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1948

Advances in Geophysical Prospecting

A. F. M. HARFORD

RECENTLY 50,000 square miles of the ocean bed off the Bahamas have been surveyed from the air by a commercial geophysical prospecting company for a group of five of the largest oil corporations. The oil companies are hoping to find general indications of regions where oil may be found. These areas they will later survey in greater detail, using more sensitive methods. An aeroplane flies low over the sea, usually only a few hundred feet above the water, with a complicated magnetic detector suspended behind and beneath it in an enclosed bomb-shaped container nicknamed a 'bird' or 'doodlebug' (see Plates 10-12). Variations in the total component of the earth's magnetic field down to one part in 2,000 are detected as changes in current and voltage in electrical circuits associated with mumetal sheets, the metallic sheets acting as a variable inductive coupling between two circuits. Mumetal is a nickel-iron alloy which is extremely sensitive to small variations in ambient magnetic fields, with resulting changes in its magnetic properties which are easily transformed into electrical impulses and recorded photographically. Variations in the earth's vertical magnetic field are, then, ultimately measured as changes in position of a line trace on a photographic negative.

In reconnaissance prospecting from the air, very large areas can be surveyed more quickly and less expensively than by any other means, and this is why it is popular for rapid initial surveys. It is most important, however, to know the exact position of the aeroplane, and this is located precisely, when flying over water, by using the 'Shoran'

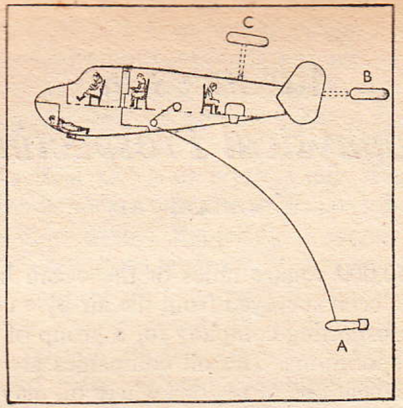


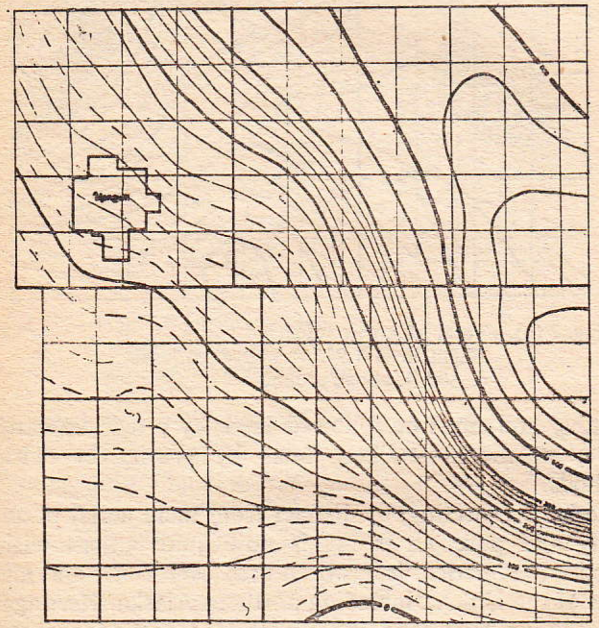
Fig. 1.—Diagram of aircraft in flight showing the position of the 'bird' (A) and alternative mountings (C and B) for the magnetic air detector units.

navigational technique: with four cutters acting as wireless stations transmitting radio signals to the aircraft. These signals are recorded alongside the magnetic trace on the same photographic strip so that they can be interpreted to give the position of the aircraft at the time of passing over any magnetic anomaly. The aeroplane flies on a level course up and down parallel lanes over the ocean, automatically recording the magnetic anomalies and their geographical position so that they can be studied at leisure on the ground by experienced geologists, who will decide if the anomaly indicates oil-bearing or associated rocks.

The magnetometer used in this particular survey was developed from M.A.D., the magnetic airborne detector designed during the war for searching for submarines from the air, and the E.F.S. system used in harbours for testing the effectiveness of degaussing equipment aboard ships. Actually the Russians were the first to attempt aerial surveying when they devised a method based on the change of inductance in a coil of wire, due to magnetic anomalies, but this was not sensitive to variations of less than onetwentieth of the earth's field and is clearly of no use in oil prospecting, although it did help them discover some large iron ore deposits.

On land the magnetic method is the quickest and cheapest for surveying, and this remains true in the air, with the added advantage that small local variations and anomalies are non-effective and eliminated, leaving only the deep structure effects, which are then relatively more pronounced, and it is deep structures which will be connected with oil pools. Even so this initial survey of the Bahamas took six to eight

Fig. 2 (a).—Magnetic Maps from Ground and Airborne Surveys of the Mangum, Oklahoma, area



Total Magnetic Intensity: Observations taken at ground surface

Note the town of Mangum in the upper left-hand quadrant of each map (see also pp. 12-4).

Contour line heights in type in figs. 2a, 2b, 2c, 2d

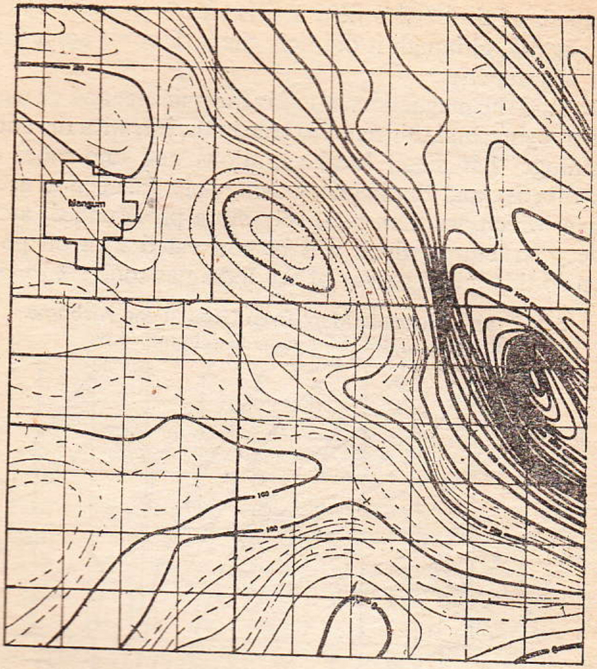


Fig. 2 (b).—Total Magnetic Intensity
Flight level 1,935 ft. above sea level
c. 300 ft. above ground

months, and must be followed later by a tedious careful survey of the most likely areas by gravity or seismic methods.

Aerial prospecting, as distinct from mere aerial photography and pure surveying, is now quite an established practice in America. It has been used over Texas and many parts of the U.S.A., including northern Alaska. Here again, when flying over land it is important to find the exact position of the aircraft and 'split-field' photographs are usually taken as the aeroplane flies over the ground. These are later correlated with accurately known ground surveys

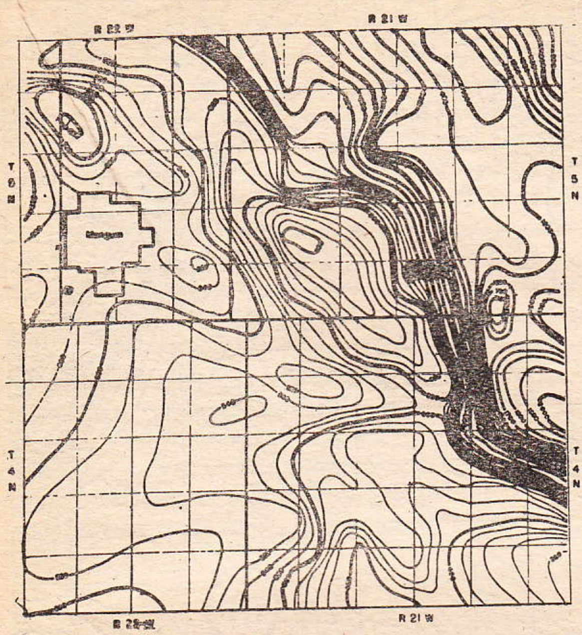


Fig. 2 (c).—Total Magnetic Intensity
Flight level 2,935 ft. above sea level
c. 1,300 ft. above ground

of hills and similar landmarks. Flying at a thousand feet, several hundred miles of survey can be recorded on one continuous strip. Figure 2, A,B,C,D, gives a set of magnetic traverses taken at various heights above the ground over the same strip of ground in Oklahoma. The characteristics can be interpreted geologically and the information gained will be about the major structure of the rocks with increasing depth as the height of the survey increases. Thus the survey at ground level will give the position of any unusual rock structures quite close to the ground surface. That taken by an airborne magnetometer at 300 feet will

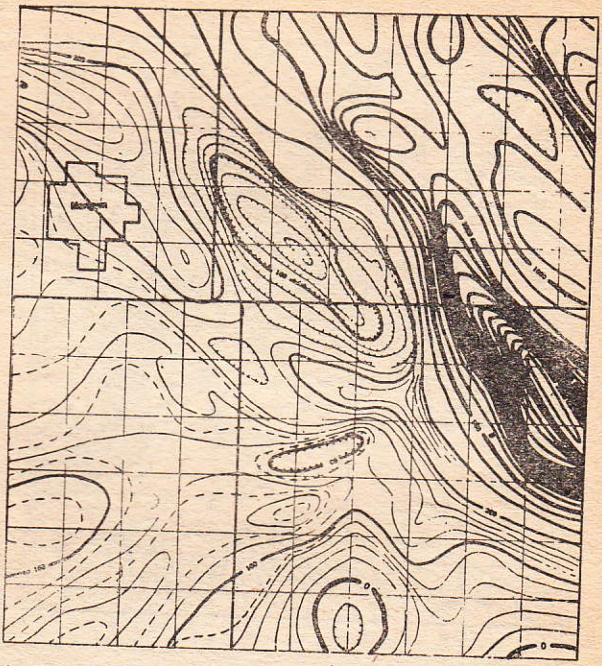


Fig. 2 (d).—Total Magnetic Intensity
Flight level 7,935 ft. above sea level
c. 6,300 ft. above ground

concern major rock structures rather further beneath the surface, i.e., more deeply seated structures as the geologist would say. Similarly the surveys at progressively increasing heights give the general rock structures at increasing depths. With increase in height, however, the absolute value of the anomaly detected will rapidly decrease and the geological interpretation becomes progressively more general and less detailed. The utility of the method is, however, clear since it gives a measure of control of the depth of the rock structures which are being investigated.

Geophysical prospecting, geophysics for short, is a commercial science which has developed so rapidly in the last two decades that it is now by far the most important technique for the discovery of new oil-fields, and uses some of the most precise and sensitive apparatus in science. It often surprises pure physicists when they find out how sensitive these geophysical instruments are. For instance the three types of gravitational instruments, the torsion balance, pendulum, and gravity meter, have all reached their ultimate practical sensitivity. Gravity meters will detect the change in gravitational attraction on raising them from a road surface to the kerb, say about four inches. They can now be made sensitive to vertical positioning to within an inch and no field surveys, in regions where oil may be found, are better than this, so there is no sense in designing more accurate equipment. Torsion balances similarly are so sensitive that the limitation in their use is the practical one of corrections for local terrain gravity attractions caused by slight hillocks, mounds, depressions and embankments.

Eötvös, in the 19th century, and Schlumberger, since

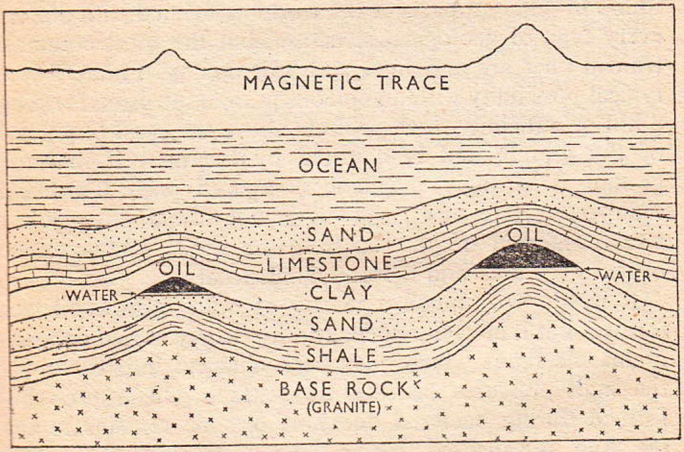


Fig. 3.

1910, were the first to be interested in applying physics to geological prospecting, but geophysics hardly began until the 1920's, since when it has expanded at a furious pace. Big business found that geophysics would detect new oil-fields with greater certainty than any other means and, as they found this new technique increased their profits, they lavished money upon it for many years. As more money was spent on better instruments and interpreters the successes increased until, in fifteen years, the gravity meter for instance reached ultimate sensitivity. Between them the physicists and geologists discovered numerous oilfields with relative ease and seemed to find the pace invigorating. Certainly the oil industry has created geophysics, which even now is little used outside problems connected with oil.

The problem in oil prospecting is to detect and locate buried geological structures which may contain oil or are often related to oil-saturated sands. Broadly speaking, oil may occur where there is a regional or local anticline beneath the surface, with a great thickness of marine sedimentary deposits above it. Oil pools have indeed been found in different parts of the world associated with almost every type of geological structure, but the most common fruitful ones are anticlines and 'salt domes'. Figure 3 is a typical possibility with an igneous granite intrusion forming a hill or anticline which projects above the local base level of the granite and is detected by the aircraft, because granite is strongly magnetic compared with the usual sediments. Here again the oil is not found directly but merely inferred or guessed from the rocks known to be beneath the area and the anticlinal structure.

It is still very much a matter of opinion how oil was formed, but it always associated with deeply buried deposits of marine muds which have been changed into shales by the high pressures beneath the surface. Oil is probably formed during bacterial decay of organic remains in the sea mud, is squeezed free as the mud turns to shale, and tends to escape to the surface. On its way up the oil prefers to travel through sands, if possible, for they are the most porous and permeable rocks. If there happens to be an upward bend in the sand strata, such as an anticline, which is capped by impervious layers of limestone or clay, the oil is trapped and gradually accumulates into a large commercially valuable pool. It is impossible, as yet, to detect oil directly from the surface, so effort is directed to finding these buried hills and estimating from known geological data for the region whether there is a reasonable chance of finding oil there.

The geophysicist sets out, then, to determine structural differences inside the upper part of the earth's crust by observations with his equipment at the surface. Variations in density, magnetic, electrical, elastic and radio-active characteristics are detected with appropriate apparatus and used to estimate the depth of the boundaries between the various rock layers. Gravity meters and torsion balances detect minute changes in mass distribution beneath the surface. Vertical magnetometers find any strongly magnetic minerals, whose magnetism is almost invariably due to their magnetite content, and hence any substances usually associated with those deposits. There are several electrical techniques which, although not especially sensitive, are quick and easy to manipulate. Rock resistivities, to either direct or alternating current, and any natural earth currents due to the self potentials of oxidising sulphide ore bodies, give the most information, and, when used together in well-logging, they will detect the sand layers likely to contain oil, provided they are not too thin. Seismic waves are sensitive to variations in density and elasticity of the rocks in which they are travelling and have been widely used for many years (see *What the Earth is Made Of* in *Science News* 8). Explosives are detonated in shallow holes in the ground and the time of arrival of reflected and refracted elastic (seismic) waves at distant points gives information about the rocks nearby. The method is very sensitive where it can be used, and is liked since it allows some control by varying the type and position of the explosion. The recently introduced radio-active technique (see below) has specialised applications already, and may be more widely used later when thoroughly proven.

These geophysical methods are most powerful when two or more are used in conjunction. Sometimes a rapid method such as the magnetic will be used for the survey and then a sensitive one, such as reflection seismic, for determining the detail in an area. It may also be combined with a relatively ambiguous method, neither of them precise in themselves, but together they cross-eliminate all the possible interpretations except one. A fine example of this was the discovery recently of the extension of the Rand banket which gave the new Orange Free State gold field. Magnetic and torsion balance surveys in co-operation with skilled geological interpretation gave the clues for this new mine.

Slowly geophysics is extending its applications, and seismic waves are now used in exploring river valleys and buried channels. Typical problems may be finding suitable hard rock on which to place bridge piers or site dam foundations – the huge new dam on the Waikato in New Zealand for instance. If geophysics had plotted the path of the old Mersey river, which probably changed its course near the estuary several thousand years ago, a lot of the troubles encountered when the preliminary tunnel met water-logged sands in the old bed of the river would have been avoided.

A few special minerals and ore body deposits can be located, gold as mentioned above is an example, but at present most of the minerals which might be detected are not sufficiently valuable to pay for costly geophysical methods. Large iron-ore deposits were found by means of magnetometers in Sweden and Russia, but iron ore is relatively abundant, which, combined with its cheapness, means it is rarely sought by geophysicists. Placer or alluvial sand deposits sometimes contain gold, and the sands may be found by magnetic traverses (if they are the so-called 'black sands') or by electrical and gravity traverses, across the old river beds of previous and present-day streams. Galena, graphite and the fine silica sand used in making the best grade optical glass can be detected and distinguished by combining electrical and gravity traverses. Graphite and good quality sand are sufficiently valuable to prospect for them. During the war many minerals were in short supply in the States, even with the increased output, and new sources of chromite and bauxite were sought and found by gravity surveys, the chromite in Cuba and the bauxite in Arkansas. Sulphur is sometimes found in huge masses in the cap rocks just above 'salt domes' along the Gulf coast. Salt domes are a favourite oil cache in that part of the world, usually located by seismic and gravity methods, and it is surprising to realise that it is economically worthwhile to search for such a cheap mineral as sulphur, although, of course, where it is found it occurs in very large quantities relatively pure.

The geophysicists' quest is, however, almost always for oil, and nuclear physics has found a minor application in radio-active well-logging, the latest technique used in looking for oil. Since oil is found only in sedimentary rocks any difference in radio-activity between sandstones, clays, shales and limestones will be a valuable way of distinguishing between them. Common sediments in order of increasing activity are: coal, salt, limestone, sandstone and shale. Shale often contains potassium micas and the salt deposits may also contain potash. In both cases radio-active potassium may be a vital clue in detecting the different strata. Rock layers with uranium or radium will be found as well. All the work is aimed at trying to find the sand strata if there are any, since that is where the oil will be.

The method is very similar to Schlumberger's resistivity logging. A long metal casing or tube contains two Geiger-Müller counters, complete with amplifiers, so that changes in radio-active intensity are magnified, sent up the cables as electric impulses and recorded at the surface. The metal tube is let down the well on the end of a very long cable and then pulled up by winch at a steady rate, recording the radio-active intensity continuously. 1,500 feet per hour is a common rate for withdrawing the detector and wells down to 12,000 feet have been logged.

Only gamma rays are sufficiently penetrating to pass through the metal well casing and container – almost all wells are lined with metal tubing to prevent the sides collapsing and filling in the well hole. Changes in radio-active intensity give a clear indication of a sand-clay boundary, and this method has advantages over the usual electrical logging since old wells can be explored through transparent casing in order to detect any oil-bearing strata which may have been missed and overlooked when the well was first drilled. Further, where oil or salt in the drilling mud at the bottom of the well make the electrical method useless, radio-active logging is quite unaffected.

It was more recently realised that more information can be got by actively bombarding the rocks with neutrons.

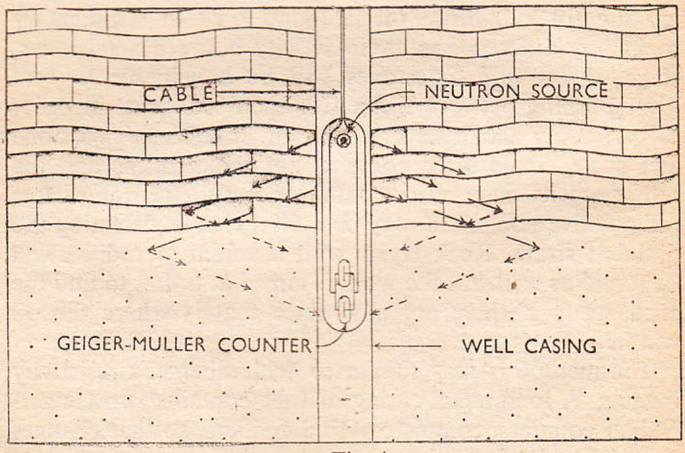


Fig. 4.

This combined with the natural intensities as found above eliminates many of the ambiguities. Indeed the neutron attack is the nearest approach to the direct detection of oil. Fast neutrons are only slowed down appreciably by atoms of approximately the same mass, i.e., hydrogen, which means, in practice, in oil wells, water or oil. When they have slowed down sufficiently the neutrons are captured by atoms in the rock minerals which then become artificially radio-active, and, being unstable, may emit gamma rays which are picked up by the detector. The neutron source, a mixture of radium and beryllium, is at the upper end of the tube and the detector at the bottom so that as the cable is hauled up the detector passes through regions just previously activated by neutrons. Figure 4 is a sketch of the technique. The combination neutron – gamma-ray logs give a distinction between sandstones and limestones, which are hard to distinguish, and in general between porous, liquid-filled regions and those which are non-porous.

The airborne magnetometer and radio-active well-logging are only the latest developments in looking for oil, which is always somewhat of a gamble. No interpretation of geophysical measurements is ever better than a good risk, a guess made with the help of local geology. Since, however, new wells are continuously being found to keep pace with the ever-increasing world consumption of oil, geophysics can well be said to be an efficient and successful young science.

STANDARD TEXT-BOOKS

(but hardly suggested as light reading)

C. A. Heiland. *Geophysical Exploration* (Prentice Hall & Co., 1946),

Jakosky. *Exploration Geophysics* (Times Mirror Press, Los Angeles. 1940).

L. L. Nettleton. *Geophysical Prospecting for Oil* (McGraw Hill & Co., 1940).

OIL PROSPECTING

SEISMOGRAPHY

Explosive charges are set off in holes drilled in the ground, to obtain a record of the speed and character of the resulting vibrations as they are reflected back from successive layers of subterranean rock. Interpretation of the records (see *Science News* 8, page 63) leads to detection of oil-bearing strata.

The following eight plates show the difficulties of ground prospecting in the quiet backwaters and swamps around Lake Arthur, Louisiana. (*Plates 1 to 9 by courtesy of the Standard Oil Company, N.J.*).

Plate 1. Quarterboats moored under trees draped with Spanish moss constitute a floating base for the entire field party.

Plate 2. Setting off for the day's work. A centrifugal pump with out-board motor head is too heavy for one man.

Plate 3. All loads are limited to thirty - five pounds per man, and there are frequent halts for rest. At times the men may sink up to their knees in mud.

Plate 4. A hydraulic drill bores holes as deep as eighty feet to receive the explosive, when the operational site is reached. Water for the drill is pumped from a slush pit, easily blown in the swamp with dynamite, using the pump seen in plates 2 and 5.

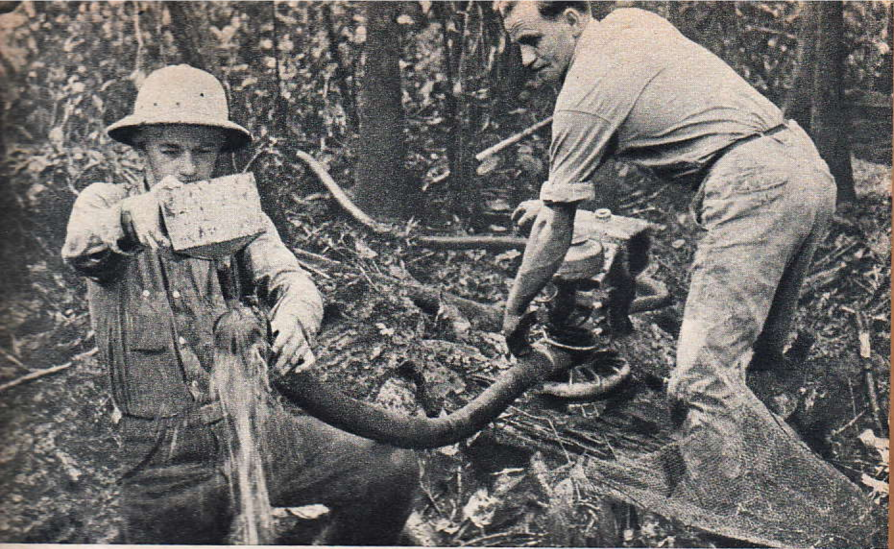


Plate 5. Priming the water-pump by pouring water into the intake head, which will then be dropped into the slush pit. The pump, under the hands of the man on the right, drives water through the line in the background to the drill (plate 4).

Plate 6. Meanwhile, the connections on the amplifiers which transmit the impulses from the pick-up microphones in the field to the recorder itself are checked over. The final record is a photograph of galvanometer movements.

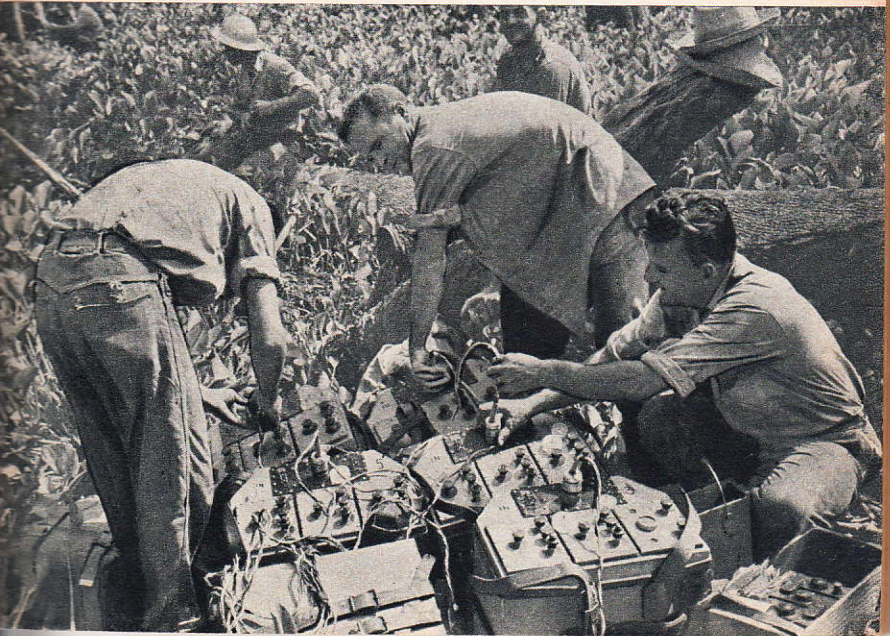


Plate 7. A lightproof changing bag is the portable dark room in which film from the recorder is developed immediately after the explosion has been made.

Plate 8. Examining the developed seismic record of the earth vibrations.

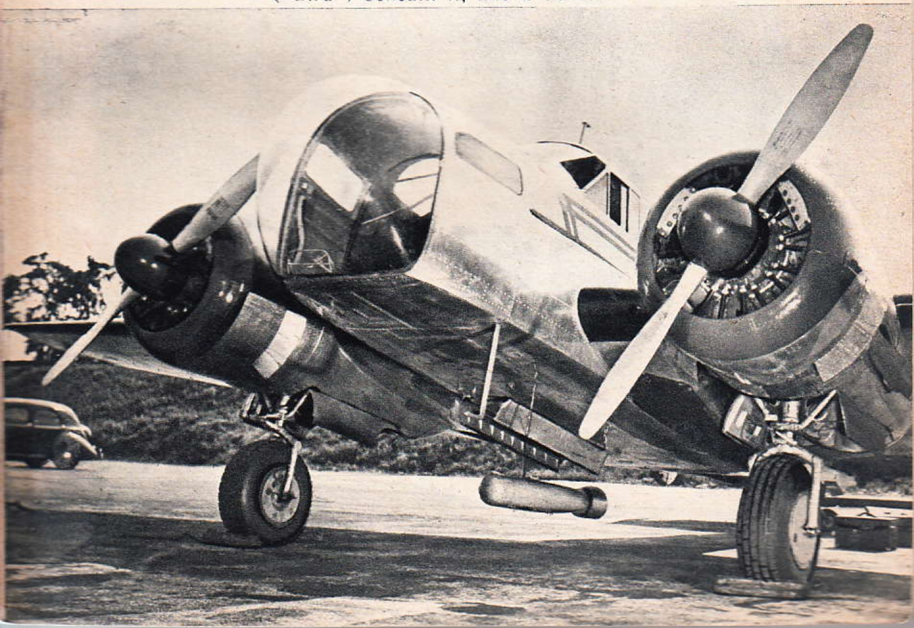
OIL PROSPECTING

MAGNETOMETRY

(See *Advances in Geophysical Prospecting* page 9).

Plate 9. Another way of studying underground rock is by measuring the strength of the earth's magnetic field at different points. Here a ground surveyor is making a measurement of the pull of the rock beneath his feet on a magnet inside the box of his instrument.

Plate 10. A modern improvement is to make the magnetic survey by aeroplane. A twin engine Beechcraft of the U.S. Geological Survey carries a special aerial magnetometer (' Bird ') beneath it, like a bomb.



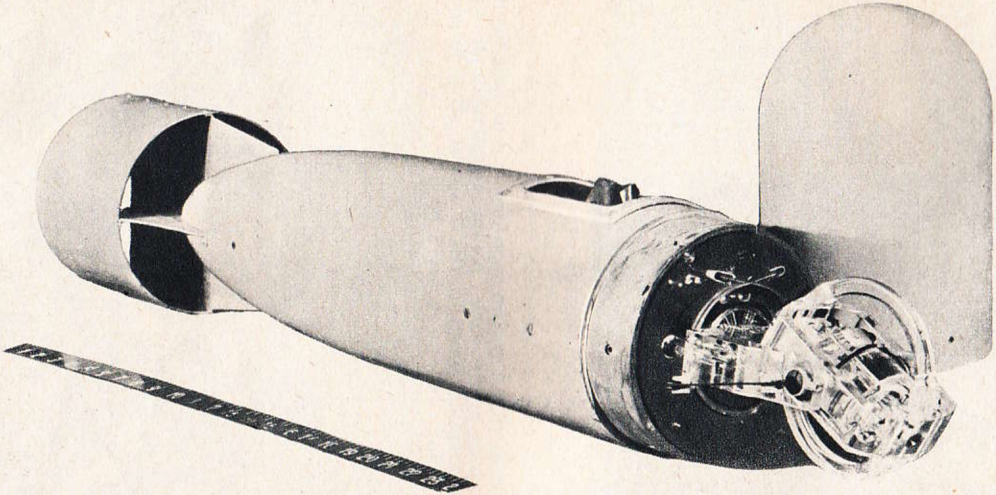


Plate 11. The " Bird " with its nose removed to show the intricate gyro-compass mechanism which orientates it in flight.

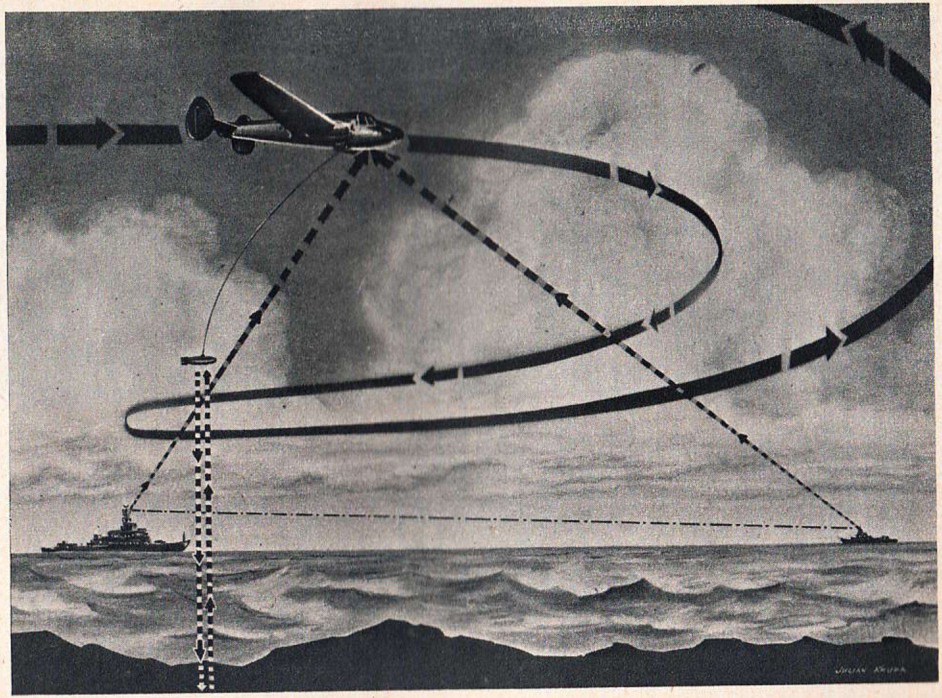


Plate 12. Here is the plane in flight, guided by Shoran stations on anchored ships, with the magnetic detector let out below it. The aircraft takes a circular course around the 'drift' station (left) and records its position by reference to the 'rate' station (right), while the detector makes a continuous record of the magnetic intensity due to under-lying rock (see maps on page 11). Shoran is a method of navigation by radio. (*Plates 10 to 12 by courtesy of 'Flying'*).