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DEEP BOREHOLE SURVEYS
AND PROBLEMS

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DEEP BOREHOLE SURVEYS AND PROBLEMS

BY

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PREFACE

The amount of trouble, litigation and random speculation that could be avoided by a correct knowledge of the course of deep boreholes is immeasurably great. It is generally agreed among those most concerned that the deep borehole which does not deviate from its intended direction has yet to be bored. Bearing these significant facts in mind I have attempted in the following pages to trace the evolution of modern borehole-surveying devices and add various problems relevant to strata location and orientation.

Since most of the world's deep borehole projects are outside the British Empire I have supplemented my experience and observations by information from many and varied sources. In this respect I have been most generously aided by many workers in America, Germany, Russia and elsewhere, and I hope these are all sufficiently acknowledged where the respective transcriptions appear in the text. In particular I am indebted to the several acute and vigorous bodies of oil-field investigators centered about Oklahoma and the Gulf Coast in America and the Rumanian societies on this side. Some methods of borehole exploration have not been dealt with here either because they are shrouded in commercial secrecy or because they do not appear to add very materially to the advancement of the art.

Generally speaking the present geological engineer does not seem to be enamored of the highly ingenious and exact suite of post-war instruments, being in many cases content to sacrifice precision to rapidity, ease and cheapness. For these reasons the old and tried acid-bottle and similar fluid methods still hold the field in point of numbers, though the gyrocompass and multiple photographic methods

have entered the lists with the weapons of accuracy and certainty which alone can solve the problem satisfactorily.

The history of our subject has not always escaped the stigma of charlatanry and perhaps it has often deserved it. With the growing application of established scientific principles and the subsequent checking and verification of these by other boreholes, shafts, etc., we may regard the day of skepticism as vanished. There is now arising an insistent and ever increasing desire for frankness, clarity and truth in borehole investigation which must one day achieve the universal respect accorded an exact science. Built on such foundations it is indeed difficult to imagine this ideal failing.

M. H. HADDOCK.

LEICESTER, ENGLAND,
September, 1931.

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DEEP BOREHOLE SURVEYS AND PROBLEMS

CHAPTER I

DEVIATION AND ITS CAUSES

The primary purpose of a borehole survey is to determine the extent of the borehole in length and deviation. The deviation is surveyed in angular deflection in amount and bearing; the amount relative to the intended initial direction and the bearing with respect to the local meridian or any other fixed reference mark.

In many boreholes frequently only the amount of deflection suffices. Thus in exploratory borings in unknown measures the direction of deflection is of less value than the degree of deflection, owing to the remainder of the data being absent from our conclusions. However, for a correct decision respecting the strata penetrated, this knowledge is unconditionally necessary.

Still more important are these determinations when the hole has to hold a pumping or bailing plant, as in certain petroleum borings. Here the longevity of the borehole is in considerable degree influenced by any noteworthy deviation from the plumb. Rods, or the bailing rope, continually chafe in the same part of the casing; in a short time it becomes seriously injured. That all deep boreholes deviate—and by deep boreholes we imply all those over 1,000 ft. in extent—is established beyond any doubt, and indeed much shallower boreholes deviate in more or less degree.

Dr. Otto Stützer of Kiel has recently cited a case¹ where two boreholes in the Moreni oil field of Rumania, com-

¹ *Z. deut. geol. Ges.*, Bd. 81, Heft 10, p. 536 1929.

menced vertically and at a distance of 60 m. apart, actually met at a depth of 850 m.

About 25 years ago interest in the survey of boreholes was quickened by a series of very ingenious contrivances which were invented to cope with borehole deviation. Borings hitherto considered vertical were now subject to doubts. In 1908 Joseph Kitchen presented the results of his surveys of some 22 deep boreholes on the Rand before the Institution of Mining and Metallurgy¹ which stimulated a wide discussion and was supported by many other instances of deflection. He surveyed the dip of the holes at intervals of about 500 ft. and averaged his results, which method, though not precise, sufficed as an indication of the great deviation in this area. With an average total borehole depth of 3,370 ft. he found an average horizontal displacement of 1,165 ft. with an average lowest depth of survey points of 3,015 ft. He shows in Table I figures of average angular deviations obtained by instrumental survey in the holes.

TABLE I.—AVERAGE ANGULAR DEVIATION IN RAND BOREHOLES¹

Depth, feet	Nos. 1 to 8, degrees	Nos. 9 to 16, degrees	Nos. 1 to 16, degrees	Nos. 17 to 22, degrees	Nos. 1 to 22, degrees
500	4.7	2.5	3.6	8.8	5.0
1,000	10.6	9.2	9.9	15.6	11.4
1,500	20.2	19.7	19.9	20.2	20.0
2,000	24.9	27.8	26.4	25.4	26.1
2,500	27.3	30.1	28.7		
3,000	32.9	34.4	33.6		
3,500	42.5				
4,000	47.7				

¹ After J. Kitchen by permission of the Institution of Mining and Metallurgy.

These tend to oppose the general rule that inclined strata exaggerate the deviation which, however, may be a local circumstance. The accompanying displacement is shown in Table II.

¹ The Deviation of Rand Boreholes from the Vertical, by Joseph Kitchen, Session 1907-1908.

TABLE II.—AVERAGE HORIZONTAL DISPLACEMENT IN RAND BOREHOLES

Depth, feet	Nos. 1 to 8, feet	Nos. 9 to 16, feet	Nos. 1 to 16, feet	Nos. 17 to 22, feet	Nos. 1 to 22, feet
500	15	10	10	35	20
1,000	85	70	75	145	95
1,500	210	190	200	290	225
2,000	400	390	395	485	420
2,500	610	635	625		
3,000	860	910	885		
3,500	1,150				
4,000	1,485

FIG. 1.—Sketch showing curves of boreholes and amount of horizontal displacement at various depths. (a) Vertical projection. (b) Horizontal projection. (After Joseph Kitchen.)

The displacement is thus in these cases proportional to the square of the borehole length and it usually tends to describe a right-handed or clockwise curve. In one case the displacement was 2,573 ft. away in a borehole depth of 4,419 ft., *i.e.*, a vertical depth of 3,288 ft. Mr. Kitchen

grouped his results graphically about the same vertical, giving the remarkable suite of horizontal displacements shown in Fig. 1a and the accompanying angular deviations shown in plan in Fig. 1b.

All other influences considered equal, the amount of deviation depends a great deal on the method of boring. Many are of the opinion that the greatest deviation is obtained in the rotary system yielding cores as in the shot, calyx or diamond processes, and the least in the percussion systems particularly the free-fall systems. In a recent¹ statistical survey of results which appear to support this contention the data yielded from 21 boreholes was as follows:

TABLE III.—SUMMARY OF SOME RUMANIAN AND RUSSIAN BOREHOLES USING DIFFERENT METHODS

Method of boring	Number of boreholes	Depth, meters	Most favorable case	Worst case	Remarks
Turbine borer.....	..	580	1° 20'		In the same strata
(Kapeljushnikov).....	4	578		2° 55'	
Rotary system.....	4	840	4° 30'		
	..	822		11° 0'	In the same strata
Rod percussive.....	1	480	1° 20'		
Rope percussive.....	1	606	3° 10'		
American rotary.....	10	580	9° 20'		
	..	700		25° 0'	
American-Chield rotary	1	595	5° 10'		

However, this point is very debatable. The diamond-drillers claim that diamond-drilled holes can not drift as much as holes drilled by other methods because the core barrel nearly fills the hole. In hard rock the core barrel normally occupies all but $\frac{1}{16}$ in. of the diameter of the hole.

The rotary drill prevents the hole from drifting as much as would occur by other methods by using at the bottom a long steel drill collar of a diameter nearly equal to that

¹ A. L. Schachnazarov, Engineer "Asnef" Oil Trust, Baku, in *Petroleum*, No. 23, p. 772.

TABLE IV.—COMPILED DATA FROM 255 CALIFORNIA BOREHOLES
(After Anderson)

Number of boreholes	Measured depth, feet	B			C			D			B : D per cent
		Maximum, feet	Minimum, feet	Average, feet	Maximum	Minimum	Average	Maximum, feet	Minimum, feet	Average, feet	
255	500	37	0	8.7	8° 20' 14.5 ft. per 100	0° 00'	2° 09' 3.8 ft. per 100	114	0.0	10.6	82
255	1,000	131	2	30.2	15° 30' 26.7 ft. per 100	0° 00'	3° 05' 5.4 ft. per 100	131	0.0	34.4	88
243	2,000	455	9	89.2	34° 15' 56.3 ft. per 100	0° 10' 0.3 ft. per 100	4° 05' 7.1 ft. per 100	457	1.5	104.5	85
219	3,000	845	9	119.5	32° 15' 53.4 ft. per 100	0° 30' 0.9 ft. per 100	6° 42' 11.7 ft. per 100	850	47.0	204.9	58
163	4,000	1,036	6	236.5	40° 15' 64.6 ft. per 100	0° 30' 0.9 ft. per 100	9° 00' 15.6 ft. per 100	1,285	77.6	307.7	76
104	5,000	1,752	29	396.8	52° 00' 78.8 ft. per 100	0° 30' 0.9 ft. per 100	13° 44' 27.2 ft. per 100	1,815	91.0	515.9	77
38	6,000	2,200	74	589.4	65° 15' 90.8 ft. per 100	2° 30' 4.4 ft. per 100	22° 35' 38.1 ft. per 100	2,228	357.0	793.1	74

B Horizontal distance between the borehole mouth and a vertical through the measured point.

C The inclination angle in degrees and feet per 100 ft.

D The total deviation, assuming the deviations are always in the same direction.

of the hole.¹ On the other hand, percussive borers claim that curvature is more easily detected and rectified by a reciprocating action especially by a free-falling tool.²

With regard to rotary boreholes a perusal of Table IV will well repay the reader. The table is taken from a compilation³ covering 255 California boreholes bored by the rotary system. The total depth was 1,158,542 ft. and the total number of measurements 13,150. As additional proof of this almost universal deviation of deep holes we may cite the recent researches of D. R. Snow and H. B. Goodrich⁴ carried out upon some 90 wells in the Seminole oil field of America. These holes have been drilled since 1927 and show the data collected in Table V.

TABLE V.—SUMMARY OF RESULTS OF 90 OIL WELLS
(After Snow)

Number of wells	Vertical correction, feet	Percentage of total wells surveyed	Maximum possible horizontal drift, 4,500 ft.
20	Less than 25	22.22	474
9	From 25 to 50	10.00	669
28	From 50 to 100	31.11	943
24	From 100 to 200	26.67	1,327
4	From 200 to 300	4.44	1,615
5	Over 300	5.56	
—			
90			

Total surveyed: 377,719 ft.

Total vertical correction: 9,290 ft. (per well, 103 ft.).

Average angle of deflection: 12 deg. 44 min.

In some relatively shallow boreholes, as in the concentric circumferential suites of boreholes preliminary to sinking shafts by the freezing process or by cementation, extreme accuracy of data respecting the course of the holes is of

¹ Diamond Drilling, U. S. Dept. Commerce, Bur. Mines, *Bull.* 243, p. 60.

² Cf. *Organ des Verein der Bohrtechniker*, No. 23, p. 279, 1910.

³ A. Anderson of Fullerton, California, in *Oil Weekly*, October, 1929.

⁴ See also *Oil Gas Journ.*, p. 32, Mar. 14, 1929, and p. 218, Apr. 4, 1929.

great importance. It is here that we find the greatest advancement in the technique of borehole-survey apparatus.

This is significant not only because the proximity of other boreholes greatly increases the possibility of deflection but ignorance of the actual courses of the holes here would give rise to great trouble and expense later on; and perhaps

FIG. 2.—Course of a full suite of boreholes for a freezing shaft (depths in meters).

disaster when encountering the unsolidified gaps between widely isolated frost walls or cementation zones. These possibilities will be apparent from a perusal of Fig. 2, which is an actual survey of the course of such holes previous to sinking operations.

As the shallower seams and veins are won in the world's mineral fields it is manifest that deep prospecting holes to

fresh deposits will become more common. In these daily growing cases, especially in those situated near property boundaries, legal disputes will be settled by the results of borehole surveys. Again the deep borehole being the most straightforward and direct verification for any completed geophysical survey, any doubt which may arise as to (1) mapped lenses being missed in the borings, (2) the nature of the body surveyed aboveground (3) its extent, etc., can only be verified by a thorough instrumental survey of the boreholes concerned. Since deviation of a string of tools may take place in the ultimate up to and beyond 60 deg. from the originally intended direction,¹ and boreholes are now attempting the enormous depth of 10,000 ft. and more, the great significance of deflection surveys is obvious.

Horizontal and inclined boreholes, particularly upward inclined holes, deviate sooner and to greater extent than vertical ones.² They also give rise to a special set of deflection apparatus, but, generally speaking, results of surveys of such holes are not so reliable as those of vertical ones. Thus most of our remarks will apply to deep vertical boreholes.

There is no doubt that the best evidence of initial or subsequent deflection in boreholes is to be obtained from the precision with which the working of the entire system of boring is checked. The onus rests almost entirely upon the boring master and personnel, chiefly because the site is usually situated far from the headquarters of the boring company and its direct command. Thus the master borer should be selected mainly on his experience, skill and ability, other qualifications notwithstanding. There is more responsibility upon him than in any other sphere of technical work. This applies more in foreign and remote lands. Thus it is important that all hands graduate in the actual school of practice from the meanest position upward.

¹ Kitchen, *op. cit.*, mentions one deflection of 66 deg.

² JUSTICE, J. N., CHANNING, PARK, *Trans. Inst. Min. and Met.*, Vol. 12, p. 319; *Proc. Lake Superior Min. Inst.*, Vol. 2, p. 23, 1894.

The modern tendency to standardized reserve parts and processes, also the recent step toward normalizing as many of the movable or removable parts as possible will tend to unify knowledge of and the results of deflection. It will tend toward closer correlation of data and more exact anticipation of deviation and therefore more successful handling of the problem when it arrives.

This will be aided by duplicating staffs too, such as smiths and fitters in diamond boring and tool dressers in chisel boring. They must always have a clear rinsing circuit with the borehole base, especially in rapid-stroke boring as by the Raky method. They will need exceptional skill in rope boring.

Another essential adjunct to the detection and elimination of curvature lies in the supervision of the water circuit by the master borer and the leading hand and by maintaining a keen supervision for traces of oil or minerals. This is closely connected with the amount of water struck in the borehole, the pressure on the rinsing pumps, etc., so that they may have to decide upon the cutting off of water according to the strata pierced or its increase under certain conditions; or even decide to change the type of borer. In their responsible positions as borehole casers and core extractors much will be learned respecting deflection which can scarcely be described in writing.

The best aid to all of these observations will be found in a thoroughly checked and entered log of progress, a study of which will assist very materially in reading any progress graph which may be attached in the derrick house. These provide pictorial and descriptive checks on the tendencies to deviate and often their causes. Strata profiles and sections should be kept as well as vertical sections. Finally the care of the actual samples, or cores, is absolutely essential as the final check on any adduced ideas as to deviation, etc. It will be seen that the requirements demanded of a good master borer are so exacting and varied that the systematic training of such a person is a really essential

need. Unfortunately, apart from Rumania, there are no actual master borers' schools in Europe.

The Detection of Incipient Curvature in Boreholes.—Suspected curvature of the rods may be checked by noting the following surface indications of the deflection. It must be noted that these indications may be entirely absent, making the curvature untraceable without instrumental means.

a. The uneven wearing of the chisel or crown bit due to encountering unequal resistances at the floor of the hole. The contact surface of the tool tends to become inclined due to excessive wear on one side. It also tends to snap off.

b. Lateral abrasions of the rods and brushing of the rope sides in rope boring. This is due to side wear and in the case of rigid rods will usually show the side on which curvature is occurring, *i.e.*, the "off" side.

c. Difficulty in Inserting the Casing.—Frequently the casing sticks fast as often does the boring tool owing to the curvature.

d. Scoring of the core and core box in rotary boring. This will often provide fair information as to the cause of the deflection.

e. Laboring of the Rig Gear.—The surface engine labors under the extra load, the bearings run hot and general signs of lack of uniformity ensue.

f. Study of the Progress Reports.—This often provides clues which can be reduced to curvature as the cause of variations in the progress graph.

g. Throttling of the circulating water, the circuit being accomplished in gusts and frequently hindering or loading the plant. Lesser deflections may be corrected by secondary boring or partial reaming. The borehole will thus be widened and the casing set without being influenced by the previous borehole walls. This simple remedy only applies to deflection which has been detected just after it has begun.

h. Instrumental Means. *The Anschütz-Kaempfe Acoustic Device.*—Nearly all of the many and varied devices for

surveying boreholes and many of those applied in core orientation may be used for detecting initial curvature or deviation. However, most of these are only suited to separate application, very few of them being fitted for employment during actual boring operations especially with percussive boring systems. The difficulty has been well solved by the device of Dr. Hermann Anschütz-Kaempfe of Kiel which provides an acoustic or audible warning of the initial stages of deflection. He invented this apparatus in 1915 and improved on it a few years later. It applies particularly to percussive boring but may be modified for rotary boring. It is essentially a means of detecting deviation, measuring it, and later correcting it. It has been applied successfully in both Europe and America. The apparatus as applied in borehole surveys is shown in Plate I, Figs. 1 to 5.

Figure 1 (Plate I) is a vertical section of the boring chisel bar and bit. Figures 2 and 3 are enlarged views of this section at an angle of 90 deg. to each other, while Fig. 4 shows the electric drive circuit. The hollow bit holder a holds the beveled bit a_1 below and the connection a_2 above to the rods, the dotted lines xx being the normal flushing circuit. A closed outer casing tube a_3 mounted in the hollow bit holder a holds the transmitter and the inner casing tube a_4 which is longitudinally adjustable in this by means of buffer springs b and b_1 and held by lugs c . An accumulator battery with electric motor d in the transmitter drives a worm d_1 with its wheel d_2 on support d_3 and thus the toothed wheels d_4 . Four pins e about the worm wheel d_2 engage consecutively on rotation with the finger f of hammer f_1 controlled by pressure spring g . Thus for each revolution of wheel d_2 four blows of the hammer f_1 are produced at f_2 . Toothed wheel d_4 engages another toothed wheel h on shaft h_1 and carries a screw thread barrel h_1 which can be disconnected by spring slides i , i_1 and i_2 . There is an electric contact k on slide i .

The ball and socket end l of the barrel shaft h_1 allows it to oscillate under the adjustable spring pressure pin m

PLATE I.—The Anschütz-Kaempfe deviation detector.

and m_1 held by springs n and n_1 and plungers n_2 and n_3 in cylinder o . Rod m_1 passes up into a hollow space in plunger n_2 so that when the pressure of spring n acts, pressing plunger n_2 downward, rod m_1 passes into the space in n_3 . This space has a check-valve controlled upper end p , which opens when the plunger n_2 descends and closes when it ascends, equilibrium of pressure being effected by a fine bore p_1 . The brackets q carry an electrical contact r which is closed when plunger n_2 is in its upper position (Fig. 2) and broken when this descends.

The lugs s hold the heavy pendulum t in a frame and the swing of t into casing a_4 is arrested by a stop u and in the other direction by a stop u_1 . This pendulum carries a second part of the contact k of slide i so that the positions of the pendulum t and slide i decide whether the contact k is opened or closed. The two electric contacts k and r are arranged in the circuit from the source of power d , which operates worm d_1 . These two contacts (Fig. 4) are arranged in series so that the motor is stopped if only one is switched out. This occurs as follows: The plunger n_2 continues its descent by momentum after the boring tool has struck its blow, and this compresses the adjusted springs n and n_1 , thus turning the screw spindle h_1 and disengaging it from the half nut h_2 so preventing slide i from moving. But contact r is now broken, stopping motor d and screw spindle h_1 . Plunger n_2 can only move back upward slowly, owing to the design of air valve p and the hollow space n_3 , and this is designed so that before the spindle can return to its working position and r close a new blow—assuming regular working—with a downward movement of the plunger takes place. In interrupted working, say over 20 sec. between blows which is a maximum time for springs n and n_1 , the mass of plunger n_2 and the valve p function; n_2 returns to its initial position, throws in spindle h_1 and closes the r contact. This starts motor d if contact k is also closed. The closure depends on the position of the pendulum t , for when we have deviation of the bit to the left throwing t to the right, or engaging it with stop u_1 , contact

k is open and the motor with its connections stops. If, on the other hand, the bit holder has deviated to the right (Fig. 5) the working circuit is closed, the motor actuating worm d_1 . Now worm wheel d_2 with pins e engages hammer f_1 to strike the wall of casing a_4 as each pin passes lug f . These blows on the casing are clearly perceived at the surface and counted by means of a listening earpiece on the rods or any simpler device.

At the same time as worm wheel d_2 starts, the screw spindle h_1 moves slide i to the left in opposition to the action of spring i_2 . The pendulum contacting on the slide follows this motion until it hangs free, breaking contact k and stopping motor d . Until this happens we get four hammer blows per revolution of worm wheel d_2 , so the observed total number of blows indicates to what extent slide i has moved to the left in order that pendulum t hangs free and vertical; that is to say, it is a measure of the deviation of the bit holder and bit.

The surface observer has now only to stop the boring blows from time to time and listen to the blows of hammer f_1 against the boring rods in order to ascertain the extent of the deviation.

Turning the chisel 90 deg. gives the inclination component in the plane of the reader's vision as against that of the drawing and where the component is greatest is the direction of maximum inclination. Otherwise two independent pendulums in planes at 90 deg. to one another can be used. Having got this line of major inclination the deep edge of the beveled chisel is turned to deal with it and correct the deviation.

Though the device gives only the inclination component relative to the chisel and not to the geographical position of the borehole, twisting of the rods need not be heeded so long as the transmitter does not twist relative to the chisel.

In this way incipient or initial deviations can be quickly detected and corrected. The device can, with suitable modification, be applied to rotary boring and it can also

be employed apart from the bit holder as a plumbing apparatus, the principle of acoustic signals being preserved.

However, in spite of all precautions we cannot always note at once a big and gradual curvature at its commencement from the above observations alone. The detection of a suspected curvature being essentially a surface task in the initial stages of deflection, the next procedure is to investigate the causes previous to checking the amount and direction of the deflection. The causes are numerous and often local, and in many cases are due to faulty surface conditions.

The Causes of Borehole Deviation.—*a. Incorrect Centering at Surface.*—This, though sometimes tending to right itself in such methods as the free-fall system, of course soon leads to heavy deflections.

b. Alternating hardnesses of successive layers of hard and soft rock. Inexpert handling of the drill feed whether by the multiple gear or hydraulic feed here tends to cause racing in the shaly and soft beds and laboring in the harder strata. The tool tends to supplement this by following the softer stratum unless fed or geared to meet the circumstances.¹ In such cases boring has to be undertaken very carefully and frequent patroning, or damming and reguiding, has to be resorted to, thus removing immediately the slightest deviation from the plumb.

TABLE VI.—MOH'S SCALE OF HARDNESS

No.	Mineral	Relative hardness
1	Talc.....	Easily scratched with the finger nail
2	Rock salt.....	Not easily scratched with the finger nail
3	Calc-spar.....	Easily scratched with a knife
4	Fluor spar }	Not easily scratched with a knife
5	Apatite }	
6	Felspar.....	Difficult to scratch with a knife
7	Quartz }	Cannot be scratched with a knife
8	Topaz }	
9	Sapphire }	
10	Diamond }	

¹ See also Hugh F. Marriott, discussion to Deviation of Rand Boreholes, etc., p. 115.

Thus if any mineral above be used in the form of a sharp point it will scratch the preceding members of the series, *e.g.*, should we find a piece of mineral which will scratch calcite but not fluorite its hardness is between 3 and 4, say about $3\frac{1}{2}$.

TABLE VII.—HARDNESS OF SOME COMMON MINERALS

Mineral	Hardness	Remarks on cores
Asphalt.....	1.5	Melts at about 100°C.
Augite.....	5.5	
Barites.....	2.5	
Bournonite.....	2.25	Brittle
Brown haematite.....	4.25	Lenticular fracture
Calamine.....	5	
Cassiterite.....	6.5	
Cerussite.....	3.25	
Chromite.....	5.5	Sometimes magnetic
Copper glance.....	2.25	
Corundum.....	9	
Felspars.....	6.5	
Graphite.....	1.5	Splits easily
Gypsum.....	1.25	Cleaves readily
Haematite.....	5.5	
Hornblende.....	5.5	
Ilmenite.....	5.5	Sometimes magnetic
Magnetite.....	5.5	Very magnetic
Malachite.....	3.25	
Micas.....	2.5	Cleaves easily
Mispickel.....	5.5	
Native copper.....	2.25	
Ozokerite.....	0.75	Melts at about 60°C.
Pyrolusite.....	2.5	
Quartz.....	7	Cleaveless
Salt.....	2.5	Dissolves in water
Silver glance.....	2.25	Breaks in slices
Soda niter.....	1.25	Dissolves in water
Spathic ore.....	3.5	Nodular
Stibnite.....	2	Sometimes flaky
Sulphur.....	1.55	Brittle
Tourmaline.....	7.25	Fractures easily
Wolfram.....	5.25	
Zinc blende.....	3.25	
Coals:		
Anthracite.....	2.25	Brittle, shelly fracture
Bituminous.....	1.25	Brittle, cubic fracture
Lignite.....	.5	Friable and platy

The hardness of minerals is fairly constant but of rocks this is not the case. This is due to the fact that minerals have a more definite and rigid chemical constitution than rocks, since the latter are aggregations of minerals. The minerals in rocks being in any proportions between certain arbitrary limits the hardness of a particular rock varies with its type, *i.e.*, the percentage of its dominant mineral.

c. Inclined strata especially rapid changes in the inclination as in boring through sharp unconformities, domes, folds and thrusts. The tool tends to follow the dip at the contact. (However, this is not a rigid statement.)¹ If we are dealing with the percussive system we must bore with short strokes so that the cutting tool meets a cleaner face since the rinsing water can better deal with the débris. With no rinsing system the hole must be sludge pumped often so that the direction of impact is in the prolonged line of the rods. If this is not done the chisel will nurse the dip. In the rotary system of boring these difficulties are often almost insurmountable.

Other geological causes of deviation of a drill hole may be:

1. Boulders, concretions and dykes.
2. Faults, thrusts and unconformities.
3. Caving and movement of strata in the uncased part of the hole.
4. General earth movement.

d. Lack of Rigidity in the Rods.—Even in the tightest joints the slightest joint play will initiate curvature with straight rods, just as railway curves can be made entirely of straight rails.

e. The Proximity of Other Boreholes.—In boring by percussive methods, for instance in the freezing process for shafts, the ground is disturbed by the continual shock of the tool so that new holes put down near by tend to deviate into the zone of least resistance. Again any iron such as parts of old tools or casing in the old hole will accentuate the deflection. This of course applies also

¹ KITCHEN, *op. cit.*, p. 100.

to new holes near those old holes which have been shattered at their base by time charges to increase the yields as was first done in the Pennsylvania oil field.

*f. Fissured Strata.*¹—These may direct a borehole in any direction.

g. Pressure on the Rods.—In many boreholes, particularly in diamond drilling, the tool tends to turn against the dip of the strata and this is greatly affected in the case of a hole nearly meeting the strata plane, *i.e.*, nearly flat strata in vertical holes; that is to say, “face on” in inclined holes. Hydraulically fed drills in these cases are best, like the Sullivan, which control the rod pressure and adapt it to keep the crown pressure constant. Thus in soft strata the water escape in the hydraulic cylinder being more rapid the drill descends more quickly and *vice versa* in hard strata. On the other hand, screw feed drill speeds are set between fixed limits regardless of petrologic changes in the hole. In harder strata greater pressure on the rods tends to produce a screwlike action.

h. Reduction of Borehole Diameter.—The necessary periodical changes in diameter to lessen the weight on the engine and crown no doubt affect the plumbness of the hole. The upper parts of the hole being wider allow the rods more latitude, and the rods tend to curve by displacing the center of the crown bit from the hole center. Alternations in hardness supplement this eccentricity. Longer core barrels up to 50 ft. have in places been adopted to ameliorate this tendency.

i. Oversetting the Diamonds in the Crown.—It is considered good practice to set the diamonds so that the hole is about $\frac{1}{16}$ in. more in diameter than the core barrel; *i.e.*, $\frac{1}{32}$ -in. projection for the diamonds over the crown.

Any greater overset makes too much play between the core barrel and hole or between drill rods and hole so tending to set up lateral movement.

j. Weak Core Barrels and Small Holes.—Weakness of the barrel especially at the crown screw tends to twist the tool

¹ DICKINSON, JOSEPH, F. G. S., *Trans. Inst. Min. Eng.*, Vol. 35, p. 397.

and in turn the hole. Thus long barrels are often faulty for want of strength and undue pressure on the crown. There appears to be much in favor of bigger holes and reduction not proceeding beyond $1\frac{1}{2}$ in. at 2,000 ft. Weak barrels may cause screw deflection. The crown often returns to its original direction after deflection has occurred in some West Australian borings. With big rod reductions the play cannot be entirely eliminated at the step joint.

k. Static Electricity and Magnetism of Rods.—This effect due to frictional abrasion is often very pronounced and can be demonstrated by means of a poker of soft iron, a hammer and compass. It must, if of definite persistent polarity, tend to deviate the rods toward the pole sought.¹ Magnetism will tend to arise also from brushing with casing and the strata if heavily iron borne as in the basic igneous rocks. Some further notion of the causes of borehole deviation may be obtained by considering the eventualities inherent in all boreholes, as yet beyond human control, as are evidenced in any attempt to fix the dip of strata absolutely from observation on a given core.

Only approximately can we obtain the dip angle of strata bored through by considering the core features alone. This is very simple but the estimating of the direction of the dip and thence the strike of the beds in such a case cannot be done without some form of stratameter which gives the dip and strike accurately *from the data presented*. The objection here is that the observation is too local and the data too scanty. We have to assume that the core yielding the data has been accurately gripped by the core catcher. Thus in the surface check on the core no account has been taken of the turn of the rods on tearing off the core previous to extraction. An American method of partially avoiding this is to score a continuous line down the rods after tightening with special joints and then check the dip shown against this line of known azimuth. Now the longer the line of rods and tools the less can they be regarded

¹ JENNINGS, J., *Jour. S. African Assoc. Eng.*, Vol. 12, p. 7, 1906; COOKE, L. H., *Trans. Inst. Min. and Met.*, Seventeenth Session, p. 126, 1907.

as a rigid rod because under the influence of their growing proper weight, rending, shear and turning forces arise which cannot be checked aboveground. Unfortunately, regardless of any errors of observation or measurement at the surface, the circumstances attending the wrenching off of the core and the working of the rods influence the deductions very greatly. In solid strata the core is wrenched off by a sharp jolt, otherwise we cannot tell whether the core and strata are in their proper natural relation as before rupture. In friable strata the core is frequently released during boring operations due to the successive boring shocks, and this also occurs frequently in rigid strata where we have intercalated beds of clayey and shaly rocks. Furthermore, the instant of jar for tearing off the core often witnesses a slight rotation of the rods. The lower surface of each core section should exhibit no traces of shear horizontally; the fracture should be clean, for then we can feel more secure that the small wrench twist is absent. In order to ensure that the twist is eliminated or minimized, the rod should be raised a little off the hole base before the fangs of the core catcher come into action. This gives the grip a better chance of making an accurate engagement, because the spin of the string of tools has abated. This spin definitely affects the direction of boreholes. The catcher now brought into action, a sharp upward thrust will stand a better chance of yielding a core with the conditions between core and strata preserved as before rupture. No change from this position must occur during extraction of the rods. The rod marks must be carefully watched and bumping of the string of tools on the borehole walls prevented. There should be no traces of turning at the core grips.

These conditions are so rigorous and so difficult of application and the circumstances attending the wrenching off of the core are so utterly beyond entire control that absolutely exact results can not be hoped for from one core alone. With cores of small diameter the small wrench twist gives an error of several degrees and the smaller the diam-

eter the greater the error; furthermore the smaller the diameter the greater the lack of control in extraction or boring, hence the greater tendency to deviate. The best dip and strike data are to be obtained from computations on depths yielded by three or more boreholes not in the same straight line.

CHAPTER II

AUXILIARY REGISTRATIONS IN BOREHOLE SURVEYS

Previous to discussing the various instrumental methods of surveying deep boreholes some of the more important ancillary records kept on modern plants will be described. These additional memoranda aid very materially in checking the accumulated borehole data in that they frequently save much time and guesswork as to causes of various curious features incident to deep boring.

PROGRESS RECORDS

These are continuous automatic checks or descriptive graphs of the progress of the borehole in respect to length and time. They provide a check on the difficult and often unreliable observations of the boring personnel. They yield conclusions as to the successive hardnesses of the strata pierced and assist in their determination, since each stratum corresponds to a definite boring pace.

The simplest device is a scale fixed on the rods and read every 5 min. and booked, but it is more exact to have a record depending on the length of hole and revolutions per minute, since the rapidity of boring through strata depends on the r.p.m. of the rods in the rotary or the number of strokes per minute in the percussive system. They are known as stratigraphs or strata-progress recorders.

Jahr's stratigraph¹ (Fig. 3) consists of a pen recording on a graph drum the latter revolving at the same rate as the rods and its motion round being at right angles to that of the pen. Thus the increase of depth of the crown bit will appear as abscissae and the corresponding revolutions as ordinates. The recorded line is thus the steeper the

¹ E. Jahr, Chief Mine Surveyor, Breslau.

faster the boring progresses and the flatter the slower the crown penetrates the measures; therefore a horizontal portion of the line shows that the tool is not piercing the rocks even though the rods are rotating; that is to say, that the rod feed is not paying out. When the plant is

FIG. 3.—Jahr's stratigraph—the derrick drive.

idle, and therefore the driving shaft of the recorder, the registration ceases. The most important inferences from the record are provided by changes of direction in the pen line because they show that different strata have been struck and thus provide valuable clues as to the conditions arising in this new ground. Such a change in the line only occurs in the flatter measures; in inclined deposits the change is more gradual because the crown only then penetrates the new stratum gradually. In Fig. 3 note that the motion

of the graph paper n is caused by the sinking of the rods a . A hook e on a ring on the boring spindle catches in the chain. This chain runs over the rollers g , g_1 and g_2 and is kept taut by the weight h . The motion of the roller g is transmitted by means of a bevel wheel on the shaft l so that the paper moves corresponding to the deepening of the borehole. The speed of the paper depends on the transmission between the bevel wheels i and k . The pen moves on an endless chain p (Fig. 4) at right angles to the direction of the drum graph, and it is driven by the toothed wheels q and q^1 .

FIG. 4.

FIG. 4.—Jahr's stratigraph—the recorder.

FIG. 4a.—Showing relation of record to measures for estimating depth and thickness of beds.

FIG. 4a.

The chain is driven by belting r from the driving shaft of the engine S . The recorder has several pens m^1 , m^2 , etc., spaced on the chain p at vertical distances equal to the depth of the record paper. Whenever a pen reaches the top edge of the paper it leaves it just as the next lower pen comes into action to continue the record, since their distances apart equal the depth of the graph paper. Thus the record is got as a continuous series of broken lines which can be cut and arranged later if desired.

It will be seen that the quicker the boring rods sink the more the curve will approach the abscissa direction and there will be a change in the curve for every different speed

of sinking. On the upper edge of the paper (Fig. 4), a curve scale can be fixed for the continuous series of borehole depths, which can be diminished to a definite scale by means of suitable transmission bevels i and k . Thus, given favorable conditions, we may obtain the approximate dip of the strata by noting the length of the transition in the curve between two changes in it. Note in Fig. 4a, which shows the progress of a diamond-drill borehole, that the curve is uniform to a as the crown is cutting in clay shales; from a onward, where the crown encounters the milder strata (coal) the curve flattens, and from b to c where it is entirely in coal it flattens more, steepening again at c on passing through the softer coal into more hard shale. An enlarged view of the borehole is shown in Fig. 4a to assist in elucidating the problems arising. Thus bd is the borehole diameter and ab the depth difference read on the curve scale, hence the strata dip

$$\tan \alpha = \frac{ab}{bd} \quad (1)$$

from which the actual thickness cg is easily obtained, since thickness of strata = $ac \cos \alpha$.

To facilitate reading, the depth of each change of strata may be marked on the record. If necessary the recorder can be driven independent of the plant. This method has been well tried with good results at one of the deepest boreholes in Germany, at Czuchow in Upper Silesia. Still it is only an aid to recording strata and is not infallible especially in very varied thin alternations of highly inclined beds. Better results would arise if the paper were made to move corresponding to the strata dips. Jahr's method may, however, be regarded as a valuable adjunct to boring.

Lapp's Stratigraph.—Here the pen moves by clockwork at a definite rate over the paper which moves corresponding to the deepening of the borehole. The recorder is connected to the rope drum shaft on the pay-out feed from which the rods hang. In Fig. 5 we have a view of Lapp's device in which the worm wheel s transmits its motion through a

chain on to the scroll paper winding on a shaft. As soon as the feed apparatus turns backward, *e.g.*, on dropping into the borehole, the paper roll is automatically cut out; the pen then indicates a straight line across, as when the plant is at rest. The pen works by clockwork and in one hour moves over the breadth of the paper and after automatic reversal works back in the next hour. Thus the record is a continuous zigzag line. The apparatus is enclosed in a glass-topped case which permits of a constant

FIG. 5.—Lapp's stratigraph.

observation of the progress of the borehole respecting the corresponding time. It does not cut out when the plant is idle as in the case of Jahr's device, and, since this latter is a check on the actual working time, it can be considered that Jahr's method is superior. But it can be applied to percussive boring since it works off the tool feed; however this may be a source of uncertainty since the feed is here hand operated. Thus the record depends on the careful manipulation of the feed which if correct, *i.e.*, if the record corresponds exactly to the progress of the hole, will give uniform results with Jahr's method. Both methods lack in that uniform rotation of the rods is not always obtained in practice.

The Foraky Recorder.—This stratigraph is a clockwork device with paper roll and recording apparatus. The

principle of recording the progress of the borehole is here again dependent on the sinking of the rods and time. The paper is turned by clockwork and the recording pen is driven by the feed device. The paper roll is chosen of such diameter that the clockwork rotates it on its axis once in 12 hr. and 1 mm. of paper corresponds to 1 min. of time. Therefore millimeter paper is chosen for the graph. The

FIG. 6.—Foraky stratigraph.

recording contrivance is driven from a screw spindle on the rod feed in such a way that a sinking of the rods of 10 cm. corresponds to a progressive motion of the pen of 1 cm.

The inked pen *C* (Fig. 6) moves¹ proportionally with the descent of the rods. It is connected to the rods by the screw spindle *d* from the feed device and by a cone-wheel transmission gear *e* actuating the screw spindle *f*. This carries a positive nut *g* holding the pen *c*. The axis of the clockwork *b* gives the true reading and the whole is encased in the casing *h* for protection. The apparatus is placed on a frame in the boring tower but not in contact with it. It has been successfully applied to depths of over 4,000 ft.

¹ *Glückauf*, p. 417, Mar. 18, 1911.

The results obtained are very satisfactory but the apparatus exhibits the same deficiencies as Lapp's apparatus because the basis of the record is time and not the revolutions of the rods, and here even in a higher degree. Since the motion of the recording surface is always uniform it turns too quickly in solid strata and too slowly in broken strata. In this way the variations in the recorded line, upon which the stratigraph depends as stated previously, are weakened, while in Lapp's method where the pen works by clockwork they are increased. The irregularities in the velocity of rotation of the rods in working are of no great importance since the expenditure of power for the proper action of the crown is small as compared with the movement of the rods.

Depth Measurers.—There are many types of these, the simplest being the direct types. Figure 7 shows the simple

FIG. 7.—Depth measurer.

direct depth measurer of the Lucey Products Corporation of Tulsa, Oklahoma, known as the Thatcher Depthometer. It is easily assembled on a rod frame and is very portable, being only 15 to 16 lb. in weight and can be used on ropes up to $1\frac{1}{4}$ in. diameter. The measuring wheel transmits its revolutions by toothed gearing for direct reading, and it can be used on bailing and apparatus lowering ropes as well; also it can be used when letting the rope into the hole or when pulling it out.

Borehole Diameter Measurers.—Decisions as to the variations in the diameter of a borehole are often necessary to settle difficulties arising during boring.

These difficulties may occur when

1. Casing operations are obstructed.
2. Cutting bits jam on extraction.
3. Abrasion develops at localized places.
4. Cushioning occurs on the percussion stroke.
5. Water circulation is affected.
6. Sludging, pumping, bailing and such operations are hindered.

The action of these gages need not be intermittent, *i.e.*, a continuous reading can be made for only one insertion of the apparatus. Former methods of laborious multiple readings are thus avoided. A borehole becomes restricted chiefly owing to the following causes:

1. Inexpert tiller work on hand-turned drilling with a straight bit; cruciform or horseshoe bits are less likely to cause diameter restriction.

2. Buckled casing due to joint or sheet rupture under internal pressure or external strata movement on weak casings.

3. Earthquakes.

4. Time charges at hole base.

5. Curvature of the borehole and its causes.

6. Uneven wear on the cutting tool not attended to in time.¹

Rumpf and Kleinhenn's Apparatus.—This apparatus can also be used for tubes and flues. The chief part

FIG. 8.

of the device (Fig. 8) consists of a system of calipers arranged to follow the inner walls of the borehole or casing, its movement being obtained as a magnified image either optically or mechanically inside the borehole.

¹ WOTZASEK, F., *Z. I.V.B.*, p. 178, June 20, 1928.

Figure 8 shows a longitudinal section of the device placed in casing 6 being examined. It will be seen that the central body 1 of the apparatus closes the tubular wall 2 into a chamber. About the central body 1 are the levers 4 which turn on axes 3 and carry rolling calipers 5 following the borehole or casing walls. These levers 4 may have any suitable form in cross section, preferably a definite form at their ends 8, *e.g.*, triangular, in order to get a sharp projection image which is thrown on the frosted glass 10 by a dry-battery lamp 9. The levers press on the casing walls by the action of springs 7, pressing them against the central boss on the other side of the fulcrum axes.

FIG. 9.

Figure 9 shows another form of construction wherein the caliper system 5 and spring 7 are arranged in another order of leverage. In each case springs 11 also assist springs 7 in centering the apparatus in the borehole or casing. A simple removal device is a set of hooks 12 and draw cables 13 uniting into a central cable.

FIG. 10.

Figure 10 shows the most recent form of the device produced in the laboratories of the Batavian Petroleum Company (Astra Romana). Here the displacement of the caliper system due to diameter variation is indicated optically in a magnified image. The caliper system 5 is here a piston system working in a cylindrical case and pressed on to the borehole or casing walls by springs 7. A source of light produces a magnified image on disc 10

through a system of lenses 14. It is found advantageous for registering results to have a series of concentric circles on the frosted glass plate 10, each circle corresponding to a definite variation in the diameter of the borehole. A kinematographic registration also suits the apparatus well, in which case the hood 10 is completely replaced by a kinematographic recording device. When employing the latter the motion of the apparatus down the hole must be uniform, so the survey film obtained will yield an exact image of the condition of the borehole or casing diameter.

We will not deal with any of the old time-wasting and tedious methods of single observations and records.

PRESSURE RECORDS

It is well known that in horizontal and inclined boreholes the tendency to deviation is greater than in vertical ones¹ Although this tendency is mostly downward with horizontal and upward with inclined holes, many holes, particularly in inclined measures, tend to deflect upward.² Alternating hardness, etc., also affects this. These deviations are accentuated by the action of gravity and lower side abrasion on the rods due to the weight of the crown. In the case of horizontal and well-inclined boreholes (from the vertical) maximum manometers are employed to register the water pressure in the hole.

The "Burbach" Pressure Recorder.—Where the deflection is downward, as in the usual cases, this method employs the principle of gaging the pressure of the rinsing water at various points in the borehole and contrasting these records with the conditions at the borehole mouth. Where the deflection is upward the pressure on the rinsing pump may be gaged.

a. When the borehole deviates downward, a tube piece is screwed on to the boring rods. The apparatus of the

¹ JUSTICE, J. N., *Trans. Inst. Min. and Met.*, Vol. 12, p. 319; KITCHEN, J., *ibid.*, Seventeenth Session, 1907-1908.

² JANSON, *Proc.*, Vol. 11, p. 48; *Lake Superior Min. Inst.*, Vol. 2, pp. 26-30, 1894.

Burbach Works, Beendorf, Germany, contains a manometer *c* with a bent measuring tube *d* (Fig. 11). The fluid enters through holes *a* from the borehole and holes *b* to the measuring chamber and gaging tube. The manometer is provided with an indicator which fixes the highest pressure. The measurements are very simple; the rods and

FIG. 11.—Horizontal borehole pressure recorder. (Burbach.)

gage are pushed into the hole to the spot to be measured, the hole being full of rinsing water. Then on pulling the gage out and reading the highest pressure thereon the deviation from the horizontal can be calculated by considering the specific gravity of the rinsing fluid. This latter, of course, is essential since water is not the only fluid; in potash mines magnesium chloride liquor is used.

FIG. 11a.—Horizontal borehole profile.

Figure 11a illustrates this simple principle, being an actual example from a German potash mine where a fluid of 1.275 sp. gr. is being employed. To get the ordinate at the length 340 m., where the gage has registered 2.5 atm. of pressure fall, proceed thus:

$$\frac{10 \times 2.5}{1.275} = 19.60 \text{ m.}$$

and similarly for the length 500 m. registering 4 atm. fall:

$$\frac{10 \times 4}{1.275} = 31.36 \text{ m.}$$

b. When the borehole deviates upward, the pressure is read at each desired spot by sending in the gage on the rods

to the place noted and then extracting and reading. Or, as said before, a continuous pump pressure record is kept.

The borehole depths read from the rod are entered as abscissae and the computed deviations from the horizontal as ordinates, as shown in Fig. 11*a* above. We thus get a line showing the course of the borehole. When the actual borehole is not intended to be horizontal the depths are projected, otherwise we get foreshortening errors. To lessen errors we may plot true borehole lengths against measured pressures direct. These methods are not affected by the smallness of the hole.¹

Brigg's "Clinoscope."—This is another and more recent method of measuring the deviation of horizontal boreholes. It consists of a mercurial transmitter and Wheatstone

FIG. 12.—Brigg's clinoscope, vertical section of transmitter.

bridge recorder, the tilting of the mercury into the horizontal position varying resistances which are measured by the bridge.

FIG. 13.—Brigg's horizontal clinoscope. Plan of transmitter.

In Figs. 12 and 13 is shown the transmitter which is a fiber box half filled with mercury *g* in the container *d*. Two circular pits at *i*, *i* (Fig. 13) are connected by a slot *s*, the surface of the mercury, when the transmitter is level,

¹ THIELE, P., Verfahren zur Ermittlung der Abweichung von Horizontalbohrungen in der Vertikalebene, *Kali*, p. 32, Jan. 15, 1913.

being at g . Two parallel resistance conductors a^1 and a^2 and a steel needle c pass through the fiber lid l . The needle connects the mercury to earth by way of the trunnion n , the case e and the borehole lining. By dipping into the mercury the conductors are connected in parallel. Any change of inclination alters the length of conductors immersed, and thus the relation between the resistance of the conductors is a direct function of the tilt. This relation is determined by means of a Wheatstone bridge which will be detailed later when discussing Professor Brigg's "clinophone" for vertical boreholes. The most disagreeable feature of the apparatus is the employment of mercury, which is an unsatisfactory medium to employ in mining owing to its so easily becoming dirtied and thence unreliable.

THERMAL SURVEYS

These are usually resorted to in cases where we need

1. The geothermal gradient of the strata of a given area.
2. To investigate the frost columns in a freezing shaft.
3. To employ geophysical data in oil zones, etc.
4. Purely scientific researches.

They are purely thermometer surveys undertaken with some special form of maximum or minimum thermometer using various fluids and systems of calibration. Numerous devices¹ have been invented to meet these needs, and in all cases it is necessary for the apparatus to remain in the hole some hours in order to acquire the temperature of its surroundings.

a. Measuring Decrease of Temperature.—The Mom-mertz apparatus (Fig. 14) is one of the best known low-temperature contrivances used in borehole temperature surveys, *i.e.*, in freezing shafts. A sheet-iron flask a contains a liquor which can withstand great cold, and this vessel is closed by means of a wooden plug. It hangs inside another flask c and between them is an insulating space on the vacuum-flask principle of exhausted air. The outer

¹ See the final chapter of Ambrohn and Cobb's "Elements of Geophysics" McGraw-Hill Book Company, Inc., New York.

flask has a screw top and suspending device. Its base is a pointed lead end.

After the flask has hung a long time at the spot being measured, it is rapidly taken out and the temperature of

FIG. 14.—The Mommertz low temperature borehole thermometer.

the solution read. This gives the temperature at the said spot after due allowance for the fluid being used. The time needed for the apparatus to assume the temperature of its surroundings is decided by trial for each case. The results are more or less approximate but useful.

b. Measuring Increase of Temperatures.—There are many kinds of maximum and minimum thermometers in use. A favorite type of *maximum* thermometer is that in which the capillary is left open and ground off into a fine point with a reservoir surrounding it for the overflow. This overflow can be measured in various ways against known bath temperatures. The Hallock¹ type has a secondary capillary for measuring the separated mercury.

FIG. 15.—The Six maximum and minimum thermometer.

A well-known type of *maximum and minimum* thermometer is that of Six (Fig. 15) in which the liquid is alcohol in the tube *A* at the end *B* of which is a thread of mercury *BC*, the remaining part of the thread and part of the bulb *D* being again alcohol. The former end of the thread is for minimum and the latter for maximum readings. There are two indexes, one of glass the other of iron or both of glass

¹ JOHNSON and ADAMS, *Econ. Geol.*, Vol. 11, pp. 741-762, 1916.

with side springs of steel as at *G*. For the bottom index glass is used. Glass being wet by alcohol the index retreats with it owing to capillarity and on rise of temperature the alcohol flows past it without moving it, the spring also holding it; thus we get the minimum reading *E*.

The upper index may be of iron, since alcohol does not wet iron, so that on rise of temperature the iron is pushed up and remains there when the column falls, showing the maximum temperature *F*. Otherwise the spring glass index is used. These can afterward be reset by a small magnet acting on the springs. Full accounts of up-to-date thermal survey methods can be obtained elsewhere.¹

Length Recorder for Use When Inspecting Ropes.—This device² is now employed for hoist ropes, and lowering

FIG. 16.—Elevation.

FIG. 16a.—Plan.

ropes for valuable apparatuses and is used to enable a rope inspector to find the position of broken wires or worn or distorted places accurately to within a few inches. In Figs. 16 and 16a a measuring wheel *a*, grooved to suit the diameter of the rope *d*, is kept in driving contact with the

¹ VAN ORSTRAND, C. E., Apparatus for the Measurement of Temperatures in Deep Wells by Means of Maximum Thermometers, *Econ. Geol.*, Vol. 19, pp. 229-248, 1924.

MCCUTCHIN, J. A., *Bull. Amer. Assoc. Petroleum Geol.*, Vol. 14, No. 5, p. 536, May, 1930.

SEIFERT, C., *Fortschritte Mineral.*, Bd. 14, Part 2, pp. 167-291, 1930, for notes on geological thermometers and bibliography.

² The firm of Reinhard Wagner, Bergwerksdarf Oberhausen (Rhld), Germany; see also *Glückauf*, Dec. 10, 1929.

latter by two rollers *b, c*, carried by a frame *e*. The bearing pressure on *a* is regulated by the screw *h* adjusting the compression of the spring *g*. The base plate *p* is notched at *r*, and the end piece *i* of the frame *f* is detachable, so that the apparatus can be put into position round the rope. The frame *f* is mounted on a beam *l* carried by the springs *o* and bars *m, n*. The castors *q*, mounted on vertical pivots, ride on the platform on which the inspector stands. The spindle of the wheel *a* is coupled directly to the recording train *k*, which indicates directly the length of rope that has passed *a* at any particular moment. The complete apparatus, which has proved quite satisfactory in practice, weighs about 57 lb.

Construction of Borehole Sections or Profiles.—Obviously it is only possible to portray the course of a borehole with any degree of accuracy by referring the observed data all to one plane. Having the depth and inclination data at hand, there are three methods of plotting these in any arbitrary vertical plane¹ *viz.*:

1. Plotting the angle from the point where recorded down to the next recorded point.

2. Reversing 1 by plotting upward to the preceding recorded point on the chart.

3. Averaging 1 and 2 by plotting at the point on the chart either way, downward and upward, halfway to meet subjacent and superjacent plotted points obtained in the same way.

Since methods 1 (*A* Fig. 17) and 2 (*B* Fig. 17) assume no gradual change of dip as usually obtaining in practice, but imply sudden regular dip changes, they are not now employed or recommended. Method 3 (*C* Fig. 17) will enable us to average subjacent data and plot this mean. The three lines *A, B* and *C* (Fig. 17) are plotted on the assumption that the hole deviates in one plane, say the *WE* plane of the paper. If a hole has been assumed to bear in

¹ These methods are also discussed by Prof. F. H. Lahee, *Bull. Amer. Assoc. Petroleum Geol.*, Vol. 13, No. 9, p. 198, to which we are indebted for Fig. 17.

only one plane (a common error of borehole chart makers) and it is later decided to allow for lateral directional deviations, or for depicting any borehole data in one plane, proceed thus:

In Fig. 17a the profile of *C* (Fig. 17) is reproduced dotted and the hole is assumed to have the *C* hole dips and depths

FIG. 17.

FIG. 17a.

FIG. 17.—Section showing methods of plotting deviation of boreholes where readings are made at intervals and angular deviation is assumed to be all in same vertical plane.

FIG. 17a.—Section showing a hole wandering in three dimensions revolved into the *WE* plane.

FIG. 17b.—Plan of Fig. 17a.

FIG. 17b.

throughout but alters in azimuthal directions from point *a* as shown on the left of the figure. Our problem is to visualize the borehole in the *WE* plane as in the previous Fig. 17. As *ab* is now bearing N.55°E. rebat it 35 deg. to *ab'*; project this line to *ab*² and drop perpendicular to the depth line of *b* at *b*³. (Imagine *a* to be the apex of a cone of side and dip *ab* with the new *ab* 35 deg. out of the old *ab* plane; the actual depth and length of the new *ab*

are unaltered except for the distortion due to projection.) Join ab^3 and draw b^3c_1 parallel to bc . The hole is now 65 deg. out of the *WE* plane; slew b^3c_1 this amount to b^3c' and project to b^3c^2 getting c^3 on the c depth line as previously. Join b^3c^3 . In the same way get the due north part of the hole cd to show a vertical c^3d^3 only, since it can have no lateral trend in the *WE* plane of the paper; and so on to e^3 , the last length being an extraneous addition to C (Fig. 17). It would be well to smooth a curve through these constructed points, and the same applies to the plan view of Fig. 17b.

Borehole Models.—These are very useful and instructive adjuncts to any scheme of deep boring or precision boring, as in freezing shafts. Thurmann of Halle, Saxony, constructed the interesting and helpful model shown in Fig. 18 in 1909 to assist in visualizing the relative trends and positions of boreholes in a freezing shaft frost wall. It will be seen that he merely erected discs of sheeting or millboard at depths on the central rod scaled from the progress chart, the said rod representing the shaft center. Thus, in the figure, the dots on the discs represent the positions of the boreholes at the various levels or depths. The dotted line shows the position of a supplementary borehole to deal with the wide space in the frost wall between boreholes 2 and 3.

Figure 19 shows a glass model of the Chanslor-Canfield Midway Oil Co.'s No. 96 Olinda oil well in California, one of the deepest wells in the world. It is thought that some facts relating to the true shape of the course taken by the lower part of the well, obtained from a study of the model, would have remained unknown without its aid.

The model is seen to be easily constructed from depth planes scaled from the boring logs and the positions of the instruments on each plane surveyed as shown. The bottom plane surveyed is 6,948 ft. deep. It is conceivable that valuable results may be had from models outlining the course of well or boreholes and these would be more exact than sketched-in hypothetical underground contours.

In this particular model the vertical line represents the plumb line from the derrick floor. The curved line is an accurate representation of the course of the drill hole through the formations. The model was made by drilling holes through sheets of glass in the surveyed positions of the hole at different depths. A black cord threaded through these holes represents the well.

The Sperry-Sun Well Surveying Company of Philadelphia also employs an attractive and useful method of depicting deviation. They

FIG. 18.

FIG. 18.—Thurmann's borehole model.

FIG. 19.

FIG. 19.—Glass model of the Chanslor-Canfield, Midway Oil Co.'s No. 96 Olinda oil well in the Fullerton, Calif., Field, showing the course of a very deep borehole. (After Anderson.)

project the surface position of the borehole on to the lowest depth model plane as the center of deviation coordinates. From this axis the relative displacements are plotted at their respective depths (Fig. 19a). The

finished model is then pasted up at the sides giving the borehole as one edge of a distorted prism (Fig. 19b).

Lesser Deflection Records for Short Holes and Small Deviations: The Plumbing Basket.—This method employed in plumbing holes which have not deflected more than

FIG. 19a AND b.—The Sperry-Sun Well Surveying Co.'s model.

the borehole width, is often resorted to, since it is rapid and cheap. It was evolved by the Parisian firm *Entreprise générale de fonçage de puits études et travaux de mines*.¹ It is much appreciated in surveying freezing shaft holes and prospect holes. It² consists of a receptacle or basket filled with lead and let down into the hole on a hawser. The basket A (Fig. 20) is slightly less in diameter than the hole.

¹ CAVALIER and DAUBINE, *Annales des mines*, Paris, 1900. Series 9, Vol. 18, p. 392; KOHLER, *Bergbaukunde*, Vol. 6, p. 634; *Berg und Hütt. Ztg.*, p. 276, 1901.

² SCHMIDT, *Trans. Inst. Mining Eng.*, Vol. 52, No. 2, p. 178, 1917; ERLINGHAGEN, *Glückauf*, p. 705, June 8, 1907.

It is preferably, but not necessarily, suspended from the pulley S over the hole center C at the surface. The distance CB varies in amount and bearing according to the deflection. If this suspension point S is at a height h above, and the basket A at a depth D below, the surface and the measurable distance CB be called m , then the deviation X of the hole is obviously

$$X = m + x = m \frac{D + h}{h} \quad (2)$$

Erlinghagen¹ simplified the process in a survey of freezing shaft boreholes for the shaft sinking firm of Gebhardt-Nordhausen. He employed a drum of 0.314 m. diameter, *i.e.*, 1 m. circumference, which carried a wound copper wire exactly 10 m. above the center of the hole mouth of the hole. It carried a heavy weight or plumb bob which moved freely, allowing the wire to take up an exact perpendicular position. A crosspiece with two measuring lines at right angles is fixed on the hole mouth to facilitate reading. The depth is taken from the number of unwound coils from the drum, each being 1 m. The computation (2) above now becomes

$$X = m \left(\frac{D + 10}{10} \right) \quad (3)$$

The method is not bound to fail when the wire fouls the sides of the hole, for in case of the hole deviating back to its original position at greater depths the wire will hang free of the sides. The method can be applied for depths down to about 300 ft., and instances of its successful application at over 600 ft. are on record. Certainly with big deflections it is useless, but for surface and near-by subsurface conditions in most holes down to 100 yd. it is a useful auxiliary record.

The all important dimension m is checked as follows (Fig. 1, Plate II). The coordinates (x_1y_1) of C , the center

¹ *Glückauf*, No. 23, 1907.

of the hole at the surface, are known with respect to the X and Y axes, and the depth of any point A on the wire can be found, since we can get the length L of the wire direct.

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

PLATE II.—Illustrating the basket method.

From the similar triangles SCB and BaA (Fig 1) right angled at C and a , we get

$$\frac{CB}{Ba} = \frac{SB}{BA} \text{ and } \frac{CB}{Ca} = \frac{SB}{SA}$$

and

$$Ca = m + x = \frac{CB \cdot SA}{SB}$$

Then, by coordinate geometry for the small length $CB = m$,

$$CB = m = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (4)$$

It will be seen that m is a function of the length L of the

hole and $L + l$ of the wire. The azimuth of CB is easily taken from

$$\frac{x_2 - x_1}{y_2 - y_1} \quad (5)$$

We first detect contact of the wire in the hole by m becoming constant, but, as already stated, it may vary again if the hole diverges back to its former direction later on. If this latter contingency arises it can be demonstrated as follows: Each deviation of the hole gives a new value in amount and azimuth for m , thus giving in a crooked hole a series of values, $a_1, a_2, a_3 \dots a_n$ at different points 1, 2, 3 $\dots n$. At each of these points trace the borehole cross sections as shown in Fig. 4. Here the circles representing the circumference at the said points 1 $\dots n$ are projected downward on to a line $a_1 \dots n$ which is the continuous horizontal traverse of the deflections $a_1 \dots a_n$ in bearing. The centers of the circles are correspondingly subscript figured 1 $\dots n$. If the line SA do not touch the borehole sides, *i.e.*, it is straight, we find it on the projected plan as the line ca_n . That is to say, that if we make a vertical section of the borehole through ca_n and draw in SA , it must not touch the sides. The points must be inside the borehole section circumference circles at the corresponding levels. If one or more do not obey this requirement, point S may be shifted for a new suspension and therefore new plan point C' . Failing any agreement with the above demands, on moving S to the limiting lateral positions, the method ceases to be of utility any further.

When point C has been retreated a distance d to C' (Figs. 1 and 5) and the projection completed, the new deviation w is got from the new suspension and hole lengths a and b . Thus

$$w = \frac{v}{a}(a + b) \pm d \quad (6)$$

Other but perhaps more troublesome methods have been adopted as modifications of the above method.¹

¹ F. SCHMIDT, *op. cit.*, p. 180.

Errors of measurement arise from the following sources.

a. Incorrect Adjustment of the Plumb in the Hole.—This arises often in unlined boreholes which frequently prevent the plumb fitting the hole like a piston. This mostly arises in chisel-bored holes which tend to ovality in cross section. Ten millimeters inexactitude renders the method unadoptable. The application of spring-centering mechanism to remedy this is not to be recommended.

b. Sag of the Rope.—This occurs with long ropes holding small weights and it renders false readings of m . These errors increase, with the slope of the hole and its depth, according to the catenary law. The rope should be very light compared with the weight; or it may be ridded by centrally fixing the plumb at the measuring place and tensioning the rope.¹

c. Incorrect Readings.—Inexactitude in reading m increases as m diminishes, greatly influencing the coordinates. Repeated micrometer readings should be made and the mean taken.

¹ See Wache's device, German Patent No. 3859, or *Glückauf*, No. 46, 1904.

CHAPTER III

INSTRUMENTAL SURVEY OF BOREHOLES

The determination of the course of boreholes by instrumental means has occupied the minds of investigators since before the middle of last century. It received great impetus during the early eighties and the opening years of this century. Since the World War much work has been done, principally in the Mid-continent oil fields of America, South Africa and Germany in devising new means to the above end. From simple tests with plumbing baskets and by simple fluid apparatuses the progressive trend through various mechanical, optical, and photographic contrivances to the highly skilled gyroscopic methods has proceeded, until today the last two named means are being exploited vigorously. Probably the most widely adopted method in employment today is a modified form of fluid method, and it is now customary for contracts in drilling to specify a limiting permissible error in verticality of 1 part in 100. Thus we are faced with a universally applicable standard of attainment expected of any method offered in the profession. The paramount requirements which have to be fulfilled by a successful device are as follows:

a. It should record continuously on going down the hole and similarly make a check record upward on extrac-tion. Very few inventions meet this need.

b. It should measure both the inclination and bearing of the borehole. This could be done by simultaneous registrations from one source or two initial sources registering at the same time. It is the great time-saving injunction.

c. It should be under direct surface control with respect to registration as well as depth.

d. It should be immune from injuries due to water or mud pressures, chemical actions in the hole or strata, etc.

e. It should be uninfluenced by local attractions such as are set up by magnetic strata, metallic linings and rod magnetism.

f. It should be simple and free from many technicalities and therefore less liable to derangement and needing less supervision.

g. It should be easily understood and, if possible, capable of being read direct with few adjustments.

h. It should be capable of registering at great depths, *i.e.*, it should be of small diameter. This claim is a failing of most instruments.

i. Its data should always be subject to check up and down the hole and also by different means.

The several methods invented to investigate the course of boreholes may be broadly classified under the following general heads, though certain instruments may be included under two or more of these:

1. Fluid methods utilizing the shape of the fluid outline in a cylindrical retainer. Such a fluid may be hydrofluoric acid, cement, gelatine, mercury, copper sulphate, wax or paraffin.

2. Plummet and magnetic needle methods in which the dip and deflection are read on special arcs in the instrument or by core measurers aboveground.

3. Electrical methods, wherein plummets are actuated or pricking cones are set in motion, also electrolytic deposition devices, wax-warming arcs, and other registration contrivances.

4. Pendulum methods either simple or compound.

5. Photographic methods wherein the position of plummets and compasses is recorded, or where kinematographic records of successive positions of these, or direct photographic views of the unlined sides of the hole, are provided. Multiple photographic devices and multiple views of shaped notches, etc., are included here.

6. **Gyrostatic methods** where the principle of the gyroscopic compass is employed.

7. **Plastic cast methods** in which set models of the hole and its core stump are provided.

8. **Pricker methods** operated by electromagnet plungers, levers, plumb bobs or in any other way, on paper strips, soft discs or plates.

9. **Inertia methods** wherein the inertia of a heavy rotating body is employed.

10. **Seismographic or geophonic methods** in which vibrations caused on the surface by explosions or the vibrations caused by drilling, particularly cable-tool drilling, are recorded.

The general subject of borehole investigation can thus, by the above methods, be broadly divided into two main issues:

a. The actual survey of the course of the borehole in azimuthal deviation and inclination from the line of its intended course.

b. Core orientation in which the original underground position of the core is established. It is, of course, limited in its field of application by being only applicable to holes yielding cores.

The two main branches *a* and *b* of our subject necessarily merge one into the other by reason of their close relation and the instruments employed being often of dual utility. Core orientation provides useful information as to the direction and amount of stratigraphic dip; information very difficult to obtain when boreholes incline through inclined beds. This will be seen by Fig. 21, where we will often meet the difficulty of having unreliable data as to whether *a* or *a*₁ is the truthful vertical thickness of the seam. The great value of core orientation surveys in fields insufficiently mapped geologically, as in wild-cat ventures, is obvious; also where evidence is misleading or misinterpreted, as often in unconformities, asymmetric conditions, hidden dislocations, alluvial deposits and where we get change of facies.¹ The retention or rejection of accumu-

¹ MACREADY, G. A., *Bull. Amer. Assoc. Petroleum Geol.*, May, 1930.

lated data bearing on the problem will be decided by this core knowledge. Also the probable line of development in the field concerned. It is singularly useful in seeking index beds or marker or key beds and therefore decides the spacing of holes and life of a lease.

It is considered that shale with a dip over 5 deg. is the most favorable stratum for core orientation, since dips are rarer in massive formations. Hard sands are more objectionable owing to their wearing out the cutters, and soft sands tend to crumble and plug the barrel; also false bedding

FIG. 21.

occurs more frequently in sands. The chief difficulty is the transporting of the cores to the surface in a satisfactory condition.

At all events sufficient has been said to show that the practice of borehole surveying and core orientation has progressed far since the day of Dr. Newell Arber¹ who was rather emphatic in disclaiming the reliability of any methods purporting to show the direction of dip of beds in a borehole.

In all methods of borehole surveying and core orientation, one of the prime factors influencing the choice is the cost, since the cost consists not only in the actual expense

¹ Geology of the Kent Coalfield, *Trans. Inst. Min. Eng.*, Vol. 47, p. 694.

of the survey but also the time loss which could otherwise be taken up in drilling.

According to recent findings¹ the direct and indirect costs of making separate directional surveys with every 500 ft. of additional hole amount approximately to 2 to 3 per cent of the total cost of a producing well. The increased cost due to the changes in drilling practice in order to keep a hole straight and the cost of straightening a crooked hole ordinarily range from 5 to 10 per cent of the total cost of the hole, depending upon the work required to correct possible crooks in the hole. Thus apart from any considerations (in oil-well drilling) of improved spacing, better drainage and higher recovery per well and per acre which arise from correct surveying of boreholes, it will be seen that good surveying will tend to lighten the burden of straightening costs. This because it also yields enlightening data on dry wells and causes of dryness.

Accuracy of Borehole Surveys.—Respecting the accuracy to be expected in a contract for borehole survey work it may be mentioned that demands here vary in stringency with the importance of the survey. Freezing shaft contracts frequently require a minimum limit of reliability in readings of 1 in 150, *i.e.*, 1 off the vertical for every 150 deep. Or again they may desire a deflection record not exceeding $2\frac{1}{2}$ deg. off the vertical, since beyond this no frost wall is safe at depths of over 100 yd. Hence the desired accuracy decides the type of apparatus being employed, whether crude methods with unreliable direction records, like pricking bobs without orientated rod couplings, or the more precise pendulum and gyroscopic methods which often yield accurate results up to 1 in 3,000. The purpose of the boring will therefore, in the end, decide the nature of the survey apparatus. The purposes for which boreholes are put down are as follows:

1. To locate a seam, stratum, oil zone, salt or any other mineral.

¹ MURPHY P. C., and JUDSON, S. A., *Bull. Amer. Assoc. Petroleum Geol.* Vol. 14, p. 603, May, 1930.

2. To obtain the thickness, depth and constitution of such deposits.

3. For shaft sites.

4. For conducting electric cables (Fig. 22), steam and compressed air pipes, also haulage ropes to the mine.

FIG. 22.

5. For hydraulic stowing.

6. For utilizing any hydraulic head which peculiar geological conditions may provide in old workings (Fig. 23).

FIG. 23.—Ideal cross section of a synclinal basin.

7. To aid ventilation by draining off gases.

8. For circulating tubes when sinking by the freezing process.

9. For cementation.

10. For checking any other boreholes.

This last item of check is probably the most important aspect of accuracy. If possible the method being adopted should be checked later by methods dependent on a totally different operating principle. Then the results

FIG. 24.—Plan of an oil well comparing results of several surveys made under varied conditions. (After Macready.)

FIG. 25.

could be compared graphically as in Fig. 24 (after R. P. McLaughlin)¹. Failing this a check survey should be made in and out of the borehole as in Fig. 25.² The manner of compiling a check will be seen from Table VIII, wherein

¹ By the courtesy of *Bull. Amer. Assoc. Petroleum Geol.* (Vol. 14, No. 5, p. 586, 1930).

² *Ibid.*, p. 588.

the old and tried method of acid etching is compared with a recent plunger-pricker method for amount of dip only.¹

TABLE VIII.—COMPARATIVE SURVEYS OF AN OIL BOREHOLE IN THE SEMINOLE DISTRICT, OKLAHOMA

Depth, feet	Driftmeter reading, degrees	Acid-bottle reading, degrees, corrected
252	0	0
499	2	0
748	1	4
1,005	4	7½
1,257	10	12½
1,360	10	
1,512	17½	19½
1,758	17	19½
2,002	24	28
2,094	28	
2,268	28	32½
2,502	34½	38½
2,745	38	39½
3,009	40½	41½
3,255	39	40½

However, these checks are relative and cannot be claimed as absolute; the only absolute checks are actual observational ones as

1. Where a hole is followed by a shaft or drift.
2. Where a hole has been bored between known and occupied places, as between stopes, working seams, etc.
3. Where boreholes deviate and meet; all methods thus registering the same meeting spot in both holes.

¹ *Petroleum Engineer*, December, 1929.

CHAPTER IV

CORE ORIENTATION

Introductory Note.—This branch of instrumental survey in boreholes being the older of the two main divisions previously noted, we will deal with it first. It has not been so extensively employed as the other department of borehole surveying dealing with the course of the borehole proper. Among the chief factors not already discussed which either influence the relative positions of boring tool and strata pierced or provide useful evidence of the same, we may mention the following, of which a running record should be kept.¹

1. The type, size, and dimensions of bit used.
2. The size of drill stem.
3. The size and depth of the hole.
4. Weight of mud used.
5. Pressure employed on the bit.
6. Speed of rotation or number of strokes per minute.
7. The stroke or fall in percussive boring.
8. The weight on the tool in percussive boring.
9. Rate of water circulation.
10. Ease of running in and coming out with drill stem.
11. Ease of setting the casing.

The various orientation methods can be nearly all grouped into the four following classes:

- a. Orientating the core barrel by measuring or aligning the drill pipe out of the hole.
- b. Attaching an instrument to the core or core box in the hole during operation previous to extraction.

¹ See also a useful questionnaire by F. H. Lahee for the Research Committee of the American Association of Petroleum Geologists, *Bull. Amer. Assoc. Petroleum Geol.*, July, 1929, for notes on checking observations, etc.

c. Lowering an instrument on to a freshly cut core and then extracting it with or without the core.

d. Photographic devices for the walls of the hole.

Kind's Method.—Kind's core drill is the earliest form known, having been employed in coal strata near Forbach in Lorraine in 1844¹ using a free-fall percussion drill (Rotary core drilling was first adopted in 1861 by the French engineer Leschot).

Kind also made the first core orientation. The method has long been superseded and information thereon is

FIG. 26.—Kind's borer.

FIG. 27.—Kind's core breaker.

scarce. It was employed in 1854 in Forbach yielding a half-meter core which was brought to bank in as unaltered a condition and position as possible.

Figure 26 shows Kind's fork-shaped borer which provided the thin core 12 to 20 in. long and was then extracted. A core breaker *a* (Fig. 27) was lowered to tear off and lift out the core *b*; this breaker had a toothed inner cylinder *c* keeping the teeth *d* forced out during insertion and suspended by a cord from the surface. To prevent turning he employed two index arms held against the rods, one by a man in the derrick near the top of the drill rod and the other at the derrick floor. These arms aligned the pipe against twist. The method yielded cores of only about half

¹ REDMAYNE, R. A. S., "Modern Practice in Mining," Vol. 1, p. 91.

MACREADY, G. A., *Bull. Amer. Assoc. Petroleum Geol.*, Vol. 14, 1930.

KOEBRICH, A., *Pr. Zeitschrift*, Vol. 36, p. 256, 1888.

the width of the hole, and diamond drilling with its small holes later on made it obsolete. A similar method was also applied by the engineer Zobel in Schönebeck in 1855.¹

Lubisch's Method.—The boring master Lubisch improved on Kind's method in the Upper Silesian mineral fields in 1887. He diamond drilled a core first without a core catcher, leaving the stub standing in the hole. Then he lowered a second tube (Fig. 28) over the stub and marked it in a definite manner respecting the meridian and later extracted it, orientating it as in Kind's method. It suited small holes better. In Fig. 29 the steel tooth of the orientating tube closes about the core and makes a definite

FIGS. 28 AND 29.—Lubisch's core marker.

FIG. 30.—Vivian's pilot-hole core compass.

mark which was expected to have a definite known surface orientation. After lifting out this marker device a core extractor was let down to bring out the scribed core. Now the scribed longitudinal mark is adjusted to the vertical plane by means of a spring pen hanging on the rods and the dip and strike read. Lubisch improved his apparatus later by adding a cap carrying a steel scriber which gave a mark at right angles to the side mark, and he also improved the joints to prevent twisting on insertion and extraction.

Lubisch's advantage over Kind was in the more rigid hollow rods and the possibility of working in smaller boreholes. For success the following demands, difficult and nearly impossible to attain altogether in practice, are to be fulfilled:

¹ *Mitt. Markscheiderwesen*, Heft 4, p. 37, 1902.

1. There must be no mud or cavings between the core and borehole walls.

2. The core must be sufficiently rigid so as not to fracture on extraction and to preserve the markings.

The changing of the rods, etc., make condition 1 very difficult, since we then interfere with the rinsing. In very hard rocks condition 2 might be impossible, owing to lack of clarity in the marking. In soft rocks this latter condition is impossible. These methods, it will be seen, take up much time and are not now in operation.

Vivian's Method.—The method of the American diamond driller, Vivian,¹ marked a new departure and significant advance in core orientation. He drilled a small pilot hole of a few inches diameter and lowered a small instrument case into it, so that a part of it was fixed in the pilot hole. This case held a compass needle clamped by a weight used in setting the case. When the core was recovered the case was also recovered attached to its upper end. Figure 30 shows the compass *c* and its arresting apparatus *a* and the tap neck *b* in the pilot hole *d*. The needle, free at first, is fixed by letting down the weight. This was all retrieved later in the normal method of core catching. Above-ground the needle is freed and the core turned to give the position before arrest. The core now is in the same position as in the hole, and so its dip and strike can be obtained. The demerits are

1. The apparatus is almost, if not quite, impossible of use under a big head of water pressure.

2. Cavings filling the pilot hole as when concussion occurs during coring, rupture of the core and mud.

3. In small holes the pilot hole thins the core itself to a too fragile degree, the wall thickness in diamond boring needing to be at least 12 to 18 mm. and in addition we must consider the play on both sides.

4. A compass can not be set vertically true in a small core.

¹ *Trans. N. E. Inst. Min. Eng.*, p. 45, 1881-1882.

5. Great loss of time in boring pilot hole, exchanging rods and extracting cores.

Vivian's method has had very little usage owing to the small probability of success.

Kendall's Apparatus.—This apparatus was invented by P. F. Kendall at Owen's College, Manchester, in 1887, and it was arranged to be set in a pilot hole like the Vivian method, but the compass in the case was clamped by lifting off the weight of the setting tool. A core was then taken out with the compass attached to the top of it. The magnetic compass is attached by means of a peg or cement to the top of the core and left standing by the boring tool,

FIG. 31.—Kendall's apparatus.

and the needle is automatically locked by the release of a spring when the lowering tool is withdrawn. In Fig. 31 is shown the compass box *a* with its strong screwed-on lid *b*, and inner glass lid *c* held by a screw collar. The pillar *d* bears the compass card *e* while *f* is a tube sliding on *d* flanged and serrated at the top. About this is a spiral spring *i* pressing the flange upward for its toothed edge to grip the compass card *e* against the glass lid *c*. A slot and pin on *d* prevent rotation of the tube. The catch lever *g* holds down *f* by the flange when the apparatus is set; it turns on pin *g'* on the box floor. The floor trigger *h* hinged to *g* has a flange and spiral spring *h'* for operating the catch lever and permitting *f* to grip the card bearing the needle. An India-rubber ring under the card aids the teeth

grip, preventing sliding. In action the lowering tool holds trigger *h* out. At the core and after sufficient time has elapsed and the needle has come to rest, the lowering tool on being withdrawn releases the trigger *h*, throwing the catch *g*, allowing *f* to ascend and lift the card off its bearing, pressing it against the glass lid *c*.

The core is now wrenched off and lifted to bank and on unscrewing lid *b* the orientation of the core is read. The weaknesses of the apparatus are the same as those of Vivian's apparatus; chiefly insufficient protection against water pressures which is more necessary here, since there are more moving parts. The drawbacks of space demands in the core and trouble in the measuring method have not been removed any more than in Vivian's method. Again there is the liability of premature disturbance of the needle due to shocks as in wrenching off the core. There appear to be as little data in professional literature respecting its actual employment as in the case of Vivian's apparatus.

Wolff's Apparatus.—This device was invented in 1889,¹ and marked the introduction of a new feature. In this method the apparatus was lowered over a stub of core in the hole and a mold taken. Clockwork was used to clamp a magnetic needle after a predetermined time. The core was then removed and orientated from the clamped needle attached to it. Figure 32 shows Dr. Wolff's method for fixing the compass in a mold or cast, the latter being a plastic material. The apparatus consists of a two-part tube A_1A_2 , with a lead filling *B*, which serves to guide and hold tight the lower plastic mass giving the imprint of the

FIG. 32.—Wolff's core-cast device.

¹ See German Patent, 47, 221, Oct. 27, 1888; also *Österr. Z. Berg-Hüttenw.*, Nos. 41–43, 1906.

core below. Between A_1 and A_2 is a compass box C of non-magnetic material with a compass D and a clockwork mechanism E screwed on tight, which has been set to operate at a predetermined time. The plastic mass having been lowered over the core stub and allowed to harden, and the needle arrested, the apparatus is raised and the position noted. The core is now lengthened by the usual coring process, wrenched off and raised to bank. Here it is fitted to the impression in the cast and turned with the compass until the needle plays in the position previously noted. The dip and strike can now be read.

The method appears theoretically to be well suited to its purpose and it has the advantage of increased protection for the compass and clockwork mechanism, and also the time taken in insertion and employment is shorter than in previous methods. However, its success depends on many factors which preclude its adoption in general practice. Thus we have the following disadvantages:

1. Mud and cavings prevent good impressions.
2. A flat upper fracture on the core surface is more suited to the process than inclined ones, because very inclined wrench faces prevent good impressions.
3. On inclined core faces tube A_2 is likely to slip and render results faulty.
4. The core must be solid and fast; this is not possible in shales, schists, etc.
5. On fitting the mold aboveground the core must have been raised in exactly the same position as it had when the mold was taken, and this is almost impossible.
6. The minimum size of core is 5 to 6 cm., otherwise the impression is not clearly recognizable.
7. Even with all the above conditions fulfilled, taking the mold, lengthening the stub, wrenching it off and raising it occupies too much time.

Koebrich's Apparatus.—In this method the position of the compass with respect to the core is ascertained by means of a clearly cut mark on the top face of the core with the aid of the apparatus shown in Figs. 1 to 6 (Plate

III). In Fig. 1 (Plate III) note that the cross-guided heavy rod a is connected to the straight bit chisel a_1 by means of a conical joint. The bit has a small recess X on one side. Over the heavy rod the gun-metal body K is fixed by a conical Öynhausen joint bb' (Fig. 2). The bored-out non-magnetic box K encloses a watertight ground-in stopper

PLATE III.—Koebrich's core orientation apparatus.

V. Inside the cap are a clock and compass and the compass is arrested by the wing F of the clock U (Figs. 3, 4) moving clockwise, taking with it the lever arm h of the double-armed lever 1, 2, 3, (Fig. 5). In this way end 3 of the lever which is bent round engages the arresting spring f and frees it. This latter springs up and clamps the needle against the cover plate of the compass. A circular graduation about the axis of F is arranged so that the interval between

the divisions is 1 hr. The glass-covered clock lies together with the compass in the frame *G* (Fig. 3). Four projections *m* are provided in the housing so that the mutual positions of the clock and compass are maintained by fitting into corresponding niches in the frame. In order that the frame itself be immovable with the gun-metal box it has four studs *n* fitting in recesses in *K*.¹

For setting up the apparatus the angle between the niche in the end of the chisel and the north end of the needle must be known. Koebrich himself gave the direction of the chisel the 12 o'clock line of the compass and let the niche of the chisel direct itself with respect to the north end of the needle. (The angle thus indicated is 0 deg). In order to avoid errors in this indication the inventor has replaced all screw joints with conical joints. In action the procedure is as follows: Adjust the arresting device to act about 15 min. after all the rods have been let down in the hole. Then assemble the apparatus as in Fig. 3 and suspend it in the hole until about three-quarters of the stroke off the floor of the hole. Now a powerful blow is struck with the chisel, producing a mark (Fig. 6) on the rock which will show the nick mark of the chisel in suitable rock. After the blow the chisel remains until the needle is set and is then pulled out and the indicated time read off the compass. In the usual way of core boring a core is made, lifted out and orientated. The free-playing compass is held so that the angle between the north end of the needle and the nick projection marked on the core has the same value as when the apparatus was assembled, and according to Koebrich 0 deg. The compass is turned so that the needle reads the previously indicated hour, thus giving the position of the core as it had formerly been in the hole. The dip and strike are now easily obtained.

Koebrich's apparatus was a big step forward over preceding methods both in respect to protection from internal injury by boring operations and in respect to the trust-

¹ FREISE, F., Die Entwicklung der Stratameter, *Österr. Z. Berg-Hüttenw.*, No. 42, p. 546, 1906.

worthiness of the results. The apparatus is durable and simple and will withstand considerable water pressure, but the difficulties of clockwork devices are here only ameliorated, not prevented. It has many disadvantages:

1. In friable marls, medium sandstones, weakly cemented conglomerates, etc., it is useless because here we get neither core nor marking satisfactory.

2. A second blow, on account of the rod torsion, would mean a turn of the chisel and a complication of the orientation.

3. Much time is used up in altering the tools for marking, coring, etc. This often takes 6 to 8 hr.

MacGeorge's Core Orientation Method. MacGeorge (1884) was the first to appreciate the importance of obtaining the inclination of the core at the time of orientation. He used a brass tube set eccentrically, and furnished with a bell mouth below, the office of which was to receive the extremity of any piece of core left standing at the bottom of the bore, and, as the apparatus is forced down, to press on one side and break off the piece of core.

A plummet *a* (Fig. 33) is suspended midway in one or more phials of warmed gelatine *b* in suitable containers in the core catcher. The whole apparatus being now left unmoved for 2 or 3 hr., until the fluid in the phials has cooled and set, is withdrawn, and the core extractor unscrewed. The phial of liquid gelatine is firmly grasped and kept in the same relative position as the core in the borehole. The phial, by means of its internal indications, will enable the piece of core to be replaced in its natural position for observation, and thus there may be readily ascertained (by examination of the markings) the true dip and strike of the strata, or the underlie and bearing of the reef, of which it originally formed a part. We shall discuss the method further when dealing with MacGeorge's deviation device later.

FIG. 33.

Gothan's Stratameter.—This device was invented in Goslar (Hartz) Germany in 1899 and is the first kind of orientating apparatus in which a recording contrivance is directly fitted to a rotary core barrel during coring. It has been used to great depths in Germany and is attached to a single-barrel core drill. It consists of an instrument case attached to the top end of the barrel, the case holding a magnetic compass (and in the Otto-Gothan device also a plumb bob), a soft sheet and a clockwork mechanism. The clock previous to lowering is set to trip at a chosen time. The core is drilled and stays until the clock trips, when the compass is clamped and the plumb bob dropped into the soft sheet, providing an indentation on it. The barrel is then withdrawn and the orientation deduced from the clamped compass and position of the indentation. Gothan also provided a swivel stand so that the position and inclination of the core may be reproduced to visualize the orientation. It has been frequently described.¹ We shall describe the Otto-Gothan device later on.

In Fig. 1 (Plate IV) note that the clockwork and compass are placed in a delta-metal box G which is fixed and guided by a second housing G_1 . The first housing is fixed to the ring e screwed into the boring cylinder a . The fixing device for the magnetic needle l consists of a spring n fixed in the upper part of the clockwork and actuated from below by the conical rod o . While the needle is free rod o bears against a lug of lever p and holds its end p_1 away from the balance q . If the pointer r is set to any chosen number, on reaching this time number, spring n acts by a lug s engaging in the corresponding notch so that the small wheel s_1 connected to arm disc s raises up arm r_1 . Thus

¹ REDMAYNE, R. A. S., "Modern Practice in Mining," Vol. 1, 1925.

MACREADY, S. A., *Bull. Amer. Assoc. Petroleum Geol.*, Vol. 14, No. 5, p. 565, 1930.

FREISE, F., "Stratameter und Bohrlochneigungsmesse," 1906.

ULLRICH H. and WERNEKE, H., *Mitt. Markscheiderwesen*, Heft 4, p. 38, 1902.

British Patent Nos. 2220, Jan. 31, 1899, and 21,183, 1901.

U. S. Patent No. 649,636.

FIG. 1

FIG. 4

FIG. 2

FIG. 5

FIG. 3

FIG. 6

the needle l is pressed up against the stay m and fixed. Simultaneously the stud o is freed from lever p and the spring t presses the lever end p_1 against the balance, thus stopping the clock.

The core is broken off now and the whole raised to the surface. The boring cylinder, provided below with two marks A and B , is now unscrewed and the core top is free. The core is marked with a diamond or in color and then it is adjusted on a disc chuck v (Fig. 4) which has a shell u so that the marks coincide with the diametrically opposite marks A_1 and B_1 on the shell u and turntable v . The compass is now placed on this (usually on a top core shell u_1) and being still fixed is turned to occupy the same vertical plane as A , B or A_1 , B_1 (Fig. 3). On releasing the needle and letting it come to rest in its north meridian, the whole table is turned until the north end of the needle registers the previously noted time. The position thus indicated is that which the core had previously in the hole and thus the strike is obtained.

Gothan's apparatus was the first to meet the demands of durability, simplicity and rapidity in manipulation with any measure of success. It has been used at great depths and experimentally tested to 100-atm. pressure for more than 2 hr.

The casing mentioned above has a further non-magnetic rod connection of 4 m. above and about 2 m. of bronze core barrel below to protect it from local magnetic influences. Very satisfactory data on its application have been obtained by Professor Schneider, of the Berlin School of Mines, in Upper Silesia and Galicia.¹ It has been used in depths of over 3,500 ft.

It is a surer apparatus and greater time saver than Koebrich's method, because it brings the orientation marks and the core to the surface. It does not depend on chisel marks like the latter and also the check is made aboveground. Further, in Koebrich's method the core has

¹ *Mitt. Markscheiderwesen*, Heft 4, p. 40, 1902; also O. ERLINGHAGEN, *Glückauf*, No. 23, 1907, for tests at Aix-la-Chapelle.

to be specially marked thus using up more time, while in Gothan's method the apparatus is actually a part of the rods so does not use up the time. Furthermore, it gives direction and amount of deviation.

The demerits of Gothan's apparatus lie in the uncertainty of the measuring device and

1. We do not know whether at the moment of arrest the needle maintains its correct relation to the strata.

2. We cannot guarantee no twisting of the core on extraction, a tendency which increases with depth.

3. Kicking of the core on wrenching cannot be avoided and this minimizes the reliability of the result.

4. We do not know the state of the core, whether fast or loose, when the needle was arrested.

5. Blunted core catchers cause faulty results. (For success a sharply defined core is required; also the core must be jerked off sharp and its lower face must be clean fractured without traces of friction markings.)

Meine's Stratameter.—Dr. Meine of Berlin invented his well-known apparatus about 1902.¹ He utilized a messenger ball dropped down the drill rods instead of a clock to trip a clamp for locking a compass needle on a core barrel.

The apparatus (Fig. 34) consists of a lower part *a*, which can be unscrewed from an upper part *b*, the former having a bored-out portion holding a needle and arresting lever. The short arm of the lever *f* can be depressed by a ring *g* lifting the needle against the plate *p* and arresting it. In the hollowed part of the lower portion the internal part *c* of the apparatus rests on a ring of wood fiber or like tightening material, and it can be screwed up tight by a screw nut *d*. Through the center plate *c* goes the rod *h* rotatable about its long axis through a stuffing box. This rod has top and bottom lugs, the lower one engaging with a flange of the ring *g* causing it to turn, while the upper or eccentric lug *k* stands tight under the conical point of the pin *l*. When the latter pin descends vertically the lug *k*

¹ British Patent No. 16,514 and German Patent No. 154,496.

is pushed aside, so that the rod *h* turns and with it the ring *g* to arrest the needle *f*.

The descent of the pin *l* cannot be directly effected by the rinsing water, but when the lead ball *n* is dropped in the rods it deflects the current and its surface is sufficient to considerably hinder its momentum. When ball *n* meets the pin *l* the obstructed current throws a back pressure

FIG. 34.—Meine's stratameter (original form).

FIG. 35.—Meine's stratameter (modified form).

on the rinsing pump manometer. Thus the ball with the water presses down pin *l* through its friction socket to actuate eccentric *k* on rod *h* and so arrest the needle. This instant of arrest can be read on the pump manometer by a visible back kick of the indicator, because then the water gets a freer passage through the channel *o* to the floor of the borehole. The whole process lasts only a few minutes. Now the rods including the stratameter, core barrel and core are lifted out and the north direction of the needle transferred to the core.

The above apparatus has a whole series of structural modifications, as for instance in Fig. 35. Here the arresting

rod *e* is borne by two rectangular shoulders through the internal housing by means of stuffing boxes or friction sockets in the base plate. These lugs are double armed and are connected by a right-angled rod *k* connected to a lever *v* through the arm *w* to the magnet needle. The upper lever is so arranged that when descending the rod *e* moves its inner arm downward and the outer one upward. In this way *k* is in tension, pulling, and the forked end of lever *w* presses down a plate *m* which touches a leather based rod *n*. As soon as *m* is let down the spring *p* presses against it and prevents it retreating. The leather ring *o* now lies on three teeth in the head of the needle and thus holds it fast in its natural north position.

In order to detect the presence of a magnetically disturbed region the precaution is taken of placing another needle about 30 in. below the first one and operated simultaneously with it. From their difference of directions the presence of a magnetic disturbance can be recognized and so a true orientation can be made.

Meine's stratameter is a simple, sure and easily manipulated apparatus well fitted for its task. It is insensitive to water penetration. Thus sand and the like can not enter to hinder the action of the finer parts, and, moreover, these parts are easily accessible for inspection and cleaning. It is very convenient to operate, since it does not interfere with the ordinary working processes of the borehole. The apparatus is inserted in the rods once and for all, it being only necessary to drop in the ball and observe the rinsing pump gage when a reading is required; then the core is wrenched off and the whole raised to the surface. It fits the tools and no extra objectionable extractions are needed. Any doubts in the results obtained are due to the same causes as discussed for Gothan's method.

Of the apparatuses in this class Gothan's apparatus is the greatest time waster and Meine's device one of the greatest time savers. The chief factors operating against Meine's apparatus are

1. Shocks may cause the arresting pin to function.

2. Slight rotation of the core on fracture in hard beds.

3. Fragile cores.

Thurmann's Stratameter.—The apparatus (Fig. 36) consists of a shell with a compass device. Above and below the shell are bronze rods; the one above is about 83 cm. long and one below about 73 cm. long, as shown. The iron rods are equally distant from the needle, *i.e.*, 1 m., but this distance is not sufficient to cut out the disturbing influences in the vicinity. The device consists of a stratameter base *A*, the interior joint cap *B* and an external casing *C*. Cast on to *A* is a petroleum container *D*, in the floor of which the small pressure compensation tube *R* is screwed and in which a leather plug *P* moves like a piston. Over this, held by a safety bar *St*, is the compass box with the magnetic needle *N*. This is covered by a glass plate which can be screwed off. Under the needle lies the horizontal arm *H* of the arresting cone *K* on the base of the box which is held by the spring-pressed nut *M*₁ and the spiral spring *F*. The rod of the cone extends up through the joint nut and a leather disc *S* placed over the rod prevents the penetration of borehole mud. A pressure or blow on the rod forces it down, thus pushing aside the arresting cone on to the erect arm of lever *H*. Its lower arm raises the needle from its seat, pressing it against the glass cover plate and holding it fast.

Mud and rinsing water cannot enter because the internal compass box and the space about the tube *R* and the cone *K*, beside being spring compressed, is full of petroleum. The external casing is now fitted and the apparatus let into the hole. The procedure from here on is exactly as with Meine's apparatus.

It will be seen that Thurmann's apparatus is very much like Meine's in form and manipulation. It has all of Meine's advantages over Gothan's apparatus and it exhibits some small improvements on Meine's apparatus.

A special advantage is that the interior of the apparatus is provided with a protective filling of petroleum against the entry of rinsing water. In percussive boring—assuming

it produces a core—Thurmann's apparatus is certain in action, since here shocks cannot bring about preliminary disturbance of the needle, a factor which is not provided for in Meine's apparatus. The internal construction of the apparatus is much simpler and the arrest of the needle

FIG. 36.—Thurmann's stratameter.

FIG. 37.—The North German Deep Boring Co.'s stratameter.

occurs much sharper than in Meine's device, because the transmission of the arresting action takes place by means of only two pieces of mechanism and not by means of a series of intermediate members.

The North German Deep Boring Company's Strata-meter.—The North German Deep Boring Company of Nordhausen have produced a device of the stratameter

type but somewhat different in construction.¹ In Fig. 37 the tube R_1 lies inside a wide tube R_2 (moved by the rods with nuts and spring) and carries in its upper part the closed compass box B filled with oil. The rinsing current escapes by way of the holes O, O , in the head of the core tube R_1 . When a determination is being made the external tube is lifted up so far that these openings are covered by the internal projections V of the external tube. In this way an excess pressure of water is set up which actuates a spring-loaded piston k a little further up through the bores n, n . This causes the rod S to free the needle which was hitherto fixed. After the needle has settled down, the external tube is lifted higher and when the water holes O, O are passed by V_1 they are again free and the piston k is unloaded. Then the spring F again comes into operation and the needle is fixed orientated. It can now be drawn further so that the core, broken off by the core breaker on the external tube, can be raised to bank.

The apparatus is in many ways similar to that of Meine or Gothan in principle and construction, but the needle is freed by the rinsing water pressure by moving the tubes relative to one another. The needle is also brought to rest in a similar way. There are two advantages in these variations over the other methods. First, there is a slight saving of time in that the needle does not follow the turning movement of the rods but after adjustment can rotate with them and swing back before coming to rest. Second, there is the by no means small advantage that the needle is always ready for measurement and cannot be thrown off through unavoidable thrusts on the pin. Unintentional freeing of the needle is absolutely impossible, since the rinsing current is suited as long as the wider openings O, O are free and should a throttling of the passage through O, O occur the piston k will soon be influenced. Such a throttling, however, cannot occur if the outer tube is raised.

¹ German Patent No. 168,596; also *Österr. Z. Berg-Hüttenw.*, No. 43, p. 561, 1906.

The instrument can also be so constructed that the needle is not freed by the relative displacement of the two tubes R_1 and R_2 but by an improved water lead in which a valve is closed under the pressure of a spring. The valve spring is so adjusted that the valve stays open with the normal rinsing current and will only shut on an increase in the speed of the rinsing pump.

The same objections apply in the main here as to the apparatus of Gothan with respect to core fractures, etc.

Lapp's Device.—This simple apparatus was invented in 1906 by Heinrich Lapp of the well-known firm of deep borers in Ascherleben, Germany. The simple principle shown in Figs. 38, and 39 has been adopted since in numerous devices. Figure 38 shows a longitudinal section¹ of this core orientator with two horizontal sections below. It consists of a cylinder a of suitable dimensions made in two halves, the lower one fitting over the core in the hole. Under the magnetic needle b , which is borne on a spring spindle bearing c , is a plate d of soft material. The needle has a lower side pricker e . Above the needle on a rod i is a plunger f carried through a shear pin h and having a ring buffer g at its bottom end.

On the rods being lowered and the bottom of the cylinder fitting over the core stub, the plunger f descends by its own weight, or by the rod action, and buffer g presses the needle down, making an imprint of e in the soft plate d and holding the needle in its position of rest. The shearing pin h prevents any turning and the lug k with the peg k' in the housing a serves for correctly adjusting the housing in the core tube.

The device suffers from the usual defects of this type of apparatus, *i.e.*, cavings, poor cores in friable strata, turning shocks, etc. Compare Hillmer's deviation and dip measuring apparatus made by the same firm and dealt with later on.

Koerner's Core Orientation Apparatus.—This apparatus was invented in 1907 by a German engineer, G. Koerner,

¹ German Patent No. 171,349, May 25, 1906.

of Nordhausen. It is essentially a double-gimbaled pendulum apparatus. It is screwed to the upper part of the core box and carries indicating needles which are fixed in posi-

FIGS. 38 and 39.—Lapp's core orientator.

FIG. 40.—Koerner's core orientating apparatus.

tion by dropping in a weight and releasing a fixing device which forces pointers into a cork disc. Like his deviation device, it shows the dip in amount better than direction, the latter being obtained by computation. The pipe drill and core barrel are orientated out of the well by measuring each stand. Figure 40 shows the apparatus for aligning

the cores on the surface. To the upper portion of the core box *a* screwed to the boring rods *b* is secured a plate holding a pipe *c*, which leaves a space between it and the walls of the core box for rinsing water. In the center of *c* are oscillating needles *d* and *e* supported on their respective gimbals or universal suspensions *f* and *g*. Gimbals *g* are weighted on one side by weight *h*, causing *e* to incline. Above *d* and below *e* are cork pistons *i* moved by springs *j* toward the needle points of *d* and *e*. The cork disc *i* is held by rod *k* allowing *d* to oscillate freely and carries an arm lever *l* rotatable about the long axis of the apparatus, the lower end of this lever holding another arm *m* by means of rod *c* to actuate the lower cork plunger *i*.

Under the top plunger *i* is a gunlock trigger-releasing device actuated by rod *n* operating springs *j* which press the cork pistons *i* against the points of pendulum needles *d* and *e*. Needle *d* is used for indicating the dip of the bore-hole and *e* for the lateral deviation due to the action of weight *h*. To facilitate this the cork discs *i* are faced with paper scales on which the needle points prick holes. As electric cables can not be introduced into the hole during boring, the positions of the indicating needles are fixed by a messenger weight dropped in releasing the above device from *n*. The movement relative to the meridian is taken with respect to a mark made on the core box.

FIG. 40a.

In core boring the needles are fixed before wrenching off the core; then the core is extracted and the core box arranged on the surface in such a manner that it is slightly inclined and a definite mark arranged on the meridian. The cork pistons *i* are withdrawn and the needles released, taking up a position in accordance with the inclination of the core box. After the needles come to rest pistons *i* are again released, and the new position of the needles, in which the scale of the apparatus coincides with the meridian, is recorded. Thus, as shown in 40a, we get the points

a and b obtained underground to take up the new positions a' and b' on the surface. In both cases the parallelogram of displacement gives the direction in which weights h have dipped plumb needle e ; which directions are shown by lines oc and oc' , and, since the line is in the meridian, angle coc' will be the rotation of the apparatus on extracting the core box. If the core is turned with its mark from points c to c' it will have its proper geographical position aboveground as below. A pendulum may be used instead of the plumb line.

The chief objections to the appliance are:

1. Dropped messenger weights are unreliable.
2. In the mud rotary system the apparatus may fail to function.
3. Much time is taken up in surface orientation.
4. Many unaccountable turning movements are not provided for.

The apparatus, particularly in respect to the methods of aligning the geographical positions above and below ground, has been subjected to severe criticism by Dr. Freise¹ and the engineer, Erlinghagen.²

Rapoport's Method.—The idea of this device³ is one embodying the former notion of a mold, as in Wolff's apparatus. It is very ingenious and though apparently unsuited to the conditions of actual practice, in its present form, contains the germ of an idea which may be useful to investigators and inventors. We have failed to trace any literature dealing with its application in the field, but believe it should not be disregarded.

Figure 41 shows the apparatus which consists of a cylinder a , let down into the borehole and having an axial channel b to which an upper conductor c can be joined for compressed air or pressure water. Underneath, channel b is closed by a valve d which opens an exit channel e on excess of internal pressure. The hollow body a possesses four borings f at 90 deg. to one another radially in superposi-

¹ *Organ des Verein der Bohrtechniker*, 1907.

² *Glückauf*, p. 737, June 15, 1907.

³ German Patent No. 172,179.

tional planes. In each of these, under the pressure of a spring, is a movable piston *g* on rods *h* carrying on their exterior ends hinged movable porcelain heads *k*. If the rod is moved outward by internal pressure these heads take a mold of the borehole walls. A compass *n* whose needle *m* is arrestable by the lever *o* actuated by the spring *p* is used for taking the strata strike. There is a piston connected to *o* which, as a result of the pressure of spring *p*, can

FIG. 41.—Rapoport's device.

close a duct leading to the channel *b*. The piston is pressed up when a means of pressure appears in *b* and the needle is freed to take up its position. If before raising the apparatus out of the hole the pressure channel is closed, the piston *g* goes in first and then *q* is brought by the spring *p* to the original position, thus again locking the needle.

Obviously very hard strata, and very friable strata too, make the application of the device, in its present form, useless; but, as said, we present the apparatus for its possible use under suitable modifications.

Florin's Method.—This ingenious apparatus was invented by a chemist, Jean Florin, of Brussels in 1908¹ and

¹ FLORIN, J., Enregistreur l'orientation des strates au fond des trous de sondage, *Annales des mines de Belgique*, Tome 13, p. 781, 1908.

consists of a photographic device with a lead block base. The apparatus was lowered over the core which had been previously marked by the trepan and the lead block took an impression of the core head while the needle inside was photographically checked by special appliances.

In Fig. 42 it will be seen that no clockwork or other complicated mechanism is required, the strong, pressure-proof box holding very little movable apparatus. This box

FIG. 42.—Florin's camera device.

is filled with water and inside suspended by rubber rings is a simple photographic apparatus *a*. Below this is a magnetic needle *b*, a phosphorescent disc *c* and an inter-changeable lead base *d*.

Staggered holes with gratings allow water to penetrate to the interior in such a way as to counteract pressure effects while preventing foreign bodies from entering. Starting at the top we have the photographic apparatus in the non-metallic box in which is a small round and rigid celluloid film covered with an emulsion of silver bromide in gelatine, very sensitive to light and obtainable at any

chemist's. This film is placed exactly so as to receive the image of the needle *b* and guide marks on the phosphorescent disc *c* below it. The very luminous objective has an aperture of *f*.3 and focal length of about 40 mm. and is specially corrected for the refractive index of water; the distance from the film is constant. In front of the objective is a small shutter plate *h* which opens only on pressure being applied, on a rod projecting externally, when the apparatus meets the core. The magnetic needle *b* is freely suspended uncontrolled by any mechanism and is swung so as to function even when the apparatus is tilted. Behind it is the thin copper disc *c* covered with a substance insoluble in water and containing calcium sulphide. (This is very phosphorescent when properly made in the way employed for this device.) It has the property of great luminous emission. Black guide lines have been traced on the disc.

A small distance from the above parts is a plate of phosphor bronze sufficiently thick and strong in which are four holes of different diameters. These holes serve as guiding points and enable one to ascertain whether the lead plate has been displaced during the manipulation of the apparatus. Other guiding points enable the bronze plate to be set; also all the rest of the movable parts of the device. Against the plate is a lead plate for taking the core impression on its outside and the impression of the holes on its upper face.

For action the disc is taken out and made very phosphorescent by burning before the surface of the sulphide a few centimeters of magnesium ribbon; this strongly excites the phosphorescence so that the disc remains luminous enough to enable one to read a watch in the dark for 4 or 5 hr. This is then screwed back in and the lead plate put on and the shutter closed. Now in a dark chamber the sensitive film is fixed and the apparatus filled with water and closed up, the water being as near as possible in temperature to that in the borehole, avoiding air bubbles. This does not affect the action of the apparatus at all. The instrument is now ready to lower into the hole.

First a trepan is sent down to mark the core head with a blow and then raised to allow the apparatus to enter. The lead plate *d* on the base outside takes an impress of the core face with its mark. At the same time the lever coming into contact with the core uncovers the objective. After a few seconds the needle is at rest and overexposure of 20 to 30 min. allowed. The image of the needle and the guide points is thus fixed on the sensitive plate. The device is now raised, an interior spring closing the shutter. At the surface the lead plate shows the core-face impress with trepan mark on the lower side and the impression of the four holes on the other. The film, when developed, shows the position of the needle and the guiding marks on the phosphorescent disc. Thus the core is orientated and later coring is completed and the core compared.

The instrument is robust, the lenses of the objective being completely isolated in the middle of it and being of great thickness are strong enough for the job. It is only necessary to clean the device carefully after use, the whole of the parts, except the needle, being of copper alloy.

If the borehole water is too hot for normal gelatine the film should be plunged into a bath of 5 per cent formaldehyde solution; this makes the gelatine insoluble and capable of resisting decay without impairing the sensitiveness of the film or the development of the image, which is done by a slow process. The phosphorescent plate is designed to do away with electric lamps with accumulators which are not suitable for shocks.

The factors operating against the device are the great consumption of time in letting in the trepan to mark the core and its extraction, etc. Cavings also affect the marking and friable strata prevent its employment. If there is no orientating coupling it suffers all the defects of any other apparatus, giving directions aligned on its own markings.

Goodman's Core Orientation and Borehole Deflection Apparatus.—This device was invented by Professor Goodman of Leeds University in 1908 and can be employed both for orientating cores and surveying borehole devia-

tions. It consists essentially of a tube which can be fitted over the core stub, the tube containing a hemispherical pendulum and clockwork arresting device adjustable to a predetermined instant.¹

In Fig. 43 the hollow cylinder *b* is shown in the borehole *a*, its prolonged lower part being capable of fitting over the core stub with a scratching tooth of steel or diamond for

FIG. 43.—Goodman's apparatus.

scribing the same. The hollow pendulum *c* bearing on pivot *d* on the circular base *e* is graduated externally on its rim *c*₁ and has an agate bearing *i* for the pivot. The cone ends in a short screwed stem *g*, and a magnet *h* rests on it. The hemispherical screwed cap nut *k* holds stem *g*, securing the needle *h* to the top of the cone *c*. The base plate *e* is borne on a flange of cylinder *b* and is framed to the upper clockwork base plate *l* by pillars *m*. On top of nut *k* a small plunger *n* is provided axially central passing through the

¹ See also British Patent No. 23,003, Apr. 29, 1909.

upper base plate *l*. Its lower end n_1 is enlarged and hollowed round to make an all-round contact on the hemispherical cap *k*. A helical spring *o* about *n* presses under *l* and against *n*. The upper end of *n* passes up through lever *p* which is hinged at *q* and has a cross pin at *r* to facilitate disengagement of *n* from *k*. On releasing *p* the spring *o* pushes plunger *n* down on to cap nut *k*, fixing the cone and needle in position. This release is provided by the clockwork in frame *s* by means of flexible wire or cord *t*, from the alarm spindle *u*. After winding up, the alarm is set at any chosen instant for release and in this state is lowered into the borehole. When release occurs *t* is unwound from *u*, freeing spring *o* and pushing *n* down, thus fixing the cone and magnet in the position in which they have come to rest. The hermetical seal is completed by means of the cap piece *w*. Other mechanical or electrical means for release may be adopted.

The magnet is secured so that its center line lies in the central plane of the cone passing through the 0 to 180-deg. mark. A gage is used to get the inclination of the highest and lowest points of the rim base of the cone above the base plate *e*, and the graduations give the azimuth. The angle of dip is got by the said difference of heights divided by the base diameter of the cone.

The scribes 4 at the foot of the tube are for marking the core by raising and lowering the tube. Then when brought to bank the dip of the strata in amount and direction can be obtained by noting these marks and the bedding lines, if any.

The apparatus while strong and reliable, given its peculiar conditions of application, has the following disadvantages:

1. Clockwork mechanism is likely to err under the effects of shock on insertion and extraction.
2. The device has to be separately used to give good results; this means much loss of time in changing tools, etc.
3. If used as a deviation recorder there is no continuous record. Each record is a separate insertion and withdrawal.

4. If there are no bedding planes visible in the core the apparatus is not so acceptable as otherwise.

5. Friable strata are against its employment as an orientator.

Hall and Armentrout's Gyrostatic Method.—This device is one of the few known instances of the application of a self-contained gyroscopic compass in borehole investigation; most other types have their gyromotors actuated by a source of electrical energy aboveground, as will be explained in Chap. IX. This apparatus¹ has been adopted in the California oil fields and is suited for employment with any rotary core drill of conventional form. In Fig. 44 it will be seen to be mounted on the bracket *a* on top of the inner core barrel *b* in a chambered casing *c* with closed top *d*. This casing has dividing partitions *e* and *f*, housing registering elements.

In the lowermost compartment is a non-magnetic compass *g* preferably a gyroscopic compass of the Sperry² type including the conventional frame *h* having trunnions *i* by which the compass as a unit is supported from the wall of the casing *c*. This compass includes a motor *j* constantly driving the sensitive element of the compass, the latter being mounted to actuate a dial *k* disposed uppermost of the compass. The motor *j* is of the alternating-current type and current is supplied thereto from an alternating-current generator *l* driven by a direct-current motor *m* with current supplied to the motor from a battery *n*. The dial *k* has an annular toothed edge adapted to be engaged by a dog fixed to the angular extension of rod *o* extending to the cutter bit at the base of the barrel to a point between certain of the bits *p*. Guides *q* are provided

¹ U. S. Patent No. 1,656,809, Jan. 17, 1928.

² British Patents Numbers 15,669/11 for the gyrocompass of E. A. Sperry; also *Engineering*, Vol. 91, p. 816, and Vol. 93, p. 722; Glazebrook, "Dictionary of Applied Physics," Vol. 4, or T. W. Chalmers, "Gyroscopic Compass," pp. 54, *et seq.*, Constable & Co., London, 1920.

For full mathematical treatment see A. L. Rawlings, "Theory of the Gyroscopic Compass and Its Deviations," p. 38, Macmillan & Co., Ltd., London, 1929.

for the rod to slide in and as the rod *p* has a sliding fit in the tool head its vertical movement causes the dog to engage or disengage the teeth on dial *k*. On engaging it locks the dial against rotation and it can seat within a groove of a stationary rim member of the compass frame *h* securing the arm of rod *o* from lateral movement. Normally the dog is urged to engage the teeth by a spring *r* to lock the dial.

The gyroscopic compass possesses the feature of indicating the astronomical north direction regardless of the proximity of magnetic masses and similar disturbances. This feature will be more fully described in Chap. IX.

In operation, the core drill rotates continuously in one direction to form the core *s*, and, with the drill in drilling position the projecting lower end of the rod *o* being in contact with the bottom of the well, holds the rod in elevated position against the action of the spring *r* to retain the dog out of engagement with the dial *k*. After the core has been completely formed the drill is brought to rest, after the lapse of a few seconds, during which the sensitive element of the compass can function to actuate the dial *k* so as to indicate due north.

FIG. 44.—The Hall-Armentrout gyrostatic core orientator.

It will be seen that on raising the drill from the well the lower end of rod *o* is pulled out of contact with the well base permitting spring *r* to function and the dog to lock the dial. This gives the direction. The core drill is now taken out, care being taken not to turn the drill pipe or disturb the recording elements by shocks and bumps. The sleeve *t* is unscrewed from drill head *u* keeping the latter

stationary and the pipe lifted from the attachment. Door *v* permits access to the gyroscope compartment. The direction of the core is read from the north indication of the compass.

The apparatus to be quite successful should have some form of orientating coupling. The amount of inclination being obtained directly from the core and frame dips, an additional dip measurer for the barrel itself should be provided to check the absolute core dip. This because a fixed gimbaled gyrocompass is by no means as reliable in dip readings as one slung from a buoyant ring in an annulus of mercury.

Dixon's Apparatus.—A. F. Dixon and D. Upham of New York first invented this device in 1924,¹ and it is essentially a core orientating appliance. Its chief parts are a base core-marking tool, an index sheet or card rotatable relative to the tool holder, its position in azimuth controlled by a gyrocompass, and a marking device for obtaining the sheet position.

Figures 1 and 2 (Plate V) are vertical sections of one form of the device, it being noted that there are several possible forms, according as the gyrocompass is in the apparatus or a surface master gyrocompass is used connected down the hole by wires to a "repeater motor" lowered into the hole with the index sheet, marking device and tool. Consider the form of construction shown in Fig. 1 where we have a bipartite cylindrical casing, the top part *A* of which is the compass chamber and the bottom *B* is the tool holder screwed on watertight. A cable *w* conducts current to the gyroscopic compass *C* which is freely suspended and carries a sheet or card *S*. Below *S* a marking device *M* is mounted on top of chamber *B* and actuated by the electromagnet *E* so that when the latter is momentarily energized by a brief current impulse the marker is rocked and pricks sheet *S*. The electromagnet circuit *x* may be closed at will by switch *s* in *B*. The cable wires *y* supply current to the *B* chamber electromotor *P* and can be

¹ U. S. Patent No. 1,130,694, May 31, 1927.

closed by switch s' . Motor P drives drill D through gear-train G . When the apparatus is lowered into the hole and the drill point strikes the bottom, the drill is pushed

PLATE V.—Dixon's gyrostatic core orientator.

up and collar U closes the motor switch s' starting the motor and driving the drill.

Shortly afterward collar V closes switch s in the circuit of the electromagnet E causing pricker M to mark sheet

S. Collar U keeps switch s' closed until the hoisting apparatus allows the drill to drop again. The drill shank is not packed to keep out pressure water; the chamber B is flooded with water unless previously filled with petroleum, glycerine or other non-corrosive fluid. The switch box is usually oil filled. Figure 2 is a modification of Fig. 1 wherein corresponding members are the same and are lettered alike with unit indexes, except that the sheet marker M' is here a stylus mounted on a carriage moved on a track M^2 by chain M^3 from drum M^4 of clockwork Z for timing M' . This clock also closes switch Z^2 by arm Z' of the motor circuit; otherwise a surface switch is used. The track M^2 is parallel to the radius of the index sheet S' part of the way, and while the stylus carriage is traveling on this part of the track the stylus marks the sheet.

Before lowering from the surface the clockwork is wound up and set to close motor switch Z' at a known time and then rotate drum M^4 for moving the stylus. On gaining the bottom of the hole the motor starts and the tool indents the rock and the mark position will depend on the twisting of the device on lowering. After this the sheet-marking device operates and marks the index sheet. The position of the marking device depends on that of the tool, but the position of the sheet is governed by the compass. After marking the sheet and rock the whole is raised to bank, a coring apparatus is lowered and a core extracted with the said indentation on it. This mark is correlated with the index sheet mark and the direction of dip ascertained. The objections to the device are the additional coring operations, dangers of cavings spoiling markings, the great consumption of time and therefore money and the diameter limitations for all such devices as previously noted.

Hanna's Apparatus.—This device which is essentially a compass and plumb-bob apparatus has been fairly extensively employed in the California oil fields, the inventor having been formerly assignor to the Associated Oil Company of San Francisco. The compass and plumb bob

are controlled by the inertia of a heavy rotating mass the rotational speed of which does not coincide with that of the rods, the resulting momentum difference being harnessed. Figure 1 (Plate VI) shows¹ the position of the apparatus capsule 7 relative to the boring bit 2 the core 6 and the rod string 4. It is filled with a non-corrosive liquid like petroleum to counteract pressure. Figure 2 is an enlarged view of the mechanism with Figs. 3 and 4 cross-sectional views of the same on lines 3, 3 and 4, 4, respectively.

The compass needle is automatically locked at a predetermined time after drilling ceases, and before breaking off the core, as also is the plumb bob, thus giving direction and amount of dip.

The capsule 7 (Fig. 1) is made of non-magnetic material as also is the portion of rod string near it, and it is supported by fasteners 8 (Fig. 2) to the inner surface of the rod string. It has a removable cap 9, for access and inspection, and an eye suspension ring 10. The compass 11 may be either of the magnetic type (as here) or gyroscopic, and from it hangs the plumb bob 12. The compass needle 14 is held by a locking rod 15 passing through the compass case 16 while the plumb bob can be locked by the reticulated disc or wire screen 17 engaging its pointed end 13.

The locking mechanism for compass and bob is a spring motor 18 on frame 19 inside the capsule. The spring-driven shaft 20 of this motor is connected to a train of gears 22 (Fig. 3) with a fan-type governor 23, and a double-cam 24 provides the vertical reciprocation of the compass locking rod 15. The plumb bob locking member 17 is also mounted on compass-locking rod 15 by set screws 28 and both locking devices are arranged so as only to move freely vertically. The ratchet wheel 31 and its pawl 32 on shaft 20 are the starting and stopping mechanism operating through the arm 34 and spring 35. The most ingenious part of the apparatus is the means for automatically starting and stopping the spring motor at the proper time with relation to the drilling operation. For this purpose

¹ U. S. Patent No. 1,665,058, Apr. 3, 1928.

an inertia motor is adopted. This is a heavy solid lead rotor 36 on a vertical shaft 37 suitably borne in bearings 38 and 39. It is so made that it will lag behind the rotation

PLATE VI.—Hanna's inertia-rotor apparatus.

speed of the drill, thus continuing to rotate some time after the latter, owing to its momentum. On shaft 37 a worm gear 40 is engaged by a toothed projection 41 on a vertically movable rod 42 supported in frame 19. As worm gear 40 rotates, with respect to rod 42 and its lug 41, rod 42

is caused to move up and down. The vertical travel of rod 42 is controlled by a light compression spring 43 and a collar 44 engaging lug 41. The attached setting rod 45 with a V kink 46 and angle bend stopper 47 moves also vertically upward or downward, and when the V bend 46 encounters the detent arm it moves it out, disengaging governor 23. Thus the inertia motor and associated mechanism provide for starting and stopping the spring motor.

For operating the device the capsule is sunk into the hole to the position shown by 7 (Fig. 1) with respect to the core and when coring commences both compass and bob are locked and the mechanism is in the position shown in Fig. 2. Owing to the inherent inertia of the motor it does not turn until the rods have rotated several turns. Thus lug 41 gets a planetary movement about the worm, moving downward on it before the rotor starts to turn. In this way rod 42 moves down the V kink 46, engages and moves out detent arm 34 clear of governor 23 and the spring motor operates shaft 20 through a quarter clockwise turn. Then by the attached mechanism described the compass is freed and the plumb bob and their locking bars held clear.

When drilling ceases the rotation of the worm gear relative to the tooth 41 takes place, for then the momentum of the inertia rotor 36 is such that it continues to rotate after the drilling action ceases when the worm gear moves tooth 41 and rod 42 upward. The mechanism may be timed for 20 to 30 sec. after the drill stops, when the V part of rod 45 will have moved up engaging the detent arm 34, allowing the spring motor to act. This action of the spring motor now moves the stud 25 upward, compressing spring 26 and locking the compass needle 14, and at the same time the grid disc 17 locks the now quiescent plumb bob in position. Thus we get the direction and amount of core dip. Cover 9 is removed at the surface and the inner mechanism taken out after noting the compass orientation marks on the case. The spring shown dotted at 48 is then rewound because it operates shaft 20.

This device has been well tried in California oil wells and has yielded reliable results. Its chief drawbacks are that for very narrow diameters its mechanism is too complicated and delicate; thus it has a critical limiting borehole width. It can not be used for the continuous survey of boreholes, being essentially a core-orientating instrument. While it does not interfere with the ordinary coring operations and requires no special lowering process or apparatus, it is confined to rotary boring methods.

The ingenious notion underlying the apparatus is extended in Riemer's apparatus wherein the surge effect of an annulus of mercury is utilized to produce somewhat similar results.

Macready's Method.—This interesting modern method was devised by George A. Macready of Los Angeles and can be utilized at depths exceeding 6,000 ft., though

FIG. 45.

FIG. 45a.

FIG. 45.—Borehole apparatus records. (*By the courtesy of George A. Macready.*)

FIG. 45a.—Types of compass pendulum photographs.

the greatest run to date is only 3,780 ft. It has been developed and employed in the Trinidad asphalt deposits, the Venezuelan petroleum fields and the western oil areas of America. It is suited to holes of fairly small diameter.

It is essentially a multiple-photograph orientation apparatus consisting of a pendulum and compass device, the positions of which are recorded on a long strip (Fig. 45).¹ The drill rod is orientated by external joint scribing at every 10 ft. and aligned on a surface reference mark. Photography was chosen as the azimuth recording medium because then the pendulum and compass needle can swing freely during recording, the photograph automatically averaging the mean point about which swing, if any, occurs. The recording instrument² is inside the inner barrel to minimize relative displacement from the core. The record is of the nature shown in Figs. 45 and 45a. The most recent development of this apparatus (Figs. 46, 46a)³ has a long photographic strip on a reel which records the position of the pendulum and compass needle at regular intervals, thus permitting a complete survey of the well and allowing for records of several positions of the core barrel during coring. In interpreting a record it will be observed that the white lozenge-shaped shadow of the magnetic compass card is eccentric to the large dark circle of the exposure. The amount of eccentricity measures the deviation of the hole from vertical at each exposure because the eccentricity is caused by the compass being suspended as a pendulum. The inner core barrel is marked (and it may also mark the core) and is attached to the instrument in a recorded position so that the relative positions of core and record are fixed and known. The inner core barrel is swiveled inside the outer barrel. The outer core barrel is rotated by drill pipe or drill rod to cut around a core and the inner barrel is forced longitudinally over the core and at the same time shaves the core a fraction of an inch smaller so that the inner barrel takes a firm friction hold on the core. A spring on the inner barrel

¹ From a private communication.

² MACREADY, G. A., Orientation of Cores, *Bull. Amer. Assoc. Petroleum Geol.*, p. 571, 1930.

³ By the courtesy of the Bulletin of the American Association of Petroleum Geologists.

FIG. 46.—Macready's multiple-photograph orientation instrument.

FIG. 46a.—Assembly of Macready orientation core drill.

holds the inner barrel firmly on the core at all times, so that the core is not parted if the outer barrel raises up because of vibration or chattering. Circulation fluid passes between the barrels and discharges at the cutters to provide cooling action. Exact dimensions of construction are important to secure best results.

Photographs can be made at 1-, 2-, 4- or 8-min. intervals from the time the instrument is set to go into a well. About 75 exposures can be made (in $4\frac{1}{2}$ hr. at 4 min. each) so that the 4-min. interval is suitable to 6,000 ft. depth. Incidentally, the course of the well is surveyed at the same time.

CHAPTER V

FLUID METHODS OF SURVEYING BOREHOLES

Introductory Note.—The outline of a fluid in a container was the first means by which the deflection of boreholes was surveyed in a systematic manner; it is still the most widely employed method.

Present-day plumbing devices are, so far as demands of reliability can go, very highly complicated, sensitive to injuries, costly and bothersome and also time absorbing in their application. Many of them also require numerous auxiliary appliances, *e.g.*, special rods. On the other hand, the fluid method which we shall describe is cheap, simple in construction and needs less special accessory tools and thereby is for most purposes satisfactory and reliable. The fluid used may be wax, gelatine, hydrofluoric acid, copper sulphate, paraffin or any other substance likely to leave the outline of its surface on the tube container. It depends on the fact that the fluid surface in hollow vessels is always horizontal, independent of what position the vessel takes up. If, therefore, the position of the surface is continually known, we may draw exact conclusions as to the position of the vessel at any time. We can fix this surface position by having a glass flask as the hollow vessel and using dilute hydrofluoric acid which has the property of etching the glass. The flask about half full of acid shows the surface in the inclined position as a clear visible ellipse. The action of the acid on the flask walls can be accelerated or retarded by altering the strength of the acid solution.

In the older methods a short bottle, as in Fig. 47, was suitably enclosed in a protecting cover, half filled with fluid and let down into the hole. In the case of an etching acid, like HF, the etching action of the fluid on the glass walls

can be accelerated by strengthening it. In a straight hole this outline is a circle and an ellipse in an inclined hole. The angle which the plane of this ellipse forms with the axis of the horizontal plane is equal to the angle between the axis of the flask and the vertical, *i.e.*, the sought angle of deviation (Fig. 47). Let MN be the vertical and AB the vessel axis then the angle β formed between these lines is the required deflection angle. In the vertical position of the flask the surface is at CD .

FIG. 47.

Actually the surface is at EF due to the deviation with CD forming the angle δ with EG .

Now δ can be solved from

$$\tan \delta = \frac{FG}{EG} \quad (7)$$

where FG is the double difference between the highest and lowest positions of the fluid surface while EG equals the diameter. For carrying out the method by means of HF a flask half filled with dilute acid is let down to the place where we wish to measure the deviation. In modern practice a larger tube is used closely fitting the borehole, say a core tube, which, however, should not be shorter than 15 ft. In a tube of less length or of essentially smaller diameter than the borehole we can not assume that the axes of the hole and tube coincide or at least any line parallel thereto. If, on the contrary, the tube is about 5 m. long and its diameter only a few millimeters less than that of the hole, the angle between the tube and borehole axes will be so small that it may be neglected for practical purposes. In order to protect the flask in the tube against the pressure of the water column present in the borehole, the tube must be made airtight above and below. The upper joint has a rod thread and both joints are provided with neck and hook flasks, whereby they can be rapidly screwed on or off. The airtight joint is absolutely necessary because otherwise water would penetrate into the tube and at the greater depths the pressure would

shatter the flask. However, for small depths and pressures bottles are still used, and in order to make the filling of the flask as convenient as possible choose a flask with a wide neck. The flasks used by chemists with ground-in glass stoppers suit very well; however, common preserving bottles with screw joints can be used. The external diameter of the flask should be about 3 to 10 mm. smaller than the tube diameter. In order to center the flask therein it is wound about with band tape to the suitable thickness. It is advisable not to put the flask directly on to the lower joint but to interpose between a small cushion or wad.

The hydrofluoric acid is to be got in the trade in various strengths, mostly at 40 per cent acid. This is diluted by water down to about 20 per cent, which will give good results. Otherwise it is advisable just before the test to fill a flask with the fluid and to determine how much time is required to get a clearly visible mark at the fluid surface. With a 20 per cent acid 15 to 20 min. are usually required.

There is yet to mention the strong etching action of the acid, for carrying which it appears advisable to have strong leather gloves. Especially should care be exercised in taking the vessel out of the borehole, as it may at any time occur that it is broken or has been eaten through by the acid, which then flows out of the opened joints over the hands of the person. The vessel is taken out of the tube at the end of the measurement, emptied and the interior and exterior rinsed in clear water; its further handling will not be dangerous.

The advantages of fluid methods of borehole surveying are:

1. The apparatus is easily constructed, read and manipulated.
2. It is cheap and the parts obtainable anywhere.
3. It can be employed in boreholes of small diameter.

The principal disadvantages of the method are:

1. It does not provide continuous registration in and out of the hole.

2. With some fluids capillarity effects are harmful to the readings, especially in small diameter boreholes.

3. Turning of the apparatus in the hole either on going down or on being raised out nullifies the direction results but not the amount results for inclinations.

4. The centering of these devices is usually neglected.

Nolten's Method.—The oldest method applying the fluid principle is probably that introduced by G. Nolten, a district counselor of Dortmund in 1873.¹ Hydrofluoric acid is used as the fluid which eats an outline at its surface on a glass cylinder. The direction of the deviation is obtained from a clockwork arrested magnetic needle in a cylinder fixed to the fluid vessel.

FIG. 48.—Nolten's apparatus.

In Fig. 48 is shown the vessel of colorless glass having an exactly cut base with perpendicular walls. If the vessel is half filled with dilute acid and left about half an hour in an inclined position we get the etched mark *ab* (Fig. 49). If we now lay the vessel horizontal we get another mark *cd*. If we draw a parallel to *dc* through *a*, then in the triangle *abf* resulting we know sides *af* and *bf* so that angle *baf* can be determined.

In the hole the glass vessel is encased in a watertight, sealed measuring cylinder *c*. This is connected by a screw spindle *l* to the rods or rope (the whole internal part can be extracted from the shell on this spindle). Gutta-percha discs *a* and *a*₁ guard the apparatus against concussion shocks. The top opening of the measuring cylinder has three notches 60 deg. apart which are for fitting on three corresponding plates *X*, *Y* and *Z*. After putting in the plates they are locked fast by a 60-deg. turn. The locking screw goes through plate *X*. On the lowest plate *Z* stands the glass cylinder *c* which has a fixed graduation

¹ See also REDMAYNE, R. A. S., Vol. 1, and *Pr. Zeitschrift.*, Vol. 27, p. 176.

of 0 to 100 deg. and a movable circular scale on its base *d*. For a horizontal position *c* coincides with a vertical line etched on *d*, which must always correspond with the 0-deg. point of the fixed scale. A rubber plate tightens the cover of *c* with the aid of a pressure screw *s* and a lead cone *e*. On the center plate *Y* is the compass *f* in a glass housing, its needle *g* being arrestable by the lever *h* when the forked end of the lever is pressed upward. This is done by means of a spring *j* which usually holds the lever off

FIG. 49.

FIG. 50.

against its pressure and is disengaged by the clock *i*. There is a 0 to 100-deg. graduation on the top of the compass which agrees exactly, in the vertical direction, with the fixed 100 scale in the base plate *Z*. The clock hanging on upper plate *X* is set to actuate the arrest about 15 min. after the instrument has reached the spot in the hole where the reading is being taken. Now from the position of the needle and marks, as in Figs. 49 and 50, and the graduated base plate we can get the deviation direction. We can obtain the amount of inclination by taking the highest and lowest points on the line. If the inclination varies as in the case of a hole with changing dip direction, we get the deviation curves etched sometimes as in Fig. 50.

The accuracy of the measurements may be enhanced by taking a plaster cast of the cylinder and lines and magnifying them, then measuring with a cathetometer. Without the compass the apparatus is not reliable for tests of the direction of deflection owing to the effects of capillarity, turning of the apparatus and the thickness of the etched mark. The apparatus has been tested for water-tightness at depths of over 3,000 ft. and has given satisfactory results.

Among the principal disadvantages of the apparatus are:

1. In hot strata special cooling devices have to be employed and they interfere with the efficiency of the method.

2. In holes varying in direction of deviation and subject to concussion of the rods there is the likelihood of there being several etched marks which give rise to confusion.

3. The apparatus can only make intermittent surveys and cannot be arranged for continuous reading down the hole.

Rühland's Apparatus.—This device was invented to obviate the confusion of lines arising from several accidental markings, as under 2 above.¹ In this method a

colored fluid was let down the hole in a special chambered container and means provided for emptying the same while a magnet was employed to give the direction of deviation.

FIG. 51.—Rühland's apparatus.

In Fig. 51 the apparatus will be seen to consist of four chambers 1, 2, 3, and 4 under one another and connected by valved orifices. The chamber 3 is made of glass and the others of a non-magnetic material. Chambers 2 and 3 can be shut off from the others by means of the valves v_1 and v_2 . Valve v_2 extends by a rod a up into chamber 1 where it supports a needle n and has a band b_1 . A tube t is screwed about rod a also projecting up into chamber 1 and ending in a band b_2 . Valves v_1 and v_2 are pressed by springs s_1 and s_2 and remain fixed on their seats as long as the angle arresting hooks c_1 and c_2 are not actuated by the coils d_1 and d_2 . The induction coils d_1 and d_2 , of which c_1 and c_2 are cores, when uncharged with current from the line leading up to the surface, keep the hooks and therefore the valves shut. The two current lines from the coils go insulated in the same cable to bank but are completely

¹ German Patent No. 148,068.

independent of each other. As soon as valve v_2 is opened by way of the coil, hook, and rod the needle is arrested against a stop head e , chamber 1 is full open and chamber 4 discharges. A circular scale is etched on the inner wall of chamber 3 for measuring the deflection of the colored surface. The whole apparatus is guided by three skids f and these with a base plate strengthen the instrument, guide it into the hole and center it. On reaching the spot to be investigated in the hole, coil d_2 is first excited from the surface which causes hook c_2 to pull up and spring s_1 opens valve v_1 to chamber 3. The colored fluid flows in from chamber 2 and indicates its position on the walls of 3. After about 10 min. coil c_1 is similarly operated by excitation from bank and so opens valve v_2 and lets the fluid flow out into chamber 4. At the same time the needle is arrested.

Now the apparatus is drawn to bank and the heights of the highest and lowest positions of the color line are easily read. This with the needle data gives the amount and direction of the deviation. Over Nolten's method this method has the advantage of certain reading, not confused by subsequent readings produced by accidental change of direction. Also the line is sharper and as the vessel is not injured by the fluid it can be utilized longer. Furthermore, the needle is not arrested by clockwork but at the direct will of the surface operator and the spherical surface of the glass magnifies the reading; it can be arranged to read to 10 min. of arc with precision verniers. Its disadvantages are those of all fluid instruments as stated in the introductory note on this section.

MacGeorge's Clinograph.—In any discussion dealing with fluid methods of surveying boreholes prominence should be given to the method devised in 1884 by E. F. MacGeorge and tested at Sandhurst and Stawell in Victoria, Australia. This because the method marked a significant advance upon all preceding methods and instituted an epoch of research into the problems attendant on borehole deflection which is still active. The apparatus will be

clear from Figs. 52 to 56 showing the phials, guide tubes and clinometer. The phials contain liquid gelatine. Clear glass phials (Fig. 52) nearly filled with a hot solution of gelatine and each containing a magnetic needle in suspension, free to assume the meridian direction, are encased in a brass protecting tube, let down to the required depth and allowed to remain for several hours until the

FIG. 52.—Gelatine phials.

gelatine has set. On withdrawal the phials are replaced at the same angle, at which they cooled, by means of the congealed surface seen through the sides of the phial; this is brought to the horizontal. Revolving the phial upon the part where the magnetic needle is seen embedded in the gelatine, until the needle is again in the meridian, the phial is then in the same position, both as regards inclination and azimuth, as it was when its contents congealed. Thus we get the gradient and bearing of the borehole at that spot, and these are measured by means of an angular instrument constructed by the inventor. The mean of the several phials gives a more accurate result. By repeating this operation at measured intervals throughout the borehole, its course is mapped.

The Phials or Clinostats.—The construction of these can be readily seen in Fig. 52, which shows the position of the magnets and plummets while the phials *are hot and vertical*. If inclined, say at an angle of 45 deg., the plummet rods, still vertical, would occupy the then uppermost part of their containing spheres, while the magnets, still horizontal and free, would rest vertically upon the pivots in the then lowest portion of their containing spheres. The clinostat is a true cylinder of glass fitting in the brass guide tube. At the lower end, the phial has a short neck and a bulb, and within the latter a magnetic needle is held upright on its pivot by a glass float, in every position of the phial. This allows the needle, which is fixed upon its "peg," to assume the meridian freely at all times without touching the sides of the hollow bulb. Passed through an airtight cork and screw capsule at the upper end is a small glass tube terminating in another bulb above, and with its open lower end inserted in a cork which enters the lower neck of the phial. This prevents the escape of the needle and float already mentioned as occupying the lower bulb. The upper bulb contains a delicate plummet rod of glass consisting of a fine rod terminating in a plumb of solid glass below and in a small bulbous float of hollow glass above. It is very carefully adjusted to the specific gravity of the solidifying fluid in which it, like the magnet, is immersed. Its poise is so adjusted as to insure that the rod or shaft shall be truly in the perpendicular line, whatever the position of the phial and bulb may be. *While fluid, the contents of each phial (which completely fill both upper and lower bulbs) permit the plummet to hang freely vertical in the center of its chamber,* and allow the needle in the lower bulb to assume the magnetic meridian exactly. When the phial is at rest in any position from vertical to horizontal, and pointing in any bearing as it inclines, the contents solidify on cooling, and by this means hold fast the indicating plummet and magnet embedding them in a solid transparent substance. The phial then contains within itself an automatic registra-

tion of the inclination and azimuth at which it set while, say, 500 ft. deep in the borehole. It is easy therefore, after its withdrawal, to tilt it to the same angle and to the same quarter of the compass as before by simply bringing the embedded plummet to the vertical, and the needle to the meridian. These clinostats are heated, inclosed within their brass protecting tubes and lowered by rods on a line to the desired spot in the borehole. Their contents are allowed

FIG. 53.—MacGeorge's clinometer.

to cool and congeal and are then withdrawn for inspection. The phial with its congealed contents is placed in a sheath of brass tubing (Fig. 53) attached to a movable arm which carries the index of a vertical arc. This sheath corresponds with the Y's of a theodolite, and carries the phial firmly upon the same principle as these carry the usual telescope. The upper bulb of the phial is brought into the field of two crossed microscopes, which are carried with the arm round the vertical arc; these are kept truly in the same plane at every angle of inclination by a parallel motion. There are vertical lines drawn upon the object glass of each microscope, these being, of course, kept truly vertical by the

parallel motion just mentioned. The phial is revolved in its sheath, and the arm is moved along the arc by the tangent worm, until the embedded plummet is made perpendicular from each point of view, or parallel with the vertical lines of reference just described, as viewed through the two cross telescopes. The phial is now at the same angle of inclination at which its contents solidified, and its lower bulb will

FIG. 54.—The Swedish clinometer-goniometer.

be found nearly in the axis of the revolving arm and an inch or more above the center of a horizontal circular mirror having a system of parallel lines engraved across its face. Reflected in the mirror will be seen the image of the embedded needle which pointed north before it was fixed by congelation in the borehole. If we now revolve the mirror until the 270 deg. of the graduated circle is opposite the north (or notched) end of the needle and until the reflected image of the needle is sensibly parallel with the engraved

lines, an index at the side of the graduated mirror frame will give the exact angle between the needle and the vertical plane of revolution of the phial. This is, in fact, the magnetic bearing of the inclined phial and of the borehole which it occupied at the time of the application of the test. The same operation is repeated with the other phials which complete the set, and then the results are combined and the mean taken in the same manner as if six separate determinations of the same horizontal angle and azimuth had been made with a theodolite or an altazimuth instrument. These six phials—or self-registering compass clinometers as they may be termed—are encased within, and protected by, the cylinder or guide tube.

Figure 54 shows the more modern clinometer-goniometer now being used in the Swedish iron fields.

Cylinder or Guide Tube.—This is a strong brass tube, about 6 ft. in length, into which the phials accurately fit (see Fig. 55 which shows part of its upper end with the phials in their brass slide in the act of entering). This tube or cylinder is securely closed against the heaviest water pressure likely to be encountered even in bores of 2,000 ft. depth the glass clinostats being too fragile to bear exposure, unprotected, to such a pressure. The guide tube is passed down the bore by means of $\frac{1}{2}$ -in. diameter service piping jointed in measured lengths, the effect of the iron being kept from the magnets by the interposition of a distance tube of brass. For use in hot strata, where cold water must be poured down this small piping in order to cool the cylinder below, the upper part of this is pierced with holes out of which the cooling stream from the tubing may issue and flow down the outside of the cylinder, thus congealing its contents. Where the bore is approximately perpendicular and the strata comparatively cool, these may be dispensed with, and the bore surveyed by lowering the guide tube with a small wire rope. Figure 56 shows an actual survey of a 500-ft. borehole by this method at Stawell, Victoria, in the early eighties. The principle of this apparatus is still widely used. The apparatus itself

is now largely of historic interest, the chief demerits accounting for its disuse being

a. It does not provide a continuous record on insertion right down the borehole, the total of many individual

FIG. 55.—MacGeorge's guide tube.

FIG. 56.—A borehole survey by MacGeorge.

insertions having to be grouped for the final reading. This is tedious, time-wasting and costly.

b. It fails in magnetic strata and steel-cased boreholes.

Maas Method: Hydrofluoric Acid with Gelatine.— In this method a small glass tube about 6 in. long by a little

FIG. 57.

FIG. 58.—Two-circle goniometer to measure inclination and direction of drill holes. (After E. E. White.)

over 1 in. in bore is used. It holds HF in one end and has gelatine in the other holding a small compass. To obviate

the danger of premature solidifying of the gelatine in holes of great depth, with the consequent fixing of the floating needle, a small thermos flask (Fig. 57) is used to hold the gelatine and needle, the other half of the apparatus having the tube of HF. Figure 58 shows the special goniometer used for checking the results. The Maas method used to be popular in the Lake Superior mining fields years ago. The method is fully described and illustrated by E. E. White.¹

The Modified Maas Method.—In the modern adaptation of Maas' method HF with either gelatine or paraffin wax is used. If either of the latter is adopted it is melted in the hole after lowering the instrument.² This obviates the thermos flask trouble of Maas and MacGeorge.

The apparatus *a* (Fig. 59) is let down on a cable *b* which carries a connection *c* to a dynamo aboveground. An arc *d* in the circuit is carried through the casing, with the glass vessel *e* inside, and when in position the current is switched on and the wax or gelatine *f* melted, giving about three-quarters of the container length of fluid. In this thinned state it has a horizontal surface and the magnet of the compass *g* enclosed in the very mobile liquid can easily move, as seen in Fig. 59. After a given time the current is switched off, the paraffin again solidifies and the apparatus is withdrawn. The amount and direction of deviation are now easily read.

The apparatus is widely used today owing to its simplicity, cheapness and reliability for most purposes. It has been well tried in South Africa.

Meine's Apparatus.—As a variation of the principle of using a fluid for marking (just for the time of the survey) the position of its surface in a vessel, Dr. F. Meine of Berlin produced the device³ of Fig. 60. In effect it consists of a body being automatically immersed in a fluid

¹ *Bull. Amer. Inst. Min. Eng.*, No. 71, p. 1277, 1912.

² FAUCK, A., Remarks at the November, 1910, Convention of Austrian Mining Engineers and Architects, *Organ des Verein der Bohrtechniker*, p. 277, Nov. 20, 1910.

³ German Patent No. 157,879.

at a definite instant and drawing the same out. The immersion and extraction are effected by clockwork, which at the same time actuates the arrest of a magnetic needle.

In Fig. 60 the casing may be screwed off into two parts *a* and *b*, and they are separated by a cross floor *c*. In the upper part are the motion apparatus and the immersion

FIG. 59.

FIG. 60.—Meine's apparatus.

body. The lower part is filled with an etching or coloring fluid. The clockwork *E* stands on plate *P* which is supported on three legs *d*, and on the upper cover plate of the clockwork a strap *S* carries a magnetic needle *N*. The spring of the clockwork moves a drive of three gear wheels *i*, *i*₁ and *i*₂ and a toothed rack *i*₃ which carries the immersion body. This arrangement causes the rack either to descend

with the immersion body or to pull it out of the fluid. This is done by automatic switching for the drive i_1 i_2 . The material of the body immersed may be altered to suit the fluid being used, and this latter may be etching or coloring. With colored fluid the curves can be indicated direct on to paper.

On taking a measurement the clockwork is adjusted so that the needle is clamped about 10 min. after entry into the hole. After this arrest, the body is immersed in the fluid for about 2 min. and is then raised out of it automatically. Since the motions can be easily fixed beforehand aboveground, one is informed as to how much time is required for effecting complete marking.

The apparatus has the advantage of great simplicity in construction and manipulation. Even if the measurements are restricted to a definite time and the apparatus must be let down anew for each reading, there is the advantage that after once adjusting the mechanism everything is automatically controlled without special attention on the part of the people attending the device. Again to be able to indicate the position of the fluid surface directly on to a paper will, in many cases, be most convenient and of advantage in the evaluation of test results by computation or graphically. The measurements need not be dependent on a time interval for operation; an electromagnet, surface operated, might be used to arrest the spring. The usual demerits of fluid methods, *i.e.*, single readings, capillarity, etc., hold, but the great defect of the method is the lack of a centering device.

Any method which gives the direction of deviation in the hole is unacceptable if it has no device, as, say, in Erlinghagen's apparatus, to prevent turning of the hole on insertion or extraction, or some other means of showing the direction *in situ*.

Macfarlane's Apparatus.—G. C. Macfarlane's apparatus was probably the first that utilized the electric current and galvanometer which appears such an important feature in subsequent inventions. He measured the electric cur-

rent variation in resistance wires which dipped into a bath of mercury, the immersion of¹ the wires deciding the resistance. The direction of the deviation was obtained at the same time by a freed needle. Two steel cylinders *a* and *b* (Fig. 61) are assembled, *b* inside *a*, with *a* fitting closely in the borehole and with *b* fixed to the boring rods. The lower part is filled with mercury which, when the

FIG. 61.—Macfarlane's apparatus.

apparatus is in the perpendicular position, reaches up to the lower edge *e* of the uppermost of the two insulated strips *e* and *f*. Another insulated strip is at *g*. The iron wires *h* and *h*₁ are insulated down to a short distance (about 1 in.) over the mercury and joined together in a copper wire *i* which goes through the rods to bank where it is connected to a tangent galvanometer and battery.

If we now turn the rods slowly in a hole deviating from the perpendicular, the thin piece of wire *k*, between *e* and *f*, emerges partially from the mercury. In this way the resistance to the passage of current will be increased and accordingly the deflection of the galvanometer will be diminished. When this deflection has reached a minimum, *e* and *g* lie in the plane of greatest inclination of the borehole.

From the difference between the maximum and minimum throws of the galvanometer we may determine, once for all, what resistance a given length of wire *k* offers and so get the inclined position of the hole. A rubber boat *l* floats on the mercury carrying a magnetic needle. This float is guided by rods *mm*. The hard rubber ring *R* standing up on two points at about 90 deg. to the piece of wire *k* is horizontal if *e*, *f* and *g* lie in the plane of greatest inclination of the hole. A steel wire encircles the lower side of *R* and is intersected by *e* and *f* at opposite places and is

¹See also REDMAYNE, R. A. S., "Modern Practice in Mining," Vol. 1, p. 177, and F. FREISE, "Stratameter," p. 43, 1906.

in connection with the supply current from the surface. The wire n is fastened to a pin. In the normal position the mercury presses the needle against the compass ring. The south pole of the needle is insulated, thus a current through n and h_1 must pass through the north pole. As soon as the dip is fixed, a pressure of air is blown on to the surface of the mercury, freeing the needle. When the pressure is taken off the needle settles. Now n and h_1 are connected to the galvanometer and battery and the direction of dip determined by noting that the deflection of the galvanometer is inversely proportional to the deflection of the north pole, which information is provided by the opposite points e and f . The demerits of the device lie in the steel casing and air pressure interfering with the needle; still the method is the forerunner of several continuous registering devices using the same principle. Variations, to the benefit of the device, will immediately suggest themselves, such as non-metallic casings and insulating the pin to the core of an electromagnet.

The Kiruna Method.—This is an electrolytic precipitation method devised by the Swedish Diamond Drilling Company with the assistance of the Jernkontoret—the Swedish Iron and Steel Society—and is named after the famous South Sweden iron field where it was first employed. Prof. Walfrid Petersson of the Royal Mining School, Stockholm, completed the analysis of the method.

As previously discussed, the elliptic outline of a fluid in an inclined container determines the dip angle, and the major axis of it the direction of this dip. If two such containers are rigidly connected a distance apart, the form of the resulting ellipses and their major axes will fully decide the dip in amount and direction. Certain terms are necessary to a mathematical comprehension of the principles involved, thus:¹

¹ PETERSSON, W., *Metoder för Mätning av Avvikelser i Djupborrhål*, *Jernkontorets Annaler*, pp. 224–262, 1922; also *Eng. Min. Jour. Press*, Vol. 117, No. 17, Apr. 26, 1924.

The *zenith angle* or angle between the borehole axis at a given point and the vertical = θ .

The *apsidal plane* or vertical plane containing the major axis of the ellipse.

The *north angle* or angle made by the section of the apsidal plane with the horizontal and measured from the true north = α .

The *apsidal angle* or angle between the apsidal plane and the plane through the borehole centrum and a generatrix scribed on the lining = ψ .

The relation between the variations of the north angle $\Delta\alpha$ and those of the apsidal angle $\Delta\psi$ is

$$\Delta\alpha = \Delta\psi/\cos \theta \quad (8)$$

Thus it is possible to survey drill holes, for the change of the north angle can be calculated from point to point after the angles θ and ψ have been measured. Thus the positions of the tangents to the center line of the hole are obtained at a number of points and the course of the hole can be determined approximately by calculating the open traverse of which these tangents are component parts. The angles are determined by electrolytic registration. This is done by sinking a cylindrical vessel containing a galvanic bath down the hole and precipitating a metallic coating on a cathode immersed in the bath. The outline of this coating shows the position of the cathode in relation to the horizontal plane and if the cathode is of cylindrical form we get either a circle or an ellipse.

Figure 62 shows the registering device consisting of the electrolytic vessel *A* and the anode connected with it, the electrolyte (CuSO_4) and the cathode *B* which is a carefully polished glided copper cylinder on which precipitation is made.

The cylindrical glass electrolytic tube has its long axis coinciding with that of the hole at the spot to be surveyed. The current is supplied from a surface battery through a base contact connected with the anode by means of a pin through the glass. The thin copper sheet anode (not shown

in Fig. 62) closely fits the inside of the glass tube. At the top the tube narrows into a neck with a threaded ring joining the glass tube with the cathode.

FIG. 62.

The registration apparatus is enclosed in a steel tube fitting closely in the hole and the registrations are made as follows:

The zenith angle θ is obtained by noting the greatest ($h_{\max}$) and the least ($h_{\min}$) heights of the precipitation on

FIG. 63.

the cathode cylinder (Fig. 63) and it is found from the relation

$$\tan \theta = \frac{h_{\max} - h_{\min}}{d} \quad (9)$$

where d is the diameter of the cathode.

The apsidal angle ψ is found by measuring the precipitation heights at four generatrices 90 deg. from each other, beginning at the one to which the apsidal angle refers. The heights found in this way are

$$h_0, h_{90}, h_{180}, h_{270}$$

from which we get two zenith angles, θ_1 and θ_2 , showing the dip of the elliptical surface of the fluid in two directions at right angles to one another:¹

$$\tan \theta_1 = \frac{h_{180} - h_0}{d}; \tan \theta_2 = \frac{h_{270} - h_0}{d} \quad (10)$$

Knowing now θ_1 and θ_2 , the direction of the major axis of the ellipse is also known.

The precipitation heights are measured by aid of a special microscope with adjustable tube in which is a scale grad-

FIG. 64.

uated in tenths of millimeters (Fig. 64). It is possible to determine the angle θ to as close as 15 min. which is considered very satisfactory.

When determining ψ less accuracy is to be expected, and this accuracy falls off the smaller the zenith angle θ , *i.e.*, the more vertical the hole. For a zenith angle of 5 deg. the

¹ From some notes kindly supplied by the Swedish Diamond Drilling Company.

average error in ψ will be about ± 5 deg. and for $\theta = 10$ deg. about ± 3 deg.

The manner of proceeding with a survey depends on the accuracy possible in measuring the angle ψ . First get the general dip of the hole by lowering an electrolytic registering apparatus on a steel wire and measuring θ at every 250 ft. or thereabouts.

1. If θ is at least 15 deg. the accuracy in measuring ψ will be such that we may proceed by the method of successive bearings, *i.e.*, a string of drill rods 30 to 100 ft. long is lowered into the hole. At the end of each is an electrolytic registering device and these are rigidly orientated to one another by a scribed mark or generatrix on the rods. The first registration is made with the upper apparatus in the mouth of the hole so that the traverse can be referred to a fixed reference mark on the surface. Then the whole string is lowered until the upper apparatus is in the position formerly occupied by the lower one and a new registration is made. In this way the hole is surveyed by successive determinations length after length.

2. If θ is less than 15 deg., *i.e.*, the hole is more or less vertical, the following method is used because the successive bearings method would be risky, since any errors would be cumulative and might render the survey void. To prevent this, orientation from the surface is used. In this method a string of drill rods is let down from the surface and it has an externally scribed generatrix. Part of it is kept out of the hole for orientating the said mark. Registering sets are put in every 200 ft. and also orientated to the mark. Instead of this mark it is often found more reliable to have a device known as an "orientating coupling." This coupling (Fig. 65) is so made that it does not allow torsion between the rods. Ordinary drill rods make up the rod string and the joints are pitched and nailed to hold them tight. This, with the orientating couplings at each end, keeps the rods straight and orientated to the surface reference mark.

When the rod string and apparatuses have been lowered into the hole the current from a surface battery is switched

on and passes through an insulated copper wire down the rods. The anode of the lowest apparatus is connected to the rod string.

In order to control the manner in which the precipitation takes place and to judge the length of time it ought to last, it is advisable to shunt in an extra registering apparatus visible aboveground.

FIG. 65.

When sufficient precipitation is obtained, the rod string is removed from the drill hole. The precipitation heights on the cathodes are measured and the angles θ and ψ calculated from the above formulae. This method of surveying with orientation from the surface, however, is slow and comparatively a time-consuming work. Therefore the method of surveying with successive bearings is generally to be preferred, if conditions permit its use. In most cases the two methods of procedure are combined. For instance, when surveying a hole vertically set, orientation from the surface is used down to the point where the zenith angle is large enough to allow surveying with successive bearings.

The Kiruna method is intended solely to give information as to the courses of drill holes that is sufficiently accurate for practical purposes. The Swedish Diamond Drilling Company has proved this new method fully.

Good results have been obtained at Kiruna and in the United States with this method. Figure 66 shows several of these, including the 1,300-ft. Oskar borehole. The designers make no pretensions to the great accuracy required in such contracts as freezing shaft holes for instance, but guarantee to survey a borehole put down in

places where the magnetic needle would be useless. Such places are, of course, in iron fields and certain of the basic

FIG. 66.—Specimen borehole surveys by the Kiruna method.

igneous rocks. Moreover, good instrumental work can be done by the Kiruna method in holes of 1.4-in. diameter after due allowance for cohesion and capillarity has been

made. Most modern multiple-photograph or gyroscopic methods have ceased to be of service long before the hole has decreased to such low dimensions, and again this method has often stood the test of repeated surveys, perhaps the most exacting check a method may face.

CHAPTER VI

COMPASS AND PLUMB-BOB METHODS

Introductory Note.—The magnetic compass as a directional agent has been known in the East since time immemorial, coming to Europe in the beginning of this millenium; consequently it is not surprising to find it one of the chief deviation measurers in borehole surveying.

It is a simple and reliable tool even in places of rapidly altering declination, since its readings in the borehole are more or less directly under the surface station where they are being deciphered. In regions of great magnetic disturbance, such as the great iron fields of Sweden and the United States and also in certain iron-bearing basic igneous rocks, it is untrustworthy and misleading. These remarks apply also to boreholes which are steel lined to spots near the place of its application and to apparatuses incorporating any other than non-magnetic material in their construction. It is also conceivable that periods of magnetic storms and the phases of diurnal and secular variation might sensibly affect the accuracy of the magnetic needle.

The plumb bob, on the other hand, is a far more constant servant obeying ever the line of gravitational pull which does not vary to any measurable degree for our present purposes anywhere on the earth. In the short length of the longest plummet used in borehole survey work, masses of great altitude like the great mountain chains or lack of them like the great depths of the sea, in its proximity, can not alter its suspension line to any measurable extent.

One of the earliest uses of the compass in borehole surveys in Britain was that adopted by Mr. Haddow at Younger's Holywood Brewery, Edinburgh, in 1884. It did much to stimulate interest in the compass as a borehole deflection

deflections and thus produced a series of curves. The compass was then stationed at the points *C* and *D* in the mine and the deflections noted. The points *CD* were marked on the plan and a tracing of the magnetic curves set over each point as shown. The observed deflection at *C* was 3 deg., and at *B*, $6\frac{1}{2}$ deg. The bore *E* was found where the curves corresponding to these deflections crossed one another, being about 8 ft. from the expected position.

Although this was a relatively short borehole it well illustrates the truth that nearly all boreholes deflect in greater or less degree. One has but to lay out a few hundred feet of securely jointed drill rods on an uneven ground surface to note how easily this virtual wire will sag and bend to accommodate itself to the local contour.

The Otto-Gothan Apparatus.—This is essentially an improvement or addition to Gothan's original stratameter described in Chap. IV (Plate IV) and the same lettering and terms apply in Fig. 68 as there. The addition consists of a bolt *q*, which, during the running of the clockwork *i*, is pressed by the end of rod *p* as a result of the action of spring *n* which actuates the time indicator *r*. The bolt *q* is pressed against the action of spring *c* so that the bolt is always in contact with another fixed point opposite thereto. On these two points a ring *t* is supported, forming the upper end of a plumb line which swings above the disc *u* of wax or any other soft material. The rod *p* is provided at its lower end with a groove or slot *z*, which, on the arresting of the clockwork, is raised by the spring *n* until the bolt *q* can pass through the slot *z*, so that the latter is pressed out of engagement with the ring *t* by means of a spring *c*, the plumb line being thereby allowed to fall a short distance and to make a mark on the soft material *u*.

The magnetic needle *l* is provided with small pinlike projections, which, when the shaft is raised by the turning of the cam *s*, become inserted in a bar or pad *m* cut from or covered with cork, paper, leather or other suitable material, and the needle is thus held securely in position until the apparatus is brought, for inspection, to the top of the boring

The whole is enclosed in a casing *f* capable of being hermetically sealed, the casing being secured to a plate *e*

FIG. 68.—The Otto-Gothan apparatus.

screwed into the bore cylinder *ab*. The indicating device can be removed from the casing as a whole by undoing the screw. The action of the device is as follows:

When a portion of the core of a boring has been broken off and removed the apparatus is lowered down into the borehole, and when it reaches the bottom the clockwork *i* is arranged to arrest the motion of the magnetic needle *l*

FIG. 69.

FIG. 70.

and to raise the spring *n*. The plumb line is thereby lowered, a mark is made on the wax or like disc *u*, and, should the position of the boring tool be inclined, the mark is outside the center of the disc. The apparatus is removed from the borehole and the direction in which the magnetic needle *l* has been arrested indicates the north and south

line, and the direction and extent of deviation can be ascertained from the mark of the plumb on the disc *u*.

The plumbing plate is scored with concentric rings 2 mm. apart and has north-south and east-west lines, their intersection being directly under the plumb point of the apparatus when the latter is in the vertical position. The plumb takes about 15 min. to come to rest, so that oil is often put in the housing to damp the swing to about 2 min.

The idea is sound and suited to precision work. If its application shows only approximate results this is due chiefly to magnetic surroundings or to its being impossible to set the axis exactly on the borehole axis.

Figure 69 shows the entire apparatus with its small conical tripod legs for fitting to the non-magnetic tube shown in Fig. 70.

Marriott's Instruments.—H. F. Marriott invented his well-known borehole survey apparatuses in 1904 and they have successfully withstood the severe test of prolonged application, particularly in the gold fields of South Africa, for many years. He produced two electrical devices: (1) a continuously working instrument and (2) an intermittently working one which sufficed only for single readings at individual points being surveyed.

Marriott's continuously recording instrument for obtaining the deflections of a borehole refers particularly to surveying the amount of dip,¹ not its direction, and is illustrated in Fig. 71. Figure 71 shows the modified form of the instrument which is essentially a method wherein a pendulum varies the resistance by a rheostat.

Here we have three plumbs *F* pivoted to the vertical rod *E* by the connecting rods *f'* instead of one plumb, as in the earlier design. The strong outside gun-metal casing *A* of the instrument has a hollow brass hemicylinder *B* pivoted truly axially inside it on pins *b*, *b'*. The securing pivot screw *b'* in the base disc *a'* is insulated in an ebony bush. So also are the discs *b*² and *b*³ in the ends of *B* insulated. An ebony disc *c* in the top of tube *A* carries

¹ *Trans. Inst. Min. and Met.*, Feb. 16, 1905.

the contact rings and is screwed to the casing. The brackets *D*, *D'* inside *B* carry the vertical rod *E* with the plumb bobs *F*. These bobs can swing freely in one plane only. The plumb-bob system is attached to a switch arm

G, having a strip of platinum on its upper end so that its movement causes the arm to describe an arc about the pivot *f*. The said strip presses on the commutator *H* carried on rod *E*, which rod also carries the resistance coil *J* connected to *H*. The alternation of conductor and non-conductor strips in *H* causes alternations of current and

FIG. 71.

FIG. 72.

FIG. 73.

cut-out as the switch arm *G* moves, as shown in Fig. 72, or it may be arranged, as in Fig. 73, to start from a maximum resistance and gradually cut out the resistance as *G* moves over *H*. Or, again, it can be arranged to increase the resistance from the minimum according to the inter-spacing of the platinum and ebonite segments in the com-

mutator *H*. The current is supplied through the wires *K*, *L*, from a battery of known electric motive force having a galvanometer and standard resistance box in the line. In this way the declination of the plumb bob is known, and therefore, by means of the galvanometer, a calibration scale can be constructed. The wire from *K* is attached to the top pivot screw *b*, and that from *L* to the hemicylinder *B*, and so to *F* and the switch arm *G*.

When the casing *A* is tilted, the weights *M*, *M*, on *B*, cause the latter to revolve on its pivots *b*, *b'* and bring it to rest in the position in which *G* moves in a vertical plane.

The cable is internally screw-threaded into the instrument at *m* by means of the plug *N* (Fig. 74) having a further external thread *n'* to assist the connection to casing. The cable *O* is also secured in the plug by a screw thread *n*², and a cap *Q* covers the top, holding the gland nut *P* with its gripping pieces *r*.

The instrument is lowered into the hole by a ½-in. wire rope containing two insulated conductors inside it. These lead through the connecting plug of Fig. 74 on the lower end, and on the other to contact rings on the sides of the surface drum on which the rope is coiled, and through which a pair of brushes make contact with the current supply. A measuring wheel, over which the rope passes, gives the distance down the hole to the apparatus. The surface recording instrument is attached at the contact rings, and by the galvanometer system of calibration can be arranged to give a continuous record of the variation in dip of the hole. This instrument does not record the direction of dip. Marriott's second form of this instrument records the amount and direction of dip, but, however, intermittently.

Marriott's Intermittently Recording Instrument for Direction and Amount of Dip in Deep Boreholes.—Referring to Fig. 75 which illustrates the instrument used in this method, it will be seen that *A* is a copper or brass tubular vessel having a screw cap *B*, details of which are shown in Figs. 76 and 77. This screws into the upper end of the

tube *A*, while in the lower end is screwed a similar plug *C* washered at *E*. The wiring connection is similar in construction to that previously described above. These wires *d*, *d'* are carried in two opposite longitudinal grooves *a*², *a*³ removing them from the circumference of the tube *A* from which they are insulated (Fig. 75). One wire *a*², is connected with the terminal *G* and the other, *a*³, with the

FIG. 74.

FIG. 75.

terminal *H*. These terminals *G* and *H* are connected to the resistance coil *J*, and projecting well up through this coil is a needle *K* affixed rigidly to the base plug *C*. When assembling the parts, *K* is screwed in through the base by means of the nut *k'* beneath. Balanced on the point of *K* (Figs. 78, 79) is a magnetic compass *L*, attached to a conical base *I*. *K* balances this hollow base inside, and horizontally over the needle *L* lies the mirror *M*.

When making a survey, the instrument is lowered into the hole by means of the cable hawser to the point at

which it is desired to investigate. A strong current is passed through the resistance frame *J* and allowed on for a length of time sufficient to enable it to liquefy the wax in the tube *A*. When this is considered accomplished the current is cut off, whereupon the magnetic compass *L* assumes the magnetic north and south directions. The wax is then allowed to cool and resolidify, after which the instrument is withdrawn from the hole.

The direction of dip is obtained by noting the declination of the silver mirror *M* from the horizontal with regard

FIG. 76.

FIG. 77.

FIG. 78.

FIG. 79

to the direction of the compass *L* (Fig. 75). The dip is obtained in some forms of this instrument by means of a gimballed dish instead of the plate *L*, which like the plate will become horizontal in whatever position the instrument may be placed when the paraffin wax surrounding it is melted by the current. A little melted paraffin is also poured into the dish or plate so as to seal the needle when it cools. This separation of the needle from the mass of the paraffin prevents the needle from being disturbed by the liquefying or solidifying of the paraffin. It is usual to fill the space about the coil and outside the dish up to the halfway mark, so fixing and warming it. Simple protractors may be used for the two fundamental angular measurements at the surface. Figure 80 shows plan and section of a survey, by these methods, of a borehole on the property of the Turf Mines, Ltd., Johannesburg. The apparatus, though one of the most reliable instruments of its class, is a time consumer in that there is no continuous record of both amount and direction of deviation down or up the borehole. The first instrument detailed registers

only dip in amount continuously and the second, though it gives both amount and bearing of dip, is intermittent. These are the only drawbacks to this clever device, which is independent of torsion in the rods or lowering rope.

FIG. 80.

Möllmann's Apparatus.—This device,¹ invented in Dortmund in 1904, is an improvement on previous pendulum or plumb-bob apparatuses in that the vertical position

¹ German Patent No. 155,849, Oct. 22, 1904.

of the plumb is taken from a pendulum swinging in a definite rotatable plane with the aid of a vernier and scale on a graduated circular segment. In this way errors in obtaining the position of the apparatus are either eliminated entirely or essentially lessened. Figures 1 to 4 (Plate VII) show the interior of Möllmann's apparatus. Through the center of the covers b and b_1 of housing a (Fig. 1) go two screws c and c_1 bearing a rotatable fork d . Below cover b is a plate f with an attachment e against the one side of which presses a spring g in a groove (Fig. 4), and this presses the portion e against a rod h . This rod h can be worked up and down by clockwork from the wheel z' on its prolonged screwed axis k . According to the lift of the rod h a lug n under disc f engages, through the bore m of disc f , a disc p held by spring pressure. Between the discs f and p there is a plate q which is bridged to the fork d and can move it up and down in a slit. The plate q and its bridge is borne on the upper part of the fork under a constant spring pressure by rod r which at its lower end lies on the nose y which is likewise spring-pressed against lever h_1 . The latter is connected by lever s_1 to the disc t (seen in end view in Fig. 2) which is displaceable laterally in the fork d and coated with felt H on one side. On the same axis as disc t is the upper end u of the indicator z which is widened here and toothed. The lower end of z carries a millimeter or circular graduated vernier while the primary scale v for this is on the fork d .

A side weight consisting of little tubes of mercury w is attached under fork d , the purpose of which is to turn the fork and indicator z at every inclined position of the borehole.

Above the apparatus a clockwork is placed which fixes a magnetic needle k' on one side and can turn toothed wheel z' with spindle k on the other side. This turning screws up rod h turning spring g so far that it brings the bore m over the lug n above the spring pressed plate p . The attachment n can now enter bore m of disc f , raising plate q and fixing it between f and p . This fixes the fork on the one

FIG. 1

FIG. 4

FIG. 2

FIG. 3

hand, and on the other hand, by the simultaneous raising of the bar r attached to q , the nose y of lever h_1 is liberated. This is drawn away by the pressure of a spring action on the head of lever s' and the felt-faced disc t is thus pressed against the widened part u of the indicator z . In this way it is brought to rest and permits of a direct reading when the whole is brought to the surface.

Though the device of Möllmann constitutes a progressive step in the science of borehole surveying it is intermittent in action. Owing to the pendulum being only allowed to swing in the plane normal to the fork beams it rapidly comes to rest, hardly 8 to 10 sec. being needed. It is also very easily read by the ordinary boring personnel. The accuracy of the scale readings is read in 20-min. arcs for 10 deg. being thus far superior to previous devices; but even this accuracy is unnecessarily high owing to its being greater than that of the compass. This apparatus is accurate, rapid, reliable and sure in action but unfortunately it is unreliable in respect to orientation of the deviation.

Bawden's Apparatus.—This device, invented in Kalgoorlie, West Australia, in 1905 by Wm. R. Bawden, contains many features which are to be seen in Gallacher's apparatus of 13 years later.

The inner tube A (Fig. 81) has head joint covers k and k_1 with counterweight sectors g, g_1 on the loaded axial pivots which support the tube A . Tube A is attached by further attachments to the counterbalance sectors g, g_1 . The magnetic needle n is likewise enclosed by a loaded spherical housing d and by means of Cardan suspensions all round is thus so mobile that its pin always stands vertical. The spherical housing d has an opening for filling with fluid gelatine and is closed from above by a screw cover and hardwood plate.

For obtaining the dip of the hole two pendulums p_1 and p_2 are provided and are rotatable with graduated arcs e and f on metal plates. On both sides of the plates are reading glasses. The tube A is connected to the plate by a bow. Before using the apparatus the pendulum housing and

compass housing are completely filled with warmed gelatine and then adjusted into tube *A* which is filled with hot water to keep the gelatine fluid. Before reading, the latter is again taken out. The protection tube *A'* is screwed over tube *A* and the apparatus sent into the hole. The counter-balance sectors always permit a rotation of the internal

FIGS. 81 and 82.—Bawden's apparatus.

tube in such a manner that the pendulum can always play free. On the gelatine solidifying the pendulum and the needle are fixed in their positions of rest and these are read aboveground.

The apparatus of Bawden utilizes the principle of Mac-George's device as also does that of Cross,¹ which latter therefore need not be mentioned here. The Bawden

¹ DENNY, C., "Diamond Drilling," pp. 76 *et seq.*, Crosby Lockwood.

apparatus does not escape all the defects of MacGeorge's apparatus but it is more convenient to handle and more robust. Its great disadvantage is that its action is not continuous up and down the hole, it having to be extracted for every reading.

Hillmer's Apparatus.¹—Hillmer also adopted the principle of a plumb-bob point let down on to a prepared base, as shown in Fig. 83. The cylindrical housing *a* (Fig. 83) is

FIG. 83.

filled with a fluid and is let down on hollow rods into the borehole. It consists of a fluid-filled cylinder *a* with a pendulum *P* supported on ball bearings in such a way that it will also maintain its upright position when the housing is inclined. Above the point *S* of the pendulum is a soft plate *G* which cannot turn and bears a spring *F* in such a way that it keeps off the pendulum point. On the upper surface of the plate, freely swinging on a point, is a magnetic needle *N* which has an attachment *A* pointing downward. A piston *K* is provided over the needle in the housing the rod of which is carried through a central opening in the housing top and carries on its top end a piston *K*₁. There is a spring *F*₁ between the latter and the top of the housing which by its pressure keeps piston *K*

in the highest position. In using the device proceed as follows: After having lowered the apparatus to the spot to be measured, and both pendulum and needle have come to rest, a means of pressure (water, compressed air, or the like) is conducted through the hollow rods on to piston *K*₁. This presses down *K* and plate *G*. The attachment *A* on the magnetic needle and the point *S* of the pendulum now bore into the soft plate and both are thus fixed. After raising the apparatus to bank, the position of the two marks can be used to get the inclination of the borehole.

¹ FREISE, F., "Stratameters and Borehole Dip Measurers," p. 53, Aix-la-Chapelle, 1906.

The device is certainly simple and ready for use at any time without delay or special preparation, and it is suited to manipulation by the ordinary boring personnel. Of its drawbacks we may mention:

1. The pressing down of the plate; the needle and pendulum point might be injured by this but it might be regulated by controlling the piston pressure.

2. The waste of time brought about by letting hollow rods into the hole.

3. It has no special centering device and it must be exactly centered. At great depths unbalanced rod loads upset instruments not specially centered.

Dr. Freise of Aachen speaks of the apparatus being shrouded in trade secrecy, a feature that unfortunately does not apply to this apparatus alone.

Gallacher's Apparatus.—This apparatus was invented in Johannesburg in 1918 and possesses features of remarkable ingenuity and mechanical skill. It is designed to survey both the deviation from the vertical and from the azimuth, these to be read direct from the instrument on withdrawal, without surface calculations. We enter into some detail respecting it here because it appears to have lacked the necessary publicity such a device merits.

It consists of an outer casing *a* (Fig. 3, Plate VIII) with an inner casing *b* longitudinally pivoted in it by means of an adjustable footstep bearing in the bottom end *c*.

The inner casing (Figs. 1 to 2*a*, Plate VIII) carries the controlling and recording elements in the form of clockwork, plumb bob (in the shape of a weighted cylinder) and compass, and spring device for controlling the clockwork and fixing the plumb bob and compass at any desired spot. This inner casing is suitably cut away and windowed opposite its weighted side.

Figure 1 shows the inner casing at the clockwork *d* end; Fig. 1*a* shows the other end of the inner casing carrying the cylindrical plumb bob *e*, compass *f* and the clamping device *g* for both.

Figure 2 is a view of Fig. 1 turned on its long axis 90 deg. with cover on.

Figure 2*a* is a view of Fig. 1*a* turned on its long axis 90 deg. partly in section and partly in elevation with cover on.

Figure 4 is an enlarged view of the plumb bob controlling and clamping device *g* in the inner casing and the compass set free with it, Fig. 5 being a sectional view of Fig. 4 on line *xx*. It is possible to have three operative positions of the fixing and clamping arrangements for the plumb bob and compass, *i.e.*,

a. Compass needle fixed from independent movement with its compass case and plumb bob free to move about their pivots.

b. Compass needle and plumb bob both free with compass case held against movement on its pivot.

c. Compass needle and plumb bob both fixed with compass case free to move on its pivot.

Figure 6 shows Fig. 4 when condition *c* above is obeyed. Figure 7 shows an enlarged view of the inner casing with compass *f* and that part of the clamping device which directly operates it. Figure 8 shows a cross section of the inner casing with compass and compass-clamping device.

In the assembled view (Fig. 3) the upper pivot *h* and bearing are of non-magnetic material, like phosphor bronze, as also are the nearest rod connections. In small holes the apparatus is placed on the end of the drill rods; in large ones it is let down by a flexible wire. Both inner case *b* and outer case *a* are cast in brass or other non-magnetic metal. The inner case is suitably weighted to cause it to turn on the end pivots, bringing the registration device under the inspection cover windows. The weighting means are the lower and heavier portions of the controlling and recording elements and the base plates, their centers of gravity lying below the center line of the end pivots and opposite the inspection covers. The clockwork control *i* (Fig. 1), near the pivot end, consists of a lever escapement, a train of wheels *j*, and their cooperating pinions *k* and main spring barrel *l*. The clock itself *d* is provided with

PLATE VIII.—Gallacher's apparatus.

independent setting and adjusting mechanism shown at *m* (Fig. 2); its dial *n* can be graduated to represent any number of hours, preferably a number not much exceeding the maximum time of its employment. The clock is, as said, controlled automatically and capable of wide and varied adjustment.

The plumb bob *e* (Figs. 1*a*, 2*a*) is a loaded pivoted cylinder with peripheral graduations for about 110 deg. and it oscillates in consonance with any variations in the inclination of the inner and outer casings *a* and *b*. Its graduations can be read through a casing cover glass *o* (Fig. 2*a*), which carries a zero mark. The spring-operated means for clamping this plumb bob are the clamping levers *p, p*, which, when in action, bear on the plumb bob, retaining it in the position it assumes at the point to be surveyed. This clamping of the bob takes place through the cam plate *q* (Figs. 1*a*, 2*a*, 4, 6). This clamping device permits of adjustment of the plumb bob and compass at any of the three positions *a* to *c* above.

Between the plumb bob *e* and the bottom pivot in the inner casing *b* is the other recording element, the compass *f* (Figs. 1*a*, 2*a*, 8). Its box is pivoted at right angles to the casing end pivots. Its clamping device is the bell-crank lever *s* engaging cam plate *q*. This lever projects to hold a spring *t* actuating the releasing and retaining lever *u* keeping lever *s* engaged in cam plate *q* and thus, by further leverage, engaging the compass box *e* about and below. The compass box is suitably borne and loose bushed for leverage clamping by means of springs working in grooves from the levers, as seen in Figs. 7 and 8. Cam plate *q* is fixed in its position by a pin *v* before insertion into the borehole and on its removal allows the necessary initial engagements to be made. In the position shown in Figs. 1*a*, 2*a*, and 4, cam *q* and its cooperating parts are set by pin *v*. The clock is now set so that after a predetermined time the end of releasing lever *u* will be engaged. This releases lever *u*, the plumb bob and compass being both free (Fig. 8) with the compass needle clamped by a spring *x*. In this

position the whole of the recording elements (plumb bob and compass) remain until the point to be surveyed in the hole is reached. In due course a pin *y* engages with the end of lever *u* (Fig. 1) until finally cam *q* engages pin *z* in the position shown in Fig. 4. This is the position of the clamping device after the apparatus has arrived at the survey point in the hole and sufficient time has elapsed for the compass box to come to rest. Here the compass box is clamped with needle and plumb bob free on their pivots. Further movement of lever *u* disengages a projection or tooth giving the position shown in Fig. 6. The ensuing movement of cam *q* actuates levers clamping the plumb bob *e* and, simultaneously by levers and connecting rods, releasing the compass box and clamping the needle by spring *x* as already said. It is clamped in the magnetic north so that the free compass box gives us the direction of deviation of the borehole directly; and the graduations on the plumb bob relative to the zero indicator on the cover plate give the amount of dip, also directly.

It will thus be seen that this instrument enables the data to be clamped or released after insertion and also gives control over the recording elements. The clock can be set at will independent of its mainspring and both compass and plumb bob can also be reset at will. All readings are direct with no additional surface computations and each element is fully controlled.

Objections which can be raised against this apparatus are

a. The mechanism is too complicated and refined for small holes.

b. Readings are not continuous down the hole, each point requiring extraction and reading at surface.

c. Liability to mechanical complications.

d. Compass unreliable in magnetic strata and lined holes.

The Briggs Clinophone.—This is a plumb bob or pendulum device with aural electrical registration applying the Wheatstone bridge principle and is employed in precision surveys of boreholes. That is to say, it is used where deviations of more than 1 in 150 are not permissible, as in

some deep freezing shafts. Here contracts frequently stipulate a survey capable of registering a deviation of 1 in 200 or 1 off the vertical in every 200 deep. The normal range of this device is about 2 deg. from the vertical.

It makes and maintains claims to simplicity, cheapness, lightness, rapidity and ability to survey narrow deep holes, giving a continuous record of amount and direction of dip. It was successfully employed at Seaham Colliery Sinkings. We are indebted to Professor Briggs for the following details and personal notes.

The Transmitter and Receiver.—The transmitter is hung in the hole on the rods and the receiver is situated near the mouth of the hole, the two electrically connected with a flexible five-strand cable.

FIG. 84.—Clinophone receiver.

The transmitter¹ has a plumb *B* (Plate IX) hung on a “G” violin string *A* connected to needle *H* through the wire wrapping of the string. The needle dips into a solution (NaSO_4) *F* in the vulcanite cup *E* which has four platinum foil electrodes e_N, e_E, e_S and e_W , 90 deg. apart (Fig. 8, Plate IX) each reaching to the cup base. These connect respectively to the rods D_N, D_E, D_S and D_W insulated from

¹ See also BRYDON, A. D., *Trans. Inst. Min. Engr.*, Vol. 71, p. 431; BRIGGS, H., *Proc. Roy. Soc.*, Vol. 46, p. 223, Edinburgh, 1926.

PLATE IX.—Briggs' clinophone transmitter.

the outer case and having terminals t_N, t_E, t_S and t_W (Figs. 1, 2). A fifth terminal t is connected to line A and therefore H . The strands c are led to the five terminals. The cable C goes out to the surface outside the rods. Cup E can be inserted in only one position and is replaced by a wooden clamping plug when not in use. A tail piece is hung 30 ft. below the transmitter to aid centering. Figure 84 shows the receiver connections which are in a wooden box 11 by 10 by 7 in. The cell b is an ordinary pocket torch, 4-volt refill, hence the claim to cheapness, and I is a small induction coil, its secondary connected to condenser C_2 for clearing the telephone note. The five strands of the cable are attached to terminals T_N, T_E, T_S, T_W and T (the last is the plummet strand, the others the above mentioned t_N, t_E, t_S and t_W of Figs. 1 and 2, Plate IX) and from there to the respective electrodes of the transmitter cup. Needle a is held by the operator and loose flexed to the dish E_1 which holds salt solution (say, NaSO_4) and has four platinum electrodes e'_N, e'_E, e'_S, e'_W . It has a glass floor with a dial scale the concentric circles of which are minutes of arc and the radial lines 5-deg. bearing each. The operator wears a low-resistance headphone R , one receiver of which is coupled to the terminals 1 and 2, giving NS deflections, the other to 3 and 4, giving EW deflections. The rods have a special orientating coupling by external scribing in relation to the vulcanite cup E .¹

It will be seen from the wiring diagram (Fig. 85) that the wiring system involves two applications of the Wheatstone bridge connections to the liquid resistances of the earphone indicators. Needle a is moved about the receiving dish base until the noise in both earphones is a minimum, when a occupies the same position in the dish as plummet needle H (Plate IX) in the transmitting cup, and this is read on the cup base dial. The receiver connections are reversed, as in Fig. 85, because H will occupy a position diametrically opposite to the hole dip. The bob must be at rest in the hole to get a clear minimum sound and it takes about 10

¹ BRYDON, A. D., *op. cit.*, p. 437.

min. to come to rest. The needle position is illustrated in Fig. 86 and is seen to be at the intersection of two equipotential lines the dotted circle being the actual range of the plummet needle which is thus the reading needle range. Differing connections, of course, vary the mesh of equipotentials, and a connection suited to a person with uneven

FIG. 85.—Clinophone wiring diagram.

FIG. 86.—Equipotential lines in receiving-dish. First arrangement.

FIG. 87.—Equipotential lines in receiving-dish. Third arrangement.

hearing is found by short-circuiting the electrodes in adjacent pairs and coupling an earphone between the pair using the good ear only. Such an arrangement (Fig. 87) will give a locus of minimum noise points as a straight line. Short-circuiting on another cardinal point electrode we get another minimum noise line. The intersection of these two loci can be easily and exactly fixed and is the point sought; now read off its dip and bearing in the dish scale. The average reading error of an observation is about 5 min. of arc with an 18½-in. plumb bob, and this may be reduced by carrying a longer plumb line or by having a check reader and alternative connections.

The instrument we have had the advantage of examining was suited to a 4-in. borehole and was about 35 lb. in weight, 40 in. long and had $\frac{5}{16}$ -in. walls. It is efficient and certainly cheap and convenient and has been tested for an external pressure of 600 lb. per square inch.

Kegel's Apparatus.—This is an ingenious floating plunger plumb-bob device invented by the mining engineer Karl Kegel of Freiberg in Saxony in 1919¹ and capable of many alternate constructional rearrangements and modifications.

It gives the apparatus at the place being surveyed a definite direction from which it cannot deviate. In Fig. 1 (Plate X) the heavy rod *b* or chisel *c* or both are attached to the main rods *a* as also are guide devices *d* and plumbing medium *e*. The action of the last named will be seen from sections *EF* and *CD*, it being premised that other constructions of plumb and connecting tubes will attain the same end. The plumb *g* here floats in the plumbing fluid *h* and has a bottom plunger carried through the guide *i* so that as a result of the buoyancy it always floats upright over the guide hole. The upper plunger of plumb *g* projects through three contacts *j*, *k* and *l* and lies against a particular contact should there be any borehole dip. The guide casing recess belonging to the particular contact concerned has its own electric motor and current supply.

There are thus three of these, one for each of *j*, *k* and *l*. The motion of any one motor is transmitted by a worm and worm wheel *m* on spindle *n*. The wheel and spindle are connected by spring and groove in such a way that the spindle may move axially through the wheel. The spindle passes through the fixed nut *o* on the housing or casing *d* and is displaced according to how it is rotated. With similar rotation any two given motors will turn back accordingly and so displace their spindles backwards. Thus the spindles act as centering screws. On being let into the hole the three motors with special supply current may be so switched in as to draw in their spindles and

¹ German Patent No. 317,663.

reverse again when the survey spot in the hole has been reached, thus pressing them out against the borehole walls. The worm wheels thus move back on the spindles and press back the contact springs *p* interrupting the direct-current supply so that only the current to the plumb *g* and contacts *j*, *k* and *l* remains. The motors can be set in action at any

PLATE X.—Kegel's apparatus.

time by means of another current supply from outside; thus the centering may be actuated at will. Instead of the plumb *g* and its connections, a gyroscope or direction indicator (magnetic needle) may be employed which will maintain a definite horizontal direction by the action of an electric motor or plummet, giving thus not only the amount of dip but its direction also. For example, the plumb *g* can be held to a definite orientation by a gyroscope and the upper plunger rod of the plumb can give a definite dip. By varying the dip and bearing of this plunger the direction of the attached boring tool can

be altered to give any *desired* curvature of borehole. We may get the centering motion without the worm wheel gearing in other ways, *e.g.*, by wedges displaced forward or backward. Likewise in place of the electric motor other power can be employed, such as valves operated by the plumb or a gyroscope. The direction apparatus can be fixed solid or detachable on the rods.

The greatest demerits of the device are that it is intermittent in action and there is no device to prevent turning on insertion or extraction.

Maillard's Apparatus.—This simple and cheap device¹ consists chiefly of a simple plumb-bob electrical contact apparatus. Figures 88 and 89 show a longitudinal section of the apparatus which is a series of hermetically sealed hollow rods *a* connected to a body *b*, which has a play of about 4 mm. in the hole lining *A*. The body *b* has external guide springs *c* for centering. In the upper part of *b* is a circular ebony membrane *d* with an opening *f*. Below the membrane *d* is a conical recess. A cable *g* passes through *f* and holds a brass plumb bob *h* of cylindrical shape with a spherical end. This latter rounded part of the bob is the only part allowed to make contact with the slanting sides of the recess; it is rounded to lessen friction on being moved up or down. Cable *g* is an insulated electric wire passing through the hollow rods *a*.

It will be seen from Fig. 89 that the complete electric circuit is by way of the source *j* at the surface, through the cable *g*, the plumb *h*, the borehole casing *A*, the galvanometer *k* and back to the source *j*.

When taking a measurement the apparatus is let down into the hole, which is already provided with casing *A*, by means of the hollow rods *a*, successively screwed up at the surface in the normal way, to the desired spot to be surveyed. The partial turns of the tube *a* which may be called $\alpha_1, \alpha_2 \dots \alpha_n$ are related to a fixed starting direction

¹ Pechelbronn Société anonyme d'exploitations minières et Georges Maillard. French Patent July 27, 1925. German Patent No. 492,573, Mar. 4, 1930.

such as the true north. The angular displacements of the apparatus in the hole are found thus: When plumb h is in last contact (*i.e.*, the last touching position before disengagement) with the sloping side of b , we are at the limiting position at which the circuit is closed and the galvanometer

FIG. 88.

FIG. 89.

deflects. By slowly hauling up the plumb bob we can find this spot, for, after it, the contact is interrupted and the needle of the galvanometer adjusts itself back to zero. We thus know the length of the plumb line hanging in b from f , because we know the amount hauled out to make last contact. Thus it will be seen that any angular positions $\alpha_1, \alpha_2 \dots \alpha_n$ given by the apparatus correspond to certain critical lengths $l_1, l_2 \dots l_n$ of the cable g . These

can be plotted for maximum, α_M , l_M and minimum α_m , l_m values of angular deviations and lengths.

In Fig. 90 we have an easy way of getting the borehole inclination i at the depth concerned. Construct the triangle xyz in which the angle xyz and the side xy are known from construction and the side xz is also known, being equal to the maximum length l_M above (previously obtained by raising and lowering h and plotting; to this add the length of the plumb bob). The angle sought is $zxy = 90$ deg. $- i$. Repeat this procedure from place to place to get the amount and direction of dip, the latter being more satisfactorily obtained by taking three such readings at 120 deg. apart in azimuth at

FIG. 90.

FIG. 91.—The driftmeter.

each given spot and making a graphic or tabular check.

It would be difficult to imagine a simpler device and it has recently been protected in Germany. We may visualize the following possible defects:

1. The angular positions α_1 , α_2 , etc., being dependent on the inner rods are not free from objections.
2. Friction of the cable at the membrane and hindrance to the same should pressure water and mud penetrate the many joints.
3. The device may become cumbersome in deep holes.
4. The borehole must be lined all the way.

The Driftmeter.—This is a recently developed American apparatus¹ being a pricking plumb-bob device. The instrument (Fig. 91) is about 3½ ft. long and weighs about 30 lb. and is suited for rope lowering with a depth-measuring appliance or it may be fitted to the rods. The principal parts are the clock, the ten 1½-volt batteries, the leaden plumb bob fixed on a solenoid or electromagnet and the magnet-controlled pricker plunger passing through a universal bearing which has a mobile suspension. Under the pricker is a 2¾-in. registering paper (Fig. 92) divided into 15 circles of 1 deg. each and is thus suitable for filing. Space is provided on the back of this paper disc to record depth, well number and other data. In this way deflection angles are found direct to about 15 min., no preliminary work being necessary, the instrument being ready for use as soon as a new paper disc is fitted and the clockwork set. The clock can be adjusted to a definite time; then by the contact brush making connection with the battery and magnet the plunger is set into action perforating the paper disc. A retracting spring keeps the plunger off the paper when the current is shut off. The resulting reading is direct and needs no computation. The same sheet can be repeatedly used by marking each perforation as made, so getting a series of indications of the deviation. Since it requires no special skill the ordinary boring personnel can

FIG. 92.—Driftmeter record.

¹ The Driftmeter Co., Inc., Tulsa, Oklahoma.

use it, thus giving a constant cheap control on the progress. The plunger being made of a non-magnetic alloy or lead eliminates any chance disturbing magnetic influences. It can be made in sizes as low as 1.9 in. for running inside 4-in. drill pipe. Its greatest disadvantage is that it is intermittent in its action, having to be hauled out after each record, the clock being reset and, if necessary, the paper disc changed.

CHAPTER VII

PENDULUM METHODS

Introductory Note.—The physical features of the pendulum which are essentially those of the plummet have been among the great attractions of physicists for the last 300 years. The outstanding features marking the discoveries of Newton, Foucault and Kater are all incorporated in modern borehole survey instruments of this class.

Our reason for distinguishing this suite of apparatuses from the compass and plumb bob section is that generally the plumb bob is used as a dropping pricker, a plunger pricker, a balanced vertical bar, or in some other way not fully utilizing its oscillatory properties. This is not a rigid statement, since many compass devices also apply the swinging bob.

The pendulum proper is being understood when we consider the elliptic or circular paths of a hanging bob or rigid-limbed pendulum. It has the outstanding advantage of independence of the magnetic north or the constitution of its surroundings, working and obeying its astronomical north-seeking faculty as well in magnetically disturbed regions as without them. Its possibilities are evidenced by the success of submarine and aerial navigation, since gyrocompass action is an adaptation of the pendulum principle.

Koerner's Apparatus for Measuring Deviation.—This device, which is essentially a spring pendulum apparatus, was invented in 1906 by G. Koerner, an engineer of Nordhausen, Prussia, the suspension of the plumb line or pendulum being altered by mechanical means and the oblique positions of the same recorded photographically.

In Fig. 93 the tube *a* is kept to the hole center by the feeler spring wheels *b* pressing on the sides of the borehole.

The central plate *c* holds a frame *d* carrying a graduated glass plate *e*. A rotatable spindle *f* in the center of these

FIG. 93.

plates *c* and *e* carries a plumb line *g* on an arm *h*, and also a graduated index *i* slotted to take the plumb line. In the bottom of the tube are four electric incandescent

lamps j for illuminating the glass plate e , the index i and the plumb line g . There is also here a camera k and a rolling film n driven by clockwork l and electrically controlled by the cable line m . The frame d and glass plate e and the plumb line g can be placed at an angle in the tube a by means of the spring o on rod p and spring q bearing on plate c .

The staple r is arranged to carry a lowering rope. If the apparatus is suspended by rod p the frame and springs will occupy the positions shown bold in Fig. 93, the springs being compressed and the rod f being parallel to the walls. If, however, the apparatus is suspended from the staple r the springs are released to the dotted position of Fig. 93, forcing the frame to the inclined position.

To make a reading the appliance is suspended by rod p with two external points on its casing in the meridian. Then plumb line g takes the position of the dip, and so the position of the dip of the borehole orifice is found. This position is photographed from below. Suspend the appliance on the staple r without turning and bring the plumb line spindle f into the inclined position. The plumb line g now assumes a position which is determined by the dip of the borehole and the inclined position of the axis f in accordance with the parallelogram of displacements. The film n is advanced by electrically releasing the clockwork l ; the lamps j are again switched in and the new position of the plumb line recorded photographically. By comparing the two readings a diagram of the type shown in Fig. 94 is obtained, from which the deviation is found. The extent of the dip is calculated from the amount of deflection of the plumb line from the center of the scale on e and i and from the length of the plumb line itself. The distance of the bottom of the plumb line is read on a special scale on i .

FIG. 94.

The objections to the apparatus are as follows:

1. Double suspension is liable to introduce turning errors.

2. There is no guarantee of continued alignment of the meridian indexes.

3. The feeler centering springs are liable to error and they also preclude the adoption of this method in very narrow boreholes.

4. Springs are objectionable in boreholes holding water under high pressure.

5. The apparatus becomes too involved if attempts are made to obtain continuous readings.

Erlinghagen's Apparatus.—This apparatus introduced a significant change in the construction of deviation instruments. It is a pendulum apparatus with electrically operated registration mechanism. It consists essentially of an electromagnet operated pendulum and a clockwork-driven recording paper strip in which the pendulum pointpricks a set of definitely arranged marks. The clockwork is also released simultaneously with the pendulum by means of drawbars.

FIG. 95.—Erlinghagen's original centering device.

Provided the apparatus keeps from turning on being let down the hole, it is a very suitable apparatus and Chief Engineer Erlinghagen of Nordhausen, the inventor, tried various devices to attain this end. He first employed a longitudinal slit *g* down the apparatus *c* (Fig. 95) with the rope *a* held in the slit. This was not entirely satisfactory. Later he employed telescopic lenses held by counterspring nuts in the apparatus, as in Figs. 96 and 97, which solved the difficulty.

Figure 96, left, shows the entire apparatus assembled ready for insertion in the hole with the lenses collapsed. Figure 96, right, shows the device in the extended condition. Only electric current is used for the determination apparatus. The tubes can be let out by loosening a brake

FIGS. 96 and 97.—Erlinghagen's new apparatus.

f which actuates two drums on which a thin wire rope h to the head of the lower tube is wound. For closing the lenses up again spiral springs on the drums coil up the wire automatically. On the top end of each tube is a headpiece

FIG. 98.—Centering device.

FIG. 99.—Erlinghagen's electromagnet.

X in which the measuring apparatus (Fig. 97) is guided by the thin ropes h exactly on the center line of the tubes or lenses. The lower spiral spring i and the levers k serve to hold the lowest lens of the telescope exactly in the middle of the borehole when in the extended condition. It will be seen that in small diameter boreholes the brake loosening device and telescope lenses would be inadvisable owing to

the thickness of the lenses themselves (which is at least 60 mm. inside width for high water pressures and 130 mm. outside). Therefore a new form of fixing device for simultaneous centering was adopted by Erlinghagen in 1906 in cooperation with Professor Klingenberg of the General Electric Company in Berlin, as shown in Figs. 98 and 100.

The borehole magnet was made by having an I-shaped bronze frame, between the webs of which on each end a π -shaped iron was placed enveloped by a magnetic coil. The legs of the iron were beveled (Fig. 99) corresponding to the internal diameter of the borehole. The coils have to be absolutely watertight. The coil was wound with enameled wire and the bearing spots repeatedly insulated from one another and the whole placed in a zinc case and waxed up. The neck has a soldered bridge through which the winding wire is carried well insulated. The construction has been tested for hours under a pressure of 9 atm.

Figure 98 shows the centering device where we have three link-arm borne steel rolls pressed outward together by a strong central steel spring, from which it swings down to the bottom of the apparatus in fixed links. Above, it is movable up and down by a linked ring and a movable center bolt. There are three of these centering devices, one to center the upper magnet, another the lower magnet and the other to hold the measuring apparatus properly in the middle. The measuring apparatus (Fig. 100) has a powerful frame of three steel rings connected by two longitudinal ribs having, in the upper part, a glass encased clockwork. Under this a roll paper 50 mm. wide winds from roll r_1 over the cork-lined plate p on to roll r_2 with uniform velocity, only roll r_2 being clockwork driven. As the angular velocity of the clock is always the same, that of the paper increases the more paper is wound on to r_2 giving a uniformly accelerating motion. To control the time points of the measurements the paper must move uniformly and this is done by means of the string drive s on roll r_2 which has a slipping arrangement. Under the paper strip moves the point of the universally suspended spring pendulum.

FIG. 100.—Erlinghagen's measuring apparatus.

The pendulum, being very sensitive to shocks and taking about 20 min. to subside, has a hair brush damping device *h* which brings it to its position of rest in about 45 sec.

For working the measuring apparatus a horseshoe magnet *m* on the floor of the apparatus is switched in so that connection is made by way of the bearing plate *e* which is attracted downward. Plate *e* is connected by drawbars to the clockwork. The weight of the clockwork is taken by springs *f* so that the magnet has very little force to overcome. The point of the pendulum sticks up into the paper strip when measuring, and at the same time four points *t*, arranged in the center ring and which lie on concentric circles on the periphery of the guard tube, mark four points on the paper strip, by which we are able to recognize the center point of the measuring figure at that instant.

The conductor wire for the magnet coils goes along one of the long drawbars to a clamp for current rod *u*. The head here is specially sealed against entry of water under high pressure, thus preserving the clockwork and magnet. This is done by means of opposed nuts *c* and copper rods *k* on floor *b* bushed to the insulating plate *l* and slip rings *d, d*.

The direction line of the paper may be noted on the outside of the tube with the whole apparatus above it, so that on letting it into the hole one knows how it stands. The conductor and lowering rope are all in one, the conductor being insulated with cement, bitumen and tape.

The inventor gives details¹ of surveys carried out with the apparatus, which did not turn on extraction or insertion, and these facts were checked by an investigation in a blind shaft between two levels belonging to the German Solvey Works in Bernburg. The results of two surveys at Solvey-hall with the apparatus and a later normal instrumental survey check are to be seen in Fig. 101. A series of 160-mm. tubes were arranged for the apparatus test; the normal survey shows a constant survey traverse distance from the apparatus survey. Erlinghagen's apparatus marked a new

¹ *Glückauf*, p. 743, June 15, 1907.

epoch in the evolution of borehole deflection apparatus; it was the impetus to many later designs and constructions.

It conquered the continuous record problem, if however crudely, successfully. We may mark from its inception the rapid evolution of new methods which began in the first decade of this century. Its chief drawbacks are:

1. It is costly and complicated to make.
2. It is heavy though easy to manipulate.
3. Its mechanism and tubes limit the diameters for which it can be adopted.

FIG. 101.—Checked survey by Erlinghagen's method.

4. Pin-pricking devices are crude and likely to cause confusion in reading.

5. Moisture is likely to injure the apparatus and cable.

Thurmann's Apparatus.—This apparatus is built on the proportionality principle, the basis of the lead-basket plumbing method, but it greatly extends the limits of applicability of that principle.

H. Thurmann, Sr., of Halle obtained reliable results with his apparatus, which is a double plumb bob and linked-tube device, at fair depths. The invention¹ (Figs. 1 to 9, Plate XI) consists of straight tubes joined by special cruciform joints movable in all side directions but not rotatable.

¹ *Organ des Verein der Bohrtechniker*, No. 17, p. 190, 1909.

PLATE XI.—Thurmann's deviation apparatus.

An apparatus t is arranged in each link tube r_1, r_2 , etc., and called a "pot head," owing to its first being made pot shaped. On the floor of this head rests a cork-lined base m_1 (Fig. 5) covered with tin foil and having impressed coordinate axes. A tong-shaped device s above the head has one fixed z and one spring-moved limb s (Fig. 2) which carries the plumb weights l . From the latter in each head or top there is a pair of common threads or wires; this common wire is laid over the transom d carried by the tongs. In the base of the little trestle of the tongs is an adjusting piece n between set screws o with two fine holes for guiding the plummet fibers. This permits of a hair adjustment of the plummet points exactly perpendicular over the zero of the coordinate axes arranged under the head on a perfectly horizontal plate.

The gudgeons of the cross joints f of the link tubes lie at right angles to one another in their crossing vertical planes. The coordinate axes of the marked plate and of the tin-foil plate have definitely arranged and assured symmetrical positions on the whole of the plumbing heads. Thus in each tube of the linked series we have a separate measuring operation assured independent of its neighbor. It does not matter if the break points between two tubes do not lie on the axis of the borehole, because the preceding and succeeding errors compensate for each other. In horizontal projection we then have a simple figure of the deviation of each tube. The metal plumb bobs are not affected by water, chemicals, pressures or mud, thus combating some of the objections to Erlinghagen's and Haussmann's apparatuses. The fundamental idea of the apparatus will be clearly seen by considering two equally swinging pendulums side by side, especially when they have a small difference in length. In each apparatus are two plumb bobs on a common string. The string is led over the transom, and when let down in a dipping tube the plummets mark parallel lines on the cross axes at a corresponding distance from the position of rest. Should the line be at any instant at greater or less distance than the normal case provides, an oblique

line will be shown. A graduated sight on the uppermost link is used for orientating in the vertical against the coordinate axes. Thus the plumb line can be viewed at any time and a new marking plate can also be put in at any time. In this way any doubtful measurements can be recognized at once and remedied at any time, an advantage which did not hold for the predecessors of this apparatus. In previous instruments a series of measurements below each other necessitated separate readings and extractions for each, or separate depth readings at each place with all the attendant trouble and waste of time. Again errors increase with the depth.

This apparatus can be arranged in lengths to suit the hole. For a 240-m. hole, say, Thurmann would not employ sixty 4-m. tubes but ten or at most twenty tubes respectively 24 or 12 m. long. There is a special plumb for each section of hole surveyed so that any errors cannot be cumulative. Moreover, each error can be corrected, as said above. Therefore it is only necessary to correctly orientate the whole apparatus from the surface down, and to aid this direction rods (Fig. 9) are used. These are a series of tubes equal in length to the link tubes and having tooth and notched ends connected by overscrewed thimble joints to prevent them rotating. The above noted diopter is adjusted to the direction rods on exactly the same line as is chosen for the uppermost plumbing section of the link tube. In this way the coordinate axes of the marking planes lie sectionally in exactly uniform orientation for plumbing.

Freezing shafts are best plumbed from the center by this device, the center being the coordinate axes center.

The inventor claimed that the method was cheaper than its predecessors for freezing shafts and also surer; that it was unaffected by water, mud, chemicals or pressures and that it was direct and easily controlled. Among its demerits we may mention:

1. There is insufficient provision against relative turning of the tubes; this spoils the deduced results.

2. It is heavy and cumbersome and thus not suited for great depths.
3. It is not easy to manufacture and in some cases, *i.e.*, big deviations, will be difficult to manipulate.
4. It uses up more time than a lighter and simpler device.
5. It has too many movable parts.

The Denis-Foraky Teleclinograph.—This is a pendulum apparatus and one of the best known of the modern precision devices employed in freezing shaft boreholes.¹ It is remarkably accurate, being in many cases somewhat of the order 1 in 3,000.² The principle is best understood as follows:

Imagine a cylindrical tube (Fig. 102) of length AO with a system of rigidly orientated coordinates XY on one end when *in situ* in the hole. Knowing the coordinates of o' and the projection of A on the coordinate plane, we also get the position of the axis zz' of the tube which on a centered plumb is the hole axis also. Then by making a series of 10-m. interval observations we can get the borehole trace in 10-m. stretches projected on the horizontal plane. The freely oscillating pendulum A will, if given an initial impulse, describe a surface the trace of which on plane XY will be an ellipse with center o' , which is the vertical projection of A . More correctly,

FIG. 102.

but differing not sufficiently to affect the results with such small angles involved, it is the sphere to which the above plane is a tangent upon which the trace is generated. On the sphere parallels are traced to the axes XX' and YY' at a distance k and actually occupied by the conducting bars (reglets) on which the pendulum point contacts every time it crosses one, closing a circuit with a registering apparatus.

¹ See a full description in Prospectus of Foraky, Société anonyme d'entreprise de forage et de fonçage, Brussels.

² ADAM, D., *Colliery Engineering*, p. 414, Nov. 24, 1924.

The movement of the point on its elliptical trajectory can be represented by that of a point moving uniformly on a circle of the same amplitude (sinusoidal law of the pendulum). In particular the passages over the bars at a, b, c and d will synchronize with the points of the same order a', b', c' and d' on the circle (Fig. 103) and $o'p$ measures on this figure, y , one of the desired coordinates for finding zz' .

FIG. 103.

FIG. 103a.

This uniform circular synchronous motion is indicated aboveground by a registering pen in the receiving apparatus; an electromagnet records the passages over the bars by controlling the penholder in the circuit.

Thus we may get the figure o'', a'', b'', c'', d'' (Fig. 103a), the last four points being the passage points of the pendulum over the bars. The value of y deduced from the diagram will then be

$$y = \frac{o''mk}{k'''} \quad (11)$$

The same reasoning with another projection following the other system of bars (reglets) would give from the same diagram completed by the other four points of contact:¹

$$x = \frac{o''nk}{k'''} \quad (11a)$$

The ratio of the recording pen and the transmitting pendulum is k''/k . k'' and k''' depend on the values of the lengths OX and OY , usually different.

¹ FORAKY, *loc. cit.*, p. 71.

The apparatus itself is in three distinct elements; the transmitter for the base of the borehole, the surface receiver connected electrically to the transmitter, and the lowering rods with orientation couplings.

The transmitter is a strong, pressure-proof, steel tube with a pendulum, the trajectory grid plate and the electrical connections inside. The pendulum¹ (Figs. 104, 104a)

FIG. 104.—The Denis-Foraky teleclinograph pendulum.

FIG. 104a.—The Denis-Foraky teleclinograph pendulum.

has a Cardan suspension at A the functions of which are resolved in an elastic system made up of two crossed springs (Fig. 105). The system has the property of acting in such a way that the instantaneous centers of rotation of the pendulum may be taken as coincident with A. The pendulum is not allowed to swing freely under the force of gravity. No two similar double systems constitute a suspension without play or friction, and this method of construction

¹ HADDOCK, M. H., "Location of Mineral Fields," p. 92, Crosby, Lockwood & Sons, London.

equalizes the elasticity constant proper to each of the two perpendicular axes, making it the same in all directions.¹

An ingenious mechanism gives the necessary impulse to the pendulum at each station. For convenience in reading, the ellipse caused by the pendulum under this impulse should be as nearly a circle as possible. This mechanism consists of a crank on point *P* (Fig. 106) capable of being displaced along its vertical axis. It is brought to its initial angular position by a coiled spring and to its vertical position by a plate spring. By the action of a surface-operated electric motor placed above the pendulum top, a half turn is given to the coil spring and simultaneously,

FIG. 105.

FIG. 106.

ously, by means of a ramp, the crank is displaced on its vertical axis. *P* strikes against a copper dome on the pendulum and the crank is liberated from the action of the motor, and under the influence of the spring it describes an arc *aM* and rises back to its former position. Point *a*, struck by *P*, describes a tangential trajectory to the arc. At the moment of release *a* is going along the tangent *M* and the pendulum has to describe the ellipse of major axis *NN'*. If the impulse is suited the path *NN'* will equal a circle *MM'*.

Actually in the grating or grid the thin bars (reglets) or coordinate lines are fine V grooves cut in the spherical silver grating plate (Fig. 107). The pendulum point (Figs. 104 and 108) breaks circuit with the grating surface at these coordinate lines, the break being recorded by the electromagnet controlled pen in the surface receiver. This receiver (Fig. 109) is a

¹ *Loc. cit.*, pp. 72 *et seq.* The counterforce of the cross springs in the suspension is analyzed here with the aid of Fig. 104.

rotating plate with a paper sheet on which the pen traces a low-pitch spiral each circuit synchronizing with the pendulum swing. The pen (Fig. 109) is on the jointed system consisting of an isochronous regulator ensuring that the periodicity of the pen circuit is constant for all positions. The trace of the grating pen is an enlarged reproduction of the pendulum swinging contact figure owing to the action of the electromagnet on the pen. This enables the coordinate axes XX and YY to be drawn.

FIG. 107.

FIG. 108.

FIG. 109.

The grooves of Fig. 107 form these axes by causing the breaks in the circle. The coordinates of the grating center, with respect to the vertical, are obtained from the diagram; thus

$$x = Cx'$$

and

$$x''/k'' = x'/k$$

Using a coordinate length of 10 m.

$$X/10 = x/l$$

and since

$$X = x''/k'' \cdot 10kC/l \quad (11b)$$

we get for a 10-m. length

$$X = x''/k'' \cdot 10kC \quad (11c)$$

x is scaled direct from the diagram using the center as zero and having the indexes at the divisions $\pm \frac{10kC}{l}$ and placing it so that these indexes coincide with the lines $y'y'$, $y''y''$ (Fig. 110).¹

FIG. 110.—Actual diagram made by teleclinograph showing method of measuring deviation by coordinates.

There is a special orientating coupling which allows the rods to follow the hole curvature but maintain their surface orientation.² Figure 111 is a survey by the teleclinograph checked from shaft records later. It was taken in the No. 8 borehole of the Steaua Romana No. 17 suite of shaft holes and well illustrates the plan wanderings of a hole. It was surveyed in 1925 and is discussed by Friedenreich.³

Kinley's Inclinator.—This instrument, invented by M. M. Kinley, the oil-field fire fighter of Tulsa, Oklahoma,

¹ After ADAM, D., *loc. cit.*, p. 412. See also SCHMIDT, F., *Trans. Inst. Min. Eng.*, Vol. 52, p. 178.

FRIEDENREICH, O. L., *Analele Minelor din România*, p. 693, November 1926.

² FORAKY, *op. cit.*, p. 82.

³ *Ibid.*, p. 707.

does not render the direction of deviation but the amount only. It is well suited to rapid, simple and fairly accurate records for working or completed wells. It is essentially a pendulum or plumb-bob recording device in a cylindrical watertight housing. The lower end of this housing is externally threaded and it is attached to the bit or core catcher. The original Kinley instrument¹ was lost in a Texas company well. Here the recording unit (Fig. 112) includes a support frame *B* with an upturned arm on a

FIG. 111.—A Rumanian borehole surveyed by the Denis-Foraky teleclinograph in 1925; plan of the hole No. 8, "Steaua Română" 17.

FIG. 112.

vertical plate on its upper end. The lower end of this plate has an inturned arm for mounting a rewind mechanism. Ball bearings *A* on the inturned arm at the lower end of the plate assist the upper ball bearings *A* to hold the recording

¹ SMILEY, T. F., *Oil Gas Jour.*, p. 44, Apr. 25, 1929.

device. The rewind mechanism is a spool on a shaft carrying a blank record strip *C*. The ends of this shaft are fixed in horizontal aligning openings at one side edge of the plate and bracket. The worm gear *D* fixed on a shaft has one side against the plate and its opposite side face in a vertical plane with the inner face of the flange of the spool. The rewind spool is secured on the shaft between the worm gear *D* and the bracket and has side flanges. About midway between the rewind spool and the upper inturned arm, and at the side edges of the plate, is a pair of idler rollers *E* mounted on pins fixed in the plate and extending inward and lying parallel with the rewind spool shaft. Over these the record strip passes from the spool (Fig. 112) presenting a flat surface for the inking device. The part of the strip down on the other side winds on to the rewind spool. The spool is driven by a spring motor *F* with a worm screw engaging in the worm gear in the space between the rewind spool and idler rollers. This revolves the spool clockwise, thus rewinding the strip, and its speed may be controlled. A pear-shaped pendulum attached by a string to an eyelet screw in the upper upturned arm of the frame lies centrally between the idler rollers and in vertical line with the

FIG. 113.

FIG. 113.—Sketch showing method of transferring plumb-bob motion to the pen.

FIG. 114.—A record with Kinley's apparatus.

FIG. 114.

zero line on the record paper. It is the inking device, for in the lower end of it is a pen resting on the horizontally extended paper below. When the hole deviates the recording unit swivels on its pivots in the housing so that the weighted side comes to rest on the lower side of the dip when the boring tool to which the whole is attached is at rest. The pendulum swings inward and the movement of the pen is here governed by a toothed segment (Fig. 113) whose teeth mesh in the sliding arm to which the pen is attached. Figure 113 shows the cylindrical bob securely fastened to the segment.¹ When the bob moves inward the pen moves outward to maintain its contact with the paper. The paper is divided into 5-deg. spaces by vertical lines so that when the instrument is vertical the pen rests on the zero line, the degree of accuracy being claimed as greater than that of the acid-bottle method. As the apparatus is run into the hole its body will swing around on the ball-bearing end pivots or sockets, and the pen arm and segment will swing as the plumb sways with the motion. Thus we get the jagged horizontal lines observed during each reading and during the "pull out" shown at the bottom of Fig. 114, which is a half-hour record from a well in the Little River Pool in Oklahoma. No calculations are needed when the record comes out of the hole. The whole is protected by a suitable steel case. It is secured to the working tool in the hole, *i.e.*, bailer, sandpump or drill pipe and read at each extraction of these. It suits 6 $\frac{5}{8}$ or 8-in. casing.

¹ By the courtesy of *Oil Field Engineering*, issue of Sept. 1, 1929.

CHAPTER VIII

PHOTOGRAPHIC METHODS

Introductory Note.—In this group we include most of the accepted methods wherein a photographic record is provided of

a. The actual walls of the borehole or the core outside the apparatus.

b. The positions of various mechanical or electrical devices inside the apparatus.

A vast amount of the world's boring is done by churn drills and other percussive drills yielding just the sludge of the percussion for examination at the surface. Even core drilling, which is about three times as expensive, does not always yield complete cores, owing to cavities and friable strata. Again the computation of dip, thickness, etc., obtained from the material produced by the drill tool suffers in direct ratio to the discrepancies due to the above geological causes.

An actual photograph of the borehole walls will remedy this defect and also supplement any faulty evidence. When the deposit is crystalline, as in certain copper, zinc, and salt deposits, little experience is needed to translate the photographic evidence and the same applies to marked geological changes shown in the photograph. In amorphous deposits and those of massive regular texture more experience must be acquired in order that one may (if possible) decipher the data presented by the film.

Photographic records of mechanically or electrically controlled devices, or those depending on gravitational action will be easily comprehended by any intelligent person. All photographic records are well suited to continuous recording in and out of the hole. They are coming more and more into favor for very deep holes, the multiple

photographic apparatus having already achieved some remarkable surveys.

The first interior photographic device was that of Oehman in 1905 in which shadows of a needle and plumb bob opposite electric light globes were recorded on a sensitized paper. The first device for photographing the borehole walls was that of Atwood in Wisconsin, in 1907.

Atwood's Apparatus.—This, the first external photographic device for boreholes, was invented in 1907 by J. T. Atwood of Wisconsin University. The camera *a* (Fig. 115)

FIG. 115.—Camera, tripod and lowering reel.

is mounted in the lower end of a watertight tube *b*, 5 in. outside diameter and 43 in. long. Near the upper end of the tube a plate-glass window with a mirror *c* behind it is mounted so as to reflect the image of an object placed before the window directly down the tube and into the camera (Fig. 116). On each side of the mirror is mounted an electric lamp *d* with a reflector, which sends the light through the window and also prevents any light from shining directly into the camera.

This iron tube, or camera tube, is lowered and raised in the well by a cable winding of the lower of two drums *e* and *f* (Fig. 15). The upper drum *f* carries an electric cable to operate the lamps and to turn the camera film.

The cable is so fastened to the tube that the window will come close to the wall of the well, and, with the lights

FIG. 116.—Atwood's borehole camera with parts removed to their relative places outside the case.

burning, the wall is brightly illuminated. In making an exposure with a No. 16 stop the lights are turned on for about 20 sec. Before making a second exposure the camera is lowered or raised $4\frac{1}{2}$ in., the distance covered by one photograph, and a new part of the film is turned into place by making and breaking the circuit of an electromagnet acting upon the roll of film. In this way a series of 50 or more photographs can be taken at the rate of 1 a minute, and they will show a continuous strip of the wall for a distance of 20 ft. or more. The window, which is $1\frac{1}{2}$ by $5\frac{1}{4}$ in. is set in litharge cement. A guard strip is riveted to the tube on each side of the window. The hoisting cable is attached to the hook *g*, 4 in. behind the window, so that in the ordinary 6-in. drill hole the window always hangs near the wall. The mirror, lamps and reflectors are mounted on an oak plate, which can be adjusted to bring the mirror in the right position behind the window (Fig. 117). The two lamps are 10 volts and 5 cp. each.

FIG. 117.—Camera with side removed.

The camera is 32 in. long and $3\frac{3}{16}$ by $1\frac{5}{8}$ in. in cross-section. It is fitted with a 9-in. Bausch & Lomb rectilinear lens. The camera¹ is so placed in the tube as to photograph the $4\frac{1}{2}$ in. of wall reflected in the mirror upon $3\frac{5}{8}$ in. of film, the maximum length obtainable with a width of film of $1\frac{1}{4}$ in. This reduction gives a photograph eight-tenths full size.

The camera is fastened in the tube by two thumb screws. One side of the camera is fitted in grooves and is easily removed for changing the film. The film winds from the end roll *i* (Fig. 117) across the flat plate for exposure and is wound upon the other roll *j* by the operation of the electromagnet *h* (Fig. 116) acting through an arm and pawl upon a ratchet wheel. The wires for the coil have a plug connection at the bottom end of the camera. A three-core cable of No. 14 wire and 250 ft. long carries the current from four small double-storage cells. A resistance coil is used to adjust the voltage for the lamps before lowering the camera tube. Connection from the cable to the battery and switches is made by a triple plug in the end of the shaft of the winding drum. The hoisting cable is a heavy line of small twisted wires, tested to over 500-lb. tension. The drum is wound with 300 ft. of this cable, and has length tags soldered to it at 5-ft. intervals. The ratchet on the drum has a double pawl permitting of $\frac{1}{4}$ -in. changes in the position of the camera tube. No attempt has been made to record the direction in which the camera hangs. This could be done by an orientating coupling rod or by mounting a magnetic needle to show in the photograph. Good photographs can be taken in a well hole both above and below water. The camera has been operated in a 200-ft. prospect hole 6 in. diameter upon the Vinegar Hill Mining Company's property, about 7 miles north of Galena, Illinois, at a depth of 162 to 200 ft. when the water stood at about 85 ft. from the surface.

The first attempt in taking photographs under water was entirely successful. The camera was filled with air

¹ *Eng. Min. Jour. Press*, p. 944, May 18, 1907.

dried by forcing through sulphuric acid. After lowering the camera tube into the water it was raised to the surface to see if in cooling any moisture had been precipitated on the inside of the window. The window was found to be dry and clear, and upon lowering the second time, the exposures were made without any regard to the location of ore bodies. The device is now chiefly of historic interest and its limitations are obvious, however its principle still survives vigorously.

Reinhold's Photographic Apparatus.—This device was invented in 1924¹ by Thomas Reinhold, Chief Geologist of the Geological Survey Department of Holland, and described at the International Congress of Geology at Madrid in 1926.

Its purpose is to provide a photographic record of the strata pierced so as to obtain the nature of the same, detect the presence of fissures and to get the dip of the beds. It will be seen to be additional to ordinary core orientation or borehole deviation methods, since it photographs the walls of the unlined part of the borehole.

The apparatus shown in Figs. 118 and 119 is attached to the upper end of the drill rods and then lowered to the required spot in the hole. It will be noted that a section of the hole is isolated in a watertight manner at the upper and lower ends by means of the packing rings *x* and *y*. This length of the borehole is then washed out by means of clean water, the wall is illuminated, and a photograph is taken. The photographic apparatus is enclosed in a strong bronze tube between the packing rings, the film camera being placed in the chamber *b*. Two electric lamps *f* illuminate a part of the wall *g*. The rays of light pass through the glass and are reflected upward from the reflector *d* to the lens *c*, throwing an image on the film *k* in the camera. A small electric motor *a* changes the exposed part of the film for a fresh one after each exposure. Enough film is provided for obtaining a few hundred exposures, one

¹ British Patent No. 226,079; see also *Colliery Engineering*, p. 371, August, 1926.

after the other, simply by moving the instrument and switching on the light.

FIG. 118.—Instrument in borehole.

FIG. 119.—Arrangement for large boreholes.

Electricity is supplied by a cable *j* running from a switchboard at the surface and located at a convenient

place near the borehole. A transformer within the instrument is provided for reducing the tension of the electric current. Current at, say, 220 volts, is used to transmit electricity in the long cable with little loss, and it is reduced to lower tension for easier manipulation in the instrument. An automatic switch is introduced to make the connections, such as switching on the motor or the lights.

The clean water is injected through the tube *h*, and the mud-laden water is forced out through the aperture *i*. This arrangement enables the apparatus to be employed in mud-laden boreholes by replacing the dirty water with clear water. In the case of oil wells, where an oily film on the object glass would interfere with the photograph, it has been proposed to wash with benzine instead of water. By changing the rubber packing rings *x* and *y* the same instrument may be employed in boreholes varying from $5\frac{1}{2}$ to 12 in. in diameter.

Near the lower end of the instrument a compass needle *e* covered with a graduated disc is placed. A small lamp *l* throws light on this disc, so that part of it is photographed at the same time as the principal photograph is taken, the rays passing by the side of the mirror *d*. In this way the direction of every face of the rock is recorded on the photographs.

In operating the apparatus it is lowered from the drill pipe to the depth at which information is required. Clear water is then turned on, and in about 10 min. the original slimy water is replaced, the view being then clear enough to start photographing. This is done by switching on the light for 10 or 15 sec. The film is changed by drawing it through the camera by means of the motor, and another photograph may then be taken. The instrument may be turned round so as to cover the whole of the circumference of the borehole with six or eight exposures, according to the diameter of the hole; in a 6-in. hole six exposures are sufficient, but in larger holes eight or more exposures are required. The instrument may be raised or lowered to photograph fresh sections. A good idea of the walls of a

borehole is obtained from about a hundred or so photographs, which may be taken in a comparatively short time.

According to a recent note from the western oil fields of the United States, this apparatus has yielded valuable information in the region of Signal Hill, in the western mineral field. A suite of very instructive photographs taken by the inventor and showing fissures and natural water veins have appeared.¹

The device has the advantage that the less expensive percussive boring can under certain conditions be made to yield as valuable geological data as a core-drilling plant. Again for finished holes with no cores available it will provide information which could not otherwise be obtained. When "torpedoing" well bases to increase the yield the shattering effect can be photographed. It can also be used for the inspection of casing as to corrosion, buckling, unscrewing, collapse, etc., and for the examination of cemented linings; also for locating lost or broken tools.

Its great drawback as a deviation instrument is that in strata thickly bedded or without stratification planes or other marked features it has nothing to photograph. It is limited to the size of hole it will suit and can only be used for orientation purposes in unlined holes.

Oehman's Apparatus.—This is a magnetic needle and plumb-bob photographic device which has been extensively employed in the deep reef boreholes of the Rand and elsewhere. It was first invented by Oehman about 1905 and later improved upon by A. Payne-Gallwey.²

From Fig. 120 it will be seen to be a non-magnetic tube *a* in two halves connected by a coupling *O*. The magnetic needle *b* is in the lower half with an independent plumb bob *c*, each swung over a gimbal *d* with a small electrical lamp *e* above each. These are held in position and pressed against a brass insulating rod *f* in the middle of the coupling

¹ *Colliery Engineering*, p. 372, August, 1926.

² HATCH, DR. F. H., A paper read before the British Association, see *Brit. Assoc. Rept.*, 1905.

by a spring *g* attached to the bottom screwed plug *h*.¹ A series of screws *i* in the side of the tube in straight parallel lines project inward about $\frac{1}{16}$ in. There are slots down the cylindrical cases carrying the lamps, and the needle and bob, the screws *i* acting as guides for these slots.

A dry battery *k* and clock *j* with spiral spring *l* attached are in the top half of the tube. This spring *l* assures contact when the two halves are screwed together by pressing on the top end piece *m*. This latter has a ball-bearing swivel *n* for attaching the wire for lowering if needed.

The vulcanite cases *p* carry the brass marine compass attachments for the magnetic needle. The plumb-bob attachment is also vulcanite for insulation purposes. The compass swings in rings. On the face of each gimbal is a fixed pin point and round the edge is a recessed ring which holds the disc of sensitized photographic paper in place, the pin points holding them in position. The plumb bob is made of gold attached to a fine silk thread swung from the center of a thin disc of plate glass *q*, which fits into a recess in the tip of the vulcanite case.

Both the magnetic needle and the plumb bob swing immediately above (almost touching) the sensitized papers. A copper lug *s* attached to the extra wheel *r* of the watch makes, at a certain time, connection with a copper spring *t* attached to the frame of the watch and so completes an electric circuit lighting the lamps above the bob and needle. Now a sharp shadow of each is photographed on the sensitized paper; these are developed to give dip and direction by making the pin pricks coincide, as shown in Fig. 121, where the hole dips 25 deg. in a direction N.20°E. (magnetic).

FIG. 120.

¹ HOFFMANN, J. L., Recent Practice in Diamond Drilling and Borehole Surveying, *Trans. Inst. Min. and Met.*, April, 1912. (After Hoffmann.)

This method was used to survey a hole in the Heidelberg district of the Transvaal which ultimately deviated 58 deg. off the vertical, the hole being 6,656 ft. deep. A special pilot wedge device (Fig. 122) 2 in. in diameter and 18 in. long with oblique face 6 in. long was first lowered (wedge face upward) and its being solid on the floor assured by letting down the rods. Another rod 3 ft. long screwed at both ends was used to get the wedge position. This last rod (Fig. 123) had a spiral spring on one end and a 2-in. cup with a $\frac{1}{4}$ -in. diameter brass pin through it at the other end. This cup was filled with lead which projected about 1 in. beyond its edge and turned to its diameter. The end of the rod with the spiral spring was

FIG. 121.

screwed into the instrument base instead of the lower plug. The top end of the instrument was screwed into a brass tube 10 ft. long and then again screwed to the ends of the drill rods. It was then lowered in on to the wedge.

A chisel cuts an impression in the lead, a photograph being taken of the magnetic needle at the same time. A disc of lead is sawed off on gaining the surface and the direction of the wedge calculated. The guide wedge (Fig. 124) is an exact counterpart of the pilot wedge and is screwed into the said main deflecting wedge, which is solid, 2 in. in diameter and 7 ft. long. These wedge devices are not an essential part of the equipment but are added because they enable other sections of the reef to be taken in the same borehole, saving the expense of extra holes.

Many successful borehole surveys have been made with this apparatus and W. Gallacher, the inventor of the instrument illustrated in Plate VIII, added to the above ancillary devices various means for obtaining successive

FIG. 122.

FIG. 123.

FIG. 124.

FIG. 122.—Pilot wedge.

FIG. 123.—Payne-Gallwey's wedge surveying attachment.

FIG. 124.—Guide wedge.

deflections in the same hole. It was also a wedge device. Mr. Hoffmann¹ gives several instances of its successful application.

¹ *Op. cit.*, p. 9.

Haussmann's Apparatus.—This apparatus was invented by Prof. Karl Haussmann at the Technical High School in Aix la Chapelle in 1907. It is essentially a double magnetic needle, spirit level and photographic device and has com-

FIG. 125.—Course of a South African drill-hole, vertical and horizontal views. (After J. I. Hoffmann by permission of the Institution of Mining and Metallurgy, London.)

manded such respect for a long time on the Continent that we shall enter into some detail regarding it.

Figure 126 shows the assembled plumbing cylinder with guide springs and an attachment for the core catcher below and one for the rope or rods above. The conductor cable runs along the rods and down into the interior of the cylin-

der. On the right is an accumulator with cells and on the left, on the tripod, a current switch connected to the accumulator and coupled to the cable reel.

The *plumbing cylinder* has a non-magnetic casing 40 mm. wide, 10 mm. thick and 750 mm. long and is in three

FIG. 126.—Haussmann's apparatus assembled.

parts; the lower one for taking the plumbing apparatus, the middle one the registering apparatus and the upper one the connection to the electric conductor. At the ends of the middle section are two corresponding graduated circles divided into 10-deg. intervals; the two other sections carry reading marks. The upper mark lies in the plane of symmetry of the suspension device and the lower one corresponds with channels in the lower casing in which

the plumbing frame with the registering apparatus is inserted. Thus one can screw up the casing without nut surfaces and still if needed be able to read the position of the registering apparatus against a guide rod.¹

The Guide Springs.—The longitudinal guides above and below the cylinder are of steel and ringed at their ends, the rings being rotatable about the plumbing cylinder. The outer ring can be adjusted up and down it. These

springs (Fig. 127) must act similarly together so that the most outer points always lie on a conical surface through the axis of the apparatus.

FIG. 127.

The Inclination Measurer.—Figure 128 shows the internal construction of the dip measurer. One of the three bars forming the frame has a lamp (4 volts, 0.45 amp.) with a reflecting parabolic mirror *b* below it (Fig. 128). The side

conductor wires leading up from the lamp are well coiled about one another in order not to influence the neighboring magnets. Next above the lamp is a plain glass plate *c* with a swinging magnetic needle *d* held by arm *e*. A little above this an adjustable level *f* is provided with a glass floor on the cover of which a second magnet swings. The glass plate may be removed so that both magnets, oppositely influenced, may give a suitable intersection angle. Above the level on its glass cover are concentric rings 2 mm. apart, then come the lenses *g* and *h* (Fig. 128). Some convex

FIG. 128.

¹ Glückauf, No. 7, p. 233, Feb. 15, 1908; Mitt. Markscheiderwesen, Heft 9, p. 53, 1908.

lenses can also be set here. On the upper surface of the level is a mark $a a$ (Fig. 129) representing the abscissa

FIG. 129.

axis on which the direction of the throw is taken. The two convex lenses g and h from which the latter is screened throw the image of the level with the concentric rings, the abscissa axis, and the upper needle ns (Fig. 129) on to a sensitive paper strip i (Fig. 128) working on rolls R_1 and R_2 and shafts r, r . This is the headpiece with registering device shown in Fig. 128. Below the frame (not visible in Fig. 128) is a central lug for sticking in the casing. There are connection screws for the level and the whole frame, for connection and screwing in the frame to the cylindrical casing.

The Registering Apparatus.—This is shown in Fig. 130 on a greater scale than in Fig. 128. A long strip of paper very sensitive to light winds from a roll R_1 over two guide roll shafts r in the image plane of the level and lens system. From here it runs on over the fixed drive roll R_2 .

There is a solenoid e above the rolls provided with a clutch n

FIG. 130. — Haussmann's registering apparatus.

which engages in a cog wheel z on the upper roll. If the current to the solenoid is shut off the core rises and the clutch turns the upper roll one tooth further, thus drawing the paper strip a corresponding piece forward. On interruption of the current the clutch is snapped into the next tooth by a small spiral spring f . The base of the registering device is fitted exactly to the end plate of the plumbing frame.

The Current Supply.—The conductor wires go from the lamp and solenoid to three concentric measuring rings which are in the cover of the registering apparatus insulated from each other. One of the rings is connected to both the lamp and solenoid. From here on the cable is led into the upper part of the casing and terminates in three spring rods sliding on three rings in the cover of the registering device when screwed up. This gives an easy connection between cable and lamp or solenoid. From the rods the cable goes through the neck of the plumb cylinder casing with suitable screw nut tightening and protection from water. It is a three-wire cable, but two will do if a suspension rope is used or rods, and, if there is a reversing device, one will do.

The Switch.—This apparatus is switched in between the source and the cable roll. It is used for cutting off, interrupting, regulating, and reversing the current. It carries a variable resistance in a wooden frame with an ammeter and voltmeter between, which is an attachment for switching in a control lamp in the circuit. The plugging arrangement is for closing or reversing the current to either the lamp or solenoid of the plumbing apparatus. There is a press button for the supply to the lamp as well as a moving measuring arm which slides over a toothed measuring plate which has spaces filled with a non-conducting substance.

A numbered rotating ring is fitted for the number of teeth. The plate is connected to the registering apparatus. If the accumulator is switched in and the arm turned the registering roll turns correspondingly. The functioning

of the apparatus depends on the action of the solenoid armature.

The Guide Rods.—If magnetic orientation fails, as, for instance, with lined holes, a mechanical means must be resorted to for obtaining a definite direction, and this is done by means of the guide rods. These are made of stiff-membered cross links as in Fig. 131. In the end of equal lengths of tube taps are fitted which are crosswise to one another and have alternate interior and exterior guide surfaces. The several members are bolted in right-angled planes immovable; thus the rods can press against a winding borehole without turning their members in shear. Over the borehole the guide jack or trestle is set up which gives a definite orientation to the rod members as they are let into the hole and for adding fresh members.

Haussmann used members 75 cm. long, 1 cm. thick, and 4 cm. wide, strengthened above.

The Level.—The level is used instead of a plumb bob and cuts out much inconvenience; the plumb oscillates a lot and slowly comes to rest and is also not so exact as the level in such a narrow space. The level on the other hand comes to rest quickly and its sensitiveness is quite independent of the length of the plumbing cylinder and no magnification of readings is necessary.

The Crossed Magnets.—Magnetic needles are suited to undisturbed regions, unlined holes, and iron-free places, but one has no control over a magnetic needle. Two needles close together, swinging in parallel planes, cross when under contrary influences; we thus have a means of locating disturbances and preventing false readings. If a magnetic deflection is present the cross angle of the two magnets will vary and on the vertical turning axis of the magnetic needles is a differential variometer for horizontal intensity. In some cases cutting out faulty orientation survey spots will not give a correct notion of the survey

FIG. 131.

as a whole, and in such cases mechanical means must be used.

The Mechanical Guide of the Rods.—The above-mentioned rods of stiff members with cross links are movable on all sides in their long axis but not at all in the cross direction, so that they can follow a winding hole without losing their orientation. Thus the borehole course is resolved into short pieces. The correct working of these guides is an important preliminary of all surveys. Trial of rods through 180 deg. before every test is considered a good check.

FIG. 132.—Borehole survey by Hausmann's method.

In plumbing a hole in undisturbed conditions, first arrange marks for depth measurements on the rope or use a measuring wheel, or, if using rods, mark the rods for a given direction on the scale of the registering apparatus. Now when ready switch in the resistance for the lamp and solenoid and read with the ammeter and voltmeter. The first survey is made with the plumb cylinder hanging free in the hole. By means of the switch lever we can

bring a new piece of photographic paper strip into the picture plane and by pressure on the middle button of the switch box illuminate the lamp. We have now to get the depth which is got from the rope or rods and in this way can carry out hundreds of surveys without pulling the plumbing cylinder out of the hole. A dark room is improvised in which to develop the sensitive figures of Fig. 129. The results can be evaluated by means of a polar coordinate scaler or a rectangular coordinate tracer.

Figure 132 shows an actual survey by this method of a borehole with a 2.9 per cent deviation off vertical, the small circles being the horizontal sections of the borehole at the respective depths in meters, the axes numbers being the lateral displacement in meters.

For Haussmann's apparatus the following advantages over previous devices have been made and they appear to be well founded:

1. A higher degree of accuracy is obtained with a sensitive level than with a plumb bob or pendulum. The level permits of a reading accuracy of 0.1 to 0.01 per cent.

2. It provides a sure reading in magnetically disturbed regions, giving reliable direction determinations.

3. Repeated measurements can be made, each giving a sharp photographic indication.

4. Good centering.

5. Simple and rapid assembling and measuring, which holds also for great depths.

Owens's Apparatus.—This is an illuminated clinometer and compass device, invented by Dr. J. S. Owens in 1925, and having an external and internal casing like Gallacher's apparatus. The inner one bearing two corner tubes is free to rotate on the long axis pivots. This, of course, keeps the inner casing with the clinometer and compass always swinging into the vertical and horizontal planes, respectively; the other inner carrier tube holds mechanism which controls the length, number and interval of exposures. This mechanism is a clock-operated controller making and breaking circuit with electric lamps. The

clinometer is an eccentrically weighted drum bearing a strip of sensitized paper which rocks close to a diaphragm with apertures in it.

The magnetic needles and apertures move on one spider and they are encircled by a strip of sensitized paper on a drum and all light is excluded except at the apertures. On top of this is an opal glass lit up by the lamps which flood the inside with subdued light, and this gives the photographic record of the needles. When horizontal each lamp lights up half of the dome, and when the instrument is vertical one lamp lights up the whole dome, so that illumination is constant at all angles. The instrument is best understood if taken part by part.¹

Figure 1 (Plate XII) shows the complete instrument. At the ends of the external casing 3 are screwed two similar watertight plugs 1 and 55 of non-magnetic material, the latter having the hauling rope eye. The two separate internal carrier tubes 5 and 39 are bayonet jointed for easy removal. In Figs. 1 and 2, on pivots 6 and 21, is a cradle 26 with a compass, clinometer and two lanterns. By way of cap bolt 21 a stud 25 makes electrical contact with a dry battery. The weight of the cradle 26 keeps the clinometer in a vertical plane, as in Bawden's method. It is borne on end pivots 7 and 19, and there are two lamps at 35 on the central line of the cradle in front of and behind the compass, the one always throwing light on the clinometer holes. These lamps are connected in parallel to bolts 20 and contact finger 57.

The clinometer 27 (Figs. 2, 3) is a drum on a spindle free to revolve at right angles to the cradle pivots and has oil damping in its bearing sleeves; and behind are spring clips 9 for the record paper 10. On its side next to the compass is the aperture plate 11.

The magnetic compass is spherical and borne on pivots 63 at right angles to the cradle pivots (Figs. 2, 4). Its lower half 33 is solid, thus being the righting weight which

¹ Dr. J. S. Owens's paper read before the Institute of Mining and Metallurgy, Jan. 21, 1926.

FIG. 3 Sectional Elevation Clinometer

FIG. 4 Section through Pivot Magnetic Compass

FIG. 1

Sectional Elevation

FIG. 2

Plan

FIG. 5

PLATE XII.—Dr. Owens's borehole surveying instrument.

keeps it horizontal, and the upper half 15 is a hollow dome. In an annular recess inside the bowl 33 is a strip of sensitized paper fixed relative to the bowl in which the needles move. The needle pivot in the bottom part of the bowl 33 holds the needle, which is a standard sewing needle, on carrier 62. There are four of these rectangular needles; two 30 flat, and two 31 on edge on the bearing spider 29. This spider has two opposite holes at right angles to the center lines of the needles, and two white paper reflectors 65 opposite the holes. In the cradle on the compass side of each lantern is a diaphragm 34 (Fig. 2) with a bell-mouthed hole with clip held screens. A number of screens of tracing cloth are placed in these to adjust the intensity of light on the dome. The compass has a sliding cover 13 over the upper half and is finished dead white inside for even lighting. This all provides uniformly diffused light of suitable intensity within narrow limits.

The controller is for determining the length and interval of exposures which may be two or four per hour, dependent on the setting of contact finger 44. A control screw 50 (Fig. 1) insulated from the control base 49 is prolonged into a spring plunger 38 by means of which a good contact is made to the dry battery. Owing to the high-pitch, left-hand thread on this small diameter screw the drum retreats from the clock when it is revolved by the crank. This crank is fixed to the minute-hand spindle of the clock and drives the drum through the insulated pin 50 projecting from the spider 52 carrying drum 51. This drum has four longitudinal metal contact strips 45 in electrical connection with the spider for giving two or four exposures per hour. The circumferential width of these strips is such that a series of exposures of increasing length are got during each revolution of the drum, and this enables the records to be identified. The drum contacts, as shown by the finger 44, on slide 41.

At the end of carrier tube 39 is the clock 48 with its minute-hand spindle extended to carry a crank 47 with a milled setting knob 54 on opposite ends. It is readable from the

opening over the controller. The standard dry battery 37 in carrier 39 bearing on plunger 38 presses its central stud on to the contact bolt 21.

The insulation rod 59 (Fig. 5, Plate XII) is attached when the instrument is in use and coupled to the drill rods or rope for lowering. Before making the survey the device is taken to a dark room where the two carrier tubes are taken out and uncoupled and record strips of bromide printing paper are fitted to the clinometer and

Inside View from above of Compass Apertures and Needle

FIG. 133.—Inside view of compass apertures and needle from above.

FIG. 134.—Compass record.

compass drums. The datum record from which deviations are measured is arranged in the dark room, this being a standard datum such as the horizontal instrument casing with the controller end toward the magnetic north. Now set the record strips with controller to give one exposure and reassemble the carrier tubes in the casing. After time sufficient for exposure the controller automatically stops and it is taken to the hole to be surveyed when the controller is reset. The eyed plug 55 is now unscrewed and the carrier

tube withdrawn sufficient to expose the controller, which is set for the desired number of records and required interval between time of setting and first exposure. The watch of the operator is synchronized with the instrument clock and the whole apparatus assembled, screwed up tight, and, with the insulation rod attached to the instrument, lowered to the spot to be surveyed. Depth and time are noted, and time for exposure at the spot exceeded, it is lowered to the next spot and so on for the number of spots being

FIG. 135.—Clinometer record.

surveyed, after which the instrument automatically ceases working and is withdrawn from the hole. It is now taken to the dark room where the record strips are withdrawn and developed.

Assuming that the instrument is horizontal and the controller end points toward the magnetic north, which is datum line direction, we get a record as in Fig. 134a. If the said end be pointed northeast, the record is as in Fig. 134b; if southwest, it would be as in Fig. 134c, the displacements being typical for these positions. The drums are designed so that 300 deg. equals 3.6 in. on the record strip surface, or 1 deg. equals 0.01 in. Thus by dividers and a diagonal scale we may read hundredths of an inch,

as seen in Fig. 134*d*, where distances b , c and d are for records 2, 3 and 4, respectively. Similar reasoning applies to Fig. 135 showing clinometer records. Figure 136 shows a

FIG. 136.—Actual survey of a Portuguese borehole.

typical borehole survey from Portugal constructed from such records. We are indebted to the proprietors of *Engineering*, and C. F. Casella & Co., London, the makers,

FIG. 137.

for the photographic views showing (Fig. 137) the compass and clinometer, (Fig. 138) the casing and inner parts ready for assembly and (Fig. 139) the clinometer and contact drum.

Anderson's Apparatus.—We have had no personal opportunity of examining this method, the full details of which

FIG. 138.—Compass and clinometer.

are not accessible. However, it is known to be another application of the orientated drill-stem method, the survey

FIG. 139.—Clinometer and contact drum.

principle being that of the multiple-photograph method wherein one or more pendulums are photographed for each position. It has been widely and successfully

employed in California. It is about $3\frac{1}{2}$ in. in diameter and about 7 ft. long (Fig. 140) and is capable of taking 88 records each trip, the distance between each setting being at the control of the operator. The survey can thus be made in a normal round trip and usually at the rate of 1,000 ft. in 70 min.

FIG. 140.—Anderson oil-well survey apparatus about to be lowered in hole, with stands of drill pipe set back in the derrick.

FIG. 141.—Demonstration frame with the machine set for certain inclination from the vertical.

The apparatus, including the pendulums, photographic equipment, timing and actuating devices, is all contained in a watertight welded casing which is constructed to be run into the well on the end of a string of drill pipe or tubing. Thus it can be used in mud and water. It is generally run on tubing or drill pipe, although in the case of one Pan-American well it was run on a sand line. In

Anderson's sand-line method a set of expansible steel-spring guides is run both above and below the instrument in its shell to prevent rotation in azimuth. A practically frictionless swivel connection is made from the end of the sand line to the instrument container.

Readings are taken at each stand length and the station distances measured on the drill lengths, the operator taking the instrument as delivered from the well and interpreting

FIG. 142.—Plan of very deep borehole surveyed by Anderson.

the results on a special orientating stand (Fig. 141). Orientation is thus measured mechanically the direction of drift being referred to a north-south line on the derrick floor so that at each exposure the directional deflection is known at the surface.

Interpretations will average within about 7 ft. of arc of being correct for vertical angles and 30 ft. for azimuth. The instrument is also self-checking in that all recorded points must fall on a curve when plotted. Various surveys

with this instrument have been published,¹ while Fig. 142 shows the course of the first 6,948 ft. of the deepest well as surveyed by this device. Goodrich² quotes an instance of one survey by this device in a well 6,522 ft. deep taking 6 hr. 45 min.

¹ SMITH, F. M., *Oil Gas Jour.*, p. 120, Dec. 2, 1926; *Eng. Min. Jour. Press*, Feb. 6, 1926; ANDERSON, A., *Oil Age*, p. 20, September, 1926.

² *Oil Gas Jour.*, p. 38, Nov. 15, 1928.

CHAPTER IX

GYROSCOPIC COMPASS METHODS OF SURVEYING BOREHOLES

Introductory Note.—The gyroscope being uninfluenced by local attraction is well suited to the survey of boreholes. The physicist, Foucault, whose pendulum researches are well known, instituted in the middle of last century the law that a spinning wheel with three directions of freedom, *i.e.*, one which is free to move in all three dimensions, is unin-

FIG. 143.—Wheatstone's gyroscope.

fluenced by the force of gravity and is suited to indicate the rotation of the earth. In order to have a freely moving wheel it must have Cardan suspension. In order that the action of gravitation be removed the three axes must all meet in the center of gravity of the system (Fig. 143). Such a gyroscope is called an azimuth gyroscope and then if no external force acts on it—whether at rest or rotating—it keeps its position in space unchanged. The term “azimuth gyroscope” is not happily chosen because the magnetic compass

also has an azimuth, only this is not optional but zero (meridian).

Foucault has also shown that a gyroscope which is compelled to move in a horizontal plane endeavors to adjust itself to the north-south line. Such an arrangement is called a gyroscopic compass or gyrocompass. In England and France experiments have been undertaken since well into last century, with the purpose of utilizing the gyroscope as a compass. In Germany experiments have been under-

taken mainly by the firm of Siemens and Halske. Owing to insufficient technical assistance and faulty knowledge these experiments were more or less abortive.

A gyroscope¹ consists of a heavy wheel mounted on bearings free to spin about different axes, usually symmetrical axes perpendicular to the equatorial plane (Fig. 143). When the conditions of dynamical symmetry are not obeyed we get bad static balance, as when

a. The center of mass of the gyroscope *O* does not lie on the spinning axis; as in the case of an eccentrically mounted disc.

b. The principal moment of inertia is not coincident with the spinning axis, a torque being thrown on the bearings; as when we get oblique but central mounting.

c. The moments of inertia about all axes through *O* are not normal to the axis of spin; as when we have an elliptical centrally mounted disc.

These are corrected mainly by distribution of small masses on the disc. When all the axes *xx*, *yy* and *zz* are as in Wheatstone's gyroscope shown in Fig. 143, it is said to be "free," and if any one is locked it is said to be "constrained." This latter feature sets up certain phenomena applied in borehole surveys.

Degrees of Freedom.—The spin of the disc about *zz* is known as the first degree of freedom, the rotation of the disc about *yy* axis the second and that about the *xx* axis the third degree of freedom. When the disc spins about *zz* there is an instantaneous angular movement of the axis *zz* known as "precession." It can be noted if a heavy cycle wheel is held vertically in front of the body with the left hand by means of an axle and spun clockwise with the right. The bearing pressure on the left palm tends to vanish and the wheel under the influence of the spin and gravitation rotates anticlockwise about the experimenter's body. The free gyroscope tends to keep the axis

¹ GLAZEBROOK, SIR R., "Dictionary of Applied Physics," Vol. 1, p. 421.
ROSS, J. F. S., "Introduction to the Principles of Mechanics," Cape, 1923.
HAUSSMANN, K., "Der Kreiselkompass in Dienste des Bergbau," 1914.

about which it spins unaltered in direction whether rotating or not. If spinning it resists any attempt to alter the direction of its axis, and the gyroscopic torque dominates when the gyroscope is given a very high speed as is common in borehole practice. This precession is so important in borehole gyrocompasses that it appears to merit fuller detail.

At the beginning of this century several trials were made to establish a gyrocompass. Doctor Anschütz-Kaempfe succeeded in bringing out a gyroscopic compass which maintained its direction for a long time—24 hr.—in the laboratory. He however recognized that it was extraordinarily difficult, perhaps impossible, to create a gyroscope complete and perfect in equilibrium; he therefore, in 1906, added to the gyroscope with three degrees of freedom one with two degrees of freedom and in this way arrived, by progressive simplification, at his first gyroscopic compass with only one high-speed wheel and with damped oscillations. In the most recent form of the Anschütz compass for nautical purposes there are three similar wheels which compensate the regular oscillations of the ship.

Precession.—When a simple wheel disc rotates and no lateral force or torque is exerted upon it, it persists in its position because every particle of mass in the disc endeavors to remain in the plane set up. This inertia grows with the mass of the disc and with the angular velocity of the rotation. If a torque is exerted on the quiescent disc (which can be imagined as an upward pull on one axis end or a downward pressure on the other end) the plane will incline laterally.

If a torque or lateral pressure be now applied to the disc when rotating, we have the inertia of the disc on the one hand and the inclination of the tilt on the other, so that it is a question of what will be the result in the motion due to these two factors acting simultaneously. Let us consider Haussmann's¹ simple presentation of these important facts, which we have slightly modified for our purpose.

¹ *Ibid.*, p. 51.

Figure 144 shows a plan and elevation of a rotating disc I with a force acting partially on its axis; also its imagined neighboring position II into which the disc is for the time being inclined. (For clarity the drawing is much exaggerated.) In the plan the narrow ellipse I gives the original position and II the inclined position of the disc. The direction of the disc in plane I in the plan is shown by the horizontal diameter AB of the ellipse. Any mass particle m of the rotating disc I will remain in this position in consequence of its inertia, even if the disc inclines a little due

FIG. 144.—Precession.

to a lateral torque. This direction of persistence must thus also be present when the particle m rotates in the inclined plane II. If the particle is now compelled to rotate in plane II it still has the tendency to remain in the direction of plane I. The tangents to plane II give the new, those to I the old, directions of movement. These directions are only equal in C and D , also in E and F ; in all other points they differ. Let the divergence of corresponding tangents be indicated by δ and the angle between planes I and II by Δ and further let the angular rotation of the particle proceeding from D be ω , then we get the relation

$$\sin \frac{\delta}{2} = \sin \frac{\Delta}{2} \sin \omega \quad (12)$$

For small angles $\delta = \Delta \sin \omega$. The value of δ is nil in points D and F , a maximum in A and a minimum in B .

Corresponding to the divergence of the tangents there appears a force acting at right angles to the disc, which is nil in D and grows to A and from here on again declines to nil at F then back to D in the same manner but taking a course in the contrary direction.

These lateral components effect a rotation of the spinning disc about the diameter DF or in relation to the original position I about the normal diameter CE ; and this turning annuls at every moment the tendency to lateral inclination. This turning motion at right angles to the direction of the applied force is called *precession*. We shall not go into the lesser motion appearing in the periodic repeated dip and rise of the axis known as *nutation*. The preceding construction applies very fully to a gyroscope imagined as frictionless. In practice the axis of the gyroscopic disc will, in the course of time, show more and more marked inclination owing to the action of friction.

As a proof that a force applied to the axis of a rotating gyroscope brings about a lateral movement we have but to consider the common spinning top or child's hoop.

The Action of the Gyroscopic Compass.—Imagine a gyroscope wheel suspended at the equator so that its axis $A_w A_e$ (Fig. 145) is horizontal and it goes round from west to east. Regarded from west or south the wheel has a clockwise direction of rotation as shown by I in (Fig. 145). Next instant the wheel, owing to the earth's rotation, is in position II (much exaggerated in the drawing).

Owing to the inertia of the disc the axis $A_w' A_e'$ stays in position II parallel to its former position $A_w A_e$, while the direction line of gravity in II makes an angle of $\omega_0 = 15t$ with that in I, owing to the interval t in time between positions I and II and the fact that gravitation acts toward the earth's center. Thus the disc axis is no longer at right angles to the direction of gravity; its east end is too high, so that the force of gravity acts unequally on the axis. On the west end an upward pull is exerted and on the east

end a down pull acts. The force of gravity thus gives rise to the precession motion of the gyroscope whereby the east extremity of the axis moves toward the north. When the axis comes into the plane of the meridian the effect of gravitation on both ends of the axis is similar and balances. The gyroscope remains in this position because the meridians at the equator run parallel, and thus it is independent of the earth's rotation. The meridian is the position of equilibrium which the gyroscope tends to attain in consequence of the earth's rotation. On the equator the turning axes of the earth and the gyroscope are

FIG. 145.

parallel and their rotational senses are the same. In general all rotating bodies tend so to place themselves that in similar turning senses their turning axes are similarly directed. If now we hang the rotating wheel not on the equator but on any other chosen spot on the earth's surface the gyroscope will still tend to set its axis in the same direction as that of the earth. This can not occur completely owing to the line of gravitation being here no longer normal to the earth's axis as at the equator, but being inclined to it. The gyroscope will now, as far as is possible, set its axis in the line of the earth's axis, and it attains its greatest proximity to this when its axis lies in the meridian. If at any place of latitude ϕ the axis of the gyroscope makes

an angle ϕ with the earth's axis, this is then the smallest of all possible angles between a horizontal line and the earth's axis. For a horizontal line of any azimuth A we get the corresponding angle of inclination α , from Napier's laws. Thus

$$\cos \alpha = \cos \phi \cos A \quad (13)$$

Angle α is greater than ϕ because its cosine is smaller. In Fig. 146 point I_ϕ rotates, owing to the earth's rotation in time t , to position II_ϕ . The gravity direction lines in

FIG. 146.

I_ϕ and II_ϕ do not now make an angle of $\omega_0 = 15t$ as at the equator, but a smaller angle ω_ϕ which can be computed from

$$\sin \frac{\omega_\phi}{2} = \sin \frac{\omega_0}{2} \cos \phi \quad (14)$$

Thus for small intervals of time we may write $15t \cos \phi$. The directing force of the gyroscope thus decreases with latitude, it being only a half in 60 deg., a quarter in 75 deg., and a tenth at 85 deg. latitude, of the force at the equator. It is nil at the pole where all great circles are meridians. On the gyroscope axis swinging into the meridian plane from the east, the east end of the axis is somewhat

too high and the gyroscope oscillates over the meridian out again. As the north axis then dips below the horizon a back oscillation sets in. To decrease these oscillations sufficiently rapidly a damping device is provided with the gyrocompass. In Anschütz's method the suspension of the compass is obtained by having it connected to a body which floats in quicksilver. Then at any azimuth of the gyrocompass the buoyancy of the mercury takes up the gravitational force, acting through the earth's rotation on the one extremity of the axis, in the form of a pull upward, and that on the other end is compensated as a pull downward by its proper weight.

The Kiel Nautical Instrument Company's Gyroscopic Compass for Borehole Surveys.—This apparatus¹ was formerly introduced for warships and submarines by the firm Anschütz of Kiel. Indeed, it alone made long-distance underwater navigation possible.

It is let into the hole on a cable and 2-m. measurements are taken with it. It is held centrally by guide brushes to maintain always the same vertical in the hole. A measuring box (Fig. 147) has two pendulums arranged to rotate about the axis of the apparatus; they swing in two planes at right angles to one another and a small gyrocompass adjusts the measuring case so that one pendulum swings in the east-west and the other in the north-south direction regardless of how the apparatus turns on being let down. Figure 148 is a schematic view of the measuring box with an east-west pendulum which hangs vertical while the box is inclined with the hole. (The dip here is exaggerated

FIG. 147. FIG. 148.

¹ MARTIENSSSEN, O., *Electrotechnische Ztschr.*, Heft 24, p. 462, 1920; p. 694, 1919; and pp. 862, 887, 1911.

being seldom more than 1 deg.) Below the point of the pendulum is the midline m , m , of the apparatus, and, owing to the dip, the pendulum deviates a little way a from this line east or west. This amount a is measured and if, say, the deviation is a mm. and the pendulum 20 cm. long, then in a length of 2 m. the hole is displaced 2 cm. to the west. If we carry all measurements at 2 m. and add all the deflections a we get the total deviation of the hole toward the west in centimeters. Similarly the north-south pendulum point may give deflections b at the same times and these are also added as above algebraically. Both displacements are plotted on coordinate paper which permits the position of the hole with respect to its origin being easily found. Thus, for example, for a 300-m. depth in a hole, we employ 150 measurements on the north-south and east-west pendulums and add them for the resulting displacement, say west and south.

Figure 1 (Plate XIII) shows the interior of the apparatus which is protected by a steel casing, for loosening which a nut at the bottom can be drawn out. It is tightened with India-rubber gaskets which will suit pressures of 150 atm.

The most important part of the device is the gyrocompass hanging under the inclination measurer, the action of which is based on Foucault's law that the earth exerts, on every horizontal rotating shaft, by its revolution, a force which turns the shaft in the north-south direction, so that the turning of the earth is of the same sense as that of the shaft.

The directing force we have discussed on page 208 to be the product of the moment of inertia of the wheel, its angular velocity, the angular velocity of the earth, the cosine of the geographical latitude and the sine of the angle between the meridian and the wheel axis.¹

If the suspension is free enough this directing force lets the axis of the wheel swing into the north-south line, for then the sine of the angle is nil, but in order to attain sufficient force the velocity of the wheel must be great.

¹ MARTIENSSSEN, O., Die Theorie des Kreiselkompasses, *Ztschr. f. Instrumentenkunde*, 1913.

The gyroscopic compass constructed to meet these demands is shown in Fig. 2 (Plate XIII) and set in the lowest part of the apparatus (Fig. 1). A ring-shaped vessel *a* filled with mercury is fixed on the rotatable measuring case in a housing with the aid of bows *b*. A ring-shaped float *c* in the mercury vessel holds the wheel cap *e* by a neck *d*. In this cap or case runs the gyrowheel on ball bearings, the wheel itself being of nickel steel and having a short-circuit rotor pressed on it. The stator of the small alternating-current motor which drives the wheel is fixed in the wheel case, and it is supplied with a 400-cycle per second current, by means of fine silver wiring, causing the wheel to make 25,000 r.p.m.

The construction of such a quick running alternating-current motor with short-circuit armature is extremely skillful; the high number of revolutions demands much copper in the rotor so that the turning moment be small, otherwise the wheel will not exceed a definite speed range.

The wheel hangs in its case as deep as possible below the float compatible with the tube width against which it would bump if very deep. In this position gravitation tends to hold the axis horizontal and the axis adjusts itself to the meridian by Foucault's principle, stated above, because the entire floating system is arranged rotatable about the center rod *f*. A directing force of some tenths gram-centimeter suffices to turn this small gyrocompass but not the whole measuring box, so for that reason the following arrangement is adopted. On the floating system is fixed a contact bead *g* which, when the float with the wheel turns right or left, makes contact with a contact spring on right or left and in this way a so-called "turning, take-up, or compensating motor" changes its rotational sense. This is to be found in the uppermost part of the inclination measurer (Fig. 3). It is a small direct-current motor with double armature winding and commutators on both sides; and by the contact bead one or the other of the windings is cut out causing the armature to rotate in the opposite way.

This take-up motor turns the measuring box with the mercury vessel and contact springs to the rotations of the gyrocompass, for the bead is only out of contact when it hangs free between the contact springs on the mercury vessel. Consequently, the measuring box is always in a definite position with respect to the gyrocompass and thus also to the meridian. In Fig. 2 (Plate XIII) the lower bearing of the compass box is shown at *l* and in Fig. 3 *L* is the upper bearing of it. The box itself is shown in Fig. 4.

The east-west pendulum *a* swings in the picture plane and the north-south pendulum *b* at right angles to this. Under each pendulum is a registering casket *kk* with a registering strip running close under the points. Over the pendulum points lie the cores or armatures *dd* of two small electromagnets as broad as the strips. When taking measurements the current is sent into the electromagnet by a telegraph key on the surface; the core strikes the pendulum and presses a fine needle on the end of the pendulum into the registering paper thus perforating it. Breaking the circuit the electromagnet operates a catchwork driving the registering strip 5 mm. forward ready for the next measurement.

On opening the apparatus at bank and taking the strips out from the casket and reading the deflection of the several holes from the midline of the paper, two separate tables are entered up with the data from the two strips. The sum of the entries in the two tables, east-west and north-south, gives the displacement at the depth concerned.

Figure 1 shows the head of the apparatus; the various leads of the cable are tightened with India-rubber the winding cable itself being of medium steel and held by bolts *b*. Eight lines encased in gutta-percha and jute yarn take the current to the wheel, take-up motor and electromagnets. The rope is also covered with gutta-percha to distribute the load at the bearing guide roll.

The cable drum and motor are in a special lorry as also are the current source and transformer for the direct-current portion and also the necessary controls for the gyro-

FIG. 1.—
Complete
instrument.

FIG. 3.—The dip
measurer.

FIG. 4.—Registra-
tion section.

FIG. 2.—The
gyrocompass.

wheel current, the take-up motor current, keys, etc. The method has been frequently applied in measuring the deviation of freezing shaft boreholes. The makers claim the remarkable accuracy of about 1 in 2,000.

Anschütz Borehole Deviation Instrument.—

Doctor Anschütz¹ employs the gyroscopic compass for fixing the direction of deviation and a rigid plumb bob for the amount of deviation. He equips both with transmitting apparatus and combines these with a receiving apparatus on the surface so that one can read there at once the position of the plumbing apparatus at any chosen position in the borehole. The plumbing device is let into the hole with a cable from which the depth is read.

Since the results are given directly on the meridian, the astronomical north and the direction of gravity the apparatus is free from partial measurement errors. Each individual observation is completely independent of the others, thus obviating the transference of errors. The superiority of this method will thus be greater at greater depths. Since an opening of the tube throughout the application is not necessary, the dip measurer is always ready for use and yields unvarying data. Figures 149 to 152 show the constructional parts of the inclination measurer. They are made up of the transmitter (Figs. 149–151) and the indicator or receiver aboveground (Fig. 152).

The Transmitter: Plumbing Cylinder and Chief

Parts.—This is shown in Fig. 149 as a pressure-proof steel cylinder *a* bearing a gyrocompass *b* giving the direction, and a rigid plumb *c* with

Cardan suspension for giving the amount of inclination of a borehole at any position. This cylinder has steel feeler brushes *d* above and below and is let into the

FIG. 149.
The trans-
mitter.

¹ HAUSSMANN, K., *Glückauf*, July 4, p. 1076, 1914, also BERGASSESSOR WIMMELMANN, *Kohle und Erz*, Nos. 13–15, pp. 323–379, 1924.

borehole by the cable *e*. Compass and plumb are both provided with a transmitter, which are connected by electric conductors in the interior of the holding cable to the receiver aboveground. The two principal parts of the plumbing cylinder are the gyrocompass and the hanging plumb bob.

The Gyrocompass.—Under the steel cover there is a lead to the compass (Fig. 150). The capped compass case *a* carries a three-phase motor with a short-circuit rotor. This consists of iron sheets with aluminum rods and star plates. Over the axis a two-pole alternating-current winding is slid.

At an alternating current of 0.25 amp. and 120 volts, 500 periods, the body wheel of the compass is made to rotate about its horizontal axis at 30,000 r.p.m. The wheel is closed about by a cap which hangs on a floating ball bearing. The ball floats in a vessel of mercury *b* (Fig. 150). On the float body a small contact ball *c* is sprung. This rotates with the wheel independent of the mercury bath and the tube. Contact paths *d* are fixed on the mercury bath and they have slits. These turn independent of the wheel with the bath and lamp *e* in the casing jacket. The mercury bath has a Cardan suspension, *i.e.*, gimbals, in the lamp *e* and is connected to the transmitter motor *g* by means of a spur wheel drive *f* through a shaft. This motor *g* rotates the bath and lamp as long as the contact bead slides on one of the contact paths *d*. As soon as the bead has reached the slit the electrical circuit is interrupted and the turning ceases. Then the transmitter motor has reached its previously known normal position compared with the wheel. The motor of the transmitter is connected electrically to the receiver motor, the graduated scale of which turns back. Here one may read off the position of the transmitter motor respecting the compass

FIG. 150.—Anschütz apparatus. The gyrocompass.

wheel and therewith respecting the meridian (by providing a meridian line or azimuth line through the borehole). Thus we get the lateral angle aboveground. The damping of the circle is easily obtained by chambers between which some oil runs in and out on the oscillations of the wheel axis.

FIG. 151.—
Anschütz ap-
paratus. The
plumbing de-
vice.

Above in the steel shell comes the plumbing device (Fig. 151). The rigid plumb bob *a* hangs by Cardan suspension in a guide and is prolonged in a rod *b* as far above as it hangs below. The plummet carries above and below a small contact bead or ball. Each of these two balls runs in a slit between contact tracts *c* and *d* on a lateral support capable of tipping *e* and *f*. In space the slits stand at right angles to one another. The upper support turns about an axis which is in a position at right angles to that of the lower one. The inclination is resolved into two components at right angles to one another. Naturally the same action can be obtained as well by two separate pendulums. When the contact balls fit laterally into their slits the current is cut off and the parts concerned will be so far displaced laterally that no further side contact can take place until the rigid plummet hangs free. The contact chariot of the transmitter is, however, connected to the corresponding parts of the receiver by means of the electrical conductor in the cable.

As long as the transmitter parts are in lateral motion the current to the receiver is cut off and it there displaces a motor contact carriage in the same manner. Both components are compounded in the receiver yielding the total motion of a magnet bar whose deviation from a mean position is shown on the concentric rings of a graduated plate by means of a small iron ball on a rod which moves according to the magnitude of the inclination of the bore-

hole. Amount and direction of inclination are read off the receiver in tenths of a degree.

The Receiver.—The mode of action of the receiver (Fig. 152) has already been described. The alternating motor *a* in the receiver runs synchronously with the motor in the gyrowheel chamber in the plumbing apparatus and turns the counter *b* (detached in the figure) back in the direction for reading the inclination. Another motor *c* displaces a

FIG. 152.—Anschütz apparatus. The surface receiver.

main carriage *d* on a horizontal spindle on which a second carriage *e* turns, also horizontal, but can be displaced 90 deg. to the main carriage. On the carriage *e* sits a bar magnet *f* with an end pointed upward 90 deg. which reaches close under the scale plate *b* and on it pulls a small iron ball. By this ball, on concentric circles, the magnitude of the inclination is read. Doctor Anschütz has investigated the possibility of a coupling table on which the course of the borehole is automatically indicated on the plumbing apparatus being let into the hole. With such a device one would only have to draw in the depth indicated by the cable on the line of course of the borehole.

The Transport Lorry.—A lorry carries the cable on a drum as well as a switch plant and all accessories. The cable is marked in 2.5 to 25 m. for reading depths. It carries inside it the conductor cable from transmitter to receiver.

The apparatus suffices for plumbings up to 700 m. and can, with corresponding cable lengths, be used for any depth.

Test Plumbings.—Tests with the above dip measurer in a pipe in a shaft of the Deutscher Kaiser works were carried out to a depth of 350 m. and have yielded the same results on insertion and extraction and on repetition. These have been checked by surveys and give agreeable results as far as comes into general practice. Since in this method partially active errors are avoided, which would make repetition results false, the conclusions to be drawn from the tests are that for a well thoughtout, ingenious and rapid working apparatus it is quite accurate and satisfies all the demands of practice. It should still be mentioned that the dip measurer is also applicable as a stratameter for cores. Speaking of this instrument, after observing a test, Prof. Haussmann of Aix says,¹ "The mathematical and physical basis on which the appliance is constructed permits us to recognize that it is free from inherent errors; thus must it also yield correct results with increasing depths." This accuracy fulfills the preliminary conditions for the success of freezing shafts, *i.e.*, by proving the course of the boreholes.

Surwel Gyroscopic Clinograph.—This remarkable device marks the most recent practice in the adaptation of the gyroscopic principle to the survey of borehole deflection. The principal features of the well-known Sperry² gyroscope of navigation are applied.

This apparatus consists of three main parts: (1) the *box level gage* (Fig. 2, Plate XIV)³ for ascertaining the vertical inclination, which is placed uppermost of the three in the apparatus; (2) the *film camera* (Fig. 3) making simultaneous moving-reel records above and below; and (3) the lowermost

¹ HAUSSMANN, K., *Mitt. Markscheiderwesen*, p. 60, Sonderdruck, 1914.

² GLAZEBROOK, SIR R., "Dictionary of Applied Physics," Vol. 1, p. 421; Vol. 4, p. 255; also British Patent No. 15,669/15; RAWLINGS, A. L., "The Theory of the Gyroscopic Compass," p. 18, Macmillan & Co., Ltd., 1929.

³ By the courtesy of the Sperry-Sun Well Surveying Company, Philadelphia.

FIG. 1.

FIG. 2.—The box level gage.

FIG. 4.

FIG. 3.—The camera.

FIG. 5.—The pointer compass.

FIG. 6.—Specimen photo strip from borehole.

PLATE XIV.—The Sperry-Sun Well Surveying Co.'s gyroscopic compass device.

unit, the *gyroscope* itself (Fig. 4). These three units are assembled, screwed tight, in a high steel jacket $5\frac{1}{2}$ in. external diameter, the apparatus itself being about $4\frac{1}{2}$ in. in diameter. The lower joints carry dry batteries operating the gyroscope and illuminating the film camera. The top joint ends in a ball-bearing swivel which enables the apparatus to be sent into the hole either on the drill stem or on a wire line. It is thus independent of many of the objectionable torsional features which render the results of so many devices unacceptable for accuracy. This latter feature plus the north orientating tendency of the gyroscope (and here the special restraining appliances) make this class of instrument independent of the effects due to twist on insertion and extraction of the apparatus. It is claimed that the casing of steel will withstand the mud pressures encountered in holes down to 10,000 ft. deep. The gyroscope, maintaining the features of *rigidity* and *precession* discussed mathematically at the beginning of this chapter, offers great resistance to any attempt to alter the direction of its axis by being caused to spin, by means of the electric motor self-contained, at a very high speed, as in the case of Anschütz model and that of the Kiel Nautical Instrument Company previously described. The direct-transmitting motor rotates the gyroscopic disc at about 10,000 r.p.m., and this latter is specially balanced to maintain its axis in the geographical meridian¹ when once set there.

A pointer coinciding with and controlled by the gyroscope (Fig. 5) is set above the gyroscope on its axis over a graduated arc. To this latter is attached a non-magnetic watch with large minute and second hands giving readings to $\frac{1}{5}$ sec. This enables computations of depth to be made for each site recorded in the hole. A thermometer may also be added here for reading the temperatures encountered which yields data not only on direct thermal conditions but for computation corrections if desired.

¹ See Rawlings, *op. cit.*, p. 124, for mathematical discussion on balancing the disc.

The *camera*¹ (Fig. 3) which is of special design employs a 16-mm. perforated motion-picture film and has a capacity of 50 ft. There are two lenses recording pictures simultaneously in opposite directions, up and down. One lens photographs the compass scale and gyroscopic pointer below with the watch and thermometer (if any), while the other photographs the position of the bubble in the graduated level gage box above. These lenses have to be very accurately aligned on the same optical axis and focus, thus superimposing two pictures on one film as shown in Fig. 6, Plate XIV. This enables one to read off the amount and direction of deflection at the same time, while the time for the depth computation is given as well. The film take-up is worked through gears by a small electric motor, which also operates a synchronized and adjustable contact device providing the necessary light flashes for taking the pictures. The camera motor is controlled by an accurate timing device guaranteed to vary less than 7 sec. per day. Thus the camera has a capacity for taking up to 1,000 photographs, giving a practically continuous record of the hole. It also records going into, and coming out of, the hole.

The *box level gage* (Fig. 2) is a ring with top and bottom of ground special glass, the former disc being spherical and having concentric graduations. The position of the bubble relative to these graduations gives the amount of vertical inclination as in the depthometer of a previous chapter. Three different levels are provided with each instrument having maximum inclinations of 20, 40 and 55 deg., respectively. This range of registration of dip angle far transcends that of any other device employing the gyrostatic principle. Preliminary runs with an acid-bottle apparatus decide which of these box level gages to select for a particular case. To ensure rapid response of the bubble to quickly altering inclinations the nature and size of the bubble are specially allowed for in the material

¹ We are indebted here for some notes kindly supplied by the makers, The Sperry-Sun Well Surveying Company, Philadelphia.

of the fluid. Lag and oscillation of the bubble have also to be provided against while temperature effects are compensated by expansion coils.

For operation with a wire line a line meter is applied to the derrick reel starting from zero, and a watch synchronized with the gyroscope watch is used for making time readings every 25 or 50 ft., according to the depth of the hole. Thus the depths are easily obtained. The apparatus is run at a fairly constant speed of 150 to 180 ft. per minute in cased holes, thus taking about 1 hr. for a 5,000 ft. hole, but this speed does not apply equally to open holes. A closed traverse is got by taking readings running into and out of the hole and this provides the check survey.

The whole apparatus is entirely automatic and the observations are taken at predetermined intervals of time. Regardless of tilt or case spin, these records yield the direction and inclination of the north pointer of the gyroscope and its amount from the bubble. The stability of the gyroscope and the sharp responsiveness of the bubble permit of this even at the above rapid lowering speeds. These and the times are recorded all together, as seen in Fig. 6, during the continuous running of the apparatus and herein will be noted the great time saving over previous types of apparatus described.

After disassembling the clinograph at bank the film is removed and developed, as in Fig. 6, whence we get the dip, orientation and time or depth. Applying now correction factors for cardinal errors, parallax and refraction (which are established for each instrument) the survey is plotted in one vertical section and two horizontal ones, respectively, north-south and east-west and a model constructed if needed.

The makers claim for their apparatus independence of magnetic and torsional influences, great saving of time, easy manipulation and interpretation of records, rapid mapping, great accuracy and simplicity in handling either on drill stem or a line, large dip range and automatic action.

CHAPTER X

GEOPHYSICAL METHODS OF INVESTIGATING BOREHOLES

Introductory Note.—Geophysical methods of locating mineral fields and particular ore bodies and minerals are already well established and can be divided into six main groups, viz., gravitational, electrical, magnetic, seismic, thermal, and radioactive methods. Of these, so far, only electrical and seismic or elastic methods have been applied to coring and borehole problems.

By a geophysical method we mean one in which some established physical property of matter, *i.e.*, ore body, oil, coal, etc., is investigated, excited or otherwise examined in contrast with its surroundings and the features betrayed measured at a distance. At present bodies at depths down to about 600 ft. have been successfully located by these means. In many cases only one particular method can be applied, *e.g.*, seismic methods (artificial ground shocks) alone suit the geological features connected with the deep oil zones of Iraq, while in Sweden electrical methods are most favored. We have detailed these methods elsewhere,¹ so will not enlarge upon them here.

Electrical Methods.—The transmission and distribution of electrical energy currents of various kinds which are sent out from artificial or natural sources form the basis of the most widely adopted methods of scientifically investigating the earth's crust. There are four chief divisions:

1. Methods in which a current is purposely generated and introduced into the ground.
2. Methods in which the currents generated in bodies themselves in the ground are harnessed.

¹ *Colliery Guardian*, May to September, 1927, and HADDOCK, M. H., "Location of Mineral Fields," Chap. VI, Crosby, Lockwood & Sons, London.

3. Combinations of 1 and 2.

4. Electrical waves.

Broadly speaking for our purpose electrical methods can be grouped into two main groups, *i.e.*, potential and electromagnetic. A brief sketch is essential to a comprehension of the method of electrical borehole investigation due to the brothers Schlumberger, the only electrical method which has been employed for this purpose.

FIG. 153.—Normal course of electric current lines between two electrodes in a homogeneous underground.

Potential Method.—If an electric potential of $+e$ volts be applied to a point a , while at another point b the voltage is zero, then between the two field electrodes, a and b , a pressure (potential) difference or electromotive force e prevails, which produces a current i , that flows from a to b in imaginary current lines, the pressure decreasing all the time from $+e$ at a to nil at b . The planes or sections which show equal potential difference toward the electrode a or b can be connected by planes of equal pressure called equipotential planes or level planes. From the potential theory we learn that such equipotential planes stand every-

where at right angles to the current lines, so that if the spacial distribution of the current lines is determined in any manner the equipotential planes are also located. These current lines have the construction of an ellipsoid of many shells, Fig. 153 being a hemispherical section for the current

FIG. 154.—Horizontal section through the equipotential lines.

lines between two electrodes in a homogeneous underground. In many cases the ore body itself also generates a polarization current in its surroundings. The distribution of the current in a body depends upon the form and

FIG. 155.—Right section through the equipotential lines. (After Schlumberger.)

spacial arrangement of the conductivity in the body and on the position of the field electrodes. Simple regular bodies are amenable to direct mathematical estimation, as in the well-known school example, while approximate rules are applied to the complicated cases of nature; deformation of the equipotential curves is sought (Figs. 154, 155) after observing the potential at a sufficient number of plotted places on or under the earth's surface.

Sufficient has been said to indicate that the electric or electromagnetic field set up by the current directed to the underground is investigated on the assumptions (1) that the earth is a good conductor, (2) that the conductivity of the object sought differs sufficiently from that of its surroundings, and (3) that the object sought lies in such a way in the current region that the deflection caused in the

FIG. 156.—Schematic example of spontaneous polarization according to Schlumberger.

electric field or electromagnetic field can be detected on the surface. Schlumberger says¹ “the equipotential curves of small radius belong to small spherical surfaces which lie at small depths in the earth and are therefore unaffected by deep-lying masses. The deep-seated masses thus only influence curves of large radius.”

Schlumberger's is distinct from any other method, where the whole measuring processes are continually fed by an electric current. It is executed by cutting out the direct-current carrying electrodes and the measurement is made on the surface by the polarization of the potential distribution brought about in an ore body. If a constant direct current flows through a mineral deposit, Schlumberger has ascertained that an electrolysis takes place in the ground on the surface of the deposit (Fig. 156) if water

¹ “Étude sur la prospection électrique du sous-sol,” 1922.

is present. Then the ore deposit will become polarized¹ and transformed into a secondary element, which discharges itself according to the interruption of the polarizing current. While the period of discharge arises if there is a measurable potential difference on the surface, he has succeeded with the help of polarization phenomena in distinguishing between minerals of metallic conductivity, such as magnetite, pyrites, lead glance, etc., and groundwater strata. Now the application of direct current also brings a polarization of the searching probes wherein the ground plays the part of an electrolyte, so that in potential line surveys special electrodes or non-polarizable electrodes² made of zinc plates in concentrated zinc sulphate solution and other chemical types are used. Alternating current of average frequency is now often applied in order to avoid this polarization phenomenon at the probes, and the course of the current in such cases no longer depends only on the ohmic resistance of the separate rock layers but also on the capacitative and inductive alternating-current resistance, which also brings about phase displacement and fluctuations in the current, thus causing variations in the form of the potential lines. However, this latter aspect does not affect electric coring methods, so that we will content ourselves with referring the interested reader elsewhere.³

Schlumberger's Method of Investigating Boreholes.—

The application of the above method has been extended by the brothers Conrad and Marcel Schlumberger of Paris to investigations on lithological data, dip of strata, faulting, intercalations and other features accounting for the deviation of boreholes. They consider the electrical conductivity of the constituents of the earth's crust which fluctuate very widely; that of the badly conducting overwhelming majority of the constituent minerals depending in a very decisive

¹ SCHLUMBERGER, C., Phénomène électrique produit par les gisements métalliques, *Compt. rend.*, p. 477, 1922.

² BARUS, C., *U. S. Geol. Survey Mon.*, No. 3, pp. 309 *et seq.*

³ AMBRONN, R., "Methods of Applied Geophysics," pp. 131 *et seq.*; HEINE, H., Die Einflüsse von Induktion und Kapazität bei geophysikalischen Potential-liniemessungen, *Ztschr. Phys.*, p. 219, 1926.

manner not only on the ground but also on its moisture content and the substances dissolved in this moisture. (We shall not submit a table of conductivities and resistivities here because they vary tremendously for the different strata of the earth's crust even in the same rocks. They should be determined experimentally for every place being investigated.) With the exception of certain metallic ores which have the property of electronic conductivity (like metals), rocks are capable of transmitting an electric current only by means of the water which they have imbibed.¹ Therefore their conductivity is solely electrolytic, and disappears entirely with drying. The solid mineral elements are almost perfect insulators, which the current skirts in following the damp veins. The following approximate laws have been deduced therefrom:

The specific resistivity of a rock is

1. Inversely proportional to the quantity of imbibed water contained in a cubic meter of rock.
2. Proportional to the resistivity of this water, therefore roughly inversely proportional to the total quantities of salts dissolved per unit volume of the water.

Thus the resistivity of a rock is in inverse proportion to the total weight of electrolytes dissolved in a cubic meter of the rock. Schlumberger says that these underlying principles are, of course, subject to many modifications, according to conditions; the angle at which sedimentary strata are inclined, for instance, affects the resistance; a rise in temperature reduces the resistance, etc.

By the accompanying illustration (Fig. 157) we see the measuring apparatus in diagrammatic form. It comprises three insulated cables 1, 2, and 3, suspended in the hole 4, and terminating toward the bottom in three electrodes *A*, *M* and *N* immersed in the well water 5. The radii, *AM* equals *r* and *AN* equals *r'*, are chosen greater than the diameter of the hole. The electrode *A* serves to send the current into the soil and the electrodes *M* and *N* to measure the difference of potential produced by ohmic

¹ BIGNELL, L. G. E., *Electric Coring, Oil Gas Jour.*, p. 33, Feb. 6, 1930.

effect between these two points by the passage of current into the soil.

To send forth a current by the electrode A the latter is connected, by means of the insulated cable 1, to one of the poles of a source of electricity E situated aboveground, the other pole of the latter being earthed at any point B close to the well. To measure the difference of potential resulting between M and N , these two electrodes are con-

FIG. 157.—Electric coring.

nected by means of the insulated cables 2 and 3 to the two terminals of a potentiometer placed aboveground.

Knowing the distances r and r' , the intensity i of the current force (measured, for example, by an ammeter) and the difference of potential ΔV between M and N (measured by the potentiometer), it is possible to calculate the average resistance of the soil surrounding the measuring field AMN , if the soil is uniform, in the following manner:

The current i flowing from A into the soil creates, by ohmic effect, a group of equipotential surfaces enveloping A . These surfaces are, by reason of symmetry, practically spheres centered in A , always excepting:

1. The region quite close to A , where the presence of the borehole full of water and the dimensions of the electrode A cause a certain disturbance.

2. The region away from A where the equipotential surfaces are affected by the earthing at B or the non-homogeneity of the soil (metal casing of the hole, etc.).

In particular, the two equipotential surfaces S and S' passing through the points M and N are spheres of known dimensions by reason of r and r' . These spheres intersect the column of water without noteworthy distortion. The measurement of potential between the electrodes M and N immersed in the water is, therefore, equivalent to a measurement made in the interior of the soil at the same distances r and r' from the electrode A .

The application of Ohm's law between the spheres S and S' leads to the formula:

$$R = 4\pi \frac{\Delta V}{i} \cdot \frac{rr'}{r' - r} \quad (15)$$

which gives the required resistance, since ΔV , r and r' are known.¹ When the soil in the vicinity of the measuring field AMN cannot be regarded as homogeneous in structure the computations become more involved but nevertheless furnish results that are sufficiently correct for practical purposes.

An advantage of this type of equipment is its portability and the speed with which a well can be surveyed or logged, the entire equipment weighing less than 3,000 lb. The surveying can be done at the rate of 3,000 ft. per hour when the machine is in position.² A chart is made on special paper wound on synchronized drums for lowering the cable with electrodes and taking the record. As these electrodes are withdrawn to the surface, readings are made at chosen intervals of 5 to 40 ft., dependent on local conditions and desire for information. The uncased part of the hole

¹ LANCASTER-JONES, E., The Earth Resistivity Method of Electrical Prospecting, *Mining Mag.*, June and July, 1930.

² BIGNELL, *op. cit.*

only is investigated because the high metallic conductivity of the casing prevents electrical resistivity readings in the lined parts of the hole. Given ample geological data, lithological sequences can be established fairly accurately by this method. This has been done in Europe and South America, while in Oklahoma and Kansas electrical key horizons have been fixed by it. By slightly altering the technique the dip of the strata can be got in favorable cases, *i.e.*, by noting the point of surface emergence of an electric current sent into a relatively conductive stratum. Since oil and gas offer high resistance to the flow of current, the conductivity of which we have seen depends on the amount of water present, we may be able to trace oil wells with the basal salt water and the other wells in the oil proper. Discontinued cores can also be completed by an electrical log so as to determine all the beds traversed and get their thicknesses.

The cost increases as the log length (uncased part of the hole) increases, and the method is useful where no cores are yielded, as in churn drilling. Electrical key horizons will make up for any lack of geological ones, thus permitting of more precise correlation. It also enables us to get the data of faulting, since these markedly affect the conductivity range. Enough has been said to show that this infant method is pretty vigorous and appears to have a hopeful future.

Seismic Methods.—This method of investigating the earth's substructural conditions has been adopted for places where the overburden wholly or partially hides the solid geological structure of the region. It depends on the propagation of waves in the earth, the passage of which are affected by the physical characteristics of the rocks traversed; they are therefore subject to the laws of the elastic theory. Consequently the velocity of an elastic wave is determined by the modulus of elasticity of the rocks, the density, and Poisson's transverse contraction coefficient for the various media. Elastic waves in air or water are known as sound waves and those in the solid mass of the

earth as seismic waves. In air and water only longitudinal condensation and rarefaction waves are formed, and in these every particle oscillates to and fro about its position of rest in a direction parallel to the direction of propagation. In air the velocity of propagation v , under a pressure p , density ρ , and specific heat ratio x at constant temperature and constant pressure, is v equals $\sqrt{xp/\rho}$, while in liquids it is v equals $\sqrt{k/\rho}$, where k is the compressibility. But in solids the relations are very complicated, and, indeed, not yet fully comprehended but are determined, as said, with the aid of Poisson's constant σ , which is the ratio of the extension of a pulled bar to its accompanying decrease in cross-section being between 0.2 and 0.5 for the different solid substances; and also with Lamé's coefficients λ and μ , particularly the latter, which indicates the stiffness or rigidity modulus and is therefore of great practical significance. These must be known from laboratory tests, because the speed of the waves varies so greatly with different media; for instance, soft friable rocks, like sand, propagate earthquake shock waves at about 400 m. per second, while hard primitive rock shows a velocity of about 4,000 m. per second; in general, from 1 to 4 km. per second, and these figures, of course, vary with the differing densities and elasticities of the different media traversed. Doctor Mintrop¹ has undertaken observations collecting and developing usable methods of investigation through the firm Seismos, Ltd., in Hanover.

All workers in this field are indebted to the pioneering work of Wiechert² and his able pupil, Gutenberg,² the result of whose labors, combined with the very extensive experimental material of many earthquake observatories, have brought about practical conclusions upon which modern

¹ MINTROP, L., "Über künstliche Erdbeben," Intrn. Kong. Düsseldorf, 1910. Abtlg. IV, Vortrag No. 14. Seismos-Gesellschaft. Mttlgn. d. I. "Erforschung von Gebirgsschichten und nutzbaren Lagerstätten nach dem seismischen Verfahren," Hanover, 1922 (the Seismos Company's own publication).

² *Repts., Imp. Soc. Sci.*, p. 195, Göttingen, Berlin, 1899; also SIEBERG, A., "Applied Earthquakes, Geological-Physical," p. 283, Jena.

methods of location by means of time-travel curves or course-time curves depend. They also depend very much on the relation of the load to the deformation, *i.e.*, Young's modulus E . The relations of E and σ on the one hand and Lamé's coefficients λ and μ on the other are as follows:¹

$$\lambda = \frac{\sigma}{(1 + \sigma)(2 - \sigma)} \cdot E; \mu = \frac{1}{2} \cdot \frac{E}{1 + \sigma}; \sigma = \frac{1}{2} \cdot \frac{1}{\lambda + \mu};$$

$$E = \frac{\mu}{\lambda + \mu} (3\lambda + 2\mu) \quad (16)$$

and when disturbances in the interior set up the usual longitudinal waves with velocity V and transverse waves with vibration velocity V' of the particles at right angles to the direction of propagation, we have²

$$V = \sqrt{\frac{\lambda + 2\mu}{\rho}} = \sqrt{\frac{E}{\rho} \frac{1 - \sigma}{(1 + \sigma)(1 - 2\sigma)}}; V' = \sqrt{\frac{\mu}{\rho}};$$

$$= \sqrt{\frac{E}{\rho} \frac{1}{2(1 + \sigma)}} \quad (17)$$

Only two equations are presented for determining these most important quantities, E , σ and ρ , or λ , μ and ρ , so that with reliable results a third relation can be found, otherwise suitably complete assumptions must be made. Comparatively little is known of the vagaries of earth wave motion, especially in the case of artificial earthquakes which are liberated for seismic ground research and borehole surveys. It will be seen that the direct study is very closely allied to seismology as applied to actual earthquakes, but the study of the behavior of purposely produced ground concussions, as by the explosion of dynamite, gives rise to many features which are not recorded of natural or long-distance earthquakes, such as surface air and sound waves, certain types of strata limit reflection, etc.

¹ ZOEPPRITZ, K., *Repts., Imp. Soc. Sci.*, p. 66, 1919, and p. 121, 1912, Göttingen; also DAVISON, C., "Manual of Seismology," Cambridge University Press.

² AMBRONN, *op. cit.*, p. 152; also HADDOCK, M. H., *Colliery Guardian*, p. 333, 1927.

When speaking of natural quakes it should be noted that about 3,000 km. is considered an average distance (epicentral) earthquake. Now the study of these waves, their accompanying waves and features, the resultant reflected waves from different boundaries in the earth, and above all the course-times of all these, depends on individual rock characteristics; hence we may by their aid learn certain rock structures and borehole deviations in the earth which could not otherwise be revealed. The chief regions of application are those in which we wish to obtain the thickness of overburden resting on older beds. This has been successfully carried out in the preliminary work of some Swedish electrical surveys.¹

Moreover, the seeking of dislocations, the determination of deeper strata directions and therewith also saddles and basins and borehole data are located by this means. These waves make themselves felt at their points of emergence at the earth's surface in slight impulses and movements, the waves themselves being in the nature of harmonic vibratory motions, which, in the case of uniform and homogeneous rocks, are shown in a correspondingly uniform and harmonic, and indeed characteristic, motion of the transmitted waves. But since the crust of the earth is decidedly heterogeneous not only in chemical constitution but in physical formation and deformation, the waves are hampered in transit and their vibratory properties defaced in a manner which often is quite bewildering, but the changes are always proportional to the changes in the material traversed. The consequent alteration in the velocity, frequency, and amplitude of the motion, and the arrival time factors at reception stations have then to be investigated as they occur. On the waves striking the limits between strata of different elasticities, etc., broken waves are set up in the second medium and at the same time a part of the wave energy is reflected, and, indeed, according to the kind of wave being discussed, *i.e.*, longitudinal or transversal, corresponding condensa-

¹ SUNDBERG, K., "Electrical Prospecting in Sweden," p. 31.

tional and distortional waves appear, making the conditions of motion very complicated and often indecipherable.¹ In addition, other kinds of waves appear which are connected only with the surface, the most important being the Rayleigh waves² which are due to the combined action of the longitudinal and transverse waves at the bounding surfaces and their state of vibration. They displace along the earth's surface with the velocity V equals $0.9V'$ approximately. The waves transverse to the Rayleigh waves are called Love's waves.³ They vibrate particles at right angles to the direction of the propagation in the upper strata.⁴ These oscillating movements are determined with their components by various means, such as pendulum weights suitably suspended or set. The relative movement of the pendulum mass⁵ about its support axis illustrates, usually after magnification by lever systems, the relative ground movement.

Those instruments with optical recording devices are preferable, owing to the freedom from friction of contact surfaces found in other types and the facility for magnification. The curves show not only the relative movement of the ground, support, and pendulum mass, but also the wave frequencies and time factors of main and subsidiary waves. Figure 158*a* shows a typical seismogram or record of an average distance natural earthquake wherein only the surface or ground types are indicated. It is now extremely important to distinguish between the several kinds of waves set up previous to discussing the record. When a quake is

¹ *Repts. Imp. Soc. Sci.*, p. 66, Göttingen, Berlin, 1919.

² *Proc. Math. Soc. (London)*, No. 17, p. 4; *Phil. Trans. Roy. Soc. (London)*, No. 203, p. 1, 1904.

³ "Textbook of Electricity 1907: Some Problems of Geodynamics," Cambridge, 1912.

⁴ For the strict theory see MAINKA, C., "Physik der Erdbebenwellen," Berlin, 1923; DAVISON, C., "Manual of Seismology"; BALLORE, MONTESSUS DE, "La géologie seismologique," pp. 453-458; *Amer. Seis. Soc. Bull.*, Vol. 2, p. 127, 1912; ADAMS, F., and E. G., COOKER, *Carnegie Inst. Pub.*, No. 46, Washington, 1906.

⁵ See KEILHACK, K., "Lehrbuch der Prak. Geol.," Vol. 2, Chap. I, for some complete information with figures.

caused purposely, as by explosive charges, air and sound waves are set up and these are not surface earth waves. Air sound waves are distinctly indicated on the record for quakes due to human agency, and they are quite distinct from those movements and tremors of the earth due to earth waves. These are propagated much more slowly

FIG. 158a.—Impulse record.

Impulse record

FIG. 158b.—(After Kithil.)

FIG. 158.

than deep earth waves; consequently, although they are generated at the same time, they appear later on the record as will be seen in Fig. 158b. Figure 159 (after Rankine) shows a gelatine shot artificial shock record.

The new and only British seismograph instrument of the Cambridge Instrument Company is an advance upon Mintrop's original apparatus being more sensitive and dependable. It has been evolved as a result of the Iraq oil-field researches of Dr. A. O. Rankine, Professor of Physics, at the Imperial College of Science and Technology.¹ Its advantages over other types lies in the linking device

¹ We are indebted to Dr. Rankine for Fig. 160 and the details. Symposium at the Institution of Mining and Metallurgy, Apr. 18, 1929; see also British Patent Specification No. 17402/29.

for obtaining greater magnification for smaller earth movements. It comprises a highly sensitive instrument

FIG. 159.—Seismographic records.

for measuring vertical vibrations (the vibrometer) and, a camera for recording them. The vibrometer, shown in

FIG. 160.—Seismograph.

Fig. 160 with the outer cover removed, consists of a heavy mass H fixed on a short lever carried on flexible steel hinges at I . This weight is balanced by springs O_1 and O_2 .

O_1 is the mainspring and O_2 is a fine adjustment spring controlled by the screw F . The lever carrying the mass H is extended by the light cone N . For transit the clamping screw G is released and the weight H is withdrawn from the tubular fitting into which it is normally fitted. The system is then automatically clamped, owing to the load on the spring O_1 . At the end of the cone N is a fine rod J , the other end of which bears lightly on a horizontal disc in such a way that any small movement of the mass H relative to the base of the instrument causes a rotation of the disc. A mirror is so mounted that this rotation causes a corresponding movement of the mirror which is recorded photographically by a compact form of paper camera. The moving mirror system, which is the only delicate part of the apparatus, forms a complete unit which can be easily removed and replaced, and which is disconnected from the rod J by a simple automatic device. Light from a lamp mounted in the camera passes through a convex lens K and is reflected from the mirror so that an image of a slit in front of the lamp is focused down to a bright spot of light on the photographic paper.

Malamphy's Seismic Method of Surveying Boreholes.—For localizing the work of a seismograph, *i.e.*, concentrating it upon a given spot, a form of wave detector of electric line microphone or geophone may be sunk to any desired depth in a borehole. This has been done by M. C. Malamphy in the western American oil fields¹ and has yielded hopeful results.

The geophone is lowered into the hole to the desired spot and shots (gelignite or dynamite) are located about the hole with seismographs at known distances from the hole, for time records. The method is much simplified and it is thought that errors are distributed uniformly by this method. If the hole is straight the time for each shot will be proportionate to the distance of each less the strata corrections, etc., for the place being considered. If the hole

¹ Seismic Method of Determining Deviation in Drill Holes, *Oil Weekly*, p. 32, Apr. 26, 1929.

is crooked the time will vary accordingly. The time taken by the wave in traveling to the geophone will give the length of its path when we know the vertical velocity of the local formations by the above or similar computations (Mr. Malamphy simplifies these computations drastically), since

FIG. 161.—(a) Plan sketch showing ideal location of shot points for determining deviation of hole from vertical. H' indicates the position on the surface directly above the point at which the detector is placed in the hole. This point is determined by arcs from the various shot points. (b) Vertical section along line EW showing crooked drill hole and path of the seismic waves to the detector. (c) Vertical section showing shooting profile to determine true depth and average vertical velocity. (After M. C. Malamphy.)

the depth of the apparatus in the hole is known direct (Fig. 161). The time taken by the shot wave from W will be less than that from E (Fig. 161b) if the hole is crooked. Knowing the depth and vertical path we may get the other side of the triangle and thus the distance from H' to E and to W ; the point H' being on the surface

directly above the spot in the hole where the detector is placed. Since we know the distance between E and W and the position of D , the hole mouth, we can thus get the apparent deviation of the hole along line EW . Now choose any other pair of shot holes say on line NS and get the borehole deviation along it similarly.

From this it will be seen that we have first to obtain this average vertical velocity of the seismic wave. The above authority proceeds as follows: The known depth of the geophone being h_c , and S the distance of the shot from the borehole mouth, then the length of the seismic path l from explosion to detector is

$$l^2 = h_c^2 + S^2 \quad (18)$$

and if t_N , t_S , t_E and t_W be the seismic times from shot points N , S , E and W , and V_a the approximate value of the average vertical velocity, we get a first approximation of

$$V_a = \frac{t_N + l_S + l_E + l_W}{t_N + t_S + t_E + t_W} \quad (18a)$$

l_S , l_E , etc., being the lengths of the seismic paths from the corresponding points S , E , etc. We then get the approximate position H' of the geophone in the hole thus

$$l_N = V_a t_N; l_S = V_a t_S, \text{ etc.} \quad (18b)$$

If the distance of the surface points directly over the detector from each shot point be S'_N , S'_W , etc., we get

$$S'_N = \sqrt{l_N^2 - h_c^2}; S'_S = \sqrt{l_S^2 - h_c^2}, \text{ etc.} \quad (18c)$$

Drawing arcs from the several shot points as centers and using S' as radii, their intersections will give the point H' on the surface directly above the detector acceptably enough for practical purposes. A refinement of the method is proposed by the inventor¹ and this of course greatly enhances the accuracy of the method.

This extra refinement, particularly in measuring the seismic times t and the surface distances S , is very important

¹ *Op. cit.*, p. 70.

and should if possible be deduced by (18c) above, because the average vertical velocity encountered will in some cases vary from 5,000 ft. per second for shallow depths up to 12,000 ft. per second for greater depths. An error of 1/1,000 sec. in the seismic time here will show an error of 5 to 12 ft. in the length of the seismic path. Hence the time record should read direct to 1/1,000 sec. and at very least 1/100 sec.

The charge of explosives should be planted at about 10 ft. down to prevent it blowing out, and greater accuracy will be had if we take $l_1, l_2 \dots$ etc., the seismic paths from shots $S_1, S_2 \dots$ etc., and their times $t_1 t_2 \dots$ etc., for getting the true depth h and the true average vertical velocity V thus

$$\begin{aligned} l_1^2 &= h^2 + S_1^2 \dots \text{etc.} \\ v^2 &= l_1^2/t_1^2 \dots \text{etc.} \end{aligned}$$

hence

$$v^2 \cdot t^2 - S^2 = h^2$$

a general equation for all points. Plotting this in the lineal form $ax + y + C = 0$ with values of x as functions of y (t^2 as functions of S^2) we get the straight-line graph with the slope $a = V^2$ and¹ the ordinate intercept $C = h^2$ in the usual way and so by normal coordinate geometry for gradients and interpolated values. The charges in the hole seldom exceed a few pounds, though in major geophysical work, as in the deep lying anticlines of the Persian oil areas, over a hundred pounds have been employed in one shot, the depth feature being in the region of 4,000 ft. in places.²

The method adds decided advantages in an extensive field in that it provides data as to subsurface conditions simultaneously with the above. One of these advantages is the structural image we get of the underground from a study of the curves when plotted as above. This will be best appreciated by an example or two.

¹ *Ibid.*, p. 70.

² Professor Rankine, lecture before Loughborough Scientific Society, 1929.

We may consider this accessory information yielded by this method in the same way as Professor Heiland of the Colorado School of Mines. In Fig. 162 we have a hard limestone overlain by loose sandy clays, the former having a wave velocity of v_2 and the latter of v_1 when a charge is fired at S . The shock wave intervals are measured off on the graph, shown where the scales E of the concussion are set off at intervals of 200 and 280 m.; the corresponding times are the ordinates.

At E_1 and E_2 the course-time and wave velocities are proportionate (straight-line law), the shock being in

FIG. 162.

FIG. 163.—Diagrams of time-travel curves over different tectonic features.

one uniform stratum with velocity v_1 , but from the latter point onward the waves lengthen, running in the deeper stratum with the higher wave velocity v_2 . The resulting course-time curve shows a nick at k , such nicks always betraying density, etc., changes in the strata. The position of the nick point gives the surface limit¹ of the hard stratum at

¹ "Electrical Prospecting in Sweden," p. 31.

right angles to the overburden of thickness h . Here v_1 equals 1,000 m. per second, v_2 equals 5,000 m. per second, and h equals 200 as will be seen at once.

The relations for inclined beds are theoretically shown in Figs. 163*a* to *d*.¹ Sufficient has been said to show the possibilities of this method.²

This method only requires about 2 hr. for planting, and survey points and measurements need only be taken every 300 to 600 ft. down the hole.

The advantages of the method are:

1. It determines the location at each depth independent of other positions.
2. It gives the horizontal and vertical location of any spot desired in the hole.
3. It will determine the bottom of the borehole without the necessity of having to survey the entire hole.

The disadvantages are mostly those due to its recent adoption, lack of experience and inexpert manipulation of the apparatus and computations.

¹ HEILAND, C., *Ztschr. f. Instrm.*, p. 417, Berlin, 1925, or *Eng. Min. Jour.-Press*, Vol. 121, No. 2, p. 54, 1926.

² SHAW, H., *Mining Mag.*, p. 201, April, 1930.

CHAPTER XI

PROBLEMS

In this chapter we purpose dealing with those problems useful in prospecting and location work generally as are provided by a study of the data afforded by borehole deviation instruments, core evidences and photographs of borehole walls.

A. ONE-BOREHOLE PROBLEMS

To Obtain the Penetration Point of a Borehole and a Stratum.—Of the several mathematical methods of dealing

FIG. 164.—Borehole dipping with the beds.

with this problem few are suited to meet the needs of borehole conditions, because the data usually assumed are frequently the least accessible. The best method for our purpose is the conditional formula method. Let the borehole BB_1 (Fig. 164, here shown dipping with the stratum but steeper than the beds) have a dip α and the stratum δ . It meets the stratum at C at a height h above a horizontal plane laid through any point A in the stratum, *e.g.*, a point known in a mine, on an outcrop or located otherwise. Point A need not be accessible if we know the dip of the stratum δ . If B' is the vertical projection of B , the bore-

hole mouth, on the said horizontal plane we can get the positions of it and point C , where the hole hits the stratum, from the condition $h + \text{gradient height of } BC = H$, the total height of B above the said plane = height coordinate of B less that of $A = B_z - A_z$, where z is the space (height) coordinate subscript above any given datum like sea level. Let the horizontal distance from B to C be x and the gradient of BC will be a function of x . The distance between C' , the vertical projection of C on the plane, and the strike line through A is A_1C' , then

$$x \tan \alpha + A_1C' \tan \delta = H \quad (19)$$

and A_1C' may be obtained from the right-angled triangle $A_1C'A_2$, which is *right angled at A_1* , thus:

$$A_1C' = C'A_2 \sin \theta_1 = (B'A_2 - x) \sin \theta_1$$

where θ_1 is the angle between the borehole and stratum strikes.

Again, from triangle $AB'A_2$ we get $B'A_2 = AB' \frac{\sin \theta_2}{\sin \theta_1}$,

where θ_2 is the angle between the line from the known point A to the horizontal projection of B at B' . That is to say θ_2 is always known from the survey notes. Therefore

$$A_1C' = \left(AB' \frac{\sin \theta_2}{\sin \theta_1} - x \right) \sin \theta_1 = AB' \sin \theta_2 - x \sin \theta_1$$

Substituting in Eq. (19) above we get

$$x \tan \alpha + (AB' \sin \theta_2 - x \sin \theta_1) \tan \delta = H$$

Whence

$$x = \frac{H - AB' \sin \theta_2 \tan \delta}{\tan \alpha - \sin \theta_1 \tan \delta} \quad (20)$$

and all the quantities on the right hand side are known so getting x , we may easily fix the space coordinates of C by first obtaining h . The signs of the various terms in this expression vary according to the position of the given magnitudes in space, thus:

a. H is positive if point B lies higher than A .

b. $AB' \sin \theta_2 \tan \delta$ is positive if point B lies on the dip side of the strike line through A .

c. $\tan \alpha$ is always positive, and the sign of the second term in the denominator is arranged thus: $\sin \theta_1 \tan \delta$ must be additive when the direction senses of the stratum and borehole are different, *i.e.*, opposed, and subtractive when the other case arises, *i.e.*, when they dip together.

d. While x is positive the penetration point C lies on the dip side of the borehole from B , *i.e.*, it is negative for a rise borehole.

I. BOREHOLES AT RIGHT ANGLES TO THE STRIKE OF THE STRATA

a. VERTICAL BOREHOLES: LENGTHS

The customary way of expressing the borehole lengths will be seen from Fig. 164 to be

$$L = BC = \frac{x}{\cos \alpha}$$

and considering this in connection with Eq. (20) we get

$$L = BC = \frac{x}{\cos \alpha} = \frac{H - AB' \sin \theta_2 \tan \delta}{\sin \alpha - \sin \theta_1 \tan \delta \cos \alpha} \quad (21)$$

In a vertical borehole, its dip being 90 deg., the above becomes

$$L = BC = H - AB' \sin \theta_2 \tan \delta \quad (21a)$$

Several cases arise in practice, and these are easily grasped from a study of surface boreholes such as oil wells, thus:

1. The Borehole Is on the Upstream Side of the Outcrop and the Stratum Dips toward It (Fig. 165).—If h be considered as the compound term following the sign in Eq. (21a) we note in this case that

$$L = H + h$$

or

$$L = H + AB' \sin \theta_2 \tan \delta \quad (21b)$$

NOTE.—The angle θ_2 is in the plane of the reader's vision in Fig. 165 and it can assume any number of values according as AB' changes in bearing; that is to say, according as the borehole mouth is displaced laterally from the known point of outcrop A .

2. The Borehole Is on the Upstream Side of the Outcrop but the Stratum Dips Away from It (Fig. 166).—Here we get

$$L = H - h$$

or

$$L = H - AB' \sin \theta_2 \tan \delta \quad (21c)$$

NOTE.—In this case h must be less than H .

FIG. 165.

FIG. 166.

FIG. 167.

3. The Borehole Is on the Downstream Side of the Outcrop and the Strata Dip toward It (Fig. 167).—Here we get

$$L = h - H$$

or

$$L = AB' \sin \theta_2 \tan \delta - H \quad (21d)$$

NOTE.—In this case H must be less than h and if the strata dip in the other direction no location is possible.

These will cover all cases of vertical boreholes.

b. INCLINED BOREHOLES: LENGTHS, DISPLACEMENTS AND DEPTHS

In these cases the boreholes may have an infinite number of dips in amount in two directions at 180 deg. from one another, *i.e.*, corresponding opposed and “together” dips, and still be at right angles to the strike of the stratum, provided the hole does not leave the plane normal to the stratum strike, *i.e.*, its full dip or rise direction plane (Figs. 168, 169). The angle θ_2 of Eq. (20) is 90 deg., making it

$$x = \frac{H \pm AB' \tan \delta}{\tan \alpha \pm \tan \delta} \quad (22)$$

according to the relations of the dips of borehole and stratum. It will be found more convenient to measure the surface slope γ in these cases.

FIG. 168.

1. The Borehole and Stratum Dip in the Same Direction with the Borehole Upstream of the Outcrop (Fig. 168).

1a. The Length of the Borehole.

$$BB'' = \frac{H}{\sin \alpha}$$

$$B''B' = H \cot \alpha$$

$$B''E = B''C \sin (\alpha - \delta)$$

$$B''C = \frac{B''E}{\sin (\alpha - \delta)} = \frac{AB'' \sin \delta}{\sin (\alpha - \delta)}$$

$$AB'' = H(\cot \gamma + \cot \alpha)$$

$$BC = BB'' + B''C = L = \frac{H}{\sin \alpha} + \frac{AB''}{\cot \delta \sin \alpha - \cos \alpha}$$

$$L = H \left(\frac{1}{\sin \alpha} + \frac{\cot \gamma + \cot \alpha}{\cot \delta \sin \alpha - \cos \alpha} \right) \quad (23)$$

If the borehole is downstream of the outcrop the first term in the bracket is negative; on a level surface H vanishes, also γ , and since then $AB'' = AB' = AB$, the above form is not applicable, a modification of either Eqs. (21b), (21c) or (21d) being then most suitable, which will yield the length, thus

$$BC = L = \frac{AB \sin \delta}{\sin (\delta - \alpha)} \quad (24)$$

and so on for other dimensions which need not be repeated here.

1b. *The Displacement of the Borehole.*—This is the shift of the hole and will be in the full dip direction here (Fig. 168).

$$\text{Displacement} = DC = B'B'' + FC.$$

$$= H \cot \alpha + B''C \cos \alpha$$

$$= H \cot \alpha + \frac{AB''}{(\tan \alpha \cot \delta - 1)}$$

$$DC = H \left(\cot \alpha + \frac{\cot \gamma + \cot \alpha}{\tan \alpha \cot \delta - 1} \right) \quad (25)$$

Wherein the first term on the right is negative if the borehole is downstream of the outcrop; and if the surface is level

$$DC = BC \cos \alpha \quad (26)$$

$$\begin{aligned}
 B''C &= \frac{B''E}{\sin (180 - \delta - \alpha)} = \frac{AB'' \sin \delta}{\sin (\delta + \alpha)} \\
 L &= \frac{H}{\sin \alpha} + \frac{AB''}{\cot \delta \sin \alpha + \cos \alpha} \\
 L &= H \left(\frac{1}{\sin \alpha} + \frac{\cot \gamma - \cot \alpha}{\cot \delta \sin \alpha + \cos \alpha} \right) \quad (28)
 \end{aligned}$$

Compare with Eq. (23) above where similar remarks apply respecting the altitudes of the derrick floor and the outerop.

When the surface is flat $AB'' = AB' = AB$ and then

$$L = BC = \frac{AB \sin \delta}{\sin (\delta + \alpha)} \quad (29)$$

Compare with Eq. (24) above.

2b. *The Displacement of the Borehole.*

$$\begin{aligned}
 DC &= B'B'' + FC \\
 &= H \cot \alpha + \frac{AB''}{\tan \alpha \cot \delta + 1} \\
 DC &= H \left(\cot \alpha + \frac{\cot \gamma - \cot \alpha}{\tan \alpha \cot \delta + 1} \right) \quad (30)
 \end{aligned}$$

2c. *The Total Depth of the Borehole.*

$$\begin{aligned}
 BD &= H + h \\
 BD &= H + \frac{AB''}{\cot \delta + \cot \alpha} = H \left(1 + \frac{\cot \gamma - \cot \alpha}{\cot \delta + \cot \alpha} \right) \quad (31)
 \end{aligned}$$

The reason for choosing the persistent term AB'' is because it is the dimension most likely to give the least trouble in obtaining in practice.

C. HORIZONTAL BOREHOLES

Here the inclination of the borehole is nil, so that in Eq. (20) $\alpha = 0$ deg., making the expression for the displacement x (Fig. 170).

$$x = \frac{H - AB' \sin \theta_2 \tan \delta}{-\sin \theta_1 \tan \delta} = \frac{AB' \sin \theta_2 - H \cot \delta}{\sin \theta_1} \quad (32)$$

d. THE SHORTEST BOREHOLE FROM A GIVEN POINT TO A STRATUM

These are not strictly normal to the strata but are best dealt with here.

We have already shown in Eq. (21) that this length is got by

$$BC = \frac{H \pm AB' \tan \delta \sin \theta_2}{\sin \alpha \pm \tan \delta \sin \theta_1 \cos \alpha} \quad (33)$$

the signs depending on the relative dipping senses of the stratum and borehole.

If we consider the point B of the borehole mouth fixed, then the length of the hole is a function of α and θ_1 , its dip

FIG. 170.—Horizontal borehole.

and bearing; it is thus dependent on two variables. The number of connections is thus infinite.

e. THE SHORTEST POSSIBLE CONNECTION, AT A GIVEN BEARING, BY A BOREHOLE TO A STRATUM

We might get, with the aid of the calculus, the values of α and θ_2 to meet this case, but the same result is obtained by stereometry, wherein we note that the line falling at right angles to the stratum dip line is the shortest in the said direction. That is to say, the hole hitting the stratum face "square on" (not perpendicular) is the shortest at a given bearing. Thus the dip of this hole will then be $90 - \delta$ and its bearing that given.

The shortest of all possible boreholes will be in the plane at right angles to the strata dip, and its dip will be $90 - \delta$,

its bearing that of the seam dip plus 180 deg., say $\beta + 180$ deg., where β is the direction of full dip of the stratum and δ its amount.

Substituting in Eq. (21) we get for the shortest connection at a bearing θ_2 between hole and stratum strike directions

$$BC = H \cos \delta + AB' \operatorname{cosec} \delta \sin \theta_2 \quad (34)$$

f. THE SHORTEST OF ALL POSSIBLE BOREHOLES TO THE STRATUM

Here the vertical plane holding point A in the stratum and B on the borehole mouth must have the direction $\beta + 180$ deg., so that $\theta_2 = 90$ deg., and we get (Fig. 171)

$$BC = H \cos \delta + AB' \operatorname{cosec} \delta \quad (35)$$

This is similar to $E'E$ of Figs. 168 and 169 also.

FIG. 171.—Borehole dipping against the beds.

We shall not deal with upward holes, since these do not come under deep boring; also we will not go into the variant forms of Eqs. (21a), (21b), (21c) and (21d) above, which arise with contrary senses of hole and strata dips. Varying these, as we have done in the cases of vertical and inclined normal holes, will give the reader no difficulty and preserve the space at our disposal.

II. BOREHOLES NOT AT RIGHT ANGLES TO THE STRIKE OF THE STRATA

All the cases are covered by Eq. (21) for length, *i.e.*,

$$L = BC = \frac{H \pm AB' \tan \delta \sin \theta_2}{\sin \alpha \pm \sin \theta_1 \tan \delta \cos \alpha} \quad (36)$$

and it appears needless to draw the upstream and downstream cases, since the previous examples are particular cases of these problems. The related displacement and depth problems will need no further embellishment here either.

The succeeding problems on boreholes not at right angles to the strata strike appear to provide sufficient variant forms of the above. Since in these cases we are dealing with cores actually at the stratum or seam being sought, our notation will have to be modified a little.

INCLINED SINGLE BOREHOLES: METHODS OF OBTAINING DIP,
THICKNESS AND DIRECTION OF BEDS

Vertical boreholes will always yield direct data for the dip of the beds especially if they provide cores. Then the dip is the maximum inclination shown by the bedding; therefore we shall not deal with them but consider inclined or meaned deviated boreholes.

1. To Obtain the True Dip of Beds from a Borehole Not at Right Angles to the Strike of the Bedding.¹—Here four possible cases of borehole penetration arise in practice, and each of these takes two forms according as the hole is a dipper or a riser, as in Figs. 172 and 173 and Plate XV, as follows:

Case 1.—Where the beds dip or rise in the same direction as the hole, but more steeply (Figs. 172, 173).

Case 2.—Where the beds dip or rise in the same direction as the hole, but less steeply, Case 2, Plate XV.

Case 3.—Where the beds dip or rise in the opposite direction to the hole and more steeply than a plane normal to the plane through the drill hole and the strike of the beds, Case 3, Plate XV.

Case 4.—Where the beds dip or rise in the opposite direction to the hole and less steeply than a plane normal to the plane through the drill hole and the strike of the beds, Case 4, Plate XV.

The general formula is most easily derived for the case of a hole dipping in the same direction as the beds (Figs. 172, 173).

¹ WHITE, E. E., *Eng. Min. Jour.-Press*, Vol. 98, No. 12, p. 524, or "Location of Mineral Fields," p. 98, Crosby, Lockwood & Sons.

Let

i = the inclination of the drill hole XX_1 from the horizontal.

δ_1 = the angle between the bedding and the axis of the hole which is obtained from an examination of the drill cores.

θ = the difference in strike of the bedding and the drill hole.

δ = the true dip of the strata.

FIG. 172.

FIG. 173.

Let

A = any point on the drill hole—in our figures it is the point at which the drill hole enters the bed or seam—from which a perpendicular can be erected on to the plane of the bedding. Call this perpendicular Ab .

Ad = another perpendicular dropped from A on to the horizontal plane which passes through the intersection of the drill hole with the plane of the bedding.

abc = the above bedding or seam plane having a right angle at c .

adc = the above horizontal plane through the intersection of the drill hole and bedding plane.

cAb and cAd represent vertical planes at right angles to ac , the strike of the bedding, and drawn through A .

Aa = the length of the seam or bed pierced as given by the core. It will be found convenient in all cases to express this as unity.

The line Ac makes an angle β with the horizontal plane, and an angle α with the plane of the bedding. (The words "bedding" and "seam" have similar meanings in the following discussion.) These angles are Acd and Acb , respectively, and, as in Case 1, their sum is equal to the full dip. Then

$$\begin{aligned}\cos i &= ad \\ \cos \delta_1 &= ab \\ \sin i &= Ad \\ \sin \delta_1 &= Ab\end{aligned}$$

$$\cos \theta = \frac{ac}{ad} = \frac{ac}{\cos i}$$

$$\therefore ac = \cos i \cos \theta$$

and

$$\begin{aligned}bc &= \sqrt{(ab)^2 - (ac)^2} = \sqrt{\cos^2 \delta_1 - \cos^2 i \cos^2 \theta} \\ Ac &= \sqrt{(bc)^2 + (Ab)^2} = \sqrt{\cos^2 \delta_1 - \cos^2 i \cos^2 \theta + \sin^2 \delta_1} \\ &= \sqrt{1 - \cos^2 i \cos^2 \theta}\end{aligned}$$

$$\text{Angle } \sin^{-1} \frac{Ab}{Ac} = \frac{\sin \delta_1}{\sqrt{1 - \cos^2 i \cos^2 \theta}}$$

$$\text{Angle } \sin^{-1} \frac{Ad}{Ac} = \frac{\sin i}{\sqrt{1 - \cos^2 i \cos^2 \theta}}$$

Referring to figures:

Case 1.—Here it will be seen by Figs. 172 and 173 that $\delta = \alpha + \beta$ therefore

$$\delta = \frac{\sin \delta_1 + \sin i}{\sqrt{1 - \cos^2 i \cos^2 \theta}} \quad (37)$$

Case 2.—Here the full dip is obtained by $\delta = \beta - \alpha$ (Case 2, Plate XV)

DIPPERS

Case 2. $\delta = \beta - \alpha$

Case 3. $\delta = 180^\circ - \beta - \alpha$

Case 4. $\delta = \alpha - \beta$

RISERS

Case 2. $\delta = \beta - \alpha$

Case 3. $\delta = 180^\circ - \beta - \alpha$

Case 4. $\delta = \alpha - \beta$

hence

$$\delta = \frac{\sin i - \sin \delta_1}{\sqrt{1 - \cos^2 i \cos^2 \theta}} \quad (38)$$

Case 3.—Case 3, Plate XV, shows that in this case the form is

$$\delta = (90 - \beta) + (90 - \alpha) = 180 - \beta - \alpha$$

consequently

$$\delta = 180^\circ - \left(\frac{\sin i + \sin \delta_1}{\sqrt{1 - \cos^2 i \cos^2 \theta}} \right) \quad (39)$$

Case 4.—The form assumed in this case is shown in Cases 4, Plate XV, to be

$$\delta = (90 - \beta) - (90 - \alpha) = \alpha - \beta$$

which gives

$$\delta = \frac{\sin \delta_1 - \sin i}{\sqrt{1 - \cos^2 i \cos^2 \theta}} \quad (40)$$

When the hole is at right angles to the strike of the bedding, the above four formulae become:

$$\text{Case 1.}—\delta = i + \delta_1 \quad (41)$$

$$\text{Case 2.}—\delta = i - \delta_1 \quad (42)$$

$$\text{Case 3.}—\delta = 180^\circ - i - \delta_1 \quad (43)$$

$$\text{Case 4.}—\delta = \delta_1 - i \quad (44)$$

2. To Find the True Thickness of a Bed Knowing Its Dip and the Direction of a Borehole in It, also the Distance Through Penetrated by the Hole.—Let A_2B (Fig. 174 plan) be the plan of the borehole AB , and A_2C_2 the direction of the strike on this plane (all lines parallel to A_2C_2 are in the direction of strike). A_2D_1 is the direction of full dip, and A_1D_1 and AD are in the same vertical plane as shown also in Fig. 174, end view. The angle θ between the directions of full dip and of the borehole is shown in its different superimposed positions in the right or projected figure. The

true dip of the seam δ is shown by the angle $A_2D_1A_1$ and its dip α in the direction of the borehole by the angle A_2BA_1 . $WXYZ$ is the horizontal reference plane

$\beta = A_2BA_1 =$ dip of borehole, and by the fundamental dip formula for an apparent dip α and true dip δ

$$\tan \alpha = \tan \delta \cos \theta.$$

$t =$ the true thickness of the beds.

FIG. 174.

The true length of the borehole AB and its direction are found from the core and the survey.

$$\begin{aligned} t &= AA_1 \cos \delta \\ &= (AA_2 - A_2A_1) \cos \delta = \left\{ AB \sin \beta - \frac{A_2B \cdot A_2A_1}{A_2B} \right\} \cos \delta \\ &= (AB \sin \beta - A_2B \tan \alpha) \cos \delta \\ &= (AB \sin \beta - A_2B \tan \delta \cos \theta) \cos \delta \\ &= AB(\sin \beta \cos \delta - \cos \beta \sin \delta \cos \theta) \quad (45) \end{aligned}$$

III. BOREHOLES TO PARTICULAR POINTS

These may be grouped into two suites:

1. Those set at a definite angle, the problem being to find where it will hit a known seam, lode, workings, etc.

2. Those which have to hit a given point in a known seam, lode, workings, etc., the problem being to find the required initial inclination and bearing of the hole.

FIG. 175.—Borehole assisting subsequent sinking.

The practical problems connected with these important groups of problems arise when it is desirable

1. To tap known bodies of water, gas, mineral, etc.
2. To assist in sinking a shaft to known workings and thus remove the débris by borehole with trams spotted beneath (Fig. 175).
3. To aid ventilation of seams being worked simultaneously.
4. To conduct haulage ropes, electric cables, compressed-air lines or stowage pipes.
5. To explore for new deposits, etc.

1. Given a Definite Angle for the Hole and Two Known Points in the Stratum to Find Where the Borehole Will Strike the Stratum.—*A* and *D* (Fig. 176) are imagined as being in the same plane as the borehole but need not necessarily be as long as they are in the seam or stratum being investigated by the borehole; their positions can be projected into the borehole plane and a lateral term included in the computation finally.

Let A be an outcrop and D a point in the workings with C the base of the borehole BC in the same or projected plane. We have given the angles α of the borehole dip and γ the surface slope so that the apex angles α' and β shown are deduced. We desire the length x or y of the known length $DA = x + y$.

FIG. 176.

$$\begin{aligned}\frac{x}{y} &= \frac{DC}{CA} = \frac{DC \cdot CB}{CB \cdot CA} = \frac{\sin \alpha'}{\sin BDC} \cdot \frac{\sin BAC}{\sin \beta} \\ &= \frac{\sin \alpha'}{\sin (\zeta - \alpha')} \cdot \frac{\sin (\zeta + \beta)}{\sin \beta}\end{aligned}$$

Expanding we get a form comparable with Eq. (27) above

$$\frac{x}{y} = \frac{\cot \beta + \cot \zeta}{\cot \alpha' - \cot \zeta}$$

Expanding and collecting

$$\cot \zeta (x + y) = x \cot \alpha - y \cot \beta \quad (46)$$

Again

$$\begin{aligned}\frac{x}{y} &= \frac{\sin \alpha'}{\sin (\zeta - \alpha')} \cdot \frac{\sin (\zeta + \beta)}{\sin \beta} \\ &= \frac{\sin (\zeta - D)}{\sin D} \cdot \frac{\sin A}{\sin (\zeta + A)}\end{aligned}$$

Expanding as before

$$\frac{x}{y} = \frac{\cot D - \cot \zeta}{\cot A + \cot \zeta}$$

Cross multiplying and collecting as before

$$\cot \zeta (x + y) = y \cot D - x \cot A \quad (47)$$

From Eqs. (46) and (47) note that

$$x \cot \alpha' - y \cot \beta = y \cot D - x \cot A$$

Now solve for x or y since α', β, D, A , and $x + y$ are known.

The Length of the Borehole.—Having obtained either x or y (and applying the lateral deviation angle if the points

D and A have had to be projected into the borehole plane) we get the length for this case, where B is an upstream derrick floor from outcrop A , by noting that δ the strata dip and γ the surface slope are known, also α the borehole dip.

Thus $A = \gamma + \delta$ and $\beta = 180^\circ - \gamma - \alpha$

hence

$$\begin{aligned}\frac{y}{L} &= \frac{\sin (\gamma + \alpha)}{\sin (\gamma + \delta)} \\ \therefore L &= \frac{y \sin (\gamma + \delta)}{\sin (\gamma + \alpha)}\end{aligned}\quad (48)$$

When the borehole and strata dip against one another we get

$$L = \frac{y \sin (\gamma + \delta)}{\sin (\alpha - \gamma)}\quad (49)$$

and so on for all the other features such as displacement, depth, etc., either normal to the stratum strike or at any bearing therewith, by making the necessary lateral angle addition to the formulae as in Eqs. (21 and 34). Therefore it is scarcely necessary to add these variant cases which will be left to the reader.

2. To Locate a Specified Point in a Stratum, Vein, Workings, etc., by Boring to It, i.e., to Find the Necessary Starting Inclination and Bearing for the Borehole and Therefrom Its Length, Displacement, etc.—This is merely the converse of the above case. We now know the distances x and y and desire α' and β which are found from Eqs. (46) and (47) as before. We solved x and y above as a ratio of the known $x + y$, so here we may get α' or β as a ratio of their sum which is also known since A and D are known.

It would be redundant to furnish a further example and it may be added here that all variant forms of this problem can be solved by either Eqs. (46) and (47) above or by Eq. (20) on page 247.

B. TWO-BOREHOLE PROBLEMS

Two-borehole problems are not very popular and are only resorted to when data for more satisfactory methods cannot be obtained. This is due to the fact that in all

FIG. 177.—(From "Disrupted Strata," by the courtesy of Crosby, Lockwood & Sons, London.)

two-borehole computations for the direction of strike of a deposit the resulting conclusions are ambiguous and have to be supplemented by observational data, usually of a geological character, in order that we may decide as to which of the dual answers to adopt.

a. Two Vertical Boreholes.—To obtain the direction of strike and amount of dip: The amount of dip is found direct

from the core by observing the maximum inclination of stratification planes in it. If A (Fig. 177) be the deepest borehole and is h ft. deeper than B and δ is the strata dip observed from the core, set out a circle of radius $h \cot \delta$ and center A . Draw the two possible tangents from B to A such as Ba and Ba' (Fig. 177). As the surface coordinates of A and B are known we also know β_{BA} the bearing of the line from B to A . The angle BAA , or $BAa' = \theta$, is the strike angle sought. The contact point lines Aa and Aa' of bearings β_a and $\beta_{a'}$, respectively, are the possible direction lines of the full dip of the stratum. We now get

$$h \cot \delta = B'A_1'' \text{ and } \frac{B'A_1''}{A''B'} = \cos \theta \text{ the angle required}$$

Hence

$$\text{or} \quad \left. \begin{aligned} \cos (\beta_a - \beta_{BA}) &= \frac{h \cot \delta}{AB} \\ \cos (\beta_{BA} - \beta_{a'}) &= \frac{h \cot \delta}{AB} \end{aligned} \right\} \quad (50)$$

The dip α in direction BA can now be found by the fundamental dip formula where α is any apparent dip $A'B'A''$, δ the true dip $A_1'B'A_1''$, and θ the angle $A_1'B'A'$ between them, *i.e.*,

$$\tan \alpha = \tan \delta \cos \theta \quad (51)$$

b. Given One Vertical and One Slanting Borehole and the Angle the Core Makes with the Bedding to Determine the Dip and Strike.—Say the vertical hole A cuts the bedding at A' at δ deg. (Fig. 1, Plate XVI), the slanting hole dipping at α from B cuts the bedding at δ_1 deg. (The point B may be moved up so that the apexes of the cones about the A and B holes coincide at A' , for this does not alter the relative angular conditions.)

Set off a cone at A' having the apical angle of $2\delta = CA'D$ about AA' and another having the apical angle of $2\delta_1 = EA'F$ about BA' . The true dip is got from the vertical hole as $90 - \delta$, since the beds make an angle of δ with the vertical.

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

The bedding planes make an angle of δ_1 with the slant hole and the locus of all planes satisfying this demand is found by the surface of the cone $EA'F$ constructed as above. The right cone of the vertical hole AA' is cut by the horizontal surface in a true circle and the cone about the slant hole of axis BA' is cut by the same surface plane in an ellipse as shown. Use any of the well-known methods for getting the section of a cone cut by a slanting plane. Here the plane slants at α to the cone axis BA' .¹

Any tangential plane to the right cone $CA'D$ of the vertical hole will be cut by the vertical hole AA' at δ deg., the angle at which this vertical borehole cuts the bedding. Therefore the tangent to both circle and ellipse satisfies the demands of both holes. This tangent XX can be drawn on both sides, making the problem ambiguous.

1. The problem has many possibilities dependent on the relative sizes and positions of circle and ellipse. Thus in Fig. 1, Plate XVI, we have the two possible strikes XX and X_1X_1 . Therefore we have only two possible strikes when circle and ellipse cut each other.²

2. If however the minor axis of the ellipse equals the diameter of the circle as in Fig. 2, Plate XVI, we also get a definite dual strike solution. Indeed the line connecting their centers is also a strike elevated or depressed, but the dip may be in either direction.

3. When the cones do not intersect, as in Fig. 3, there are four possible solutions to the problem.

4. When the cones are externally tangential there are (Fig. 4) three possible solutions, and the tangent strikes need not be parallel.

5. When the cones are internally tangential there is only one tangent (Fig. 5), we get only one strike and the problem is therefore solvable.

6. Another single solution case arises when the slant hole follows the true dip of the strata and is therefore a point in plan. If it did not follow the true dip but still

¹ HADDOCK, M. H., "Disrupted Strata," p. 19, Crosby, Lockwood & Sons, 1929.

² LOBECK, A. K., "Block Diagrams," p. 134.

To get the full dip δ , applying the rule of Eq. (52) above we get

$$\frac{\tan \delta}{\tan \beta} = \frac{\sin 90^\circ}{\sin \theta_2} \text{ or } \tan \delta = \frac{\tan \beta}{\sin \theta_2} \quad (56)$$

so that Eqs. (55) and (56) provide the full solution.

Second Solution.—This alternate method is adopted when we do not desire to obtain the angles θ_1 and θ_2 by

construction. Let the known lines AB_1 and BE equal l_1 and l_2 , also let the known depth difference between B and A be h_1 and between C and B be h_2 . Produce AB_1 (Fig. 179) to take a perpendicular DG let fall on it from

FIG. 179.

D , and draw BF_1 and B_1F_1 meeting at F_1 each normal to AD the strike line so that the angle $BF_1B_1 = \delta$ the full dip.

$$DB_1 = h_1 \cot \beta \quad (57)$$

$$\tan \phi_2 = \frac{DG}{GB_1 + B_1A} \quad (58)$$

$$DG = DB_1 \sin \phi_1$$

and

$$GB_1 = DB_1 \cos \phi_1$$

By substituting in Eq. (58) we get

$$\begin{aligned} \tan \phi_2 &= \frac{DB_1 \sin \phi_1}{DB_1 \cos \phi_1 + l_1} = \frac{h_1 \cot \beta \sin \phi_1}{h_1 \cot \beta \cos \phi_1 + l_1} \\ &= \frac{h_1 \frac{l_2}{h_2} \sin \phi_1}{h_1 \frac{l_2}{h_2} \cos \phi_1 + l_1} = \frac{h_1 \frac{l_2}{h_2} \sin \phi_1}{\frac{h_1 l_2 \cos \phi_1 + h_2 l_1}{h_2}} \\ \tan \phi_2 &= \frac{h_1 l_2 \sin \phi_1}{h_1 l_2 \cos \phi_1 + h_2 l_1} \quad (59) \end{aligned}$$

Third Solution.—Using the above figure and notation and noting that the bearing of AC is β_1 , of BC , β_2 and for

the full rise FC , β_d and h the difference in depth of the deepest hole A and the shallowest C :

$$h = \frac{C_1F}{\cos (\beta_d - \beta_2)} \tan \beta = C_1F \tan \delta = \frac{C_1F}{\cos (\beta_1 - \beta_d)} \tan \alpha$$

Dividing we get

$$\frac{\cos (\beta_d - \beta_2)}{\cos (\beta_1 - \beta_d)} = k = \frac{\tan \beta}{\tan \alpha} = \frac{1}{m}$$

Whence

$$\tan \beta_d = - \frac{\cos \beta_2 - k \cos \beta_1}{\sin \beta_2 - k \sin \beta_1} \quad (60)$$

Which gives the full rise bearing from which $\beta_d + 180$ deg. is the full dip bearing and the amount of dip can be got from the fundamental formula (51), thus

$$\tan \delta = \frac{\tan \beta}{\cos (\beta_d - \beta_2)}$$

or

$$\frac{\tan \alpha}{\cos (\beta_1 - \beta_d)} \quad (61)$$

First Graphical Solution.—Assume the surface survey reduced to level is as shown in Fig. 180 and the stratum is 800 ft. deep at A , 550 at B , and 200 at C .

Plot triangle AC_1B_1 from field notes and erect perpendicular C_1C on B_1C_1 at C_1 and equal to the difference in elevation between C and A . On this line measure off CE equal to the difference in elevation of C and B . Draw EB parallel and equal to C_1B_1 . Connect C and B and produce to meet C_1B_1 produced in D . Join AD and draw C_1F perpendicular to AD ; and on C_1B lay off $C_1M = C_1F$. Join C and M . Now C_1F is the direction of dip and CMC_1 its amount.

Second Graphical Solution.—Lay off the surface level triangle ABC or the original triangle (Fig. 181) leveled to a given datum. Set off at the shallowest and deepest holes, A and C , their respective depths AA_1 , 800 ft., and

CC_1 , 200 ft. at right angles. Join A_1C_1 and on AA_1 and CC_1 scale off the depth of the hole of intermediate depth, i.e., $B = 550$ ft., so getting Aa and Cc . Join a to c and where it cuts A_1C_1 at d erect a perpendicular dE to AC . Join EB thus getting the line of strike. From either or

FIG. 180.

both of the points A or C drop a perpendicular on to this strike line and complete the right-angle dip triangle by setting off the depth of the point concerned respecting the

FIG. 181.

B depth normal to this line. For example, AF is normal to BE the strike and $FG = A$ depth minus B depth = $800 - 550 = 250$ ft. Hence AGF is the amount of dip. Check with CH normal to strike and $HJ = 550 - 200 = 350$ ft., the difference in depth of C and B . This again gives the amount of dip, and its direction is from F toward A the lowest point.

angle $CFC_1 = \delta$, the full dip of the stratum. The angles θ_1 and α also the lengths AC_1 and CC_1 are known.

$$FC_1 = AC_1 \sin \theta_1$$

and

$$\tan \delta = \frac{CC_1}{FC_1} = \frac{CC_1}{AC_1 \sin \theta_1} = \frac{\tan \alpha}{\sin \theta_1}$$

or

$$\tan \delta = \tan \alpha \operatorname{cosec} \theta_1 \quad (62)$$

Given Three Deviated Boreholes to Determine the Dip and Strike of the Stratum.—Having surveyed three bore-

FIG. 183.

holes A , B and C and found their net horizontal displacements and depths a line may be drawn in a direction connecting the source and end of each. This line will usually be the shortest line between these points and will have the average deflection of the hole throughout.

Let us consider a concrete case of three holes set vertically but now deviated until when reduced as above we get their bases data also. Let the surface and borehole data be:

	Coordinates		Net bearing of hole	Length of hole, feet	Dip from horizontal (90° off vertical), degrees
	X	Y			
A	1,000.00	500.00	N.50°E.	1,200	60
B	100.00	-800.00	S.80°E.	300	75
C	-600.00	200.00	N.10°E.	400	80

These points are set out in ABC (Fig. 184).

Set off from A a line at the hole bearing $N. 50^\circ E.$ and on it the dip angle of the hole, *i.e.*, 60° , setting off on the dip line $AA_1 = 1,200$ ft. the borehole length. Drop a perpendicular A_1A_2 to meet the direction line from A in A_2 , and A_2 will be the plan position of the end of the borehole from A . In a similar manner, using the relevant data, get B_2

FIG. 184.—The three slanting borehole problem.

and C_2 . $A_2B_2C_2$ is the actual area encompassed by the borehole bases. On line A_2C_2 set off the depths of A_2 and C_2 at these points, respectively, at right angles to this line, so getting A_3 and C_3 . Join A_3 to C_3 and produce to meet A_2C_2 produced in x . (Note that A_2A_3 is the depth of A_2 and B_2B_3 is that of B_2 and C_2C_3 that of C_2 .) Similarly set off $A_2A'_3$, the depth of A_2 , and B_2B_3 , the depth of B_2 , at right angles to A_2B_2 as shown. Connect A'_3 to B_3 and produce to meet A_2B_2 produced in y . x and y are on the strike of the stratum. Drop a perpendicular C_2D on to the strike line xy and erect one, C_2E , at C_2 equal to its depth. Join ED and the angle EDC_2 is the amount of dip and its direction is DC_2 . Check by B_2GF using the same reasoning.

NOMOGRAPHIC AND ALIGNMENT METHODS

These simple and easily understood charts are becoming more and more popular because they can, as a rule, be manipulated by the boring personnel and others who wish to save time.

Figure 185¹ shows the well-known versed-sine relation which can be applied to a hole the deviation of which is either regular or can be approximately meaned throughout its course, giving a straight deflection; that is to say, a constant off-vertical angle. The alignment chart itself

(Fig. 186) is constructed by putting on the left the logarithmic scale *A* with the scale of versed sines *B*₁ or *C*₁ on its right and the vertical correction scales corresponding at *B*₂ and *C*₂. To get a correction, place a straightedge at the desired depth of hole on *A* scale, say 100 ft., and at the proper off-vertical angle on *B*₁ scale; continue and read off the correction on *B*₂ or *C*₂ scale. If the straightedge falls off scale *B*₂, then use scales *C*₁ and *C*₂. If the measured depth is greater than scale *A* divide it by 10 and multiply the corresponding results on *B*₂ or *C*₂ by 10. Thus if the depth is 2,500 ft. and the off-vertical angle 10 deg. use 250 ft. and multiply the resultant vertical correction of 3.75 ft. by 10, giving 37.5 ft. Use a transparent celluloid straightedge with a fine black parallel line near one edge.

FIG. 185.

Based on Fig. 185 Mr. Brindel² discusses a simple employment of mathematical tables and formula, noting that

1. By the Cosine Method.

The corrected measurement = (actual measurement) $\times$
 (cosine of off-vertical angle),
i.e., in Fig. 185 $AB = AD \cos BAD$.

¹ BRINDEL, H. F., *Oil Gas Jour.*, p. 41, Apr. 11, 1929.

² *Ibid.*, p. 41.

2. By the Versed Sine Method.

The corrected measurement = (actual measurement) —
 (actual measurement $\times$ ver-
 sine of off-vertical angle)
i.e., $BC - AD \text{ vers } BAD$.

PLATE XVII.—Milliken's vertical correction chart for drill holes.

A table of natural cosines and another of natural versines should be kept, the latter being the simpler to use having least multiplying figures. A check on each of these methods would be always advisable; *e.g.*, in a 200-ft. hole

FIG. 186.—Alignment chart for determining vertical corrections in crooked holes.

5 deg. off the vertical the cosine rule will give a correct vertical distance of 199.24 ft. and the versine rule will give the same. Table IX¹ shows tabulated data, the results of several such examples as the above.

Plate XVII shows Milliken's chart² for the graphic determination of vertical corrections in crooked holes. It is drawn on logarithmic paper, the off-vertical angles being

¹ By the courtesy of R. Van A. Mills, of *Petroleum Engineering*.

² Charles V. Milliken, of the Amerada Petroleum Corporation, in *Oil Gas Jour.*, p. 102, 1930.

represented by diagonal lines. The measured interval scales are shown on the left and right margins. Pick off the proper measured interval on the left or right margin and follow the horizontal line from this point on the measured interval scale to its intersection with the proper off-vertical line. From here follow a vertical line to the upper or lower margin, as the case may require, where the vertical correction in feet is indicated.

TABLE IX.—EXAMPLE AND FORM OF NOTES FOR VERSINE VERTICAL CORRECTION METHOD

Measurement from point of last measurement, feet	Off-vertical angles, degrees	Factor, natural versine of angle	Vertical correction, feet	Corrected measurement, feet	Total true depth, feet
200	5	0.0038	— 0.76	199.24	199.24
190	10	0.0152	— 2.89	187.11	386.35
195	24	0.0865	—16.77	178.23	564.58
220	6	0.0055	— 1.21	218.79	783.37
240	15	0.0341	— 8.18	231.82	1,015.19
238	7	0.0075	— 1.79	236.21	1,251.40
242	9	0.0123	— 2.98	239.02	1,490.42
256	6	0.0055	— 1.41	254.59	1,745.01
239	30	0.1340	—32.03	206.97	1,951.98
250	25	0.0937	—23.43	226.57	2,178.55
Total 2,270	..		—91.45		2,178.55

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ABBREVIATIONS IN THE LITERATURE INDEX

<i>A.A.P.G.B.</i>	Bulletin of the American Association of Petroleum Geologists, Tulsa, Oklahoma.
<i>A.I.M.M.E.</i>	American Institution of Mining and Metallurgical Engineers, New York.
<i>A.I.M.E.B.</i>	American Institution Mining Engineers Bulletin, New York.
<i>A.M.B.</i>	Annales des Mines, Belgique, Brussels.
<i>A.M.P.</i>	Annales des Mines de Paris, Paris.
<i>A.M.R.</i>	Analele Minelor din România, Bucharest.
<i>A.P.</i>	American Patent, Washington.
<i>A.P.I.B.</i>	American Petroleum Institution Bulletin.
<i>B.A.R.</i>	British Association Report.
<i>B.b.</i>	Bergbaukunde.
<i>B.H.J.</i>	Berg-und Hüttenmännische Jahrbuch, Loeben.
<i>B.H.Z.</i>	Berg-und Hüttenmännische Zeitung.
<i>C.M.J.</i>	Canadian Mining Journal, Gardenvale, Canada.
<i>C. Eng.</i>	Colliery Engineering, London.
<i>C.G.</i>	Colliery Guardian, London.
<i>D.R.P.</i>	German Patent.
<i>Eng.</i>	Engineering, London.
<i>E.M.J.</i>	Engineering and Mining Journal, New York.
<i>E.Z.</i>	Elektrotechnische Zeitschrift, Berlin.
<i>Gl.</i>	Glückauf, Essen.
<i>I.P.T.</i>	Institution of Petroleum Technology, London.
<i>I.Z.B.</i>	Internationale Zeitschrift für Bohrtechnik, Erdölbergbau, und Geologie, Vienna.
<i>I.C.T.R.</i>	Iron and Coal Trades Review, London.
<i>J.A.</i>	Jernkontorets Annaler, Stockholm.
<i>J.G.</i>	Journal of Geology.
<i>J.I.P.T.</i>	Journal of the Institute of Petroleum Technologists, U.S.A.
<i>J.S.A.A.E.</i>	Journal of the South African Association of Engineers, Johannesburg.
<i>J.S.A.I.M.E.</i>	Journal of the South African Institute of Mining Engineers, Johannesburg.
<i>K.</i>	Kali, Halle, Saale.
<i>K.E.</i>	Kohle und Erz, Berlin.
<i>M.J.</i>	Mining Journal, London.
<i>M. Mag.</i>	Mining Magazine, London.
<i>M.M.</i>	Mitteilungen aus dem Markscheiderwesen, Freiberg.

<i>N.P.N.</i>	National Petroleum News, Cleveland, Ohio.
<i>N.S.K.</i>	Neftianoe i Slantzenoe Khoziaistvo, Moscow.
<i>O.A.</i>	Oil Age.
<i>O.B.</i>	Oil Bulletin.
<i>O.B.Z.</i>	Österreichische Zeitschrift. Berg-und Hüttenwesen, Vienna.
<i>O.F.E.</i>	Oil Field Engineering, Philadelphia.
<i>O.G.J.</i>	Oil and Gas Journal, Tulsa, Oklahoma.
<i>O.V.B.</i>	Organ des Verein der Bohrtechniker, Vienna.
<i>O.W.</i>	Oil Weekly, Houston, Texas.
<i>Pat.</i>	British Patent, London.
<i>P.A.G.</i>	Pan-American Geologists.
<i>Pet.</i>	Petroleum, Berlin.
<i>P.E.</i>	Petroleum Engineer.
<i>Proc. L.S.M.I.</i>	Proceedings of the Lake Superior Mining Institute.
<i>Pr. Zt.</i>	Preussisch Zeitschrift, Berlin.
<i>P.T.</i>	Petroleum Times, London.
<i>P.W.O.A.</i>	Petroleum World and Oil Age.
<i>S.A.M.J.</i>	South African Mining Journal, Johannesburg.
<i>T.A.I.M.E.</i>	Transactions of the American Institution of Mining Engineers, New York.
<i>T.I.M.E.</i>	Transactions of the Institution of Mining Engineers, London.
<i>T.I.M.M.</i>	Transactions of the Institution of Mining and Metallurgy, London.
<i>U.S.B.M. Bull.</i>	Bulletin of the United States Bureau of Mines.
<i>U.S.B.M.R.</i>	United States Bureau of Mines Report.
<i>U.S.G.S.</i>	United States Geological Survey, Washington.
<i>Z.D.G.G.</i>	Zeitschrift der deutschen geologischen Gesellschaft, Stuttgart.
<i>Z.I.B.V.</i>	Zeitschrift des Internationalen Bohrtechniker Verbandes, Berlin.
<i>Z.I.V.B.B.</i>	Zeitschrift des Internationalen Vereines der Bohringen- ieure und Bohrtechniker, Vienna.

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