accurately the location, size, character and depth of the geological formations under the surface of the earth, provided only that the sub-surface formations have the characteristic of transmitting sound more rapidly than the surrounding terrain and that the surrounding terrain be one through which sound will travel with substantially uniform velocity. Such conditions are often found in geological explorations. Thus by means of my invention I am able to locate valuable mineral deposits associated with such geological formations which could not otherwise be located.

In practicing my invention I make use of the fact that sounds which are of long wave length (25 feet or more) are capable of being readily diffracted. Because of the nature of diffraction, I have found that it is possible for such sounds, originating at the surface of the earth, to travel diagonally downward through a stratum of earth having the characteristic of transmitting sound with comparatively low velocity, thence along a stratum of high sound velocity in a direction substantially parallel to the surface of contact between the two strata and then diagonally upward again through the upper stratum to the surface where it may be detected at a receiving station some distance from the point of origin. Where the sending and receiving stations are sufficiently far apart in relation to the depth of the underlying stratum and there is sufficient difference between the sound transmitting characteristics of the upper and lower strata, it is apparent that a sound wave following the indirect path indicated may arrive at the receiving station ahead of a sound wave travelling directly from the sending to the receiving station through the upper stratum. The sound wave which proceeds by the indirect path downward to and through the lower stratum and then upward through the upper stratum to the receiving station I call the "diffracted wave". The sound wave which passes directly between the two stations through the upper stratum I call the "direct wave". By providing means for accurately measuring the time of arrival of these waves I am able to make accurate deductions as to the character and location of the underlying stratum. And by changing the location of the sending and receiving stations and repeating the tests and comparing the results I provide data from which the depth, contour, slope and characteristics of the lower stratum may be accurately determined.

The principal objects of the invention are to utilize my discovery as a method for ascertaining matters of the character indicated and to provide simple and efficient apparatus for carrying it out.

Other objects and advantages of the invention will be made apparent by the following description of a preferred mode of operation of my invention taken in connection with the accompanying drawings, wherein

Fig. 1 is a wiring diagram of transmitting and receiving stations adapted for carrying on the invention.

Method and apparatus for locating geological formations

Filed March 30, 1926.

Fig. 1.

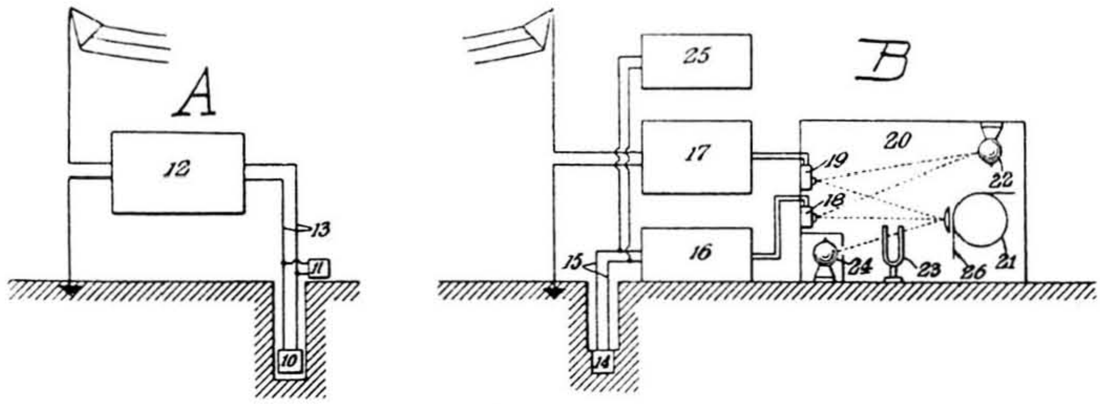


Fig. 2.

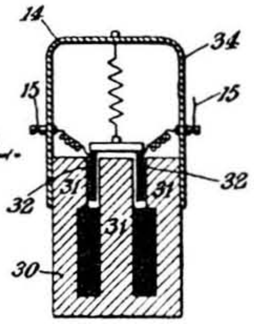


Fig. 3.

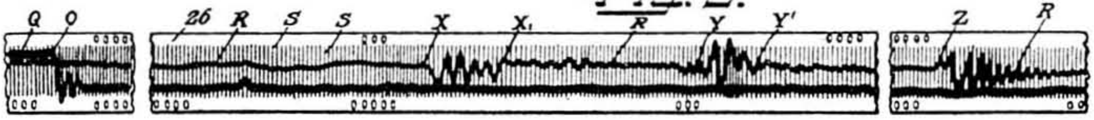


Fig. 4.

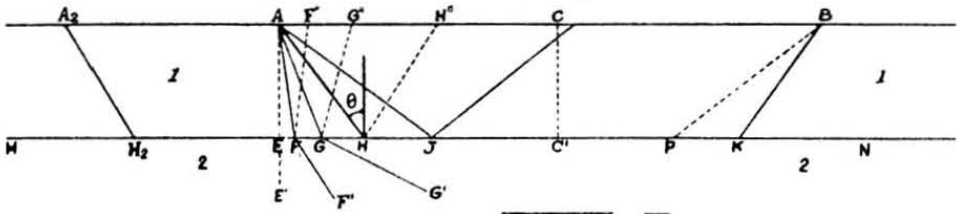
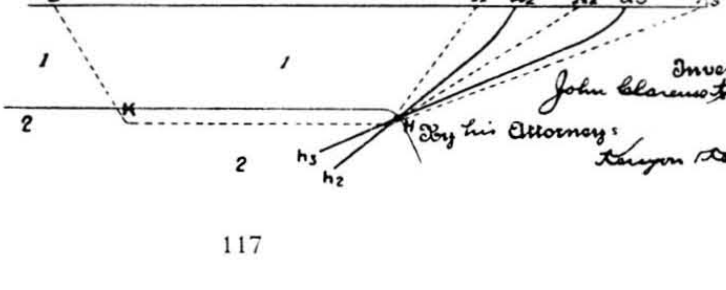


Fig. 5.



Inventor
John Clarence Karcher
By his Attorneys:
Kenyon & Kenyon

Fig. 2 illustrates a preferred form of geophone for use at the receiving station.

Fig. 3 illustrates a convenient method of recording relative times of arrival of sound waves, being a section of photographic film bearing graphic indications of the operation of the receiving devices shown in Fig. 1.

Figs. 4 and 5 are illustrative diagrams of the paths of sound waves through the earth, illustrating successive tests whereby the character, location and shape of the sub-surface formation may be determined.

Referring to Fig. 1, an explosive charge 10 is buried just far enough below the surface of the ground so that its detonation will produce suitable sound waves through the earth. In general it is sufficient to locate the charge at a depth of 10 to 20 feet below the surface for this purpose. A second explosive charge 11 ist preferably placed for detonation at the surface of the earth immediately above the charge 10. Nearby may be located a wireless transmitter 12. All of the above-described devices are located at the sending station hereinafter referred to as A. The explosive charges 10 and 11 and the wireless transmitter 12 are preferably connected by electric wires 13 with a suitable source of electrical energy, not shown, and any appropriate means is provided for simultaneously detonating the charges and operating the wireless transmitter circuit so that three sets of waves may be simultaneously propagated from the sending station, being (1) sound waves of long wave length, characteristic of the detonation of an explosive charge, from the charge 10 through the earth, (2) a second set of sound waves from the charge 11 through the air, and (3) a set of radio frequency waves from the transmitter 12.

At the receiving station, hereinafter referred to as B, are located means for detecting sound waves through the earth, sound waves through the air and radio frequency waves. The earth impulses may be detected by means of a geophone 14 or other appropriate apparatus, the sound waves through the air may be detected by a microphone 25, and the radio frequency waves may be detected by any appropriate form of radio receiver 17. Any one of the well known forms of microphone may be employed which is sensitive to sounds of long wave length such as those produced by the detonations of explosive charges. The geophone 14 and the microphone 25 may be electrically connected by wires 15 to the input of an amplifier 16, which in turn is suitably connected to operate the oscillograph element 18. If desired, separate oscillographs may be employed for the geophone and for the microphone respectively. The wireless receiver 17 is connected to operate an oscillograph element 19. These oscillograph elements are installed in and constitute a part of the oscillograph recorder 20. The arrangement of the source of light 22, the oscillograph elements 18 and 19 and the mechanism 21 for moving the film 26 is well known to those versed in the use of such instruments. The oscillograph recorder is also provided with a suitable device for recording equal time intervals, such as a tuning fork 23 provided with slits through which light may pass from a lamp 24 to the film 26, which has been found to work successfully, though any other appropriate means may be employed.

A special form of geophone, well adapted to use for practicing this invention, is shown in Fig. 2. It consists of an element possessing inertia and which is free to move relatively to a second element which is imbedded in the earth. The two elements are coupled electromagnetically or electrostatically in such manner that an electrical potential is generated in an electric circuit by relative movement between the two elements. In the form of geophone illustrated in this figure the fixed element 30 constitutes a magnet having pole pieces 31, 31, 31. The magnet may either be a permanent magnet or may be an electro-magnet. The inertia element is a coil 32 freely suspended from the fixed bracket 34 and adapted to move up and down relative to the pole pieces 31 when the latter are oscillated by earth vibrations. This relative movement generates an electrical potential at the terminals of the coils 32 which is conveyed by wires 15 to the amplifier 16 and oscillograph element 18 above described. This form of geophone is not essential to the invention but is advantageous for use in connection therewith.

The operation of the invention may be illustrated by reference to Fig. 4 in which the line A—B represents the surface of the earth. 1—1 represents a stratum of the earth having relatively low speed sound transmitting characteristics and 2—2 represents an underlying stratum having relatively high speed sound transmitting characteristics. The surface of contact between the upper and lower strata is indicated by the line M—N.

In order to determine the presence of a sub-surface formation having relatively high speed sound transmitting characteristics, sending and receiving stations such as those illustrated in Fig. 1 may be set up on the surface of the ground at points A and B respectively. When the various recording devices at B are in readiness the electric circuit 13 at A may be energized to simultaneously propagate the sound waves from charges 10 and 11 and radio frequency waves from transmitter 12 as above described.

The points A and B may be located a mile or more apart and preferably at a distance greater than four times the estimated depth of the sub-surface formation 2—2 to be examined.

Upon energizing the circuit 13—13 at A three sets of waves are propagated. First a radio frequency wave which instantly energizes the wireless receiver 17 at B and causes a record to be made on film 26 through oscillograph element 19. The time of travel of the wireless impulse being negligible, a record is thus made on film 26 at the instant of detonation of charges 10 and 11.

Second, a sound wave through the air from explosive charge 11 which in due course is received at microphone 25 and recorded on film 26.

Third, a sound wave through the earth from charge 10 to geophone 14.

If a high-speed sound transmitting stratum underlies the surface stratum where the tests are being made, this sound wave through the earth will be divided and will reach B in the form of two or more sets of vibrations as I will now explain.

The wave set up by detonation of charge 10 spreads in all directions from A on a substantially spherical wave front. The portion of it that proceeds directly to B on the line AB in stratum 1—1 I have called the "direct wave". Its time of arrival at B will depend on the distance AB and the velocity, V_1 of sound through the medium 1—1. Another portion of the wave from charge 10 will proceed straight downward on the line AE, other portions diagonally downward on the lines AF, AG, AH, AJ etc., with velocities depending on the character of the medium through which they travel, and if it is homogeneous in character they will all proceed with substantially the same velocity V_1, through the stratum 1—1 and with a substantially spherical wave front.

But an important change in the wave front occurs at the plane of contact MN between the strata 1—1 and 2—2. The wave proceeding on the line AE perpendicular to plane MN will be broken up at E, the major portion proceeding in the same line toward E' and other portions proceeding radially in all directions from E by diffraction in accordance with the theory of propagation of impulses known as "Huygen's principle" (p. 159 "Theory of Optics" — Drude, translated by Mann & Milleken). One of these diffracted waves will proceed from E on the line EK substantially along the plane of contact MN between the upper and lower strata 1—1 and 2—2.

Meanwhile another portion of the original sound wave from A proceeding on line AF will reach plane MN at F. The major portion of it will be refracted, on well known principles, so that it will proceed with increased velocity on line FF' through stratum 2—2, another portion will be reflected back through stratum 1—1 to point F" at the surface, and other portions will be diffracted radially from F through 2—2, a portion of the diffracted wave proceeding on line EFK in plane MN.

Another portion of the original sound wave from A will strike plane MN at G. Its refracted portion will continue through stratum 2—2 on line GG', its reflected portion will travel back through stratum 1—1 on line GG", and a diffracted portion will travel toward K in the plane MN.

It is well known in the science of optics and sound propagation that there is a critical angle of refraction between media of different density such that when the angle of incidence of the wave impulse exceeds this critical angle, no refraction occurs. This angle depends on the relation of the velocities of transmission of the impulses through the two media and is expressed as follows:

$$\theta = \sin^{-1} \frac{V_1}{V_2} \quad (1)$$

where

θ is the critical angle of refraction,

V_1 is the velocity with which the impulse travels through low speed sound transmitting medium, and

V_2 is the velocity with which it travels through the higher speed sound transmitting medium.

According to this theory, the portion of the original sound wave from A proceeding on the line AH, where the line AH makes the critical angle of reflection with plane MN, will have no refracted portion through stratum 2—2, but there will be reflection on line HH" and diffraction radially from H, a portion of the diffracted wave proceeding on line EHK.

Thus it appears that the original sound wave at A will transmit sound energy in line EK by diffraction due to the length of the original sound waves and the difference in sound velocities of the media on either side of the separating plane MN.

By further operation of Huygen's principle, diffraction of the sound energy in line EK occurs at each point in its travel, as, for example at points P and K and from each of these points a diffracted impulse proceeds toward B to effect vibration of the geophone 14 and make a resulting record on film 26.

The diffusion of the sound through this repeated diffraction would result in very feeble vibrations at B were it not for the fact that they tend to reinforce each other with a maximum intensity just following the instant of reception of the diffracted sound wave which has followed the shortest time path through plane MN from A to B so that with the instruments I have provided a very clear record of the arrival of the diffracted wave at B appears in film 26 if there be no substantial interference by other sounds.

I have found that the order of arrival of these diffracted wave portions from A to B via plane MN depends on their course of travel through the media 1—1 and 2—2 of different sound velocities and that that diffracted portion reaches B first which travels from A to MN and from MN to B on the lines AH and KB which form with MN angles complementary to the critical angle of refraction above referred to. For

$$t = \frac{(L - 2D\tan\theta)}{V_2} + \frac{2D}{V_1\cos\theta} \quad (2)$$

where

t=the time of travel of the diffracted wave,

L=the distance between A and B, and

D=the depth of MN below the surface, i. e., the length of line AE.

When t is a minimum, that is, when the angle θ is such that the path AHKB is the shortest time path, then

$$\frac{dt}{d\theta} = O \quad (3)$$

Differentiating the equation (2) with respect to θ.

$$\frac{dt}{d\theta} = \frac{2D}{V_2\cos^2\theta} - \frac{2D\sin\theta}{V_1\cos^2\theta} = O \quad (4) \qquad \sin\theta = \frac{V_1}{V_2} \quad (5)$$

I presume that the reinforcing of the diffracted wave referred to above is due to the fact that although the energy which follows the shortest time path AHKB arrives first, the energy travelling by line AGKB will tend to reinforce the energy travelling by line AHKB for its path though longer in the aggregate is shorter through the low velocity stratum; and likewise the energy travelling by lines AJKB and AHPB will tend to reinforce the energy travelling by line AHKB for their paths though shorter in the aggregate are longer through the low velocity medium. Thus the diffracted wave is built up to such magnitude that if it arrives ahead of the direct wave from A to B through stratum 1—1 it is clearly distinguishable on film 26 from the vibrations recording the normal unrest of the ground. The first vibration of the group of vibrations caused by the diffracted waves may therefore be read as indicating the arrival of the diffracted wave which has come by the shortest time path, AHKB.

The record of arrival of these four sets of waves (i. e. the radio frequency wave, the sound wave through the air, and the direct wave and the diffracted wave through the earth) at station B will appear on the film 26, when the same has been developed, somewhat as shown in Fig. 3. Referring to that figure the line Q—Q is the record made by the oscillograph element 19 under control of the wireless receiver 17. The line R—R is the record made by the oscillograph element 18 under combined control of the microphone 25 and the geophone 14 through amplifier 16. The lines S—S represent time intervals recorded by tuning fork 23. (One hundredth second intervals have been found to be satisfactory.) The sharp break in line Q—Q at point O indicates the instant of arrival of the radio frequency wave and therefore the instant of explosion of charges 10 and 11. This marks the zero instant of the test and all other time intervals may be read by counting the number of line S—S between O and the point in question. The vibrations in line R—R up to the point X represent the normal earth tremors detected by geophone 14. The vibrations of line R—R between points X and X' represent the record of diffracted sound waves received through geophone 14. The vibrations between points Y and Y' represent the record of direct sound waves received through geophone 14. The vibrations of line R—R following point Z represent the record of sound waves from explosion 11 received through the air by microphone 25.

By counting the time interval lines S—S between point O on line Q—Q and point Z on line R—R the exact elapse of time between the propagation of the sound wave from charge 11 at A and its receipt at B may be determined. The distance between A and B may then be accurately calculated from the known velocity of sound through the air with corrections for temperature, altitude, wind, etc. Other appropriate means may be employed for determining the distance A—B but I have found it more convenient to proceed as above indicated rather than by surveying or measuring the distance and there is the further advantage in the present method that it makes the distance reading a part of a single record strip upon which all of the data for calculations are based.

Inasmuch as the direct wave from A to B through stratum 1—1 produces vibrations of line R—R of greater amplitude than those produced by the diffracted wave, I am able to identify and distinguish the respective vibrations which come through the earth. As a rough check on this method of distinguishing the two sound records it is desirable by preliminary test to determine the velocity of transmission of sound through the surface stratum 1—1. With this velocity known and the distance A—B known it is possible to estimate the expected time of arrival of the direct wave vibrations. If this estimation shows that the direct wave vibrations should not normally arrive at B until the beginning of vibrations Y—Y′ of line R—R then there is no explanation for the vibrations of line R—R recorded between points X and X′ other than that they are sound vibrations which have come more rapidly either than the direct wave from charge 10 or than the sound wave through the air from charge 11. The record of the vibrations between points X and X′ therefore indicates without question the presence of a high-speed sound transmitting stratum in the earth somewhere below and between points A and B.

When the presence of the high-speed stratum 2—2 has thus been ascertained accurate data as to its character, location and depth may be collected by repeating the tests and making new records for different locations of points A and B. For example, the sending station A may be moved to a new location A_2 further away from B on line AB and new charges 10 and 11 set and detonated as above described. From the film strip 26 made in this second test, it will be possible to calculate as above the distance between the sending and receiving stations A_2 and B and the time of travel of the diffracted wave by the shortest time path A_2H_2KB. Since the distance $A_2A = H_2H$, the time of travel of the diffracted wave from H_2 to H may be calculated. This gives the velocity of sound travel, V_2, through the high-speed medium 2—2, and permits the solution of equations (1) and (5) above and the determination of the angle θ. With this angle known, equation (2) may be resolved to determine the depth of the plane MN below the ground.

A direct equation for determining the depth D of the lower stratum below the surface of the ground is as follows:

$$D = \frac{V_1}{2\cos\theta}\left(t - \frac{L}{V_2}\right) \quad (6)$$

This assumes that the line HK in plane MN is parallel to the line AB at the surface. The equation (6) may be more generally written

$$D_a + D_b = \frac{V_1}{\cos\theta}\left(t - \frac{L}{V_2}\right) \quad (7)$$

where D_a is the depth of plane MN below the surface at A and D_b is the depth of plane MN below the surface at B.

The slope of the plane MN may be determined by making tests and observations as above at three surface station A, B and U located in triangular relation. If the tests and observations be made in the following order A to B, B to U, U to A, then

$$D_a + D_b = \frac{V_1}{\cos\theta}\left(t_a - \frac{L_a}{V_2}\right);\ D_b + D_u = \frac{V_1}{\cos\theta}\left(t_b - \frac{L_b}{V_2}\right);\ D_u + D_a = \frac{V_1}{\cos\theta}\left(t_u - \frac{L_u}{V_2}\right) \quad (8)$$

where t_a, t_b, t_u indicate the times of travel of the diffracted waves by the shortest time path from A to B, B to U, and U to A respectively, and L_a L_b, L_u indicate the respective distances between AB, BU and UA. By solving these equations simultaneously the depths to plane MN may be determined and the three points thus located serve to indicate the sloping boundary plane between strata 1—1 and 2—2.

In this manner anticlines and other high-speed sound transmitting formations may be definitely located, their depth and upper boundaries determined, and their physical characteristics may be judged from the speed with which they transmit sound.

In addition, the edges and contour of subsurface formations such as salt domes and the like may be determined by the application of this invention in the manner now to be explained.

After generally locating the formation by random tests, the receiving station B (see Fig. 5) is set up at a point on the surface AB and as nearly as can be centrally over the supposed position of the sub-surface formation to be examined. The sending station is then set up successively at positions A_1, A_2, A_3 etc., on line BA such that A is successively at greater distances beyond the supposed position of the edge to be located. By making and recording tests from these different positions of the sending station it is possible to make determinations as follows:

Let t_1, t_2, t_3 equal the times required for travel of the diffracted wave from A_1, A_2, A_3 respectively to B, and let

$$\Delta t_1 = t_2 - t_1;\ \Delta t_2 = t_3 - t_2;\ L_1 = \overline{A_2B} - \overline{A_1B};\ L_2 = \overline{A_3B} - \overline{A_2B}$$

Then draw the lower left hand limb of the hyperbola

$$\frac{4V_1^2X^2}{\Delta t_1^2} - \frac{Y^2}{4L_1^2 - \frac{\Delta t_1^2}{4V_1^2}} = 1 \quad (9)$$

where X's are abscissas and Y's are ordinates with the origin at A_2. This hyperbola appears on Fig. 5 as a_2 h_2. Also draw the lower left hand limb of the hyperbola

$$\frac{4V_1^2X^2}{\Delta t_2^2} - \frac{Y^2}{4L_2^2 - \frac{\Delta t_2^2}{4V_1^2}} = 1 \quad (10)$$

where X's are abcissas and Y's are ordinates with the origin at A_3. This hyperbola appears on Fig. 5 as a_3 h_3. The intersection, H, of these two hyperbolas indicates the point sought, i. e., the edge of the formation under examination.

This point may also be found by solution of the simultaneous equations:

$$\frac{4V_1^2X^2}{\Delta t_1^2} - \frac{Y^2}{4L_1^2 - \frac{\Delta t_1^2}{4V_1^2}} = 1 \text{ and } \frac{4V_1^2(X+L_2)^2}{\Delta t_2^2} - \frac{Y^2}{4L_2^2 - \frac{\Delta t_2^2}{4V_1^2}} = 1 \quad (11)$$

using the point A_2 as the origin.

Similarly the opposite edge of the sub-surface formation may be located, and then, by placing the sending station at various points on other lines radiating from B, the location of the edge of the formation unter these lines may be determined. It will generally be found necessary to change the location of the receiving station, B, from time to time in order to get the clearest results. It may be found, for example, that B is so close to one edge of the formation that the direct wave through 1—1 reaches B before the diffracted wave. Since the vibrations recorded on film 26 by the direct wave are generally of much greater amplitude and duration than those recorded by the diffracted wave, the latter are not easily distinguishable from the former unless they reach B first. Accordingly, if vibrations from the direct wave appear first on the record, it is because the path HK of the diffracted wave through plane MN is too short. This is likely to be the case if B is too near the edge of the formation and in such case it is desirable to draw B back to a new position more nearly over the supposed center of the formation. Where the formation is extensive it may be necessary to make many changes in the position of B as well as of A.

No confusion is likely to occur between the record of the sound waves through the air and those through the ground for the latter travel with many times the velocity of the former. Thus the zone of vibrations YY' on film 26 due to the ground waves set up by explosion of charge 10 will have long since subsided and passed before the first sound of the explosion of charge 11 reaches microphone 25 through the air. For this reason I prefer to provide a single oscillograph 18, but separate oscillographs or other recording devices for the microphone 25 and geophone 14 may be provided as desired.

I am aware that it has been proposed to investigate sub-surface ores by means of observations as to the velocity and inflection of sound waves of short wave length electrically produced and transmitted between instruments located in borings as deep in the earth as the formation under examination. But my invention is quite distinct from such proposal in that I make use of the principle of diffraction of sound waves by employing sounds having long wave length so that, instead of observing the refracted or reflected waves as in the earlier proposal, I make use of the diffracted waves. I thereby obviate the necessity of deep borings and provide means as well for determining with accuracy the size, shape, depth, slope and other characteristics of the formation which have not previously been ascertainable by any means within my knowledge other than actual excavation or sinking of shafts.

My invention results from the discovery that certain sounds may be diffracted under the conditions described and that despite diffusion of the diffracted sound the momentary reinforcement of the sound immediately following the arrival at the receiving station of the diffracted wave by the shortest time path is sufficient to energize sensitive receiving and recording apparatus of the character described so that the record of the time of arrival of the diffracted wave by the shortest time path may be distinguished from the record of normal unrest of the ground. The time of travel of this diffracted wave may thus be made available for use in the many calculations and deductions referred to.

The devices and combinations which I have described and prefer to employ as constituting the sending station are well adapted for propagation of sounds of the character required to secure diffraction under the stated conditions of use. The devices described as constituting the receiving station are peculiarly adapted for receiving and accurately recording impulses of the character employed. But it will be obvious to those skilled in the art from the foregoing description that many changes, omissions and additions may be made in the apparatus and combinations of devices described without departing from my invention.

The preferred form of geophone described and illustrated herein is not essential to my broad invention but is novel in itself and is especially adapted for the use described because of its high sensitivity to sounds of long wave length and because it permits amplification and recording of the vibrations of electric potential set up in circuit 15—15 by the ground impulses without substantially distorting the record as in the case of other devices.

By my preferred combination of sending, receiving and recording devices I am able to make accurate time measurements, to calculate distances accurately without the use of surveying instruments or measures, to provide data with negligible factors of error, to provide simple and efficient apparatus for carrying on the process, and to accomplish results in the investigation and determination of characteristics of sub-surface geological formations which are novel and important and capable of a wide variety of uses.

While I have described my invention in connection with preferred forms and combinations of devices, it will be understood that I do not thereby intend to restrict myself to such illustrative means as I intend to include in my invention all possible modifications and variations in method and apparatus which fall within the scope of the appended claims.

What I claim as new and desire to secure by Letters Patent of the United States is:—

1. In a system for locating subsurface formations, the combination of means for simultaneously transmitting a sound of long wave length and a radio frequency wave, means for receiving said radio frequency wave, means for receiving the diffracted wave by the shortest time path resulting from said sound wave and means for recording said waves as they are received.

2. In a system for locating subsurface formations, the combination of means for simultaneously transmitting sound waves through the earth and through the air and transmitting a radio frequency wave, means for receiving said radio frequency wave, means for receiving said waves transmitted through the earth, means for receiving the waves transmitted through the air and means for recording said waves as they are received.

3. In a system for locating subsurface formations, the combination of a transmitting station having a source of radio frequency waves and a source of mechanical impulses, and a receiving station having means for receiving said radio frequency waves, means for receiving said mechanical impulses and means for recording said waves and said impulses as they are received.

4. In a system for locating subsurface formations, a source of radio frequency waves, a source of mechanical impulses, means for receiving said radio frequency waves, means for receiving said mechanical impulses, means for determining the time of travel of said impulses through the subsurface formation and means for determining the time of travel of said impulses through the media overlying said formation.

5. In a system for locating subsurface formations, a source of radio frequency waves, means for producing mechanical impulses through the air and through the ground, means for causing the simultaneous transmission of said radio frequency waves and said mechanical impulses, means for receiving and recording said radio frequency waves at a point distant from that of transmission means for receiving said mechanical impulses at the same point, and means for separately recording the time of arrival of said mechanical impulses through the air and the direct and diffracted impulses resulting from said mechanical impulse through the ground.

6. The method of locating subsurface formations which comprises transmitting radio frequency waves, transmitting sound waves through the earth simultaneously therewith, receiving said radio frequency waves at a point distant from the transmitting station, automatically recording the time of arrival of said waves at the receiving point, receiving said impulses travelling through the earth and automatically recording the time of their arrival at the same point.

7. The method of locating subsurface formations which comprises transmitting radio frequency waves, transmitting mechanical impulses through the earth simultaneously therewith, receiving and recording said radio frequency waves at a point distant from the transmitting station, receiving said mechanical impulses at the same point, and recording the time required for said impulses to travel through the formation under observation and to travel directly through the earth from the transmitting station to the point of reception.

8. The method of locating subsurface formations which comprises transmitting radio frequency waves, transmitting mechanical impulses through the earth and through the air simultaneously therewith, receiving and recording said radio frequency waves at a point distant from the transmitting station, receiving said mechanical impulses at the same point, and receiving and recording the time of arrival of said impulses through the earth and through the air and the time intervals between the arrival of such impulses.

9. The method of locating subsurface formations which comprises transmitting radio frequency waves, transmitting mechanical impulses through the earth and through the air simultaneously therewith, receiving and recording said radio frequency waves at a point distant from that of transmission, receiving said impulses at the same point and automatically recording the time required for said impulses to travel through the formation under observation, the time required for said impulses to travel directly through the earth and the time required for said impulses to travel through the air.

10. Mechanism of the character described including in combination means for producing a sound of long wave length through the earth and simultaneously making a time record at a distant receiving station and means at said station for making a time record at the instant of arrival of the diffracted sound by the shortest time path through the earth and for recording the time interval between the two time records.

11. Mechanism of the character described including in combination means for simultaneously producing sounds of long wave length through the air and earth from a common sending station and making a time record at a distant receiving station at the instant of such propagation, and receiving devices at the receiving station sensitive to such sounds and adapted to make a time record of the arrival of the same and to record the time interval between such time records.

In testimony whereof, I have signed my name to this specification.

JOHN CLARENCE KARCHER.

CONCLUDING REMARKS.

The charges made against German Reich Patent No. 371 963 "Method for the determination of the structure of rock strata", which were mentioned in the preface, were refuted by the decision of the Reich Court of Germany, under date of June 28, 1930. A translation of the decision is appended.

JUDGMENT

– of the –

REICH COURT OF GERMANY

— dated —

28th June 1930.

I. 281/27

IN THE NAME OF THE REICH

In the patent proceedings
of Dr. *Ludger Mintrop* of Bochum, Herner Strasse 45,
Defendant and plaintiff on appeal
versus
Prof. Dr. *Karl Mainka* of Ratibor, Upper Silesia, Bahnhofstr. 4^{I},
Plaintiff and defendant on appeal

The Reich Court, I. Civil Senate, at the session of 28th June 1930 in which

President Katluhn
and the Reich Court Councillors Dr. Nieland, Triebel,
Dr. Georg Müller, Dr. Conze

took part, decided:

That the decision of the Reich Patent Office of 12th May 1927 be cancelled.

That the action for nullity be rejected.

That the expenses of the proceedings in both actions shall be borne by the plaintiff.

As a matter of right.

FACTS OF THE CASE

A process for ascertaining the geological structure of strata was protected in favour of the defendant by the patent No. 371 963 in force as from 7th December 1919, which in the patent claim is characterized as follows: In the district to be examined elastic waves are to be artificially produced, for instance by the explosion of a blasting charge. These waves are thereupon received by a seismograph set up at a suitable distance, from the records of which the speeds of the various waves and the depth which they have reached may be ascertained. By this means — especially on the basis of comparison with measurements at places of known geological structure — it is said to be possible to form conclusions as to the sequence, thickness and density, as well as regarding the strike and dip of the rock strata. The plaintiff has applied for this patent to be declared null, as the process described in the patent specification can already be gathered from previous publications. The defendant requested rejection of the plaint. He alleged that the prior publications only contained scientific discussions, whereas by his patent he had been the first to work out the seismic process as applying to practical geology and mining.

The Reich Patent Office, by its decision of 12th May 1927, declared the patent attacked to be null, because the patent specification published nothing as to the practical working out of what was already previously treated in technical literature.

The defendant lodged an appeal, applying that the plaint should be rejected and that the decision of the Reich Patent Office should be set aside.

The plaintiff moved for dismissal of the appeal.

The Senate in the first place called Prof. Dr. Harbort of Berlin as an expert, who, however, died after submitting a written report dated 8th April 1929. The Privy Mining Councillor Prof. Dr. Kühn of Berlin thereupon called in as an expert, made a written report dated 26th April 1930, and explained same at the hearing.

GROUNDS FOR THE DECISION

In the patent objected to the defendant set himself the task to determine the composition of the rock strata in the upper layers of the earth from the velocity of mechanical waves. In the preamble of the patent he mentions that apart from the inadequate means of the borings and the divining rod, electrical waves had already been used for investigating the structure and peculiar character of rock strata and then (p. 1 lines 24 ff.) he lays down the starting point for the path followed by him, the perception that the connection of the mechanically produced elastic waves with the characteristical properties of the rock strata, such as density and elasticity, is more direct and intimate than their interrelation to electric waves.

The solution of the problem is described in the patent specification from page 1 line 33 forward, and is again summarized in the claim. The process commences with the production of waves — for instance by the explosion of blasting material — the elastic propagation of which is recorded by the seismograph set up at the suitable distance. If it is then further stated that these records are employed in order to construct the so-called time-distance curve and to calculate the speeds of the waves at the various depths, and if, in connection therewith, similar investigations in seismology are referred to, the expert, i. e., the geologist acquainted with seismology draws two kinds of conclusions therefrom (as Prof. Angenheister has convincingly set forth as the technical adviser of the defendant). Scientifically he is reminded of the fundamental researches of Wiechert which also form the basis here, as he at once acknowledges. He is reminded that Wiechert was the first one who, in 1907, (with his students) established a serviceable method of calculating the greatest depths to which earthquakes penetrate, which is based on a travelling time curve, i. e., on a compilation of the travelling times of elastic waves. For practical work, however, he at once concludes that, if he only measures at one place, he must explode blasting material at various (possibly many) places, or, if he wishes to restrict the explosion to one spot, he must use various (possibly many) seismographs, unless, which of course is also possible, he wishes to use the same seismograph over and over again at new places for repeated explosions. Finally comparative measurements at places, the geological structure of which is already known, are essential for the process and are therefore expressly stated not only on page 2 lines 46 and following in the description, but also in the patent claim itself. According to all these characteristic features, the expert knows how he is to go to work.

The patent specification thereupon further gives him important directions for the utilization of the process (p. 2, lines 26 ff.). It points out that from the speeds and depths of the waves, in particular from the mutual relation between the longitudinal waves (i. e., those oscillating in the direction of their propagation) and the transverse waves (i. e., those oscillating perpendicular to same), conclusions can be drawn as to the elastic properties of the rock strata which are traversed by the waves. From turning points and breaks in the time-distance curve it is said that conclusions can be drawn as to discontinuities in the elastic properties of the rock strata as well as to diffractions and refractions in the bounding planes. In practice this concerns especially the determination of interfaces of discontinuity in the depth, as the expert Kühn set forth, i. e., the determination of the plane of division between two rock bodies, which allows, for instance, to calculate the thickness of a rock stratum downward. In this connection the specification refers to the drawing. The doubt which the expert Kühn (contrary to the late expert Harbort) in the first instance expressed against the two illustrations of the patent specification, has been dissipated by the hearing, and especially by the expositions of Prof. Angenheister. The illustrations correspond with the Wiechert method of determining depths, to which the expert (vide above) was already referred in another passage of the patent specification, and without leading astray, serve to illustrate the Mintrop Method, geological details being unimportant here.

The Mintrop process as an expert gathered it from the patent description in its entirety, was new at the time of the application for patent. Suggestions to use artificially produced waves for the exploration of rock strata, were indeed made before. In preference to all others those two publications which alone were discussed somewhat more in detail at the hearing might be considered as a pre-publication of the invention, namely the article by Belar "On a new practical application of seismometers" published in "Erdbebenwarte" 1st annual volume 1901, page 59 and the paper by Wilip "On an artificial earthquake recorded at Polkowo", 1914.

It cannot be denied that the ideas expressed by Belar in view of the purposes of tunnel construction allow to discern the method now patented in favor of the defendant, in general outlines and in detail, from artificial earthquakes and their recording on to the conclusions that must be drawn therefrom. In so doing, however, the decisive point must not be left out of sight, that in the year 1901 no practically serviceable process could as yet be drawn from such exposition, because it was only in the year 1907 that Wiechert's researches provided the indispensable basis for so doing, in calculating the greatest depth into which earthquake rays penetrate as well as their velocities. Belar's article can accordingly not be brought up in opposition to the defendant's patent.

When Wilip's paper was published, in 1914, Wiechert's results were already known. But all Wilip ventures to point out is the possibility of some day determining by expensive experiments the time-distance curve for seismic rays of the upper earth strata, and perhaps drawing conclusions therefrom as to the earth strata which are of interest to mining. Wilip did not go beyond this consideration. He anticipated nothing as to the process patented by the defendant.

The step which the defendant first took of utilizing the Wiechert earthquake calculation for the rock strata accessible to mining, was not by any means obvious to the average expert, not even in consideration of the Belar publication, but is rather to be considered as an inventive performance. As the expert Kühn has explained, the perception, which at the time of the patent application was of a nature to cause general surprise, was necessary that the seismograph not only records the waves proceeding immediately under the surface, but that towards it, i. e., back to the surface, there also proceed the radiations which penetrate from the blasting spot into the depths. As Prof. Angenheister stated at the hearing, and as also appears from the reports as to the meeting of the Committee on Ores of 15th December 1921 contained in the documents on the file, even Wiechert himself thought fit to seriously doubt this fact in the first instance, and he only allowed himself to be convinced by the experimental results of the defendant. This perception was the indispensable foundation for the process which the defendant proposed in his patent, for it first opened up the surprising possibility of calculating rock strata at considerable depths. The merit of the defendant is having made same serviceable to mining. An important enrichment of ~~mining~~ technics may be recognized in the considerable facility thereby afforded to the preparatory works of mining.

According to this the action for nullity had to be rejected whilst quashing the decision of the Reich Patent Office.

Document under seal and signature

The Reich Court 1st Civil Senate

By Order

(sgd) Katluhn

President of the Senate.