THE FOTOBOR SYSTEM

AN INTEGRATED SYSTEM OF BORE HOLE MEASUREMENT WITH DEPTH PROGNOSTICATION, CURVATURE DRILLING HOLE BRANCHING AND CORE ORIENTATION WITHIN THE FIELD OF DIAMOND DRILLING TECHNIQUE.

Content

Introduction.

The mining engineer of yesterday, who had a task to make mining plans for a new deep level, very soon found that technical and economical realities to a great extent was a question of the accuracy of investigation drilling.

Bore hole measuring equipments were defective and seldom used. One way to solve the problem was to arrange drilling places so close to the goal that bore hole deviations were kept within acceptable limits.

A list of development wishes was long. In the first place a simple, fast and accurate equipment, insensible to geophysical disturbancies in the rock.

It showed that solving of the problem did not demand for a high grade genius, but perhaps a unique combination of fairly elementary knowledge and interest within different sectors of general technics.

Technical imagination makes possible in such cases a synthesis of known parametres to working units. If the imagination includes a capability to understand one's own limitation, a step is short to find skilled colleagues.

Thus the bore hole camera Reflex-Fotobor was created together with Tryggve Ramqvist and Sture Örtenblad.

In the course of time many bore hole measurements have increased the knowledge of hole curvature factors - knowledge which has made possible the development of new technics within the field of diamond drilling.

The mining engineer of today can thus make safer mining plans with better economy.

Malmberget, november 1987

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1. General points.

The only information obtainable from a diamond drill hole, that has not been measured, is that from the cores.

If the hole is measured, so that the situation is known throughout its entire length, the amount of information will increase remarkably. Unfortunately one piece of information could be that the hole had deviated so much that the goal area was missed, and the money wasted.

:1 The purpose of the hole, some examples.

:11 Prospecting.

:111 Depth investigations.

A geophysical anomaly of some kind has to be investigated, fig 1. Will the hole reach the anomaly?

Fig 1

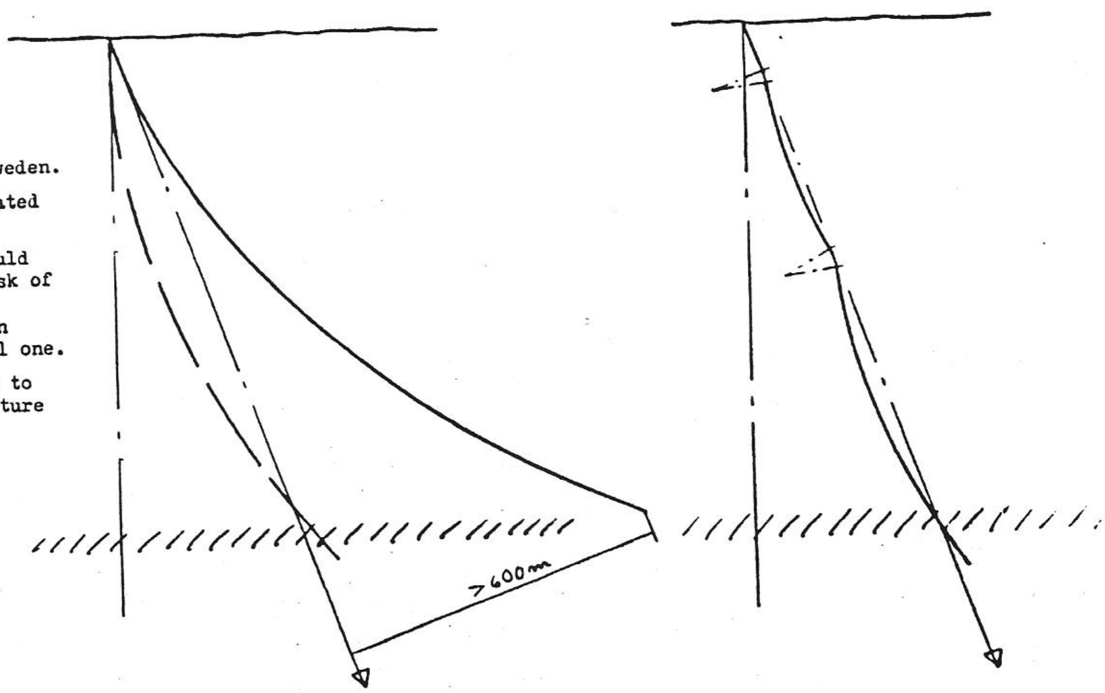
Fig 1a

An event from central Sweden.

A 1365 m deep hole deviated more than 600 m.

An early measurement would have pointed out the risk of missing the anomaly.
The hole could have been abandoned for a vertical one.

Nowadays it is possible to correct a hole by curvature drilling, fig 1 a.

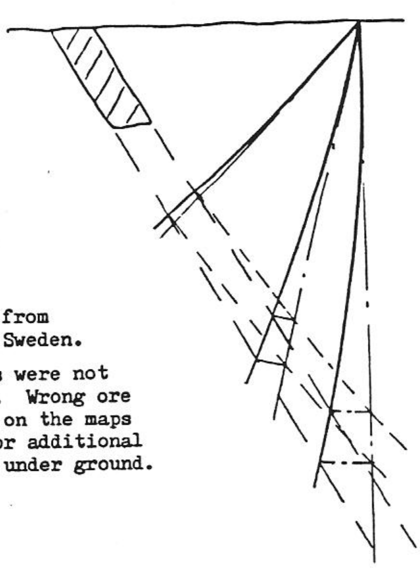


:112 A new main level.

The situation of an ore bed is to be determined with some drill holes from the surface, fig 2, or - if the depth is great - from an investigation drift in the hanging wall, fig 3.

Will the holes show correct ore limits?

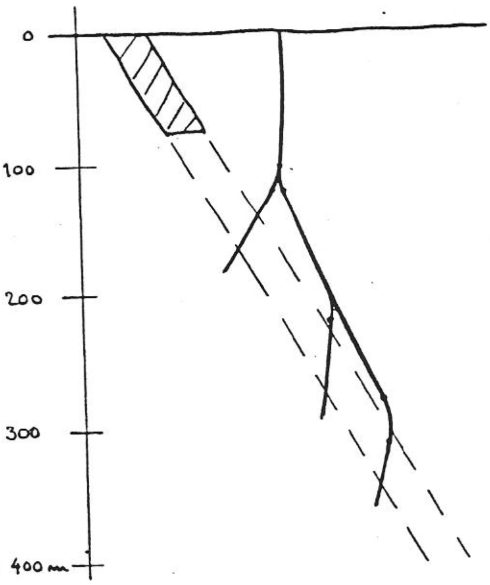
Fig 2.



An event from Northern Sweden.

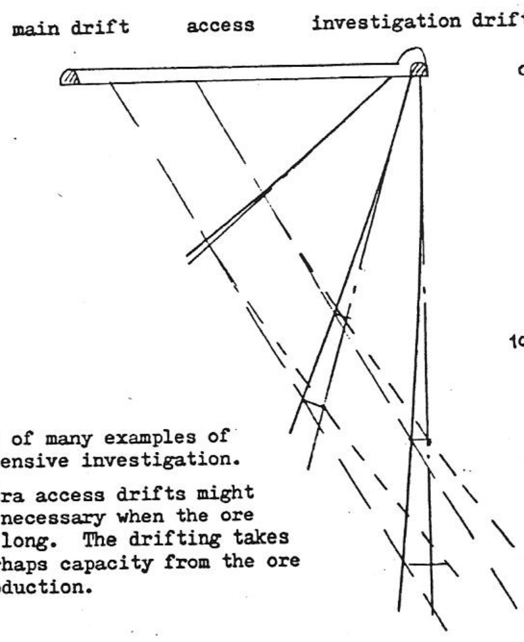
The holes were not measured. Wrong ore position on the maps called for additional drilling under ground.

Fig 2a



Branching and curvature drilling will decrease standard drilling by one third.

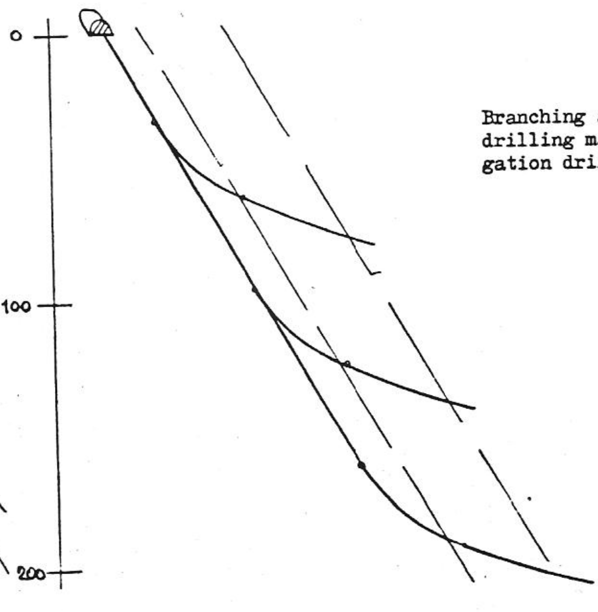
Fig 3



One of many examples of expensive investigation.

Extra access drifts might be necessary when the ore is long. The drifting takes perhaps capacity from the ore production.

Fig 3a



Branching and curvature drilling make the investigation drift needless.

:113 Strike and dip of the ore.

In a mine where the geology is folded sedimentary rock, cores show that the ore obviously has changed strike or dip or both, fig 4.

How were the cores oriented?

Fig 4

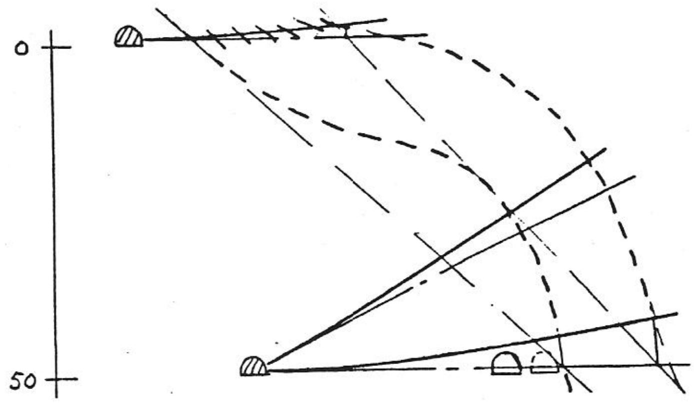
An event from Northern Sweden.

The structures in the cores from the upper hole showed that the ore obviously was folded.

A middle hole drilled after that observation revealed the planned longwall shrinkage stoping to be impossible.

Sublevel stoping with scraping was a logical solution.

The footwall loading drift was partly completed with a new one close to the ore limit.



:12 Technical holes.

:121 Pilot holes etc.

A hole has to be drilled for e.g. an electric cable, drainage, venting or later reaming, fig 5.

Will the goal be reached?

An event from a water power station in Northern Sweden.

A measurement in the first hole showed great deviation.

A number of holes in the following weeks of drilling did not reach the tunnel. At last a drift was driven to one of the holes.

Diamond drilling, early measurement and correction drilling would have resulted directly.

Fig 5.

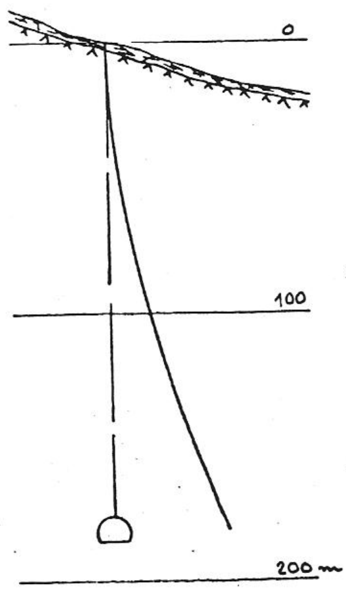
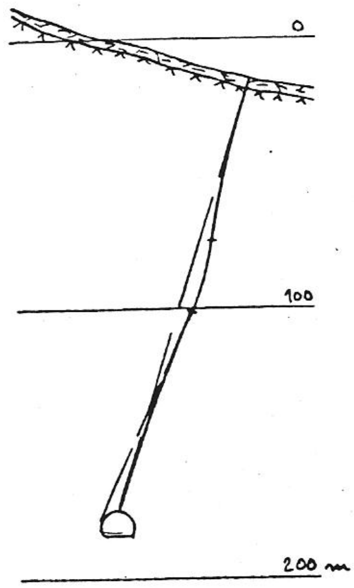


Fig 5 a.



:122 Systems of weakness in the rock.

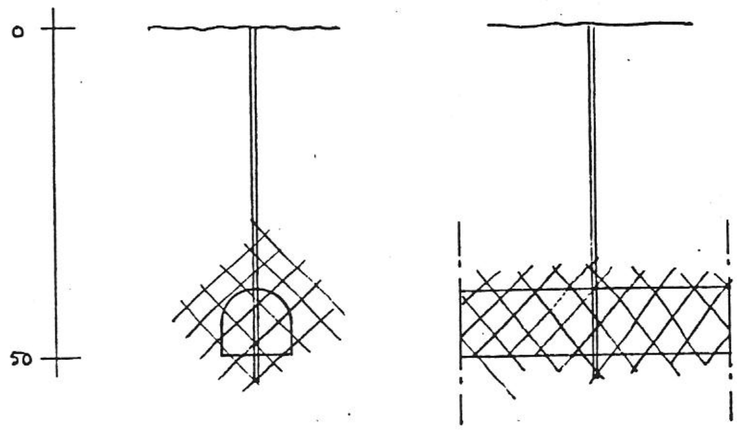
An underground cavity is planned. Cores show fissure and joint systems, which might increase risks and costs if this is not taken into consideration, fig 6.

How were the cores oriented in the rock?

Fig 6

When the situation and frequency of the systems of weakness are known, a basis for correct decisions is existing.

The need of reinforcement is easier to see.



2. Bore hole deviation.

Deviation can be caused by many different factors.

:1 Initial errors.

An erroneous line up causes a linear error of nearly two metres per degree for each hundred metres.

:2 Dislocations in the rock.

Fissures and cavities causing deviations are relatively few and irregular. Their negative influence on drilling is probably more troublesome than the deviation.

:3 Regular curvature.

Practically all holes are affected by regular curvature. The causes are mechanical or environmental. This type of deviation is characteristically stabile throughout the entire hole.

It is an old observation that the drill tends towards a perpendicular angle to structures with alternating hard and soft stratified rock. In folded rock the hole curvature can increase and decrease concurrently with the changing situation.

When mechanical and environmental factors combine the deviation can be extreme. There are examples where the curvature over 20-30 metres has been one third of a degree per metre, that is about what a tight sequence of wedges could give. But the same factors can also counteract so that the curvature will be slight.

The error propagation is exponential.

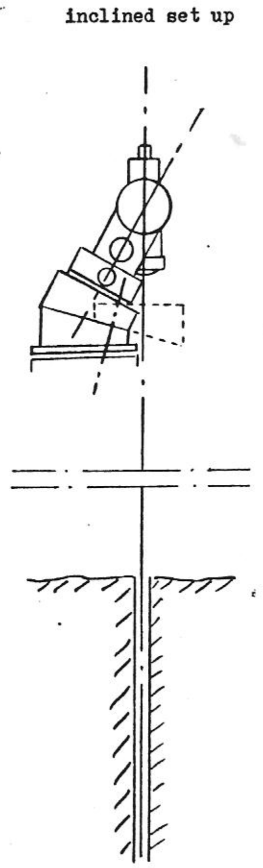
3. Measurements and calculations.

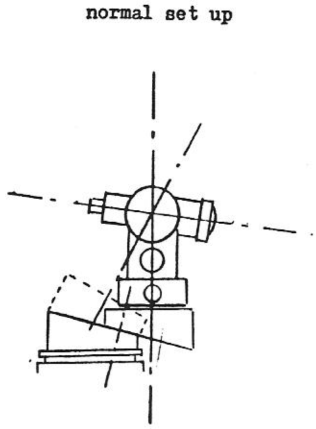
:1 The collar.

The situation of the collar, dip and direction of the hole can be determined in different ways. There is, however, only one generally dependable way, namely to direct the telescope of a theodolite into the hole, especially if the hole is steep. This will need a special arrangement, fig 7.

Figures and formulae are described in point 12, page 43.

Fig 7





Observations from the inclined set up are: a) the hole,
b) some reference objects,
c) known points.

From the normal set up are observed only the reference objects.
The reference objects are either two plummit lines or three marking pins.
The plummit lines make together a vertical plane and the three pins make an arbitrary plane.
The situation of the planes in relation to the vertical axis of the theodolite can be determined in both cases. The observations from the inclined set up can thus be transformed to the nomal set up.

:2 The depth situation.

This investigation comprising the examination of about one hundred holes measured with the Reflex-Fotobor bore hole camera has been undertaken primarily in respect to curvature. The evident pattern provides a basis for better use of known tecnics and the development of new ones.

:21 The pattern of curvature.

Almost all diamond drill holes have a common pattern. Mostly the path of a hole is similar to an arc of a circle. The differences between separate holes are different sizes of radius of curvature and different inclination of the planes of curvature. Even if sometimes there are divergences in the pattern, some signs presage complications.

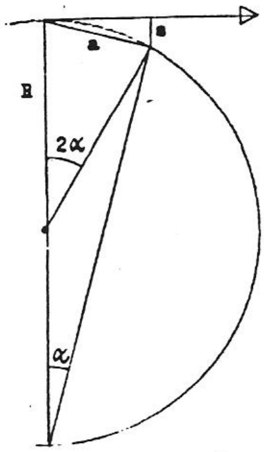
:211 Arc of circle.

If the path of the hole corresponds to an arc of a circle, fig 8, the relations between the deviation s, the chord a, the radius of curvature R from an arbitrary tangent is

$$s = \frac{a^2}{2R}.$$

Thus the deviation increases with the square of the depth.

Fig 8



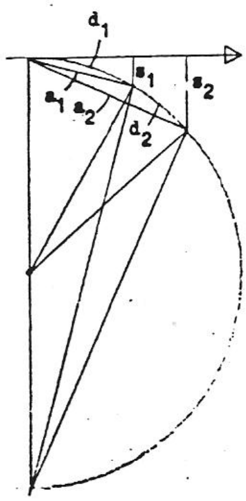
If the deviation s_1 in a shallow depth a_1 is known, it is possible to predict the deviation s_2 lying deeper in the hole:

$$s_2 = s_1 \cdot \left(\frac{a_2}{a_1}\right)^2.$$

In practice the depth d and the chord a are almost of the same size, even if the centre angle 2α should approch to the value of one radian

$$s_2 = s_1 \cdot \left(\frac{d_2}{d_1}\right)^2.$$

Fig 9



:212 The radius of curvature.

Usually the deviation is stated as a percentage of the depth of the hole. This is often misleading, as the value increases markedly with the depth. A better way is to use a fictious radius of curvature at 100 metres hole depth. The radius changes slowly with the depth and gives a good indication of the behaviour of the hole at depth.

In normal Scandinavian bedrock the radius of curvature is usually 1,5-2 km, corresponding to 2-3 metres deviation at 100 metre hole depth.

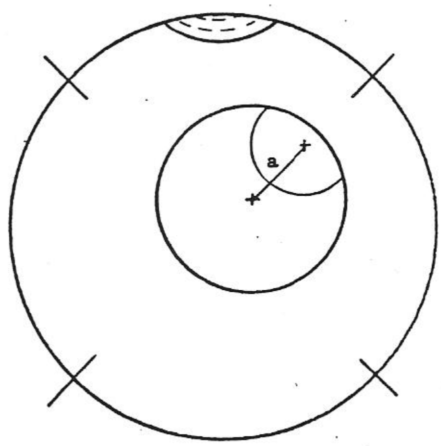
The shortest measured radius at 100 metres was less than 300 metres, the longest was more than 30 km.

In the film from the bore hole camera the radius of curvature can be determined in each frame, fig 10, magnified for evaluation.

Fig 10

The radius of curvature in kilometres is got by dividing 9,55 with the distance in millimetres between the centres of the 3- and 6-metres rings:

$$R = \frac{9{,}55}{a}\ \text{km}$$



:213 The curvature exponent.

At each point P_n, the relation is $s_n = s_1 \cdot \left(\frac{d_n}{d_1}\right)^{k_n} = s_1 \cdot m^{k_n}$

and conversely $k_n = \dfrac{\ln \frac{s_n}{s_1}}{\ln m}$.

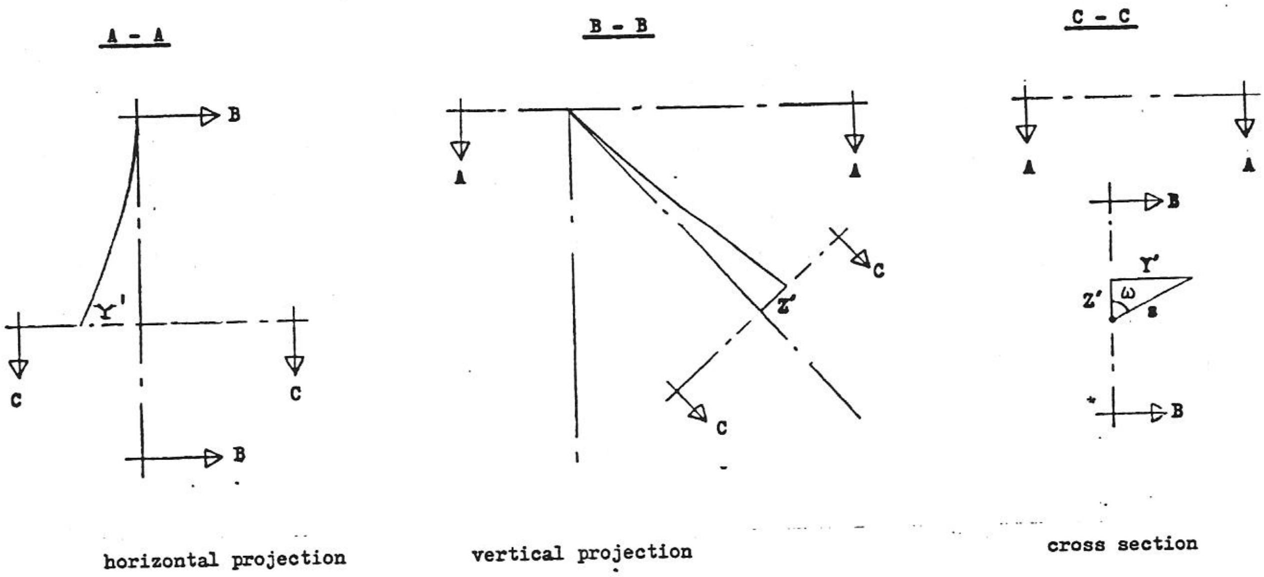
The curvature exponent changes at depth mostly in a regular way, depending on its numerical value and the size of the radius of curvature. If k is large while the radius is small, the value of k decreases quickly at first, and thereafter more slowly with increasing depth. When k is less than 2 the change is slight if the radius is small but increases with increasing radius at depth.

:214 The plane of curvature.

The curvature of the hole defines a plane, the curvature plane, which usually has a stable dip ω, relative to the reference line and the vertical plane through that line, fig 11.

The dip ω shows sometimes a moderate and occasionally a considerable change. The stability decreases with increasing radius of curvature.

Fig 11



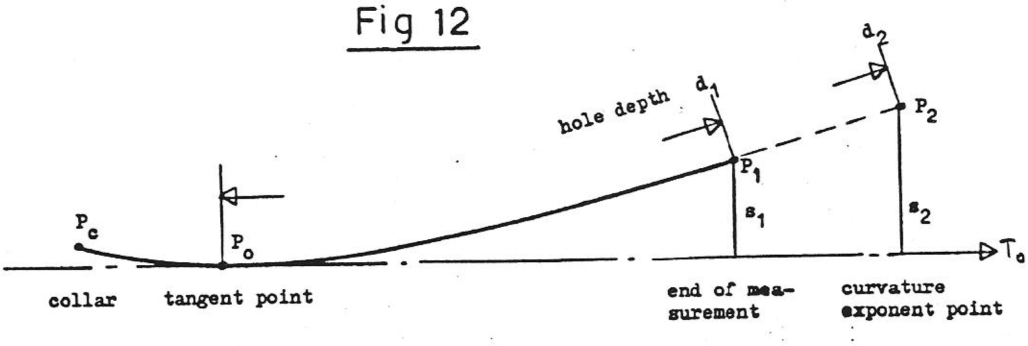
:215 The reference line T.

The reference line, fig 12, must start so deep in the hole that continuity prevails during the drilling. The collar line is not dependable.

The reference point P_1 is situated at the deviation distance s_1 from the reference line T in the dip ω_1 of the plane of curvature.

An accurate calculation can be made from this point to determine a point a short distance lower in the hole and thus the curvature exponent k.

Fig 12



4. Depth prognosis.

:1 Empiric formulae.

Relative to the reference line T, which has its tangent point between 9 and 36 m, the deviation, the plane of curvature and the curvature exponent have been calculated tightly in different combinations down to 120 m in depth and thereafter each thirtieth metre to the bottom of the hole.

Deep holes have been divided into sections, which have been treated as independent holes.

Each combination of measured points has been fitted to a power curve in order to determine the development of the curvature exponent.

Obtained empiric formulae have been tested on each single hole.

:2 Reliability.

The error in the prognosis of the size of the deviation sometimes exceed one per cent of the hole depth down to 250 m, two per cent down to 350 m and three per cent down to 400 m of hole depth.

Because of the difficulty in forecasting the dip of the plane of curvature the error of the prognosis increases, however usually relatively moderately.

From the parametres one can get a useful knowledge of the reliability of the forecast.

When the radius of curvature is slight while the curvature exponent is great the deviation will be overestimated.

However, the deviation will be underestimated when the radius is big and the exponent small.

The greater the part of the hole taken as a basis for the forecast the more reliable it will be. But the value of the prognostication is above all the possibility of the early knowledge that the hole will be useful for its purpose.

:3 Tests.

The formulae have been tested on holes, which are not included in the empiric basis, table 1-3, p. 15-17.

Each table contains 20 holes in order of increasing radius of curvature.

Table 1 contains holes from Canada, not especially deep, but some extremely crooked. The measurements are assumed to have been made at 72 m of hole depth.

Table 2 and 3 contain Scandinavian holes measured at 96 m of hole depth.

TABLE 1 (canadian holes)

start values			depth values												
54 - 72 m			150 m			210 m			270 m			hole bottom		
No. depth	ω_{54} ω_{72}	R_o k_o	ω_p ω_d	s_r s_d	s_p e	ω_p ω_d	s_r s_d	s_p e	ω_p ω_d	s_r s_d	s_p e	ω_p ω_d	s_r s_d	s_p e
8445 246 m	- 35 - 31	0,28 1,54	- 26 - 2	31,7 - 0,5	32,2 0,8	- 24 - 2	56,2 0,6	55,6 1,1				- 24 0	72,9 0,6	72,3 0,6
8316 150 m	- 39 - 38	0,41 1,92	- 37 0	19,2 - 1,3	20,5 1,3									
838 150 m	- 20 - 22	0,42 1,96	- 19 - 5	24,4 0,2	24,2 1,3									
8446 309 m	- 30 - 27	0,45 1,91	- 20 - 5	26,1 - 0,6	26,7 1,3	- 18 - 5	46,2 - 0,3	46,5 2,4	- 18 - 3	70,6 0,4	70,2 2,4	- 18 - 2	89,2 1,6	87,6 2,5
8412 150 m	- 27 - 28	0,47 2,08	- 31 2	23,2 3,1	20,1 3,2									
8437 135 m	- 23 - 25	0,53 2,35										- 31 5	15,5 1,2	14,3 1,6
8447 228 m	- 11 - 15	0,64 2,36	- 14 - 4	20,1 2,0	18.1 2,2	- 13 - 8	40,9 6,4	34,5 7,4				- 13 - 8	48,0 7,6	40,4 9,0
8315 180 m	6 - 4	0,89 2,07	- 8 - 4	13,2 2,7	10,5 2,8							- 12 - 3	22,5 7,5	15,0 7,5
8431 144 m	- 28 - 31	0,95 2,88										- 35 2	15,4 1,7	13,7 1,7
8310 198 m	- 4 - 10	1,00 3,56	- 17 2	22,6 1,8	20,8 1,9							- 16 - 2	39,4 - 9,4	48,8 9,5
8411 240 m	- 23 - 21	1,04 2,08	- 22 3	12,8 1,7	11,1 1,7	- 24 6	25,5 5,0	20,5 5,3				- 26 8	36,2 10,2	26,0 10,7
8410 150 m	- 15 - 18	1,11 1,90	- 23 3	10,1 1,2	8,9 1,2									
8440 210 m	- 21 - 15	1,12 1,38	- 6 - 4	5,6 0,2	4,7 0,4	- 9 2	12,6 3,0	9,6 3,0						
841 150 m	- 11 - 16	1,17 2,51	- 20 0	11,0 1,1	9,9 1,1									
848s 258 m	- 29 - 22	1,45 2,32	- 27 10	8,0 - 0,2	8,2 1,1	- 25 13	14,7 - 1,8	16,5 3,2				- 21 12	21,2 - 3,7	24,9 5,3
8453 228 m	- 15 - 13	1,49 2,13	- 19 8	6,8 2,2	4,6 2,3	- 22 12	15,9 5,7	10,2 6,3				- 23 13	19,6 7,3	12,3 8,2
843 156 m	128 129	2,20 2,12	118 12	5,2 0,2	5,0 0,8							117 13	5,7 0,3	5,4 1,0
8423 210 m	- 8 - 12	2,28 1,83	- 23 8	8,7 2,4	6,3 2,5	- 27 10	20,1 9,0	11,1 9,1						
848u 150 m	190 185	2,70 2,11	-183 - 36	3,2 - 0,1	3,3 1,9									
847 159 m	8 0	2,96 1,84	11 - 17	4,6 - 0,4	5,0 0,8							12 - 19	5,0 - 0,5	5,5 1,0

Definitions:

No. = name of hole

depth = prognostication depth (even hole bottom)

ω_m = the dip of the curvature plane at depth stated

R_o = nominel radius of curvature

k_o = nominel exponent of curvature

ω_p = prognosticated dip of the plane of curvature

ω_d = error of the prognosticated dip of the plane of curvature

s_r, s_p = real respectively prognosticated deviation

s_d = difference between real and prognosticated deviation

e = the distance from prognosticated to real situation

T A B L E 2 (Scandinavian holes)

start values			depth values (prognostication depth is limited to 390 m)											
78 - 96 m			210 m			270 m			330 m			hole bottom		
No. depth	ω_{78} ω_{96}	R_o k_o	ω_p ω_d	s_r s_d	s_p e_p	ω_p ω_d	s_r s_d	s_p e_p	ω_p ω_d	s_r s_d	s_p e_p	ω_p ω_d	s_r s_d	s_p e_p
136 384 m	18 20	0,39 1,77	28 - 6	43,4 0,1	43,3 3,0	31 - 8	66,5 - 0,4	66,9 6,3	31 - 6	93,5 - 1,2	94,7 7,8	32 - 6	121,5 - 1,8	123,3 10,3
40 390 m	181 178	0,43 1,63	172 3	44,3 0,1	44,2 1,2	172 1	68,1 1,9	66,2 2,0	171 0	95,8 3,9	91,9 3,9	172 - 3	126,4 5,0	121,4 6,5
79007 345 m	61 63	0,47 2,58	64 1	45,9 1,8	44,1 2,0	63 4	71,3 - 5,1	76,4 6,3	62 6	98,7 -18,8	117,5 20,9	62 6	105,8 -23,3	129,1 25,5
15,79 243 m	-120 -122	0,47 1,18	-120 - 4	28,0 - 4,3	32,3 4,5							-120 - 5	34,6 - 6,9	41,5 7,2
181 390 m	178 175	0,55 1,98	179 - 7	25,6 - 1,8	27,4 3,5	181 - 11	36,7 - 8,5	45,2 11,0	184 - 16	46,2 -19,9	66,1 24,0	186 - 20	55,2 -36,6	91,8 42,4
135 390 m	3 5	0,59 1,73	10 - 3	48,4 2,6	45,8 2,8	10 - 2	72,0 4,6	67,4 4,7	10 0	99,3 7,3	92,0 7,3	10 1	130,0 10,3	119,7 10,4
2 354 m	70 65	0,93 1,77	50 9	14,6 - 0,5	15,1 2,1	47 9	23,9 - 0,5	24,4 3,5	44 9	35,6 - 0,1	35,7 5,1	44 8	40,9 0,1	40,8 5,1
18 330 m	- 7 - 3	1,05 2,95	- 8 10	32,7 6,7	26,0 7,9	- 10 14	62,3 12,4	49,9 17,2	- 11 17	98,9 16,1	82,5 29,0			
80,75 390 m	179 171	1,16 1,27	128 34	10,3 - 0,4	10,7 4,4	113 44	16,0 0,6	15,4 9,5	107 45	23,6 2,2	21,4 14,6	108 40	33,0 3,6	29,4 18,1
4,79 219 m	-102 -105	1,20 0,84	- 97 - 11	11,7 - 1,9	13,6 2,1							- 99 - 10	12,2 - 2,2	14,4 2,4
3 300 m	52 52	1,24 1,47	54 - 2	9,5 - 1,2	10,7 1,2	53 - 1	13,5 - 3,0	16,5 3,0				53 - 1	15,7 - 4,1	19,8 4,1
000 360 m	25 30	1,25 1,74	35 1	20,3 2,6	17,7 2,6	34 5	31,4 4,7	26,7 4,9	32 10	44,7 7,5	37,2 8,7	31 12	52,3 9,3	43,0 11,5
1 390 m	13 14	1,31 1,78	12 3	17,8 3,0	14,8 3,1	14 2	31,3 8,2	23,1 8,2	12 4	48,6 16,0	32,6 16,2	10 7	67,9 24,2	43,7 24,7
181,76 270 m	17 23	1,40 1,93	32 - 2	12,9 - 0,6	13,5 0,7	31 2	19,4 - 2,3	21,7 2,4						
395 219 m	2 - 1	1,41 2,05	4 - 8	16,8 2,8	14,0 3,3							4 - 9	18,4 3,1	15,3 3,7
1679 210 m	159 157	1,42 1,58	147 8	13,2 0,8	12,4 1,3									
133,76 390 m	- 20 - 11	1,45 2,24	22 - 23	15,2 - 0,6	15,8 4,3	28 - 23	24,9 - 0,8	25,7 7,7	31 - 21	36,3 - 1,7	38,0 10,7	35 - 20	49,3 - 3,0	52,3 14,1
1669 210 m	8 10	1,53 1,85	21 - 9	10,7 - 0,4	11,1 1,3									
1670 222 m	- 24 - 20	1,58 3,02	- 11 - 4	21,5 1,8	19,7 2,3							- 11 - 4	24,5 1,6	22,9 2,1
1666 270 m	13 - 2	1,77 3,23	- 10 - 9	12,8 - 1,9	14,7 3,2	- 8 - 20	25,9 - 6,7	32,6 13,4						

Definitions: see table 1

TABLE 3 (Scandinavian holes)

start values			depth values (prognostication depth is limited to 390 m)											
78 - 96 m			210 m			270 m			330 m			hole bottom		
No. depth	ω_{78} ω_{96}	R_o k_o	ω_p ω_d	s_r s_d	s_p e^p	ω_p ω_d	s_r s_d	s_p e^p	ω_p ω_d	s_r s_d	s_p e^p	ω_p ω_d	s_r s_d	s_p e^p
63,77	45	2,08	61	9,0	8,8	64	14,5	13,8	70	20,7	20,4	76	28,4	28,6
390 m	49	1,86	- 7	0,2	0,9	- 8	0,7	1,7	- 12	0,3	3,4	- 18	- 0,2	7,5
153,76	- 11	2,15	- 8	11,5	11,8	- 8	18,6	18,5	- 8	27,1	26,7	- 9	30,2	30,0
351 m	- 11	2,02	- 3	- 0,3	0,5	- 3	0,1	0,7	- 3	0,4	1,1	- 2	0,2	0,8
257	56	2,21	33	9,9	9,4	34	18,0	16,7				34	25,7	23,0
312 m	50	2,33	10	0,5	1,6	6	1,3	2,0				3	2,7	2,9
18,78	14	2,28	26	9,4	10,1	31	14,3	15,6	34	19,8	23,3	38	26,1	30,0
390 m	16	1,82	- 8	- 0,7	1,0	- 12	- 1,3	2,3	- 13	- 2,5	4,0	- 16	- 3,9	6,6
151,76	- 18	2,31	- 66	7,6	7,3	- 75	11,8	11,9	- 80	15,4	17,3	- 85	21,3	23,8
390 m	- 23	1,78	37	0,3	3,7	43	- 0,1	7,0	45	- 1,9	10,4	47	- 2,5	15,2
17	189	2,50	-199	8,3	7,0	-186	15,4	12,1				-186	16,6	12,9
279 m	195	2,01	1	1,3	1,3	- 9	3,3	3,8				- 8	3,7	4,1
232	79	2,58	91	6,5	6,6	93	14,7	14,4	93	22,6	21,7	91	31,8	30,3
390 m	79	2,11	- 12	- 0,1	1,3	- 14	0,3	2,8	- 14	0,9	4,4	- 12	1,5	5,5
154,76	81	2,58	70	8,3	9,2	66	13,9	15,7				65	18,2	21,0
369	80	2,28	9	- 0,9	1,4	12	- 1,8	3,1				12	- 2,8	4,4
1666	6	2,65	- 7	12,8	6,7	- 9	25,9	12,1				- 7	35,1	15,5
300 m	9	2,22	19	6,1	6,8	23	13,8	15,4				22	19,6	21,4
44,79	100	2,66	92	6,4	5,9	91	13,8	12,9	91	20,4	19,3	93	27,9	26,8
390 m	98	1,96	4	0,5	0,6	4	0,9	1,1	2	1,1	1,3	- 1	1,1	1,2
1.	- 18	2,68	- 3	7,7	8,9	- 6	10,0	14,2	- 8	11,8	20,5	- 13	13,5	28,0
390 m	- 18	1,90	- 15	- 1,2	1,7	- 12	- 4,2	4,5	- 10	- 8,7	8,9	- 5	-14,5	14,5
81,78	37	2,77	46	8,7	8,5	43	13,7	13,4	43	20,0	19,6	45	27,8	26,8
390 m	46	1,91	10	0,2	1,0	19	0,3	3,0	24	0,6	5,9	28	1,0	9,6
159,76	120	2,80	134	9,5	9,1	133	15,4	14,9	137	23,8	22,2	138	34,1	31,1
390 m	121	2,17	- 12	0,4	1,4	- 10	0,5	2,1	- 14	1,6	4,5	- 14	3,0	7,0
1,79	125	3,13	116	7,0	7,4	123	11,6	12,0	138	17,5	18,4	144	24,5	25,4
390 m	121	1,96	0	- 0,4	0,4	- 9	- 0,4	1,4	- 26	- 0,9	5,9	- 35	- 0,9	11,1
16,76	101	3,14	99	8,0	8,6	95	13,0	14,9	90	21,3	25,4	86	27,4	34,2
390 m	99	2,35	- 2	- 0,6	0,6	1	- 1,9	1,9	4	- 4,1	4,3	7	- 6,8	7,4
41,77	53	3,34	35	9,9	9,2	34	16,8	15,2	35	25,3	22,7	36	35,2	31,7
390 m	50	2,29	12	0,7	1,4	11	1,6	2,7	8	2,6	3,6	5	3,5	4,2
1	- 44	4,54	- 71	4,5	6,1	- 68	6,7	10,3	- 63	9,0	15,7			
330 m	- 51	2,15	12	- 1,6	1,8	5	- 3,6	3,6	- 4	- 6,7	6,7			
24,77	110	4,90	109	4,1	4,3	108	6,7	7,3	105	9,9	11,2	103	13,3	16,0
390 m	110	2,01	1	- 0,2	0,2	2	- 0,6	0,6	5	- 1,3	1,5	7	- 2,7	3,1
233	140	5,81	158	4,6	5,9	151	6,7	10,0						
270 m	143	2,24	- 12	- 1,3	1,5	- 3	- 3,3	3,3						
254	25	5,94	55	6,3	7,8	53	11,4	13,6	51	18,1	21,2	49	23,6	27,5
372 m	38	2,64	- 2	- 1,5	1,5	8	- 2,2	2,6	17	- 3,1	5,8	25	- 3,9	9,9

Definitions: see table 1

5. Practical applications.

:1 Hole corrections.

The forecast shows that the hole will not hit the target area. The hole can be abandoned for a new one or it can be corrected.

:11 Wedging.

Wedges of many different types have been used for a long time. There are different ways to orientate them.

Wedging is, however, ineffective, expensive and time consuming.

:12 Arc drilling.

In oil drilling it is common to drill intentionally curved holes with relatively small curving radii. The rotation of the bit is achieved by means of a universal coupling.

This principle has also been tried in diamond drilling without success. Strength problems could not be mastered.

Some years ago the problem was solved by use of a flexible shaft. An astonishing bonus was that some cores could be orientated.

Branch holes can be deflected by plugging the hole with concrete and arc drilling through the concrete out of the master hole.

:121 Equipment.

The equipment consists of a guide pipe fastened to the feeder in such a way that it can not revolve. In the guide pipe is an eccentrically journalled core barrel, which conveys the rotation to the bit.

:122 The radius of curvature.

From experience we know that the equipment can stand an abrupt curvature of more than one degree. A small radius gives a short correction drilling with resultant strain on the equipment. The best result will be obtained when the radius of curvature is about 100 metres. The continuous angle change is then more than half a degree per metre.

A diamond drillhole for oil in Gotland had an initial dip of 60 degrees. With a drilling radius of about 100 metres a continuous drilling was carried out for 100 metres until the hole was horisontal in a narrow oil bearing sandstone, fig 13. Another example is shown in fig 14.

:123 Orientation of the guide pipe in the plane of curvature.

The plane of curvature can be orientated in two ways: with the bore hole camera or with a special electromagnetic orientation apparatus. Both ways are dependable.

CRAELIUS/MICRODRILL
GOTLAND
HOLE: RISUNGS 4A
85.04.24

PLOT NO. 2
VERTICAL PROJECTION
X-LOC, Z-PLANE
SCALE 1:2000

Fig 13

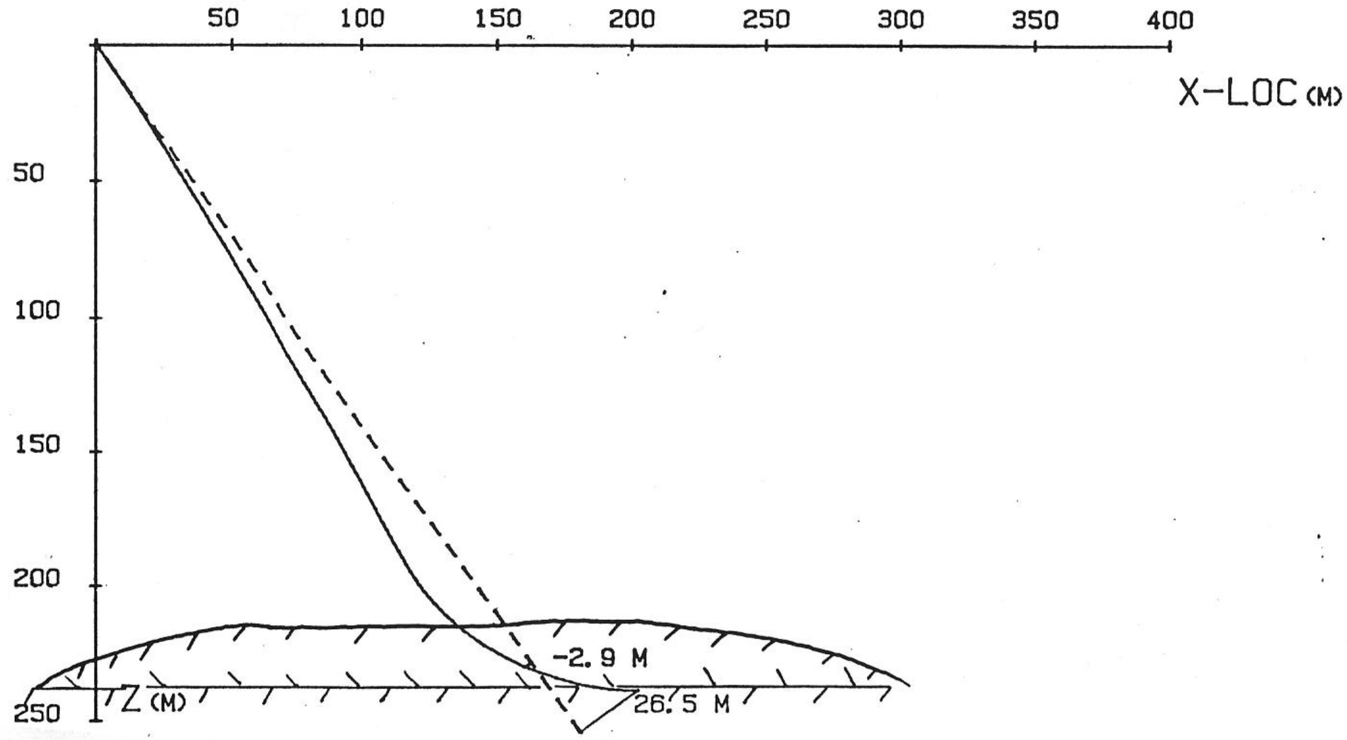
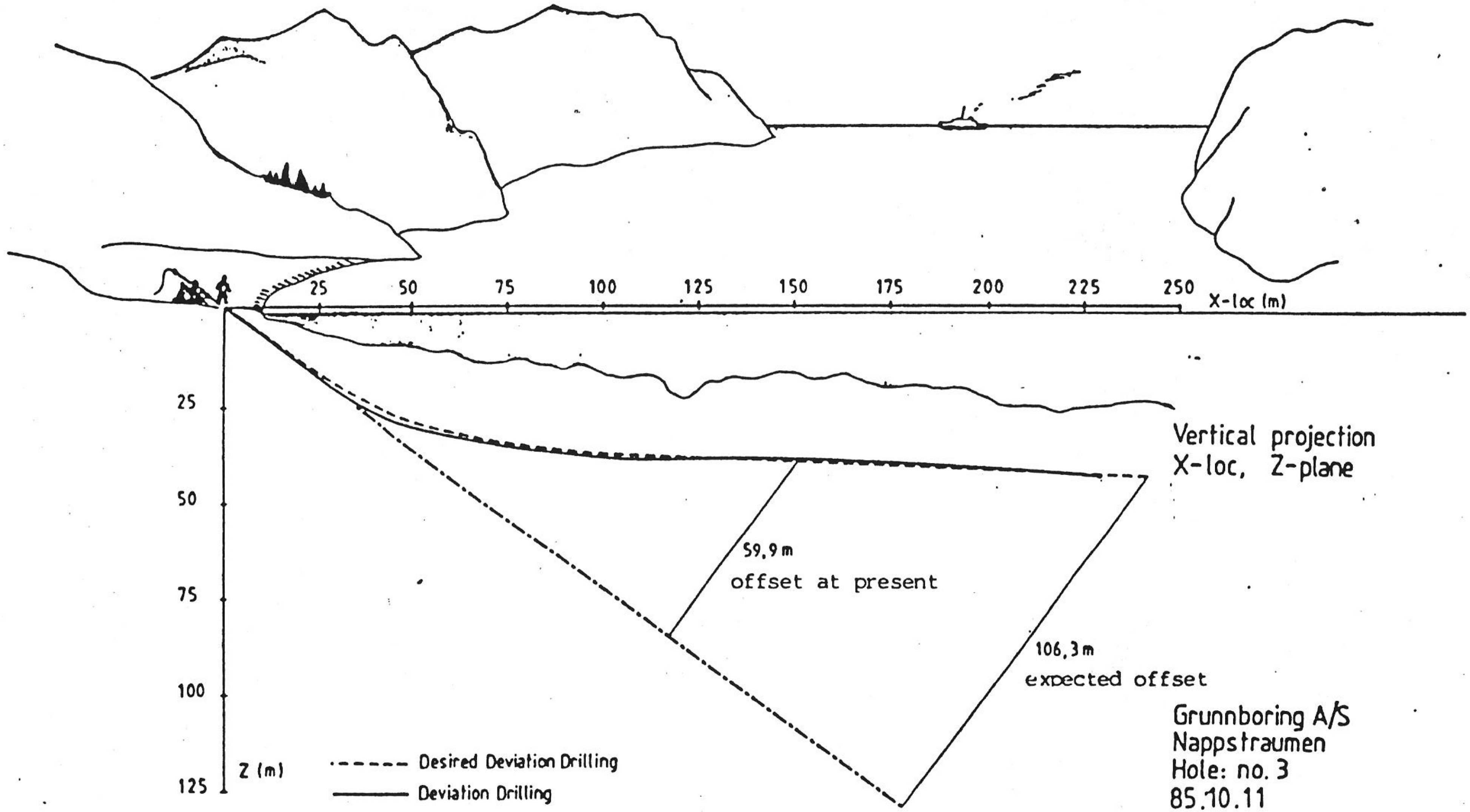


Fig 14

COURTESY CRAELIUS

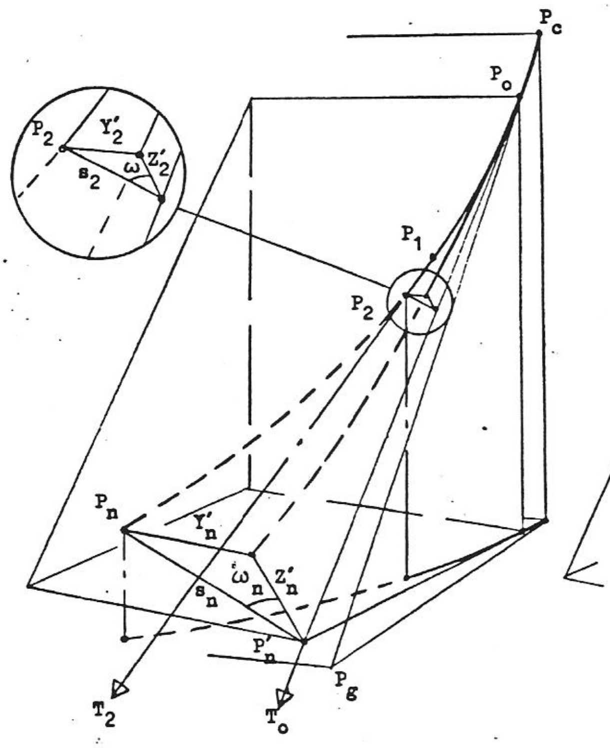


:124 Summary of the operation sequence.

The operation begins with the camera measurement. All necessary data are obtained: the deviation, a forecast of the probable situation at different depths, orientation of the equipment, and the length of the arc drilling, fig 15 and 16.

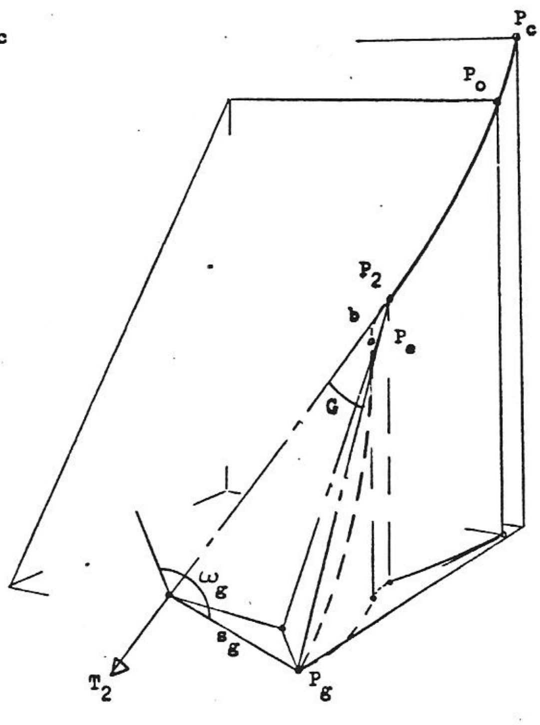
The guide pipe and casing are put down and the orientation apparatus is pumped to the guide pipe. The casing is turned until a signal from the orientation apparatus shows correct orientation and the apparatus is hoisted. The drillrods with the core pipe are put down and the drilling can begin with or without cores.

Fig 15



P_1 is the end of the camera measurement.
P_n is the probable position at the depth.
P_g is the planned position.
ω_n is the dip of the plane of curvature.
s_n is the deviation from T_o.

Fig 16



b is the length of the arc drilling.
An overcompensation in arc drilling takes into consideration the expected deviation corresponding to s_g.
ω_g is the orientation of the guide pipe.

:2 Branch holes.

Plugging the hole with fast hardening concrete allow new holes to be deflected. Wedges are thus unnecessary.

A systematic way to deflect and arc drill is shown in fig 2 a and 3 a.

:3 Core orientation.

A standard drilling after arc drilling gives the first core with an eccentric plug in the upper end. As the plane of curvature is known from the measurement, the core can be orientated, fig 17.

If the radius of curvature is small a ten centimetres long core can be orientated as it is slightly crooked. Laid on two rulers it rocks and settles in equilibrium with vertical plane of curvature, fig 18.

Fig 17

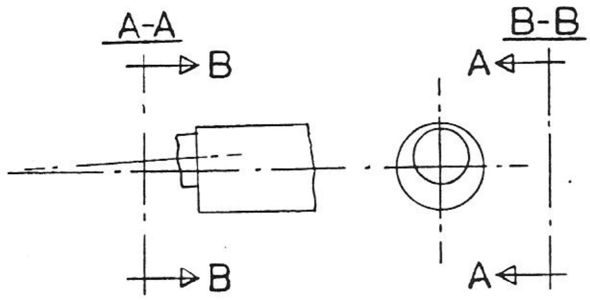
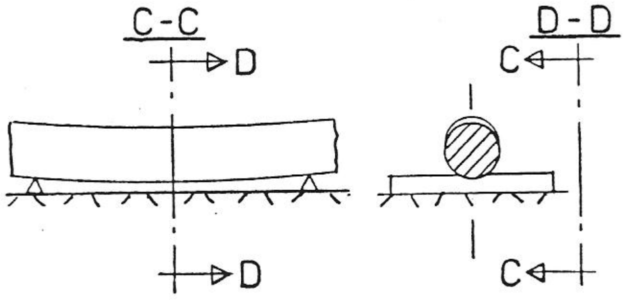


Fig 18



6. Strategy for the drilling.

To know as early as possible that the hole will be useful for its purpose, an initial measurement is undertaken when the hole is 60-75 metres deep, preferably in connection with a break or change of work shift.

One and a half or two hours later - even out in the bush - the film can be developed and evaluated. The basis for decision is complete and contains:

a) hole situation
b) forecast on depth situation
c) dip and direction for an eventuel new hole
d) if arc drilling: orientation and length of arc drilling in consideration of expected deviation in following standard drilling.

The correct decided steps follow, and when the hole is 50-75 m from a predetermined depth, the final measurement is made. One need, in fact, not wait for full hole depth, because the prognostication error at 75 m extrapolation can be ignored.

An important advantage with an early measurement is that an eventuel arc drilling will be short, usually less than 10-15 metres, and the costs, thus, on a low level.

The risk that the hole will be useless for its purpose is eliminated.

Following pages content figures and formulae, a description of line of action and a numerical example.

7. Figures and formulae.

A check measurement at an early stage of drilling as a base for a forecast of depth situation opens a possibility to correct dip and direction of the hole to reach the goal area.

:0 Legend.

Points: (metre) fig 21, 26, 28

P_c	collar
P_g	goal area
P_o	zero point of prognostication
P_1-P_5	prognostication base
P_4+ 3m	end point of check measurement
P_a	fictious centre of bore hole curvature from P_o to P_4
P_b	centre of curvature drilling
P_e	end point of curvature drilling
P'_a	fictious centre of bore hole curvature from P_e against P_g
P'	prognosticated point a distance P_4P_g from P_o
P''	prognosticated point a distance P_4P_g from P_e
P_n	any point in the bore hole

Hole depths: (metre)

D_n	depth from collar P_c to P_n
d_n	depth from P_o to P_n

Coordinates and deviations: (metre and gon) fig 19

X_n, Y_n, Z_n	coordinates of P_n
Δx, Δy, Δz	coordinate differences
h	the resultant to Δx and Δy
X'_n	horizontal distance from a given reference point projected on the A-plane in the reference point
Y'_n	side deviation i.e. the distance from P_n to the A-plane
Z'_n	dip deviation i.e. the distance from P_n to the I-plane
ω_n, s_n	the polar equivalent to the rectangular Y'_n and Z'_n

Constants: (see p. 30 :221) fig 21

q	extrapolation factor
ρ	radian (200:π for gon and 180:π for degree)

Angles: (gon) fig 19, 26, 27, 28

A_c	direction. i.e. the vertical plane through the azimuth in P_c
I_c	dip i.e. the slant plane through P_c (right angle to A_c-plane)
T_c	the tangent to the hole in P_c (line of intersection A_c and I_c)
A_n, I_n, T_n	do. at P_n
ε_n	angle difference $(T_n - T_o)$
B_1	centre angle at P_b between P_4 and P_g
B_2	do. between P_e and P_g
G	the angle between T_4 and P_4P_g
ω	arc tan Y′:Z′
(ω)	slanting plane of ε

Radii: (metre, exception r_o kilometre) fig 21, 22, 26, 27, 28

R	radius as a function of hole depth and fictious centre angle
r	radius as a function of hole depth and deviation

Exponent of curvature: (dimensionless) fig 22, 23, 24

k_o	primary exponent, a function of P_o, P_4 and P_5
e	correction value, a function of r_o
k′	$(k_o + e)$ is secondary exponent of curvature
f	correction value, a function of k_o, k′, r_o and hole depth d
k_n	(k′ + f) is real exponent of curvature at P_n

Distances: (metre) fig 27

a′	the distance P_4P_g
b′	the arc P_4P_e
c′	the distance P_bP_g

Observations in the measurement film: (centigon) fig 20

α, β, γ	dip observations
δ	discrepancies in dip observations
a, b, c	side observations
d	discrepancies in side observations

:1 Figures.

:11 Deviations.

Calculation of deviation.

XYZ-coordinates yield a regional system, the collar is $X_cY_cZ_c$. $X'Y'Z'$-coordinates yield a local system of the bore hole usually with the collar in origo and the azimuth plane A_c coinciding with the vertical plane through $Y' = 0$. X' is the horizontal distance from the collar projected on the azimuth plane A_c. Y' is the side deviation, positive to the right, negative to the left of the A_c-plane. Z' is the dip deviation, positive above and negative under the inclination plane I_c.

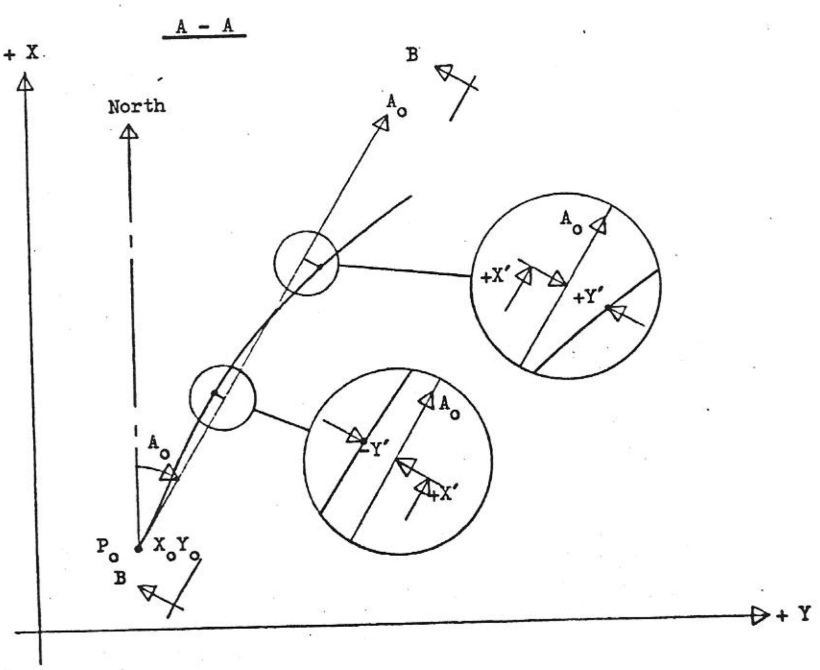
The deviations, however, can refer to any point P_o and its azimuth A_o and dip I_o.

Horizontal projection A - A, fig 19 a.

$$X' = (X - X_o)\cos A_o + (Y - Y_o)\sin A_o \quad . \quad . \quad . \quad . \qquad (1.1)$$

$$Y' = (Y - Y_o)\cos A_o - (X - X_o)\sin A_o \quad . \quad . \quad . \quad . \qquad (1.2)$$

Fig 19 a



Vertical projection B - B, fig 19 b.

$$Z' = X'\sin I_o \pm (Z - Z_o)\cos I_o \quad \ldots\ldots \quad (1.3)$$

The positive sign is used when Z is positive upwards and the negative one when Z is positive downwards.

Fig 19 b

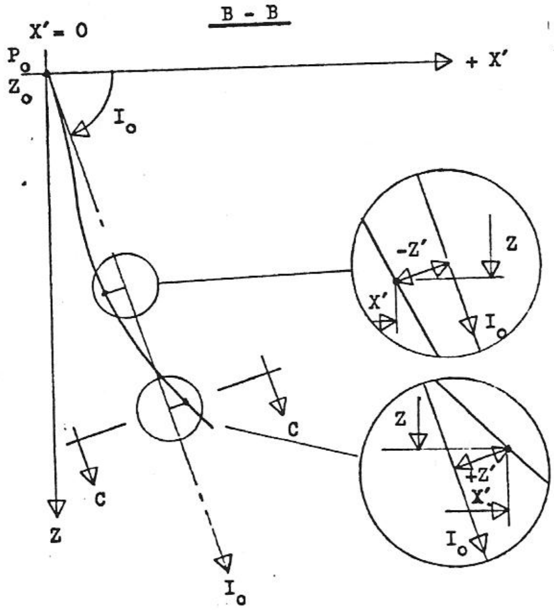
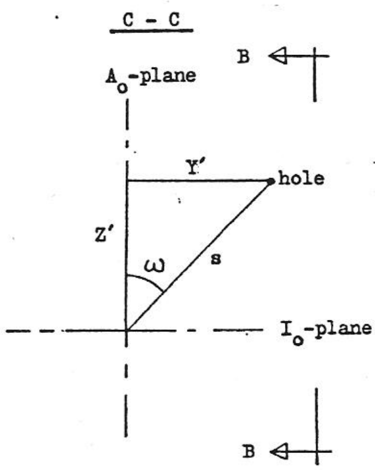


Fig 19 c



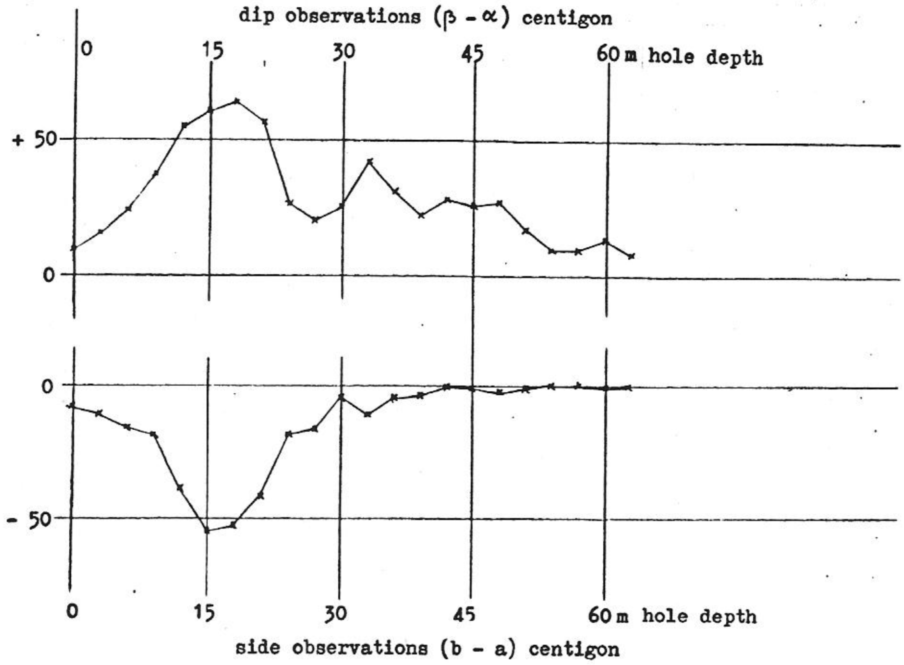
Cross section, C - C, fig 19 c.

Convert from rectangular to polar coordinates:

$$\begin{matrix} Y' \\ Z' \end{matrix} R \rightarrow P \begin{matrix} \omega \\ s \end{matrix} \quad \ldots\ldots \quad (1.4)$$

:12 Basis of prognostication.

Fig 20 (hole No. 8445)



see p 40.

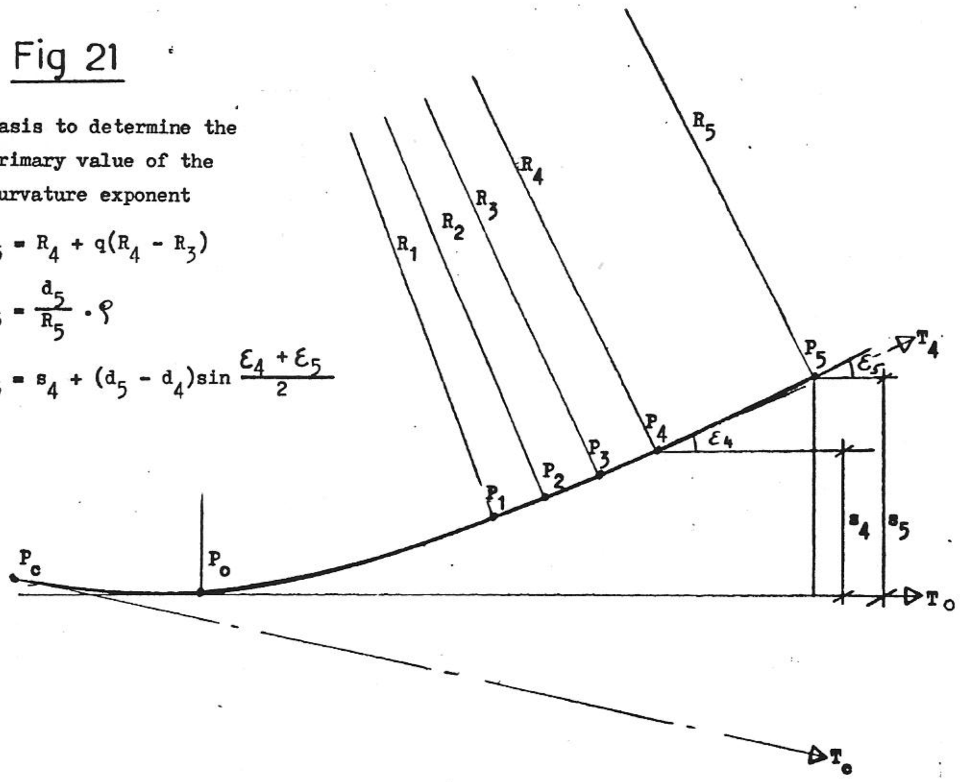
Fig 21

Basis to determine the primary value of the curvature exponent

$$R_5 = R_4 + q(R_4 - R_3)$$

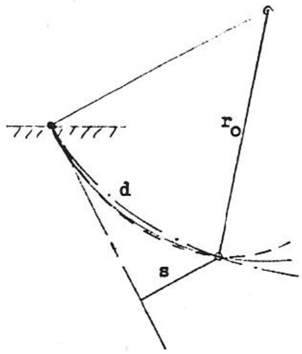
$$\varepsilon_5 = \frac{d_5}{R_5} \cdot \rho$$

$$s_5 = s_4 + (d_5 - d_4)\sin \frac{\varepsilon_4 + \varepsilon_5}{2}$$



:13 Curvature exponent.

Fig 22 Nominel radius of curvature, r_o



$$r_o = \frac{d_4^{\,2}}{2s_4} \cdot 10^{-3} \text{ km}$$

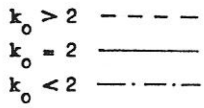


Fig 23 Correction value e

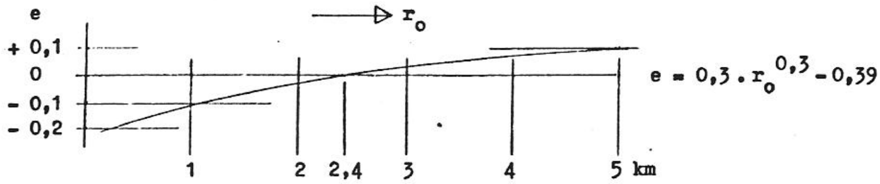
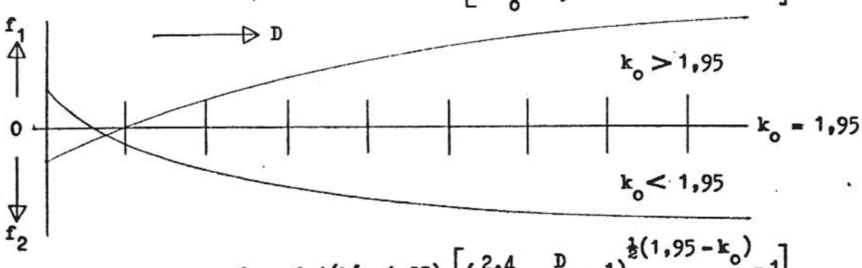


Fig 24 Correction value f

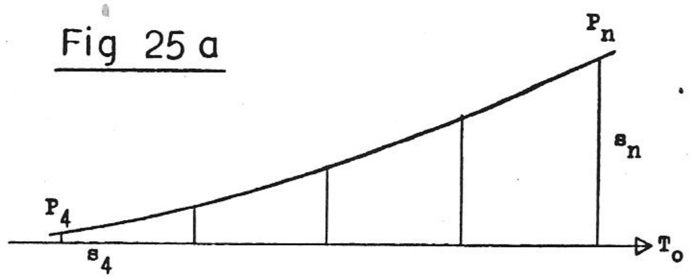
$$f_1 = 0{,}1(2k' - 0{,}9)\left[\left(\frac{2{,}4}{r_o}\cdot\frac{D}{50} - 1\right)^{(1{,}95 - k_o)} - 1\right]$$



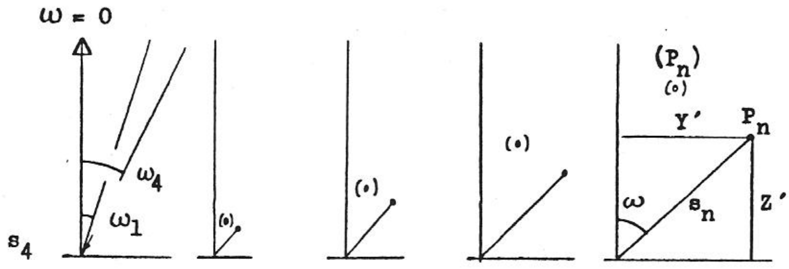
$$f_2 = 0{,}1(k' + 1{,}05)\left[\left(\frac{2{,}4}{r_o}\cdot\frac{D}{50} - 1\right)^{\frac{1}{2}(1{,}95 - k_o)} - 1\right]$$

:14 Prognostication..

Fig 25 a



$$s_n = s_4\left(\frac{d_n}{d_4}\right)^{k_n}$$



$$\omega_n = \omega_4 + (\omega_4 - \omega_1)\sqrt{\frac{d_n - d_4}{d_4}}$$

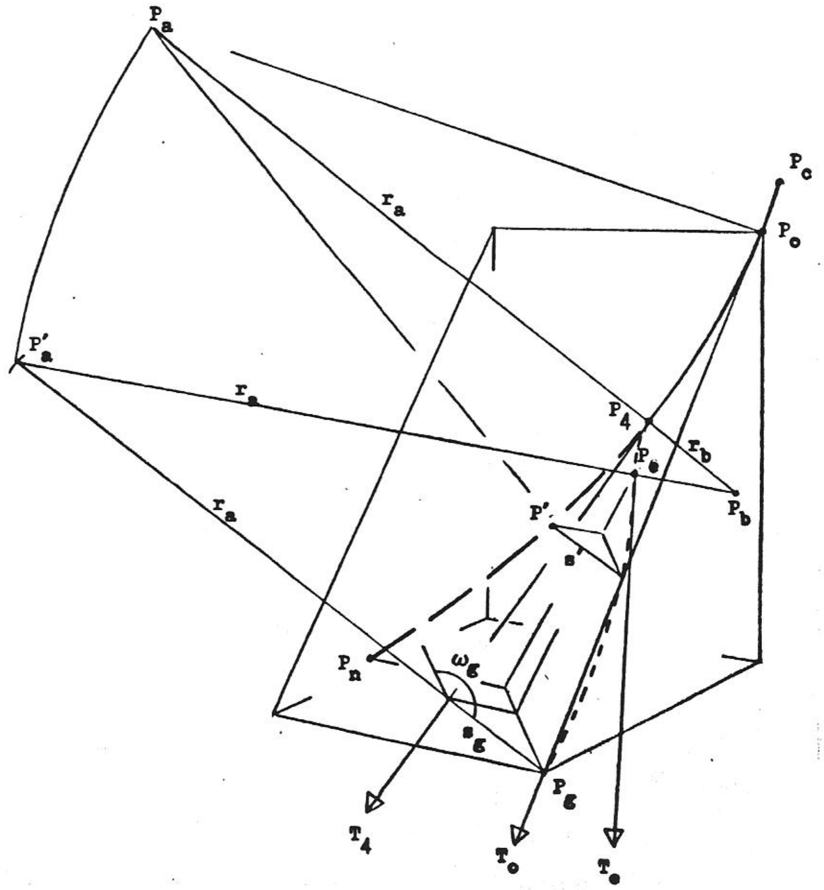
(•) is a prognosticated situation in a stable plane of curvature

• is a prognosticated situation in a bulging plane of curvature

Fig 25 b

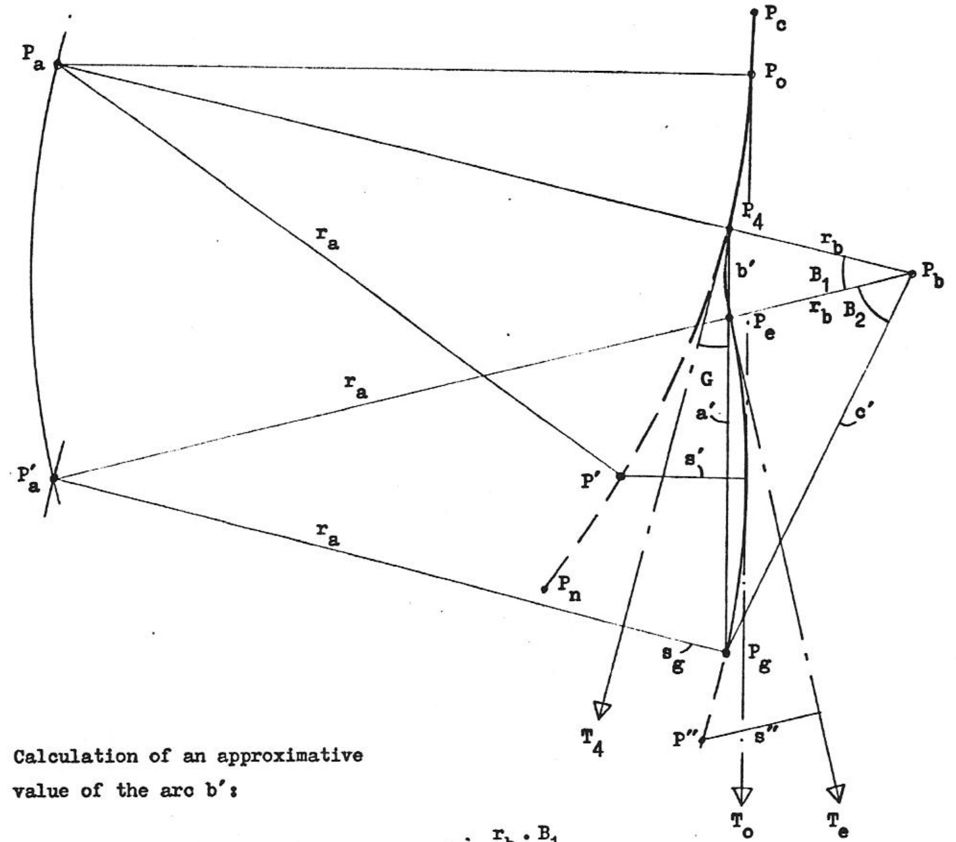
:15 Correction drilling.

Fig 26



In the block diagram the dip of the correction drilling plane is ω_g gon.
The angle ω_g is situated in a plane at right angle to the tangent T_4. It is positive clockwise and negative anti-clockwise from the vertical plane through T_4 and has its zero point in zenith.
r_a is a fictious radius for the arc P_oP'. The length of the arc is equivalent to P_4P_g.
r_b is the radius of the correction drilling.
P_b is the centre of the arc $P_aP'_a$.

Fig 27 Correction drilling plane ω_g



Calculation of an approximative value of the arc b':

$$P_oP' = P_eP'' = P_4P_g = a' \approx d' \qquad b' = \frac{r_b \cdot B_1}{\varrho}$$

$$s' = s_4\left(\frac{d'}{d_4}\right)^{k_{P'}} \qquad r_a = \frac{d'^2}{2\,s'}$$

$$a' = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} \qquad G = \arcsin \frac{s_g}{a'}$$

$$c' = \sqrt{a'^2 + r_b^2 - 2\,a' r_b \sin G}$$

$$(B_1 + B_2) = \arcsin \frac{a' \cos G}{c'} \qquad B_2 = \arccos \frac{r_b^2 + 2\,r_a + c'^2}{2c'(r_a + r_b)}$$

A check measurement in order to get the real radius of curvature r_b can be accomplished after drilling of 3/4 of b'. The new value of r_b is used for better determination of b'.

8. Calculation formulae.

Notations of formulae are printed also in the comments and in the numerical example.

:01 The goal point P_g, polar to rectangular transformation:

$$\begin{matrix} I_c \\ D_g \end{matrix} \; P \text{---} R \; \begin{matrix} \Delta z \\ h \end{matrix} \qquad - \quad - \qquad (0.11)$$

$$\begin{matrix} A_c \\ h \end{matrix} \; P \text{---} R \; \begin{matrix} \Delta y \\ \Delta x \end{matrix} \qquad - \quad - \qquad (0.12)$$

$$X_g = X_c + \Delta x \qquad - \quad - \qquad (0.13)$$

$$Y_g = Y_c + \Delta y \qquad - \quad - \qquad (0.14)$$

$$Z_g = Z_c + \Delta z \qquad - \quad - \qquad (0.15)$$

:1 Hole deviation fig 19 a-c.

$$X' = (X - X_o)\cos A_o + (Y - Y_o)\sin A_o \qquad - \quad - \qquad (1.1)$$

$$Y' = (Y - Y_o)\cos A_o - (X - X_o)\sin A_o \qquad - \quad - \qquad (1.2)$$

$$Z' = X'\sin I_o \pm (Z - Z_o)\cos I_o \qquad - \quad - \qquad (1.3)$$

plus

$$\begin{matrix} Y' \\ Z' \end{matrix} \; R \text{---} P \; \begin{matrix} \omega \\ s \end{matrix} \qquad - \quad - \qquad (1.4)$$

:2 Prognostication basis, fig 20-21.

$$\begin{matrix} \tan (A_n - A_o)\cos I_n \\ \tan (I_o - I_n) \end{matrix} \; R \text{---} P \; \begin{matrix} (\omega)_n \\ \tan \varepsilon_n \end{matrix} \qquad - \quad - \qquad (2.11)$$

$$R = \frac{d}{\varepsilon} \cdot \varrho \qquad - \quad - \qquad (2.12)$$

$$R_5 = R_4 + q(R_4 - R_3) \quad (\text{se} \quad 30{:}221) \qquad - \quad - \qquad (2.21)$$

$$\varepsilon_5 = \frac{d_5}{R_5} \cdot \varrho \qquad - \quad - \qquad (2.22)$$

$$s_5 = s_4 + (d_5 - d_4)\sin \frac{\varepsilon_4 + \varepsilon_5}{2} \qquad - \quad - \qquad (2.23)$$

:3 Curvature exponent, fig 22-24.

$$k_n = k_o + e + f \qquad - \quad - \qquad (3.0)$$

$$k_o = \frac{\ln \frac{s_5}{s_4}}{\ln \frac{4}{3}} \qquad - \quad - \qquad (3.1)$$

$$r_o = \frac{d_4^{\,2}}{2\,s_4} \cdot 10^{-3}\ \text{km} \qquad - \quad - \qquad (3.11)$$

$$e = 0{,}3 \cdot r_o^{\,0{,}3} - 0{,}39 \qquad - \quad - \qquad (3.12)$$

$$k' = k_o + e \qquad - \quad - \qquad (3.121)$$

$$k_n = k' + f \qquad - \quad - \qquad (3.13)$$

$f = f_1$ if k_o 1,95:

$$k_n = k' + 0{,}1(2k' - 0{,}9)\left[\left(\frac{2{,}4}{r_o} \cdot \frac{d_n}{50} - 1\right)^{(1{,}95 - k_o)} - 1\right] \qquad (3.131)$$

$f = f_2$ if k_o 1,95:

$$k_n = k' + 0{,}1(k' + 1{,}05)\left[\left(\frac{2{,}4}{r_o} \cdot \frac{d_n}{50} - 1\right)^{\frac{1}{2}(1{,}95 - k_o)} - 1\right] \qquad (3.132)$$

:4 Prognostications.

:41 Deviations.

$$s_n = s_4\left(\frac{d_n}{d_4}\right)^{k_n} \qquad - \quad - \qquad (4.11)$$

$$\omega_n = \omega_4 + (\omega_4 - \omega_1)\sqrt{\frac{d_n - d_4}{d_4}} \qquad - \quad - \qquad (4.12)$$

$$\begin{matrix}\omega_n \\ s_n\end{matrix} \quad P \text{ --- } R \quad \begin{matrix}Y'_n \\ Z'_n\end{matrix} \qquad - \quad - \qquad (4.13)$$

:42 Situation.

$$X' = Z'\sin I_o + \cos I_o\sqrt{d_n^{\,2} - s_n^{\,2} \cdot \frac{4}{3}} \qquad - \quad - \qquad (4.21)$$

$$X_n = X_o + X'\cos A_o - Y'\sin A_o \qquad - \quad - \qquad (4.22)$$

$$Y_n = Y_o + Y'\cos A_o + X'\sin A_o \qquad - \quad - \qquad (4.23)$$

$$Z_n = Z_o \mp \frac{X'\sin I_o - Z'}{\cos I_o} \qquad - \quad - \qquad (4.24)$$

Minus sign when Z is positive up and vice versa.

Dip angle I = 0 horizontel and always positiv down.

:43 The deviation in relation to the collar has to be calculated according to (1.1) - (1.4).

:5 Correction drilling, fig 26-27.

$$b' = \frac{r_b \cdot B_1}{\varrho} \qquad - \quad - \qquad (5.1)$$

$$s' = s_4 \cdot \left(\frac{d'}{d_4}\right)^{k_{p'}} \qquad - \quad - \qquad (4.11)$$

$$r_a = \frac{d'^2}{2\, s'} \qquad - \quad - \qquad (5.21)$$

$$a' = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} \qquad - \quad - \qquad (5.22)$$

$$G = \arcsin \frac{s_g}{a'} \qquad - \quad - \qquad (5.23)$$

$$c' = \sqrt{a'^2 + r_b^2 - 2\, a' r_b \sin G} \qquad - \quad - \qquad (5.24)$$

$$(B_1 + B_2) = \arcsin \frac{a' \cos G}{c'} \qquad - \quad - \qquad (5.25)$$

$$B_2 = \arccos \frac{r_b^2 + 2\, r_a r_b + c'^2}{2\, c'(r_a + r_b)} \qquad - \quad - \qquad (5.26)$$

$$B_1 = \arcsin \frac{a' \cos G}{c'} - \arccos \frac{r_b^2 + 2\, r_a r_b + c'^2}{2\, c'(r_a + r_b)} \qquad (5.27)$$

9. Explanations and comments to the formulae.

:01 Measurement with the Reflex-Fotobor camera.

The measurement is a usual 3 m interval. Two variations occur. The first when the hole is at least 66 m deep and the second when the hole is 90-100 m. In both cases no overburden is included.

The earlier information in the first case is got with a disregard for the precision in the prognostication.

:02 Evaluation of the measurement.

To the usual start data must be added the depth to the goal P_g or coordinates of P_g.

Evaluation of the measurement film is made as usual. The discrepancies δ and d should be shown and compared to a limit value e.g. 2,5 centigon. If the limit value is exceeded the computer will ask for a check.

It is an advantage to show the angles $(\beta - \alpha)$ and $(b - a)$ in a diagram and a table, fig 20 and p. 40.

:021 The situation of P_o, fig 21.

If possible choose a favourable position of P_o e.g. in the beginning of a calm part of the hole. P_o should be situated at least 9-12 m preferably 15-18 m into solid rock.

P_4 must not be deeper than the 6 m reflex ring in the deepest camera position.

:0211 Case No. 1 with P_4 54 m from P_o.

If the hole 66 m, P_o must not be placed deeper than 9 m. A normal depth is 18 m.

:0212 Case No. 2 with P_4 72 m from P_o.

P_o can be situated between 12 and 24 m into solid rock. A normal depth is 24 m.

:0213 The situation of the basic points from P_o.

point	1st case	2nd case
P_o	0	0
P_1	36	54
P_2	42	60
P_3	48	66
P_4	54	72
P_5	72	96

The position of P_5 from T_o is calculated as an extrapolation on the basis of the previous ones.

:1 Account of result.

In the following description each formula is shown according to p. 26-28.

:11 Bore hole measurement evaluation, p. 40-42.

The position of P_g should be calculated (0.11)-(0.15) and shown in the introduction.

The tables, p. 40, will be printed (with exception of the prognostication).

The deviations (1.1)-(1.4) should be completed with their polar coordinates.

:12 Prognostication and correction drilling.

The computer asks for the position of P_o and P_4, whereupon the prognostication is printed according to the table.

The computer then asks for the radius of curvature drilling if a correction of the hole is likely. The output comprises the orientation of the DEVIBOR, length of curvature drilling and drawings according to fig 28 a-c.

:2 Basis of prognostication, fig 21.

:21 Calculation of P_1 - P_4.

:211 The angle ε, (2.11).

The tangent to the hole in P forms the angle ε to T_o.

:212 The radius R of curvature, (2.12).

The radius R is a function of the hole depth and the angle ε.

The four radii R_1-R_4 and the differences, p. 35 :212, are printed.

A curve of the differences is usually continuous but sometimes the discontinuity is marked.

:22 Calculation of P_5.

The extrapolation of the curve to P_5 has given best result by linear application. An uneven curve calls for common sense. Differential calculation or curve fitting to linear or exponential curve have given irregular results.

:221 The radius R_5, (2.21).

With about linear process of change the value q is 3 in the 1st case and 4 in the 2nd one. Another value can be used in extreme cases.

When the deviation is small and R thus great, the curve often is irregular and vice versa.

In the tables p. 10-12 the value 3 is used in table no. 1 and 4 in the other two.

:222 The angle ε_5, (2.22).

When R_5 has been calculated the angle ε_5 can be determined.

:223 The deviation s_5 of P_5, (2.23).

The deviation of P_5 is got as a sum of s_4 and the extrapolated value in the rise of the curve between P_4 and P_5.

:3 The curvature exponent, (3.0).

The curvature exponent has two basic values and a third variable real value, which depends on the first two ones and the hole depth.

:31 Primary curvature exponent, k_o, (3.1).

The value of k_o depends on the relations between P_o, P_4 and P_5. Its numerical value tells nothing about the hole but its getting straighter if k_o is less than 2 and getting more crooked if k_o is larger than 2.

:311 Nominel radius of curvature, r_o, fig 22, (3.11).

An importent parametre in the real exponent of curvature is the nominel radius of curvature. It is a function of hole depth and deviation of P_4, and is the only parametre expressed in kilometre instead of metre. It shows very clearly the size of the curvature.

:312 Secondary curvature exponent, k', fig 23, (3.12), (3.121).

The difference, e, between real and calculated value of k at different depths of a great number of bore holes dotted in a diagram with r_o along the abscissa and e along the ordinate form a flat curve, which cuts the abscissa at about 2,4 km. The value of e, (3.12) is negative less than 2,4 km and positive above 2,4 km.

:313 Real curvature exponent, k_n, fig 24, (3.13), (3.131), (3.132).

The exponent k_n changes at depth with a value, f, corresponding to a function:

$$y = a(x^b - 1).$$

$f = f_1$ when k_o is bigger than 1,95 and $f = f_2$ when k_o is less than 1,95.

The exponent in the formulae shows that the curve is decreasing in f_1 and increasing i f_2. f is zero when k_o is equivalent to 1,95.

When r_o is larger than 4 km the prognostication is meaningless, as the hole is rather straight.

A new check measurement can be well-founded after 100-200 metre additional drilling.

:4 Prognostication of hole situation.

The prognostication depends on four parametres, the nominel deviation, the hole depth, the curvature exponent and the curvature plane.

:41 The complex deviation, fig 19 c, 25 b.

The deviation is complex as both the size s and the inclination ω of the curvature plane change with increasing depth.

:411 The deviation, s, fig 25 a, (4.11)

The deviation s changes always exponential at depth. That does not prevent inflexion points to occur. If the hole follows something like an arc of a circle the deviation increases with the square of the depth.

:412 The curvature plane, ω, fig 25 b, (4.12).

The curvature plane usually is rather stable. Sometimes there are bulging planes, which mostly change their slant angle, ω, in a regular way often against a stable end value.

:413 The complex deviation, fig 26, (4.13).

After calculation of s and ω the direction and dip deviations can be calculated as a conversion from polar to rectangular coordinates.

:42 Regional coordinate system, (4.21) - (4.24).

From the deviation and the hole depth the regional coordinates can be calculated through coordinate transformation.

:43 The deviation in relation to the collar, fig 19 a-c, (1.1) - (1.4).

Until this point all calculations has been made in relation to P_o and T_o. When the regional coordinates are known the deviation in relation to the collar is easily calculated.

5: Correction drilling, fig 26, 27, 28.

When the forecast shows that the deviation cannot be accepted, the dip and direction of the hole can be changed by use of the DEVIBOR curvature drilling equipment.

A continued drilling would likely be of the same type and curvature as the previous one. Therefore the curvature drilling should not stop at bringing back the hole to the collar dip and direction. The curvature drilling must also overcompensate for the expected deviation after that so the hole can reach the goal area P_g.

:51 Orientation of the DEVIBOR, fig 26.

The position of P_g in relation to P_4 is calculated according to (1.1) - (1.4).

ω_g is the nominal orientation of the DEVIBOR. An adjustment according to (4.12) might be necessary, fig 25.

:52 Length of curvature drilling, fig 27, (5.1) - (5.27).

The probable deviation s" for the distance P_eP'' is calculated approximatly for an assumed hole depth from P_o to P', which corresponds to the distance from P_4 to P_g.

The curvature exponent, $k_{P'}$, at that hole depth is calculated and s' can be determined, (4.11).

When s' is known the fictious radius of curvature r_a can be calculated, (5.21). The triangle $P_4P_gP_b$ has to be solved, (5.22) - (5.25).

The angle B_2 in the triangle $P_bP'_aP_g$ can be calculated with the cosine theorem, (5.26)

At last the length b' of the curvature drilling has to be calculated, (5.1).

10. Dependability.

The value of the forecast increases if it is known how the size and mutual relations of the parametres act on the reliability. As a matter of fact it is possible to determine the dependability by looking at the following conditions.

When the curvature exponent k_0 is big and the radius r_0 small or vice versa the prognostication should be limited to moderate depths.

When at the same time both the exponent and the radius are big or small the forecast will be rather safe, particularly the latter.

The stbility of the curvature plane is an unsafe factor. However, the stability regularly is reliable at small radii e.g. when the deviation is big. If the size s of the deviation is correct, but the dip of the curvature plane has changed an angle v, the error will be the product of s and v divided by ρ. If s is very erronious the change of the plane will act very little on the result. An example: if s is half or twice the forecast, the error increases less than 10 % up to a change of the plane of 20 gon.

There is no case in this investigation where the practical result of a prognostication would have been useless.

The deviation usually is big when the rock is stratified and the hole cuts obliquely through the layers. In folded sedimentary rock, often stratified, the curvature plane can be changed, and the forecast thus deteriorated. When the hole is finished, a measurement exposes a prognostication error that obviously is a consequence of a change in dip and direction of the layers. Combined with a look at the cores better knowlidge of the tectonic can be the result.

It is peculiar that irrespective of an accurate or an erronious forecast the information will be valuable in such a kind of rock. And, as a fact, just in that kind of rock almost all ores are situated.

The first hole in unknown rock can be straight or crooked in any direction. Even in known rock surprises are common. An early measurement sets aside an unpleasent surprise.

An infallible method to indicate the dip and direction of the layers is to put in a system to use the curvature drilling a few metres 30-40 metres before the hole is finished. It is not necessary to orientate the DEVIBOR. The first core in the resumed standard drilling as well as a long one in the curvature can surely be orientated. The continued drilling has indeed a change in dip and direction, however without any practical disadvantage.

11\. : Numerical example, Hole 8445, table 1, p. 10 and 40-42.

:0 The hole is 246 m deep and has deviated up and to the left:

X′	Y′	Z′	ω	s
190,0	- 34,6	64,2	- 31,4	72,9

:01 Check measurement.

The hole should according to the planes go 200 m below the collar. In reality the depth was only 150 m.

If the hole had been checked at 75 m depth the following informations had been obtained.

:02 Evaluation.

Input collar situation. Z is positiv up.

X	Y	Z	I	A
222,04	29,74	1276,99	59,39	200,06

The hole depth to the goal: polar to rectangular transformation,

$$\begin{matrix} 59{,}39 \\ 246 \end{matrix} \quad P - R \quad \begin{matrix} 197{,}62 \\ 146{,}50 \end{matrix} \qquad (0.11)$$

$$\begin{matrix} 200{,}06 \\ 146{,}50 \end{matrix} \quad P - R \quad \begin{matrix} -\ 0{,}14 \\ -\ 146{,}50 \end{matrix} \qquad (0.12)$$

Goal area P_g:

X	Y	Z
75,54	29,60	1079,37

Input of filmdata $\alpha\ \beta\ \gamma$ and a b c. The computer prints a table according to p. 40 and a diagram according to fig 20.

:021 The position of P_o and P_4.

P_o is placed at 18 m and P_4 at 72 m hole depth.

:1 Result.

:11 Coordinates of the hole 0 - 75 metre depth, p 40.

:12 Prognostication positions.

The following sections :2 - :6 show how the results are obtained.

:2 Basis for the prognostication, fig 21.

According to case 1 the basic points are:

P_o	P_1	P_2	P_3	P_4	P_5
18	54	60	66	72	90 m

:21 Extrapolation of P_5.

:211 The angle ε, (2.11).

tan (190,31 - 195,12).cos 47,52	R - P	- 27 (ω)
tan (55,25 - 47,52)		tan 8,49 ε_1

:212 The radius of curvature R_1, (2.12)

$$R_1 = \frac{36}{8,48} \cdot 63,66 = 270,2 \text{ m}$$

The other radii are calculated in a similar way:

point	D	ε	R	difference
P_1	54	8,48	270,2	
				33,0
P_2	60	8,82	303,1	
				26,0
P_3	66	9,29	329,1	
				26,1
P_4	72	9,68	355,2	

:22 Extrapolation to P_5.

:221 Radius R_5, (2.21).

$$R_5 = 355,2 + 3 \cdot 26,1 = 433,6 \text{ m}$$

:222 The angle ε_5, (2.22).

$$\varepsilon_5 = \frac{90-18}{433,6} \cdot 63,66 = 10,57 \text{ gon}$$

:223 The deviation s_5 at P_5. s_4 is 5,23 m.

18 m extrapolation from P_4: (2.23)

$$s_5 = 5,23 + 18 \cdot \sin \frac{9,68 + 10,57}{2} = 8,08 \text{ m (real value 8,13 m)}$$

:3 The curvature exponent, k_n, (3.0).

:31 The primary value, k_o, (3.1).

$$k_o = \frac{\ln \frac{8,08}{5,23}}{\ln \frac{4}{3}} = 1,513$$

:311 Nominel radius of curvature r_o, fig 22, (3.11).

$$r_o = \frac{(72 - 18)^2}{2 \cdot 5,23} \cdot 10^{-3} = 0,279 \text{ km}$$

:312 The secondary value, k', fig 23, (3.12), (3.121).

$$k' = 1,513 + 0,3 \cdot 0,279^{0,3} - 0,39 = 1,328$$

:313 The real value, k_n, fig 24, (3.13).

As k_o is less than 1,95 the formula of f_2 is used, (3.132)

$$f_2 = 0,1(1,328+1,05)\left[\left(\frac{2,4}{0,279} \cdot \frac{246-18}{50} - 1\right)^{0,5(1,95-1,513)} - 1\right] = 0,289$$

$$k_{246} = 1,328 + 0,289 = 1,617 \quad \text{(real value 1,638)}$$

:4 Prognostication.

:411 The deviation s_{246}, fig 25, (4.11).

$$s_{246} = 5,23 \cdot \frac{246-18}{54}^{1,617} = 53,7 \text{ m} \quad \text{(real value 55,3 m)}$$

:412 The dip of the curvature plane, ω_{246}, fig 25 b, (4,12).

$$\omega_{246} = -30,9 + (-30,9+34,8)\sqrt{\frac{228-54}{54}} = -23,9 \text{ gon} \quad \text{(real value -24,0)}$$

:413 Side and dip deviations, fig 19 c, (4.13).

$$\begin{matrix} \omega & -23,9 \\ s & 53,7 \end{matrix} \; P - R \; \begin{matrix} -19,4 & Y' \\ 50,1 & Z' \end{matrix} \quad \left(\text{real value } \begin{matrix} -24,0 \\ 55,3 \end{matrix} \; P - R \; \begin{matrix} -20,4 \\ 51,4 \end{matrix}\right)$$

:42 The situation in the regional coordinate system.

:421 The horizontal distance X', (4.21). (approx)

$$X' = \cos 55{,}25 \sqrt{(246-18)^2 - 53{,}7^2 \cdot \frac{4}{3}} + 50{,}1 \sin 55{,}25 = 180{,}1 \text{ m}$$

(real value 181,2 m)

:422 The X situation, (4.22).

$$X = 211{,}09 + 180{,}1 \cos 195{,}12 + 19{,}4 \sin 195{,}12 = 33{,}0 \text{ m}$$

(real value = 32,0 m)

:423 The Y situation, (4.23).

$$Y = 29{,}96 - 19{,}4 \cos 195{,}12 + 180{,}1 \sin 195{,}12 = 63{,}1 \text{ m}$$

(real value = 64,1 m)

:424 The Z situation, (4.24).

$$Z = 1262{,}71 - \frac{180{,}1 \sin 55{,}25 - 50{,}1}{\cos 55{,}25} = 1127{,}7 \text{ m}$$

(real value = 1128,4 m)

:43 The deviation in relation to the collar.

:431 The horizontal distance X', (1.1).

$$X' = (33{,}0-222{,}04)\cos 200{,}06 + (63{,}1-29{,}74)\sin 200{,}06 = 189{,}0 \text{ m}$$

(real value = 190,0 m)

:432 The side deviation Y', (1.2).

$$Y' = (63{,}1-29{,}74)\cos 200{,}06 - (33{,}0-222{,}04)\sin 200{,}06 = -33{,}5 \text{ m}$$

(real value = - 34,6 m)

:433 The dip deviation Z', (1.3).

$$Z' = X'\sin 59{,}39 + (1127{,}7-1276{,}99)\cos 59{,}39 = 62{,}9 \text{ m}$$

(real value = 64,2 m)

:434 Polar coordinates corresponding to Y' and Z', (1.4).

$$\begin{matrix} Y' & -33{,}5 \\ Z' & 62{,}9 \end{matrix} \; R - P \; \begin{matrix} -31{,}2 & \omega \\ 71{,}3 & s \end{matrix}$$

(real value = - 31,4 gon)
(real value = 72,9 m)

:5 Correction drilling.

:50 Orientation of the DEVIBOR, fig 26.

The position of P_g in relation to P_4.

:501 The horizontal distance X', (1.1).

$$X' = (75,54-173,15)\cos 190,03 + (29,60-35,32)\sin 190,03 = 95,49 \text{ m}$$

:502 The side deviation Y', (1.2).

$$Y' = (29,60-35,32)\cos 190,03 - (75,54-173,15)\sin 190,03 = 20,87 \text{ m}$$

:503 The dip deviation Z', (1.3).

$$Z' = X'\sin 46,33 + (1079,37-1224,73)\cos 46,33 = -45,01 \text{ m}$$

:504 Polar coordinates corresponding to Y' and Z', (1.4).

$$\begin{matrix} Y' & 20,87 \\ Z' & -45,01 \end{matrix} \quad R - P \quad \begin{matrix} 172,36 & \omega \\ 49,62 & s_g \end{matrix}$$

P_g is situated about 50 m down to the right of the tangent to the hole in P_4.
The DEVIBOR has to be orientated so that its curvature plane coincides with ω_g. According to :412 the prognostication shows a twist to the right. The orientation is thus corrected to 165 gon.

:51 The length of the curvature drilling, fig 27.

The curvature drilling starts in the hole depth 75 m and is orientated in the curvature plane 165 gon. The curvature radius is about 100 metres. The following standard drilling is about 174 metres.

The curvature exponent k_{174} is $k' + f_2$, (3.132).

$$k_{174} = 1,328 + 0,1(1,328+1,05)\left[\left(\frac{2,4}{0,279}\cdot\frac{174}{50} - 1\right)^{0,5(1,95-1,513)} - 1\right]$$

$$k_{174} = 1,586$$

the deviation $s' = s_{174}$. (4.11).

$$s_{174} = 5,23 \cdot \left(\frac{174}{54}\right)^{1,586} = 33,46 \text{ m}$$

Fictious curvature radius r_a for the standard drilling: (5.21)

$$r_a = \frac{174^2}{2 \cdot 33,4} = 452,4 \text{ m}$$

:522 The distance a′ from P_4 to P_g, (5.22).

$$a' = \sqrt{(173,15-75,54)^2 + (35,32-29,60)^2 + (1224,73-1079,37)^2} = 175,2 \text{ m}$$

:523 The angle G between T_4 and P_4P_g, (5.23).

$$G = \text{arc sin} \frac{49,62}{175,2} = 18,28 \text{ gon}$$

:524 The distance c′ from P_b to P_g, (5.24).

$$c' = \sqrt{175,2^2 + 100^2 - 2 \cdot 175,2 \cdot 100 \cdot \sin 18,28} = 175,4 \text{ m}$$

:525 The angle $(B_1 - B_2)$ between P_bP_g and P_bP_4, (5.25).

$$B_1 + B_2 = \text{arc sin} \frac{175,2 \cos 18,28}{175,4} = 81,45 \text{ gon}$$

:526 The angle B_2 between P_bP_g and $P_bP'_a$, (5.26).

$$B_2 = \text{arc cos} \frac{100^2 + 2 \cdot 100 \cdot 452,4 + 175,4^2}{2 \cdot 175,4(100 + 452,4)} = 52,63 \text{ gon}$$

:527 The angle B_1, (5.27).

$$B_1 = 81,45 - 52,63 = 28,82 \text{ gon}$$

:51 The length of the curvature drilling b′, (5.1).

$$b' = \frac{100 \cdot 28,82}{63,66} = 45,3 \text{ m}$$ say 45 m

Remaining standard correction drilling is 175 - 45 = 130 m.

:6 Check with a better value of P_oP', changed to 130 m:

k_{130} = 1,328 + 0,226 = 1,554

s = 20,48 m

r_a = 412,5 m

B_1 = 29,5 gon

b′ = 46,4 m

Hole No. 8445, observations in the measurement film, centigon.

depth	dip observations α	β	γ	δ	side observations a	b	c	d
0	5	14	28		- 12	- 21	- 35	
3	5	20	42	- 1	- 15	- 26	- 40	4
6	12	36	-	- 1	- 11	- 27	-	0
9	26	64	-		- 14	- 33	-	
12	50	-	-		- 24	-	-	
15	62	-	-		- 55	-	-	
18	61	-	-		- 57	-	-	
21	68	-	-		- 48	-	-	
24	44	70	-		- 36	- 55	-	
27	22	42	-		- 22	- 38	-	
30	17	42	-		- 17	- 22	-	
33	41	84	-		- 12	- 24	-	
36	46	77	-		- 20	- 26	-	
39	30	52	-		- 15	- 19	-	
42	17	45	-		- 9	- 10	-	
45	29	55	-		- 5	- 7	-	
48	31	58	-		- 7	- 10	-	
51	26	42	55		- 5	- 7	- 9	
54	16	25	34	- 2	- 11	- 11	- 11	1
57	6	15	27	0	1	1	- 5	0
60	12	25	36	0	0	- 6	- 7	2
63	21	29	36	- 1	0	- 1	- 3	- 2
66	13	20	30	0	- 4	- 7	- 10	0

Hole situation to 75 m (camera lens in 66 m). Prognostication to 246 m depth.

point	depth	X	X'	Y	Y'	Z	Z'	I	s	A	ω
P_c	0	222,04		29,74		1276,99		59,39		200,06	
	3	220,25		29,74		1274,58		59,19		199,61	
	6	218,46		29,75		1272,18		58,88		199,21	
	9	216,65		29,77		1269,78		58,39		198,67	
	12	214,83		29,81		1267,40		57,63		198,08	
	15	212,98		29,86		1265,04		56,50		196,83	
P_o	18	211,09		29,96		1262,71		55,25		195,12	
	21	209,15		30,10		1260,42		53,94		193,56	
	24	207,18		30,31		1258,17		52,81		192,32	
	27	205,17		30,50		1255,96		52,29		191,77	
	30	203,14		30,81		1253,76		51,88		191,30	
			18,90		- 1,06		1,35		1,72		- 42
	33	201,10		31,09		1251,58		51,38		191,16	
	36	199,05		31,38		1249,41		50,52		190,82	
	39	196,97		31,68		1247,28		49,90		190,64	
	42	194,86		31,99		1245,16		49,46		190,53	
	45	192,75		32,21		1243,05		48,90		190,50	
	48	190,61		32,63		1240,97		48,38		190,45	
	51	188,46		32,96		1238,90		47,85		190,38	
P_1	54	186,30		33,29		1236,85		47,52		190,31	
	57	184,10		33,62		1234,82		47,34		190,33	
P_2	60	181,94		33,96		1232,79		47,16		190,31	
			40,10		- 4,25		5,89		7,26		- 39
	63	179,75		34,29		1230,76		46,87		190,20	
P_3	66	177,55		34,63		1228,75		46,70		190,19	
	69	175,35		34,98		1226,74		46,50		190,13	
P_4	72	173,15		35,32		1224,73		46,33		190,03	
	75	170,93		35,67		1222,74					
Prognostication P_5	90	159,9	62,2	37,4	- 7,7	1212,9	11,8		14,1		- 37
	150	113,4	108,6	45,7	- 16,1	1176,2	27,2		31,6		- 34
	210	64,1	157,9	56,0	- 26,5	1144,2	47,8		54,7		- 32
	246	33,0	189,0	63,1	- 33,5	1127,7	62,9		71,3		- 31

Calculation of depth situation, 6 m interval.

depth	X	X'	Y	Y'	Z	Z'	I	s	A	ω
78	168,71		35,03		1220,75		45,74		189,91	
84	164,24		36,74		1216,81		45,16		189,73	
90	159,74		37,48		1212,92		44,59		189,69	
		62,29		- 7,79		11,88		14,21		- 37
96	155,22		38,23		1209,05		44,37		189,51	
102	150,67		38,98		1205,20		44,01		189,43	
108	146,10		39,75		1201,39		43,71		189,40	
114	141,53		40,52		1197,59		43,63		189,44	
120	136,94		41,28		1193,79		43,15		189,21	
		85,09		-11,62		18,81		22,11		- 35
126	132,32		42,08		1190,06		41,52		188,62	
132	127,61		42,94		1186,43		40,88		188,34	
138	122,88		43,82		1182,85		39,92		188,02	
144	118,08		44,74		1179,37		38,17		187,56	
150	113,21		45,72		1176,00		36,95		187,23	
		108,82		-16,07		27,28		31,66		- 34
156	108,28		46,73		1172,74		36,05		187,01	
162	103,32		47,76		1169,53		35,48		186,80	
168	98,33		48,80		1166,36		35,29		186,62	
174	93,34		49,87		1163,21		34,96		186,40	
180	88,33		50,96		1160,08		34,59		186,21	
		133,69		- 21,34		37,78		43,39		- 33
186	83,31		52,08		1156,99		34,01		185,89	
192	78,27		53,22		1153,95		33,46		185,54	
198	73,20		54,38		1150,95		32,94		185,74	
204	68,11		55,54		1147,99		32,36		185,98	
210	62,99		56,69		1145,08		32,14		185,38	
		159,02		-27,08		49,20		56,16		- 32
216	57,88		57,88		1142,19		31,67		185,54	
222	52,73		59,06		1139,34		31,12		185,43	
228	47,58		60,31		1136,53		30,51		184,62	
234	42,40		61,57		1133,77		29,91		185,16	
240	37,20		62,84		1131,07		29,31		184,49	
		184,81		-33,27		61,57		69,98		- 32
246	31,97		64,13		1128,42		28,58		185,14	
		190,04		-34,55		64,19		72,90		- 31

Fig 28 a

Horizontal projection A - A

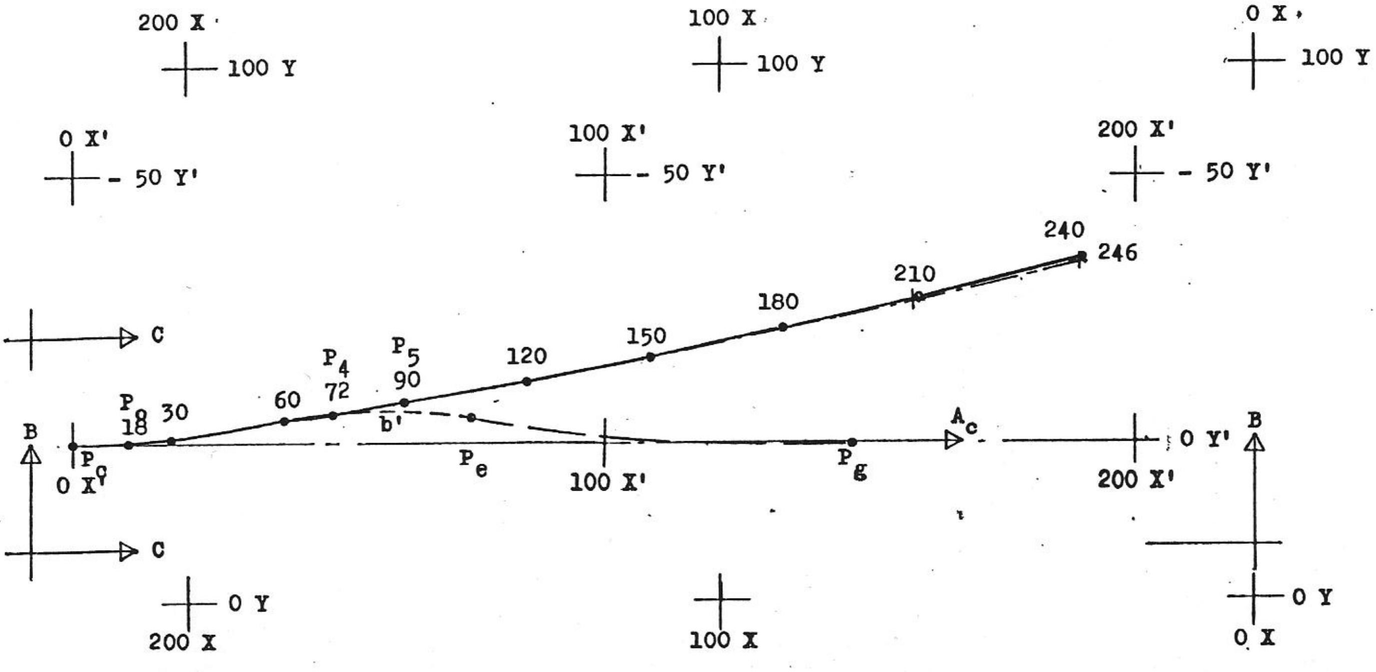
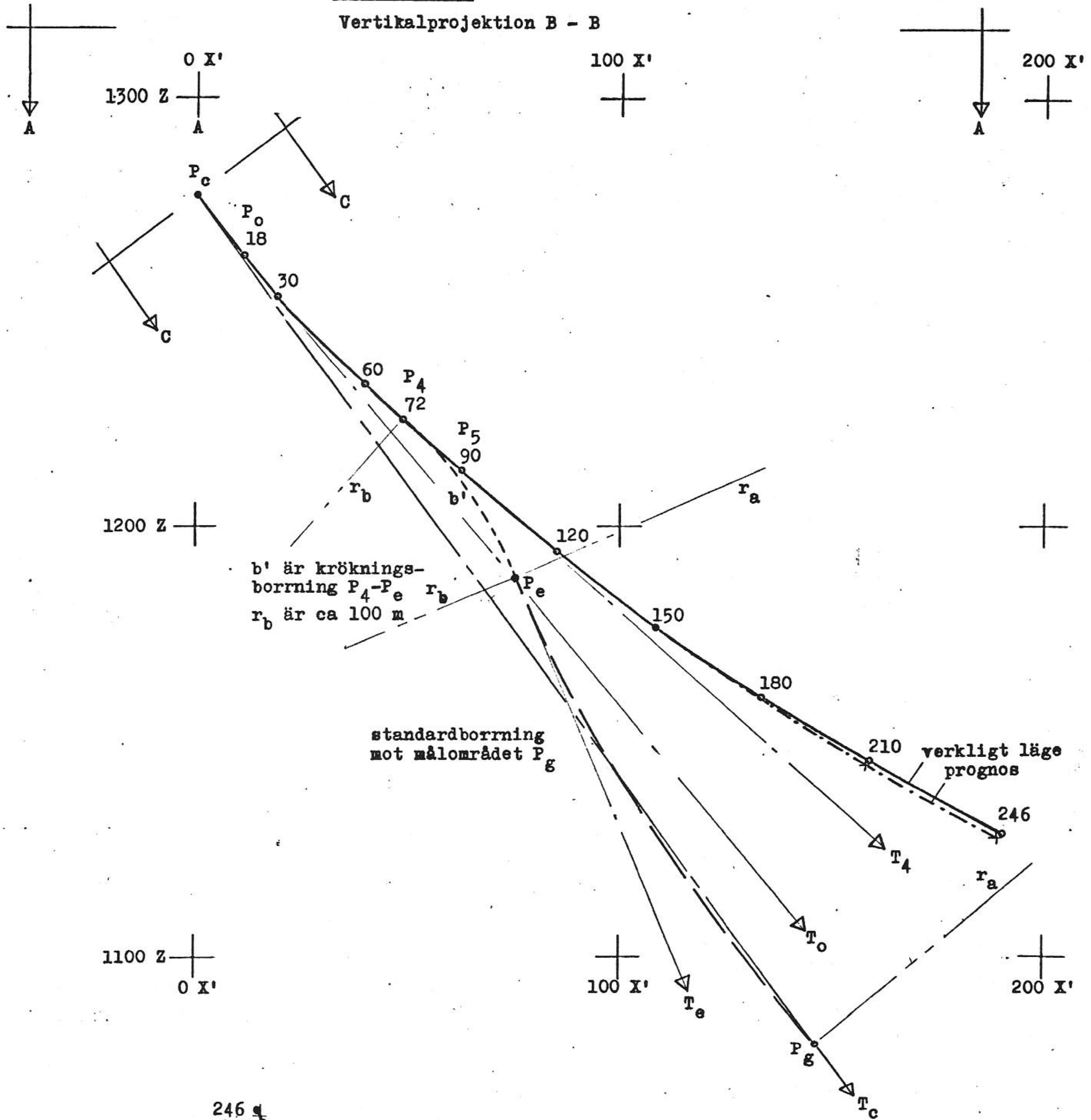


Fig 28 b

Vertikalprojektion B - B



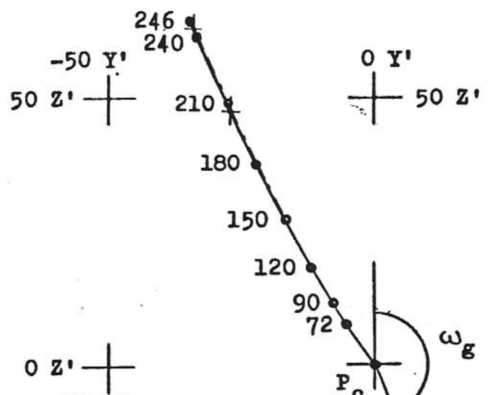


Fig 28 c

Tvärprojektion C - C