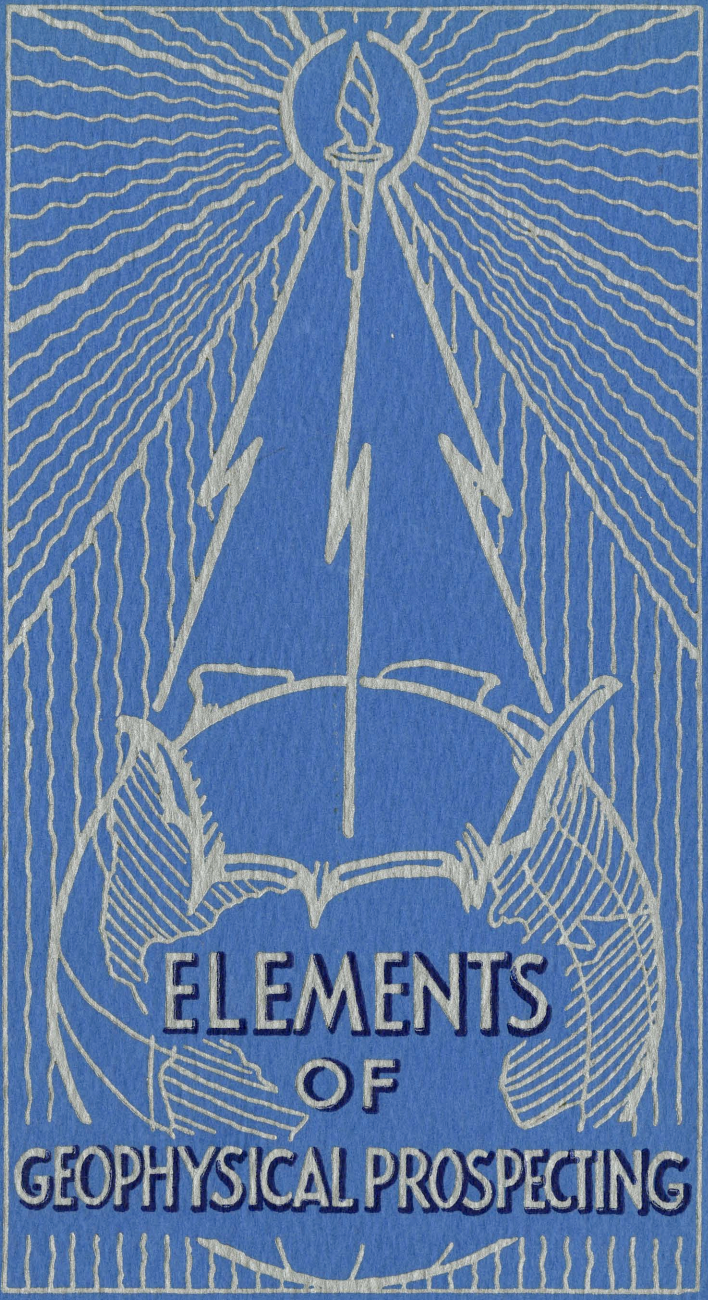


ELEMENTS OF GEOPHYSICAL PROSPECTING

as demonstrated at

A CENTURY of PROGRESS, CHICAGO 1933

in the GEOPHYSICS SECTION of the

AMERICAN PETROLEUM INDUSTRIES EXHIBITS

ELEMENTS
of
GEOPHYSICAL PROSPECTING

as demonstrated at
A CENTURY OF PROGRESS, CHICAGO, 1933
in the GEOPHYSICS SECTION of the
AMERICAN PETROLEUM INDUSTRIES EXHIBIT

Fig. 1—Front View of the Geophysics Exhibit in Science Hall

ACKNOWLEDGEMENTS

The writer wishes to express his gratefulness for the cooperation of the Petroleum Exhibits Committee of the American Petroleum Institute, particularly Chairman L. S. Wescoat, vice president of the Pure Oil company, in making it possible to publish this bulletin.

The writer also wishes to thank Dr. M. F. Coolbaugh, president of the Colorado School of Mines, for his interest in the preparation of the geophysics exhibit and for his cooperation in permitting members of the School of Mines staff and faculty to devote their time to the construction of the exhibit.

Dr. F. M. Van Tuyl, head of the department of geology, not only assisted materially with suggestions for improving the geologic sections, but spent a great deal of time in preparing these sections. He was ably assisted by Mr. L. O. Green.

Mr. Charles H. Hull, instrument maker at the School, constructed most of the mechanisms and instrument models in the animated exhibits.

The courtesy of the American Askania Corporation and of the Geophysical Service, Inc., of placing geophysical instruments at the disposal of the exhibit for the duration of the Exposition is here gratefully acknowledged.

CONTENTS

ELEMENTS OF GEOPHYSICAL PROSPECTING

By C. A. Heiland

Professor of Geophysics, Colorado School of Mines

THE DIVINING ROD

Ever since man has made use of the earth's mineral products the thought has been in his mind that it should be possible to predict, by some means or other, the location of mineral deposits hidden from his view.

In antiquity and the medieval ages, such possibilities were placed altogether in the realm of magic. The "Divining Rod" in particular was thought to possess the supernatural faculty of locating all kinds of mineral deposits. Although it has never been proved that this device can furnish identical indications at the same place at different times, or for different operations, its use has not been entirely discontinued.

When we illustrate the well known divining rod scene from Agricola (**Fig. 2**) at the right entrance to the Geophysics Booth, it is not done because we regard this device as a geophysical instrument or even as a prototype of such, but because we want to illustrate the trend of man's thought about the possibilities of locating mineral deposits through the ages.

In this connection, it is not the charlatan user of the divining rod, nor the bona fide operator who holds our interest. The former may be passed up without further comment, and about the latter it may be said that if he is actually capable of psychic reactions to concealed objects, they could manifest themselves in other ways without necessarily using a divining rod. It is a third type of operator in the early days of the device who deserves mention; the type who, by logical analysis of such indications as topography, soil color and vegetation, formed some conclusions as to the occurrence of mineral deposits, but was too clever to expose to the public his way of reasoning and preferred to be regarded as a magician gifted with strange and supernatural powers.

THE GEOLOGIC METHOD

Many important advances have been made in the past two centuries in the development of the "geologic" approach to the problem of mineral location, the early beginnings of which have just been pictured. Not only by mapping of surface indications, but also by the observation of the structural arrangement of formations in outcrops and wells, and an analysis of their lithologic character and fossil content, it has become possible to predict the location of mineral deposits much more accurately. The "geologic" method of mineral location has received a considerable stimulus in late years through the demand for new mineral products by the chemist and metallurgist, and for new oil fields by the increasing volume of the automotive industry.

There are, however, decided limitations to the "geologic method" of mineral location. Its accuracy depends entirely on the accessibility of geologic formations, and the interval of observation points. More specifically, and in oil work in particular, it depends upon the presence of bore holes, their interval, and depth.

THE GEOPHYSICAL METHOD

An altogether different avenue of approach to the problem of mineral location has now been opened by the advances made in the past two centuries in the science of physics, in the fields of electricity and magnetism in particular. With the ever increasing refinement of physical apparatus it has become possible to measure not only the forces that control the movement of the earth in space, but also the forces that are related to its constitution. Physics as applied to the earth is called "Geophysics"; although many a reader may not be familiar with the name, he is undoubtedly acquainted with the forces, the measurement of which is the object of study of this science; for instance, the earth's magnetism, gravity and earthquake phenomena.

The possibility of determining the constitution of the earth's interior by observation and analysis of the surface distribution of such phenomena as just mentioned was early recognized. The scope of these observations was first more regional in character and was gradually narrowed to the investigation of local disturbances in search for individual mineral deposits.

To illustrate this, let us use again the earth's magnetism, gravity and earthquakes as examples.

Earth's Magnetism

About 1600, Gilbert, from an analysis of the distribution of the earth's magnetic force, came to the conclusion that the earth behaves as a great magnet; about a century later, De Castro recognized the relation between the earth's magnetic attraction and geologic structure, and as early as 1640 compass-like instruments were used in Sweden for the location of iron ore deposits. There, these instruments were developed to a great degree of perfection for the purpose mentioned, chiefly in the last half of the nineteenth century. Further refinements added in late years have made it possible to use magnetic instruments in search for oil structures and gold deposits.

Gravity

A much similar development may be observed in the evolution of the knowledge of earth's gravity and its application. Bouguer, about 1740, established the fact that the plumb line direction is not always vertical but is attracted by heavy masses. Cavendish, in 1798, succeeded in "weighing" the earth and thereby proved that materials heavier than those at the surface must be present in the interior. The nineteenth century marks the development of the gravity pendulum and its application to the determination of the mass distribution in the earth's crust. In 1888, Eötvös constructed an instrument intended to measure minute mass attractions, called torsion balance (similar to the device used by Cavendish in his experiments). We are still using the Eötvös instrument, almost in its original form, in

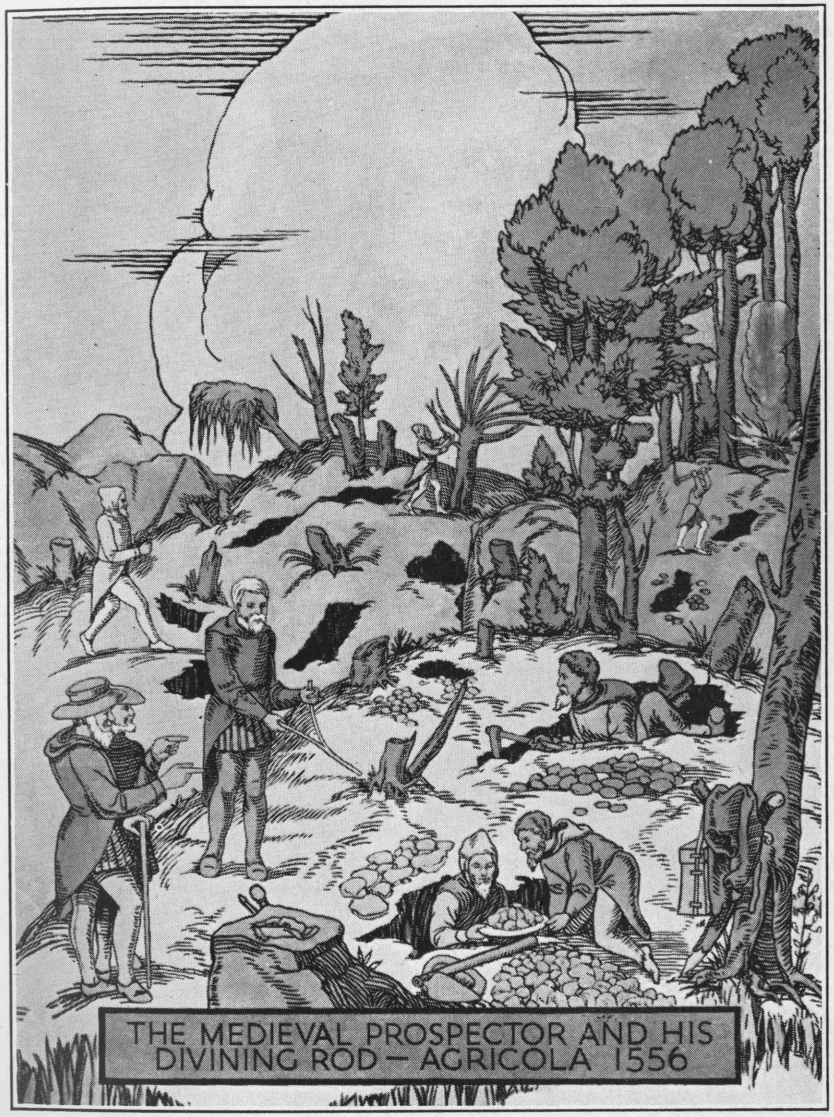


Fig. 2—The Medieval Prospector and his divining rod, reproduced from Original Woodcut from Agricola's De Re Metallica, Sixteenth Century.

search for salt domes and other oil structures, after von Böckh and Schweydar, in 1917, had demonstrated that the instrument is applicable for such purposes.

Seismology

A division of geophysics which has probably contributed most to our knowledge of the earth's interior is the science of earthquakes, or "seismology". In order not to weigh this introduction down with too much historical data, it may merely be recalled that in the nineteenth century instruments for earthquake registration, called "seismographs", were developed to a high degree of perfection, which made it possible to recognize various types of waves, travelling from the origin of the earthquake through the earth's interior, to the recording station. By determining the time of their travel to various stations, and thus their velocity through various depths of the crust, geophysicists were enabled to state the makeup of the earth's interior with a remarkable degree of accuracy. The application of this principle on a small scale, to determine geologic structure in exploitable depths, was made by Mintrop in 1917; and from then on, the "seismic method" scored remarkable success, chiefly in the discovery of salt domes in the Gulf Coast.

Thus, geophysics is a science which truly enables us to "look into the earth" in a manner quite remote from the supposed possibilities of the divining rod. The power of Geophysical Science is symbolized in the central front part of the Exhibit by an edge-lighted glass etching, showing the torch of science radiating light and energy, symbolized by thunderbolts which lay bare the interior of the earth by splitting the crust. **(See cover).**

ILLUSTRATIONS OF THE PRINCIPLES OF GEOPHYSICAL PROSPECTING

Geophysical prospecting, as compared to geophysics, simply means the application of the principles of geophysics on a smaller scale for commercial purposes. For it is not only the large structural features of the earth such as continents and oceans, mountains and depressions, crust and subcrust, that have different physical properties and therefore affect the earth's magnetism, gravity and earthquake waves. Many mineral deposits also differ from their imbedding media in magnetism, or density, or electrical conductivity, or elasticity. They can, therefore, be detected by magnetic, gravity, electric or seismic measurements at the surface. This is a fundamental principle which we want to impress forcibly upon the visitor to our exhibit. Hence, a large edge-lighted glass plate in the central front part of the exhibit reads

> "Geophysical prospecting in the location of mineral deposits by surface measurements of physical quantities which are affected by their structural arrangement and physical properties."

Let us take three examples to illustrate this point:

Prospecting for Iron Ore

Iron is often found in nature in the form of lodestone (magnetite), which, as everybody knows, is highly magnetic. Suppose there are indications of the existence of such deposit in a given area, and the problem is to determine its exact location. The reader will think that such should be easy by using a compass, or a similar instrument. This is correct; it is

exactly the way we proceed; only we ordinarily do not use a compass, but a device better suited for the purpose, called a magnetometer. Where we obtain the greatest attraction, the sought deposit is likely to occur.

We may proceed, however, in another manner. Magnetite usually weighs more than the rock in which it ordinarily occurs. Then we may employ instruments that are capable of detecting differences in gravitational attraction; i. e., attraction due to excess or deficiency of mass, such as the Eötvös torsion balance previously mentioned. The advantage in using this method in addition to magnetic measurements is explained by the fact that a magnetite deposit often is not uniformly magnetized, while its density varies less. Thus, there may be less difficulty in interpreting the results of the gravity measurements than in analyzing the more variable magnetic attractions.

Or else, we may make use of the fact that magnetite usually conducts electric current better than the imbedding rock. We may put current through the ground by means of two stakes and measure how the voltage changes along the surface between the stakes. That will show us where a better conducting medium is buried but, (making the electrical measurements alone) it would not mean that the discovered conductor is magnetite. However, if magnetic measurements have also been made, we may conclude that the conductor is magnetic, too; and if we also have measured the variation of gravity and have observed a greater gravity attraction at the location where the conductivity is low, we know that the subsurface body causing this disturbance is heavy. As there are not many minerals besides magnetite that are magnetic, and also heavy and conductive, the problem of determining the nature of the subsurface body has been solved with a good deal of certainty.

Prospecting for Gold

This problem is not nearly so easy as the first one, and has only lately been solved for a limited number of cases. Not all gold deposits can be discovered geophysically because the gold occurs in quantities too small and in a form too finely dispersed through the rock. There is, however, one form of geologic occurrence that lends itself to geophysical prospecting. This is the occurrence of gold in river channels, present or past. The reason is that in a river the waters when slackening speed for instance, on the inside of their turns, will drop out the heavy minerals first, like gold and magnetite, so that often (not always) gold may be found associated with magnetite. Therefore, by locating with a "magnetometer" the trends of greatest attraction, the places where gold is most likely to be found may be located. However, it must be borne in mind that they are not necessarily areas of gold concentration; whether or not enough gold can be found in an area of magnetic attraction has to be determined by the drill.

Let us see now what our other two methods, which we used before in locating iron ore, could do for us in this case. It is true enough that gold is heavier than the sand or gravels in which it occurs. However, the quantity present is not enough to affect any gravity measuring instrument. Besides, as we are dealing with attraction due to mass, a large gold nugget at the bottom of the river channel would probably give the same indication as a small boulder near its surface. Thus, the gravity method is not applicable, as far as the direct location of gold is concerned.

However, the method can be of decided help in areas where the gold-bearing river channels are buried and nothing about their course is known.

The river gravels, due to their looseness, are lighter than the more solid bedrock into which the channel has been cut; therefore, the trend of the channel can be determined by gravity measurements, which thus could locate the gold by finding the *structure* in which it is *likely* to occur.

Let us investigate now what the third method would do for us here which we used before to locate our iron ore deposit, namely the electrical method. No doubt the gold is a better conductor for electricity than the associated minerals or rocks, gravels, sands, etc., but that would not be of great help because again the gold occurs in too small quantities to be detectable. However, the electrical methods may be of help in the problem in an indirect way; namely, by either locating an unknown channel or by determining, in a known channel, the depth to bedrock. This is made possible because the river gravels and sands are usually saturated with mineral waters and are, therefore, more electroconductive than the dry and more consolidated bedrock. How the depth to bedrock may be determined with electrical methods will be shown later on. Suffice it to say here that it can be done satisfactorily in most cases, and moreover, that this method is very valuable in another field of application of geophysics, Civil Engineering, when it comes to the problem of selecting the best site for a dam.

Prospecting for Oil

The previous example of locating a gold deposit will have demonstrated the indirect nature of the procedure; i. e., the prospecting for a mineral or geologic formation which is *associated* with the sought mineral.

Geophysical prospecting for oil uses at present predominantly the same idea. Admittedly, there are a number of physical properties of the oil itself which at first glance appear promising. It is lighter than water and a poor conductor for electricity. Thus, there appear two possibilities of, for instance, separating oil from water geophysically. The second one is indeed utilized in wells on a commercial scale at the present time. As shown in one of our exhibits, a "contacting" arrangement is lowered into an uncased well and an oil sand shows immediately by a much higher resistivity, a water sand by a lower resistivity.

Despite the contrast in conductivity of water and oil, and despite the possibility of detecting this contrast *when we have direct access* to a formation, the direct location of oil by electrical measurements from the surface is, at present, only rarely possible. This is due to the fact that both oil and water do not occur, as most laymen think, in large pools, caves or reservoirs below the surface. On the contrary, they are confined to the pores of sands, sandstones and cavernous limestones, in which their migration and separation due to specific gravity is very slow. Now we have seen before that in any one individual formation, sand or sandstone, the electrical resistivity is quite different depending on whether oil or water fills the pores. If there were only one oil- or water-bearing formation in an area, if its depth were shallow, and if it were under- and over-lain by strata of a much different but homogeneous constitution, it might be possible to determine from the surface by electrical measurements where, for instance, the water in it begins and the oil stops, or vice versa.

In 99 per cent of the oil fields, however, such simple conditions do not prevail. Oil sands are over- and under-lain by formations of great variations in porosity and, therefore, great variations in water content. Considering that the mineral content of the pore water will also vary within very

wide limits, it is seen how much the electrical conductivity is likely to vary in the whole section. Thus, even if an oil sand did excel in resistivity, its effect is likely to be blurred by the immense variety of resistivities in the geologic column above and below. Furthermore, it is a fact that the variation in resistivity encountered in different formations by the varying water content is very often of the order of the difference in resistivity introduced by the presence of oil. Thus, the direct location of oil by resistivity measurements at the surface has not yet been developed as a commercial method.

However, there are numerous ways at our disposal to locate formations, or geologic structures, in which oil is *likely* to be found. For, the occurrence of oil is intimately associated with definite types of structures; these types resulting simply from the fact that oil, being lighter than water, has a tendency to migrate toward the highest point of a given formation. Oil accumulation, therefore, is almost invariably dependent upon an *inclination*, or dip, in geologic formations (besides, of course, depending on their porosity); second, on some sort of a trap at the highest point. Formations were tilted in the earth's geologic history by folding, uplifts of certain

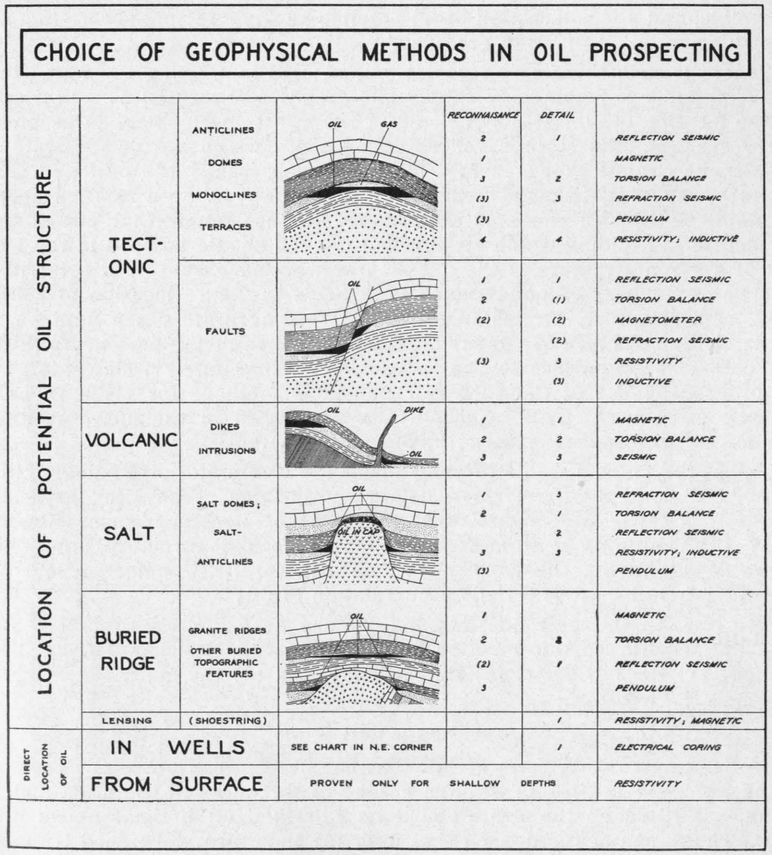


Fig. 3a—Choice of Geophysical Methods in Oil.

portions of the crust, and by deposition of sediments on hilly, ancient land surfaces. In a simple fold, the oil, therefore, will be found on its highest point (**Figs. 5, 6, 12, 14, 17**); along a fault, usually near the highest point of inclined beds (**Figs. 6, 8, 12, 14 and 18**); near a salt dome which has broken through a zone of weakness and has tilted up formations along the edge, near the border of the salt and sometimes above its cap (**Figs. 5, 6, and 15**); finally, in porous sediments on the flanks of an ancient buried hill (**Figs. 4 and 10**).

It is exactly these types of geologic structures that we are seeking by geophysical methods in indirect search for oil. In other words, we are trying to locate structures *favorable* for the accumulation of oil. Whether such structures actually contain oil, remains ultimately for the drill to discover, because structure alone does not mean the presence of an oil deposit. Three factors, chiefly, have to be present in addition to structure: (1) source beds; (2) reservoir rocks; and (3) adequate porosity to enable migration to follow structure. The reader will realize that it is a long way between locating a structure and recommendation for drilling. A very exhaustive interpretation of the geophysical data, use of more than one geophysical method if possible, and a consideration of all possible geologic factors controlling the accumulation of oil, have to precede it.

There is such a variety of geologic structures in which oil is found that it is impossible to recommend simply *one* geophysical method as a "cure-all" for the location of oil. It may be said of the latest development in geophysical prospecting, the seismic reflection method, (which we demonstrate in our seismic exhibit shown in **Fig. 15**) that it is possibly the best and most accurate way of mapping geologic structure; however, even this method is not applicable in all cases. Furthermore, another factor that enters into the picture in deciding which geophysical method should be used in the location of a given structure is the question of whether a survey of a territory is to be of a purely reconnaissance type (i. e., the mere location of a high point, of a structure, for instance), or whether accurate depth data on all points of the structure are desired. The experience of the past years in the application of geophysics to the location of oil has fairly well established the order of choice of the various geophysical methods for given types of geologic structures. This is graphically illustrated in the chart entitled: "Choice of Geophysical Methods in Oil" (**Fig. 3a**).

What the layman wants to know about the location of oil by geophysical methods, then, is this: (1) How do we know which geophysical method to use, if it is fairly well established what type of structure we are dealing with? (2) If nothing at all is known about the geologic structure, how would we go about finding the localities which structurally would represent the most favorable locations for the accumulation of oil?

To answer the first question, let us use as examples three types of geologic structures, the location of which geophysics has chiefly been applied: (1) the *salt dome*, (2) the *anticline*, and (3) the *fault*.

Locating a Salt Dome

A "salt dome" is a mass of salt that has been forced up by the pressure of the overlying sediments through a zone of weakness in the crust and, in rising, has tilted up the strata round its edge and often times above it as well. The flanks of the dome (**Figs. 5, 6, 15**) thus form very good traps for the oil, and it is for this reason that in regions geologically suitable for the

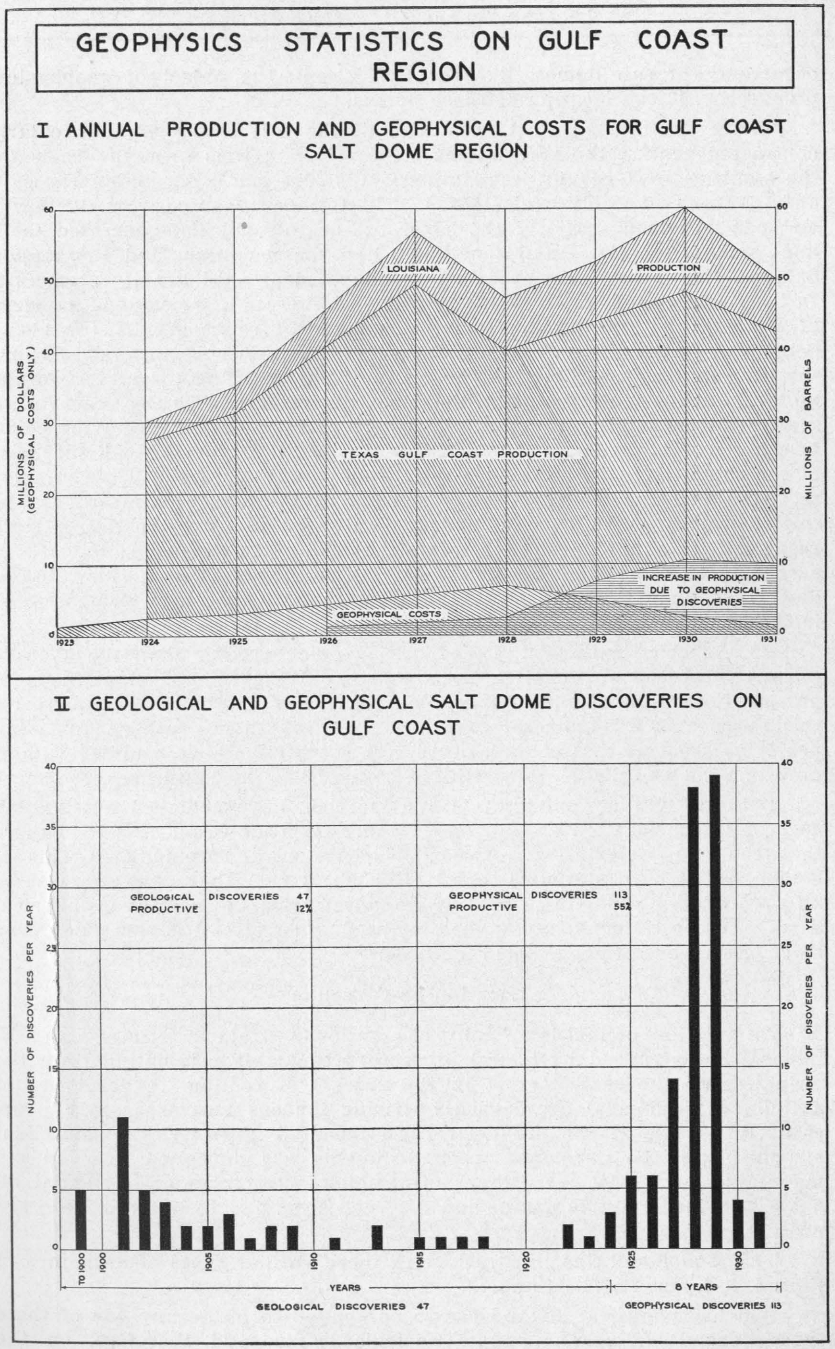


Fig. 3b—Gulf Coast Salt Dome Statistics.

occurrence of salt domes, like the Gulf Coast, the object of geophysical prospecting is the location of these domes.

There are two physical properties of the salt which are particularly contrasted against the surrounding sediments and thus form the basis for the application of geophysical methods: (1) The small density of the salt, and (2) its great rigidity (elasticity). The former makes possible the use of methods measuring gravity; the latter, the use of explosion-generated (seismic) waves. In the gravity methods, like the pendulum and the torsion balance, the salt would appear as a zone of decreased gravity attraction. In the seismic methods, it would appear as follows: If we explode a charge of dynamite at one point, set up a number of seismographs (or sound detectors) on the circumference of a circle about the shotpoint, and measure the time that elapses between the firing of the shot and the arrival of the vibration at the receiving point, this time interval would be the same for all receivers if no salt mass was present between shot point and receiving point. In other words, the sound would arrive through the ground at all receivers at the same time. If, however, a salt dome would intervene between some receivers and the shotpoint, the time interval would be *shorter*, as the seismic waves would have a tendency to travel through the deeper high speed salt, (i. e., along the path where they can make the fastest time). An arrangement of receivers in reference to the shotpoint, different from the one described; namely, along a profile through the shotpoint, is demonstrated in the Seismic Exhibit shown in **Fig. 15.**

As the electrical resistivity of salt is much greater than the average resistivity of the surrounding beds, it is seen that electrical methods of prospecting would also be applicable. They have actually been used for this purpose in a number of cases; however, as their depth range is not nearly as great as that of the seismic and gravity methods, and their interpretation not as reliable, they will not be described in detail here.

Both the gravity and the seismic methods have achieved outstanding success in the location of salt domes along the Gulf Coast, and it is there that the geophysical discoveries have been most spectacular. This is demonstrated by a statistical chart (**Fig. 3b**) which shows the increase in oil production of the Gulf Coast as compared with the cost of geophysical work, and the tremendous increase in the number of salt domes discovered since the advent of geophysical methods.

Locating an Anticline

An anticline or fold is an uplift of a series of strata in form of a saddle, in most cases caused by lateral pressure presumably originating from the wrinkling of the earth's crust in the process of cooling. Other types of anticlines (or domes) are caused by rising igneous masses or by the upthrust of salt plugs as previously described. A third type of anticlinal structure may be developed when sediments are deposited over an old mountain range. All these types of anticlinal structures are potential oil fields, provided suitable source and reservoir beds and hydrostatic head are present.

The reader will find illustrations of these various types of anticlines in **Figs. 4, 5, 6,** and **10, 12, 14** and **17.**

Which geophysical method has to be applied to locate any one of these types depends altogether on its geologic origin, and therefore, on the presence of a *contrast* in some *physical property* of the anticline as a whole

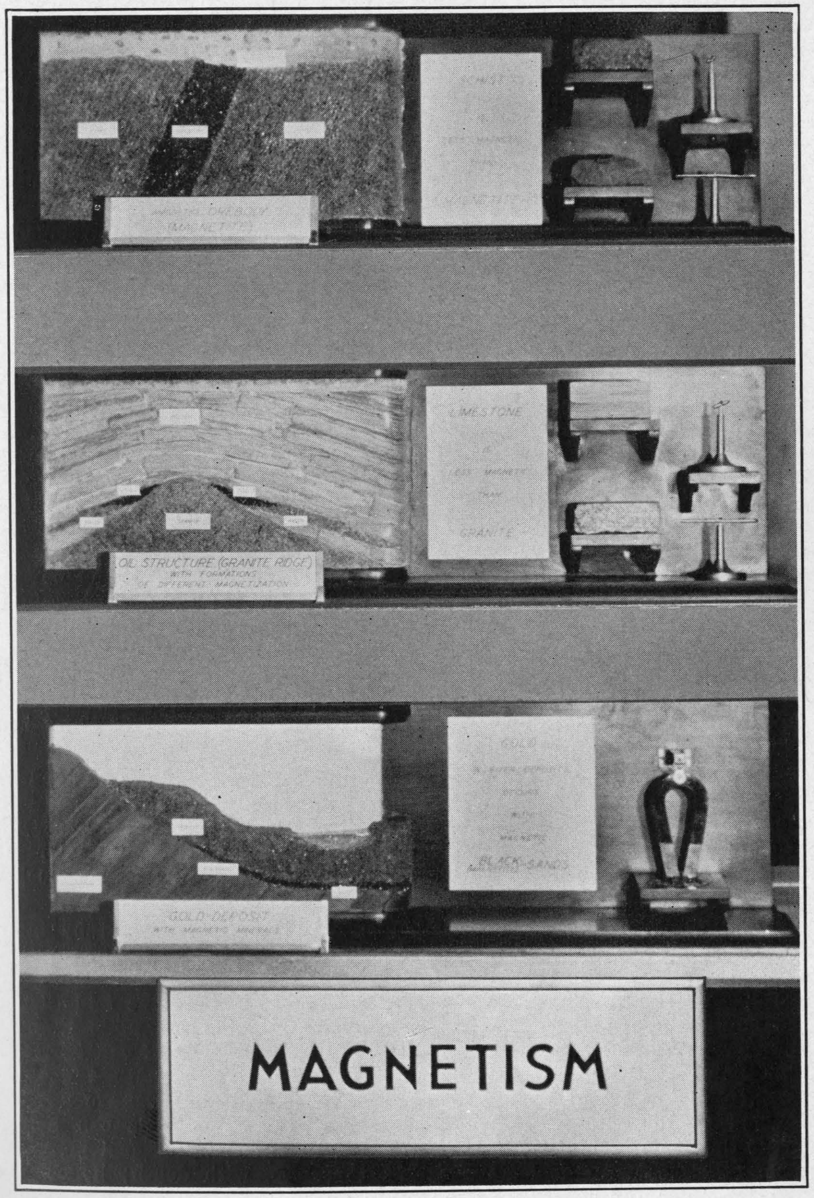


Fig. 4—Exhibits demonstrating rock magnetism.
Top—Compass needles show that schist is less magnetic than magnetite.
Middle—Compass needles show that limestone is less magnetic than granite.
Bottom—Illustrating that gold in river deposits occurs with magnetite.

or a part of it. Take for instance a dome developed by the upthrust of igneous masses, like the basalt plugs in Mexico. Basalt is a very magnetic rock; consequently, the logical method to apply first is such a case would be the magnetic method, since it is the fastest. Because basalt is heavier and more rigid than the covering sediments, gravity and seismic surveys may also be applied. It should be understood that in all these cases the information obtained refers only to the core of the structure, which is the basalt, and the geophysicist can in the assumed case say nothing about the structure in the covering sediments.

Take another type of anticline, the "buried hill" type, developed by burial of an ancient mountain range. These old ranges are made up mostly of crystalline rocks like granite and gneiss, and here again, the magnetic method is the most logical one to use first. An example of this kind is demonstrated in **Fig. 10**. In this case, also, the gravity methods may be applied, as the buried "basement" rocks are usually denser than the covering sediments. It is readily seen how it would help the geophysicist to apply both of these methods in the same area. The magnetic method would give information only about the magnetic part of the buried ridge, while the gravity methods would give him a picture of the outline of the whole ridge, regardless of whether it is magnetic or not. Therefore, in practice, the magnetic method is usually employed first as it is the cheapest and fastest in application, and is then generally followed by the gravity methods. It is further seen that the magnetic method gives information about the anticline only as far as its "core" is concerned, as usually the covering sediments are not magnetic. Provided differences in density exist in the covering sediments, however, the gravity methods would not only pick up an uplift in the basement rocks, but they would also react to a doming in the overlying strata, and the results would show the combined effect. Finally, any uncertainty as to whether a doming is actually present in the covering strata may often be eliminated by the application of the seismic reflection method, if a reflecting bed is present.

We have gone purposely into these details to illustrate how we gradually accumulate information on a structure by applying various geophysical methods which react to *different* physical properties and to *different parts* of a structure, and to show how the interpretation of the geophysical results must of necessity be tied in with a consideration of all possible geologic factors.

Finally, let us take the example of a regular fold caused by lateral pressure, that is, not by any of the agents discussed before. When a series of strata are folded up, usually the deepest formations or "basement rocks" are also affected and are, therefore, higher in the core of the fold than on the flanks. As the basement rocks are usually more magnetic than the younger formations, we see again that the magnetic method can locate the high point of the structure. Sometimes, however, this method does not work, if the basement rocks are too deep to be detected or have not been affected by the folding. Then usually the gravity methods can help to locate the dome. This is due to the fact that the density of geologic formations increases with geologic age and, therefore, with depth; hence, in a fold, the older and denser formations are closer to the surface in the center than on the sides. Furthermore, the older and denser formations are usually more rigid than the upper and younger ones, so that the application of the seismic methods will furnish a clue to the structure by working on a rigid key bed or series of beds. Finally, the older formations are often poor

conductors of electricity, so that the electrical resistivity method may be applied to locate the high point.

Locating a Fault

We have seen before that inclined beds favor the migration of oil to the highest point. That is why in an anticline the oil and gas is found in the crest. In the course of the earth's history, not only folds or anticlines were produced, but often-times the continuity of formations has been broken; they have been sheared off and displaced vertically. A condition of this sort is shown in **Fig. 18**, and in **Figs.** 12 and 14. It is called a "fault". It is seen how a fault can be a very efficient trap for the oil; many important oil fields are associated with faults; they offer, fortunately, good possibilities for practically all geophysical methods.

It has been mentioned before that older formations are ordinarily denser than younger ones. In addition to this, there is usually some sort of a vertical differentiation in density in the geologic column; i. e., sands alternate with shale, limestone beds intervene, etc. If the horizontal continuity of such section is broken by a fault, beds of different densities are placed in the same horizontal level, which gives rise to a change of density in horizontal direction, and, therefore, also to a change of gravity in a horizontal direction. For the detection of such changes, we have a very sensitive gravity instrument, called the torsion balance. It is demonstrated in **Fig. 14** how this instrument reacts to such horizontal changes in density underneath which are brought about by a fault or by an anticline.

Chances are, furthermore, that when formations of different densities have been thrown in the same level by a fault, these same formations differ in rigidity. As shown in the upper exhibit of **Fig. 6**, it may thus happen that a series of limestone beds has been thrown into the same level with a series of shales, through which the speed of elastic waves is much less than through a series of limestones. Hence, when setting up a number of seismic receivers along a line at right angles to this fault, firing a shot at one side and measuring the time differences between the shot and the arrival of the elastic waves, the presence of the fault is detected immediately.

It was also stated before that more dense and more rigid formations have a higher electric resistance. Thus, using the same example of limestones brought into contact with shales by a fault (**Fig. 8, middle**), it follows that we can detect the presence of the fault by running a resistivity survey across it with an apparatus shown in **Fig. 17**.

Indirectly, the fault can, finally, be detected by making a determination of the depth of a conductive key bed on either side of it, using the inductive electrical method, or the reflection seismic methods, which will both be explained later on in greater detail.

The magnetic method has been found to be of comparatively little use in the location of faults as compared with the other methods mentioned before.

Location of Oil Structure in Virgin Territory

In the preceding paragraph we have answered the first question raised on page 12, namely, what geophysical method should be used for the location of oil structure if the type of geology is fairly well known. The second question, what to do in an area where nothing is known about the geology, is more difficult to answer. The reader should not forget that in the last case any exploration method is handicapped by a twofold uncertainty: first, as to whether any formations are present which are likely to be oil-bearing; and second, as to the type of structure with which the oil is associated. This point is brought out to emphasize again that we are not locating oil *as a substance*, but merely *oil structure*.

Geophysical oil exploration in virgin territory, then, is usually carried out in such manner that a connecting survey is made to an area where the geology is better known. In addition, more than one method is employed in order to get reactions from portions of the geologic structure with as many varying physical properties as possible.

CONDENSED FACTS ON GEOPHYSICAL PROSPECTING

The salient features of the operating principles of geophysical prospecting, which have been described above by using a number of examples of the most frequent applications, may be summarized into four sentences which are shown as a transparency entitled "Four Facts on Geophysical Prospecting" in a prominent place of the exhibit, and which read as follows:

1

Mineral Deposits are related to the Earth's Geologic History and were formed where the geographic, biological, chemical and physical conditions were and continued to be favorable.

2

These conditions gave rise to their varying physical properties and structural arrangements; they produce spontaneous (magnetic and gravitational) attractions, or offer varying resistance to sound waves or electric currents.

3

The object of Geophysical Prospecting is the measurement of such physical forces as stated in 2, and the interpretation of the results in geological terms, i. e., type of structure and depth.

4

Frequently, as in the location of *oil* and gold, not the sought mineral, but associated *structures* or minerals, produce the observed effects.

PHYSICAL PROPERTIES OF ROCKS

From these four facts on the principles of geophysics, two important conclusions may be drawn in reference to its practical application in search of minerals: First, the choice of a geophysical method depends on an analysis of the geologic situation and upon an evaluation of the physical properties which are possessed either by the sought deposit itself, or by associated minerals or geologically related formations or structural elements. Second, the success of any geophysical method in a given case depends (1) on the contrast in the physical properties of the sought mineral or formation and the embedding medium, and (2) on the effectiveness of this contrast by virtue of the structural arrangement, size and depth of the sought geologic body.

We shall not dwell here upon the second part of this last statement, namely, the effect to be expected upon a geophysical method by a given structural arrangement, size and depth of a geologic body. These effects may be calculated for almost any geophysical method by the use of higher mathematics, and are the basis for the interpretation of the observed

effects in terms of geologic structure; however, it would mean going too far into details to digress into the principles involved in such calculations.

The tremendous range of application of geophysics not only in the field of oil location, but also in the fields of mining exploration, civil and military engineering, is due to the variety of physical properties inherent to most types of geologic structures *and* their comparative degree of uniformity in a space great enough to make a given geologic body discernible as a unit in the geophysical results. The physical properties that lend themselves most readily to the application of geophysical methods are:

1. Magnetism
2. Density
3. Speed of seismic waves
4. Electrical conductivity.

In each of the three fields of application of Geophysics (oil exploration, mine exploration, and engineering work) there are certain types of geologic structures which, as experience has shown, lend themselves most readily to its use because they display differences in these physical properties most contrastingly and most uniformly. These representative types of structures have been selected for the exhibits demonstrating the four properties stated above, magnetism, density, speed of sound waves, and electrical conductivity.

ROCK MAGNETISM

For this exhibit three geologic situations have been selected, typifying the application of geophysics to the location of an iron ore body (**Fig. 4**, top) to the locating of oil (**Fig. 4**, middle) and to the location of gold (**Fig. 4**, bottom).

In each of these exhibits we see a geologic section built up of actual rock specimens and showing the manner in which the sought minerals (iron, oil and gold) occur underground. Specimens of the rocks differing in magnetism are shown in the upper and middle exhibit, placed on shelves; one of these attracts a compass needle, while the other does not. Thus, it is seen that magnetite, composing an iron ore deposit, is magnetic, while the embedding schist is virtually non-magnetic. In the exhibit showing a granite ridge it is seen that the granite is magnetic, while the overlying limestoné is not. The lowest exhibit in this group shows a section through a river channel filled with gravels at the bottom of which magnetite has been deposited together with gold; a mixture of gravels, gold and magnetite placed under a horseshoe magnet shows that the magnetite is attracted, while the gravels and gold are not.

To such types of geologic structures as demonstrated in this exhibit, then, geophysical methods based upon the measurement of magnetic attraction are applicable.

DENSITY

For this exhibit (**Fig. 5**) two types of structures, important in the application of geophysics to oil exploration, and a third showing the application of geophysics in mining, have been selected.

In the upper exhibit we notice a nickel ore body flanked by quartzite on one side and by a dark igneous rock, called norite, on the other. When placing a given volume of the nickel ore in one, and an equal volume of norite in the other, pan of a scale, the nickel ore will appear to be heavier.

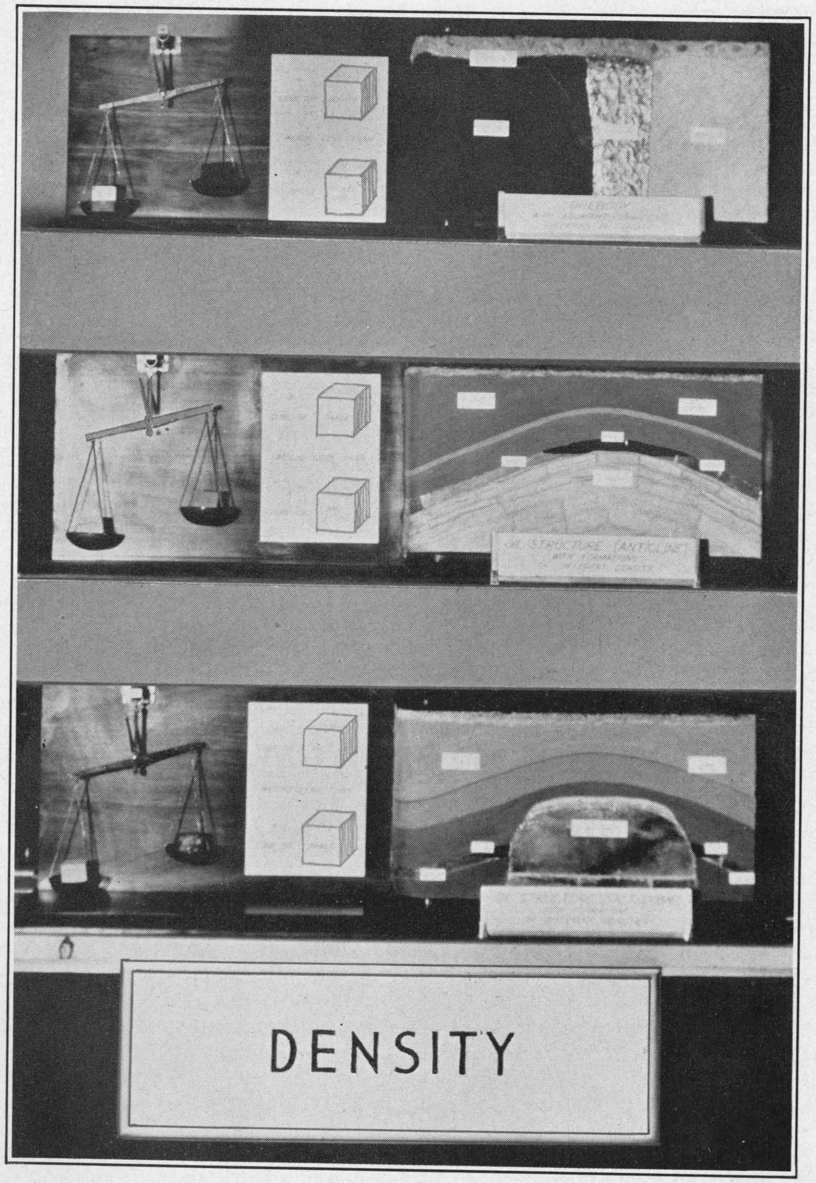


Fig. 5—Exhibits demonstrating rock density.

Top—Showing that a cube of norite weighs less than cube of salt.

Middle—Showing that a cube of shale weighs less than a cube of limestone.

Bottom—Showing that a cube of salt weighs less than a cube of shale.

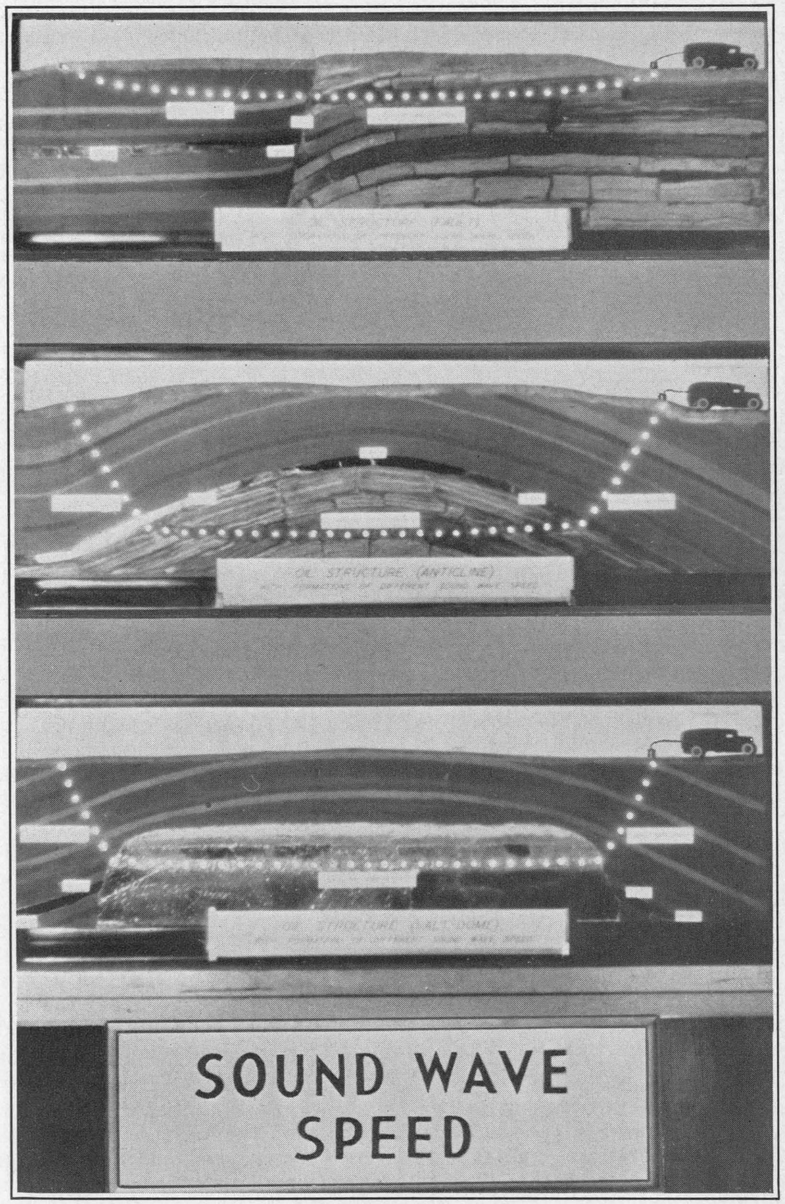


Fig. 6—Exhibit demonstrating speed of elastic waves in rocks.

Top—A fault oil structure.

Middle—An anticline oil structure.

Bottom—A salt dome oil structure. (Light bulbs show speed of the sound waves).

In the exhibit below that, an anticline composed mainly of limestone is shown with an oil sand above, overlain by a series of shales. When placing a cube of limestone in one, and a cube of shale in the other, pan of a scale, the shale will be found to be lighter than the limestone.

The last exhibit in this group shows a section through a salt dome which again is built up of actual salt. Oil is shown to occur in a sand on the flanks of the dome. The salt is surrounded by shale beds. Performing the same experiment with the scale as described above, we see that the salt is lighter than the shale.

To such types of geologic structures as demonstrated here, and many others involving a difference in density, geophysical methods based upon the measurement of gravity attraction are applicable.

SEISMIC WAVE SPEED

In this exhibit we are showing only structures which have become of importance in the application of geophysics to oil exploration, because experience has proved that there is much less application of geophysical methods utilizing elastic waves in mining and in civil engineering than there is in oil work.

The first exhibit shows a fault type structure, the second an anticline, and the third a salt dome, all built of natural rocks. The travel of the sound or seismic waves in each case is demonstrated by a string of lights which are flashed on at a rate corresponding approximately to the proportionate rate of propagation of explosion waves through the various kinds of formations concerned. As compared with the actual speed, the rate of travel in these exhibits is slowed down considerably in order to make the phenomenon visible. The waves start at the shotpoint with a flash representing the explosion, then travel first through the low-speed medium, thence to a high speed medium and out through a low-speed medium again, to a "detector" which converts, like a microphone, the vibration energy into electricity and actuates a recording instrument in a truck, a miniature of which is also shown. In actual practice, generally a number of such receivers are employed and the time interval is measured between the explosion and the arrival of the elastic waves at each receiving point. In order not to complicate, however, this exhibit with numerous wave paths to each receiver as shown in **Fig. 15,** we have chosen only one path to one receiver to explain the phenomenon.

Comparatively little is required in the explanation of the first (upper) exhibit in this group. The seismic wave is seen to travel from the shotpoint first slowly through the shales and will then pick up speed in the limestones on the right side of the fault. This illustrates how a fault and associated oil accumulation may be located by means of the seismic method.

As far as the second exhibit is concerned, the uninitiated will at first wonder why the wave path is bent upon entering the anticline composed of the limestone. Before explaining this phenomenon, it should be mentioned that there are, of course, a great many rays emanating from the shotpoint in all directions. Some of these will enter the limestone anticline, will be bent in the manner shown, but most of them will never reach the receiver. It is the ray which is deflected into a horizontal direction of travel and which leaves the anticline by the same angle at which it enters, which is picked up at the receiving point.

The bending, or "refraction", of the ray upon entering the limestone formation is a phenomenon analogous to everyday observation in light. When light enters a medium in which it propagates at a rate different from that in air, the light ray is bent. If we look at an object sideways through a piece of plate glass, this object will appear to be displaced from its regular position. Or, if we look at the sun near the horizon where the atmosphere is usually loaded with a great deal of foreign matter, its shape will appear distorted. Or, if we immerse a stick in water, it will appear to be broken at the surface of the water. All of this is due to the difference in the rate of light propagation in two adjacent media. The same goes for the seismic ray, which upon entering a "high-speed" medium, is "refracted". In the two lower exhibits, the presence of the high speed medium makes itself felt, in addition to the refraction of the seismic rays, by the faster rate of travel of the waves in the limestone and in the salt.

Thus, geologic structures similar to the ones shown, may be located by applying the "seismic" methods of geophysical prospecting, which are explained in greater detail later on.

For those familiar with the principles here demonstrated a brief description of the mechanism which operates this exhibit may be of interest. It is housed in the lowest exhibit and is shown in **Fig. 7.** An electric motor drives a drum, to the surface of which a number of contacts are attached which in turn pass a series of brushes when the drum revolves. The spacing of the contacts is the same for each exhibit; however, the greater rate of wave travel in the high speed media is simulated by connecting two or more lights to one brush. The drum is divided in three parts to operate the three exhibits shown in **Fig. 6;** however, in order to operate the exhibits in succession, a control flasher is provided which turns the common negative first to the first, then to the second, and then to the third exhibit; this control flasher may be seen in the upper right-hand corner of the flasher shown in **Fig. 7.**

ELECTRIC CONDUCTIVITY

Nearly everyone is familiar with the terms electric "insulator" and electric "conductor", and with the fact that electricity is conducted especially well through metals. The first thought that will occur to the reader in regard to electric conductivity is that electrical methods of prospecting should be applicable chiefly to the location of metallic ore bodies. This is indeed the case. Another field of application of electrical geophysical methods which may not be so obvious is the location and depth determination of bedrock in dam site and other civil and military engineering projects. At present, the application of electrical prospecting to problems of oil exploration ranks probably third; it is not the fact that the oil is an insulator which makes this possible, as previously explained, but the variations in conductivities of geologic formations.

Hence, in the exhibit demonstrating electric conductivity (**Fig. 8**) we have endeavored to show the application of electrical prospecting to these three types of problems, mining, oil exploration and civil engineering. In the three exhibits of this group, the representative types of geologic sections are shown on the right. On the left of each exhibit, there is a panel with a wire carrying negative electricity on the right and another carrying positive electricity on the left. The two terminals are connected in succession through two specimens of rocks which show the greatest difference in conductivity in the respective geologic section, and through an amperemeter

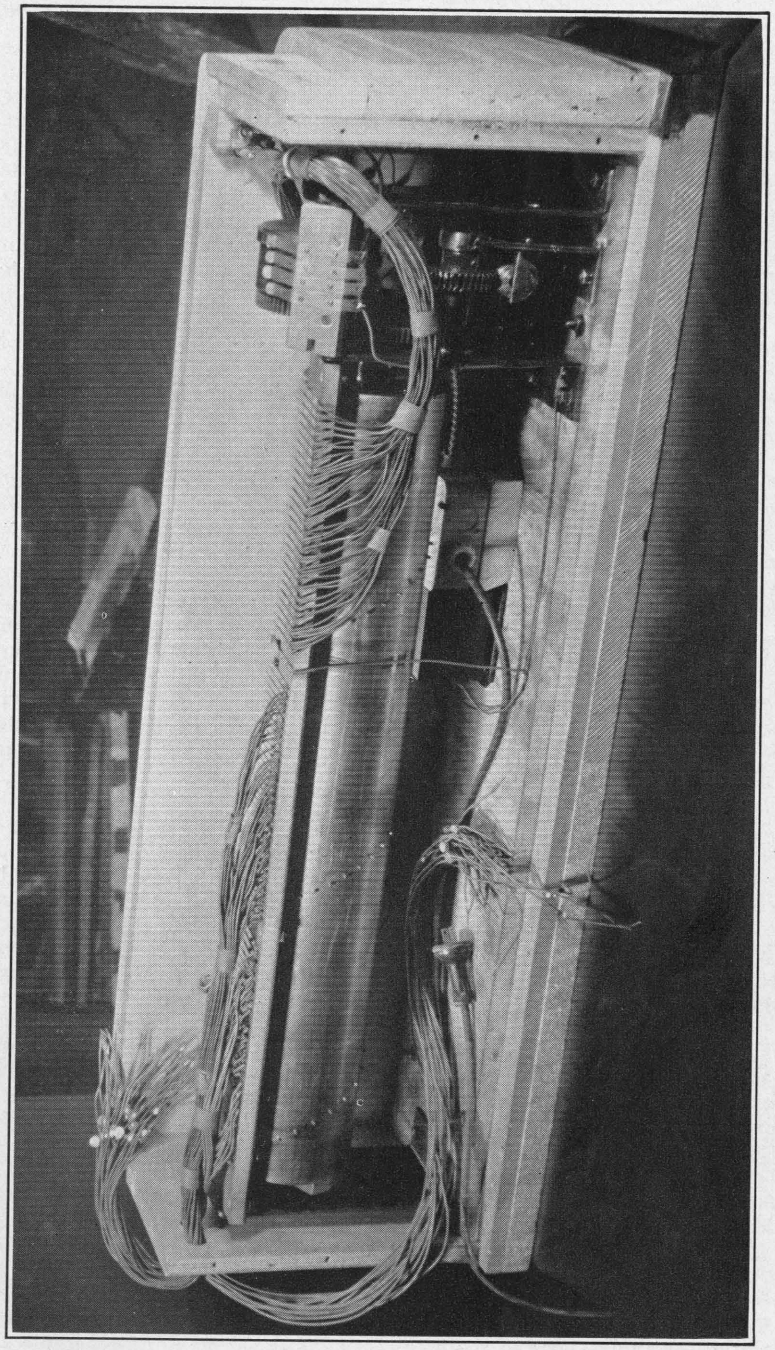


Fig.7—Mechanism for actuating exhibits shown in Fig. 6

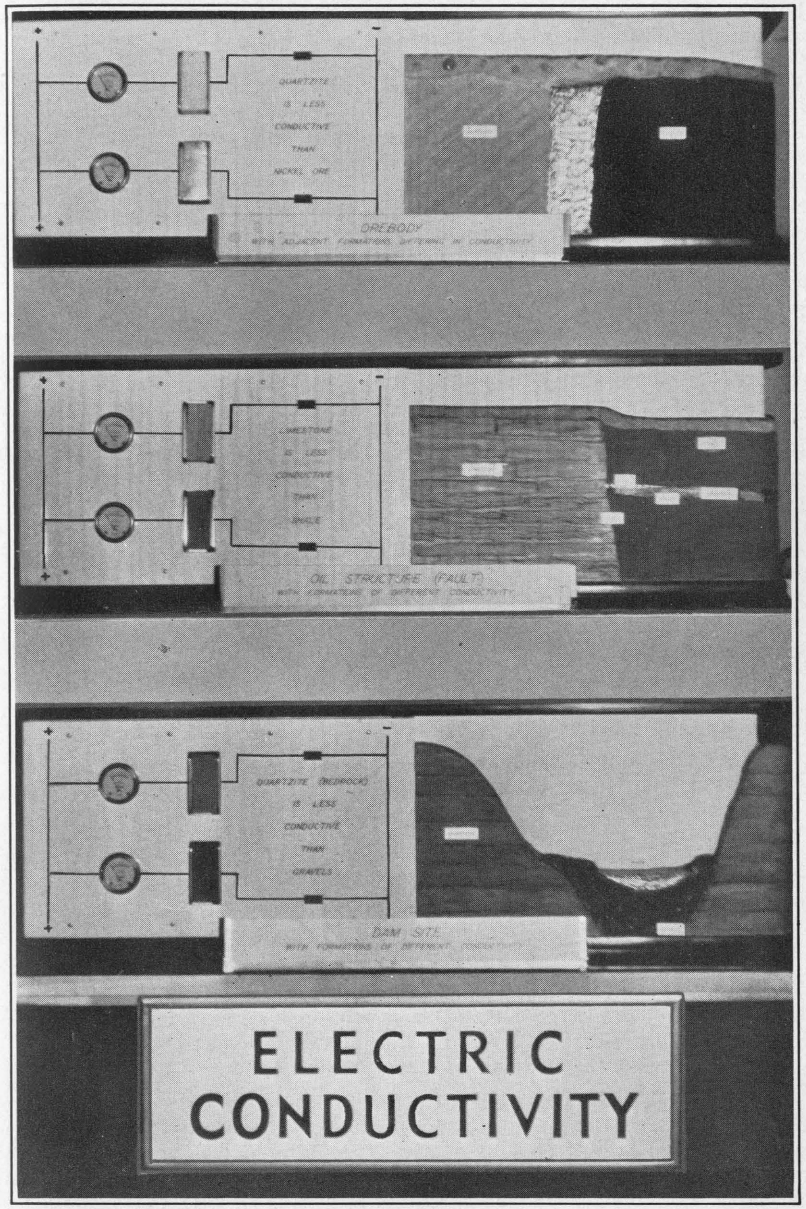


Fig. 8—Exhibits demonstrating electric conductivity.
Top—Electric conductivity shows that quartz is less conductive than nickel ore. Middle—Electric conductivity shows that limestone is less conductive than shale. Bottom—Electric conductivity shows that bedrock is less conductive than gravels.

the function of which is familiar to everyone from the action of the same instrument on his automobile. Therefore, if the rock specimen through which the current passes is a good conductor, the deflection of the amperemeter is large; if its conductivity is poor, the deflection is small. Thus, in the first exhibit showing a nickel ore body, flanked by quartzite and norite, the current passes first through a specimen of quartzite and then through the specimen of nickel ore; the amperemeter shows a small deflection in the first, a large deflection in the second case, thereby demonstrating that the nickel ore is a better conductor than the quartzite. A small pilot light indicates in each case through which specimen the current is passing. The second exhibit of this group shows a fault bringing limestones on the left in contact with shales on the right. The current passes, above, through a specimen of limestone and below, through a specimen of shale. In the first case, the ammeter deflection is small; in the second, larger. Hence, the limestone is less conductive than the shale. This exhibit serves to demonstrate that measurements of electrical resistivity at the surface are capable not only of locating faults on which formations of different conductivities are brought together, but also types of structures in which similar differences in conductivity prevail, such as a limestone anticline overlain by shales, shown in **Fig. 17.** In the last exhibit of the group shown in **Fig. 8,** the application of electrical methods to problems of civil engineering is demonstrated. The geologic section is a dam site; the country rock is quartzite, and the river bed is filled with gravel. The determination of the depth of bedrock underneath the gravel is often of practical interest, and is possible on account of the fact that the (moist) gravels are much better conductors than the bedrock, which again is demonstrated by the corresponding ammeter deflections.

In this group of exhibits, the demonstration takes place automatically by a light flasher housed in the lower exhibit which turns the current into the six circuits described above.

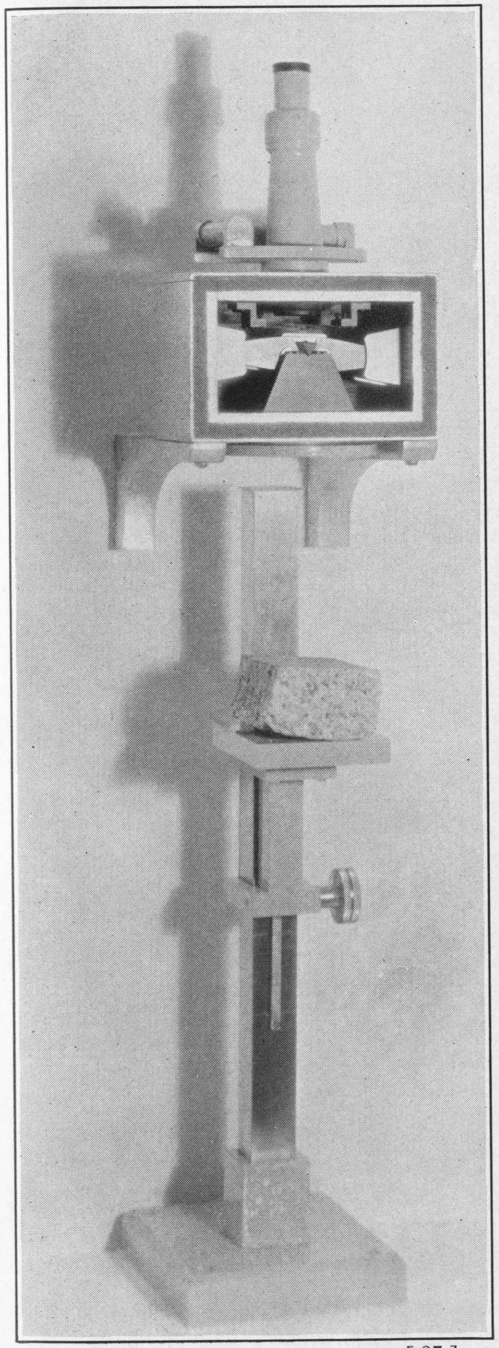
OPERATING PRINCIPLES OF THE MAJOR GEOPHYSICAL METHODS

In order, now, to establish the connection between the physical properties of rocks just discussed, and the operation of the various geophysical methods, let us recall the statements made under 2 and 3 in the "Four Facts on Geophysical Prospecting" (pp. 24 and 25) which read as follows:

> "The physical properties, and structural arrangement of mineral deposits produce spontaneous (magnetic and gravitational) *attractions*, or offer varying *resistance* to sound waves or electric currents."
>
> "The object of geophysical prospecting is the measurement of such forces as stated above, and the interpretation of the results in geologic terms, that is, type of structure and depth".

The purpose of the exhibits demonstrating the operation of the major geophysical methods is to show in detail (1) how the various types of instruments employed are affected by a given type of structure, and (2) how the physical data derived from the instrumental records are related to the structure. For this reason, the exhibits are arranged, with the exception of the seismic exhibit, as follows: **(Figs. 10, 12, 14, 17 and 18).**

In the lower part of the exhibit a representative type of structure is shown, built up of actual rock specimens. The type of structure selected corresponds in most cases to an actual geophysical survey and so do the



geophysical data; the latter as well as the geological data having sometimes been simplified to bring out the essential features. For the structural section, both the horizontal distance as well as the depth scale are given. Above the structural section is an illuminated niche, in the horizontal portion of which the respective geophysical instrument is automatically moved back and forth across the structure. The instrument is stopped at thirteen stations, an observation is taken (shown by the deflection of a moving part inside the instrument, which is in all cases exaggerated), and the physical datum computed from the deflection is flashed on by a light upon the curve in the vertical part of the niche. This curve indicates the physical data obtained on all stations in profile form, and, therefore, brings out the relation of the *shape of the curve* to the *shape of the geologic body.* In addition, the physical quantities observed on a number of such traverses as described, are also shown in map representation on the horizontal part of the niche which is to bring out the relation between the "contours" of the physical data measured and the structural contours.

In all these exhibits only the application of geophysics to the exploration of oil structures has been considered, inasmuch as this geophysics is a part of the exhibit of the American Petroleum Industries.

MAGNETIC METHOD

We will describe the magnetic exhibits first because the principles of this method are more readily explained than those of the others.

Fig. 9—Deflection of magnetometer by granite specimen.

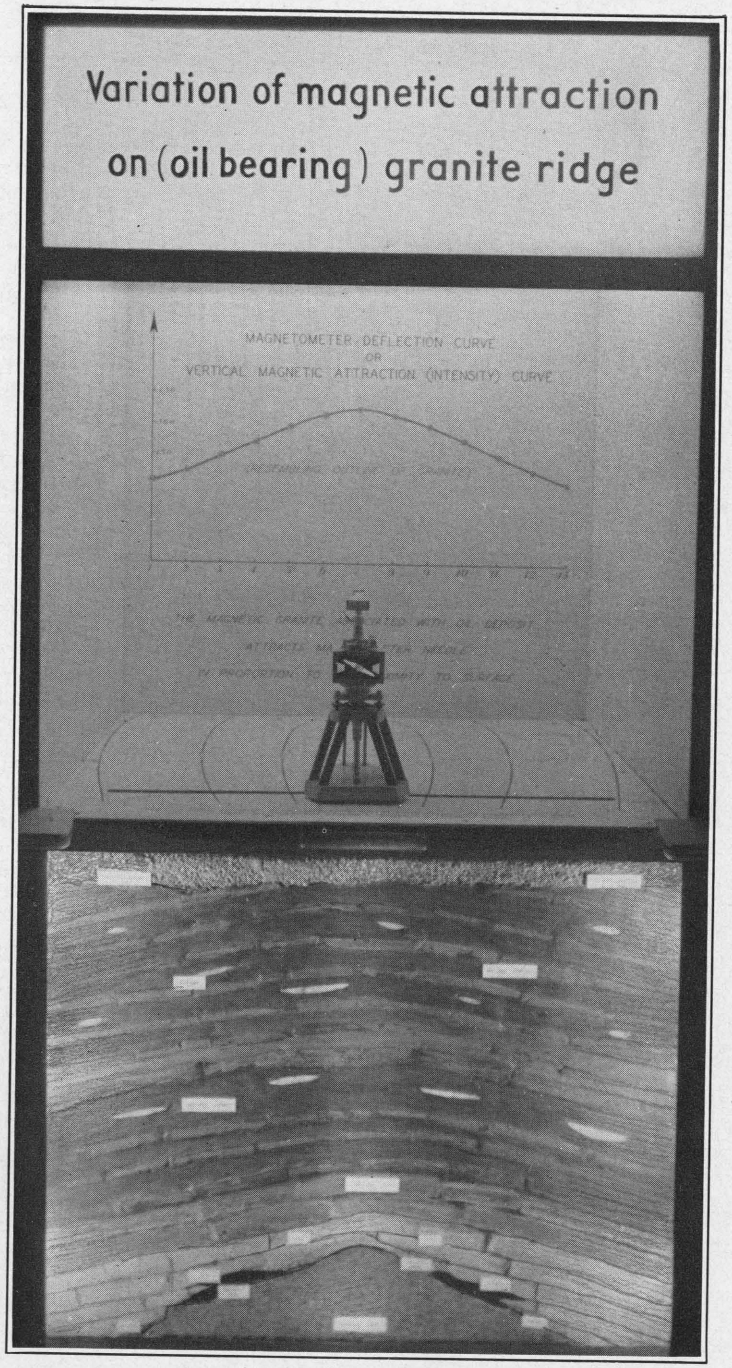


Fig. 10, a—Variation of magnetic attraction on granite ridge, showing magnetometer on crest of ridge, needle is dipping.

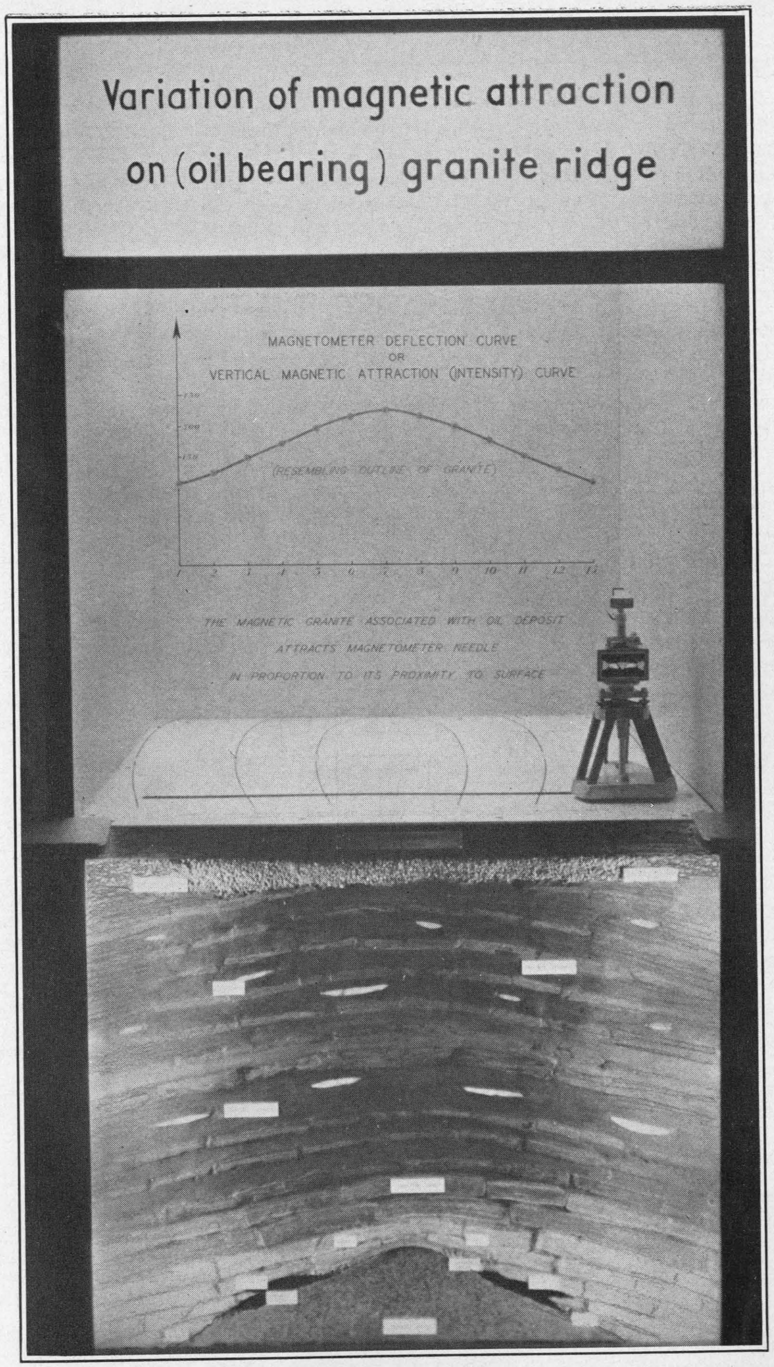


Fig. 10, b—Variation of magnetic attraction on granite ridge, showing magnetometer on flanks of ridge, needle is horizontal.

Magnetic methods are based upon the *measurement of magnetic attraction* exerted by magnetic rocks, formations, or magnetic portions of geologic structures. For the observation of the attractional force we use a compass-like instrument in which the magnetic needle, however, is free to oscillate in a vertical rather than in a horizontal plane. Thus, an increase in the angle of deflection of this magnetic needle from the horizontal position means an increase in the (vertical component of the) magnetic force. This attraction increases the closer the magnetic rocks come to the surface.

This idea can be verified by the visitor himself by carrying out the experiment shown in **Fig. 9.** There we have a magnetometer, open in front, with a magnetic system in it. A specimen of granite is placed below and its distance from the magnetometer may be changed by a rack and pinion movement. The visitor will notice that the right end of the magnetic needle will dip the closer he moves the granite to the instrument.

Exactly the same procedure is followed in the field. However, the deflection of the magnetic needle is so small in field operation that it can only be detected by using the telescope-magnifier on top of the magnetometer.

In the exhibit shown in **Fig. 10,** the reading which an observer would obtain in this telescope is projected to the visitor's eye by an illuminated projection attachment (not present in the actual instrument). He will observe this reading to increase when the dip of the magnetic needle is increased. As the model magnetometer moves across the buried granite ridge, the reading will first be small, will then increase to a maximum above the highest point of the ridge, and will then decline again. Plotting these readings at each stop, a curve is obtained which in its shape will resemble the outline of the granite ridge. **Fig. 10, a** and **b,** shows how the dip above the high-point of the ridge is much greater than on the flanks where the ridge is deeper; the dip has been greatly exaggerated, but the readings are given on the curve in the same magnitude in which they would be observed on such type of granite ridge as shown. If we should make a number of traverses across the ridge parallel to the one illustrated, we should obtain curves similar to the one indicated on the panel; this would enable us to connect the points with equal readings and thus get a "contour map" with lines of equal magnetic attraction. This contour map would resemble a map of contours of the granite ridge, and is shown in generalized form on the horizontal part of the niche.

It should be clearly understood that the magnetic method merely locates the granite ridge; whether and where the oil occurs on it remains to be determined by geological considerations or experience, and definitely only by the drill.

It may be of interest to some to learn how the automatic operation of this and similar exhibits is accomplished. Earlier experiments with this type of exhibit indicated that it was not feasible to use the actual variation of dip of the magnetic needle produced by the granite. Therefore, a system had to be devised whereby the magnetic needle could be operated mechanically at every point. This system is illustrated in **Fig. 11.** A motor which is geared down to a considerable extent, drives a cogwheel with teeth only on one-half of its circumference. Two smaller cogwheels, mounted on two opposite sides of this wheel, are driven by it so that one of them is always moving when the other is stationary. One of these two cogwheels drives a spindle with overcut left- and right-handed thread and thus moves the

instrument back and forth across the structure at definite intervals. At each stop the other cogwheel functions and drives a cam rod with grooves so cut as to produce the required instrument deflection at every point.

In addition to the two magnetic exhibits illustrated in **Fig. 9** and **10,** a regular magnetometer (Schmidt vertical balance) has been provided for the Geophysics Exhibit by the courtesy of the American Askania Corporation. It may be operated by the visitor and to this end has been provided with artificial illumination and a fairly unsensitive magnetic system which cannot be easily damaged.

GRAVITY METHODS

The principle of these methods is the measurement of gravitational attraction, or attraction due to mass, such as is produced by differences in density of geologic structure beneath. This gravitational attraction is not magnetic attraction; it is the same force which holds the earth and moon in their orbits, balancing the centrifugal force resulting from their travel around the central body.

Pendulum

There are various means of measuring gravity attraction. One of the oldest methods known is that of the pendulum. A pendulum will oscillate faster when gravity is greater and vice versa. Therefore, when a heavy formation approaches the surface, the gravity will be greater near the high-

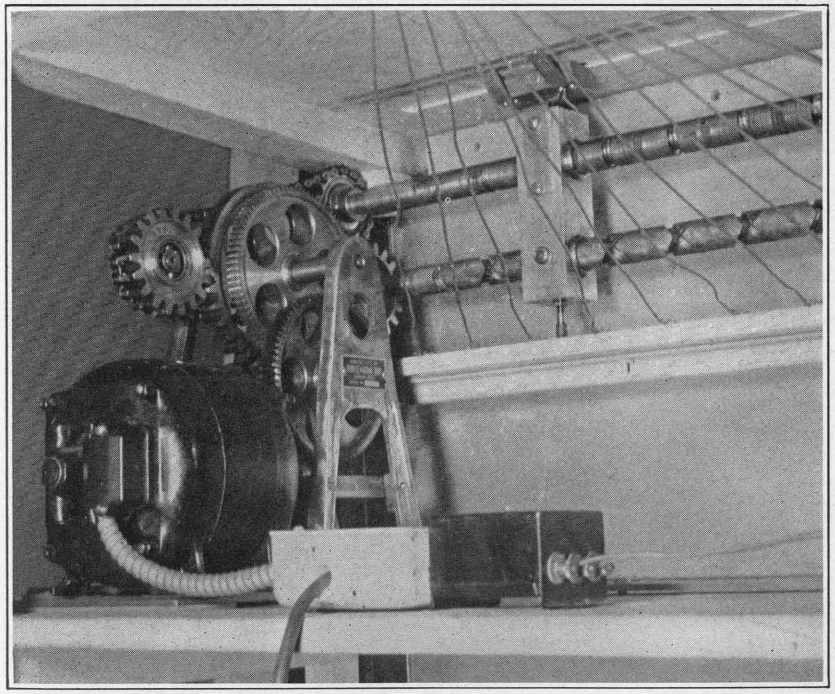


Fig. 11—Mechanical arrangement for operation of animated exhibits.

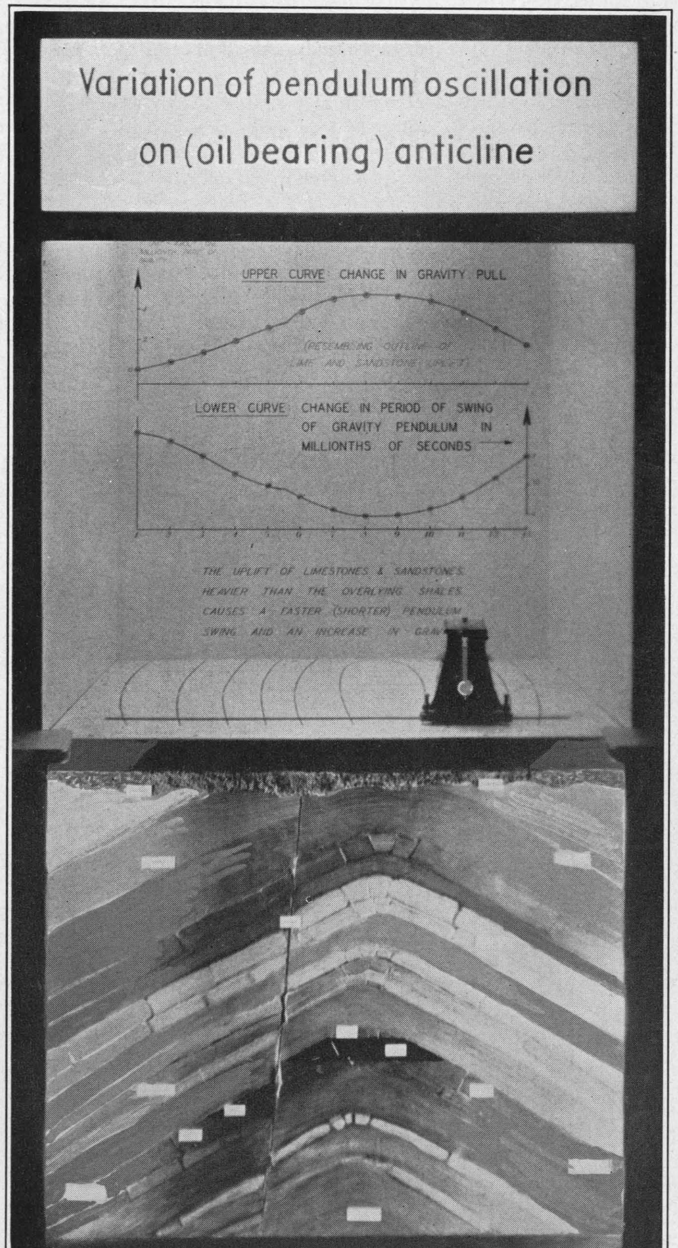


Fig. 12—Variation of pendulum oscillation on anticline.

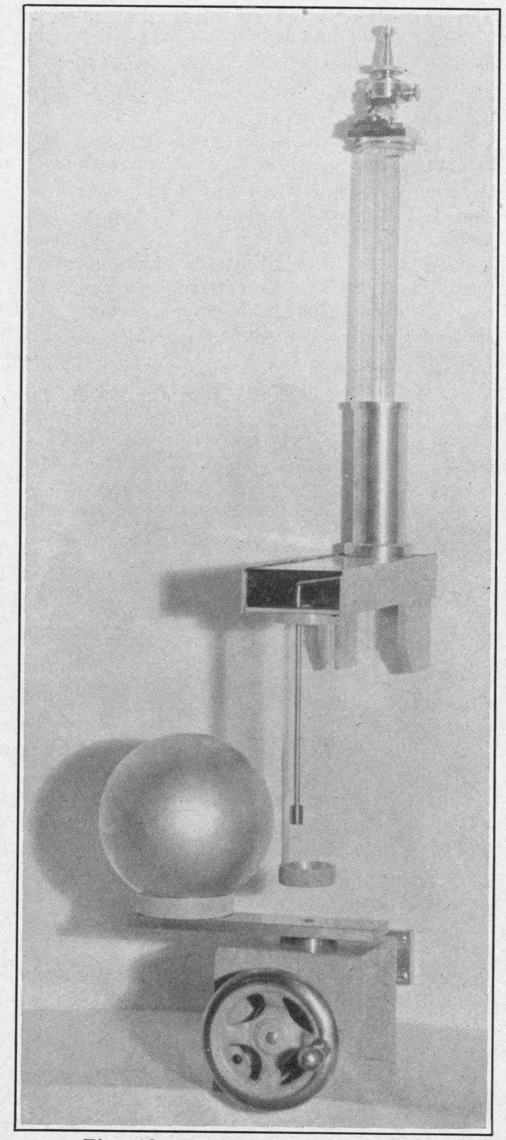


Fig. 13—Torsion balance deflection by lead sphere.

point than on the sides, and the pendulum will oscillate faster above the highest points than above the flanks.

The variation in the rate of oscillation of a gravity pendulum on such types of structures as encountered in oil exploration work is exceedingly small; it cannot be detected by the naked eye and has to be measured with special apparatus which we shall not discuss here. The variation on such type of structure as shown in **Fig. 12** is of the order of millionth of seconds, and the corresponding variation in gravity is of the order of millionth parts of gravity. In the exhibit, however, the variation in the rate of oscillation of the pendulum had to be greatly exaggerated to make the difference visible.

In the exhibit shown in **Fig. 12** we have selected an anticlinal type of geologic structure consisting of folded sandstones and limestones which are heavier than the covering shale beds. Above, a pendulum apparatus is seen to move across the structure. The type of apparatus shown here is the Coast and Geodetic Survey single pendulum type which has been selected on account of its simplicity; in commercial work generally more complicated types of apparatus, using two or more pendulums at the same time, are employed. At every stop, the pendulum oscillates and the corresponding rate of oscillation, together with the gravity attraction which may be computed from this oscillation, are flashed on two curves on the vertical panel. The upper curve showing the variation of gravity pull is of particular interest, because its shape resembles the shape of the anticline underneath the surface. Making similar observations on more traverses across the structure, calculating the gravity at all observation points and connecting the points of equal gravity by lines, we again obtain a contour map such as shown on the horizontal panel, which resembles the structural contour map of the anticline below.

Torsion Balance

Another instrument that also measures gravitational attraction, and which is at present in more widespread use than the pendulum, is the torsion balance. It does not measure gravity itself like the pendulum does, but the *horizontal rate of change of gravity*. Therefore, we obtain the greatest torsion balance deflection where the *change of density underneath* in a horzontal direction is greatest. As a consequence, when the torsion balance is set up on the left of a heavy mass, it will be attracted by it to the right; if it is set up on the right side, the deflection will be toward the left. Directly above the mass, there will be no deflection.

The torsion balance is essentially a beam provided with weights on either end and suspended in the center by a fine thread. However, the two weights are not attached to the beam in the same level, but one of the weights is attached to the beam at a lower level by a vertical stem. This may be seen in **Fig. 13**, showing an experiment which the visitor may operate and observe the beam deflection produced by a heavy mass on one side of the beam.

The experiment consists of one torsion balance beam af actual size and a lead sphere which may be moved to either side of the hanging weight of the balance. It will be observed that the deflection of the beam is to the *left* when the *sphere* is at the *left*, and to the right when the mass is to the right.

This experiment will illustrate why in the exhibit shown in **Fig. 13** the torsion balance deflection is to the right on the left flank of the anticline and to the left on its right flank. The geologic section selected for this exhibit is the same as that used in the preceding exhibit which demonstrated the pendulum, and the gravity curve obtained before by the pendulum is reproduced on the vertical panel for comparison. As the beam deflection is to the right on the left of the anticline and to the left on the right, it follows that, when relating this beam deflection in regard to direction and magnitude (upper curve) to the gravity (lower curve), it is nothing else but the rate of change of gravity, or the *grade*, or slope, of the lower curve. For the slope is up to the right on the left flank of the anticline; hence, the beam deflection is to the right there. On the left flank the slope is up to the left, and therefore, the beam deflection is to the left. On top of the anticline, where the gravity curve is flat and therefore has no slope, there is no beam deflection.

In this exhibit we had to use rather simple terms to explain the action of the torsion balance; furthermore, we have used a type of instrument which is actually not in practical use, as the commercial torsion balances have two beams instead of one. The instrument gives not only the horizontal rate of change as shown here, but other data on the gravity field which we shall not discuss here on account of their complexity.

The sensitivity of a torsion balance is exceedingly great. The attractions measured by it are of the order of million-millionths parts of gravity. The beam deflections observed in the field are, of course, not as great as those demonstrated in this exhibit. The instrument used in practice is very delicate and is usually operated automatically, with an arrangement to

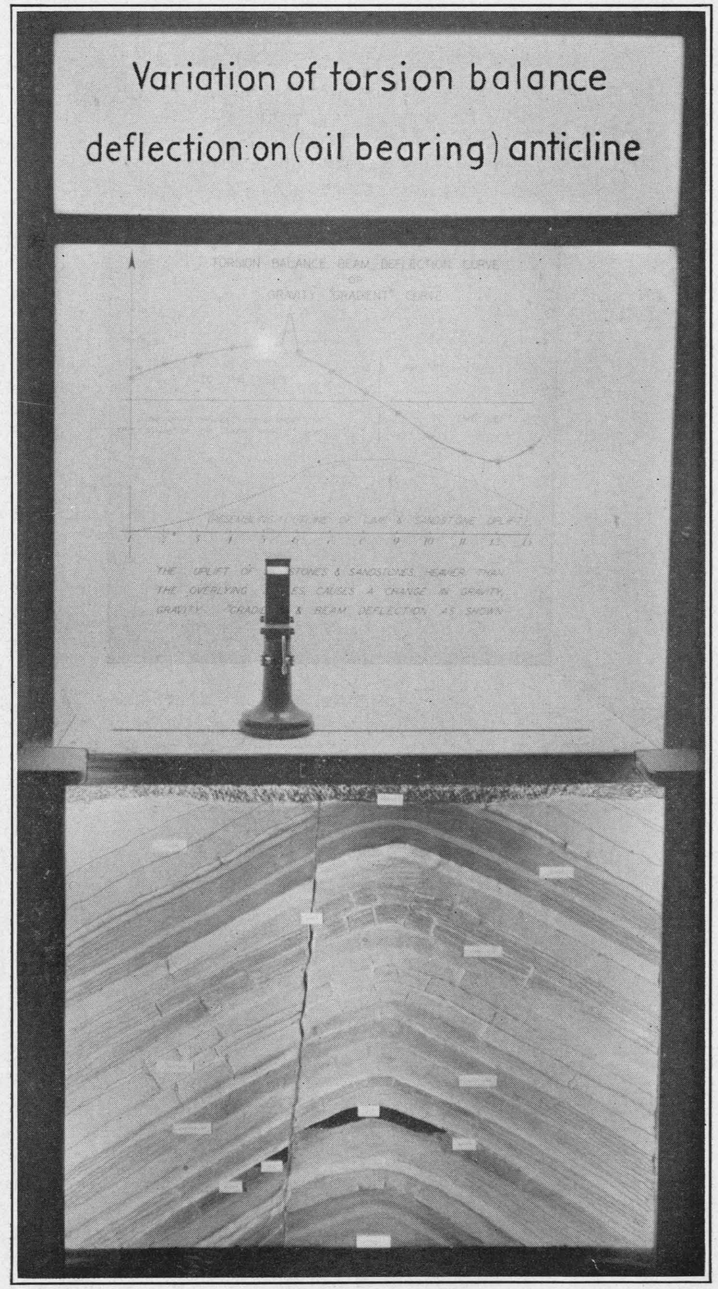


Fig. 14—Variation of Torsion Balance Deflection on Anticline.

photograph the beam deflections not only in one position of the instrument as shown in this simplified exhibit, but in three positions at every set-up with a double beam system. It would lead too far to discuss here why this is being done.

Through the courtesy of the Askania-Werke, a standard torsion balance has been provided for the geophysics exhibit. It is the so-called Z-beam type balance, one beam of which is shown in **Fig. 13,** while the actual instrument has two beams. This instrument is provided with an automatic mechanism to take pictures of the beam deflections in three positions of its upper part (120 degree apart); in field work it takes about 40 minutes for the beams, suspended by very fine wires, to come to rest so that the picture may be taken. The instrument set up in the geophysics exhibit has been so modified that the visitor can observe this cycle of operation in a much shorter time, and can also see the beams moving and come to rest before the instrument turns into its next position. This is done by using very short wires which allow the beams to come to rest in about two minutes, by a projection arrangement to make a continuous observation of the beams possible, and by an electrical contacting arrangement which turns the case of the instrument at angular intervals of about 120 degrees every three minutes. From the theory of the instrument it follows that a complete revolution, or an observation of the beam positions in at least three positions 120 degrees apart, is required to evaluate the record; in actual field work, two or more positions are generally recorded as check. Then the photographic plate is developed and the instrument is moved to the next station. Therefore, the actual operation of this device is much more complicated than shown in our exhibit, where we have assumed that the torsion balance case always remains in the same position, and has only one beam, the deflection of which is observed at every station.

SEISMIC METHODS

The seismic and electrical methods of geophysical exploration now to be described differ radically in principle from the magnetic and gravity methods treated above. In the latter, we deal with spontaneous effects of geologic structures; in the former, we have to "energize" them first to get a response. Using the analogy of electric current flow in both cases, we measure in the seismic and electrical methods generally the "resistance" to the flow of the energy in some manner or other.

This fundamental differance between the gravity and magnetic methods on one hand, and the electric and seismic on the other, is of great importance for their efficiency in practical work. For, in the magnetic and gravity methods, we observe effects from *all* bodies depending on their depths and size, and can do virtually nothing to separate them. In the seismic and electrical methods, however, we can arrange at will to obtain any desired depths within the limits of the method. This is due to the fact that the "depth of penetration" depends on the spacing between the point where the energy is applied and the point where it is received. The greater this distance, the greater the depth penetration. This effect may be compared with an optical phenomenon within everybody's range of observation. Suppose we take a telescope and look at any given view. We will notice that at a distance of fifty feet, for instance, an object five feet tall will occupy the entire field of vision. At a distance of 500 feet, however, we will find that now an object fifty feet tall occupies the field. In other words, the greater

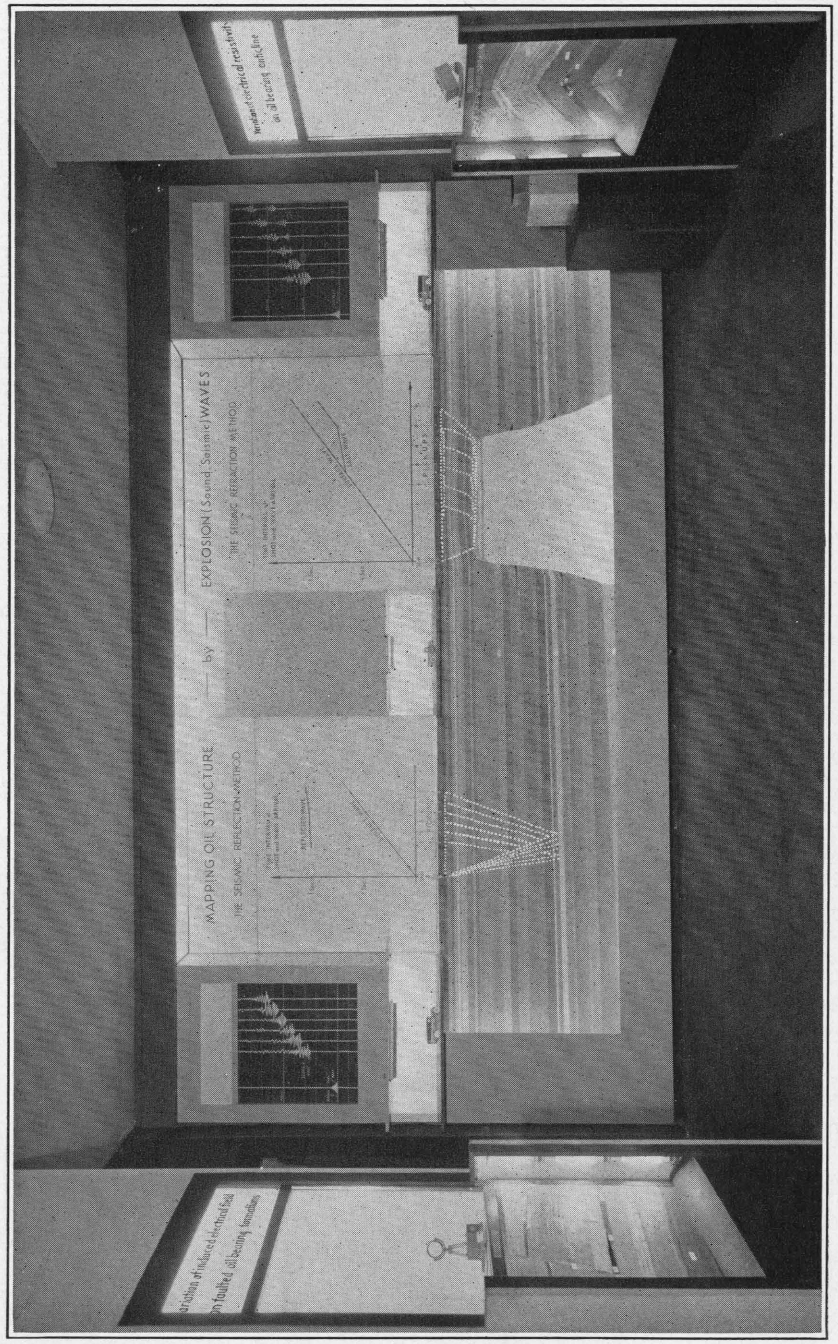


Fig. 15—Exhibit showing the seismic reflection and refraction methods.

the vertical height we want to cover in our telescope, the greater has to be its distance. The same principle applies in geophysics.

The principle of the seismic methods is the measurement of the time interval between the firing of an explosion of dynamite and the arrival of the seismic wave impulses of various kinds at the receiving points. At the latter, we use certain devices called "pick-ups", "detectors", or "seismographs" (more specifically, electrical seismographs) which are constructed in a manner much similar to a microphone. In these devices, the ground-vibration is converted into electricity; the fluctuations of electricity corresponding to the ground vibrations are amplified and made to operate some sort of an electrical measuring device, called galvanometer or "oscillograph". The oscillations of the latter are recorded photographically on a moving film, thus obtaining what we call "Seismograms" (**Fig. 15**). Generally, the vibration of all pick-ups used are recorded on the same film. In order now to "time" the records, that is, in order to determine the time interval between explosion and the arrival of a given type of wave in the seismogram, two things are being done. First, time marks are projected, by a tuning fork or similar device, upon the moving film. Their interval is about 1/100 of a second in the reflection seismogram and about 1/10 of a second in a refraction seismogram. Second, the instant of the explosion is recorded by winding a wire around the dynamite, supplying it with current and recording this current on one of the oscillographs; then, as the explosion occurs, the oscillograph will show a deflection when the wire is broken. This is the method used in reflection work. In refraction shooting, we transmit by radio a signal to the recording truck which is recorded again by an oscillograph and which is interrupted when the power is cut off from the transmitter by the explosion.

We have used before the terms reflection and refraction shooting. They indicate that a different type of wave is utilized. In the first, it is the reflected wave or the *echo* which we are using. In the second, it is the refracted wave, or the wave that travels *through* a high speed formation underneath on a sort of a "detour", in a manner explained previously and illustrated in **Fig. 6.** Both types of waves exist, of course, at the same time for any explosion, but arrangements are so made that in one method only the first, and in the other only the second, is observed or emphasized respectively.

Reflection Method

The principle of the reflection method is easily explained. We utilize the same phenomenon that is observed by everyone when speaking in a large room; he will observe that his voice is repeated (often more than once), due to the echo from the walls. More specifically, we use a method that has been employed by skippers in Alaska for some time. Navigating through narrow channels between the islands along the coast at night, they blow a whistle and determine the distance of the ship from shore by timing the echo from the steep cliffs. Or, to use a most recent application of the reflection methods as a final comparison: A method has been perfected and is in use on most modern liners by which a cartridge is exploded on one side of the ship and the echo from the ocean floor is received by a microphone on the other; explosion and echo actuate a device which permits one to read the depth to ocean bottom directly in fathoms. In mapping oil structure by the reflection method, we cannot use such a simple device, as the speed of the wave to the reflecting bed is not always the same. Suffice

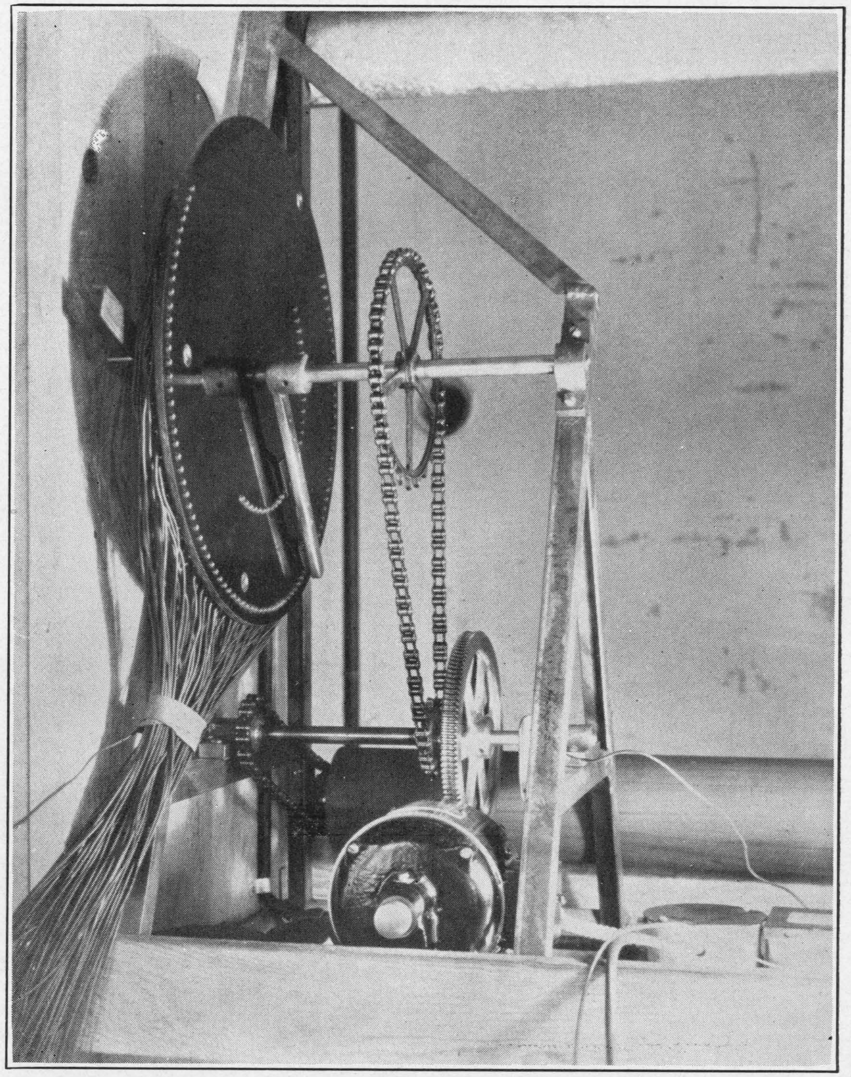


Fig. 16, a—Mechanism operating seismograms and wave travel in the reflection exhibit.

it to say that this "average velocity" can be determined by various means. Then by simply timing the interval between explosion and reflection record, we can calculate the depth to the reflecting bed.

Experience shows that usually limestones overlain by shales form ideal reflecting beds. It is possible to map more than one reflecting bed, but too many beds make identification and interpretation difficult.

Theoretically it would, of course, be possible to make a depth determination with the echo method by using just one receiver. However, as the echo always arrives later than other types of waves, identification as such is difficult unless we use a number of receivers. Then the reflected wave in the record is characterized by almost simultaneous arrival at all points, while all other wave types arrive at different times.

This is seen clearly in the "travel time curve" for the reflection methods shown in **Fig. 15.** A "travel time curve" is a graph showing the time of

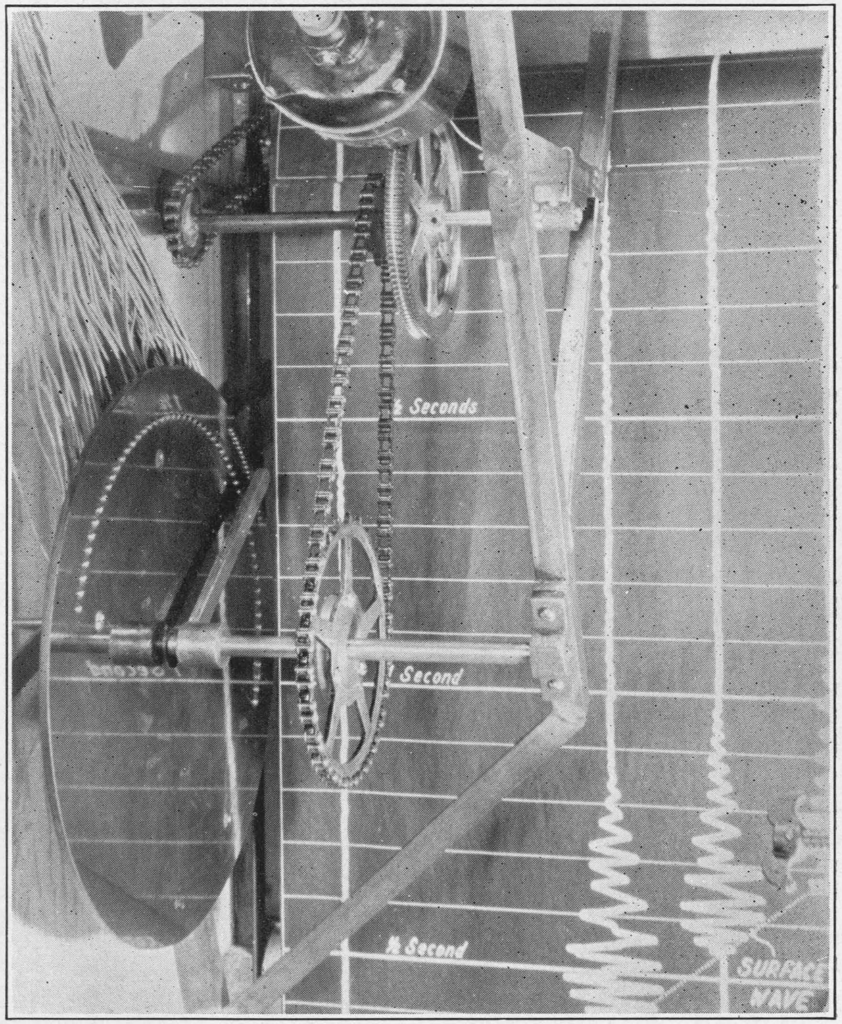


Fig. 16, b—Mechanism operating seismograms and wave travel in the refraction exhibit.

arrival of a wave for the various receiving points. For the reflected wave, the time is seen to be almost identical, while for the wave travelling in a horizontal direction from shotpoint to the receiving points (the so-called surface wave producing the first motion in the seismogram, **Fig. 15**) the time interval increases in proportion with the distance of the receivers, that is, in a straight line.

For the demonstration of the seismic methods (**Fig. 5**) we have selected a geologic section through a salt dome and adjacent strata on the Gulf Coast, and have assumed that a reflecting limestone bed exists in a depth of about 5,000 feet. The exhibit shows the seismic refraction method on the right, and the reflection method on the left. Along the surface, we notice on the left the reflection shot, six receivers, a recording truck, and a shooting and drilling crew (the latter boring the holes for the shots). In the center, we see the crew firing the explosion for the refraction method and the transmitting radio; on the right, we have the recording truck and the receiving radio, and also the refraction shot and six receivers.

For each method, three phenomena are shown in animated fashion, and correctly synchronized. First, the travel of the seismic waves is symbolized by flashing on a great many small lights along the wave path. The rate of travel has been slowed down considerably as compared with the actual speed to enable the visitor to follow the phenomenon. Second, the moments of arrival of the surface wave, reflected and refracted impulses are flashed on by lights on the travel time curves above the geologic section. Third, two continuous seismograms are seen to be moving all the time on the right and left side of the exhibit. They are illuminated from behind by a lighted slot (representing the spot where the lights from the oscillograph mirrors in the recording camera strikes the photographic paper). Thus, when the lights in the geologic section arrive at a pick-up, a light marking its arrival lights up at the travel time curve, and at the same time the corresponding vibration record passes the illuminated slot in the moving seismogram.

The mechanism that produces a synchronization of all three phenomena is described below, because it will help materially to explain the time sequence of the observed phenomena. Let us take the mechanism for the reflected wave first, shown in **Fig. 16a.** A motor is geared down and drives a wooden drum which in turn moves the continuous seismic record. This drum movement is geared to an arm which makes contact with two rows of buttons on a bakelite disk. These two rows work the lights along the paths of the surface and the reflected waves simultaneously. As the distance of the buttons is equal, the lights connected to the outside row are flashed on in a more rapid succession than those connected to the inside row, corresponding to the greater circumferential speed of the contact arm. This is in accordance with the fact that the speed of the reflected waves is greater than that of the surface wave. Each contact button is connected with a number of lights which lie on a so-called "wave-front", i. e., points which are occupied by the wave at the same time. It is easily seen that the wave fronts for the wave going down are circles about the shotpoint, while the wave fronts for the wave going up from the reflecting bed are circles about the "image" of the shotpoint as reflected on the limestone bed, i. e., about a point vertically below the shotpoint in a depth twice that of the reflecting bed. Truly, therefore, the contact mechanism may be called a "seismic time clock", as the position of the contact arm shows where any wave (surface or reflected) is at any one time.

As stated before, the *depth* of the reflecting stratum may be computed from the time interval of shot and arrival of the reflected wave in the seismogram, and practical experience shows that such depth determinations can be made at present with an accuracy of about 0.5%. Therefore, geologic structure may be mapped by this method with an accuracy and completeness that even rivals the drill. Thus, the reflection method has attained the most prominent place among all other geophysical methods in the past year.

Refraction Method

The mechanism of wave propagation underlying the seismic refraction methods is more intricate than that of the reflection method; it may seem strange, therefore, that the reflection method came into use much later than the refraction method.

We noted that in the reflection method impulses arriving much later than the surface wave impulses are utilized. This is due to the fact that we work at rather close range to the shotpoint. If we should go farther out, we should notice, provided a formation with higher wave speed was present below, that beginning with a certain distance the surface wave is no longer the first to arrive at the receiving points. For, all seismic rays which radiate from the shotpoint will not travel at the surface, but there will be some that will follow the path where they can make the best headway; that is, they will tend to remain in the high speed medium for as long a time as possible. Thence they will return to the surface, and it will thus happen that the "lower" wave arrives ahead of the slower surface wave, despite the "detour" which this wave has taken.

This is a phenomenon which again is exemplified by everyday observation. Suppose two motorists start out in their cars from a given point at the same time, bound for the same destination. There may be two roads that they can follow: one, which may be the shortest but a very rough and muddy road; the other, longer, a paved highway. Everybody knows, then, that the motorist who took the longer road but travelled on the paved highway will arrive ahead of the other motorist if given sufficient distance to travel on the paved highway.

In refraction seismology, we have the same principle. The time advance which the lower seismic ray can make depends on the distance which it can cover in the highspeed medium, and the ratio of the velocities in the high speed medium and the surface medium.

Therefore, there will then be a distance at which the two types of waves arrive simultaneously, and this distance will depend on the length of the "detour" taken by the lower ray, i. e., the depth to the high speed medium, and also the ratio of the velocities of the surface and high speed media. This distance is of great practical importance, because it is possible to obtain from it and the two velocities the *depth* to the high speed medium by the use of a very simple formula.

The reader will ask how it is possible to obtain at the surface the velocity of the high speed medium. This is a very remarkable feature about the seismic refraction method: namely, that we are not only able to determine the depth of a high speed medium, but its velocity and therefore its physical constitution as well. The answer is simple enough. The wave travels in the high speed medium in a horizontal direction and sends up waves to the surface from every point reached. Therefore, these branches of the lower wave propagate along the surface at a rate identical with the

rate of propagation in the lower medium. Hence, when we plot again the time of arrival of the lower ray impulses (see **Fig. 15**) we obtain a line, the inclination of which gives us the velocity in the lower medium; and then, we have all data to compute not only its depth, but also its physical characteristics.

In this connection attention may be called to the fact that, if we set up our receivers at equal intervals and also obtain their records in the seismogram equally spaced as shown (see **Fig. 15**), all we have to do is to draw lines through the surface and lower wave impulses to obtain the travel time curve.

The mechanism operating this exhibit is shown in **Fig. 16b**, and is similar to the one employed in the reflection method. In this figure, the continuous refraction seismogram is also seen rolling over the drums, in synchronism with the movement of the contact arm. The "seismic time clock" has again two rows of buttons, their radial and circumferential distance being in proportion to the ratio of the speed of the surface and "salt wave". Each button is again connected to so many lights in the wave paths as are on a wave front, i. e., which are reached by the elastic impulse at the same time. The shape of the wavefronts in this case is, however, not nearly as simple as in the case of the reflection method, and we shall not discuss it here for that reason.

The geologic structure selected for the demonstration of the refraction method is a Gulf Coast Salt dome; its depth and travel time curve are in accordance with data obtained on an actual dome. The refraction method has attained outstanding success in locating and detailing salt domes on the Gulf Coast, and a great many discoveries shown in the statistical chart of **Fig. 3b** are to its credit.

In connection with the exhibits shown in **Fig. 15**, a demonstration of an operating seismograph is also provided. This apparatus was placed at the disposal of the geophysics exhibit through the courtesy of E. McDermott of the Geophysical Service, Inc., in Dallas, Texas. An electric seismograph is placed on the floor, and connected to an amplifier and oscillograph on a table above. The oscillograph is provided with a revolving mirror so that the wave motion may readily be viewed in a manner similar to a slow motion picture. The exhibit is operated by the visitor himself. He taps the floor and observes at the same time how the wave motion appears in the viewing attachment of the oscillograph recorder.

ELECTRICAL METHODS

As previously stated, the chief fields of application of the electrical geophysical methods are the search for metallic orebodies and the location of dam sites and ground water in civil engineering. There is a great variety of electrical methods which is illustrated in the tabulation given on P. 50. Only two of these have been found to be of importance in oil exploration work. The first is the resistivity method and the second the so-called inductive method.

Resistivity Method

The function of this method is indicated by its name, namely, the measurement of electrical resistivity. If a medium is homogeneous and if we measure the resistivity at any one point along the surface, the observed resistivity is the resistivity of this medium. Not so, however, when a

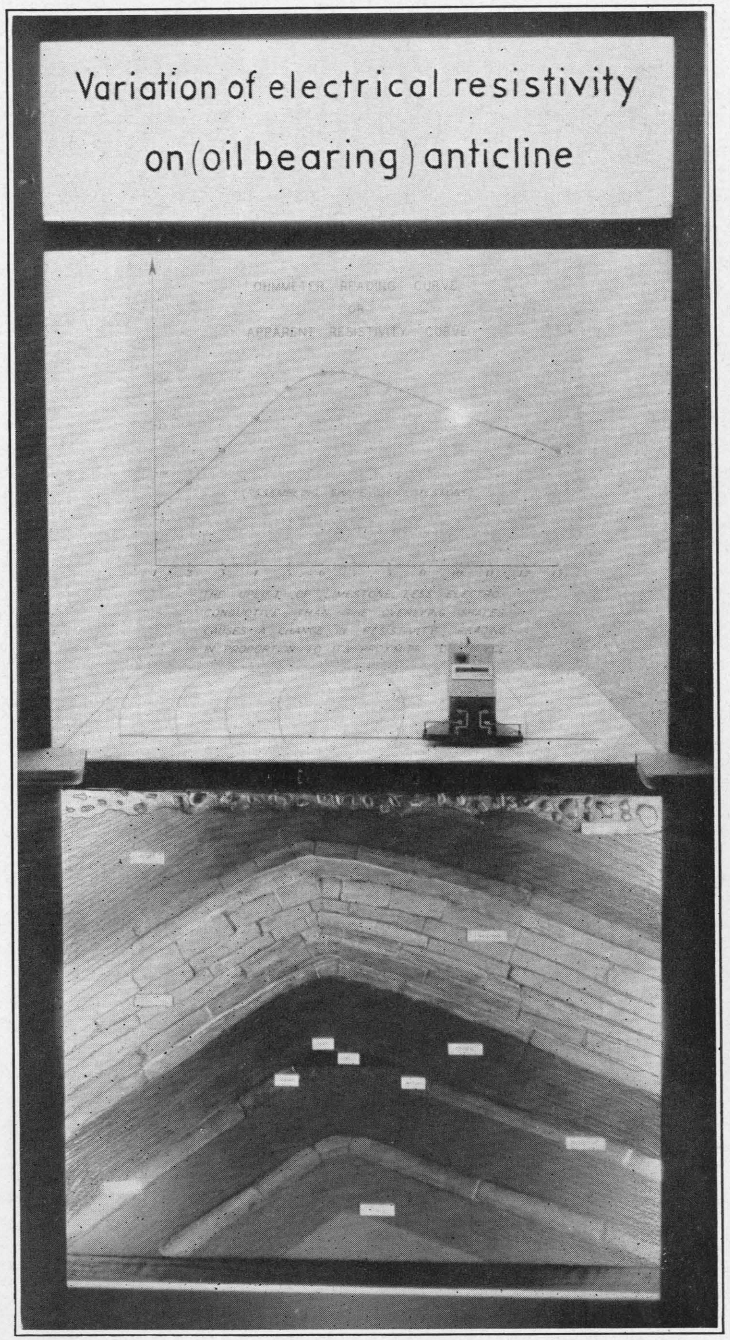


Fig. 17—Variation of resistivity on anticline.

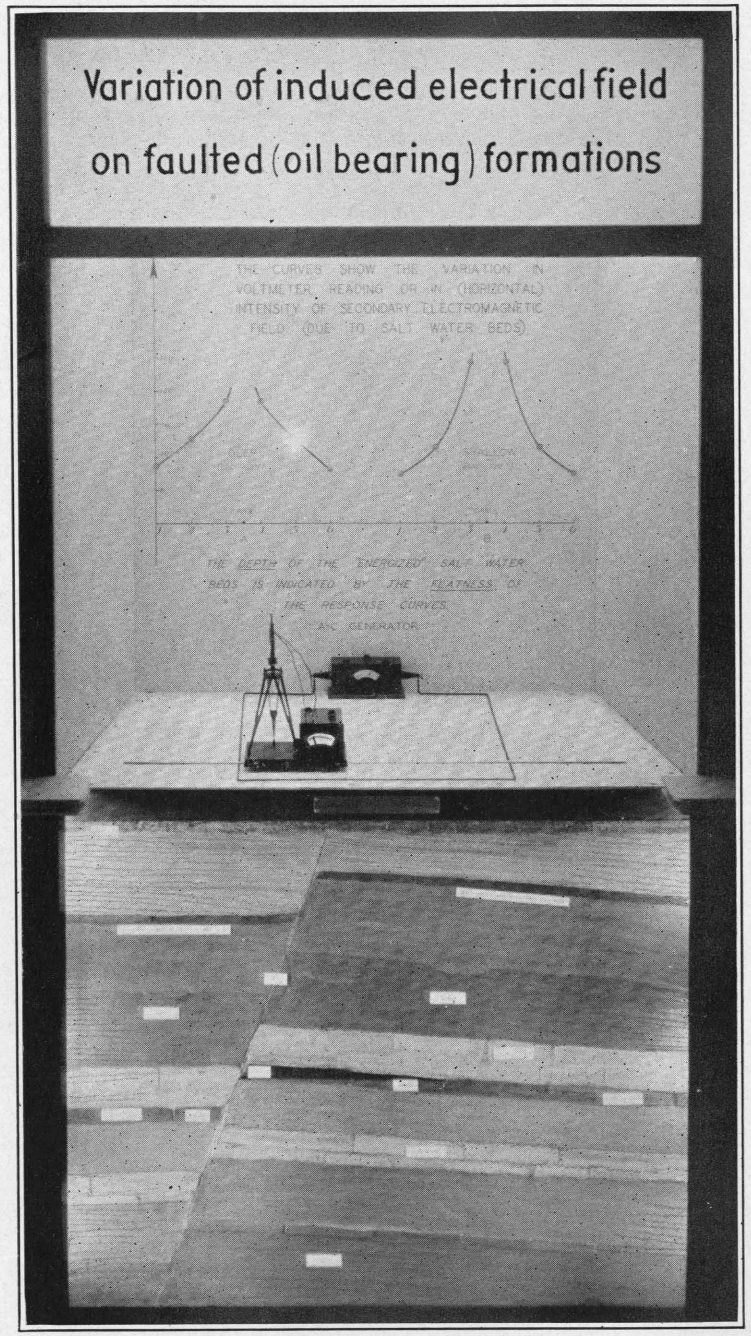


Fig. 18—Variation of induced electrical field on fault.

medium of higher or lower resistivity is present below. Then the resistivity observed at the surface is no longer the surface resistivity but the so-called "apparent" resistivity which is a rather complex function of the depth, and the resistivity of the lower and of the surface medium. In order to "catch" this lower medium, we proceed in a manner very much similar to the seismic refraction method, in which we could "catch" the lower medium only by going out from the shotpoint far enough to make the lower wave overtake the upper one. In the resistivity method, we employ a "contacting arrangement" consisting of four ground stakes. Current from a handcranked generator is supplied to the two outside stakes and measured, and the voltage difference between the two inside stakes is also observed. We employ an instrument for this purpose which automatically measures the ratio of voltage and current (which is equal to the resistance) and which is called an Ohmmeter. The type employed here with the four ground stakes is called a "Megger" and is shown in the exhibit of **Fig. 17.**

The four ground stakes are driven into the ground at equal intervals, and here is where the comparison with the seismic refraction method comes in. If this interval is smaller than the depth to the medium with different resistivity, the surface readings will not catch it and will give only the surface resistivity. However, the lower medium will enter as soon as that interval is made larger than its depth.

Here is one way then to proceed with this method in mapping an oil structure. (**Fig. 17**). Suppose an anticline of limestone is overlain by shale, being of lower resistivity, and the problem is to determine approximately the shape of the fold. We then use an electrode interval greater than the expected depth of the fold, and make a traverse across the structure, keeping the interval constant and taking a reading at a number of stations. Then the apparent resistivity curve, representing the readings taken at these stations, will resemble the shape of the fold.

Another way to proceed at any one set-up would be to start out with small electrode separations and gradually increase that interval, i. e., to measure the resistivity as a function of the electrode separation and thus as function of depth of penetration. In this manner it would be possible to make depth determinations at every point and thus supplement the curve of relative data obtained before with constant electrode separations, by absolute values for the depths.

For this exhibit, we have selected a structure on which such measurements were actually taken. A model "Megger" is moved across this structure and the ohmmeter in it reads at every set-up the amount of apparent resistivity flashed on the vertical panel. The horizontal panel shows again lines of equal resistivity resembling contour lines of the structure, as they would be obtained from observations on a number of traverses.

Inductive Method

Most every oil structure has certain beds which carry salt water and are, therefore, highly conductive. The object of the inductive method is the mapping of these beds, i. e., the determination of their depth in a given area, by means of which it becomes possible to locate, for instance, a fault indirectly, as demonstrated in the exhibit shown in **Fig. 18.**

The procedure in the inductive methods is as follows, giving a simplified description. In order to obtain a "response" from the conductive beds, they have to be "energized." This is done by using an alternating current

generator and connecting its terminals to a rectangular loop which is laid out in the area to be surveyed in a manner shown in **Fig. 18.** Passing an alternating current through this loop, an alternating magnetic field will result about it. This alternating magnetic field will cause currents to flow in the conductive salt water bed, which in turn have an alternating magnetic field which can be picked up at the surface. The action of the transmitting loop and the salt water bed is similar to that of a transformer with the functions of which most readers will be familiar.

The magnetic field of the currents which are "induced" to flow in the salt water beds is picked up by a receiving or "search" coil shown in the figure. The alternating field produces induction currents in the coil, this again being similar to the action of a transformer. The current may be amplified and rectified, and the "intensity" of the induced field may be read on a voltmeter. The variation of this voltmeter reading is what we show when the receiving equipment moves across the structure.

It remains to be explained how the depth of the salt water bed can be determined by recording the voltmeter readings on a number of points. For this purpose, we remember the action of a reflecting bed in the seismic reflection method. We found there that the reflected waves appear to come from a "secondary" shotpoint which was obtained by reflecting the true shotpoint on the reflecting bed, i. e., from double the depth of the reflecting bed.

The action of the salt water beds is exactly the same. They react as if a secondary cable was present in double the depth of the salt water bed; i. e., the salt water bed acts as a mirror for the insulated loop. The cable, or loop, in double the depth has a circular magnetic field around it which is picked up at the surface by the search coil. Thus, when the salt water bed is shallow, the magnetic field of the "secondary" cable will decline rapidly away from its maximum (see right side of the fault, **Fig. 18**). When the depth is greater (left side), the response curve will be flatter. From this behavior of the response curve the depth on either side of the fault may be calculated.

Actually the process of measurement is much more complicated than the one described, and for this reason will not be discussed.

For the geologic section, we have selected a fault zone on which such measurements as the ones described have actually been carried out.

OTHER GEOPHYSICAL METHODS

In addition to the major geophysical methods which are demonstrated in the exhibits previously described, there are some others which are used occasionally in oil work. The methods used in wells for correlation of beds, location of oil sands which may have been passed up in the process of drilling, and for obtaining certain structural information come under this heading. They are *resistivity measurements* and *temperature observations.*

In the former, a "contacting" arrangement is lowered into an uncased water-carrying well and the resistivities for every depth are recorded at the surface. In this manner certain formations which may not possess sufficient lithologic differences to be detected in drilling, may be correlated from one well to another. In the latter, a thermometer is lowered into the well and temperature measurements are taken in a number of depths. In a number of wells, depths of the same temperatures may be connected by lines or surfaces, called "isothermal" surfaces, which have been found to resemble rather closely the trend of structure.

Both the method of "electrical coring" and "geothermal" measurements are demonstrated in a transparency near the exit from the Geophysics Exhibit.

It may be said again in this connection that owing to the purpose of the geophysics exhibit, only the main and representative types of geophysical

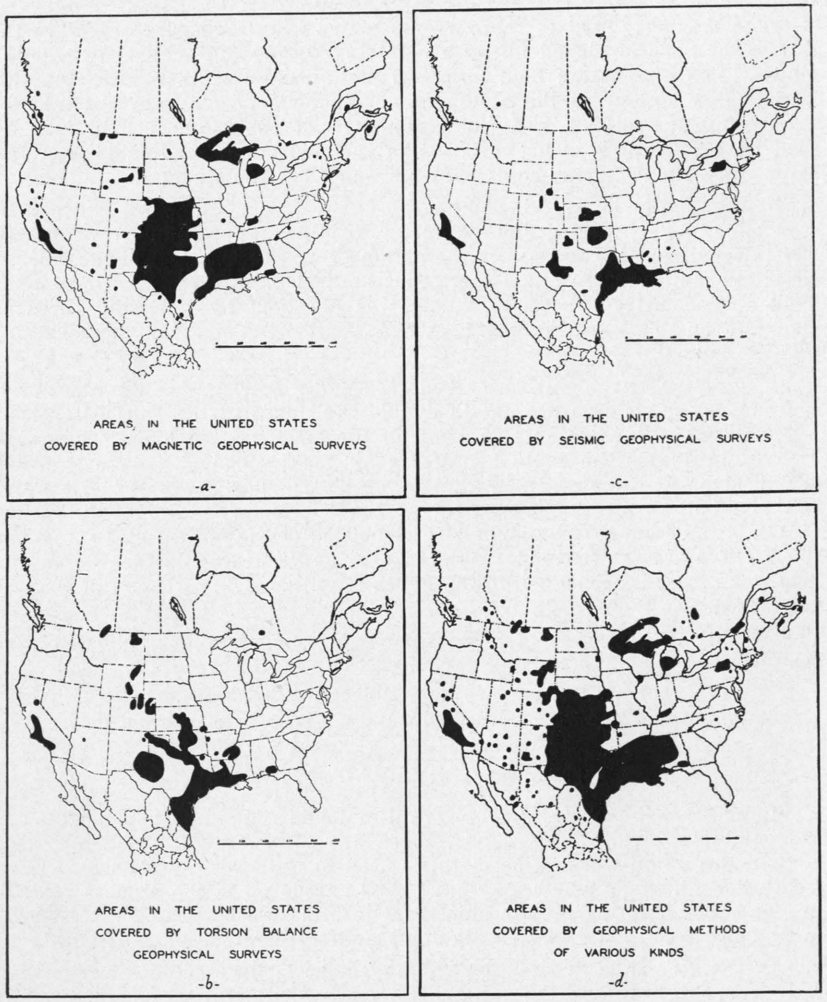


Fig. 19—Areas covered in the United States, Canada and Mexico by

(a) Magnetic methods.
(b) Torsion Balance surveys.
(c) Seismic Surveys.
(d) Geophysical methods of all kinds.

methods could be demonstrated, and a number of methods which are of minor importance, or are modifications of the ones described, and those applied in electrical prospecting for ore and in civil engineering, had to be omitted. The tabulation on the next page gives a summary of most geophysical methods, includes those which could not be treated here and shows their mutual relationship.

The tabulation aims to bring out the difference between methods which are based on spontaneous effects and, therefore, offer no possibility of controlling the depth of penetration; and those, which involve the determination of their reaction to artificial fields and make possible a regulation of the depth of penetration and thus a more ready determination of the depth of geologic bodies. It is further stated in this tabulation in which field and to which special geologic problems the various methods are applicable.

STATISTICS ON GEOPHYSICAL PROSPECTING

One could fill a whole book with data about the results obtained with various geophysical methods in different parts of the world, their successes and failures, and discoveries of oil and ore deposits made on the basis of geophysical work. For the area of the most spectacular success of geophysics, the Gulf Coast, some data have been shown before in **Fig. 3b.** For the same area, our exhibit contains a map showing all salt domes which have been discovered in Texas and Louisiana by geological and geophysical methods, as well as essential production data about them.

Geophysics is a science of which a great many people have never heard and consequently consider as something which has not found a very wide application. Few realize that comparatively large areas in the United States alone have been surveyed geophysically, not only once, but sometimes many times, owing to competitive activities and gradual perfection in the instrumental and interpretative technique.

Fig. 19 will serve to give an idea about the work done in the United States, Southern Canada, and Northern Mexico with magnetometers, torsion balances and seismographs. The last map in this figure represents all geophysical activities combined.

CONCLUSION

As a concluding feature in the presentation of the various geophysical methods the visitor sees, upon leaving the exhibition booth, a painting on one side of the booth, which makes an effective counterpart to the medieval prospector and which shows the modern scientific prospector with his various devices **(Fig. 20)**.

In this painting, the application of geophysics in oil exploration, mining and civil engineering fields are symbolized by the oil field, the mill and the power plant in the distance. In the foreground, we notice magnetometer observations being taken, a torsion balance in its field house, resistivity measurements, terrain observations for torsion balance measurements, and the tracing of equipotential lines to locate an ore body, while another operator handles a gasoline-driven generator supplying the power. In the central part of the picture we notice, finally, a blast set off by a shooting truck, while a recording truck with its crew is stationed more in the foreground.

TABULAR SUMMARY OF THE FOUR MAJOR GEOPHYSICAL METHODS

	Method				Chief Field	Geologic Application	
Spontaneous Action	I. Gravitational			A. Torsion Balance	Oil	Anticlinal Structures; Buried Ridges; Salt Domes; Faults; Intrusions.	No Depth Control
Spontaneous Action	I. Gravitational			B. Pendulum	Oil	Salt Domes; Buried Ridges; Major structural trends.	No Depth Control
Spontaneous Action	II. Magnetic				Oil Mining	Anticlinal Structures; Buried Ridges; Intrusions; Faults; Iron-pyrrhotite and assoc. Sulphide ores; gold placers.	No Depth Control
Spontaneous Action	III. Electrical	A. Self-Potential			Mining	Sulphide Ore Bodies	No Depth Control
Reaction to Energizing Fields	III. Electrical	B. Galvanic Application of Primary Energy	1. Potential Distribution of Second'y Field measured	a. {Equipotent. / Potential Prof.} b. Resistivity c. Pot. Drop Ratio	Mining Civil Eng. Oil	General Stratigraphic and Structural Conditions; Bedrock Depth on Dam Sites; Ground-Water; Oil Structures; Sulphide Orebodies.	Control of Depth of Penetration
Reaction to Energizing Fields	III. Electrical	B. Galvanic Application of Primary Energy	2. Electromagnetic Field meas.		Mining	Sulphide Orebodies.	Control of Depth of Penetration
Reaction to Energizing Fields	III. Electrical	C. Inductive Applic. of prim. Energy			Oil Mining	Faults; Anticlinal etc., Structure; Sulphide Orebodies.	Control of Depth of Penetration
Reaction to Energizing Fields	IV. Seismic			A. Refraction	Oil	Salt Domes; Anticlinal Etc. Structures; Faults.	Control of Depth of Penetration
Reaction to Energizing Fields	IV. Seismic			B. Reflection	Oil	Low Dip Structures; Buried Ridges; Faults.	Control of Depth of Penetration

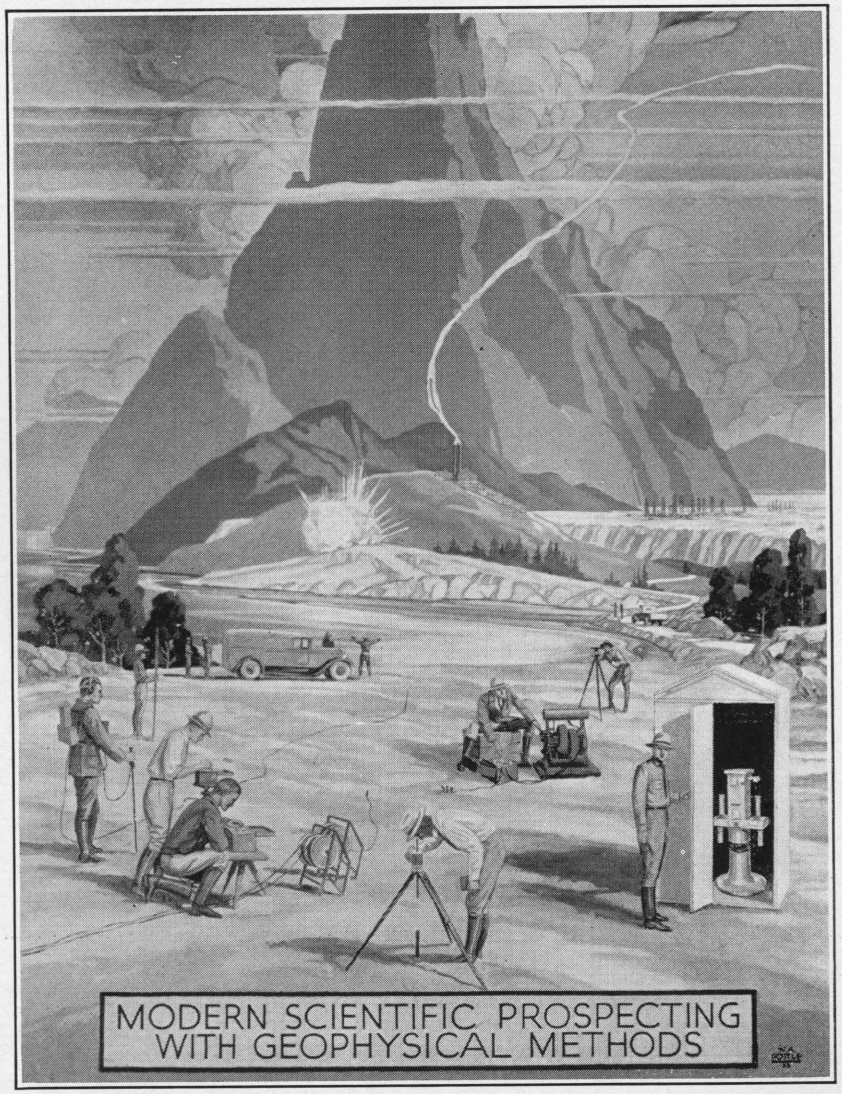


Fig. 20—Modern scientific prospecting with geophysical methods.

PURPOSE OF THE GEOPHYSICAL PROSPECTING EXHIBIT

It has not been the purpose of the Geophysics Exhibit to present a collection of instruments and geophysical results. The aim has been to demonstrate the fundamental principles in as elementary a manner as possible by animated exhibits, showing the relation of instrument deflection, geophysical data, physical rock properties and geologic structure. Details not related to these principles have been omitted and the actual relations often had to be simplified to adhere to the elementary method of demonstration.

The geophysical literature of the past years contains many good articles of both general and special nature which may be studied by those who wish to obtain further knowledge in respect to instruments, methods and interpretation beyond the fundamentals shown in the exhibit. The Colorado School of Mines Quarterly No. 3 of Volume 26 contains a list of about 200 references to geophysical prospecting, arranged with respect to the various methods and classified into articles on theory, rock properties, interpretation and results, etc. This booklet may be obtained from the business office of the Colorado School of Mines, Golden, Colorado.

It has not been the object of this pamphlet to present merely a description of the geophysics exhibit which could have been given in a few words, but to outline, by means of it, the fundamental principles of geophysics in elementary language. It has been written not only for the benefit of those who have seen the exhibit and wish to add to their knowledge gained from witnessing it by studying an elementary summary of the field, but also for those who have not had an opportunity to visit it. If it has succeeded in arousing the interest of a wider group in this subject, its purpose will have been accomplished.