Feb. 2, 1932. K. SUNDBERG 1,843,407

UNDERGROUND STRATA PROSPECTING

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Fig. 1,

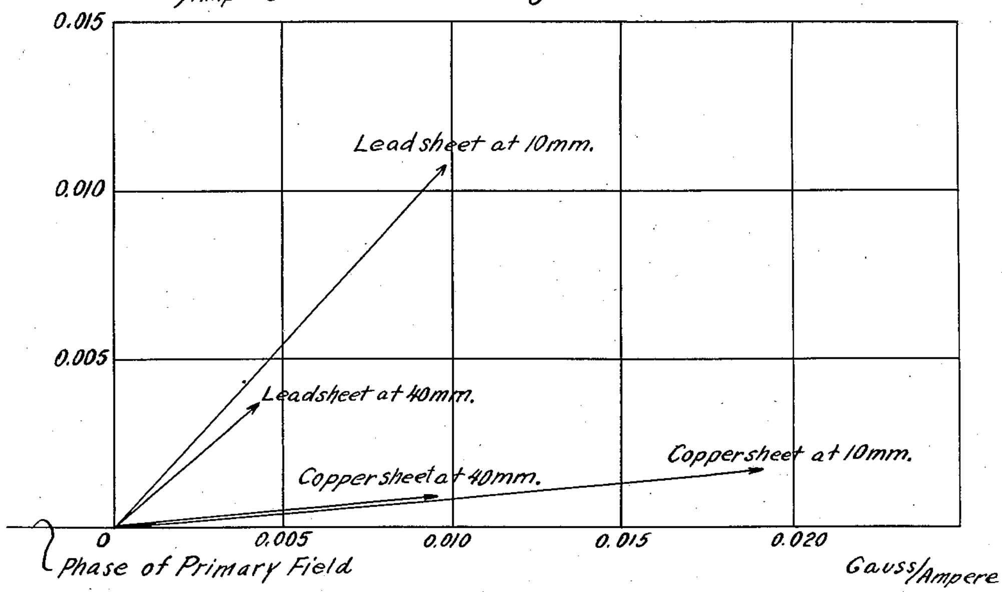

Fig. 2,

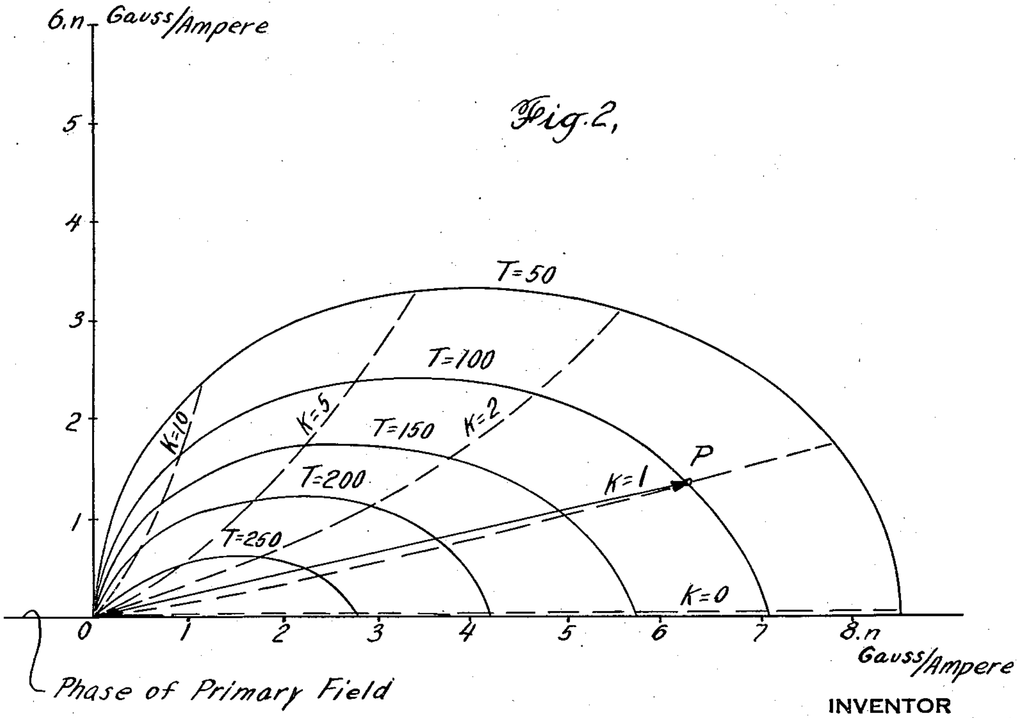

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Fig. 3.

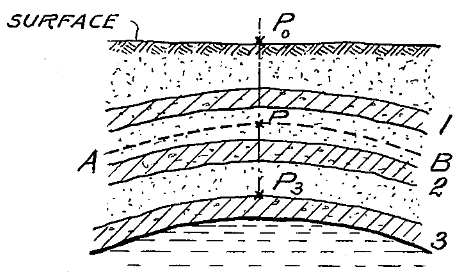


Fig. 4.

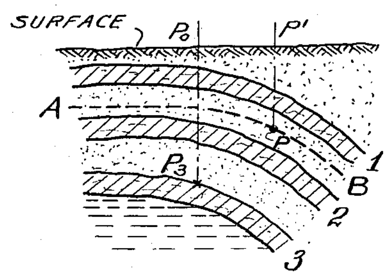


Fig. 5.

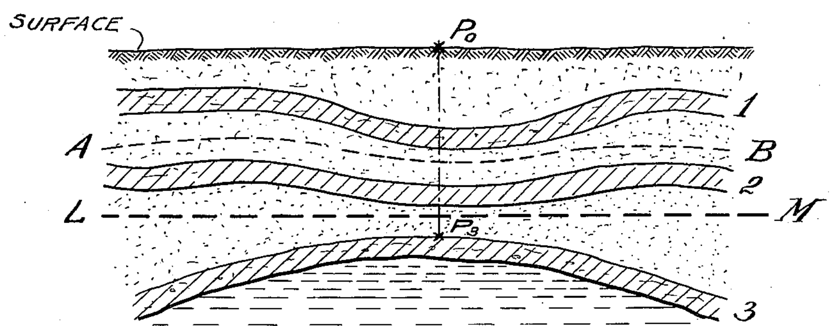


Fig. 6.

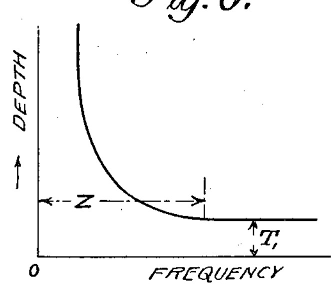
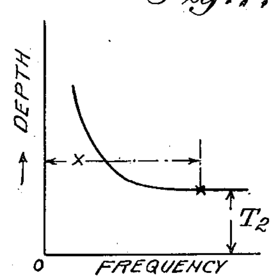


Fig. 7.



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UNITED STATES PATENT OFFICE

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UNDERGROUND STRATA PROSPECTING

Application filed March 5, 1928. Serial No. 259,131.

This invention relates to underground strata prospecting and has for its object the provision of an improved method of determining the structure and configuration of underground strata. The invention more particularly relates to oil-bearing strata.

Various proposals have been made, and numerous practices have been resorted to, to locate oil-bearing strata. In years gone by, many oil fields were located by oil seepages or similar traces of oil on the ground, but such readily discoverable deposits have nearly all been exploited. At the present time, therefore, the problem confronting the oil prospector is one of locating deposits which have been so completely sealed off that no trace of oil can be found on the surface.

Oil geologists attack this problem by locating the most probable area of oil accumulation within a district where the existence of formations likely to contain oil is known or suspected.

Whether or not a formation is likely to contain oil deposits depends chiefly on its structure and configuration. Because oil is lighter than salt water, which almost always is present in oil-bearing formations, it accumulates in areas where, through folding or faulting or the formation of terraces, the beds have been elevated. A knowledge of the geological structure of a given region, therefore, is of the utmost importance in predicting the existence of oil deposits in that region.

Generally, such knowledge is obtained by taking geological observations of the strike and dip of the outcropping formations in the territory being investigated. The information which can be obtained in this way is in most cases, however, too meagre to serve as a basis for a reliable structure map of the territory because enough outcrops to prepare such a map are generally found only in mountainous regions, whereas by far the greater number and largest oil deposits exist in topographically flat regions, where outcrops are few in number. For this reason, recourse is sometimes had to the drilling of a series of test holes down to a "key-bed" characterized by the presence of fossils or other rock features of a certain kind. As will be suspected, such a practice is very slow and expensive, because the depth to a reliable key-bed is usually rather great and because a large number of test holes is necessary to avoid missing structural features which may be of importance.

In contrast to such methods as have been heretofore practiced, the present invention concerns a method whereby the structure and configuration of underground strata may be determined electromagnetically and a reliable structure map obtained. More particularly, the present invention comprises the determination of the depth to the underground strata by investigating at various points on the surface the nature or character of an electromagnetic field.

The practice of the invention is based on the difference which exists in the electrical conductivity of the various beds constituting the sedimentary column. In the particular case of oil-bearing strata, the salt water carrying beds constitute good electrical conductors, their conductivity being higher the greater the content and concentration of salt water in them. By utilizing this conductive property of salt water beds to determine their structure, it accordingly becomes possible to map the subsurface structure in any given locality and thus to predict with considerable accuracy the presence or absence of oil deposits.

Generally speaking, the determination of the structure of such conducting beds is carried out, in accordance with the invention, by setting up at any given point in the region to be investigated an alternating electromagnetic field as by means of a wire circuit or loop laid on the surface of the ground. The field thus set up, usually termed the primary field, induces in any conducting bed within its influence, alternating currents which set up an electromagnetic field of their own, ordinarily called the secondary field. The field actually existing accordingly is different from the primary field which would exist if the conducting bed or beds were absent. By investigating this actual or resultant electromagnetic field at various points on the surface, in a manner which will be hereafter explained, it is possible to obtain an accurate indication of the depth at which the conducting bed is located.

If it be assumed for the moment that but one conducting bed is present in a given region, it will be clear from what has been explained above that the resultant field will be made up of the generated primary field and the secondary field due to the single bed. Suitable investigation of this resultant field at a number of arbitrary points, in the manner contemplated by the present invention, accordingly will enable the determination of the depth to this bed at the various points at which observations are taken. If these depth values are then plotted and contour lines drawn, the true configuration of the single conducting bed will be made available for study and analysis.

Ordinarily, however, more than one conducting bed is present. The resultant field existing at various points, accordingly is more complex than in the simple case above assumed because it includes the combined secondary fields of the several beds instead of merely the secondary field of one bed. It therefore is necessary to employ some scheme whereby the secondary fields can be separately considered, because depth determinations in the manner previously described will represent only the average of the depths to the different beds and consequently will not provide a true picture of the configuration of each bed.

The present invention, accordingly, further provides a method whereby the depth to each of a plurality of conducting beds can be determined and contour lines drawn showing the true configuration of each bed. The existence of an anticline or dome in a bed lying beneath a number of other beds of different configuration can therefore be determined and a possible oil-bearing area located, even though the shallower beds give no indication of such an area.

In order that a better understanding of the invention may be had, reference is made to the accompanying drawings, wherein:

Fig. 1 is a vectorial representation of a laboratory investigation in accordance with the invention.

Fig. 2 is a graph adapted for use in determining the value of certain quantities entering into the calculation of the observed results of an investigation in accordance with the invention.

Figs. 3, 4 and 5 are sections of the earth's crust showing superposed conducting beds of different form.

Fig. 6 is a chart showing the relation between conducting bed depth and primary field frequency, when but one bed is assumed to exist.

Fig. 7 is a chart showing the relation between conducting bed depth and primary field frequency when two beds are assumed to exist.

Considering the drawings more in detail, Fig. 1 represents the results of a laboratory investigation undertaken to illustrate the operability of the present invention. In this laboratory test, large horizontal sheets of copper and lead were employed at different times and a primary field generated by means of a horizontal loop made up of a number of turns of wire. The copper sheet was 2.04 mm. thick and the lead sheet 1.06 mm., while the loop was rectangular, its dimensions being 160 x 320 mm. The frequency of the current in the loop was 500 cycles.

At a point located 20 mm. from the long side of the loop, observations of the horizontal component of the electromagnetic field were taken for two different distances of the sheets beneath the loop plane, namely 10 and 40 mm. Such observations are vectorially depicted in Fig. 1.

Since the field is alternating, it is represented not only by its strength but also by its time or phase displacement. During the time of one cycle, 1/500 of a second in this case, both the current in the loop and the field will vary from zero to a maximum in one direction and then back to zero and a maximum in the other direction. The strength of the field is its maximum strength during one cycle. Its phase, on the other hand, with reference to the current in the loop, is the time difference between the moment when the current passes from maximum through zero in a certain direction and the moment when the field passes from maximum through zero in the same direction.

The vectors in Fig. 1 accordingly represent by their length the strength of the field and by their angular displacement from a fixed reference line the phase of the field. As a reference direction, the phase of the primary field, which is identical with the phase of the current in the loop, is customarily used, and in the figure is represented by a correspondingly designated horizontal line. A convenient unit for the strength of the field is the gauss, and because the strength of the field is proportional to the strength of the current used, it is most convenient to measure and represent the strength of the field in gausses per ampere of current in the loop. In this way, the measurements may be made independently of fluctuations in the current.

From the figure it may be seen that the field vector, in the case of both the lead sheet and the copper sheet, clearly indicates a change in the distance from 10 mm. to 40 mm. Likewise, for a constant distance, for instance 40 mm. the vector also indicates a change in the electrical properties of the sheets as represented by the two metals copper and lead. It accordingly is evident, that by such a method as is herein disclosed, it is possible to determine the depth as well as the electrical properties of a conductor, as represented by the metal sheets, by observing the magnetic vector. In the test but one point was used for observation; in practice, observations would be taken at a number of points and the nature of the vector determined at each point to indicate the depth and character of the conducting bed.

The question might arise why metal sheets were used in the test when the conducting beds encountered in practice are of much lower conductivity. The reason is that the laboratory measurements were, of necessity, made on a small scale, and consequently, to obtain corresponding magnetic fields when changing scale, it is necessary to increase the conductivity of the observed bed n^2 times when decreasing all other linear dimensions n times. The specific resistance of copper is about 1.8 x 10^{-6} ohms/cm.^{3} and of lead about 21.1 x 10^{-6} ohms/cm.^{3}. Assuming the linear dimensions in practice to be 10,000 times larger than in the test, the results shown in Fig. 1 would be applicable to beds 20.4 m. and 10.6 m. thick with specific resistances of 180 ohms/cm.^{3} and 2100 ohms/cm.^{3}, respectively, and located at depths of 100 and 400 meters. Such figures are of about the same magnitude as occur in practice.

Both theory and laboratory experiments of the kind above described, show that the magnetic vector above the conducting layer is completely determined by the depth to the layer and the numerical value of a factor K, where

$$K=\frac{r}{vd}$$

in which r=specific resistance of layer; d=thickness of layer; v=frequency of primary field.

By actually measuring the magnetic vector, for instance by the arrangement disclosed in copending application Serial No. 168,527, it therefore is possible to determine the depth to a conducting layer and also its K value. The simplest way to make corresponding interpretations of field measurements is to prepare a chart based either on theoretical calculations or laboratory experiments, showing the value of the vector for different depths and K values.

Such a chart is shown in Fig. 2, the units of depth and K values being arbitrary. If the measurement made in practice gives, for instance, a vector such as OP at a certain point, the depth to the layer can be read from the chart as 100 and its K value as 1.

As has been explained before, the measurement of depth is comparatively simple as long as only one conducting layer exists. Where several beds exist, each bed will give a certain component of the magnetic vector. Furthermore, the strength of a component H_n, due to a certain layer N at a depth T_n having a value K_n, will be weaker the greater the depth T_n.

The value F_n of the primary field at the layer N, and thus also the secondary field component H_n, have been proven by theory and experiment to depend, except for T_n and K_n, only upon the K values of the layers existing between the layer N and the surface. The smaller the K values of the layers are the smaller are the values of F_n and H_n. If the K value of any layer is zero, then no magnetic field exists beneath the layer. In other words, the layer acts as a screen, the smaller the values of K the better the screening effect.

As has been previously shown, however, in connection with the equation

$$K=\frac{r}{vd},$$

the factor K depends on the frequency of the current used, and therefore can be changed by varying the frequency. Accordingly, certain conducting beds can by choice be made perfectly screening beds by selecting a suitable value of frequency which will make the K value for such beds substantially zero. This frequency may be termed the critical frequency, and at this frequency, no primary field will penetrate beneath the bed and consequently, no secondary field will be set up by any beds existing at a greater depth.

Consequently, if the frequency of the primary field is increased until the value of the vectors determined at each of the various points of measurement remains constant regardless of a further increase in frequency, the value of the frequency at which the magnetic vector measurements become constant will be the value of the critical frequency of the conducting bed nearest to the surface, and the vector determined at the various points will be an indication of the depth of this shallowest bed at those points in accordance with the chart, for example, obtained from laboratory experiments. Also, since this shallowest bed will then be a totally screening bed, the secondary field measured at the various points will be the secondary field of this bed only.

With the necessary values thus determined, the secondary field due to the shallowest conducting bed can be calculated for any frequency. Then, by gradually reducing the frequency, and noting the field vectors and taking into consideration the corresponding vectors for said first layer, a second point can be obtained at which the depth calculations remain constant, indicating the critical frequency for the next lowest bed, and the secondary field due to this bed is determined by subtracting the known value of the secondary field of the shallowest bed from the actually measured secondary field at that frequency. Similarly, the secondary field due to a third bed can be determined by taking the known values of the secondary fields of the first two beds into consideration, and so on for any number of succeeding conducting beds.

Considering the other figures in the drawings, Fig. 6 represents graphically the result of depth calculations at different frequencies, made under the assumption that but one conducting bed exists. As the frequency is increased the values of depth become smaller and smaller until a constant value of depth, shown as T_1 in the figure, is obtained. The frequency at which the value of the depth becomes constant represents the critical frequency of the conducting bed, and is shown in Fig. 6 as Z. Beyond this value the depth will remain constant and at frequencies lower than this value Z the depth will be greater, owing to the effect of the deeper conducting beds existing below the single bed assumed to be present.

After the determinations have been made for the shallowest conducting bed and a value of depth T_1 obtained, corresponding calculations are carried out for frequencies lower than the critical frequency Z of Fig. 4, and a second point reached at which a constant value of depth T_2 (Fig. 7) is obtained. This value T_2 represents the depth of the next lowest conducting bed, and the value X of the frequency at which this constant depth is obtained is the value of the critical frequency. At frequencies below this value the depth will be greater because of the effect produced by such conducting beds as may exist below the second bed. In a similar manner, calculations can be carried out for conducting beds located still deeper and corresponding values of depth determined.

Accordingly, if in practice a field of the nature shown in Fig. 3 is encountered, wherein the oil is trapped in a dome beneath a deep bed or layer such as 3 and a number of similarly crowned beds 1 and 2 are disposed between this layer 3 and the surface, calculations can be made at several different frequencies and the depths of the layers 1, 2 and 3 successively determined and the point P_3 located. The projection of this point on the surface P_0 will then determine the point at which, if a drilling is made, the crown of the oil dome will be struck at the already determined depth of the point P_3.

If depth calculations are made with a given fixed frequency, a set of average depth readings will be obtained defining a hypothetical line such as A—B and locating a high point such as P. Where the beds are all similarly formed, as in this case, the error will not be serious because the line A—B will be of the same configuration as the beds, although the depth of the point P will not represent the actual depth of the oil at the point P_3.

If a more complicated field is encountered, such as shown in Fig. 4, for example, the advantage of using different frequencies becomes more apparent. By my method I can determine the position of the several beds 1, 2 and 3 and locate the point P_3 and so fix the point P_0 on the surface at which a drilling should preferably be made to reach the oil beneath the layer 3. By the fixed frequency method, however, the hypothetical layer A—B will be determined and the point P located and projected to the surface at P′. Because of the displaced position of the beds, the line A—B will not give a true indication of their configuration and, consequently, a drilling made at the point P′ will miss the oil below the point P_3 entirely.

Ordinarily, the complicated formation of the conducting beds shown in Fig. 5 is considerably more common in the field than the formations shown in Figs. 3 and 4. Instead of the beds being all of the same general form, the beds 1 and 2 above the discordance L—M are not parallel to the bed 3 located beneath the discordance. Particularly, is this true where a number of irregular conducting beds exist very close to the surface, because such beds are seldom, if ever, parallel to deeper beds.

It is in connection with formations of this irregular form that my method is of particular importance, because the region above the discordance gives no indication of the configuration of the bed 3 or of the consequent possible accumulation of oil. By employing a fixed frequency the depth calculations might define a line such as A—B in the figure, which clearly would be of no practical value. In fact, from a study of such a line it might well be concluded that no anticline or oil dome such as the bed 3 exists at that particular point in the field, and consequently, the oil would be overlooked.

On the other hand, by taking readings at different frequencies, and plotting the calculated results, a profile can be obtained showing the configuration of each of the separate beds and their position above one another. The presence and form of the layer 3 can therefore be determined and the crest P_3 of the dome located and projected to the surface to fix the point P_0.

While the above example relates in large parts to the determination of oil-bearing strata, it will of course be understood that the invention is not to be restricted to oil-bearing strata. The principles of the invention are applicable to the determination of the structure and configuration of other kinds of strata as well, such, for example, as ores, ground-water and the like.

I claim:

1. In the method of underground strata prospecting the steps which comprise setting up at any given point in the region to be investigated an alternating primary electromagnetic field adapted to induce in any conducting bed within its influence alternating currents which set up a secondary electromagnetic field of their own, varying the frequency of the current to obtain a critical frequency at which no primary field will penetrate beneath said conducting bed and no secondary field will be set up by any conducting bed existing at a greater depth.

2. In the method of underground strata prospecting the steps which comprise setting up at any given point in the region to be investigated an alternating primary electromagnetic field adapted to induce in any conducting bed within its influence alternating currents which set up a secondary electromagnetic field of their own, increasing the frequency of the primary field until the value of the vectors determined at each of the various points of measurement remain constant regardless of a further increase in frequency thereby fixing the value of the critical frequency as the value of the frequency at which vector measurements become constant, and determining the secondary field due to said conducting bed for said critical frequency.

3. The method according to claim 2, which comprises gradually reducing the frequency until a second point is obtained at which vector determinations remain constant thereby fixing the critical frequency for the next lowest conducting bed, and determining the secondary field due to said next lowest conducting bed for said critical frequency.

4. In the method of underground strata prospecting, the steps which comprise setting up at any given point in the region to be investigated an alternating primary electromagnetic field adapted to induce in any conducting bed within its influence alternating currents which set up a secondary electromagnetic field of their own, increasing the frequency of the primary field until the value of the vectors determined at each of the various points of measurement remain constant regardless of a further increase in frequency thereby fixing the value of the critical frequency as the value of the frequency at which vector measurements become constant, determining the secondary field due to said conducting bed for said critical frequency, gradually reducing the frequency until a second point is obtained at which vector determinations remain constant thereby fixing the critical frequency for the next lowest conducting bed, and determining the secondary field due to said next lowest conducting bed for said critical frequency by subtracting the known value of the secondary field of the shallowest bed from the actual secondary field at that frequency.

In testimony whereof I affix my signature.

KARL SUNDBERG.