Some Aspects of Applied Geophysics *

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PERHAPS some apology, or at least explanation, is necessary for the choice of a subject for which I have not even been able to find a satisfactory title. Applied geophysics may clearly be taken to include certain aspects of meteorology or oceanography, or, indeed, any branch of knowledge in which physics is applied, in the service of mankind, to the elucidation of the properties of the earth. I propose to deal with what is in fact only a limited field of work. Put briefly, it covers the application of physical methods to the examination, without digging or boring, of what lies beneath the surface of the earth at relatively shallow depths of less than a few thousand feet. The application is more particularly directed to the discovery of deposits of economic importance, such as minerals or oil, or the structural formations with which they are likely to be associated.

Truly this is a subject as different as it could very well be from those flights of theoretical physics—relativity, quantum theory, wave mechanics, and the like—which those of us with slower minds and more pressing other occupations try so desperately to follow. In our admiration and, perhaps, envy of the apparent ease with which the pioneers in these new fields make progress, we are inclined, wrongly, I think, to allow it to be assumed that modern physics and atomic physics are one and the same thing. It should not be overlooked that physics is making rapid strides forward also in other directions. Much that is new in the precision of measurement, in the choice of methods, and in the invention and design of physical tools for the attack on old problems hitherto unsolved, has been added to our knowledge in recent years. This is true with regard to the particular branch of physics we are now to consider. Its fundamental basis is not new. It involves no appeal to, let us say, wave mechanics; the old gravitational theory of Newton and the electromagnetic theory of Maxwell serve well enough our purposes. Yet its successful application continues to demand the highest experimental skill that training in physics can provide, and initiative ability equal to that more frequently directed in less practical channels.

The subject is also a border-line one, and, perhaps for that reason, has not received so much attention as it deserves, at any rate in Great Britain. Its practice involves the co-operation of geologists with physicists, except in those rare examples of the same person being expert in both branches of knowledge. It was a famous geologist, the late Prof. de Böckh, who suggested to the equally famous physicist, Baron von Eötvös (whose work we shall consider more fully later), that the Eötvös torsion balance should be used to locate and delineate buried salt domes—geological features with which oil is frequently associated. Prof. de Böckh once told me that at first Eötvös was horrified at the idea. He regarded the use of his instrument for such an economic purpose as debasing science, and it was only with great difficulty that he was eventually persuaded to initiate what has now become a common and successful practice in various parts of the world.

I may perhaps mention, too, that when I first became interested, about five years ago, in applied geophysics, I was very doubtful of its use. Could conditions underground, I asked myself, ever be so simple and free from complications that physical observations on the surface would point unequivocally to the solution? The answer to this question is, generally speaking, in the negative; but here the geologist comes in again. He carries out his preliminary survey by his own methods, and is often able to indicate both the limited region where a geophysical survey seems desirable and, in a general way, the kind of formation which is to be sought, thus enabling a suitable choice of method to be made. He provides, in fact, the *selection rules* for the geophysicist, in much the same way as the quantum theorist does for the spectroscopist, as regards both where to look and what to expect to find. It is true that sometimes a *forbidden* result persists in obtruding itself inconveniently upon the geological interpretation, just as a *forbidden* spectral line may refuse to be extinguished. But usually the solution of a problem has to depend upon the combined result of geological and physical evidence, and is only approximate at that.

It is mainly the physical basis of the work that I wish to review. Here I should point out that this limitation will exclude 'divining', whether for water or any other underground feature. Innumerable claims of successful use have been made for the divining rod and similar indicators, but the *modus operandi* has never been explained, and none has been established on an acceptable physical basis. But I am glad to escape from this highly controversial ground by defining in a sufficiently exclusive manner what is a geophysical method in relation to the search for minerals. The basis of every geophysical method is the differentiation, usually abrupt, of some physical property as between rocks. The four principal methods—gravitational, magnetic, seismic, and electrical—depend, in fact, upon differences, in the various media underlying the earth's surface, of density, of magnetic susceptibility, of velocity of elastic wave propagation, and of electrical conductivity respectively. Associated with these variations of physical properties, either naturally or through stimulation by artificial means, there are produced, at or near the earth's surface, calculable physical effects which may be capable of measurement by suitable apparatus. There must be something physical to measure, and the instrument must be able to measure it.

* From the presidential address to Section A (Mathematical and Physical Sciences) of the British Association, delivered at York on Sept. 2.

THE GRAVITATIONAL METHOD

I do not think that Eötvös has yet received in Great Britain the full recognition which his work deserves. Possibly this is because the early accounts appeared in rather inaccessible journals; or, possibly, there were real doubts concerning the validity of his claims. I remember, as a student, hearing vaguely about his experiments—and his name, without anyone knowing how to pronounce it. In the same lectures we learnt much fuller details of Boys's classic measurement of the constant of gravitation, without realising how remarkably similar in essential form the Eötvös and Boys instruments were. But the fact is that when Boys was inventing and making the quartz fibres for his torsion balance to weigh the earth, Eötvös had already tackled successfully the difficult task of making robust and portable for field work another torsion balance of not greatly inferior sensitivity. While Boys was busy with his measurements in a constant temperature cellar, Eötvös was completing the protection of his portable instrument against the temperature variations inevitable in the rigours of the field. A few years later he made notably successful gravitational surveys on the frozen surface of Lake Balaton and on the Great Hungarian Plain; but it was not until Shaw and Lancaster-Jones had demonstrated in 1923 that an Eötvös balance, acquired for the Science Museum before the War, behaved according to specification, that the remarkable nature of Eötvös' achievement began to be appreciated here.

Even now I do not think it is well enough understood how small were the effects which Eötvös measured under the unfavourable conditions of field work. We can illustrate this in a very striking way. The earth's gravitation field, even apart from local irregularities, is not uniform, or, rather, spherically symmetrical. Owing mainly to the earth's rotation, the apparent value of the gravitational intensity increases in passing from equator to pole. The total change is about 5 cm./sec.^{2}, and the maximum rate of horizontal variation is at latitude 45°. In this region the change of g for a step of one metre northwards is 8×10^{-7} cm./sec.^{2}, or, approximately, only one thousand millionth of the gravitational acceleration. This the Eötvös torsion balance was capable of indicating definitely, being several times as large as the limit to which the instrument would respond. Further, the measurement could be made with the instrument occupying a single position in a space of less than a square metre, simply by making observations with the apparatus as a whole in a number of different azimuths. Eötvös, in effect, multiplied by a thousand the accuracy of measurement of terrestrial gravity variations.

This remarkable sensitivity was secured by deliberately excluding gravity itself from exercising any control in the instrument, which was constructed so as to respond only to *variations* of the gravitational field.

It would take too long to describe the instrument, and at the same time do justice to those used in other branches of geophysical surveying. It must suffice here to indicate that the Eötvös torsion balance provides means of measuring, normally by observations of the changes of torsion accompanying changes of azimuth of the instrument as a whole, two properties of the local gravitational field, each having magnitude and direction. The magnitude of the first, for which a satisfactory name has not yet been devised—the *horizontale Richtkraft* according to Eötvös—is the product $g(c_1 - c_2)$, where c_1 and c_2 are the greatest and least curvatures of the local 'level' or equipotential gravitational surface; its direction is horizontal and in the vertical plane of least downward curvature. The other departure from gravitational uniformity which the balance measures is the *gravity gradient*, or the rate of change of the vertical gravitational intensity with horizontal distance in the direction in which the change is greatest. It is a vector, and both its magnitude and direction can be obtained from the instrumental observations.

The reaction of the instrument to these two differential 'fields' provides the means of measuring the particular gravitational distortions which they represent. This part of the work is pure physical measurement of a straightforward character, and attaining, as I have indicated, a surprising degree of precision. It is in the interpretation of the results that the real difficulties arise. The problem is to ascertain to what extent the gravitational irregularities measured are due to density differences in the buried structure, and to assign to the latter a position and shape consistent with the observations. In country where the surface is otherwise than virtually horizontal it is necessary to survey its irregularities and make calculated allowances for their contribution to the total measured gravitational distortion. This topographical effect may indeed sometimes be so large in comparison with that of hidden structure as to render gravitational surveying ineffective. The earth's rotational effect, of course, has always to be eliminated, but this presents no difficulty. What remains after these corrections constitutes the data for geophysical interpretation; and this is the stage where the geologist's 'selection rules' have to be applied. As in all geophysical methods, interpretation is necessarily indirect. Underground structures, agreeable to the geologist's experience, have to be taken as hypotheses, and tested by calculation and comparison with the data provided by surface observations.

I have, rather regretfully, to leave at this stage this part of my subject. My recent practical experience with torsion balances has aroused in me the greatest admiration for the work of the original inventor and his successors, and for the skill and precision with which most of these remarkable instruments have been constructed by the makers. It comes as something of a shock, even though we do not doubt the universal law of gravitation, to see for the first time a small mass of gold being attracted by a neighbouring lead sphere a few inches in diameter. With a torsion balance at our disposal the same becomes commonplace, and is indicative of the great power of these instruments for geophysical purposes. Accumulated evidence from the field confirms this view. There is convincing proof that extensive underground features, such as salt domes, limestone anticlines and synclines, rock faults, and deposits of hæmatite or of brown coal, produce, if not too deeply buried or masked by complicating irregularities, gravitational disturbances large enough to lead to their delineation.

The Seismic Method

The seismic method of prospecting began to be used about 1919, chiefly owing to the initiative of Mintrop. To some degree it has replaced the gravitational method, on account of the greater speed with which it enables a given area to be surveyed—a most important economic criterion, of course. But there are other important reasons why, under certain conditions, it must be preferred. If, for example, the topography of the country is too irregular for the corresponding corrections to be applied reliably to torsion balance observations, gravity surveying is excluded ; and seismic work, which is not so sensitive to surface conditions, may still prove of value. Again, the structure to be determined may itself settle the choice of method. For example, if the problem were to determine the depth of a horizontal interface of discontinuity between two strata of very great extent, the torsion balance would not find anything to measure ; the seismic method, on the contrary, would be confronted, as we shall see, with its most direct and simplest task. But while admitting these undoubted advantages, and recognising the many notable successes of seismic surveying under suitable conditions, it is necessary to state that this method does not yet rest on so sure a theoretical foundation as the law of gravitation ; nor do the portable seismographs employed give records so unambiguous as the readings of the torsion balance.

The basis of the seismic method is the same as that underlying the investigations of the propagation of earthquake shocks in relation to the determination of the structure of the earth's crust. The difference is only one of degree. In so far as there is a theory of natural earthquake propagation, it serves also for the seismic method of geophysical prospecting. In trying to determine the depth of an underground stratum, the most direct method of attack would be to measure, if possible, the time of travel of a particular disturbance from the surface to the interface and back to the surface after reflection. This method has been used with great success in determining the depth of the ocean by means of the Admiralty echo-sounding machine. But it fails in application to the solid earth, for the reason that the attenuation of vibrations with distance is far greater in the earth than in the sea ; consequently, much larger initial disturbances have to be used—in fact, violent explosions. Even if—as ought always to be done for the sake of efficiency—the explosion is arranged so that the surface of the ground is not broken, thus eliminating danger to observers, the delicate seismographs cannot as yet be properly protected against the direct effect. They would thus be so greatly disturbed as to mask completely the onset of the small reflected disturbance arriving shortly after. This effect, indeed, persists to a less but still important degree even when the seismograph is removed to quite large distances from the explosion. It is true that some important results have been obtained by employing this so-called reflection method, but the reading of the records is a matter of considerable uncertainty, owing to the difficulty of identifying the time of onset of the reflected disturbance in the midst of the effect of that propagated directly.

This uncertainty has led to the more general adoption of a method, properly called the diffraction method, although the term 'refraction' is sometimes incorrectly used. Its great advantage is that it enables the inevitably feeble disturbances, which have penetrated to and through the lower medium, to reach the seismograph, under certain conditions, *in advance* of the much greater direct wave. Consequently, the times of arrival of these indirect, or diffracted, disturbances are recorded unmistakably upon the seismogram, however much the instrument may be agitated later on.*

The principles of the method can be readily applied to structures less simple than a single horizontal interface ; and the observations obtained in the field, plotted on time-distance graphs, enable such features as the slopes and curvatures of strata and the depths of more than one successive bed to be recognised under favourable conditions. For success the principal requirement is a large velocity-ratio as between the rocks constituting the various beds. Salt domes under alluvial deposits, for example, are in this respect suitable structures, and the location of many such domes was the first achievement of the seismic method. It has also been employed with valuable results in determining the underground contours of limestone anticlines and deep-seated granitic basements at depths of several thousand feet.

The Magnetic Method

We pass now to the magnetic method. In actual practice it is the simplest and least costly. It consists of measuring, with suitable portable magnetometers, local variations of components of the earth's magnetic field, usually the vertical and horizontal intensities. The instruments which have been designed for the purpose enable observations to be made quickly, so that a large number of stations can be occupied and a wide area covered in the course of a single day. Under suitable conditions, therefore, much information regarding underground structure may be obtained by means of a survey lasting only a relatively short time and involving comparatively little expense. But it should be pointed out that this apparent economy has sometimes led to the method being employed on problems for which it is at present unsuitable, and to claims being made as to its performance which are doubtful.

It is necessary to bear in mind that the basis of magnetic surveying is the differentiation of rocks in

* The theory and practice of the seismic method is discussed in articles in NATURE, 123, 684, 718, May 4 and 11, 1929.

respect of magnetic susceptibility, and the consequent discontinuities of magnetisation under the influence of the earth's general magnetic field. For the field distortion thereby produced at the earth's surface to be marked, it is necessary for the responsible rock structure to have a large susceptibility; this implies that only highly ferruginous rocks will be easy to find.

I do not mean to imply that the magnetic method of surveying is limited to the detection of ore bodies like magnetite. Igneous rocks generally, and particularly basalt, may contain considerable quantities of iron, and consequently possess an effective magnetic susceptibility much larger than non-ferrous materials. There is abundant evidence that structures of such rocks have been determined, under favourable conditions, by the use of magnetic variometers. But if we are to hope to bring within the scope of the magnetic method non-ferruginous underground formations, we must improve greatly the sensitivity of the instruments, and at the same time exclude the operation of certain disturbing factors.

The chief difficulty with the variometers at present available is the application of the corrections for diurnal variation of the earth's field and for temperature changes. If we could escape the necessity of applying the corrections which these important effects involve, we should feel much safer in attaching significance to anomalies only a few times larger than the limit of measurement of the apparatus.

A year ago I thought I saw the way to do this, and brought a method before this Section of the British Association. It was to make use of the essential principle which gives to the Eötvös gravity balance its extraordinary sensitivity, namely, to measure the space-variation only of the forces in question. I found later that Eötvös himself had worked on these lines, and actually constructed an instrument partially fulfilling the conditions; although it is not clear that he realised the full significance of complete success. I have to confess that unexpected practical difficulties of construction have so far prevented realisation, but I have not given up hope that a magnetic instrument can be constructed to operate in the same way as the proved gravity instrument. Accordingly, it may be worth while to indicate what a device of this kind might be expected to achieve.

The chief virtue of such a magnetic torsion balance is that it would discriminate between *time-variation* and *space-variation* of the earth's magnetic field. The variation with time of a magnetic field remaining spatially uniform would not affect it; it would respond only to a sufficient distortion in space. Calculation shows that with the magnets and suspending wires now available we could anticipate an instrument which would be just about sensitive enough to respond, in the average magnetic latitude, to the non-uniformity of the earth's main field. The additional lack of uniformity arising from diurnal variations, or even magnetic storms, is by comparison small, because the amplitude of the variations is only a small fraction of the total field, and they are very widespread in character; consequently, they would fail to disturb the instrument appreciably. We should therefore be able to attribute the distortion observed solely to local magnetic features, apart from a nearly negligible correction for general earth's magnetism. The effect of changes of temperature also would be comparatively small, for they would be proportional to the variation of field intensity over the limited space occupied by the suspended system, instead of to the full intensity at the station. In the gravity torsion balance they are, in fact, negligible, and they could be made equally so here.

ELECTRICAL METHODS

I have left until last reference to electrical methods, not because they are of less importance, but because I am less familiar with them, and could not speak with any of the authority which comes from practical experience. Accordingly, I shall simply use this opportunity of directing special attention to the work of the Imperial Geophysical Experimental Survey ("The Principles and Practice of Geophysical Prospecting": Cambridge University Press, 1931), which operated in Australia from 1928 until 1930. This survey, under the leadership of Mr. Broughton Edge, whose extensive experience of electrical surveying is well known, was concerned chiefly with electrical investigations. It is, I think, no exaggeration to say that the report is the most comprehensive and authoritative treatment available of the subject of electrical surveying.

FUTURE OF GEOPHYSICAL SURVEYING

Much, however, remains to be done in all branches of geophysical surveying, in order to put it on a more secure basis and to determine more certainly the scope of its applications. It must be confessed that until quite recently practically all the work was being done by German investigators. By its nature the work is necessarily costly. Except as regards some aspects of the construction and improvement of instruments, it cannot be confined to a laboratory; and, with the same limitation, it can rarely be an individual effort. Effective research in the field implies adequate scientific personnel, transport, labour, and materials, in addition to the instrumental equipment. If we are to make substantial progress in this direction, the expense must be faced.

I recognise that it would be foolish, as well as useless, to press now for the initiation of any costly schemes. But it is permissible to hope and believe that the subject will not be completely neglected in these difficult times. We can occupy the lean years in making ourselves more familiar with what is already known, and in conducting new investigations on a modest scale—as, indeed, is being done at South Kensington by the Imperial College with the assistance of the Department of Scientific and Industrial Research. Then, when the fat years come, and the mining industries again call for the help of geophysicists, we shall be found, at least, not wholly unprepared.