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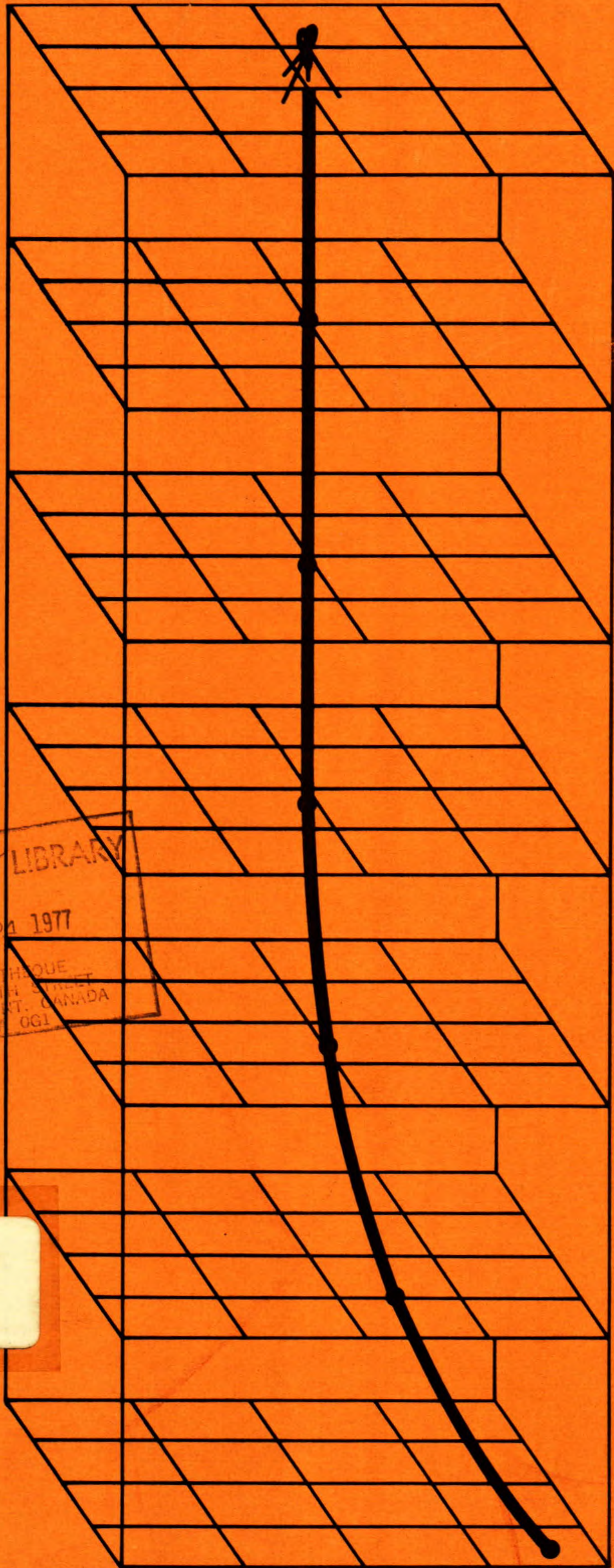

Mining Research Laboratories,
Canada Centre for Mineral
and Energy Technology,
Department of Energy, Mines
and Resources

May 1975

CANMET Monograph 883

Study of Hole Deviation in Diamond Drilling

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Mining Research Centre
Mines Branch
Department of Energy,
Mines and Resources

Study of Hole Deviation in Diamond Drilling

Acres Consulting Services Limited
Niagara Falls, Ontario

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FOREWORD

This study was carried out by Acres Consulting Services Limited, Niagara Falls, under Contract OSP3-0103 of the Department of Supply and Services, Ottawa, for the Mining Research Centre, Mines Branch, Department of Energy, Mines and Resources, Ottawa.

The scientific authority at the Mining Research Centre was Mr. Amil Dubnie to whom the authors express their appreciation for his encouragement and assistance during the course of this study.

The principal authors of the report at Acres Consulting Services Limited were Drs. R. V. Dawson and R. G. Charlwood. Mr. R. Pine also made a significant contribution to the study.

In addition, various other specialists at Acres were consulted, including Drs. O. T. Sigvaldason, R. P. Benson, L. Wolofsky and D. R. McCreath.

D. H. MacDonald
Acres Consulting Services Limited

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1 INTRODUCTION AND SUMMARY

1.1 Introduction

Deep hole drilling is essential to the mineral industry.

Deep-hole drilling to obtain cores is an essential part of both the exploratory and mining development work carried out by the mineral industry. Holes are normally of small diameter (less than 3 inches) and drilled with diamond coring bits. The fact that such holes deviate from their initial path has long been recognized to be a major problem by those involved in diamond drilling (Dames and Moore, 1973). Canada, being a land rich in valuable minerals and ores (Dubnie, 1973), has a special interest in improving the technology of diamond drilling.

Oil and gas industry has developed theories useful in control and prediction of hole deviation.

The oil and gas industry has devoted much effort to research on hole deviation and has developed theories useful in the control and prediction of hole paths. The fact that a hole which strikes a target is the means by which the oil or gas is transported to the surface has justified this expense. In the mineral industry, however, drilling is merely a tool necessary to accurately locate ore, and the major costs of mining development and ore extraction must be borne after drilling has been completed. Some research is carried out by mining companies, drilling equipment manufacturers, drilling contractors etc., but economics generally dictate that this work be a part of the day-to-day operation of these organizations, with the result that a planned program of research is very difficult to undertake. Much of the research and development, then, has to be carried out on a trial and error basis, and conclusions are often limited to drilling in particular locations under specific drilling conditions. Recognizing the need for a more fundamental attack on the problems of hole deviation, the Mines Branch of the Department of Energy, Mines and Resources retained Acres Consulting Services Limited to investigate the theoretical aspects of hole deviation in diamond drilling.

This report describes the work carried out and it identifies areas where further theoretical development and field testing could improve diamond drilling technology.

1.2 Summary

In this report the state of the art of controlling and predicting hole deviation in the diamond drilling industry is assessed.

Theoretical work relating to hole deviation which has been carried out by the oil and gas industry is studied to determine its applicability to diamond drilling. In particular, Lubinski and Wood's equilibrium angle concept is examined.

In core drilling, the presence of a reaming shell close behind the bit implies that an equilibrium angle cannot exist. A new mathematical model which takes into account the reaming shell and permits calculation of the hole profile for an isotropic bit penetrating isotropic ground is developed. It is shown that a continuously curving hole should be expected when core drilling with a reamer. Parametric studies have been carried out using the theoretical reamer model to demonstrate the relative importance of the various factors which could be used for directional control. Bit weight, hole clearance and corebarrel stiffness are the most important and potentially useful variables.

Mechanisms of hole deviation in complex geological conditions are identified and the applicability of theories to various ground conditions is considered.

Data obtained from surveyed drill holes are studied in the light of the theoretical concepts. Experimental and field work necessary to test these concepts are suggested, and recommendations for future research into the problem of hole deviation are made.

2 HOLE DEVIATION – THE EXTENT OF THE PROBLEM

2.1 General

Many contacts made with the diamond drilling industry.

In order to assess the extent of the problem of hole deviation and obtain an up-to-date picture of the technology of diamond drilling, mining companies, drilling contractors, equipment manufacturers and individuals in Canada and United States with an interest in drilling were visited by Acres personnel. Many others were contacted by letter or telephone.

Correspondence took place with organizations in Australia and South Africa. A list of the contacts made during the study is provided in Appendix A.

2.2 Literature Search

The literature search was initiated by obtaining references relevant to the problem from A. Dubnie of the Mining Research Centre in Ottawa. Other sources of information used were the Geotechnical Abstracts, Rock Mechanics Abstracts, and Rock Mechanics KWIC Index reference retrieval systems. The references obtained from these sources led to most of the papers researched during this study.

Publications were obtained from the diamond drilling industry, including Canadian and American equipment manufacturers and drilling contractors.

A search was made for studies at universities and colleges in North America, but little research directly relevant to the problem of drill-hole deviation was found.

The oil and gas industry proved to be the most fruitful source of previous studies. Most of the useful references from this source were obtained from the Drilling and Production Practice volumes of the American Petroleum Institute, World Oil, The Oil and Gas Journal, and the Society of Petroleum Engineers Journal. Some papers were obtained from Russia, mainly through commercial translation services. These references were originally located in the Rock Mechanics KWIC Index.

The Australian Diamond Drillers Association, South African Core Drilling Association, Los Alamos Scientific Laboratory and the U.S. Bureau of Mines also provided papers during the literature search.

2.3 Deviation Control in the Mineral Industry

There are no theoretical techniques for predicting hole deviation in diamond drilling.

At present, no theoretical techniques are available for predicting deviations in drill holes bored with diamond coring bits, and there is no complete explanation of the deviations which do occur. In many areas where there has been much previous drilling, the local experience gained can be used in an empirical manner to predict trends in future holes. It is well known that varying the load on the bit (bit weight) will change the deviation pattern, but this can be quantified only by trial and error.

Deviation is minimized by using sharp bits and limiting penetration rate.

In the mineral industry today, the term "controlled drilling" (Bonsall, 1957) is used when attempts are made to limit deviation in the following ways:

(a) The bit is changed frequently (about every 20 feet) to ensure that a sharp bit is maintained.

(b) The penetration rate is controlled (e.g. on screw feed machines a limit is placed on the gear setting to be used; 500 revolutions per inch is typical for hard rock).

(c) Frequent hole surveys are carried out (e.g. at 100-foot intervals) to ensure that deviations are tolerable.

(d) If deviations are excessive, wedges are placed to force the hole in the required direction. This is a time-consuming, and therefore expensive procedure, and the wedges may result in fatigue failures in the drill string.

Even if hole deviation could be quantified theoretically, the diamond drilling industry would face many problems in the implementation of deviation control theories. Much of the equipment still used in diamond drilling is not sufficiently sophisticated to control bit weight. Moreover, there is great difficulty in finding crews capable of operating even simple drilling equipment, so a major education program would be necessary for the efficient utilization of more complex machines. The bonus system, which often operates in the drilling industry, aggravates the problems as the incentive encourages increased footage rather than improved deviation control.

3 DRILLING EQUIPMENT

3.1 General

The objectives of the oil and gas industry and the mineral industry, when drilling, are not the same, and the development of equipment within each industry has taken place along different lines (Cumming, 1971).

The oil and gas industry normally drills large diameter (5- to 12-inch) holes which can be used for production purposes, and the primary goal is to hit a target area rather than to obtain detailed geological information throughout the length of a hole. Thus, most drilling in the oil and gas industry is non-coring, permitting the use of heavy stiff drill collars immediately behind the bit. Rotary tricone bits are the most common bit design, although non-coring diamond bits are also available.

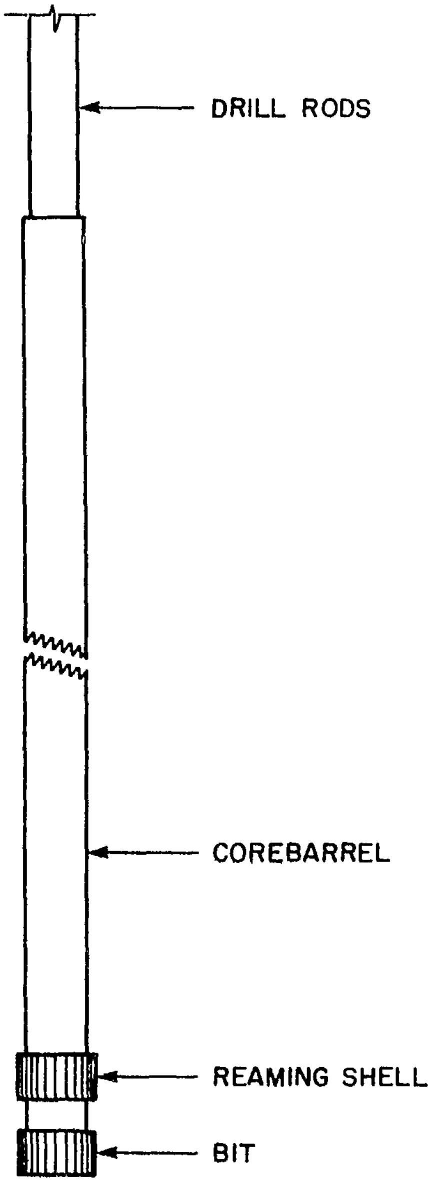
Oil and gas industry normally drills large-diameter holes using tricone bits.

The mineral industry is interested in detecting mineral intrusions, dikes, etc., which often requires core drilling throughout the length of a hole. Holes are for exploratory rather than production purposes and need only be large enough to yield the requisite geological information. Diamond coring equipment is available for EX (1-1/2-inch diameter), AX (1-15/16-inch diameter), BX (2-3/8-inch diameter), NX (3-inch diameter) and HX (3-29/32-inch diameter) hole sizes, but in almost all deep-hole drilling in Canada today, AX or BX holes are used. A typical drill string layout is illustrated in Figure 3.1. Several equipment designs are available, but standardized dimensions have been developed over the years by the Diamond Core Drill Manufacturers Association in the United States and the Canadian Diamond Drilling Association. Dimensions of corebarrels, bits and reaming shells for AX and BX holes are listed in Table 3.1. The T-series corebarrel and bit for AX holes were developed and are commonly used in Canada. The AXT bit cuts a larger core than the AX bit used in the United States. Equipment for BX holes is now available in the T-series, but most equipment for this hole size operating in Canada is of the standard X-series.

In mineral industry holes are smaller and cores are taken.

Diamond drilling is also an essential tool in the field of engineering geology, and the same equipment is used as in the mineral industry.

Hole deviation is not a problem in engineering geology.



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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

DRILL STRING LAYOUT

FIG. 3.1

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TABLE 3.1

COREBARRELS AND KERFS

	Corebarrel		Corebarrel Properties					Kerf Properties				Clearances (Defined in Fig 5.2)		Reaming Shell
	Type	Series	OD (in)	ID (in)	Thickness (in)	Moment of Inertia (in^4)	Weight (lb/in)	OD (in)	ID (in)	Thickness (in)	Area (in^2)	C (in)	S (in)	Set Dia (in)
Equipment for AX holes (1-15/16" Dia)	Single-Tube	X	1.812	1.250	0.281	0.409	0.384	1.875	1.185	0.345	1.658	0.063	0.031	1.890
		T	1.844	1.375	0.235	0.392	0.338	1.875	1.281	0.297	1.472	0.047	0.031	1.890
	Double-Tube	X	1.812	1.500	0.156	0.281	0.231	1.875	1.185	0.345	1.658	0.063	0.063	1.890
		T	1.843	1.531	0.156	0.297	0.235	1.875	1.281	0.297	1.472	0.047	0.047	1.890
		G,L,M	1.812	1.531	0.141	0.260	0.210	1.875	1.185	0.345	1.658	0.063	0.063	1.890
	Wireline		1.812	1.438	0.187	0.319	0.271	1.875	1.062	0.407	1.875	0.078	0.078	1.890
Equipment for BX holes (2-3/8" Dia)	Single-Tube	X	2.281	1.718	0.281	0.902	0.501	2.345	1.655	0.345	2.168	0.047	0.042	2.360
		T	2.312	1.844	0.235	0.835	0.436	2.345	1.750	0.297	1.914	0.032	0.047	2.360
	Double-Tube	X	2.281	1.969	0.156	0.591	0.296	2.345	1.655	0.345	2.168	0.047	0.078	2.360
		T	2.312	2.031	0.141	0.567	0.273	2.345	1.750	0.297	1.914	0.032	0.047	2.360
		G,L,M	2.281	2.000	0.141	0.544	0.269	2.345	1.655	0.345	2.168	0.047	0.063	2.360
	Wireline		2.250	1.812	0.219	0.729	0.397	2.345	1.433	0.456	2.706	0.032	0.063	2.360

However, good core recovery is a more important consideration than hole deviation and holes are usually relatively short, so deviation of holes does not present much of a problem.

3.2 Conventional and Wireline Diamond Drilling

Wireline drilling is more economical than conventional diamond drilling, but deviations are greater.

Conventional drilling in the mineral industry is normally carried out using corebarrels of lengths of 5, 10, 15 or 20 feet. Long corebarrels are generally most economical, since each time a corebarrel is full the complete drill string must be pulled to the surface.

Wireline equipment is an innovation which allows the core, contained within an inner tube, to be withdrawn without pulling the drill string. This necessitates the use of a smaller diameter core and drill rods of larger inside diameter than conventional equipment. Wireline drilling has many obvious advantages–faster core retrieval, longer equipment life, lower costs per foot drilled, etc., and is becoming increasingly popular. The main disadvantage is that wireline drilling has been found by experience to produce holes with greater deviation than conventional drilling.

When it is important to minimize deviation, the complete drill string has to be pulled frequently to change the bit, so the benefits of wireline drilling are reduced.

3.3 Diamond Bits

Diamond bit design depends on formations to be drilled.

A diamond coring bit consists of a steel blank bit onto which is fused a metal matrix surface set with diamonds. The most suitable matrix is one in which diamonds and metal wear down at the same rate. A wide range of standard coring bits are available and the best design depends on the formations to be drilled. Generally, smaller diamonds are best for hard sound rocks, but they tend to break in fractured rock and "mud-up" in sticky ground. An impregnated bit, in which graded diamond grit is impregnated into the metal matrix, presents greater area of cutting surface and consequently drills with less pressure than a conventional bit. An impregnated bit is not reset and operates on the principle of presenting a fresh cutting face as the metal matrix wears down. All diamond bits have cutting surfaces on the inside and outside circumferential faces as well as on the transverse face of the kerf. This provides some capability to drill laterally as well as axially.

Radial grooves allowing the passage of water and removal of cuttings are located in the bit kerf. Only two such waterways may be necessary in hard rocks, whereas in soft shale in which clay is the cementing material, it may be necessary to provide as many as six. It is advisable to have as few waterways as possible to allow for the greatest cutting area of kerf. Face discharge bits are suitable for soft friable formations. The water ejects from holes in the face of the kerf and avoids flowing down the inside of the bit and washing the core.

Several kerf shapes are available in standard bits and it is common practice for drilling contractors and mining companies to experiment with different kerf types made to their own specifications. Figure 3.2 shows a selection of popular kerf cross sections. The stepped kerf is claimed to produce less hole deviation than unstepped designs, and for this reason is used in wireline drilling.

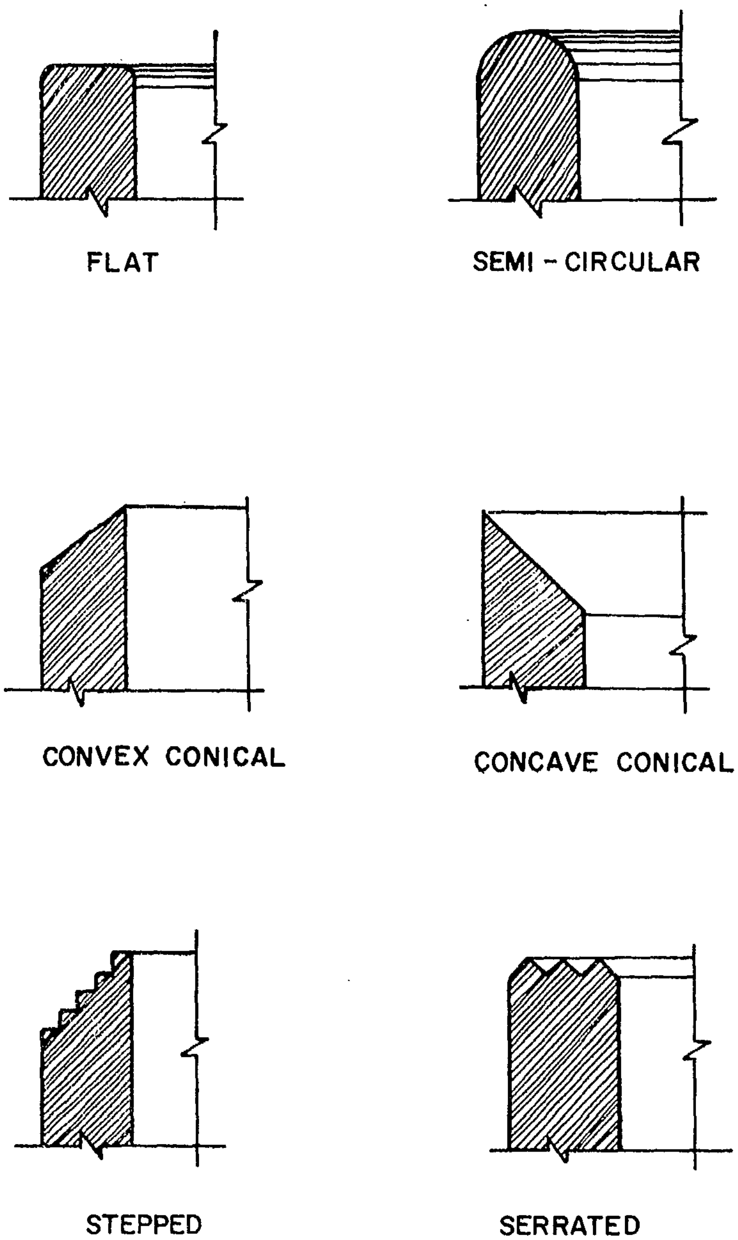
In drilling deep holes, rather than using a single bit until it is worn down, several bits are used in rotation. This practice helps maintain a more uniform hole diameter.

The smallest kerf thickness (see Table 3.1) is used in the Canadian T-series bits. The necessity for small-diameter cores for wireline equipment has led to the development of wide kerfs for wireline drilling.

There are very few firm data available on the bit pressures which act during drilling. If the pressure is too low, the diamonds are polished and their cutting ability is reduced. If the pressure is too high, the heat generated accelerates wear of the bit and may produce cuttings too large to be efficiently removed by the circulating water. Craelius Co. (Spink, 1973) suggests the use of bit pressures from 850 psi to 1,070 psi when drilling in medium-hard formations with impregnated bits. Several of the individuals contacted during this study quoted 2,000 psi as a suitable average kerf pressure for drilling with a conventional bit in hard unfractured formations.

Bit pressures during drilling are normally unknown.

2,000 psi is often quoted as suitable bit pressure for drilling in hard unfractured formations.



NOTE:
THE KERF IS THAT PORTION OF THE BIT SET WITH DIAMONDS

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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

KERF SHAPES FOR DIAMOND BITS

FIG. 3.2

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Spink (1973) maintains that it is possible to achieve equally good penetration rates using bit pressures much lower than previously considered useful. He reasons that when a moving diamond elastically depresses a surface, behind the diamond there is a tension zone which can crack at loads below those necessary to produce the permanent indentations and the "ploughing" normally associated with the abrasive process of diamond drilling.

Lower pressures may be satisfactory.

3.4 Reaming Shells and Stabilizers for Diamond Drilling

As a coring bit penetrates, the diamonds are worn down and the hole loses gauge. This can cause jamming of the drill string when the worn bit is replaced by a new full-gauge bit. To avoid this problem, a reaming shell containing peripheral diamonds is located at a short distance behind the bit. Common reaming shell designs are illustrated in Figure 3.3. The outside diameter of a diamond set reaming shell is 1/64 inch greater than the set bit diameter, so the reaming shell cuts the hole to its full size even when the bit is full gauge. Reaming shells are also subject to loss of gauge, though this is not nearly so severe as in the case of bits. However, it is good practice to use several shells in rotation as drilling progresses, in order to keep the loss in gauge uniform. Nominal hole sizes are slightly larger than reamer outside diameters, but it has not been possible to find published data on measured hole diameters.

Reaming shell which cuts hole to full gauge is located at short distance behind bit.

True hole sizes are not known.

In normal practice, no non-reaming stabilizers are used on the corebarrel. Often, pads of a hard, wear-resistant alloy (e.g. tungsten, borium) are located at the rear of the corebarrel to improve the wearing characteristics, but these are not intended to act as stabilizers, and no attempt is made to eliminate clearances between corebarrel and hole.

In normal practice, corebarrel is not stabilized along its length.

Reamer-stabilizers which are claimed to provide tighter fit of the drill string in the hole are available commercially. One unit is manufactured of three stabilizers located within a distance of about 10 inches behind the bit. The two stabilizers closest to the bit are flush-set with diamonds, with flats rather than the points at the surface. There is, therefore, little reaming capability. The final stabilizer does not contain diamonds, but has tungsten carbide inserts.

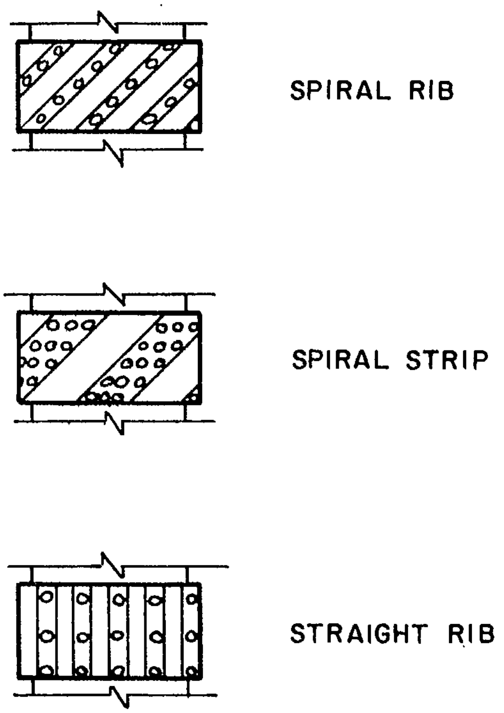

FIG. 3.3

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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

REAMING SHELLS

ACRES

Another reaming shell assembly aimed at reducing deviation is the "Mini-Deve" (Gorgendiere, 1973). A diamond reaming shell follows close behind the bit. Immediately behind the reaming shell there is a chrome-plated sleeve with diameter 0.006 inch less than set gauge of the reamer. This gives less clearance between the drill string and hole than in a conventional corebarrel set-up. The annulus between the sleeve and the wall of the hole is too small to allow the necessary volume of water flow, so the water is ported internally through the sleeve. A chromed-spiral stabilizer follows behind the sleeve.

3.5 Corebarrels for Diamond Drilling

Corebarrels may be single- or double-tube design. Single-tube corebarrels are only used in unfractured rock.

Conventional (i.e. non-wireline) corebarrels may be of either single- or double-tube design. The single-tube corebarrels are stiffest and most robust but, since the water washes down the full length of the core, they are only suitable for drilling in hard, sound rock. If the rock is broken, pieces of core may be washed down causing grinding of the core and diamond breakage. Single-tube corebarrels are often used with non-coring bits in lengths of hole where it is not necessary to recover core, since for a given bit weight the deviation is less than if no corebarrel is present.

In double-tube corebarrels, the drilling water passes through the annular space between inner and outer tubes and only a short length of core close to the bit is subjected to washing. Where the formations being drilled are hard and only slightly fractured, good core recovery is generally obtained using rigid corebarrels in which both inner and outer tubes rotate. It is possible to obtain inner tubes made from stainless steel or with chrome plating on the inside face in order to reduce friction between core and corebarrel and improve core recovery. For rock which is badly fractured or soft and friable, the most suitable corebarrel has a swivel head and the inner tube remains stationary.

Corebarrel stiffness is an important parameter in the hole deviation problem. The moment of inertia about a diametrical axis provides a measure of stiffness, and this was calculated for the corebarrels in Table 3.1. In the moment of inertia calculation for double-tube corebarrels, the presence of the inner tube was neglected. This is attached rigidly to the outer tube only at the corebarrel head and should add little stiffness to the system. From Table 3.1 it can be seen that single-tube and wireline corebarrels are stiffer than the corresponding double-tube corebarrels.

Single-tube and wireline corebarrels are stiffer than double-tube corebarrels.

3.6 Drill Rods for Diamond Drilling

Sizes for X-series and W-series drill rods are listed in Table 3.2. The X-series conforms to old standards, and the W-series rods which are in common use today are of larger diameter and stiffer. Wireline drill rods are of larger diameter than conventional drill rods, but they are considerably thinner with the result that they are slightly less stiff.

Conventional drill rods are stiffer than wireline rods.

Aluminum drill rods are also available, but they are seldom used for drilling. However, they find common use in the lower part of the drill string when a hole is being surveyed using magnetically sensitive equipment.

3.7 Driving Equipment for Diamond Drilling

The driving power for most surface drilling of deep holes is obtained using a diesel engine. The throttle setting more or less fixes a constant rotational speed of the drill string, provided the maximum torque available is not exceeded. Practical rotational speeds for drilling are in the range of 1,000 to 2,000 rpm. For underground drilling, the use of compressed-air machines avoids the problem of exhaust fumes.

Drilling motors are equipped with either screw feed or hydraulic heads which control the advance of the bit (Hall, 1956). With a screw feed head, the bit advances by a fixed distance for each revolution of the drill string. Three or four sets of feed gears are available on a machine. Gear feeds of 200, 400, 600 and 750 revolutions per inch are typical. For a constant rotational speed, the lowest gear feed actually provides the greatest penetration rate and highest bit load. Since a constant penetration rate is maintained in a given gear feed, the load on the bit varies according to the medium being drilled, and there is no direct means of controlling this parameter. The feed used is usually at the discretion of the drill operator, his decisions being made on the basis of experience and "feel" for the system.

Screw feed drilling machines provide a constant penetration rate but bit load is unknown.

Two types of hydraulic feed systems are available. The most common one controls the rate of feed by means of a valve which regulates the bleed-back feed from the hydraulic rams. Thus, the

TABLE 3.2

DRILL RODS

	Series	OD (in)	ID (in)	Thickness (in)	Moment of Inertia (in^4)	Weight/ Unit Length (lb/in)
Rods for AX holes	X	1.625	1.125	0.250	0.264	0.307
	W	1.718	1.250	0.234	0.308	0.310
	Wireline	1.750	1.375	0.188	0.285	0.261
Rods for BX holes	X	1.906	1.250	0.328	0.528	0.462
	W	2.125	1.688	0.219	0.603	0.473
	Wireline	2.188	1.812	0.188	0.596	0.336

Note: These dimensions refer to "parallel wall" rods. Some manufacturers also produce "upset wall" rods which have increased thickness at the threaded portion.

pistons and bit are forced down at a constant rate unless the rock is too resistant to allow penetration at the rate corresponding to the bleed valve setting. The principle of operation is similar to the screw feed system and there is no direct control over the load on the bit. The most recent development has been a hydraulic head with direct control over bit pressure. With this equipment, the hydraulic pressure can be reduced with increasing depth to make allowance for the weight of the drill string and maintain a reasonably constant bit load.

Most hydraulic feed drilling machines provide constant penetration rate, but machines with direct control over applied load are available.

4 DEVIATION THEORIES IN THE OIL AND GAS INDUSTRY

4.1 General

If no holes have been drilled in an area, local geological information and drillability properties of the formations are unlikely to be sufficiently well defined to be useful in any theory to predict deviation. Thus for a first hole, theoretical developments are useful in the control rather than the prediction of hole deviation. In a homogeneous set of ground conditions, data obtained during drilling can be used to quantify deviation resulting from change in the significant parameters (e.g. bit weight).

In oil and gas industry, deviation theories are used to control deviation for the first hole in an area. If ground conditions are uniform, future hole paths may be predicted.

If the geological formations are sufficiently uniform, the data obtained from the first hole can be used to theoretically predict deviations of future holes in the same area.

4.2 Equilibrium Angle Concept

The oil and gas industry has traditionally used large-diameter holes (5 inch to 10 inch) drilled with tricone bits. Such drilling is non-coring and the lower part of the drill string is made up of larger diameter collars which have greater weight and stiffness than the drill rods. Much progress has been made in the past 25 years in understanding the deviations which take place in these holes.

Lubinski's (1950) studies of the buckling of a drill string in a vertical hole made it clear that, as penetration progresses the string eventually buckles, causing the hole to deviate. Thus, it is impossible to drill a truly vertical hole. This led Lubinski and Woods (1953) to study the equilibrium of a drill string in a sloping hole. They assumed the string lay along the low side of the hole and carried out model tests to identify situations where helical buckling invalidated this assumption. The bit was assumed to be isotropic, implying that in isotropic ground conditions it would penetrate in the direction of the resultant force of the bit on the bottom of the hole. Anisotropy in rock was taken into account by

Vertical hole cannot be drilled. Hole seeks equilibrium angle and propagates in straight line.

Bit is assumed to be isotropic, i.e. it penetrates in direction of resultant force on rock.

means of an anisotropy index relating the drillability perpendicular and parallel to bedding planes. It was shown that in a fixed set of drilling conditions the hole seeks out an equilibrium angle and, having attained this angle, propagates itself in a straight line until conditions change. This equilibrium angle is a function of drill string stiffness, its submerged weight in drilling mud, weight on the bit, clearance between drill collars and hole, and the slope and anisotropy index of bedding planes.

Equilibrium angle is function of drill string stiffness, submerged weight, clearance, anisotropy and slope of bedding planes, bit weight.

The complexity of the relationships between the various parameters induced Woods and Lubinski (1954) to prepare practical charts to aid in the solution of hole deviation problems. When a straight hole is drilled, and the inclination angle, formation dip, hole size, drill collar size and bit weight are known, these provide a set of established data. If a new set of problem data is considered, in which one of these quantities is unknown, it can be computed using the Woods-Lubinski charts.

Woods and Lubinski (1955) extended their work to consider drill strings with stabilizers in place. The optimum stabilizer location was found, and the additional weight which could be put on the bit to produce the same equilibrium angle as the non-stabilized case was calculated. Hoch (1962), Moore (1962) and Wiley (1965) developed some of these ideas by considering various stabilizer locations and presented the advantages of using a "packed-hole" system in which the lower part of the drill string is more or less continuously stabilized.

Equilibrium angle theory has been developed to include stabilizers on drill string.

Application to field problems has proved that, at least in some ground conditions, the equilibrium angle concepts are valid and useful. (Moore and Brantly, 1955). It has been stated (Lapinskie, 1974) that in extremely complex and contorted geological formations such as exist in the foothills of the Rocky Mountains, the rapid changes in anisotropy which occur with depth limit the practical value of the equilibrium angle theory.

Equilibrium angle theory has proved useful in practice.

The latest major development of the equilibrium angle theory was carried out by Murphey and Cheatham (1966) who considered the equilibrium of a drill string in a hole of constant curvature rather than the limiting case of a straight hole. As well as simplifying the mathematical representation of previous work, they were able to

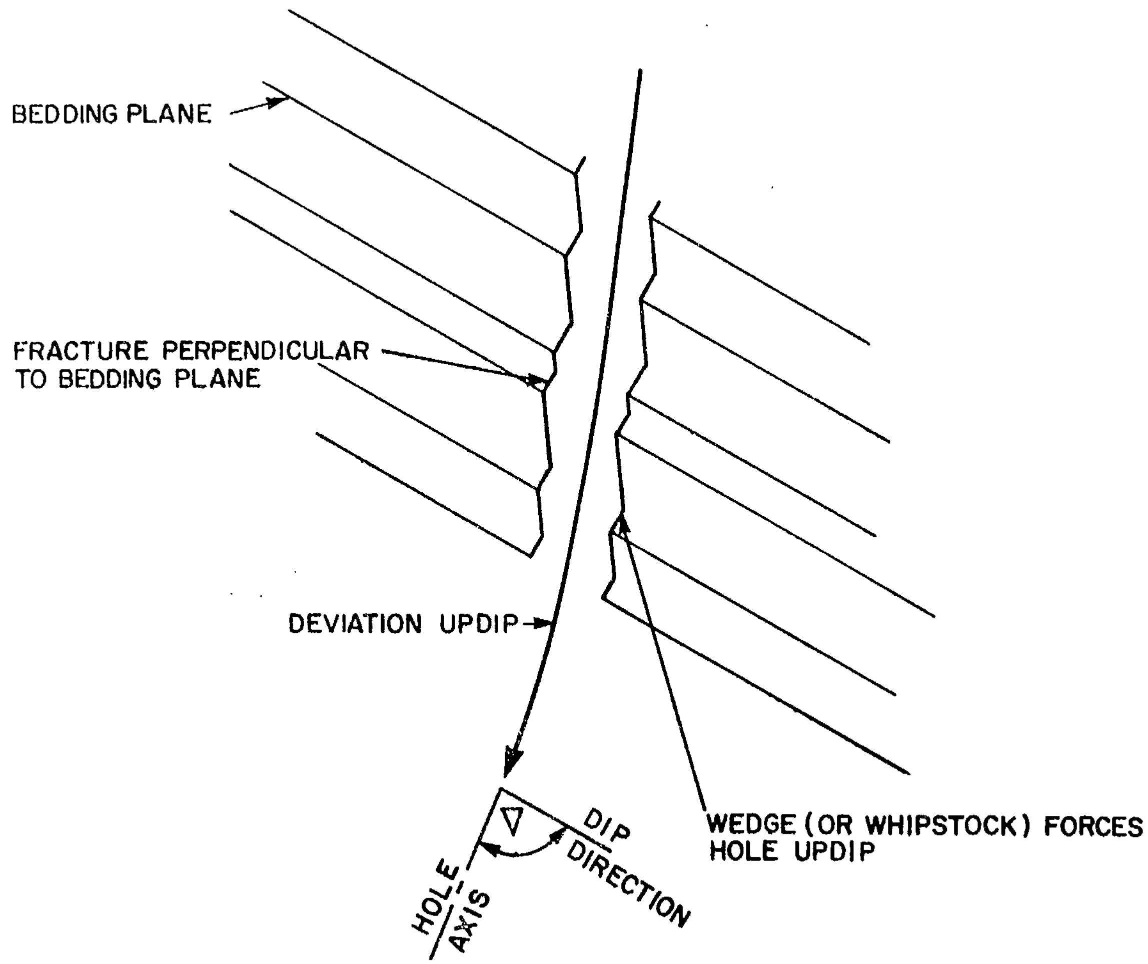
General case of unstabilized drill string in circular hole was considered and equilibrium angle theory verified and simplified.

introduce consideration of the rate of change of hole angle and thus suggest an approximate technique for determining the distance to be drilled between any two specified values of hole inclination. The application of this theory to a practical problem is tedious, involving much trial and error in the solution of equations. Murphey and Cheatham did not solve any practical problems and no subsequent attempt to do so or to check their theoretical developments with practice has been published.

4.3 Miniature Whipstock Theory

Miniature whipstock theory suggests that in closely bedded rock, hole is forced normal to bedding plane.

Tests carried out by the Hughes Tool Company (Rollins, 1959) have suggested that in strongly bedded ground conditions, the mechanism of rock failure results in miniature whipstocks or wedges which force the hole updip. The theory has been described by Wiley (1965) and is illustrated schematically in Figure 4.1. As the bit progresses through each lamination, a stage is reached where the load cannot be supported and fracture through to the next lamination occurs. Since laminated rocks usually fracture perpendicular to the bedding planes, small wedges are formed, forcing the bit to deviate updip. With increasing bit load, fracture occurs higher in each lamination, forming larger wedges and causing more rapid deviation. Ultimately, the hole drills perpendicular to the laminations. This theory is qualitative in nature, but does explain some of the behavior observed in the field. It does not, however, provide a complete explanation since holes do not always become perpendicular to the bedding, and downdip drilling is known to occur in steeply dipping formations.



NOTE:

IN "UPDIP DEVIATION" THE ANGLE, ∇, BETWEEN THE HOLE AXIS AND THE DIP DIRECTION INCREASES AS THE HOLE PROGRESSES, WHEREAS IN "DOWNDIP DEVIATION" THIS ANGLE DECREASES.

FIG. 4.1

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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

MINIATURE WHIPSTOCK THEORY

5 DIAMOND DRILL HOLE DEVIATION THEORETICAL CONCEPTS

5.1 General

Theories for deviation control and prediction are most useful in reasonably homogeneous rocks.

The restrictions imposed on the use of deviation theories (see Subsection 4.1) in the oil and gas industry by the necessity for geological and geotechnical data apply equally well to diamond drilling. It follows that the direct usefulness of theoretical developments in deviation control and prediction is likely to be restricted to situations where ground conditions are, at least over considerable depths, reasonably homogeneous. Unfortunately, many of the regions richest in desirable minerals (e.g. Sudbury Basin) are often foliated, folded and faulted, greatly intensifying the problems of hole deviation. Nevertheless, a better understanding of the mechanics of hole deviation should be useful in so far as it can provide a rational basis for the development of equipment and techniques for minimizing deviation.

Understanding mechanics of hole deviation in diamond drilling provides basis for equipment development.

5.2 Factors Affecting Hole Deviation

Study of diamond drilling literature, field experience and consideration of the mechanics of the problem have led to the following compilation of factors affecting hole deviation. In any particular drilling situation, some factors may predominate and some may not be relevant. Not all factors lend themselves to quantification at the present stage of theoretical development. Those which do are considered in Subsections 5.3 to 5.5.

5.2.1 Geotechnical Factors

Geotechnical factors affecting hole deviation are identified.

(a) Anisotropy and non-homogeneity of rock mass, e.g. bedding planes, joints, schistosity, shear zones, etc.;

(b) Variation of rock properties, e.g. compressive strength, elasticity, hardness and brittleness;

(c) Crystal structure and grain size of rock;

(d) Ability of rock wall to provide support for drill string (i.e. competence of rock wall of hole).

For practical purposes the cumulative effect of the geotechnical factors is often described by a dip angle and an anisotropy index for each formation. This index relates the penetration rate of an isotropic drill (i.e. in isotropic rock it penetrates in the direction of the reaction of the bit on the ground) cutting perpendicular to the bedding planes at a constant bit weight to the penetration rate when it cuts parallel to the bedding planes with the same bit weight.

Geotechnical parameters are described by anisotropy index and slope of beds.

5.2.2 Mechanical Factors

Mechanical factors affecting hole deviation are identified.

(a) Stiffness of drill string – this can be affected by joints and couplings;

(b) Weight per unit length of drill string;

(c) Clearances between drill string and hole – these are obviously affected by the cross-sectional shape of the hole;

(d) Bit weight – i.e., resultant thrust of bit on the ground;

(e) Instability of the drill string – in-plane and helical buckling may occur;

(f) Bit design – the lateral stability of the bit (see Subsection 5.6), kerf shape, diamond pattern and eccentricity of bit crown can all affect deviation;

(g) Locations and types of stabilizers and reaming shells;

(h) Eccentricities in the drill string;

(i) Vibrations of drill string;

(j) Frictional effects between drill string and hole.

All these factors are not necessarily independent. For example, the weight per unit length of the drill string (b) bears some relationship to the stiffness (a). Similarly, eccentricities in the drill string (h) or frictional effects (j) may be the cause of vibrations (i).

5.3 Application of Equilibrium Angle Concepts to Diamond Drilling

The equilibrium angle theory introduced by Lubinski and Woods (1953) is now studied in order to investigate its applicability to small-hole diamond drilling.

Figure 5.1 shows a drill string lying along the low side of a straight sloping hole. The drill bit is represented as a ball which cannot transmit moment. The reaction of the bit on the ground can be resolved into a force W along the hole and a force H transverse to the hole. Lubinski assumed that, in isotropic ground conditions, the bit drills in the direction of the resultant force on the ground. In this case, the equilibrium angle of the hole, α_e, corresponds to the situation where H = O. Murphey and Cheatham (1966) showed that the equilibrium angle in isotropic ground conditions can be estimated from the relationship.

In equilibrium angle theory bit is assumed unable to transmit moment.

$$\frac{W^2 C}{E I p \sin \alpha_e} = 2.71 \qquad (5.1)$$

Where:

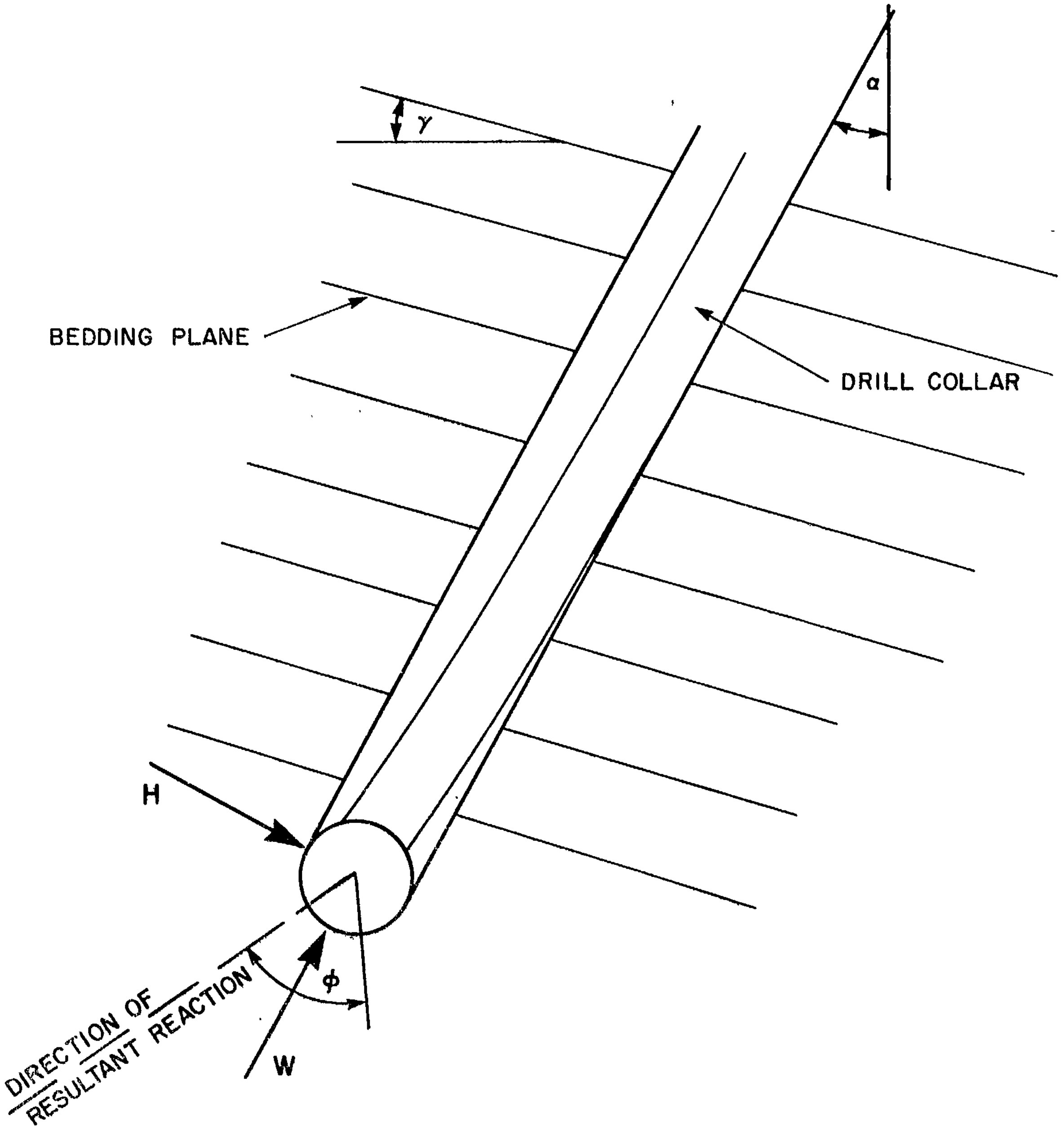
W = bit weight
C = difference in hole and drill string radius
E = Young's modulus of drill string
I = moment of inertia of drill string
p = weight per unit length of drill string

When ground conditions are anisotropic and bedding planes lie at an angle γ to the horizontal, an equilibrium angle still exists but the component of ground reaction transverse to the hole, H, is no longer equal to zero. Lubinski showed that instead,

$$\frac{H}{W} = \frac{h \tan(\gamma - \alpha_e)}{1 - h + \tan(\gamma - \alpha_e)} \qquad (5.2)$$

The anisotropy index, h, is an empirical constant which reflects the drillability of the rock formations in the directions perpendicular and parallel to the bedding planes. In bedded formations it has been found that drilling perpendicular to bedding planes is easier than drilling parallel to them. Defining ϕ to be the angle between the resultant force of the bit on the ground and vertical, Bernhard (Discussion, Lubinski and Woods, 1953) expressed the condition of equation (5.2) in a different form:

In bedded formations it is easier to drill perpendicular to beds than parallel to them.



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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

LUBINSKI-WOODS IDEALIZED DRILL STRING

FIG. 5.1

ACRES

$$\tan(\alpha_e - \gamma) = (1 - h)\tan(\phi - \gamma) \qquad (5.3)$$

Application of equilibrium angle concepts to diamond drilling is considered.

The major differences between diamond drilling for mineral exploration and non-core drilling for oil and gas are considered here. In diamond drilling the presence of the corebarrel, core, coring bit and reaming shell at a short distance behind the bit all call for modification to the basic Lubinski-Woods Theory. Each of these factors is considered separately.

The Lubinski-Woods Theory assumes that the drill string does not buckle. It is, therefore, also necessary to consider the possible modes of buckling and their effects.

5.3.1 Presence of Corebarrel

Corebarrel cuts down on drill string–hole clearance.

The main effect is to cut down on clearance between drill string and hole. If the corebarrel is sufficiently long for the point of contact with the hole to lie somewhere along the corebarrel, the Lubinski-Woods concepts can be applied directly, using the appropriate value of clearance.

If contact takes place only at the top edge of the corebarrel, the mode of action is presumably similar to the case where a stabilizer is present at that point. The Lubinski-Woods Theory requires mathematical development to allow for the change in cross section, but the basic principle of stabilization is applicable.

5.3.2 Presence of Core

Core can add weight and stiffness to corebarrel.

The fact that a core is taken from the hole obviously affects the bit design which, in turn, affects deviation. However, it appears that there are two direct influences which the core can have on the shape of the drill string. It can add weight to the corebarrel and, by restricting displacement (i.e. guiding the corebarrel), can cause an effective increase in drill string stiffness.

(a) Weight

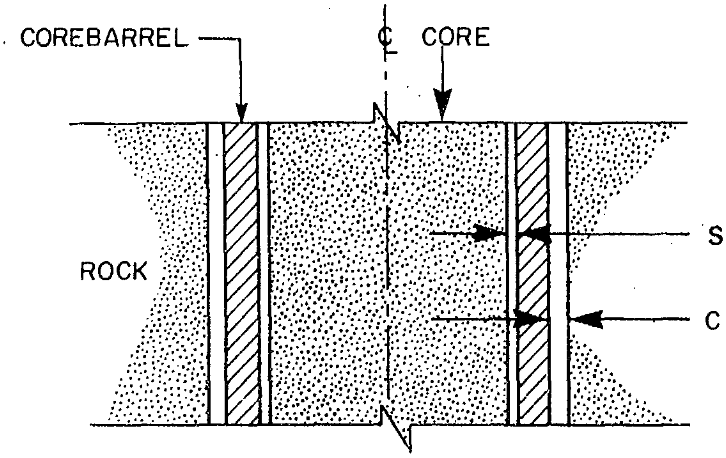
In a sloping hole, if the core remains rigid and intact, it does not add weight to the corebarrel. However, if it is fractured or soft, gravity will cause it to rest against the side of the corebarrel. The inner tube of a double-tube corebarrel may provide some support, but it is only about one-tenth as stiff as the outer barrel and will deflect under the weight of broken core to come in contact with the outer barrel. The influence of the effective core weight on deviation is studied in Subsection 5.5.1 (b), using the proposed mathematical deviation model.

(b) Stiffness

Figure 5.2 shows, schematically, the core inside the corebarrel and defines the clearances S and C. If S < C and the core remains unbroken, when the outer corebarrel bends it contacts the core before touching the wall of the hole. This restriction to deformation may guide or add an apparent stiffness to the corebarrel. Values of S and C, based on nominal hole and core sizes, are listed in Table 3.1. For double-tube corebarrels it appears that S = C for AX holes and S > C for BX holes. In fact, the smaller values of C obtained for BX holes are a result of the nominal hole diameter being only 0.015 inch greater than the set reaming shell diameter. For AX holes the nominal diameter is 0.048 inch greater than the reaming shell diameter. Core sizes have been measured to be slightly smaller (Simons, 1973) than nominal size. There are no measurements of true hole sizes available, but it would probably follow that holes are oversize. The question is complicated further by the fact that a bit and reaming shell are likely to decrease from their original diameters as drilling progresses. It is not possible, then, to quantify the stiffening influence of the core. This would be a problem even if accurate data on hole sizes were available, and an experimental study would probably be more fruitful than analytical investigation.

Bearing in mind that inner tubes have low stiffness, cores are often broken and clearances do exist, it is felt that the additional stiffness provided by a core is of minor importance.

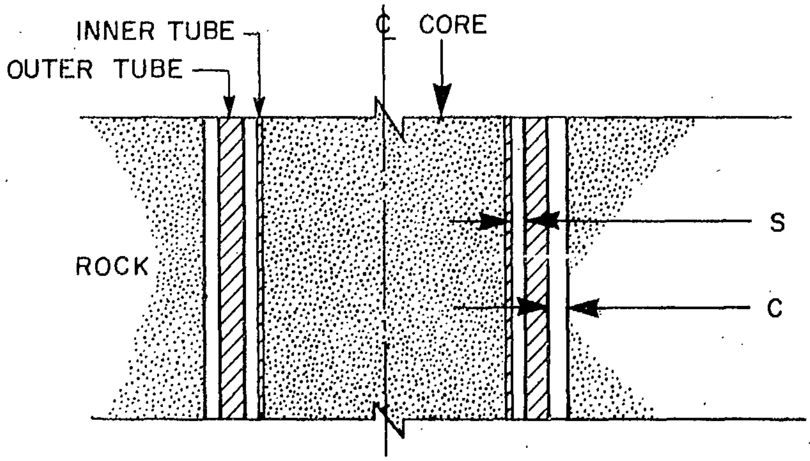
Stiffening influence of core is probably small.



S = (INSIDE RADIUS OF COREBARREL) – (CORE RADIUS)

C = (HOLE RADIUS) – (OUTSIDE RADIUS OF COREBARREL)

(a) SINGLE-TUBE COREBARREL



S = (INSIDE RADIUS OF OUTER TUBE) – (OUTSIDE RADIUS OF INNER TUBE)

C = (HOLE RADIUS) – (OUTSIDE RADIUS OF OUTER TUBE)

(b) DOUBLE-TUBE COREBARREL

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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

CORE – COREBARREL – HOLE CLEARANCES

FIG. 5.2

ACRES

5.3.3 Anisotropy of Bit

Bit assumed isotropic in all previous theoretical work.

In all theoretical work to date, the bit has been considered to be isotropic, i.e. in isotropic ground it drills in the direction of the resultant force on the ground. Hughes Tool Co. carried out an extensive test program investigating the drillability properties of tricone bits in various directions, but the results were scattered and no firm conclusions could be drawn (Lubinski, 1974). The isotropic bit assumption, therefore, appeared as good as any other assumption and provided reasonable results in practice, so no further modification to the theory was introduced. In the case of tricone bits, this assumption may be acceptable, but in the case of diamond coring bits some allowance for directional preference appears necessary.

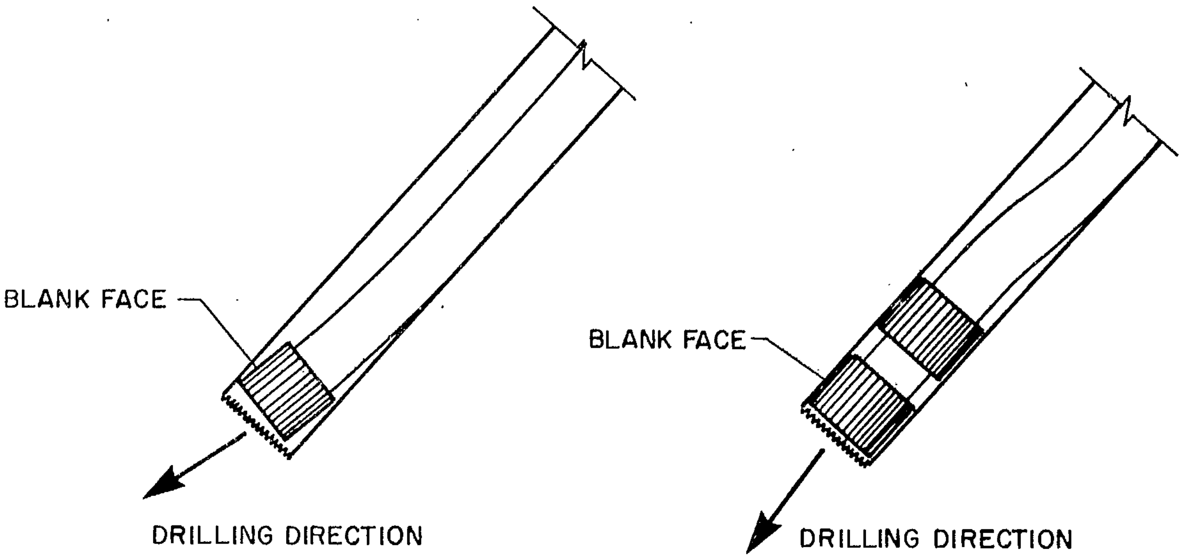
Equilibrium angle theory modified to allow for bit anisotropy.

In Appendix B an approximate theoretical technique for modifying the equilibrium angle theory to take into account bit anisotropy is presented. A bit anisotropy factor, d, is introduced. This is the ratio of the penetration rate of the bit transverse to its axis with a constant bit weight applied in this direction to the penetration rate along the bit axis when the same bit weight is applied along the axis. The equilibrium angle condition expressed by equation (5.3) is modified as indicated in equation (B.1) in Appendix B. At the present time, this development is not of practical use since no tests are available from which a value of d can be estimated. The analysis does point out that an unstabilized drill string cannot produce a straight hole unless the bit has some ability to drill laterally. If the bit has blank edges and, therefore, no ability to drill sideways (i.e., $d = 0$), it will penetrate in the direction in which it points. As illustrated in Figure 5.3, this may promote deviation in an unstabilized drill string, whereas when reamers or stabilizers are present to point the bit in the direction of the hole, a straighter hole may be achieved.

5.3.4 Presence of Reamer

Presence of reaming shell invalidates equilibrium angle theory – theoretically straight hole cannot be drilled.

The presence of a reaming shell a short distance behind the bit produces some degree of fixity at the bottom of the drill string, as illustrated in Figure 5.4 (a). This invalidates



(a) WITHOUT REAMING SHELL

(b) WITH REAMING SHELL

FIG. 5.3

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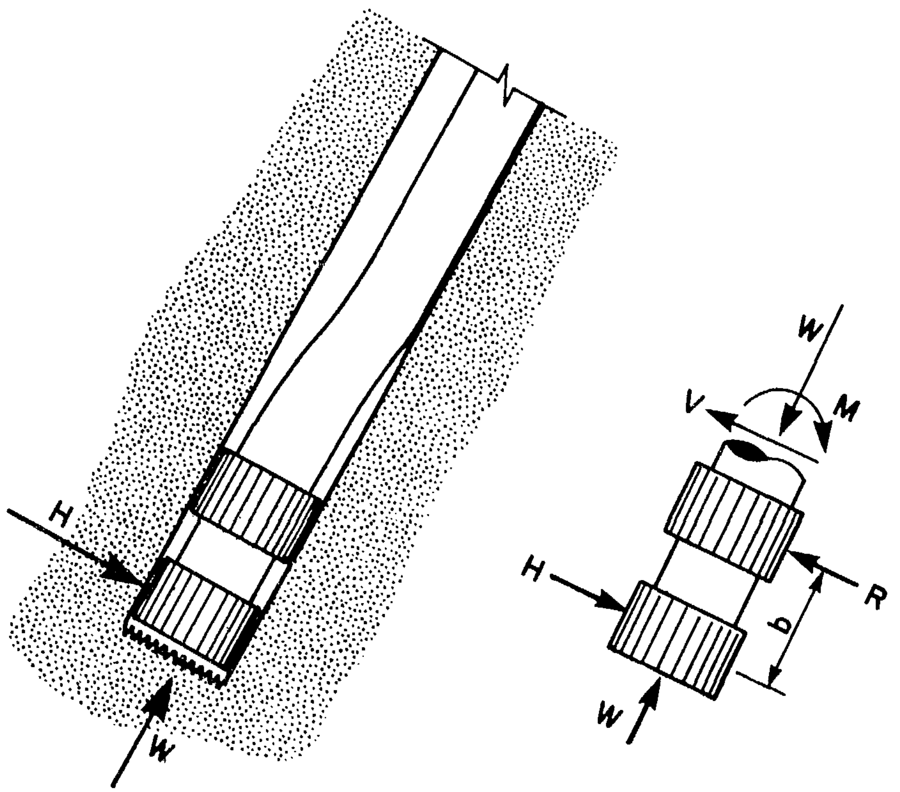
A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

DRILLING WITH BLANK-EDGED BIT



(a) DRILL STRING WITH REAMER

(b) FREE-BODY DIAGRAM OF BIT AND REAMER

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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

DRILL STRING WITH REAMER PRESENT

FIG. 5.4

ACRES

Lubinski's assumption of zero moment at the end of the drill string. In a straight hole a moment always exists at the reamer. This is shown as M in the free-body diagram of bit and reaming shell shown in Figure 5.4 (b). Moment equilibrium requires that there be transverse force, H, where:

$$H = \frac{M}{b}$$

Since M is always greater than zero, H must also have a positive value. It follows that the resultant reaction of the bit on the ground cannot act along the axis of the hole and it is not possible to drill a straight hole.

Deviation theory is developed to predict hole path of isotropic bit penetrating isotropic ground.

In Appendix C, a theory is proposed to take into account the fixity provided by the reaming shell. It is assumed that the drill string is uniform and lies on the low side of the hole, that the lower part of the hole is of constant curvature, and that the hole propagates itself in such a way as to eliminate the moment at the reaming shell at all times. Parametric studies using this model are described in Subsection 5.5.1.

5.3.5 Buckling of the Drill String

Lubinski's concepts and the developments presented in Appendix C are only applicable for holes in which the drill string lies along the low side of the hole. It is therefore appropriate to consider the buckling behavior of the drill string which would invalidate this assumption.

(a) Euler Buckling

Euler buckling of drill string causes deviation of vertically collared hole.

When a hole is collared vertically, it can theoretically propagate itself in a straight line until the drill string first buckles. The length of hole drilled before buckling takes place is a function of the load applied to the bit, the restraint present at the drilling machine and the bit, the stiffness and weight of the drill string in water, and imperfections in the drill string. The rotational speed may have some influence in so far as the dynamic effect causes amplification of initial imperfections. The end restraints on the drill string are not well defined, but an upper limit on the depth at which buckling occurs in a straight drill string can be obtained by assuming complete fixity at both ends of the drill string. In this case, the relationship between buckling load, P, and length of drill string, ℓ is given by:

$$P = \frac{4\pi^2 EI}{\ell^2}$$

E = Young's modulus
I = Moment of inertia

This formula neglects the weight of the drill string, which is small compared to the buckling bit loads. The presence of a corebarrel means that the drill string is really a stepped column, but there is not a great deal of difference between corebarrel and drill rod stiffness (see Tables 3.1 and 3.2). The buckling load for the stepped column lies between that of a uniform column with the corebarrel stiffness and one with the drill rod stiffness. For drill strings in AX and BX holes then, theoretical buckling loads are a function of length and lie within the zones indicated in Figure 5.5. In practice, imperfections within the drill string will reduce the buckling lengths. It is clear that only a relatively short portion of a deep hole can be drilled before the drill string buckles and deviation occurs.

(b) In-Plane Buckling

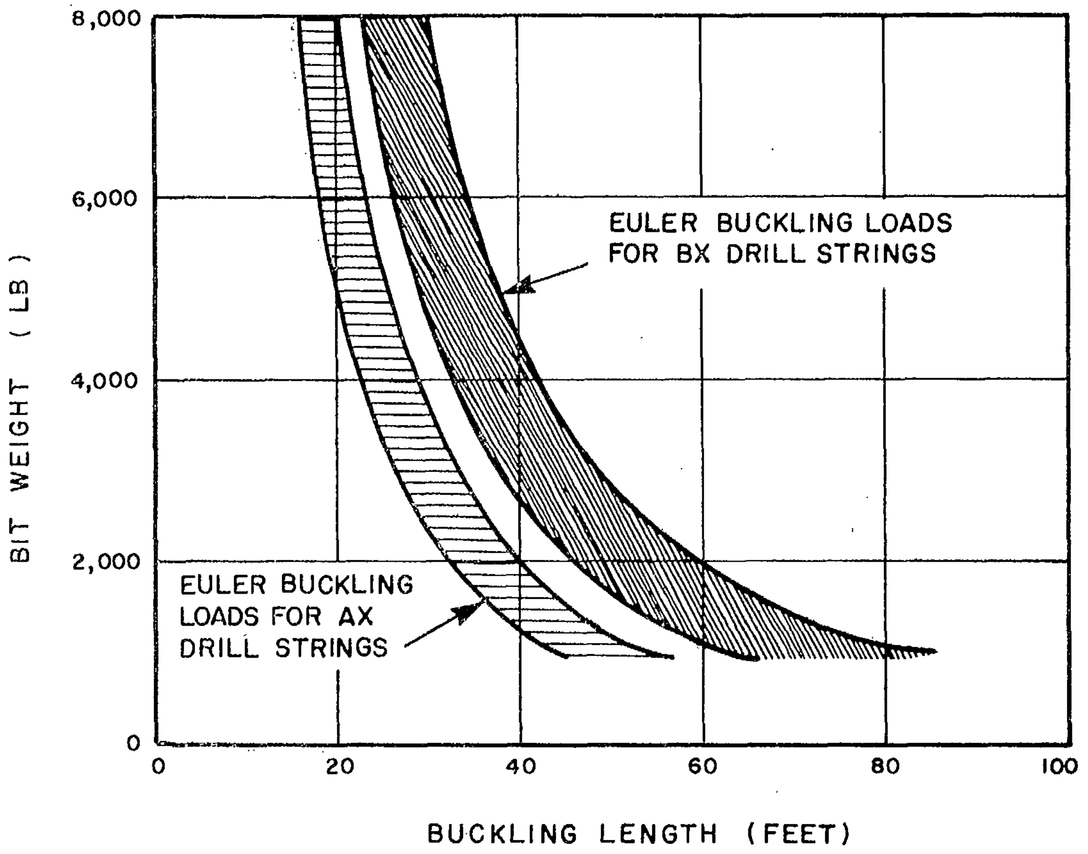
In curved hole in which inclination is increasing, in-plane buckling cannot occur.

Bogy and Paslay (1964) considered the in-plane buckling of a drill rod lying along an inclined hole. They have shown theoretically that if the pipe is initially straight, in-plane buckling cannot occur. An approximate large deflection buckling theory was developed from which the load required to buckle a drill string with a known in-plane imperfection can be calculated. However, when a hole is curved with the inclination angle increasing (i.e. hole is flattening) this mode of buckling is not relevant.

(c) Helical Buckling

Load to cause helical buckling in straight sloping hole is function of hole inclination,and stiffness, clearance, density and length of drill string.

No complete theoretical solution to the problem of helical buckling has been developed taking into account all the complexities of the real problem. In fact, Lubinski and Woods (1953) resorted to physical model testing in order to establish zones of helical buckling within the charts they produced for the calculation of equilibrium angles. The



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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

EULER BUCKLING OF DRILL STRINGS

FIG. 5.5

ACRES

only attempt at predicting theoretical helical buckling loads for a drill string was made by Paslay and Bogy (1964). They considered a uniform drill collar pinned at both ends lying along a straight smooth hole. Axial load was applied to the rod and the analysis allowed for the self-weight of the rod. Initially, the presence of torque was taken into account, but its effect was very small and actually increased the stability of the rod. In the buckled configuration, the rod was restricted to be in contact with the sides of the hole over the complete length. Details of the stability equations and their solutions are provided in Appendix D.

There are several discrepancies between the idealized model and the real situation. In practice, a drill string does not contact the sides of the hole close to the bit and there is a sudden change in stiffness and clearance at the junction of corebarrel and drill rod. In addition, the hole usually has some curvature. Unfortunately no results of tests on even simple physical models have been published, so the application of the helical buckling theory to the real problem, with all its complexities, must be treated with reservation at this time.

For the purposes of this analysis, the corebarrel is ignored and the problems of drill rods lying in AX and BX holes are considered. The reduced clearance which exists in the presence of a corebarrel should result in the following estimates of helical buckling loads being low. According to Paslay and Bogy (1964), the buckling load and mode shape is a function of the length of the rod. This is demonstrated in Figure 5.6 where, for an arbitrarily chosen slope of hole, the theoretical bit weight to cause buckling was calculated for several discrete values of length. It is obvious from Figure 5.6 that there is a critical length of rod which corresponds to the minimum bit weight, W_{min}, to cause buckling. Taking this load as a conservative (i.e. low) estimate of the helical buckling load, analyses were performed to evaluate W_{min} as a function of the inclination angle, α. Results for AW rods in an AX hole and BW rods in a BX hole are shown in Figure 5.7. Calculations were based on nominal hole dimensions. Increasing clearance between drill string and hole causes lowering of the helical buckling curves. For a given slope of hole, bit loads lying above the curves in this figure represent conditions where helical buckling theoretically occurs.

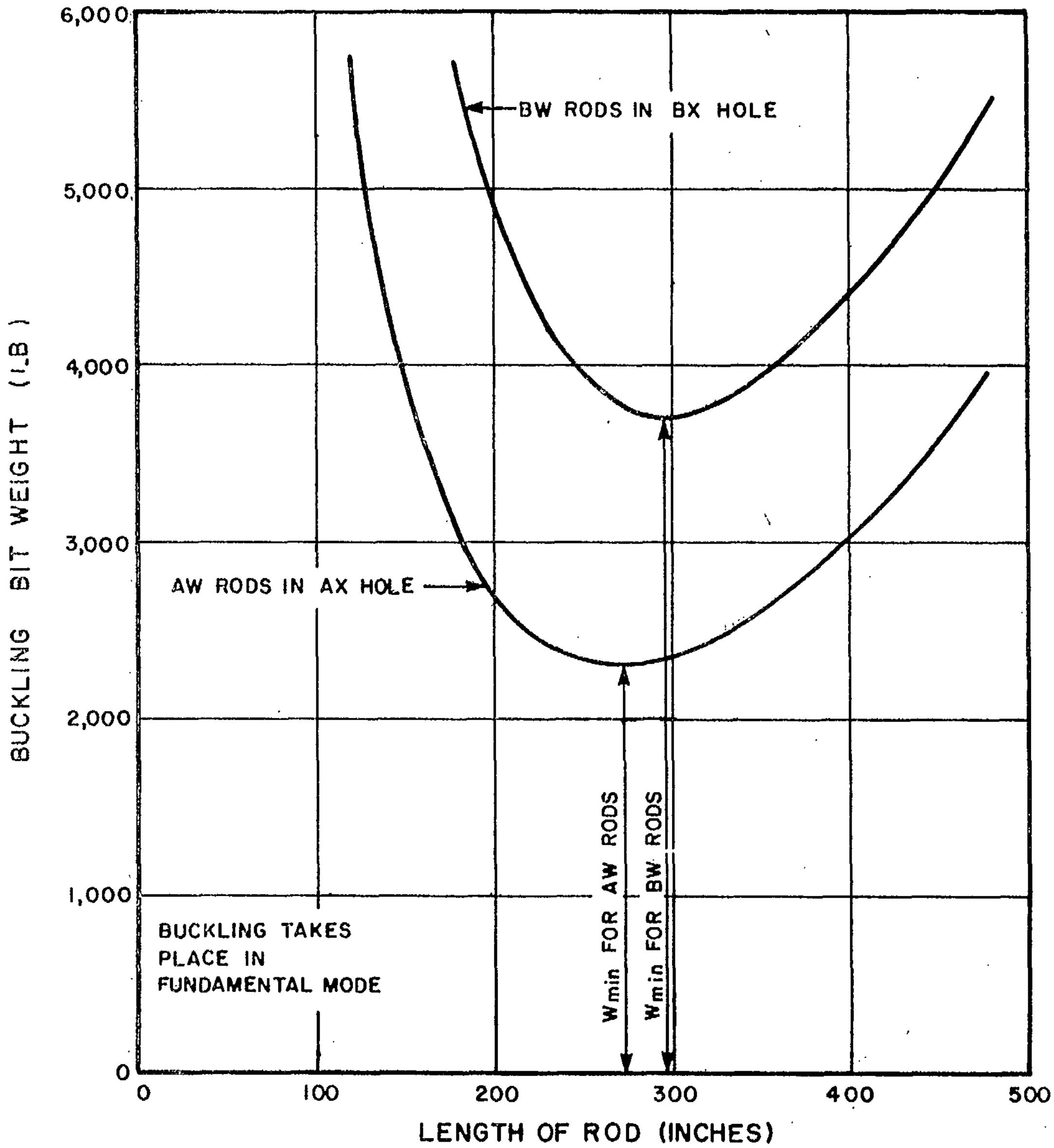

FIG. 5.6

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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

BUCKLING BIT WEIGHTS AS A FUNCTION OF DRILL STRING LENGTH

ACRES

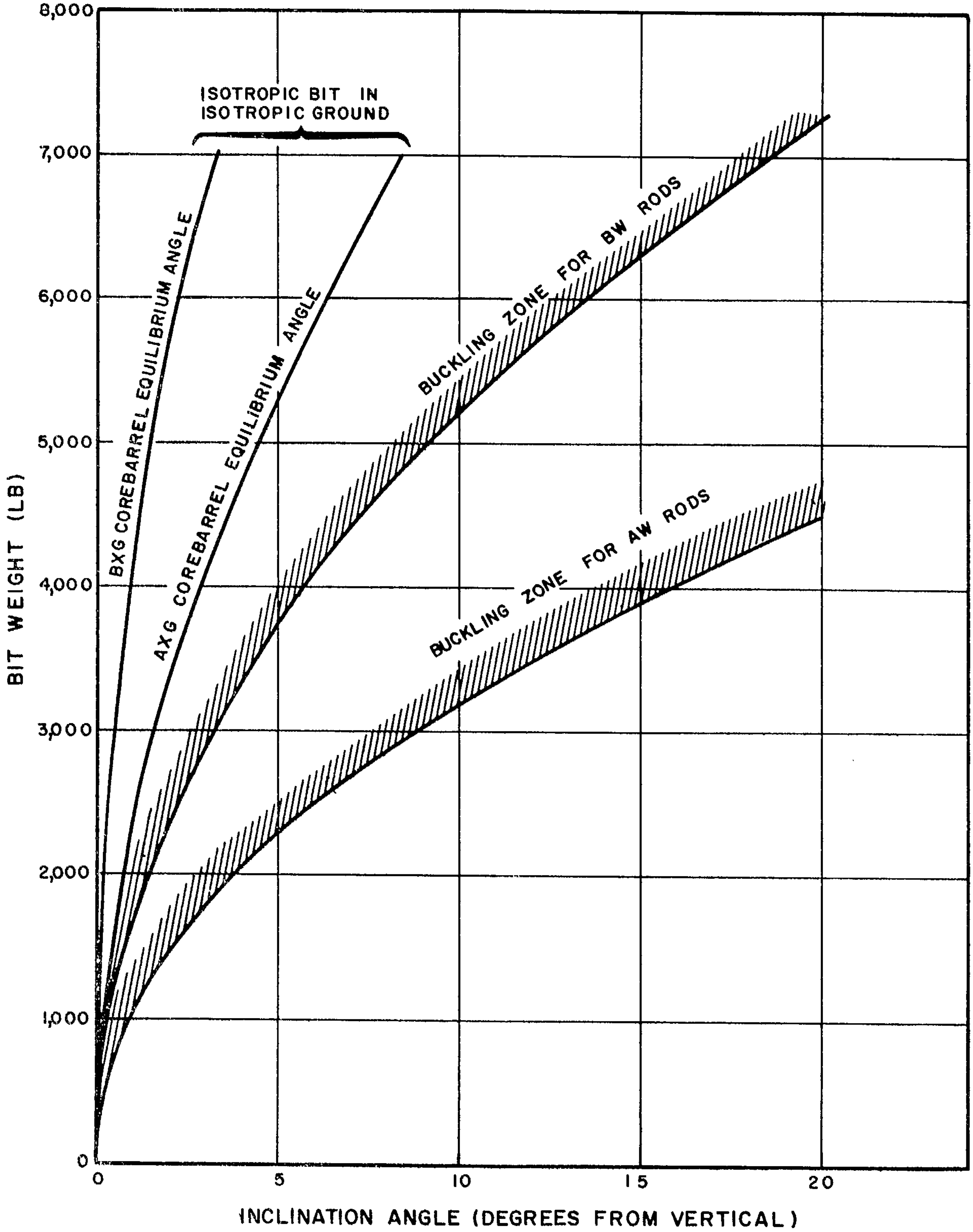

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FIG. 5.7

A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

CRITICAL BIT WEIGHTS AND EQUILIBRIUM ANGLES

ACRES

5.4 Effects of Buckling on Equilibrium Angle Concepts

As discussed in Section 5.3.4, the presence of a reaming shell close behind the bit appears to preclude the existence of an equilibrium angle. However, it is interesting to evaluate equilibrium angles which would exist if no reamer was present. Assuming the ground conditions and the bit to be isotropic, equilibrium angles can be estimated using Murphey and Cheatham's approximate formula which was given in equation (5.1). The equilibrium angle is a function of the corebarrel used and the bit weight applied. The conventional (i.e. non-wireline) corebarrels listed in Table 3.1 can all be used with the W series drill rods, whose theoretical buckling characteristics were considered in Figure 5.7. The largest equilibrium angles are obtained when the least stiff corebarrels, namely the G series, are used and these are plotted on Figure 5.7 as a function of bit weight. Because of the small clearances involved, the equilibrium angles obtained are very low and lie within the region where, theoretically, helical buckling takes place. It follows that, even if there is no reamer on the drill string, buckling would invalidate the equilibrium angle concept for a drill string with an isotropic bit.

If the ground is anisotropic and the bedding planes are horizontal, equilibrium angles would be smaller than in isotropic ground, increasing the likelihood of buckling occurring.

When inclined beds are present with a high degree of anisotropy, equilibrium angles could, theoretically, exist at large inclinations at which helical buckling would not take place. For example, in the limiting case where the bit can only drill perpendicular to the bedding planes (i.e., h = l), the equilibrium angle would equal the inclination angle of the beds.

If no reamer present and bit isotropic, equilibrium angle depends on ground conditions.

5.5 Application of Mathematical Model of Drill String With Reamer

5.5.1 Parametric Studies

The theoretical behavior of AX and BX holes in isotropic ground was investigated by carrying out parametric studies using the mathematical model of a drill string and reamer which was developed in Appendix C.

Parametric studies of mathematical model of drill string with reamer were carried out.

(a) Influence of Bit Weight

Increasing bit weight increases deviation.

For a given corebarrel and hole size, if the load on the bit is known, the inclination angle of the hole to vertical can be obtained as a function of the depth drilled. This function is plotted in Figure 5.8 for several values of bit weight acting on an AXT corebarrel. In obtaining these curves, an initial inclination angle of 1 degree was chosen arbitrarily, although it should be pointed out that there is a possibility of helical buckling occurring at low angles.

The curves in Figure 5.8 are only plotted for the range of validity of the expressions which relate the inclination angle and depth drilled (equation (C.6) in Appendix C). The rate of change of inclination angle at any depth is given by the inverse of the slope of the tangent to the curve for the bit weight under consideration. In general, rate of change of hole angle increases with depth, although the greatest variation occurs at shallow depths. The orders of magnitude of the rates of angle change are indicated by the following examples. For an inclination angle of 20 degrees, the rates of angle changes are 3.4, 4.0, 4.6 and 5.3 degrees per 100 feet for bit weights of 3,000, 4,000, 5,000 and 6,000 pounds, respectively.

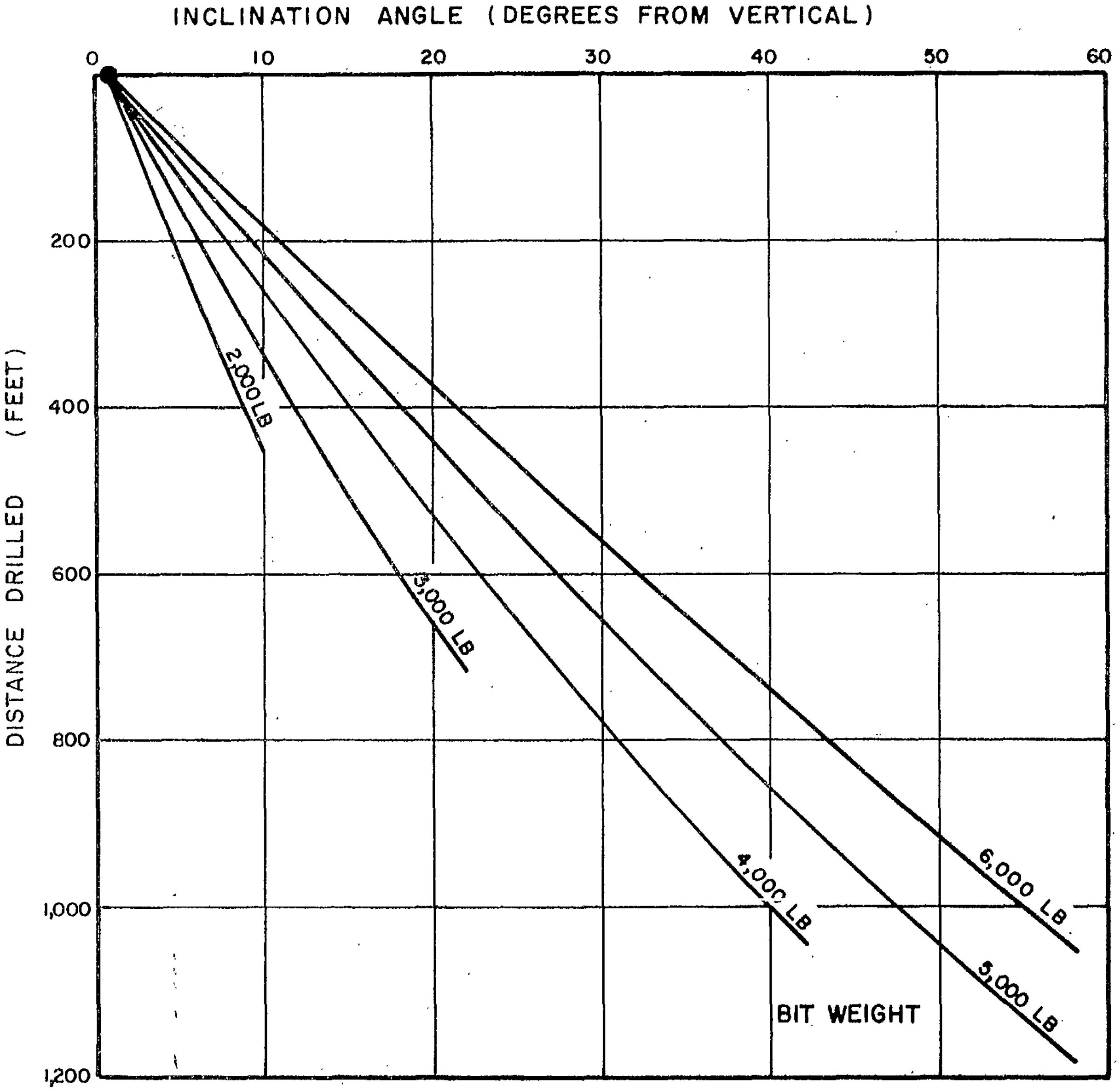
For a given length of hole, the inclination angle appears to be almost linearly related to the weight applied to the bit.

(b) Influence of Weight of Core

Core weight has little effect on deviation.

In the calculations performed above, it was necessary to assume a value for the weight per unit length of the drill string. The value used corresponded to the weight of the outer corebarrel and so neglected the presence of the core. The sensitivity of deviation to the weight of core was studied by comparing theoretical deviations of an AXT double-tube corebarrel, when the weight of core is neglected, with the deviations when the outer barrel is considered to be full of core with density 166 pounds per cubic foot.

The results which are plotted in Figure 5.9 indicate that, although the increased weight per unit length causes small



AXT DOUBLE-TUBE COREBARREL

FIG. 5.8

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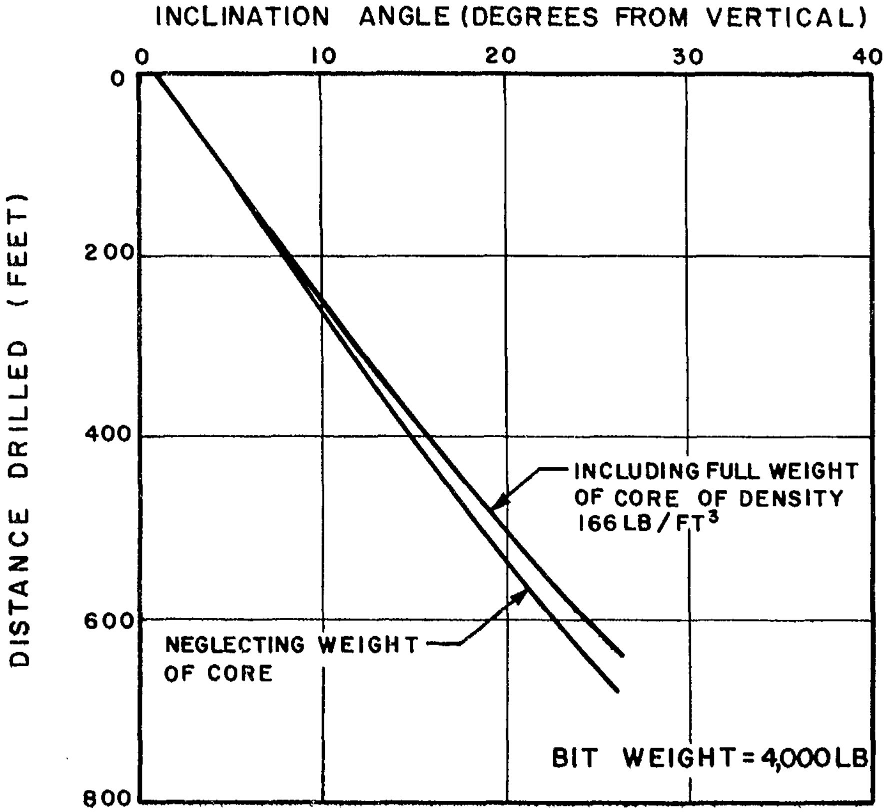
A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

INFLUENCE OF BIT WEIGHT ON DEVIATION

ACRES



AXT DOUBLE-TUBE COREBARREL

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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

FIG. 5.9

INFLUENCE OF WEIGHT OF CORE ON DEVIATION

ACRES

increase in inclination angle at a given depth, deviations are not sensitive to the effective weight of the core. In further calculations the weight of the core was ignored.

(c) Influence of Clearance

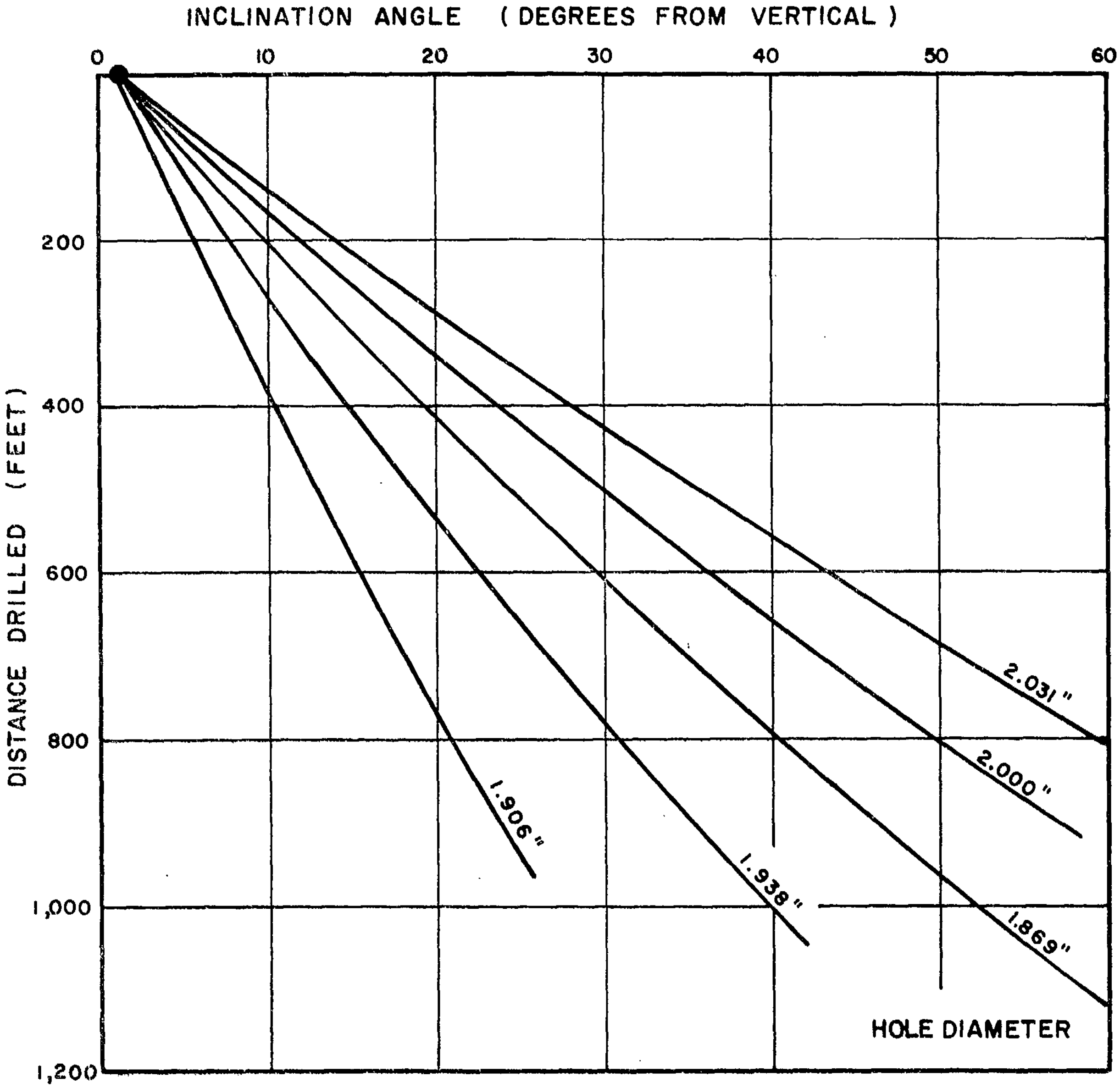
Increasing clearance increases deviation.

The clearance between corebarrel and hole was defined in Appendix C to be the difference between the radius of the hole and the radius of the corebarrel. Corebarrel dimensions are known from manufacturers' specifications, but unfortunately there appear to be no data available on the true size and shape of holes. The sensitivity of deviation to clearance was studied by considering a constant bit weight (4,000 pounds) applied to an AXT corebarrel and calculating the inclination angle as a function of depth drilled for various values of clearance. The clearances used were those which would occur in a hole 1/32 inch undersize, a hole of nominal size, and three other holes with diameters increasing in 1/32-inch increments. The results, plotted in Figure 5.10, indicate that deviations are greatly affected by the clearance present. For example, a hole 800 feet long which is 1/32 inch undersize has an inclination of 21 degrees and a rate of change of inclination angle of 2.9 degrees per 100 feet; whereas, if it is 3/32 inch oversize its inclination angle is 60 degrees and rate of change of inclination angle 8.2 degrees per 100 feet.

(d) Influence of Type of Corebarrel

Type of corebarrel influences deviation.

For a given hole size, the various corebarrels which are available have different stiffnesses and clearances, and so deviations should theoretically be different. The kerf thickness used with all corebarrels is not the same, so when comparing deviations which occur in various systems, it is appropriate to use a constant kerf pressure rather than a constant bit weight. Using a kerf pressure of 2,000 psi, inclination angle is plotted in Figure 5.11 as a function of depth drilled for AX holes drilled using the corebarrel-bit combinations listed in Table 3.1. The AXT systems, which have thinner kerfs than other systems, show considerably less deviation. Single-tube corebarrels, being stiffer than their double-tube counterparts, also drill straighter holes.



AXT DOUBLE-TUBE COREBARREL
BIT WEIGHT = 4,000 LB

FIG. 5.10

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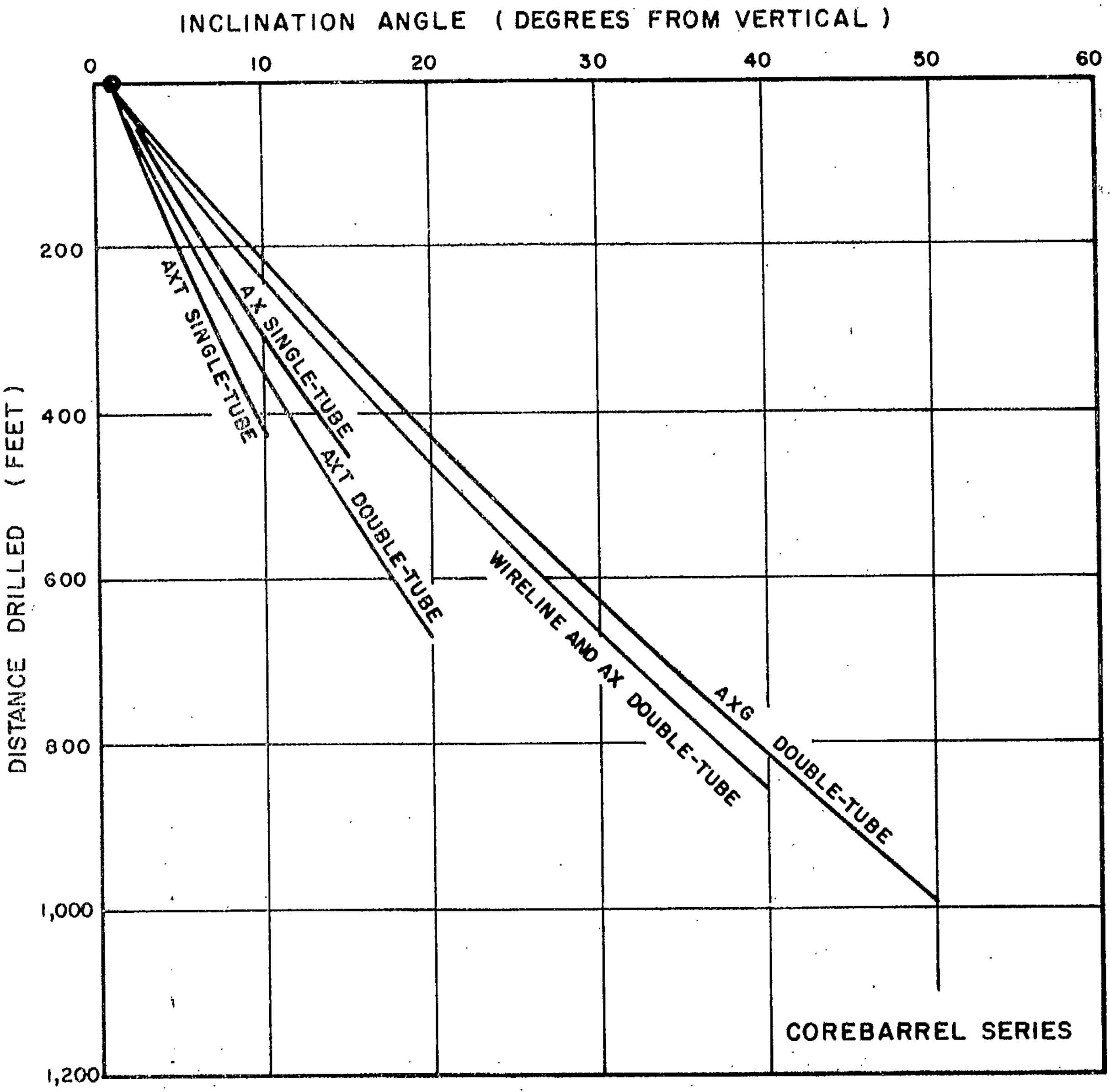
A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING
INFLUENCE OF CLEARANCE ON DEVIATION



BIT PRESSURE = 2,000 PSI
AX HOLE DIAMETER = 1.938"

FIG. 5.11

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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

THEORETICAL DEVIATIONS OF AX HOLES

The AX wireline system deviates much more than the Canadian AXT system, but the deviation curves for AX double-tube and AX wireline systems almost coincide.

(e) Influence of Hole Size

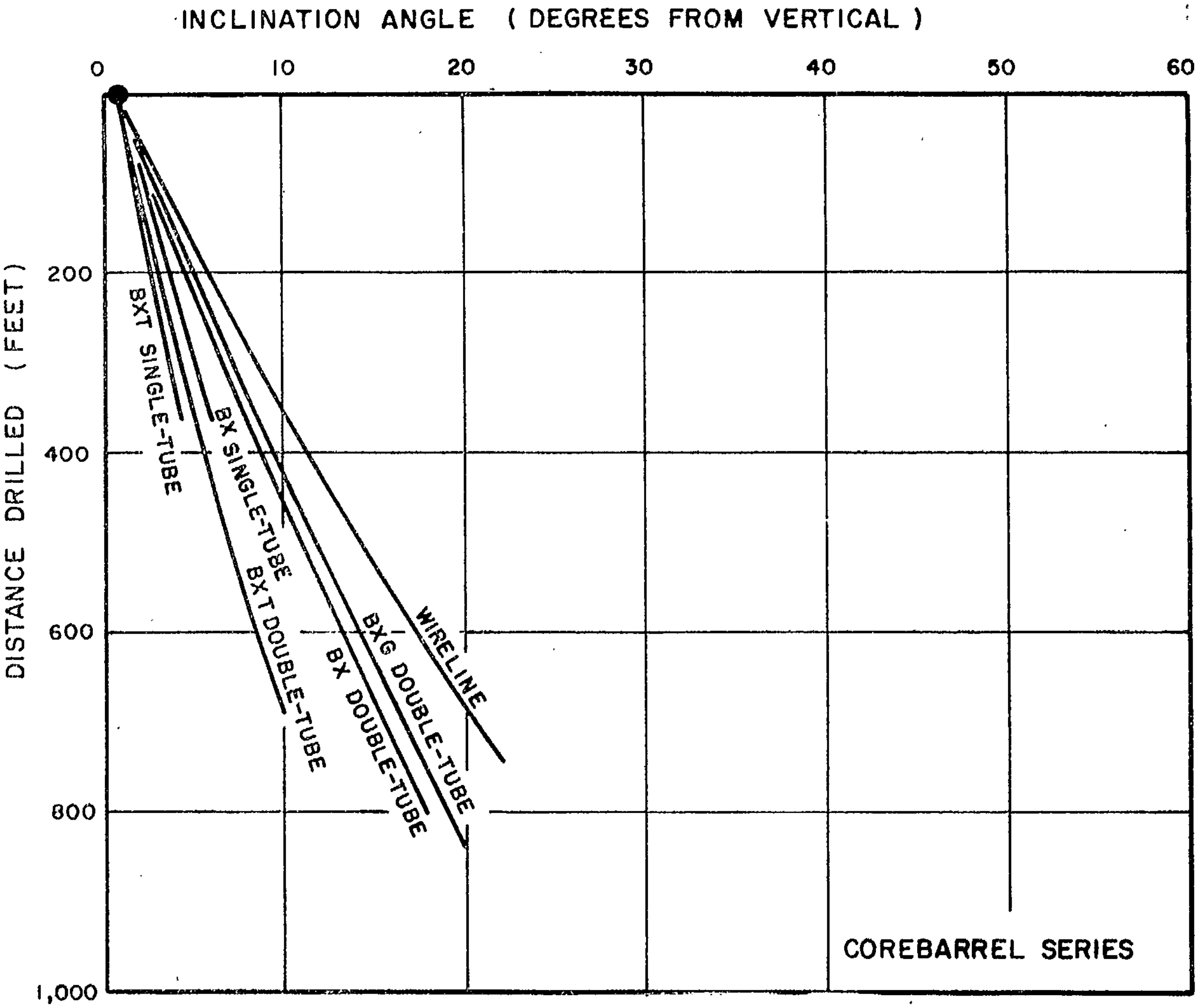
Small holes deviate more than large holes.

Deviation curves for the BX corebarrels listed in Table 3.1 were calculated using a kerf pressure of 2,000 psi and clearances based on the nominal hole size, namely 2-3/8 inches. From Figure 5.12, it can be seen that in this case the wireline system shows considerably greater deviations than other systems. Comparing Figure 5.12 with Figure 5.11, it appears that all BX systems deviate much less than corresponding AX systems. However, an anomaly arises because of the use of nominal sizes. An AX hole of nominal size, 1-15/16 inches, has a clearance of 0.0475 inch with an AXT corebarrel in the hole, whereas a BX hole of nominal size, 2-3/8 inches, has a clearance of 0.0315 inch with a BXT corebarrel present. In fact, in both cases the reaming shell protrudes from the corebarrel by the same amount, so a fairer comparison of deviations in AX and BX holes is made by assuming the same clearance between corebarrel and hole in each case. To do this, the curves of Figure 5.12 were recalculated using a BX hole size of 2.408 inches and plotted in Figure 5.13. The larger clearance resulted in greater deviations, but all BX corebarrels still produced much smaller deviations than the equivalent AX corebarrels. For example, when a hole is drilled using an AX double-tube corebarrel, after 700 feet of drilling it has an inclination of 32 degrees and a deviation rate of 5.2 degrees per 100 feet, whereas the corresponding figures for a BX double-tube system are 20 degrees and 3.2 degrees per 100 feet.

5.5.2 Contact Between Corebarrel and Hole

Contact point between corebarrel and hole is closer to bit than theory predicts.

The mathematical model of Appendix C can be used to calculate the location where the corebarrel makes contact with the side of the hole. It is interesting to study this topic, since some indication of zones of contact in the field can be obtained from observation of the wear which has taken place in used corebarrels.



BIT PRESSURE = 2,000 PSI
BX HOLE DIAMETER = 2.375"

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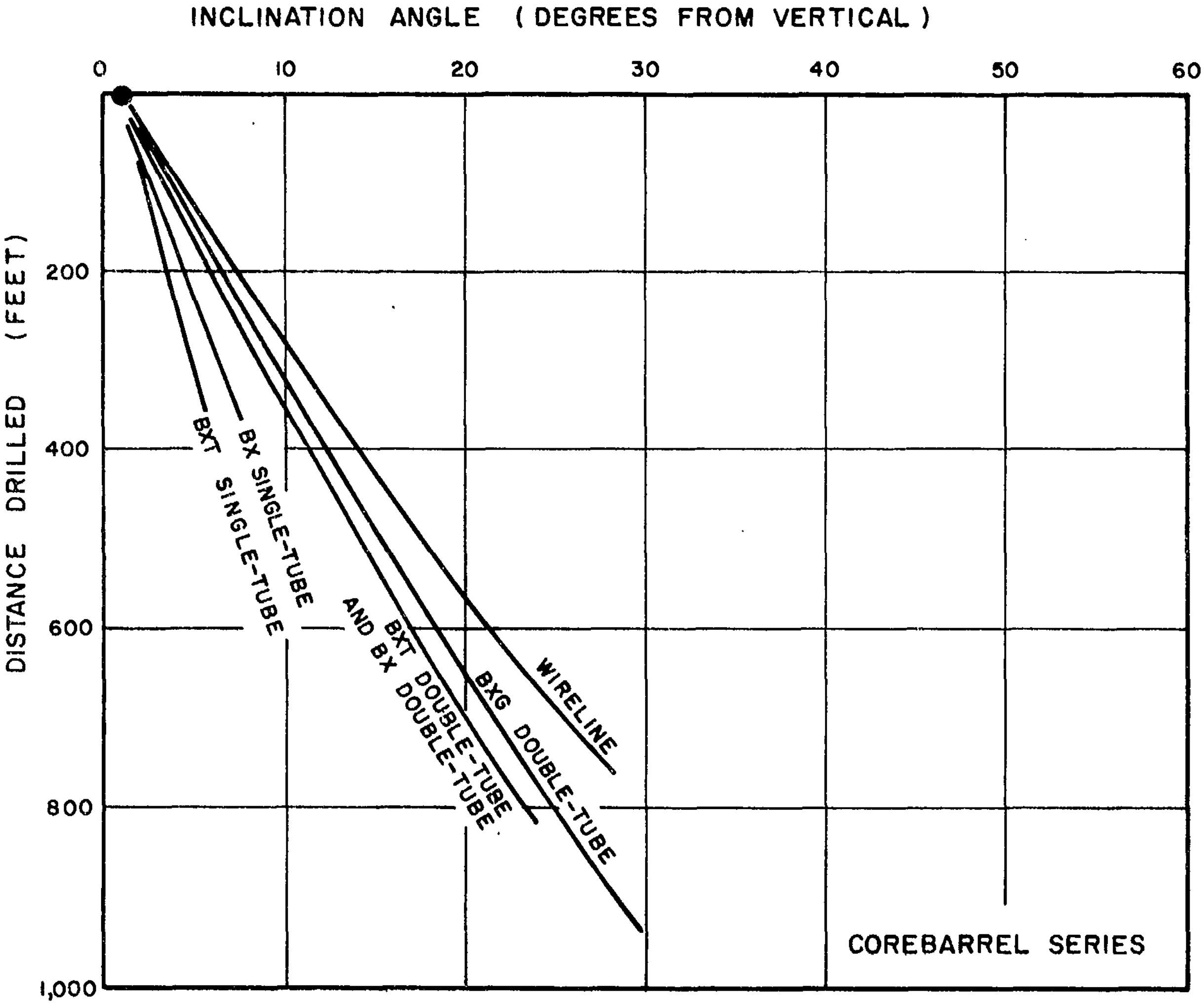
A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING
THEORETICAL DEVIATIONS OF BX HOLES
FIG. 5.12
ACRES



BIT PRESSURE = 2,000 PSI
OVERSIZE BX HOLE DIAMETER = 2.408"

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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

FIG. 5.13

THEORETICAL DEVIATIONS OF OVERSIZE BX HOLES

The theoretical distance, L, from the reaming shell to the point of contact of corebarrel and hole can be calculated from the expression

$$L = \ell \sqrt{\frac{EI}{W}}$$

Where:

ℓ = a dimensionless parameter
W = bit weight

In the parameter studies carried out in the previous section, the inverse of the dimensionless radius of curvature (i.e. l/r) had values greater than 2 (see Appendix C). From Figure C3 in Appendix C, ℓ shows little variation in the range of 1/r of interest, with the lowest value of ℓ = 1.94 occurring when 1/r = 2. Using this value for ℓ, L is plotted as a function of W in Figure 5.14 for an AX and a BX double-tube corebarrel.

Liebenberg (1971) measured the diameter of a BX corebarrel at 6-inch intervals along its length and found that the greatest wear took place at 3.4 feet behind the bit face. He concluded that this was the point where the corebarrel contacted the hole. Figure 5.14 suggests that, theoretically, contact between corebarrel and hole should not exist so close to the bit. The fact that greatest wear was evident does not necessarily imply that this is the location where contact most frequently takes place. The degree of wearing is also related to the force acting and, in general, the reaction between corebarrel and hole increases as the point of contact approaches the reamer. There is also the likelihood that severe wearing could occur close to the bit when dog legs are created in the hole. The question of contact between corebarrel and hole in various circumstances could best be resolved by field testing.

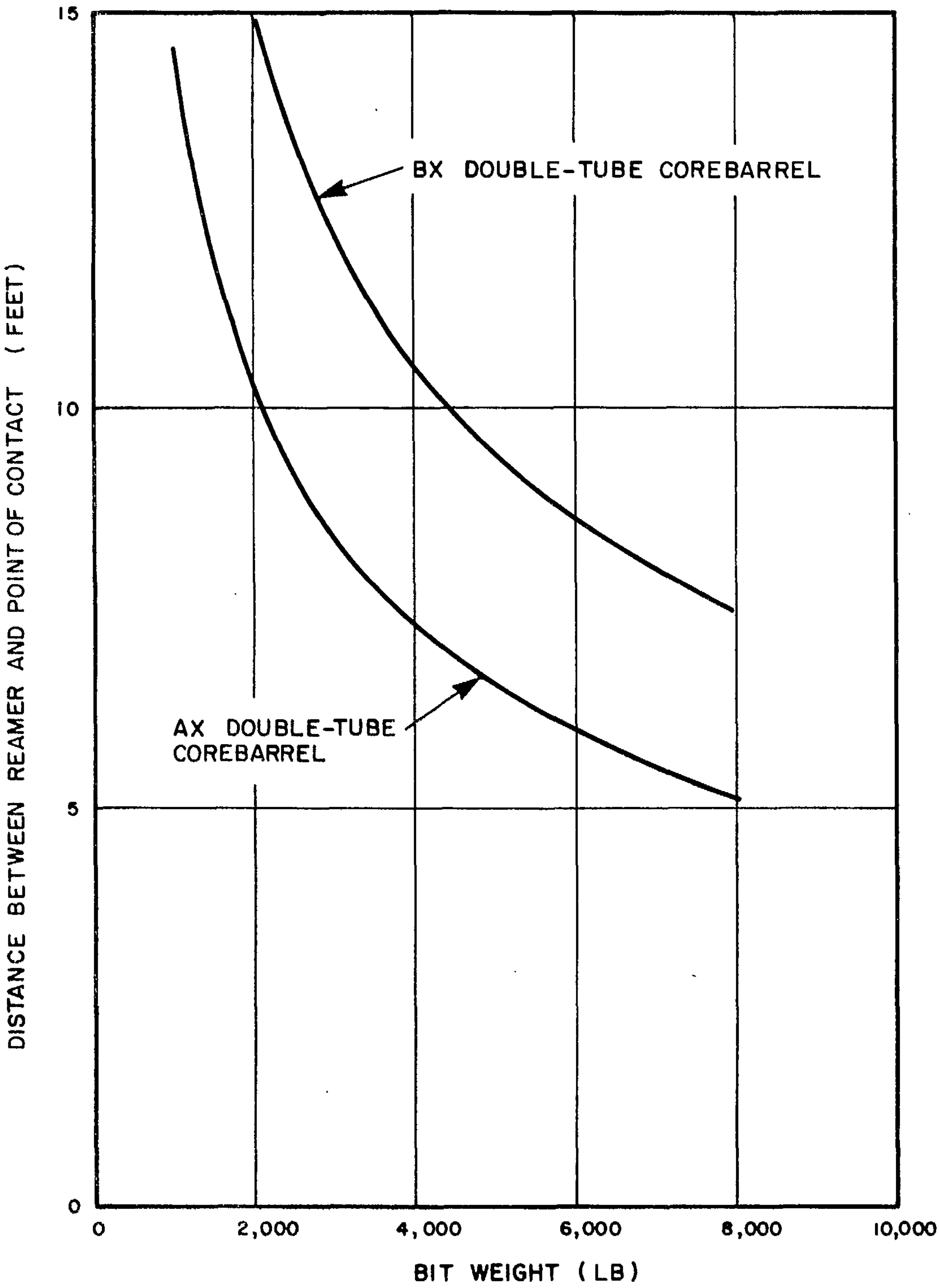

FIG. 5.14

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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

CONTACT LOCATION AS A FUNCTION OF BIT WEIGHT

ACRES

5.6 Transient Effects

Deviation can occur at interface of hard and soft rock.

In addition to deviation within homogeneous rock, localized deflection of a drill hole may occur at the interface of formations of different hardness. Gauthier (1967) proposed the theory that a pivoting effect occurs when a conventional bit with a rounded kerf drills from soft to hard rock. This is illustrated in Figure 5.15. He stated that when the interface is steeply sloping, there may be a tendency for the bit to slide down it, causing deviation toward the soft rock. Kopylov (1962) considered this type of deviation to be possible only when the transition is from very hard to very soft rock and the hard rock generates a large enough reaction on the bit to cause plastic action in the threaded portion of the bit.

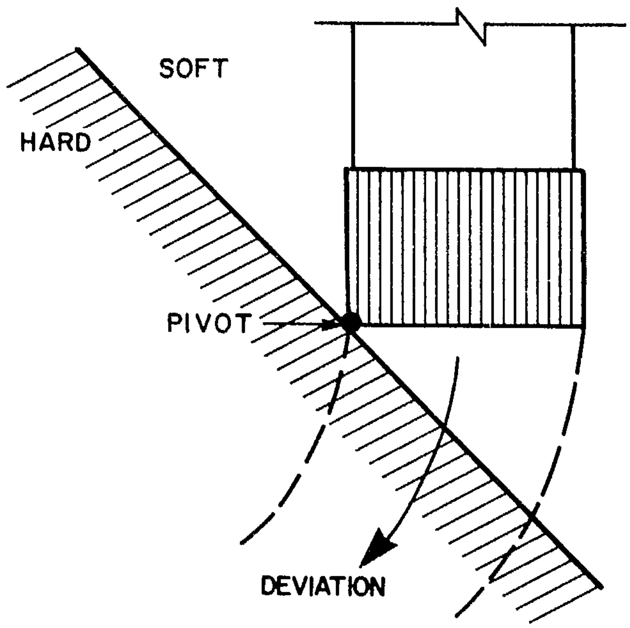
Reamer location influences direction of deviation.

One factor not considered in previous research which could influence the deviations at an interface is the reamer location. Contact exists between the drill string and the hole wall at the reaming shell. The direction of deviation, then, could depend on the relationship between the reaction from the hard rock and the reamer location. This is illustrated in Figure 5.16, where, for simplicity, reaction from the hard rock on the bit when initial contact is made is considered to be perpendicular to the interface. In Figure 5.16 (a), the slope is low and the pivoting action described by Gauthier occurs; in (b) the slope is steeper and the bit has a tendency to tilt in the opposite direction; in (c) the reaction from the hard ground passes through the centre of the reamer and there is no tendency for the bit face to deflect. The reamer location for this situation, defined in the Figure 5.16 (c), can be looked upon as an optimum reamer position for the given slope of interface. Alternatively, for a fixed reamer location there is a critical value of formation slope below which the hole tends to curve into the hard rock. For normal bit-reamer set-ups this angle would be 20 to 30 degrees. The presence of friction on the interface surface would be expected to increase this critical slope.

Optimum reamer location may eliminate deviation.

Kerf shape influences direction of deviation at interface.

In order to explain the influence of bit design on deviation, Gauthier introduced the concept of bit instability. For a given shape of kerf, it is possible to evaluate a pressure distribution for an axial load, P, on the bit, and the sum, I, of all the transverse pressure components can be calculated by integration over the complete kerf surface. The bit lateral instability index, i, is defined to be the ratio I/P. For a normal crown with the kerf of half-circle profile, i = 0 and the bit is considered to be inherently stable. In this case,



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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

PIVOTING AT INTERFACE

FIG. 5.15

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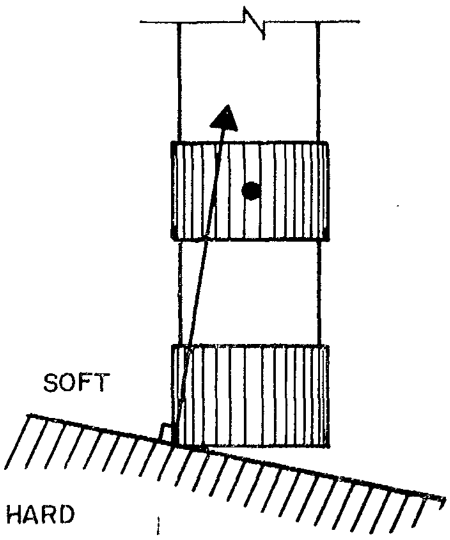
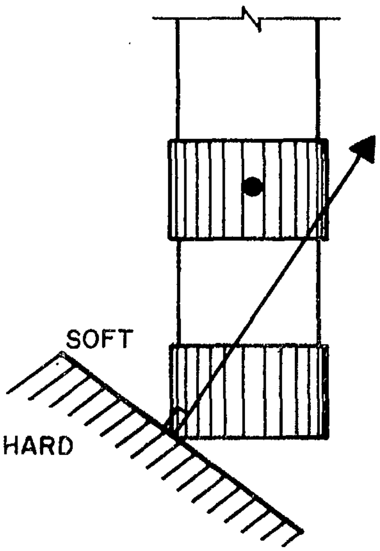
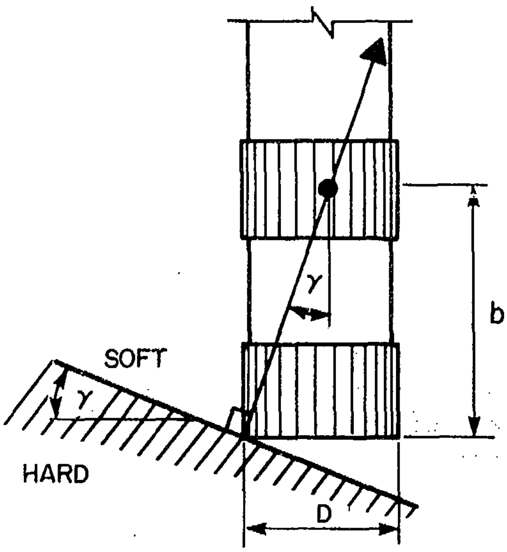


(A) GROUND REACTION PRODUCES CLOCKWISE MOMENT ABOUT CENTRE OF REAMER



(B) GROUND REACTION PRODUCES ANTICLOCKWISE MOMENT ABOUT CENTRE OF REAMER



$$b = \frac{D}{2\ \text{TAN}\ \gamma}$$

(C) GROUND REACTION PRODUCES NO MOMENT ABOUT CENTRE OF REAMER

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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

INFLUENCE OF REAMER ON PIVOTING

FIG. 5.16

ACRES

any elemental segment dψ , illustrated in Figure 5.17 (a), is in a state of transverse equilibrium due to the pressure distribution. For kerf shapes with i not equal to zero, as is the case in Figure 5.17 (b), any discontinuity or non-homogeniety in the formations can cause perturbation. For an unstable bit the out-of-balance transverse component of rock pressure must be equilibrated by hoop tension or compression in the kerf. It is presumably the spontaneous release and restoring of circumferential strain energy as the kerf comes into contact with variable rock properties which set up the vibrations described by Gauthier.

The concept of bit instability and consideration of bit profile are significant when drilling across a soft/hard interface. Gauthier demonstrated this by considering kerfs with conical faces as shown in Figure 5.18. In addition to any pivoting action about the hard rock, the horizontal component of the pressure on the kerf influences deviation. When the conical surface is on the inside face of the kerf [Figure 5.18 (b)] it will increase the deviation into the hard ground, whereas when it is on the outside of the kerf, it will promote deviation down the slope of the interface [Figure 5.18 (a)].

Corresponding tendencies for deviation in the transition from hard to soft rock are illustrated in Figure 5.19.

It is clear that with increased drill string stiffness and smaller clearances between corebarrel and hole, the possibility of the pivoting actions described above is reduced.

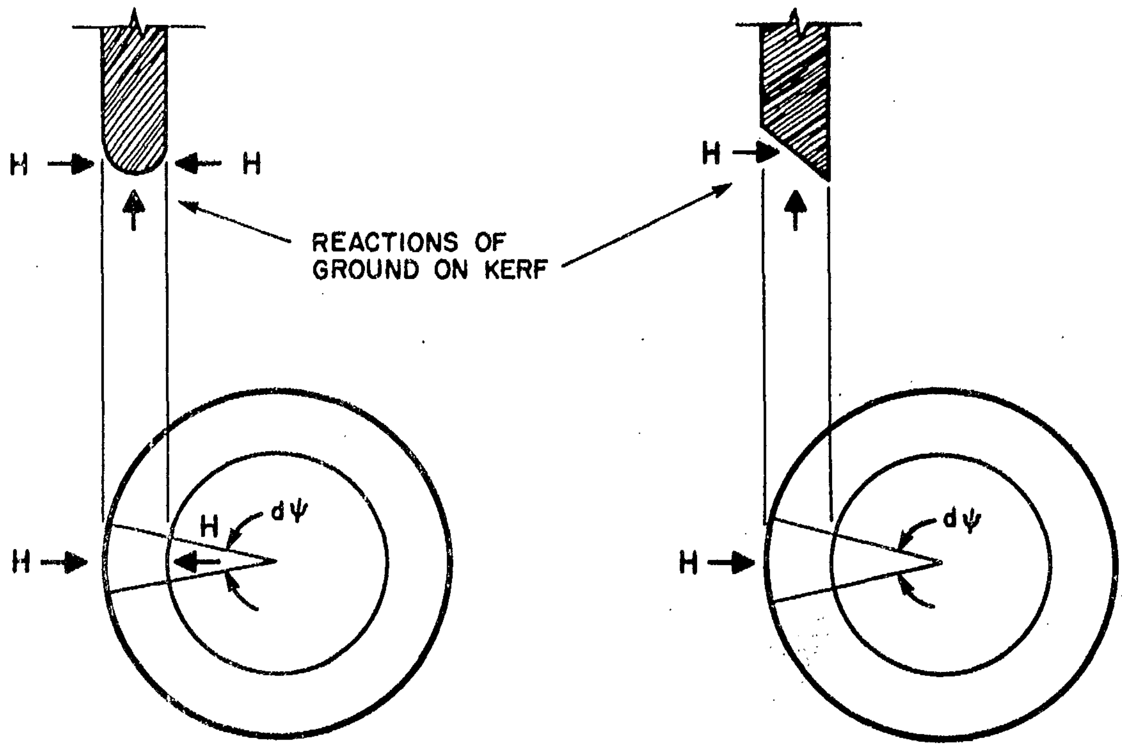
Increasing drill string stiffness and reducing clearance reduces deviation at interface.

To date, no theory has been proposed which quantifies the deviation of a hole as it passes through an interface, and much laboratory or field testing would be necessary to verify any theory. The usefulness of predictions based on this theory is likely to be extremely limited, since deviation is a function of the detailed geometry of the interface at the location where the bit crosses rather than being dependent on the average slope of the interface in the region.

5.7 Three-Dimensional Considerations

Hole deviations may occur in three dimensions.

In theoretical aspects of diamond drilling which have been discussed so far, hole deviation has been dealt with as a



(a) STABLE BIT

(b) UNSTABLE BIT

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BIT INSTABILITY

FIG. 5.17

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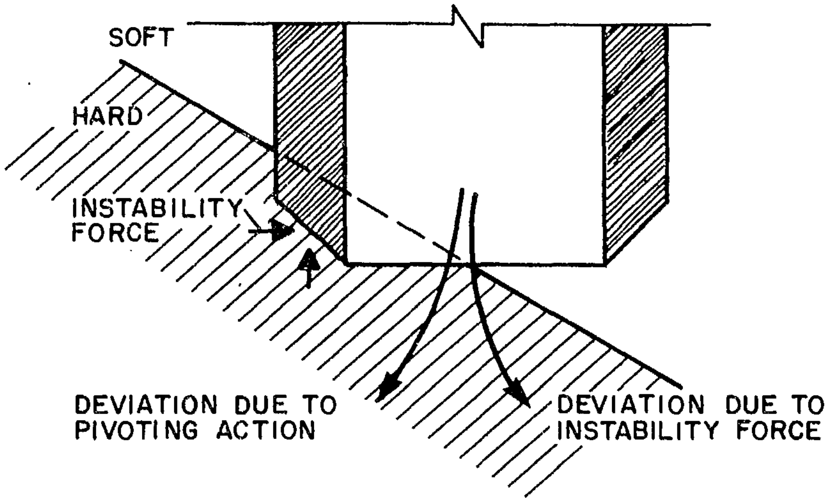
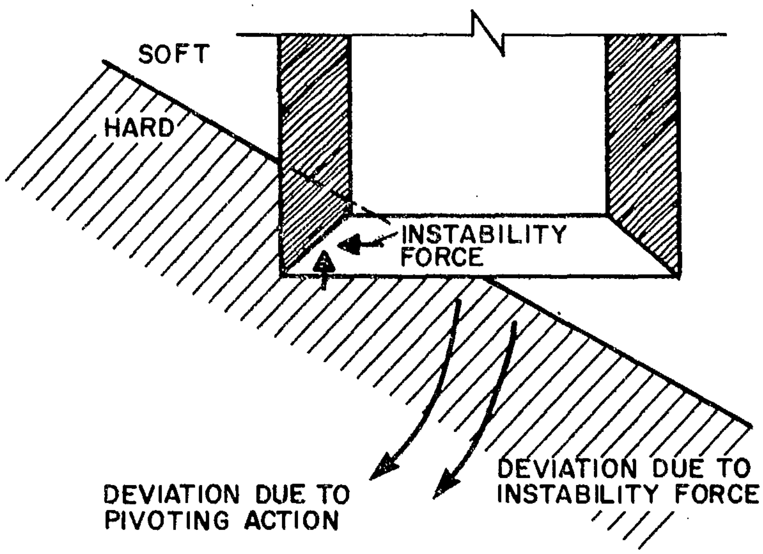


(a) CONVEX BIT



(b) CONCAVE BIT

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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

DEVIATION AT SOFT/HARD INTERFACE

FIG. 5.18

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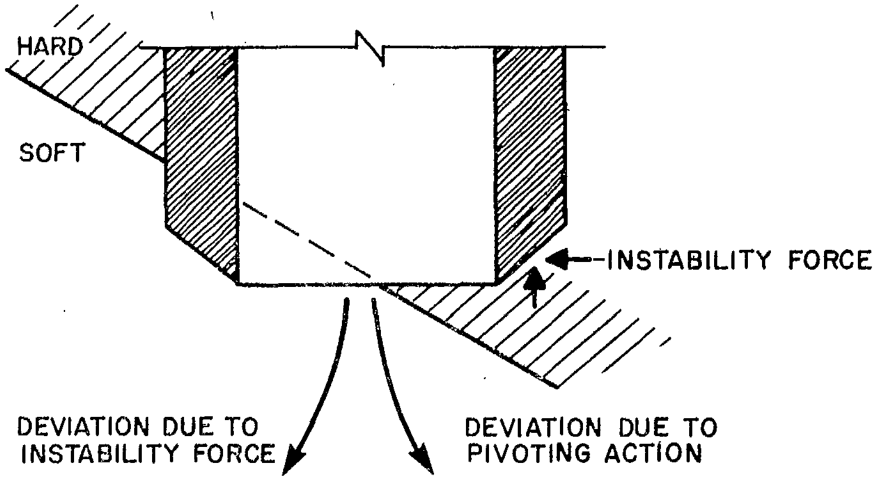
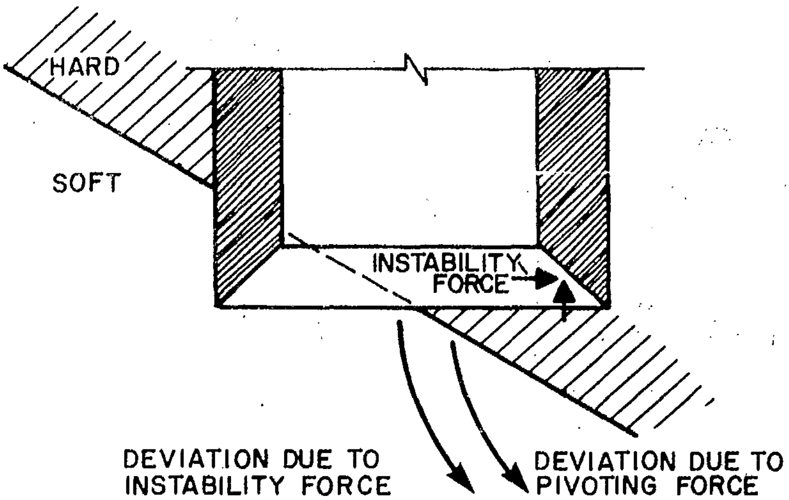


(a) CONVEX BIT



(b) CONCAVE BIT

FIG. 5.19

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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

DEVIATION AT HARD/SOFT INTERFACE

two-dimensional problem. In some instances, it is obvious that deviation will not be restricted to a vertical plane. For example, when a hole crosses a hard/soft interface, the problem is two-dimensional only if the hole axis lies in the interface dip plane. Similarly, if helical buckling takes place, three-dimensional changes in hole path are to be expected.

Lubinski assumed that when drilling in inclined beds with different drilling properties in-plane and perpendicular to the plane of the beds, holes deviate in the vertical dip plane of the beds. Bernhard (Discussion, Lubinski, 1953), using the concept of an anisotropy index, showed theoretically that this assumption is correct if rotational and frictional effects are neglected. When the beds are horizontal or the ground isotropic, there is no uniquely defined vertical dip plane and the initial direction of deviation is random. For this reason, if it is desirable to deviate in a specific direction, it is necessary to collar the hole at an angle. Once a direction has been established, neglecting frictional and dynamic effects and assuming the bit load is lower that the helical buckling load, the drill string takes up the minimum energy configuration lying along the low side of the hole. The influence of gravity on the portion of drill string between the point where it contacts the side of the hole and the bit ensures that the elastic line of the string lies in the vertical plane through the axis of the hole. Thus, the reaction of the bit on the ground also lies in this plane, and extension of the hole takes place accordingly.

Frictional effects in sloping hole cause azimuthal deviation.

In a short vertical hole in which the drill string is centred, friction at the bit should not create any preferential direction of deviation. However, in a sloping hole the bit "rolls" to one side of the hole as shown in Figure 5.20, where the clockwise rotating bit tends to deviate to the right in plan. By similar reasoning, an anticlockwise rotating bit should cause deviation to the left.

Mechanics of cutting in anisotropic rock result in azimuthal deviation.

Boyarko and Rozhkov (1965) in Russia considered the cutting action of the diamonds on a bit and showed that anisotropy in the rock influences azimuthal deviations as well as inclination of a hole. As in Lubinski and Wood's work, the rock was considered to have a plane of anisotropy, the direction of least resistance being defined to be normal to this plane. For anisotropic rock, the depth to which a diamond cuts is a function of the orientation of the cutting vector to the direction of least resistance.

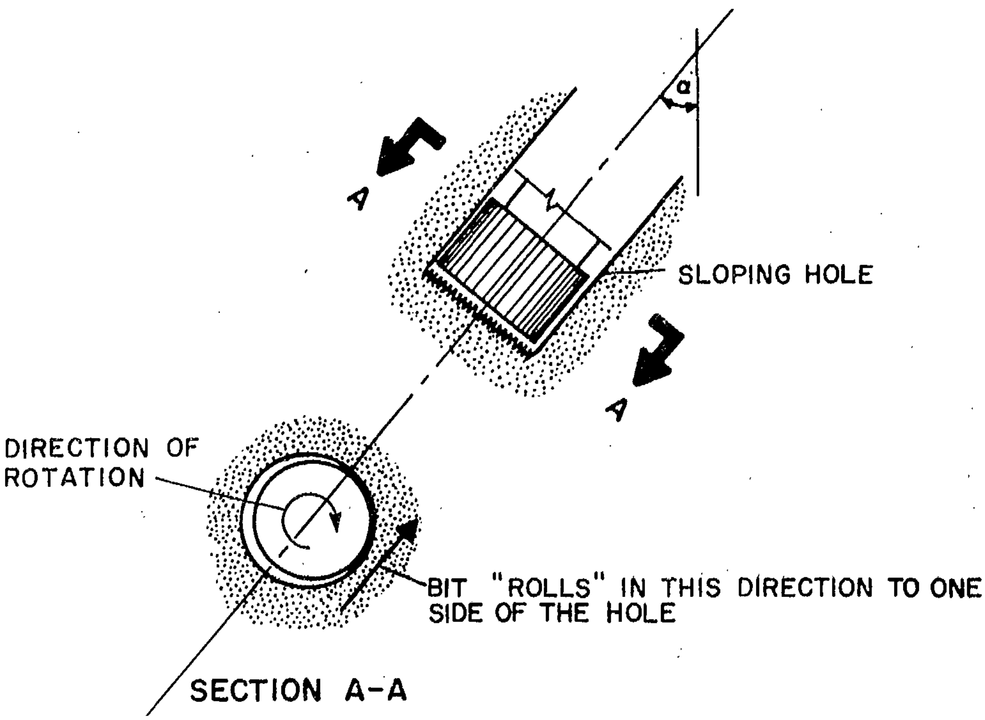

FIG. 5.20

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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

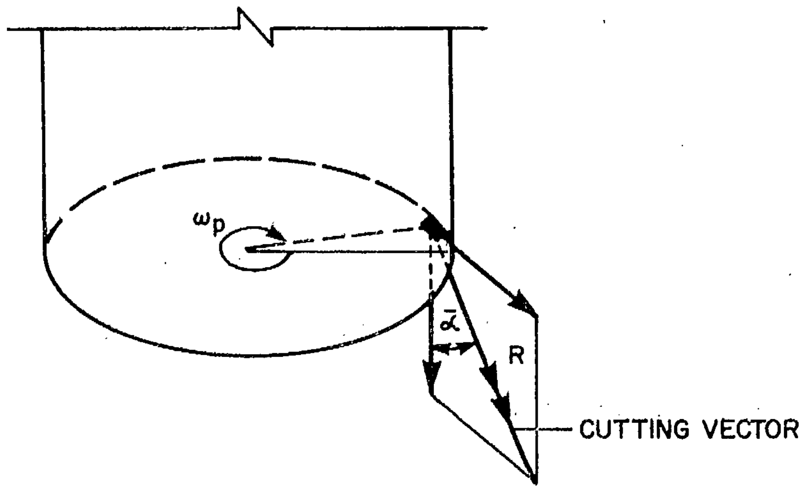
FRICTIONAL EFFECTS

ACRES

The cutting vector, R, produced by each diamond is the resultant of a tangential force in the plane of the kerf tip and a force parallel to the bit axis, and acts at an angle $\bar{\alpha}$ to this latter force (Figure 5.21). As the bit rotates the vector R also rotates and the angle $\bar{\gamma}$ between R and the line of least resistance is a function of the position of the diamond. To define the location of the diamond under consideration, the line of least resistance is projected onto the plane of the face of the bit, and the rotation of the diamond ω_p, is measured clockwise from this line as shown in Figure 5.21. Defining ϵ to be the angle between the line of least resistance and the bit axis, the following relationship was derived by Boyarko and Rozhkov:

$$\cos \bar{\gamma} = \cos \bar{\alpha} \cos \epsilon + \sin \bar{\alpha} \sin \epsilon \sin \omega_p .$$

The main feature of interest in this equation is that for given values of ϵ and $\bar{\alpha}$, $\bar{\gamma}$ increases as ω_p varies from 270 degrees to 90 degrees and decreases from 90 degrees to 270 degrees. They demonstrated this for the particular values of $\bar{\alpha}$ = 15 degrees and ϵ = 30 degrees and plotted the polar diagram shown as Curve I in Figure 5.22. Now when $\bar{\gamma}$ is smallest (at ω_p = 90 degrees) the vector R is closest to the line of least resistance of the rock and the depth of cut is greatest, whereas when $\bar{\gamma}$ reaches its maximum value (at ω_p = 270 degrees) the depth of cut is smallest. Boyarko carried out tests on amphibolite to relate the depth of cut to the inclination of the applied cutting vector. Since diamonds are located around the kerf, the deformation of the bottom of the hole can be estimated by plotting radially from the kerf the depth of cut appropriate for each value of $\bar{\gamma}$. Boyarko and Rozhkov obtained Curve II in Figure 5.22 in this way. It can be seen that one side cuts deeper than the other, so the bit will tend to tilt and deviate in the direction of B. The resulting behavior is illustrated in Figure 5.23 where an inclined hole heading updip swings in azimuth to the right, whereas a hole heading downdip swings in azimuth to the left. Reversal of the direction of rotation of the bit causes Curves I and II in Figure 5.22 to rotate through 180 degrees so the updip hole now turns left and the downdip hole turns right.



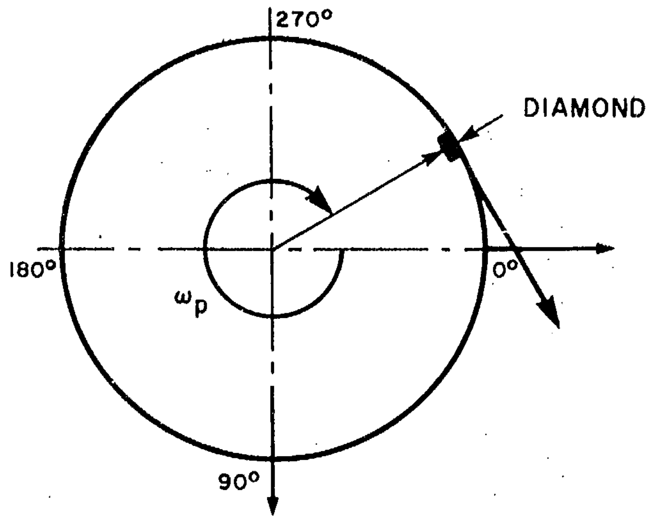


FIG. 5.21

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ORIENTATION OF CUTTING VECTOR

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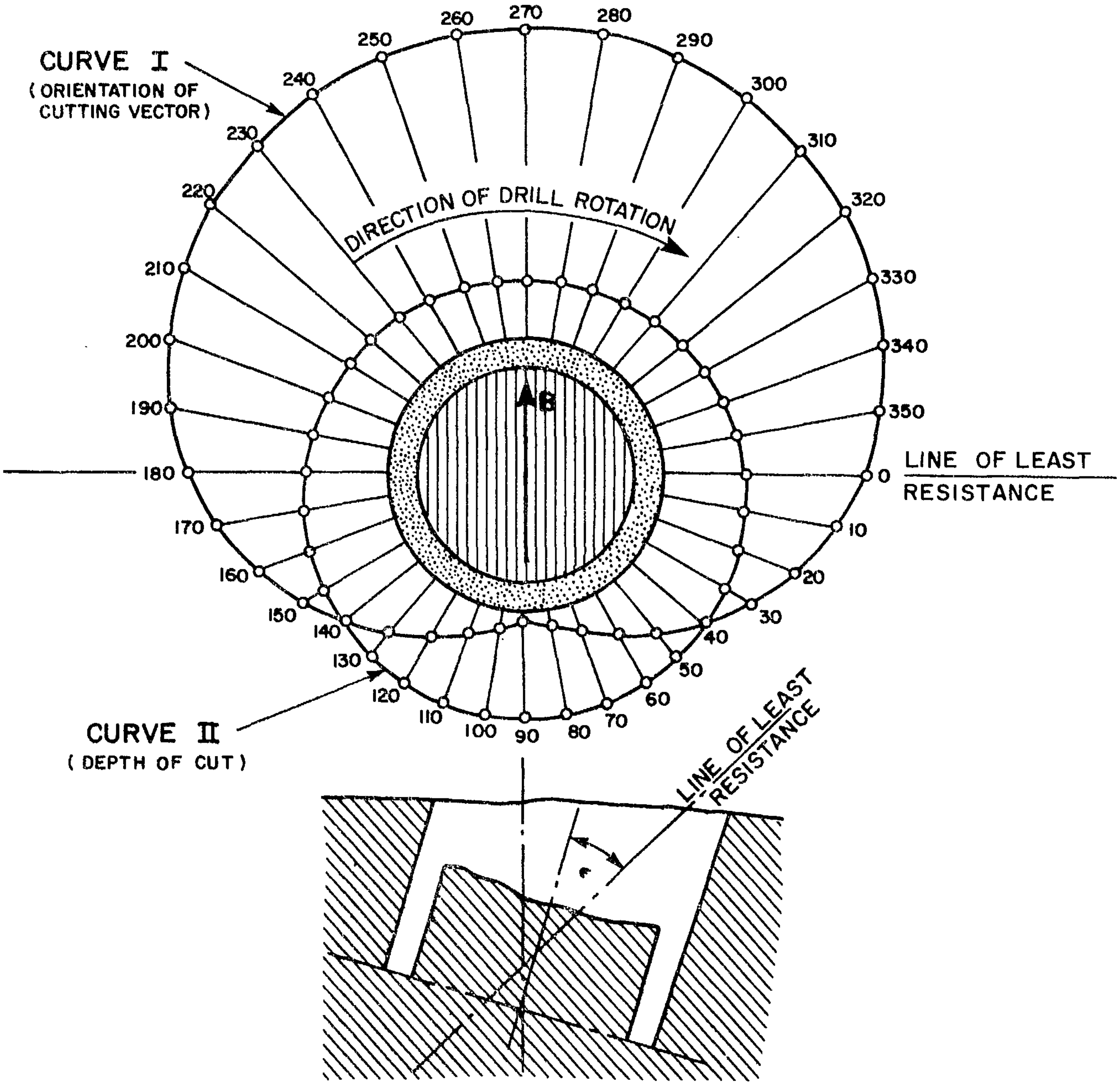

SOURCE:
FROM BOYARKO AND ROZHKOV (1965)

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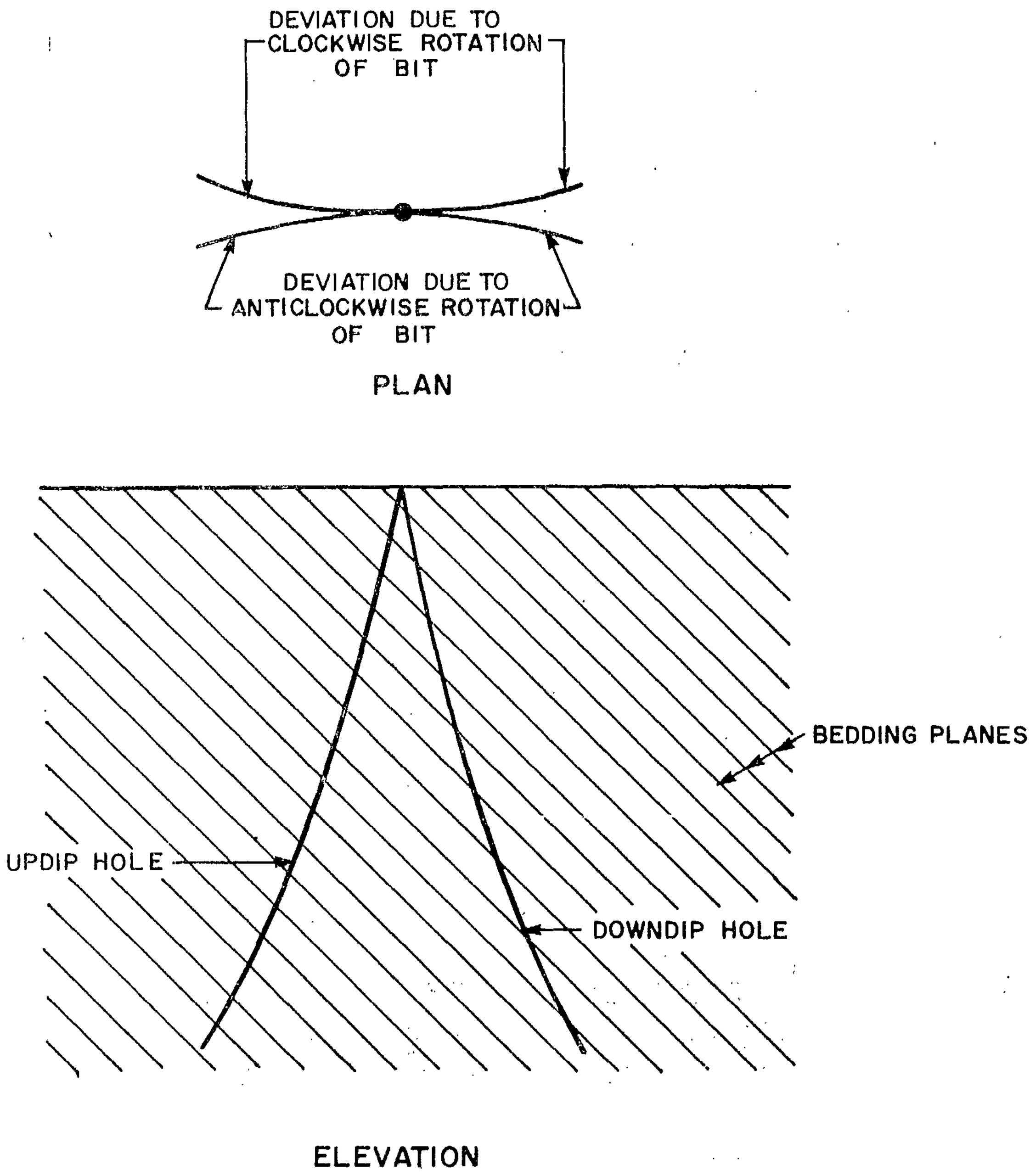
A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

FIG. 5.22

INFLUENCE OF ANISOTROPY ON AZIMUTHAL DEVIATION



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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

AZIMUTHAL DEVIATIONS DUE TO ROCK ANISOTROPY

FIG. 5.23

ACRES

Theoretically then, any azimuthal deviation resulting from both ground anistropy and frictional effects may be reversed by reversing the direction of rotation of the bit. Boyarko and Rozhkov presented a case history where this procedure was carried out successfully. However, the necessity for having left-hand and right-hand threaded equipment available on site makes this remedial measure for azimuthal deviation impractical with present-day equipment.

Direction of bit rotation affects azimuthal deviation.

6 OBSERVED BEHAVIOR OF HOLES

6.1 Introduction

Available hole data are of limited use since significant parameters not recorded

Hole data from several sources have been studied to check theoretical concepts and establish the order of magnitude of hole deviations in the field. Most hole data which are available are of limited use, since information relevant to the problem of hole deviation has not been recorded. The most important unknown quantity is bit weight. Details of the equipment used (e.g. bit design, type and location of reaming shell, etc.) would make a more exhaustive study of hole data possible.

6.2 Hole Surveying

Holes are surveyed by measuring inclination and azimuthal bearing of hole at several depths.

Survey methods used to define the path of a hole are based on the measurement of the angle of inclination to the vertical and the azimuthal bearing at discrete locations throughout the length of the hole. Hole co-ordinates can be derived from these measured data.

The simplest and most common survey technique used in practice is the acid bottle test, which measures only inclination angle. In some cases, where experience has shown azimuthal deviation to be small, this may be satisfactory. The test is based on acid etching a mark on the inside of the bottle which contains it. Acid bottles can be located at several positions along the length of a drill string and inclination angles derived from the etches which are obtained. Where accurate surveys are required the acid bottle test is often used to supplement the data obtained using more sophisticated equipment.

The commonly used survey instruments which measure both inclination and bearing operate on a magnetic principle. These consist basically of a compass mounted in gimbals with a timing mechanism set to lock after the unit has been positioned in the hole. The drill string has to be withdrawn and the instrument read and unlocked before the next reading can be taken. This difficulty has been overcome by the development of multishot equipment containing a miniature camera to photograph the readings in place, allowing survey of as many depths as required without withdrawal of the drill string. All instruments incorporating a compass needle may give anomalous results in the vicinity of rock with magnetic properties. A gyroscopic compass small enough to be used in AX holes has been developed, but high cost has discouraged its use in Canada up till now.

6.3 Holes at Henry Borden II Power Plant, Brazil

Acres was involved in the drilling of several holes in connection with dewatering operations at the Henry Borden II Power Plant in South America. Figure 6.1 shows a plan and longitudinal section of the region in which the holes were located. The holes, apart from hole S-5A, were collared vertically and drilled NX size through the weathered rock and cased in BX casing. The remaining lengths of the holes were drilled with BX size diamond coring equipment without casing. Double-tube corebarrels were used except for hole DH-3 which was drilled with a single-tube corebarrel with guide rods (oversize drill rods) behind the corebarrel. Hole surveys were carried out at intervals of 10 to 15 metres. Typical survey results, for holes DH-3 and DH-4 are presented in Table 6.1. With the exception of hole S-2A, which was located at the top of a plateau where the rock is deeply weathered, holes tended to deviate updip in the plane perpendicular to the strike of local foliation. In anticipation of the updip deviation, hole S-5A was collared at 4 degrees to vertical, heading downdip. It deviated to become vertical at about half its final length and remained close to vertical for the remainder of the hole.

Holes at power plant deviate close to plane perpendicular to strike of regional foliation.

Although the general trend was to deviate close to the plane perpendicular to the strike of foliation, there were slight differences in the azimuthal deviations of the various holes. For example, holes DH-3 and DH-4 curved to the right in plan, whereas hole DH-1 curved to the left and hole S-8 deviated in different directions in different portions of its length. This behavior is probably dependent upon the orientation of the plane of buckling of the drill string, as well as the orientation of local foliation and jointing.

Small azimuthal deviations occur.

Rates of change of inclination angle of the holes were studied by plotting inclination angles to the vertical as a function of depth drilled. Typical curves are plotted in Figures 6.2 and 6.3 for holes DH-3 and DH-4, respectively. With the exception of hole DH-4, after the initial change of azimuth, the rate of change of the hole inclination with depth remained reasonably constant throughout

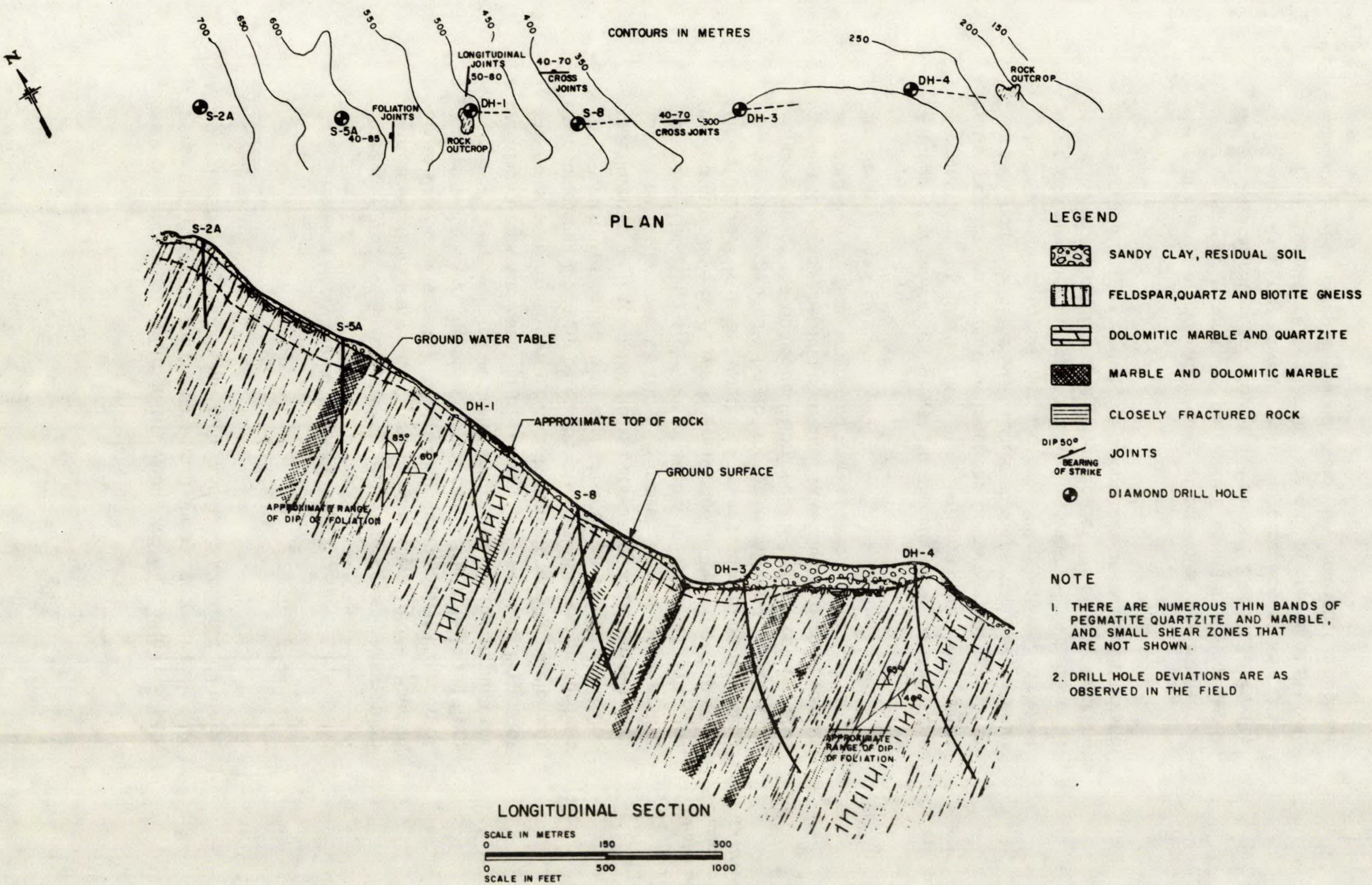

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FIG. 6.1

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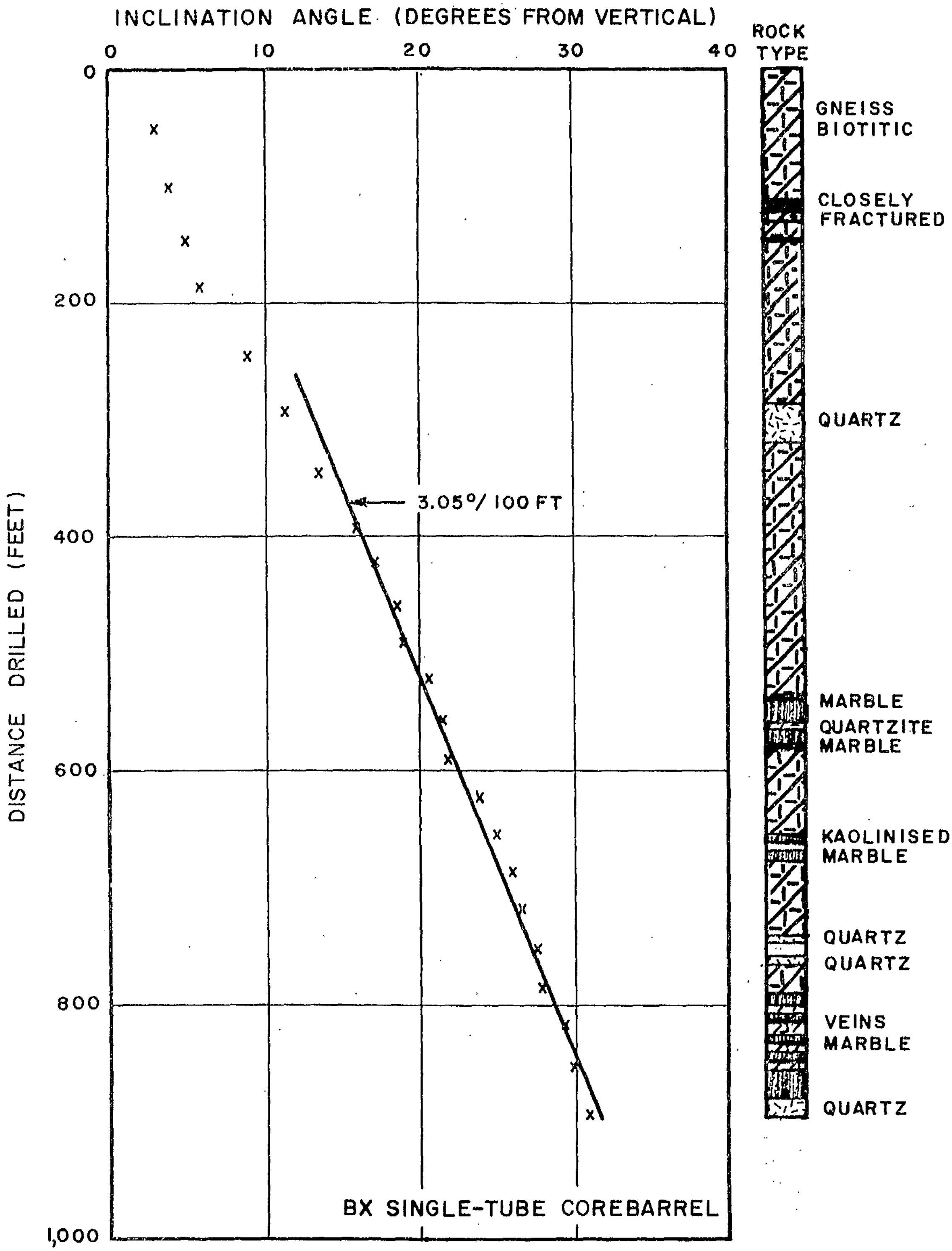
A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING
HOLES AT HENRY BORDEN II POWER PLANT

ACRES

TABLE 6.1

SURVEY DATA FOR HOLES DH-3
AND DH-4 AT HENRY BORDEN PLANT II

Hole DH-3			Hole DH-4		
Depth (feet)	Inclination Angle (degrees from vertical)	Azimuthal Bearing (degrees)	Depth (feet)	Inclination Angle (degrees from vertical)	Azimuthal Bearing (degrees)
49	3.0	59.0	49	1.0	59.0
98	4.0	82.5	98	2.0	99.0
148	5.0	84.0	148	5.0	112.0
188	6.0	93.0	196	7.0	115.0
246	9.0	105.0	246	9.0	116.0
295	11.5	110.0	295	12.0	121.0
344	13.5	108.0	344	15.0	123.0
393	16.0	109.5	393	18.0	123.0
426	17.0	112.0	426	19.0	124.0
459	18.5	110.0	459	20.0	125.0
492	19.0	102.5	492	23.0	126.0
524	20.5	113.0	524	23.5	123.5
558	21.5	113.0	558	25.5	124.5
590	22.0	114.0	590	27.5	125.5
623	24.0	114.5	623	30.0	126.0
656	25.0	114.0	656	30.5	126.5
689	26.0	118.0	689	32.5	128.0
721	26.5	114.0	721	33.5	126.5
754	27.5	111.5	754	34.0	125.5
787	28.0	119.0	787	34.5	126.0
820	29.5	117.0	820	35.0	128.5
853	30.0	119.0	853	36.0	128.0
894	31.0	116.0	872	36.5	128.0



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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

HOLE DH-3 AT HENRY BORDEN II

FIG. 6.2

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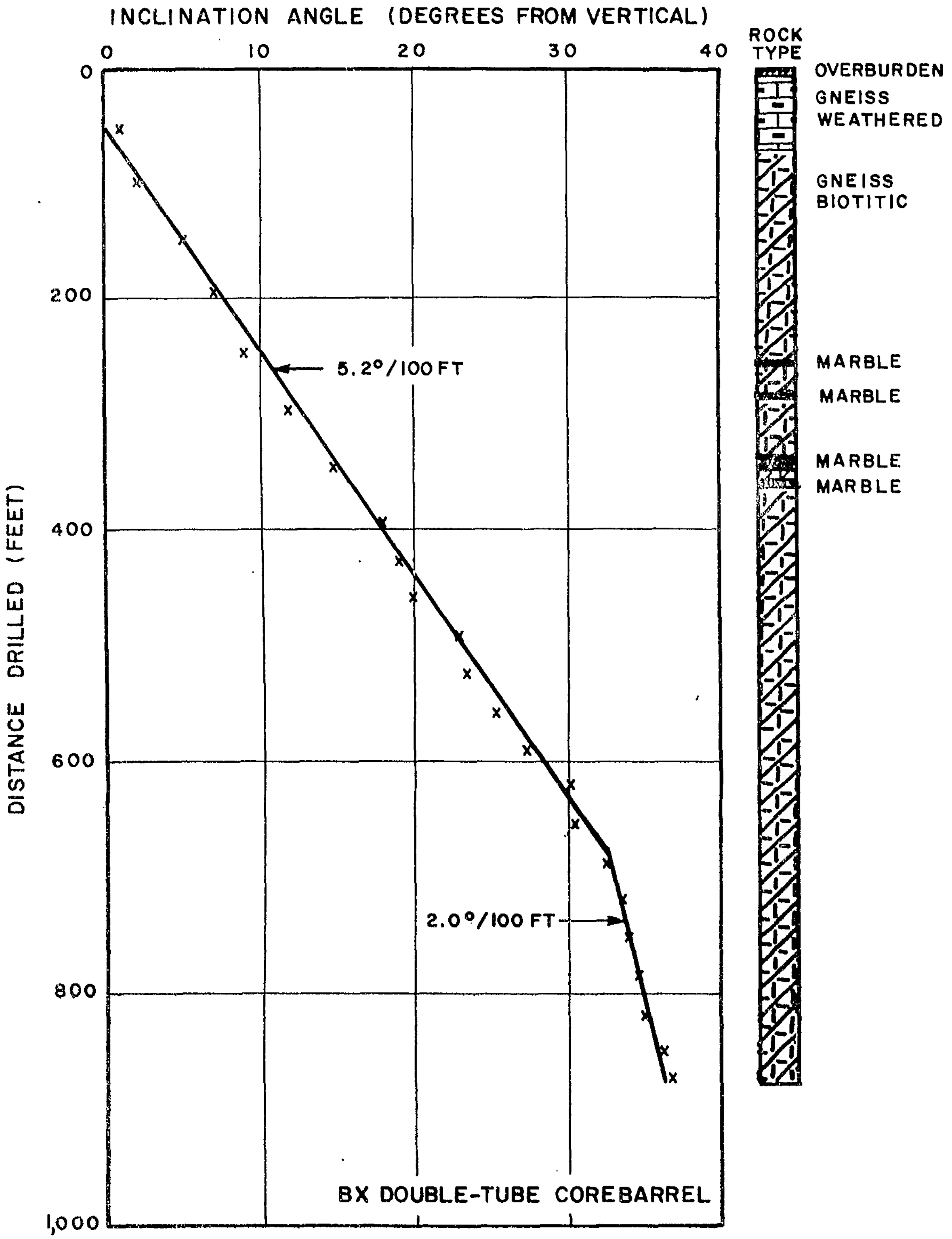

FIG. 6.3

MINING RESEARCH CENTRE, DEPARTMENT OF ENERGY, MINES AND RESOURCES

A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

HOLE DH-4 AT HENRY BORDEN II

ACRES

the length of each hole. Deviation rates were 2.2 degrees per 100 feet, 3.4 degrees per 100 feet and 3.1 degrees per 100 feet for holes DH-1, S-8 and DH-3.

Longest hole shows distinct decrease in deviation rate close to bottom.

Hole DH-4 had a rate of change of inclination of approximately 5.2 degrees per 100 feet throughout most of its length but this changed to 2.0 degrees per 100 feet near the bottom of the hole. There was no significant change in rock conditions, so it is likely that the decrease in deviation rate was associated with the hole approaching normality to the foliation. Although hole DH-3, drilled with the single-tube corebarrel with guide rods, deviated less than holes DH-4 and S-8, it deviated more than hole DH-1, so conclusions cannot be drawn as to the effectiveness of the guide rods and single-tube corebarrel. It should be pointed out that about half the length of hole S-8 was originally an AX hole which was widened to BX size. There was, however, no distinct difference in the deviation rates in the old and new portions of the hole.

6.4 Canadian Experience

Very little material has been published on diamond drill hole deviations in Canada. Robertson (1962) studied deviations which occurred in AX holes drilled in the sedimentary rocks of the Blind River syncline. He produced Table 6.2 giving average deviation rates for various stratigraphic units, but noted that the values include the influence of wedges and so may be minimal for a particular unit. Greatest deviations occurred in the Middle Mississagi formation which is made up mainly of soft, fine-grained, banded argillite or grit, with occasional harder bands of fine-grained quartz or feldspar. The mechanism of deviation described in Section 5.6 for a bit passing through materials of different hardness could well be relevant in this situation. Most holes were collared vertically, and all holes deviated updip, tending toward normality to the bedding. However, Robertson pointed out that in cases of severe deviation holes passed through the normal and continued deviating updip. This is an important observation, since it is consistent with the concept of continuous deviation anticipated by theoretical consideration of reamer action.

High deviation rates occur in argillite and holes continue to change inclination after passing through normal to foliation.

Some data from holes drilled in the Sudbury Basin of Ontario have been made available to Acres. There is great variability in the deviations which occur in the area, with greatest deviations in the most complex geological conditions.

Data from holes in Sudbury Basin were examined.

TABLE 6.2

DEVIATION RATES OF AX HOLES
AT BLIND RIVER from Robertson (1962)

Stratigraphic Unit	No. of AX Holes (AXT cores)	Average Increase in Deviation (degrees per 100 feet)	Remarks
Espanola Greywacke	7	0.5	Medium hard
Bruce Limestone	10	0.8	Medium soft
Upper Mississagi	39	0.32	Hard
Middle Mississagi	39	1.36	Soft
Lower Mississagi	39	0.5	Hard

Low deviation rates occur in unfractured norite.

All the holes examined in one region, where the rock is reasonably homogeneous and unfractured, had rates of change of inclination angle of less than 0.5 degrees per 100 feet. Figure 6.4 shows the angle of inclination plotted as a function of depth for one of the longer AX holes. The norite in the vicinity has plagioclase laths lying in a plane dipping at about 17 degrees, and the hole deviated updip with very little change in azimuth. Three wedges prevented the hole inclination becoming large, and the maximum deviation rate which occurred was close to 0.5 degrees per 100 feet. Another hole only 200 feet away had a maximum deviation rate of 0.2 degrees per 100 feet. Several holes in the vicinity did have significant changes in azimuth, but there was not a consistent pattern to this deviation. More detailed information on strikes and dips of crystal layering in the vicinity of specific holes is necessary before these can be fully explained.

AX hole deviates at three times rate of BX hole.

An example where an AX and a BX hole were drilled from the same underground station is illustrated in Figure 6.5, which shows projections of the holes in elevation onto the local mine grid. In both cases, wireline equipment fitted with a Mini-Deve stabilizer (see Section 3.4) was used. A major length of each hole was drilled in reasonably sound homogeneous norite with no obvious evidence of foliation. However, in other regions of the Sudbury Basin, crystal layering which cannot be easily detected is known to exist and a closer study might well prove that it occurs here also. Close to the contact with the granite gneiss of the footwall rock, the norite is contorted and fractured. The granite gneiss in this region also has a complicated structure, but the foliation generally trends parallel to the contact. Inclination angles obtained in surveys of the AX and BX holes are plotted in Figures 6.6 and 6.7. The AX hole, which was collared at an inclination of about 15 degrees, initially steepened slightly before flattening out at a rate of about 0.47 degrees per 100 feet. The BX hole, which was collared vertically, deviated at one third of this rate, i.e., 0.16 degrees per 100 feet.

Significant steepening found in some AX holes.

In the same general area, two other AX holes showed very significant steepening as indicated in the survey data in Figures 6.8 and 6.9. Elevations of the holes are provided in Figure 6.10. Both holes were drilled with conventional drill strings, using AX rods and AXT corebarrels and bits. Hole I remained straight on crossing the

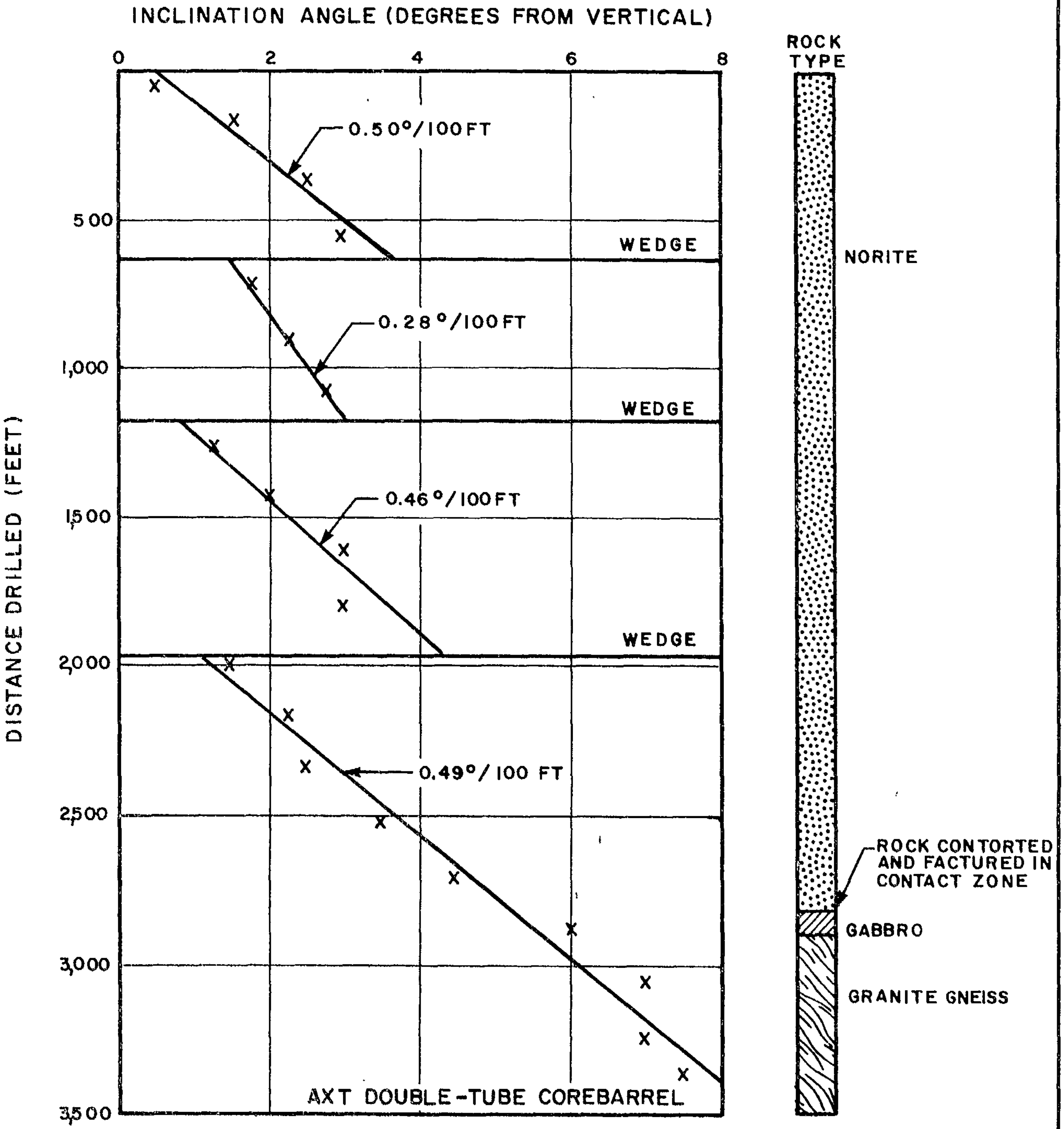

FIG. 6.4

MINING RESEARCH CENTRE, DEPARTMENT OF ENERGY, MINES AND RESOURCES

A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

WEDGED HOLE IN NORITE

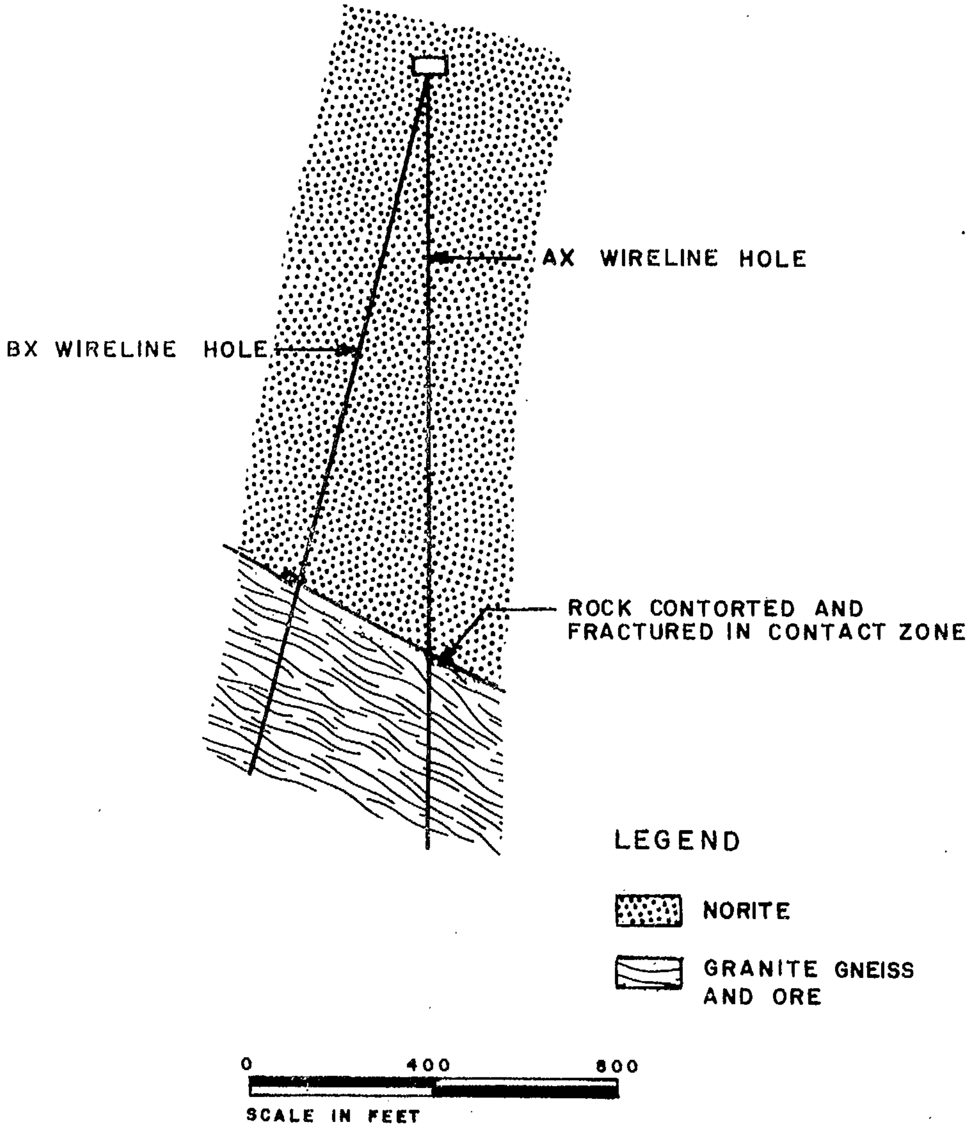

FIG. 6.5

MINING RESEARCH CENTRE, DEPARTMENT OF ENERGY, MINES AND RESOURCES

A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

ELEVATION OF WIRELINE HOLES IN NORITE

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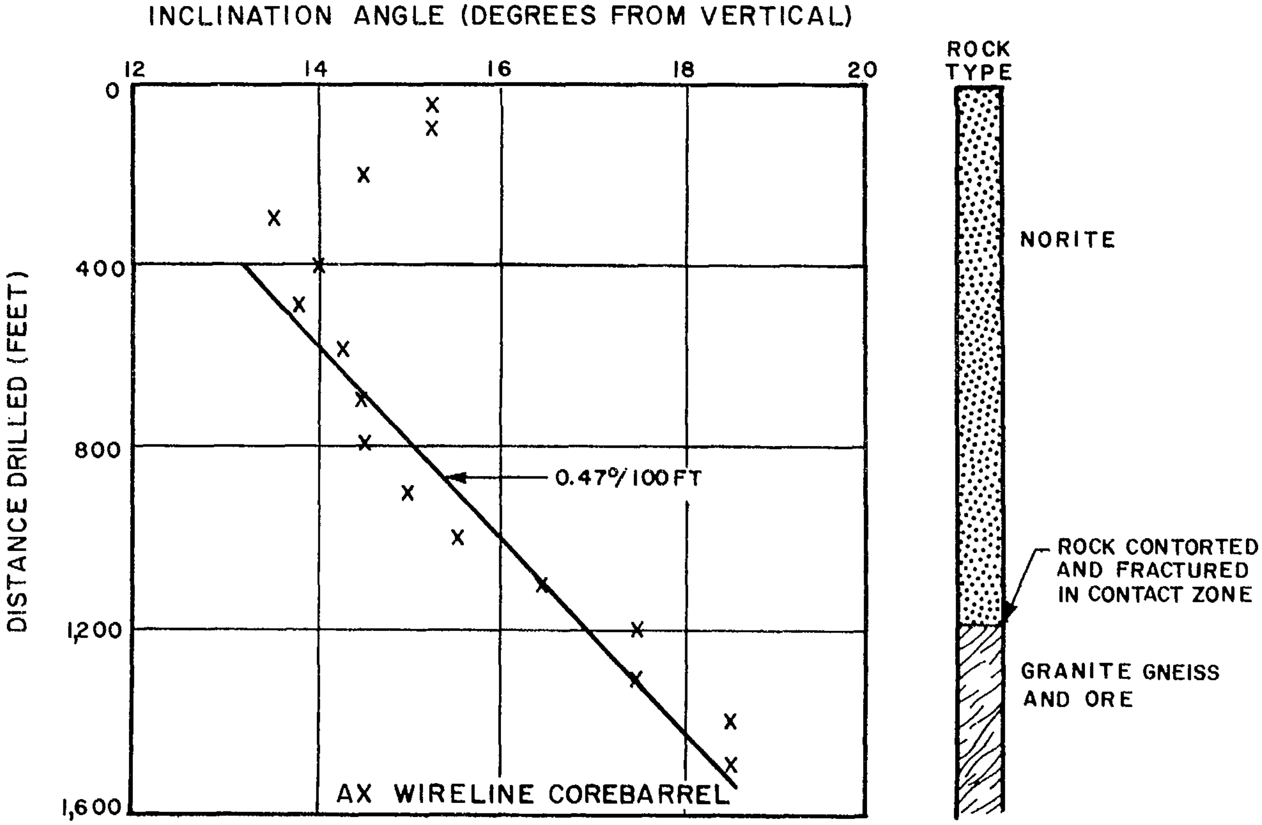

FIG. 6.6

MINING RESEARCH CENTRE, DEPARTMENT OF ENERGY, MINES AND RESOURCES

A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

AX WIRELINE HOLE IN NORITE

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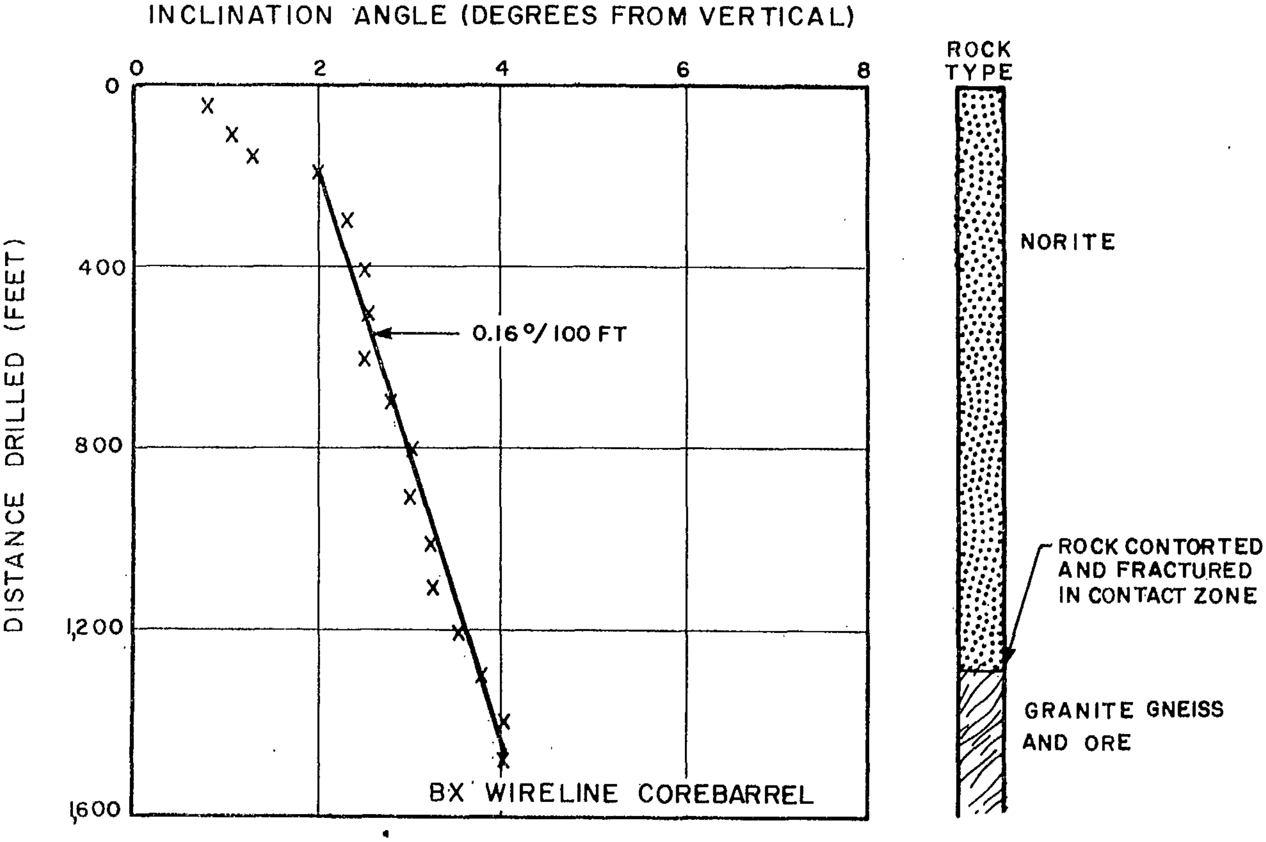

MINING RESEARCH CENTRE, DEPARTMENT OF ENERGY, MINES AND RESOURCES

A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

BX WIRELINE HOLE IN NORITE

FIG. 6.7

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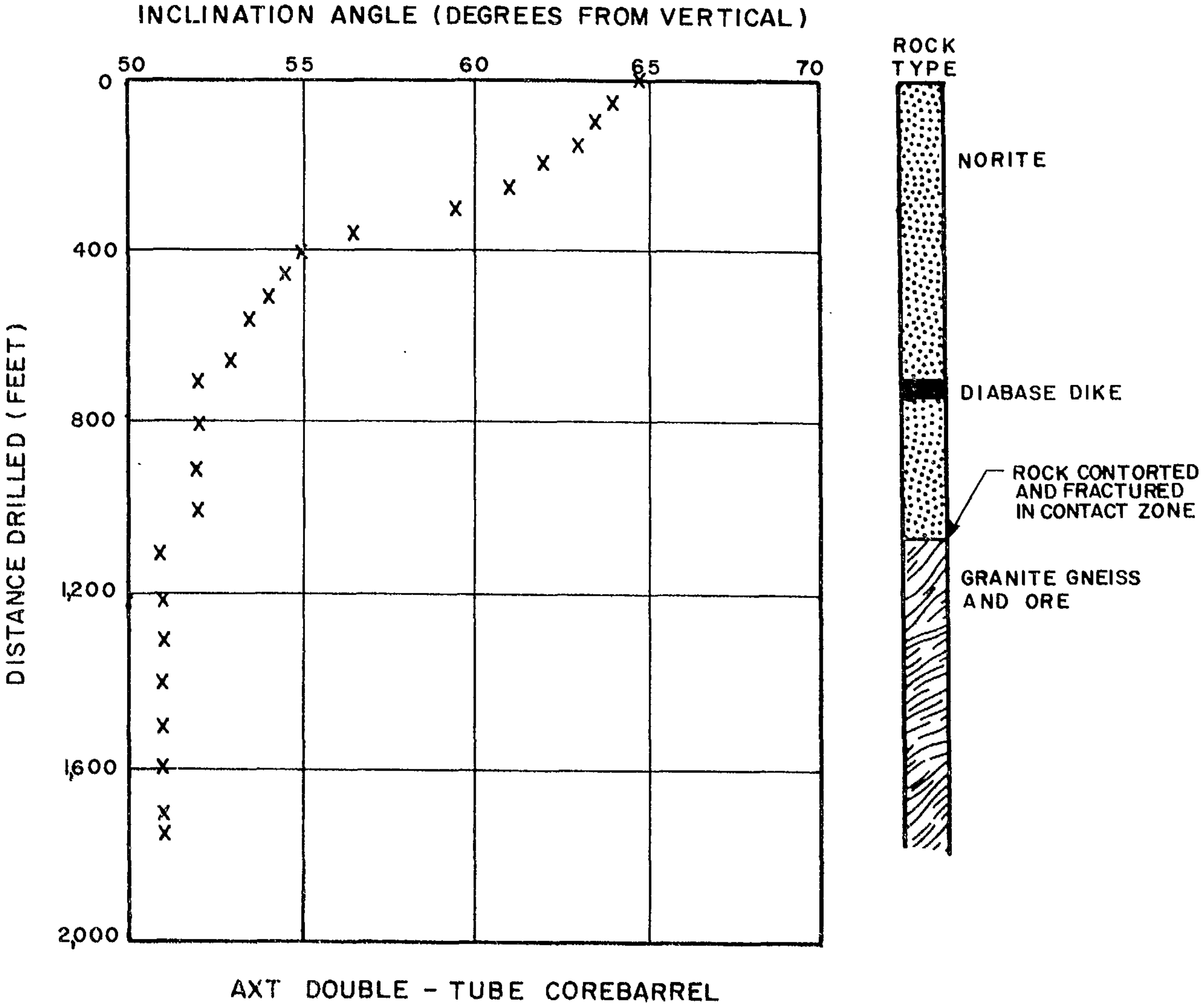

FIG. 6.8

MINING RESEARCH CENTRE, DEPARTMENT OF ENERGY, MINES AND RESOURCES

A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

STEEPENING HOLE I IN NORITE

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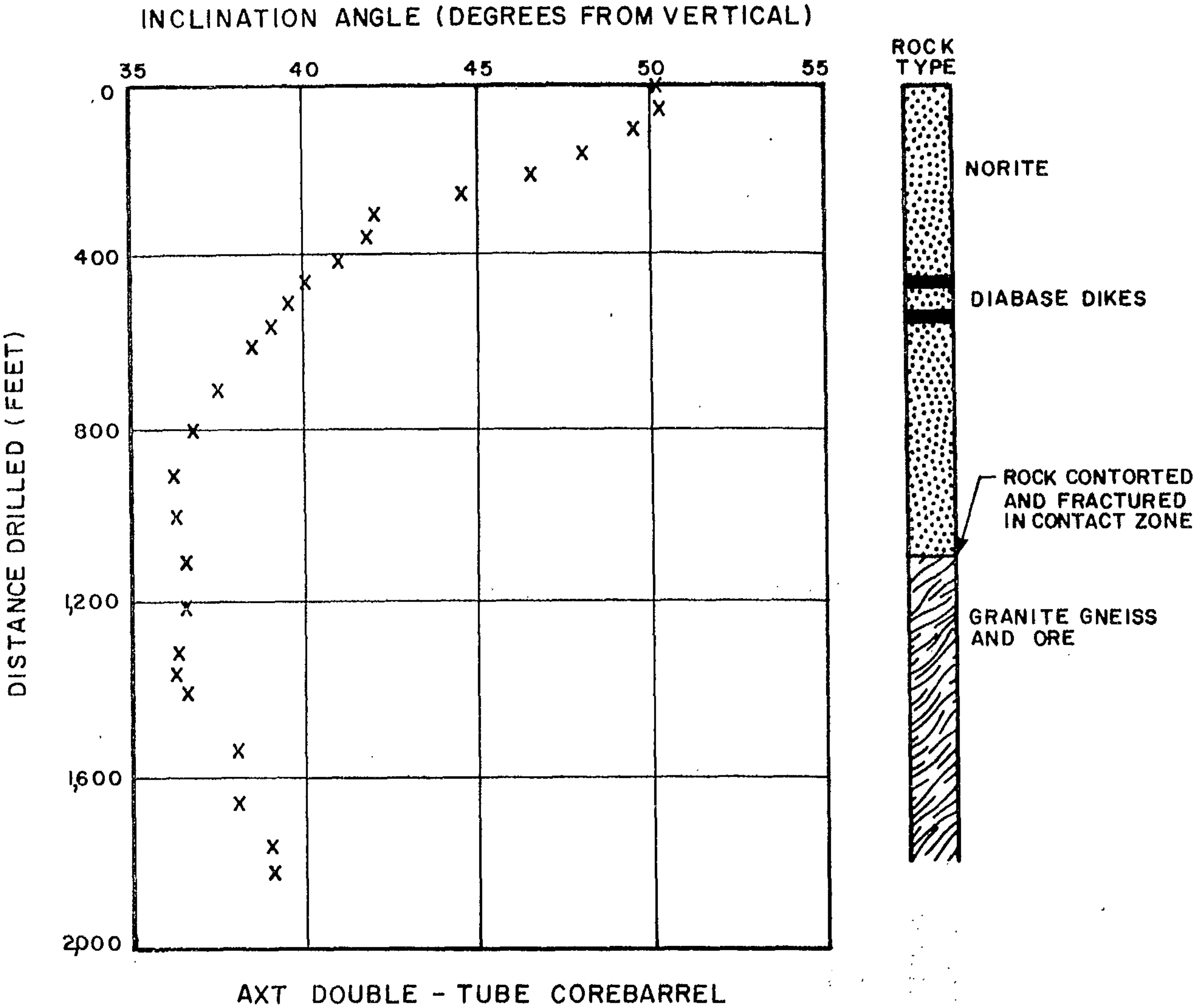

FIG. 6.9

MINING RESEARCH CENTRE, DEPARTMENT OF ENERGY, MINES AND RESOURCES

A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

STEEPENING HOLE II IN NORITE

AGRES

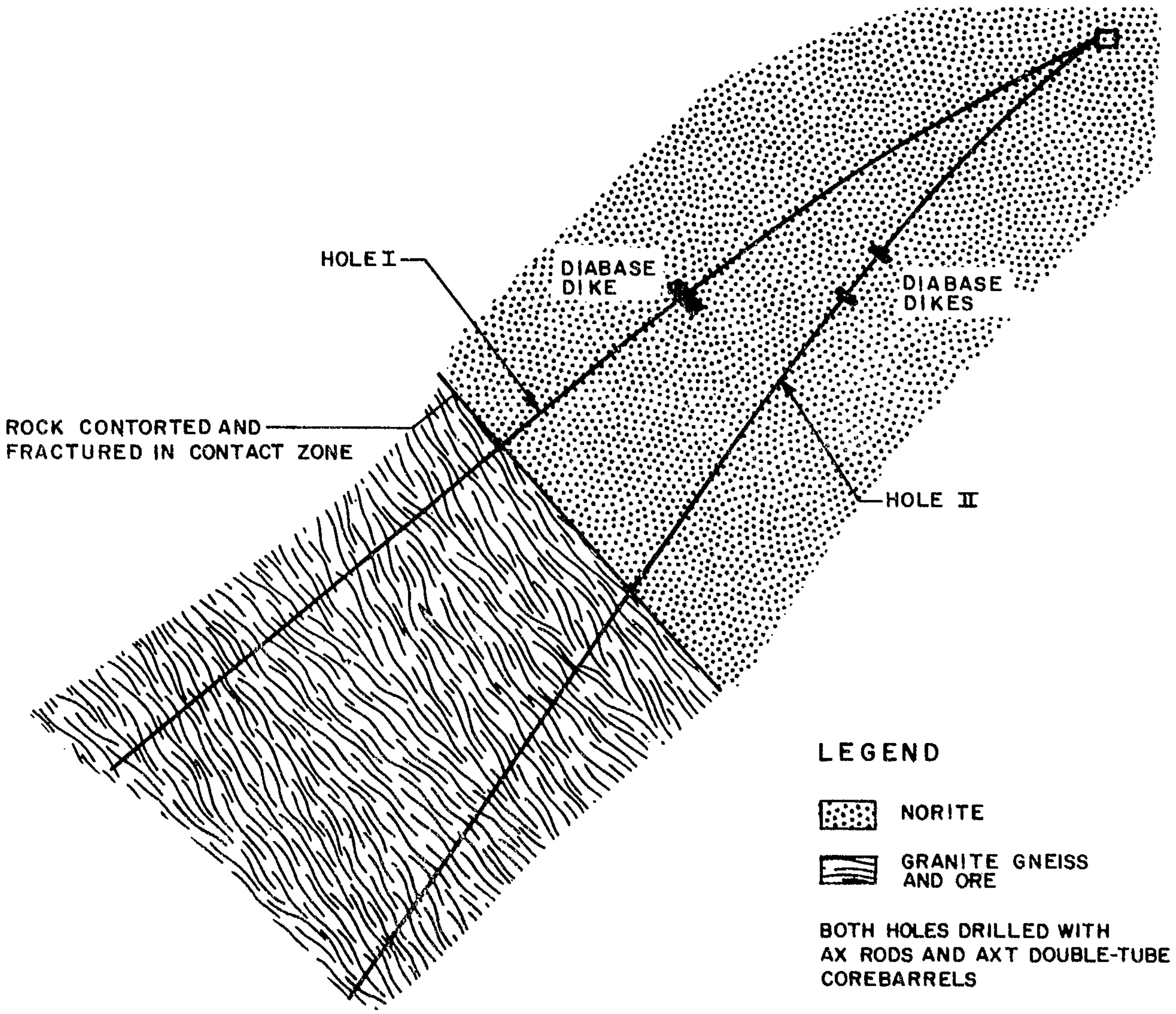

FIG. 6.10

MINING RESEARCH CENTRE, DEPARTMENT OF ENERGY, MINES AND RESOURCES

A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

ELEVATION OF STEEPENING HOLES IN NORITE

ACRES

norite-footwall contact, whereas hole II started to flatten. It is interesting to observe the different orientation the hole paths have with respect to the normal to the footwall contact. Hole I is flatter than the normal, whereas hole II is steeper, and since the foliation of the gneiss probably runs parallel to the contact, the deviation of hole II tends to bring it toward the normal. However, hole I does not steepen in the gneiss, as would be expected if all holes tended to become normal to the foliation. The dikes crossed by the holes do not appear to have changed hole direction. Survey data for a case in which a dike did cause deviation are presented in Figure 6.11. The hole maintained more or less a straight path for about 1,000 feet and then deviated rather erratically after crossing a diabase dike. There is, unfortunately, no information available on the orientation of the dike. Another example where a hole was drilled for 1,000 feet without deviation is presented in Figure 6.12. Nine wedges had to be placed to deviate this hole in a desired direction, after which deviation continued at a rate less than 1 degree per 100 feet. These last two examples are the exception rather than the rule, but they do provide evidence that in some conditions a straight hole can be drilled.

Straight hole is deflected by dike.

Straight hole can sometimes be drilled.

6.5 Experience in Other Countries

Cottle (1961) described deviations occurring at Rosebery, Tasmania, where no attempt is made to keep holes straight. Sufficient experience has been gained to anticipate deviation and offset the collar in such a way that a hole strikes target. Most holes are drilled at right angles to the strike of the regional schistosity, and azimuthal deviations are small. The general behavior illustrated in Figure 6.13 has been found to occur in zones of distinct schistosity. Holes drilled 2 or 3 degrees steeper or flatter than the schistosity have totally different characteristics. Holes directed along the line of schistosity eventually swing one way or the other toward normality to the schistosity Cottle claims there is no tendency for holes at acute angles to the plane of schistosity to seek parallelism to this plane. The geology of the area and the behavior of four holes are illustrated in Figure 6.14. There is a marked schistosity dipping at 55 degrees east in the lower three formations, but it is not certain whether this is preserved in the massive pyroclastics. These are highly competent rocks in which

Holes at Rosebery tend to swing toward normality to schistosity.

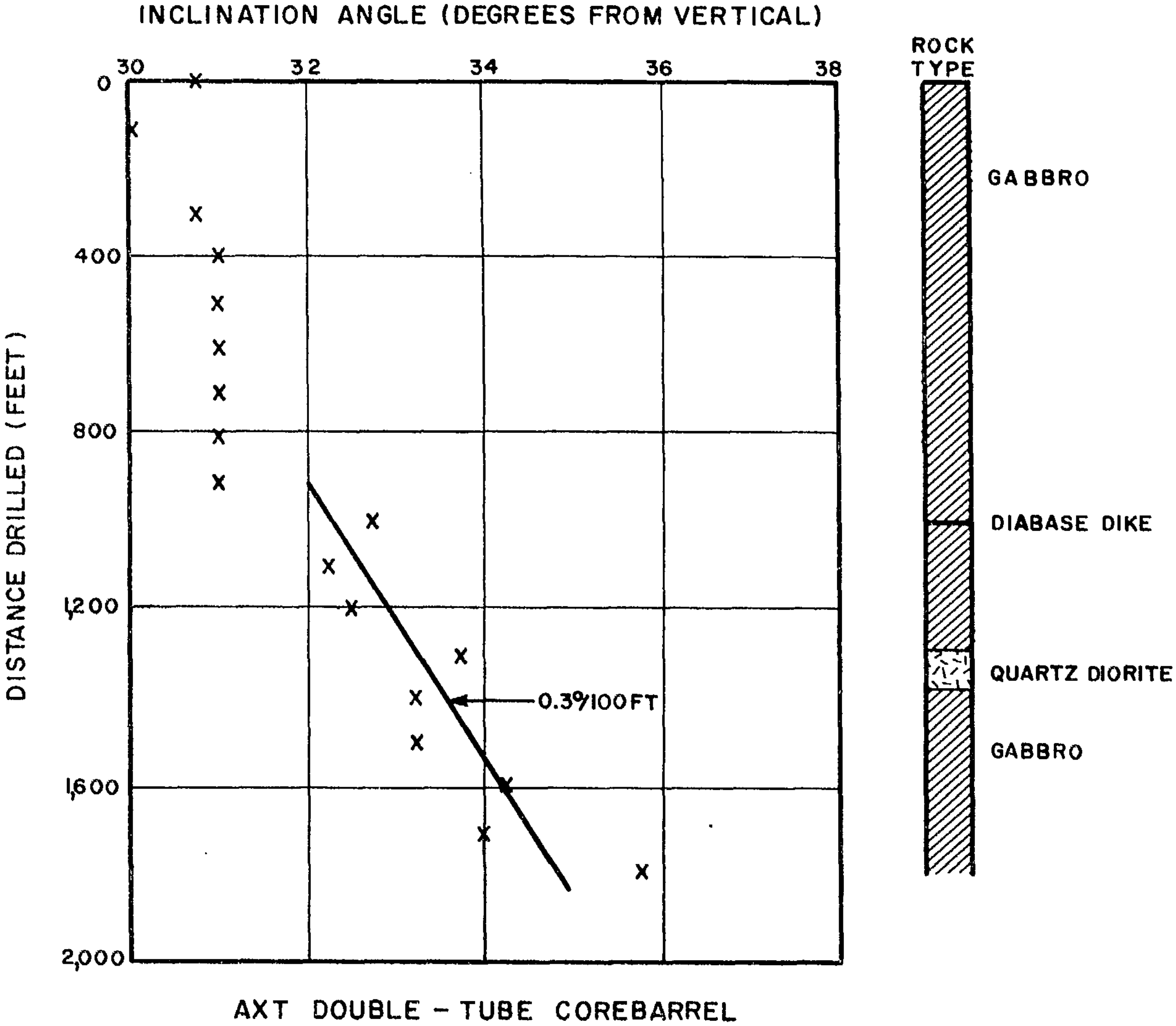

FIG. 6.11

MINING RESEARCH CENTRE, DEPARTMENT OF ENERGY, MINES AND RESOURCES

A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

DEVIATION CAUSED BY DIKE

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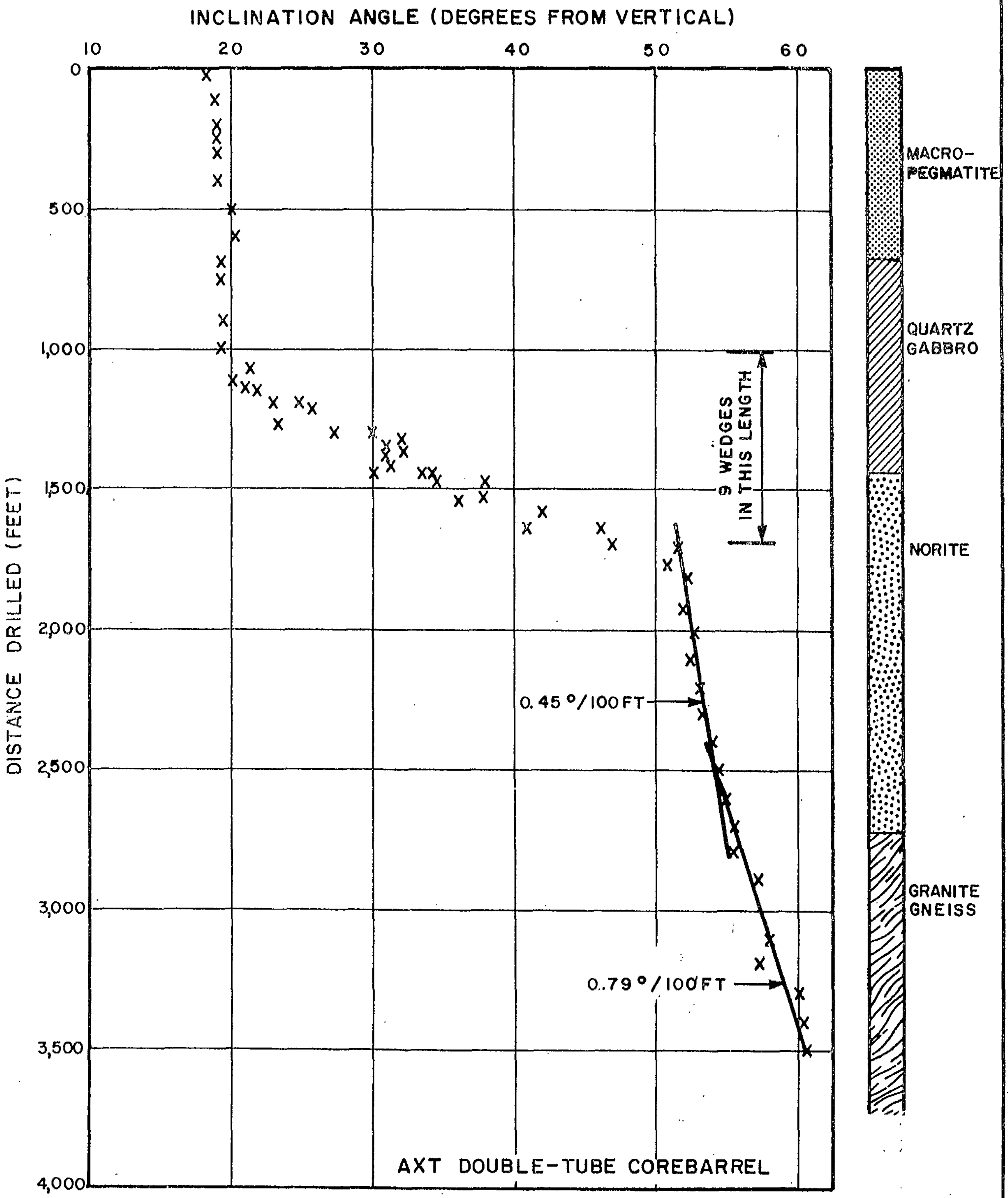
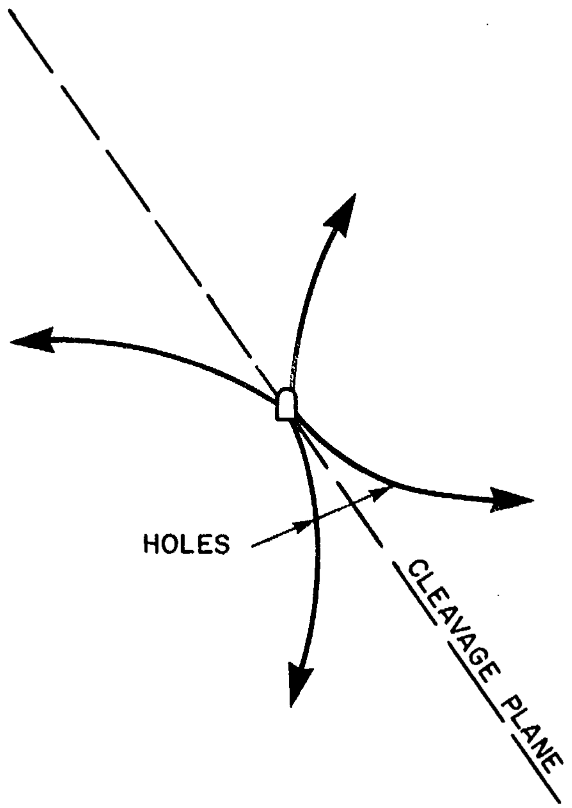


FIG. 6.12

MINING RESEARCH CENTRE, DEPARTMENT OF ENERGY, MINES AND RESOURCES

A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

WEDGING TO BEND A STRAIGHT HOLE



SECTION THROUGH MINE SHAFT

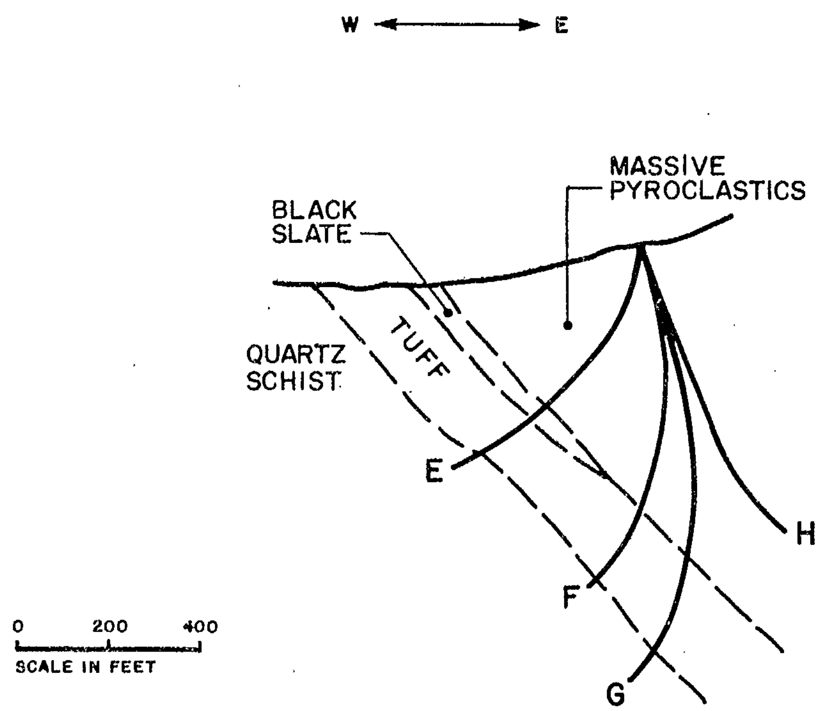
SOURCE:
FROM COTTLE (1961)

FIG. 6.13

MINING RESEARCH CENTRE, DEPARTMENT OF ENERGY, MINES AND RESOURCES

A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

BEHAVIOUR OF HOLES AT ROSEBERY, TASMANIA



SOURCE:
FROM COTTLE (1961)

FIG. 6.14

MINING RESEARCH CENTRE, DEPARTMENT OF ENERGY, MINES AND RESOURCES

A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

HOLE PROFILES AT ROSEBERY, TASMANIA

schistosity becomes weaker as distance from the boundary increases. It has been found that holes drilled at dip angles less than 75 degrees east will deviate toward the east, whereas steeper holes will turn west. In Figure 6.14, holes E, F and H are all AX holes, collared as shown. Hole G was drilled BX to 1,014 feet and then decreased to AX size in order to increase deviation. The difference between the paths of holes F and G then is due to the difference in hole size. Average deviation rates at Rosebery are quoted as:

Deviation decreases with increasing hole diameter.

6-1/2 degrees per 100 feet for EX holes
4-3/4 degrees per 100 feet for AX holes
2 degrees per 100 feet for BX holes.

The behavior of holes drilled with wireline equipment in the Rhodesian Copperbelt was described by Squirrel (1961). The rocks vary from cherty and cavernous dolomites in the upper zones through course-grained gritty sandstones to glassy quartzites and unconsolidated shales. In general, holes deviate updip and turn in a long pitch right-hand spiral. However, when the dip of beds is between 60 degrees and vertical, drill holes deviate into a direction parallel with the bedding. Hole deviations have been found to be more severe with wireline than with conventional equipment. The technique of offsetting the hole collar to allow for deflection is stated to be impractical in this area because of the great variation in dips, strikes, hardness, etc.

Some holes deviate parallel to bedding.

Holes drilled at the Klein Aub Mine in South Africa have large deviations. Liebenberg (1971) does not describe the geological conditions, but presents examples of BX holes deviating at rates greater than 4 degrees per 100 feet. Experiments with bit types have been carried out and the AXT bit has been found to produce smaller deviations than the AX bit. This is in agreement with the mathematical model of the drill string with reamer presented in Appendix C. When large deviations are necessary, a change of inclination of up to 30 degrees per 100 feet can be obtained by operating at a high load (10,000 pounds) on a non-coring bit.

AXT bit deviates less than AX bit – agrees with mathematical model.

Paine (1961) found that azimuthal deviations were not a problem in the Robson area of Captain's Flat, Australia, but an average change in inclination of 3 degrees per 100 feet was estimated. However, specific examples of much larger deviation occurred (11.3 degrees per 100 feet in an AX hole in steeply dipping beds).

One AX hole has deviation rate of 11.3 degrees per 100 feet.

Hole deviations recorded at North Broken Hill, Australia were analyzed by Spielvogel (1961), who plotted deviation rate as a function of core angle. He argued that since most deviations took place in the plane perpendicular to the strike of schistosity or bedding, the core angle (i.e. acute angle between core axis and plane of schistosity in core) represented the angle between the hole axis and the bedding plane. Results for AX and BX holes drilled in the three more massive rocks in the area, namely—granite gneiss, argillaceous rock and quartzitic rock—were plotted on a single graph as shown in Figure 6.15. There is obviously a great deal of scatter, but an average curve peaking at 2 to 2-1/2 degrees per 100 feet for core angles between 40 and 60 degrees were obtained. A similar curve for schist peaked at 5 degrees per 100 feet for core angles between 70 and 80 degrees. Low core angles produced low deviation, and the rate of change of inclination appeared to decrease for core angles over 80 degrees.

Deviation rate appears to be function of core angle.

Haycraft (1961) carried out similar analysis of BX holes at Kalgoorlie. Figure 6.16 is reproduced from his paper and shows the rate of change of inclination obtained in three different rock types. The quartz dolerite greenstones are weakly schistose and deflection rates are low, with a maximum of 1-1/4 degrees per 100 feet. The relatively soft chloritic basaltic lavas have greater deviations, but the maximum deviation rate (3 degrees per 100 feet) at Kalgoorlie occurred in the highly cleaved and bedded Black Flag sediments (tuffs, shales, slates, etc.).

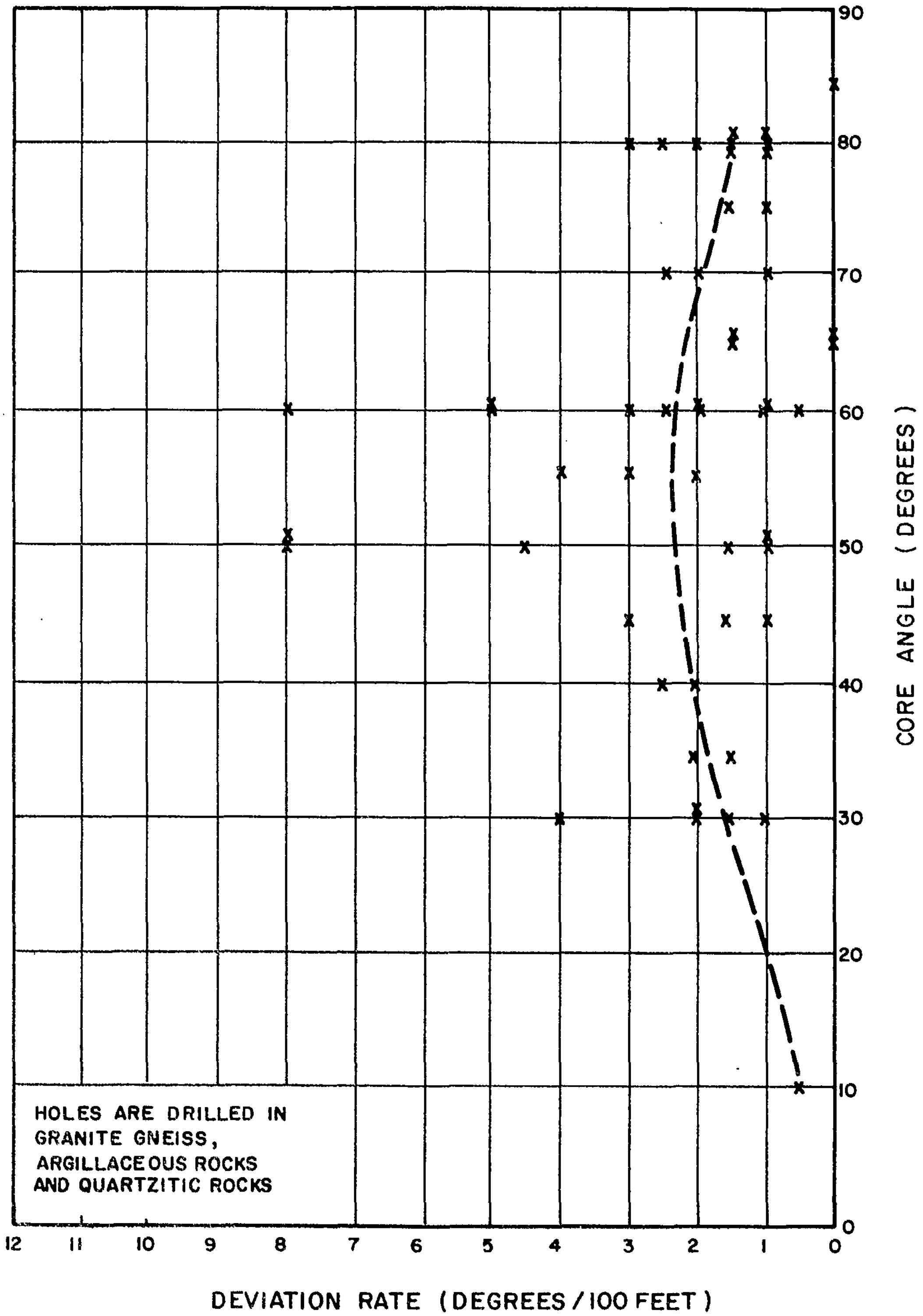
6.6 Review of Hole Observations

The limited data available makes it clear that no single theory of hole deviation will completely explain the behavior of holes drilled with diamond drills.

Varied behavior of holes indicates that several theories necessary.

Most holes tend to flatten in the vertical dip plane. This is consistent with Lubinski's concept of an anisotropy index. However, the fact that some holes do exhibit azimuthal deviation from the dip plane implies that frictional effects and/or the orientation of cutting vectors to the plane of anisotropy (Boyarko and Rozhkov, 1965) probably have some relevance. Local variations of rock properties in the vicinity of the bit could also play a role.

In elevation, holes generally deviate toward normality to any foliation or bedding. There is conflicting evidence as to their behavior when they achieve this normality. In some instances they



SOURCE:
FROM SPIELVOGEL (1961)

FIG. 6.15

MINING RESEARCH CENTRE, DEPARTMENT OF ENERGY, MINES AND RESOURCES
A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING
DEVIATION RATES OF AX AND BX HOLES AT NORTH BROKEN HILL, AUSTRALIA

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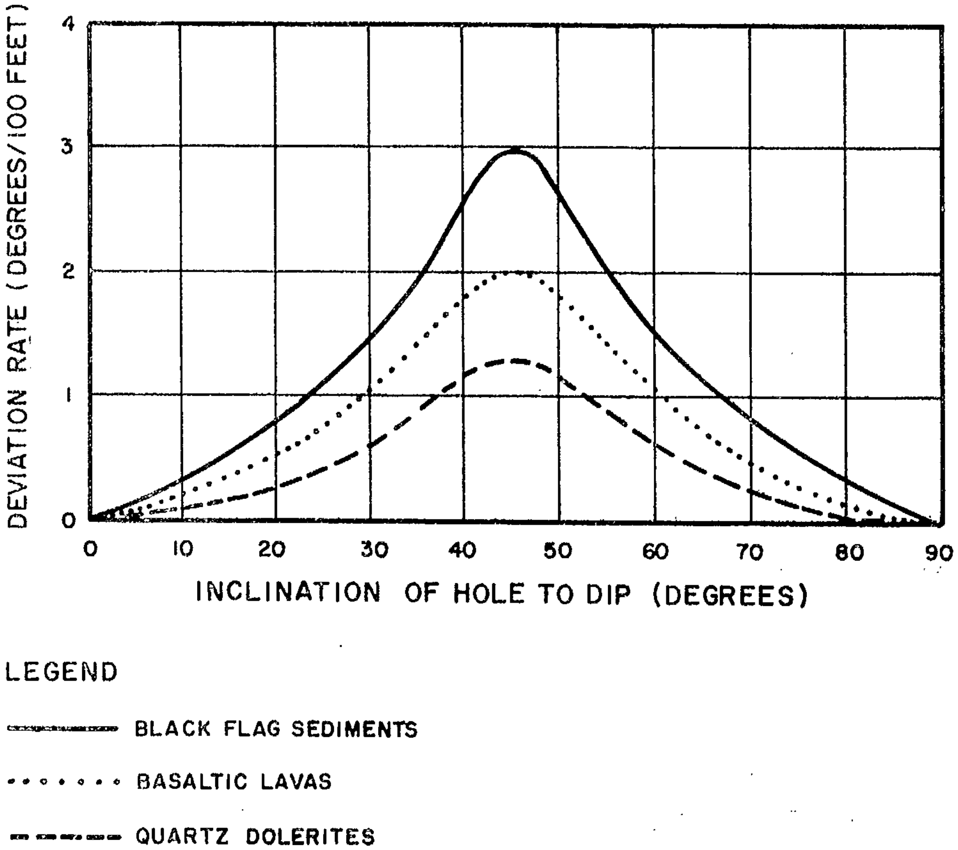


SOURCE:
FROM HAYCRAFT (1961)

FIG. 6.16

MINING RESEARCH CENTRE, DEPARTMENT OF ENERGY, MINES AND RESOURCES

A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

DEVIATION RATES OF BX HOLES AT KALGOORLIE, AUSTRALIA

ACRES

remain straight on further propagation, behaving in the manner predicted by the miniature whipstock theory, whereas in other cases deviation continues in accordance with the mathematical model of a drill string with a reamer.

Qualitative agreement with theoretical concepts is often found.

BX holes are known to deviate less than AX holes and wireline holes usually present greater deviation problems than holes drilled with conventional equipment. These observations are in general agreement with the mathematical reamer model, but further quantification is not possible.

In some homogeneous unfractured ground, more or less straight holes can be drilled. There is, however, little evidence to suggest that these are akin to the straight holes of Lubinski's equilibrium angle theory, since they can be drilled at various angles.

Deviation at interfaces of rocks of different hardnesses is known to occur, but insufficient information is available to quantify these effects here.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

At present no theoretical techniques are used in diamond drilling to control or predict deviations occurring in drill holes. Any engineering of holes which is carried out is based on previous experience and on trial and error in the field.

No single theory can completely explain the behavior of diamond drill holes. The applicability of various theories is illustrated in Figure 7.1 for a hole penetrating through different formations.

In-plane buckling occurs in vertical hole.

A vertical hole collared in isotropic or horizontally bedded rock remains straight and vertical until the length of the drill string is such that its buckling strength is exceeded and in-plane buckling occurs. The length of the initial straight portion of the hole is a function of the bit weight and drill string stiffness, so for a given drill string, this length can be increased by reducing the bit weight. If the hole is collared in inclined beds, the bit does not necessarily penetrate vertically, even when the drill string is unbuckled.

Helical buckling may occur in steep holes.

When deviation begins, at low inclination angles there is a zone in which there is a possibility of helical buckling. The load to cause helical buckling is a function of the stiffness, weight and length of the drill string, hole-drill string clearances, and hole shape. No complete theory is available at present to predict helical buckling loads taking into account all these variables, so the extent of the zone is not well defined. Within the helical buckling zone, it is not possible to predict deviations, and changes in azimuth as well as inclination may occur.

No equilibrium angle possible when reamer present

When hole inclination has increased to the point where helical buckling is no longer possible, continuous deviation takes place until the hole strikes a new formation. The presence of a reaming shell close behind the bit theoretically implies that an equilibrium angle is not reached. A mathematical model which takes into account the reaming shell and permits calculation of hole profile has been developed in this report (see Appendix C). The analysis is limited to the case of an isotropic bit drilling in isotropic ground.

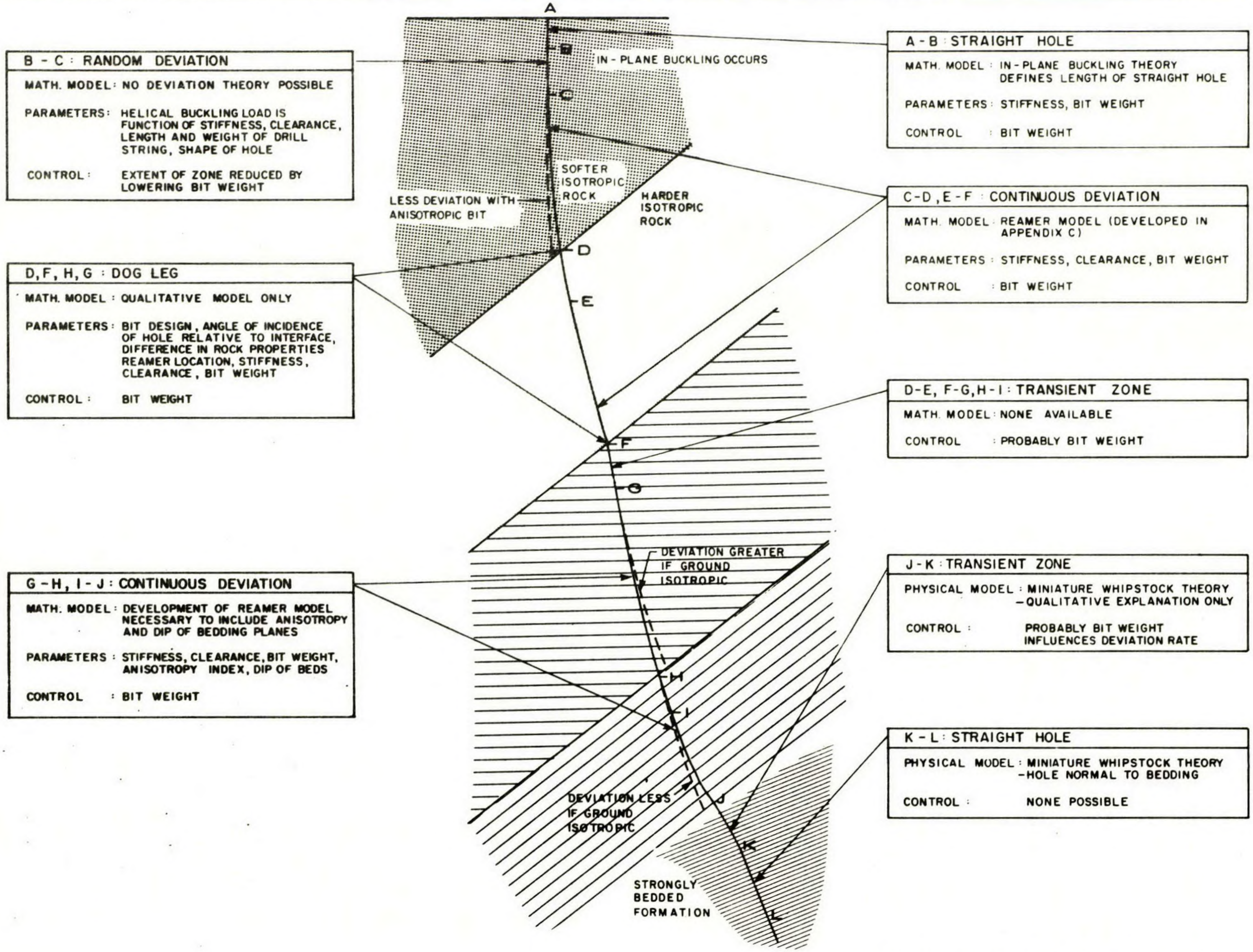


FIG. 7.1

MINING RESEARCH CENTRE, DEPARTMENT OF ENERGY, MINES AND RESOURCES

A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

APPLICABILITY OF DEVIATION THEORIES

The factors affecting hole deviation taken into account in the mathematical model are bit weight, corebarrel stiffness and weight, and clearance between drill string and hole. Parametric studies carried out on the mathematical model prove that qualitatively, it behaves in a realistic manner. Increasing bit weight or clearance between corebarrel and hole increases deviation, whereas increasing the corebarrel stiffness reduces deviation. Small holes, theoretically, deviate more than large holes. Unfortunately, quantitative comparison of the theoretical model with actual holes is not possible since data on drilling in isotropic conditions with known bit weight are not available. The mathematical model indicates that control during drilling can be achieved by control of bit weight, although there are obviously practical limits to bit weight which can be used. If it is too high, the bit may be damaged and if too low, penetration may be unacceptably slow.

Mathematical model of drill string with reamer behaves in realistic manner.

Further development of the mathematical model of continuous deviation is necessary to take into account bit anisotropy. However, when the bit has greater ability to penetrate axially than laterally, deviation should be reduced.

Anisotropic bit reduces deviation.

The mathematical model ceases to be valid when the hole strikes an interface between rocks of different hardnesses. A dog leg occurs as the bit crosses the interface and, although quantification is not yet possible, it is known that the direction and magnitude of the deviation in this region are a function of bit design, orientation of the hole with respect to the interface, drill string stiffness, clearance, location of the reaming shell and bit weight.

Dog leg occurs at interface between rocks of different hardness.

Following an interface there is a transient zone in which the drill string does not lie along the low side of the hole as assumed in the mathematical model. The hole path in this zone is obviously dependent on the shape of the dog leg, but no mathematical model is available to describe the deviation. In isotropic rock, the mathematical model of a drill string with reamer will resume validity when the drill string lies on the low side of the hole.

Further development of this mathematical model is necessary to include rock anisotropy. The additional parameters to be introduced are an anisotropy index and the inclination of bedding.

Future development of mathematical model should include rock anisotropy.

In practice, rock is generally found to be more "drillable" perpendicular than parallel to bedding or foliation planes. This implies that when a "vertical" hole is drilled in horizontal bedding or foliation, the deviation is less than in isotropic ground. However, in inclined bedding, when the hole is steeper than the normal to the bedding or foliation planes, deviation is greater than in isotropic conditions. When the hole achieves normality to the bedding or foliation, according to the mathematical model of drill string with reamer, it should continue to change its angle of inclination. However, in strongly bedded or foliated formations there is some evidence that fracturing of the rock may occur perpendicular to the bedding, as described by the miniature whipstock theory. This phenomenon forces the hole perpendicular to the bedding and it propagates in this direction. In all other circumstances, deviation can be controlled to some extent by adjusting bit weight, but where this theory is valid, there is no possibility of control.

Hole may penetrate perpendicular to dip plane in strongly bedded rocks.

In azimuth, holes generally trend toward the dip plane of regional bedding or foliation. However, frictional effects imply that a clockwise rotating bit in a sloping hole may cause some azimuthal deviation to the right, whereas an anticlockwise rotating bit may cause deviation to the left. In addition, the cutting action of the diamonds in anisotropic rock can, theorectically, cause azimuthal deviation, the sense of the deviation being dependent upon both the orientation of the hole with respect to the bedding or foliation and the direction of rotation of the bit. With conventional clockwise bit rotation, the hole deviating updip swings in azimuth to the right, whereas the downdip hole deviates to the left. Reversal of direction of rotation causes reversal of the azimuthal deviations.

Frictional effects and rock anisotropy can induce azimuthal deviation.

7.2 Recommendations for Future Research

The theoretical studies presented in this report have pointed to several areas where incomplete knowledge does not permit a full understanding or quantification of deviation in diamond drill holes. The following research programs, presented in order of priority, could fill the gaps in knowledge and allow further development of theories to control and predict deviation:

(a) Field Parametric Studies

It is recommended that a field research program be carried out in a location where geological conditions are well defined and

More field research is necessary.

preferably simple. Measurement of bit load and true hole size could lead to experimental quantification of the factors affecting deviation. This would be useful information in itself as well as providing data for future theoretical developments. Knowledge of the locations of contact between corebarrel and hole would be useful in assessing any theoretical analysis which considers the deformed shape of the corebarrel (e.g. the mathematical model described in Appendix C). This information might be obtained by painting corebarrels and observing the areas where the paint has rubbed off during drilling.

(b) Anisotropy of Bit

Testing could determine anisotropy of bits.

It has been pointed out that anisotropy of the diamond bit can have a significant influence on hole deviation. As a first approximation bit anisotropy might be represented by a single factor, d, relating the ability of the bit to drill axially and laterally. Previous investigation of anisotropy in tricone bits did not prove to be very successful (Lubinski, 1974). However, there is a likelihood that the behavior of diamond coring bits would be more consistent and a laboratory investigation would provide useful information for future theoretical development.

(c) Helical Buckling of Drill String

Model tests would define helical buckling zone.

The present state of the art of buckling analysis does not permit a well-defined description of the conditions under which helical buckling takes place in the drill string. Model tests which take into account curvature in the hole and the influence of the change of section at the corebarrel-drill rod connection would define conditions where helical buckling invalidates deviation theories.

(d) Stiffness Contribution of Core

Load-deflection tests would quantify stiffness contribution of core.

Corebarrel stiffness has been identified as an important parameter in hole deviation. Although the stiffening effect of the core is probably of minor importance, simple load-deflection tests on corebarrels, both with and without core present, together with accurate knowledge of hole diameters would allow quantification of effective increase in corebarrel stiffness due to the core.

(e) Development of Mathematical Model

Development of mathematical model should include bit anisotropy and rock anisotropy.

Further development of the mathematical model of Appendix C could now be carried out to include bit anisotropy and anisotropic ground conditions. Unfortunately, inclusion of either of these factors invalidates the simplifying boundary condition that in a curved hole there is zero moment at the reaming shell. It appears that the moment would now be a function of the depth drilled, considerably complicating the analysis. It is likely that ground anisotropy would be included in a similar manner as in the equilibrium angle theory, i.e., data obtained during drilling would be used to deduce anisotropic rock properties for use in control and prediction theories.

Theoretical development to study the influence of additional stabilizers or reamers at various locations along the corebarrel is also desirable.

(f) Azimuthal Deviations

Three-dimensional theories could be developed.

When distinct bedding or foliation is present, holes generally deviate in the dip plane with little azimuthal drift. However, in some instances it may be necessary to collar a hole to deviate out of the dip plane in order to pass through an ore body at some desired angle. In this case major azimuthal deviations occur and development of deviation theory to three dimensions is necessary to handle this problem.

(g) Transient Effects

Testing could quantify transient deviations.

Laboratory or field tests are necessary to verify and quantify deviations which occur at an interface of rocks of different hardnesses. Deviations can be quite significant, but this topic is given low priority because it is an extremely localized effect, and in most drilling situations it is unlikely that geological conditions be known in sufficient detail to anticipate transient deviations before the event.

7.3 Recommendations for Drilling Practice and Equipment Development

Reduce clearance.

(a) Clearance between corebarrel and hole is an important factor in the hole deviation problem, and any measures which can be taken to reduce clearance should produce straighter holes.

The use of corebarrels with continuous spiral ribs or stabilizers should effectively reduce clearance and still allow the passage of water between corebarrel and hole. Similar benefits could result from the use of corebarrels of hexagonal cross section.

(b) The presence of a reaming shell close behind the bit theoretically aggravates hole deviation problems, mainly because of the pivoting action. It may be possible to drill without a reaming shell by commencing the hole with a diamond bit of oversize set gauge and using a slightly smaller gauge each time the bit is changed. One attempt at drilling without a reaming shell appears to have been successful (Cocking et al, 1968).

Experiment with reamer location.

Location of the reaming shell at the rear rather than the front of the corebarrel may be beneficial, since there would be less clearance between corebarrel and hole and the pivoting action of the reaming shell close to the bit would be eliminated.

(c) If a bit has no ability to drill sideways, in isotropic conditions it will drill in the direction in which it points. When no reaming shell is present, this may increase deviation.

Develop blank-edged bit.

However, in conjunction with reamers or stabilizers close to the bit pointing it in the direction of the hole, straighter holes may be achieved if no diamonds are set on the sides of the bit.

(d) Frictional effects and the cutting mechanism of diamonds on the bit theoretically cause some azimuthal deviation from the dip plane. The extent of this problem requires further examination of deviations in the field, but, theoretically, such deviations can be reversed by reversal of the direction of rotation of the drill string. This suggests the development of drill rods which are capable of transmitting torque in both clockwise and anticlockwise

Develop equipment for reversal of rotation.

directions. Perhaps the simplest arrangement would involve a shear pin at each set of threads in the drill rods.

(e) The difficulties involved in anticipating a rock interface have been discussed already. Pritchard-Davies (1971) has suggested the development of equipment to control this deviation. A coupling would detect change of orientation of the bit face and apply differential pressure to correct the tendency. Since this involves a closed-loop system of detection and correction, the development of such equipment is a major undertaking.

Develop equipment to control deviation.

(f) Drilling experience in a given area can be used in an empirical way to estimate the behavior of future holes. This procedure is more likely to be successful if factors affecting hole deviation are recorded for future reference. Thus, recording of the following drilling data would be useful:

Record drilling data for analysis.

- type of corebarrel
- type and location of reaming shells and/or stabilizers
- type and condition (fresh, worn, etc.) of bit
- bit weight, where possible. When this is not possible, drilling rates in feet per hour may provide information on relative values for bit weight in known ground conditions. Downtime of rigs should be taken into account in calculating drilling rates.
- geological conditions (rock type, dip and strike of bedding, etc.).

REFERENCES

Bogy, D. B. and P. R. Paslay. (1964). "Buckling of Drill Pipe in an Inclined Hole". *Transactions of ASME Journal of Engineering for Industry.* Vol. 86, pp 214 – 218. May.

Bonsall, E. (1957). "Directional Diamond Drilling in the Sudbury Area". *Canadian Diamond Drilling Association.* Annual Convention.

Boyarko, Yu. L. and V. P. Rozhkov. (1965). "Anisotropy in Mechanical Rock Properties as a Cause of Azimuthal Deviation in Core Drilled Holes". *Izv. Vyssh. Ucheb. Zaved. Geol. i Razved.* No. 10, pp 134 – 143.

The Chemical Rubber Company. (1970). *Standard Mathematical Tables.* 18th Edition. Cleveland. p 423.

Cocking, J. R. et al. (1968). "Deep Wireline Drilling at the Southern Leases of New Broken Hill Consolidated Limited, Broken Hill". *The Australasian Institute of Mining and Metallurgy.* Broken Hill Mines.

Cottle, V. M. (1961). "Diamond Drillhole Deflection at Rosebery, Tasmania". *Proceedings, Symposium on Diamond Drilling.* Broken Hill, Australia. Paper No. 15.

Cumming, J. D. (1971). *Diamond Drill Handbook.* 2nd Edition. J. K. Smit and Sons of Canada Ltd., Toronto.

Dames and Moore. (1973). "A Report on the Current Status of the Diamond Drilling Industry and Evaluation of Future Research Needs in Canada". *Department of Energy, Mines and Resources, Mines Branch.* Int. Report No. 73/149.

Dubnie, A. (1973). "Mining Technology in 1972". *Department of Energy, Mines and Resources, Mines Branch.* Int. Report No. 73/53.

Gauthier, G. (1967). "Basic Theories of Deflection in Diamond Drilling". *Science and Technology of Industrial Diamonds.* Vol. 2. Technology. pp 135 – 141.

Gorgendiere, C. J. Dela. (1973) "Mini-Deve — A Concept to Minimize Deviation of Wireline Drill-Holes". *Canadian Diamond Drilling Association.* Annual Convention.

Hall, P. B. (1956). "Hydraulic vs. Screw Feed". *Canadian Diamond Drilling Association.*

Haycraft, J. A. (1961). "Influence of Rock Types and Geological Structures on Diamond Drill Deflection". *Proceedings, Symposium on Diamond Drilling.* Broken Hill, Australia. Paper No. 17.

Hoch, R. S. (1962). "A Review of the Crooked Hole Problem and an Analysis of Packed Bottom-Hole Drill Collar Assemblies". *Drilling and Production Practice, API.* pp 27 – 39.

Kopylov, V. E. (1962). "Deflection of Diamond Drilled Wells". *Razvedka i Okhrana Nedr.* Vol. 28. No. 6, pp 21 – 24.

Lapinskie, D. C. (1974). *Personal Communication.* Heath and Sherwood Drilling. Copper Cliff, Ontario.

Liebenberg, B. F. (1971). "Controlled Diamond Drilling at the Klein Aub Mine, South West Africa". *South African Core Drilling Association.* Special Meeting. July.

Lubinski, A. (1950). "A Study of the Buckling of Rotating Drilling Strings". *Drilling and Production Practice, API.* pp 178 – 214.

Lubinski, A. (1974). *Personal Communication.* Amoco. Tulsa, Oklahoma.

Lubinski, A. and H. B. Woods. (1953). "Factors Affecting the Angle of Inclination and Dog-Legging in Rotary Bore Holes". *Drilling and Production Practice, API.* pp 222 – 250.

Moore, S.C. (1962). "Recent Trends in Controlling Hole Deviation". *Drilling and Production Practice, API.* pp 15 – 26.

Moore, S.C. and M. M. Brantly. (1955). "Classifying Drill Collars and Bottom Assemblies for Crooked Hole Studies". *World Oil.* pp 134 – 142. November.

Murphey, C. E. and J. B. Cheatham Jr. (1966). "Hole Deviation and Drill String Behaviour". *Soc. Petr. Eng. Journal.* Vol. 6. No. 1, pp 44 – 54. March.

Paine, V. R. (1961). "Influence and Use of Rock Characteristics in Diamond Drilling at Captain's Flat". *Proceedings, Symposium on Diamond Drilling.* Broken Hill, Australia. Paper No. 37.

Paslay, P. R. and D. B. Bogy. (1964). "The Stability of a Circular Rod Laterally Constrained to be in Contact with an Inclined Circular Cylinder". *Transactions of ASME. Journal of Applied Mechanics.* Vol. 86. pp 605 – 610. December.

Pritchard–Davies, E. W. D. (1971). "The Future of Direction Control in Diamond Drilling". *Industrial Diamond Review.* February.

Robertson, D. S. (1962). "A Discussion of Deep Drilling in the Blind River Area". *The Canadian Mining and Metallurgical Bulletin.* pp 467 – 472. July.

Rollins, H. M. (1959). "Are 3 Degree and 5 Degree 'Straight Holes' Worth their Cost?". *The Oil and Gas Journal.* Vol. 57. No. 46, pp 163 – 171. November.

Simons, B. (1974). *Personal Communication.* Inspiration Drilling Operations. North Bay, Ontario.

Spielvogel, L. N. (1961). "Influence of Rock Characteristic on Deviation". *Proceedings, Symposium on Diamond Drilling.* Broken Hill, Australia. Paper No. 16.

Spink, K. (1973). "The Nature of the Diamond Drilling Process". *Diamonds in Industry–Rock Drilling.* De Beers Industrial Diamond Division. London, England.

Squirrel. (1961). "Wireline Diamond Core Drilling in Rhodesian Copperbelt". *Proceedings Symposium on Diamond Drilling.* Broken Hill, Australia. Paper No. 40.

Wiley, C. (1965). "The Use of Near-bit Stabilizer Subassemblies for Control of Hole Deviation". *Drilling and Production Practice, API.* pp 66 – 75.

Woods, H. B. and A. Lubinski. (1954). "Practical Charts for Solving Problems on Hole Deviation". *Drilling and Production Practice, API.* pp 56 – 71.

Woods, H. B. and A. Lubinski. (1955). "Use of Stabilizers in Controlling Hole Deviation". *Drilling and Production Practice, API.* pp 165 – 182.

APPENDIX A

1 VISITS

The following companies and individuals were visited by Acres representatives:

- Heath and Sherwood, Drilling Division, Toronto, Ontario
- Canadian Diamond Drilling Association, Toronto, Ontario
- Pilot Diamond Tools Ltd., North Bay, Ontario
- Inspiration Drilling Operations, North Bay, Ontario
- Canadian Longyear Ltd., North Bay, Ontario
- International Nickel Company of Canada Limited, Sudbury, Ontario
- Falconbridge Nickel Mines Limited, Falconbridge, Ontario
- Longyear Company, Minneapolis, Minnesota
- J. K. Smit and Sons International, Toronto, Ontario
- D. S. Robertson and Associates, Geologists, Toronto, Ontario
- Professor Fairhurst, University of Minnesota.

2 CORRESPONDENCE AND TELEPHONE COMMUNICATION

Communication in writing or by telephone took place with the following companies, organizations and individuals:

- Australian Diamond Drillers Association Ltd.
- South African Core Drilling Association
- Los Alamos Scientific Laboratory
- U. S. Bureau of Mines (Minneapolis and Pittsburgh)
- Christensen Diamond Products, Salt Lake City, Utah
- Boyles Operations, Orillia, Ontario
- Hughes Tool Co., Houston, Texas
- Henry Woods, Hughes Tool Co. (Retired), Houston, Texas
- Arthur Lubinski, Amoco, Tulsa, Oklahoma
- Joy Manufacturing, Michigan City, Indiana

APPENDIX B

AN EXTENSION OF THE EQUILIBRIUM ANGLE CONCEPT TO INCLUDE BIT ANISOTROPY

It is assumed that in isotropic rock, the bit anisotropy is defined by the ratio:

$$\frac{\text{penetration rate perpendicular to bit axis per unit force perpendicular to bit axis}}{\text{penetration rate along bit axis per unit force along bit axis}} = \text{constant} = d \text{ (say)}$$

Using an isotropic bit (i.e., d = 1), Lubinski and Woods (1953) defined the anisotropy index, h, of bedded formations in the following way:

$$h^{I} = I - h = \frac{\text{penetration rate parallel to beds per unit force parallel to beds}}{\text{penetration rate perpendicular to beds per unit force perpendicular to beds}}$$

Figure B.1 shows an anisotropic bit in a hole inclined at an angle α to the vertical. The bit axis is at angle η and the resultant bit force at angle ϕ to the vertical and bedding planes slope at an angle γ to the horizontal.

The component of force along the bit axis = $R \cos(\phi - \eta)$

This results in an instantaneous component of displacement perpendicular to beds

$= n R \cos(\phi - \eta) \cos(\eta - \gamma)$

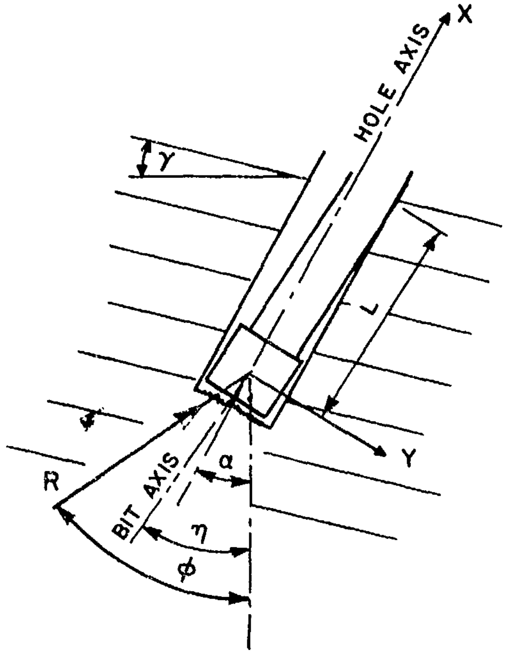
and an instantaneous component of displacement parallel to beds

$= n h^{I} R \cos(\phi - \eta) \sin(\eta - \gamma)$

Where n is a proportional factor.

The force perpendicular to the bit axis

$= R \sin(\phi - \eta)$



$$\bar{x} = \frac{X}{m}$$

$$\bar{y} = \frac{Y}{m}$$

$$\bar{l} = \frac{L}{m}$$

ASSUMED SHAPE OF DRILL STRING :

$$\bar{y} = \frac{C}{m} \left[\frac{\bar{x}}{\bar{l}} + \frac{1}{\pi} \sin \pi \frac{\bar{x}}{\bar{l}} \right]$$

I = MOMENT OF INERTIA OF DRILL STRING

E = YOUNG'S MODULUS

p = SUBMERGED WEIGHT PER UNIT LENGTH

C = (RADIUS OF HOLE) - (RADIUS OF DRILL STRING)

$$m = \sqrt[3]{\frac{EI}{p}}$$

FIG. B1

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DRILL STRING WITH ANISOTROPIC BIT

ACRES

This results in an instantaneous component of displacement perpendicular to the beds

$$= -ndR \sin(\phi - \eta) \sin(\eta - \gamma)$$

and an instantaneous component of displacement parallel to the beds

$$= ndh'R \sin(\phi - \eta) \cos(\eta - \gamma)$$

Thus, total penetration perpendicular to beds

$$= nR \cos(\phi - \eta) \cos(\eta - \gamma) - ndR \sin(\phi - \eta) \sin(\eta - \gamma)$$

and total penetration parallel to beds

$$= nh'R \cos(\phi - \eta) \sin(\eta - \gamma) + ndh'R \sin(\phi - \eta) \cos(\eta - \gamma)$$

If ψ is the penetration angle with respect to the vertical,

$$\tan(\psi - \gamma) = \frac{nh'R \cos(\phi - \eta) \sin(\eta - \gamma) + ndh'R \sin(\phi - \eta) \cos(\eta - \gamma)}{nR \cos(\phi - \eta) \cos(\eta - \gamma) - ndR \sin(\phi - \eta) \sin(\eta - \gamma)}$$

If an equilibrium situation exists where the hole does not change angle, then

$$\psi = \alpha_e ,$$

and

$$\tan(\alpha_e - \gamma) = \frac{h' \cos(\phi - \eta)\sin(\eta - \gamma) + d h' \sin(\phi - \eta)\cos(\eta - \gamma)}{\cos(\phi - \eta)\cos(\eta - \gamma) - d\sin(\phi - \eta)\sin(\eta - \gamma)}$$

$$\therefore \tan(\alpha_e - \gamma) = \frac{h' \tan(\eta - \gamma) + d h' \tan(\phi - \eta)}{1 - d\tan(\phi - \eta)\tan(\eta - \gamma)}$$

Now if β is the angle between the bit and hole axes,

$$\eta = \alpha_e + \beta$$

Using Szego's [Discussion, Lubinski and Woods, (1953)] approximation for the shape of the drill string (see Figure B.1).

$$\bar{y} = \frac{C}{m}\left[\frac{\bar{x}}{\bar{\ell}} + \frac{1}{\pi}\sin\frac{\pi\bar{x}}{\bar{\ell}}\right] \qquad \therefore \frac{d\bar{y}}{d\bar{x}} = \frac{C}{m}\left[\frac{1}{\bar{\ell}} + \frac{1}{\bar{\ell}}\cos\frac{\pi\bar{x}}{\bar{\ell}}\right]$$

$$\left(\frac{d\bar{y}}{d\bar{x}}\right)_{x=0} = \frac{2C}{m\bar{\ell}}$$

Since β is small,

$$\beta \approx \tan\beta = \left(\frac{d\bar{y}}{d\bar{x}}\right)_{\bar{x}=0} = \frac{2C}{m\bar{\ell}}$$

$$\therefore \tan(\alpha_e - \gamma) = \frac{h' \tan\left(\alpha_e + \frac{2C}{m\bar{\ell}} - \gamma\right) + d h' \tan\left(\phi - \alpha_e - \frac{2C}{m\bar{\ell}}\right)}{1 - d\tan\left(\phi - \alpha_e - \frac{2C}{m\bar{\ell}}\right)\tan\left(\alpha_e + \frac{2C}{m\bar{\ell}} - \gamma\right)} \qquad \text{(B.1)}$$

Equation (B.1) represents a more general form of the equilibrium angle condition expressed by equation (5.3) in Subsection 5.3.

In the special case of an isotropic bit, d = 1and equation (B.1) reduces to:

$$\tan(\alpha_e - \gamma) = h' \tan(\phi - \gamma)$$

which is the same as equation (5.3).

It is interesting to note that in isotropic ground conditions ($h' = 1$) with a unidirectional bit (d = 0), equation (B.1) reduces to:

$$\tan \alpha = \tan(\alpha_e + \beta)$$

Thus, for a hole to propagate in a straight line, β must be zero degrees. This is impossible if clearance exists between corebarrel and hole, implying that a straight hole cannot be drilled unless the bit has some ability to drill transversely as well as axially.

Physically this is apparent, since d = 0 implies the bit can only drill in the direction in which it points. Unless it points along the axis of the hole, the hole cannot be propagated in a straight line.

APPENDIX C

MATHEMATICAL MODEL OF DRILL STRING WITH REAMER

Murphey and Cheatham (1966) considered the deviation of a drill string with an isotropic bit penetrating through isotropic ground. No reaming shell was present and the hole deviated in a straight line at the equilibrium angle for the particular set of drilling conditions. In Subsection 5.3.4, it was shown that a reamer close behind the bit theoretically causes continuous deviation. Using the same dimensionless groups as Murphey and Cheatham, a mathematical model which takes into account the reaming shell is now developed.

Figure C.1 shows an idealized representation of the lower portion of a uniform drill string in a hole of variable curvature. The X-axis is defined tangential to the centre line of the hole at the reaming shell and the Y-axis radiates from the centre line of the hole. A free body diagram of the bit and reaming shell is shown in Figure C.2. It is assumed that the influence of the reaming shell is to add fixity to the drill string such that the tangent to the elastic curve at the reamer is parallel to the X-axis.

The differential equation describing the elastic behavior of the drill string can be written as

$$EIY'' = -M_X$$

Where: M_X is the moment in the drill string at location X.

Thus

$$EIY'' = VX - WY + \frac{X^2}{2} p \sin\alpha + XY p \cos\alpha - p\cos\alpha \int_0^X Y dX + M$$

Differentiating,

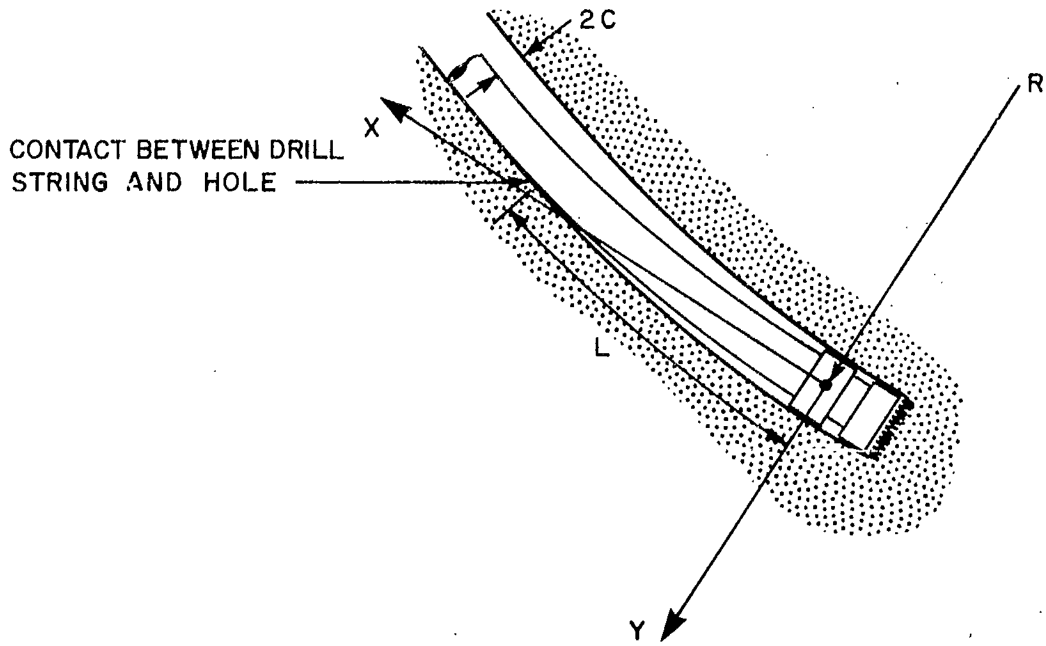
$$EIY''' + (W - X p \cos\alpha) Y' = V + X p \sin\alpha$$

E = YOUNG'S MODULUS OF DRILL STRING

I = MOMENT OF INERTIA OF DRILL STRING

R = RADIUS OF CURVATURE OF HOLE CENTRELINE

p = SUBMERGED WEIGHT PER UNIT LENGTH OF DRILL STRING



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IDEALIZATION OF DRILL STRING IN HOLE

FIG. C1

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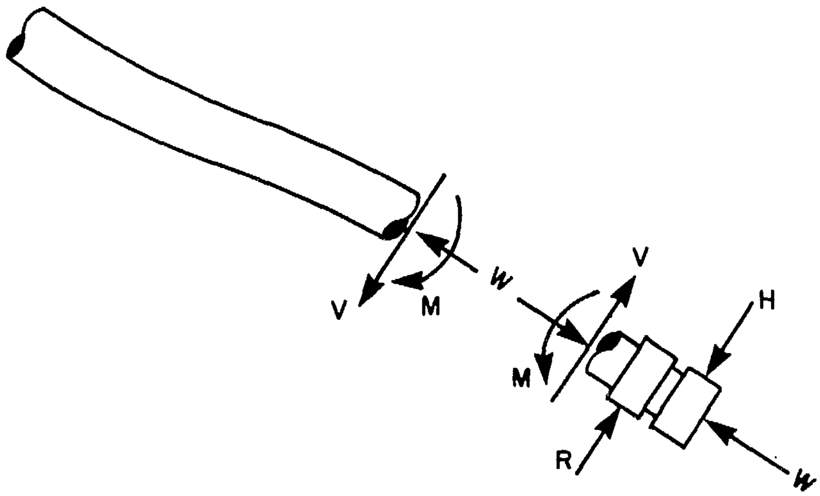
M, V, W ARE MOMENT, SHEAR AND AXIAL LOAD AT REAMING SHELL



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A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

FREE BODY DIAGRAM OF END OF DRILL STRING

FIG. C2

ACRES

The boundary conditions are:

$$Y(o) = o, \quad Y'(o) = o,$$

$$Y(L) = C - \frac{L^2}{2R}, \quad Y'(L) = -\frac{L}{R},$$

$$Y''(L) = -\frac{1}{R}$$

Here it is assumed that the length L of the hole is of constant curvature.

Assuming that $W \gg Xp \cos\alpha$, the term $XY'p \cos\alpha$ is neglected.

Changing into dimensionless form using the relationships,

$$y = \frac{W^2 Y}{EI p \sin\alpha}, \quad x = X\sqrt{\frac{W}{EI}},$$

$$c = \frac{W^2 C}{EI p \sin\alpha}, \quad \ell = L\sqrt{\frac{W}{EI}}$$

$$\frac{1}{r} = \frac{W}{R p \sin\alpha}, \quad v = \frac{V \sqrt{W}}{\sqrt{EI}\, p \sin\alpha}$$

the differential equation and boundary conditions become

$$y''' + y' = v + x \qquad \text{(C.1)}$$

$$y(o) = o, \quad y'(o) = o,$$

$$y(\ell) = c - \frac{\ell^2}{2r}, \quad y'(\ell) = -\frac{\ell}{r}, \quad y''(\ell) = -\frac{1}{r}$$

The solution to equation (C.1) can be written as

$$y' = A \cos x + B \sin x + v + x$$

Integrating,

$$y = A \sin x - B \cos x + vx + \frac{x^2}{2} + D$$

Where A, B and D are constants of integration.

$$\text{At } x = o, \quad y = o, \quad \therefore B = D$$

$$y' = o, \quad \therefore A = -v$$

$$\text{At } x = \ell, \quad y'' = -\frac{1}{r}, \therefore B = -v \tan \ell - \frac{1}{\cos \ell}\left(1 + \frac{1}{r}\right)$$

Thus, the solution to the differential equation is:

(C.2)

$$y = -v \sin x + \left[v \tan \ell + \frac{1}{\cos \ell} \left(1 + \frac{1}{r} \right) \right] \cos x + vx + \frac{x^2}{2} - v \tan \ell - \frac{1}{\cos \ell} \left(1 + \frac{1}{r} \right)$$

$$y^{\prime} = -v \cos x - \left[v \tan \ell + \frac{1}{\cos \ell} \left(1 + \frac{1}{r} \right) \right] \sin x + v + x$$

$$y^{\prime\prime} = +v \sin x - \left[v \tan \ell + \frac{1}{\cos \ell} \left(1 + \frac{1}{r} \right) \right] \cos x + 1$$

The two remaining boundary conditions can be used to obtain two relationships between the four variables, ℓ, v, r, c.

At $x = \ell, \; y^{\prime} = -\frac{\ell}{r} \; \therefore \; v = \frac{\left(1 + \frac{1}{r} \right) (\tan \ell - \ell)}{1 - \cos \ell - \sin \ell \; \tan \ell}$ (C.3)

and $y = c - \frac{\ell^2}{2r} \; \therefore \; c = \left(1 + \frac{1}{r} \right) \left(1 + \frac{\ell^2}{2} - \frac{1}{\cos \ell} \right) + v (\ell - \tan \ell)$

Eliminating v we obtain:

$$c = \left(1 + \frac{1}{r}\right)\left[\frac{\ell^2}{2} - \frac{(\tan\ell - \ell)^2}{(1 - \cos\ell - \sin\ell\ \tan\ell)} + 1 - \frac{1}{\cos\ell}\right] \qquad (C.4)$$

In the mathematical development, so far only the equilibrium of the drill string has been considered. An additional constraint on the mathematical model is obtained from consideration of the way in which a hole propagates. Equilibrium of the free-body diagram in Figure C.2 implies that:

$$H = \frac{M}{b}$$

Thus, for any value of hole radius for which M is not zero, a side reaction H exists and the resultant force of the bit on the ground is not tangential to the hole. Both the bit and rock are assumed to be isotropic, so penetration takes place in the direction of this resultant force and a dog-leg occurs. It is therefore reasonable to assume that in steady-state drilling conditions where a smooth hole is produced, the hole propagates in such a way that the resultant force in tangential to the hole and the moment at the reamer, M, is zero. Since in the mathematical analysis the tangent is measured at the origin of the co-ordinate axis, i.e. at the reaming shell, the short length of drill between reamer and bit is assumed to remain straight.

The additional boundary condition is now applied to the differential equation (C.2).

At $x = 0$, $M = 0$ $\therefore$ $y'' = 0$

$$\therefore \; -v \tan \ell - \frac{1}{\cos \ell}\left(1 + \frac{1}{r}\right) + 1 = 0$$

Substituting for v using equation (C.3), we obtain:

$$\frac{1}{r} = \frac{2 - 2\cos \ell - \ell \sin \ell}{\cos \ell + \ell \sin \ell - 1} \qquad (C.5)$$

$\frac{1}{r}$ is plotted as a function of ℓ in Figure C.3. It is not possible to obtain an explicit relationship between $\frac{1}{r}$ and c, but they can be calculated for discrete values of ℓ using equations (C.4) and (C.5). In this way the plot of $\frac{1}{r}$ versus c shown in Figure C.4 was obtained. It is interesting to note that for $\frac{1}{r} > 2$, there is a linear relationship between $\frac{1}{r}$ and c which can be written in the form

$$\frac{1}{r} = Ac + B,$$

where A and B are constants.

Now the length of curve between two values of $\alpha = \alpha_1$, and $\alpha = \alpha_2$ is given by

$$S_{1,2} = \int_{\alpha_1}^{\alpha_2} R \, d\alpha$$

where R is a function of α, $R = \frac{W}{p \sin \alpha} r$

For a given drill string with a constant bit weight applied,

$$S_{1,2} = \frac{W}{p} \int_{\alpha_1}^{\alpha_2} \frac{r}{\sin \alpha} \, d\alpha$$

Now provided that

$$\frac{1}{r} > 2, \quad r = \frac{1}{Ac + B}$$

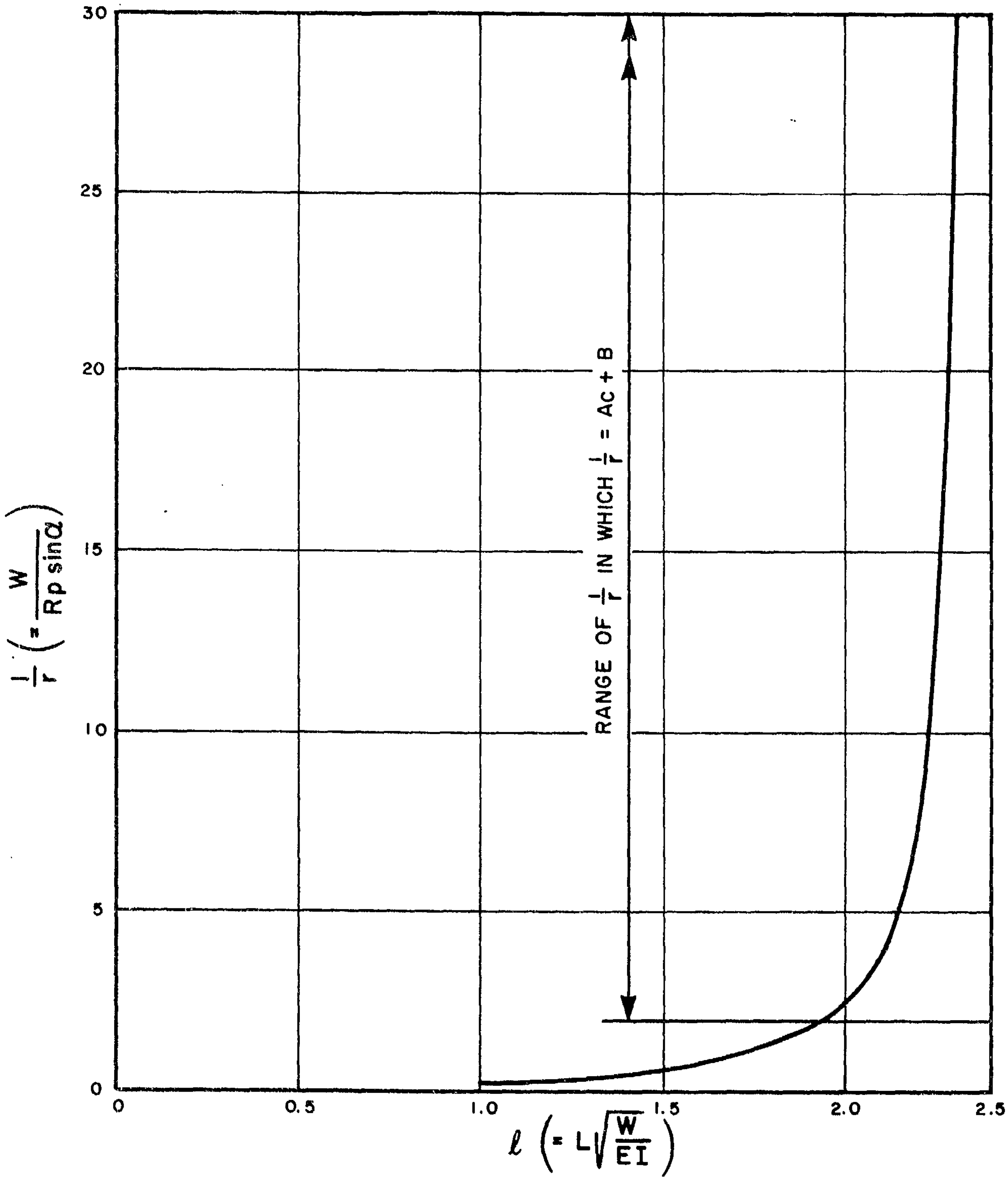

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FIG. C3

INVERSE OF DIMENSIONLESS RADIUS OF CURVATURE (1/r) AS A FUNCTION OF DIMENSIONLESS DISTANCE (ℓ) FROM REAMER TO POINT OF CONTACT

ACRES

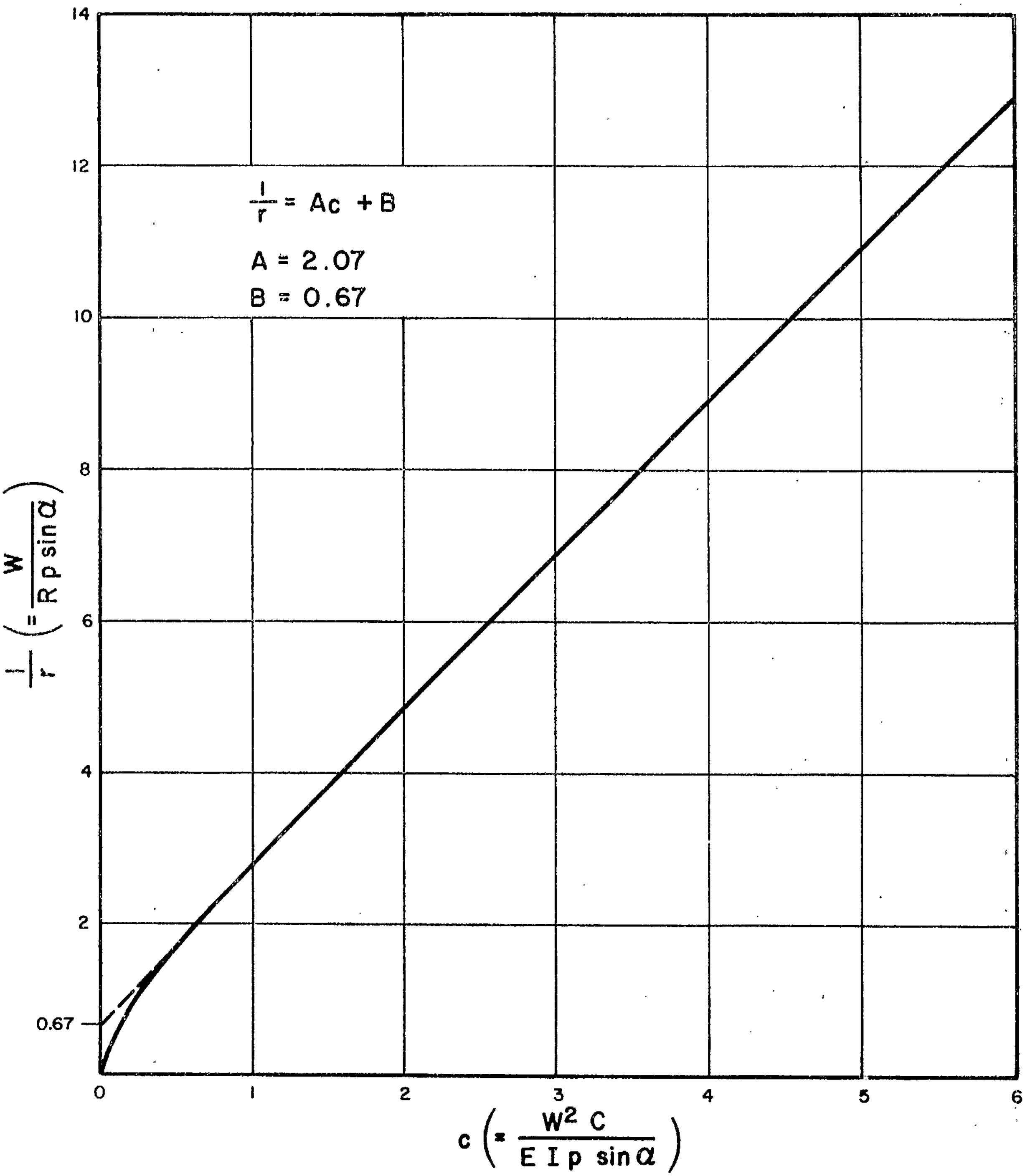

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FIG. C4

A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

INVERSE OF DIMENSIONLESS RADIUS OF CURVATURE ($^1/r$) AS A FUNCTION OF DIMENSIONLESS CLEARANCE (C)

From Figure C.4, $A = 2.07$ and $B = 0.67$

$$\therefore \; S_{1,2} = \frac{W}{p}\int_{\alpha_1}^{\alpha_2} \frac{d\alpha}{\sin\alpha\left(\frac{AW^2C}{EIp\sin\alpha} + B\right)} = \int_{\alpha_1}^{\alpha_2} \frac{d\alpha}{\left(\frac{AWC}{EI} + \frac{Bp\sin\alpha}{W}\right)}$$

Writing $K_1 = \frac{AWC}{EI}$ and $K_2 = \frac{Bp}{W}$

$$S_{1,2} = \int_{\alpha_1}^{\alpha_2} \frac{d\alpha}{(K_1 + K_2\sin\alpha)}$$

This integral can be evaluated explicitly (The Chemical Rubber Company, 1970).

For $K_2 > K_1$,

$$S_{1,2} = \frac{1}{\sqrt{K_2^2 - K_1^2}}\left[\ell n\left(\frac{K_1\tan\frac{\alpha_2}{2} + K_2 - \sqrt{K_2^2 - K_1^2}}{K_1\tan\frac{\alpha_2}{2} + K_2 + \sqrt{K_2^2 - K_1^2}}\right) - \ell n\left(\frac{K_1\tan\frac{\alpha_1}{2} + K_2 - \sqrt{K_2^2 - K_1^2}}{K_1\tan\frac{\alpha_1}{2} + K_2 + \sqrt{K_2^2 - K_1^2}}\right)\right] \qquad \text{(C.6a)}$$

For $K_2 < K_1$,

$$S_{1,2} = \frac{2}{\sqrt{K_1^2 - K_2^2}}\left[\tan^{-1}\left(\frac{K_1\tan\frac{\alpha_2}{2} + K_2}{\sqrt{K_1^2 - K_2^2}}\right) - \tan^{-1}\left(\frac{K_1\tan\frac{\alpha_1}{2} + K_2}{\sqrt{K_1^2 - K_2^2}}\right)\right] \qquad \text{(C.6b)}$$

For $\frac{l}{r} > 2$, these formulae provide theoretical estimate of the distance to be drilled in homogeneous isotropic ground to change the slope of the hole by any given amount. They were used to produce the curves in Figures 5.8 to 5.13, Subsection 5.5, which are plotted only in the range of $\frac{l}{r}$ (i.e. $\frac{l}{r} > 2$) for which the analysis is valid. Hole inclination was evaluated for discrete values of depth drilled, the calculations being performed on the GE415 electronic computer at Acres.

In principle the method could be used for any value of $\frac{l}{r}$, though equation (C.6a) and (C.6b) would not be valid for $\frac{l}{r} < 2$, and integrals would have to be evaluated numerically.

APPENDIX D

HELICAL BUCKLING EQUATIONS

Paslay and Bogy (1964) have shown that torque in the rod has a very small effect and actually increases the stability of the system. It is, therefore, neglected in the stability analysis carried out in this work.

An inclined hole and drill string are shown in Figure D.1. It is assumed that the top and bottom of the rod are pinned to the hole and that, throughout its length, the buckled rod remains in contact with the edge of the hole.

The buckled shape of the rod can be represented by a Fourier Series containing n terms. In this case the stability of the drill rod is defined by the eigenvalue equation:

$$[B]\{\xi\} = P[C]\{\xi\}$$

i, j = integers taking values 1,2 · · · · · n

$$C_{ii} = \frac{c^2 \pi^2 i^2}{\ell} \qquad \text{and} \qquad C_{ij} = 0 \left(i \neq j \right)$$

$$B_{ii} = \left[\left(1 - \nu \right) \bar{E} \, \frac{c^2 \pi^4}{\ell^3} \right] i^4 - \left(\frac{1}{2} \, p c^2 \pi^2 \cos \alpha \right) i^2 + \left[\left(1 - \nu \right) p c \ell \sin \alpha \right]$$

$$B_{ij} = 2 p c^2 \cos \alpha \, \frac{i j (i^2 + j^2)}{(j^2 - i^2)} \left[(-1)^{j-i} - 1 \right], \; (i \neq j)$$

$$\bar{E} = \frac{(1 - \nu) E}{(1 + \nu)(1 - 2\nu)}$$

A computer program to generate the required matrices and solve the equations was written.

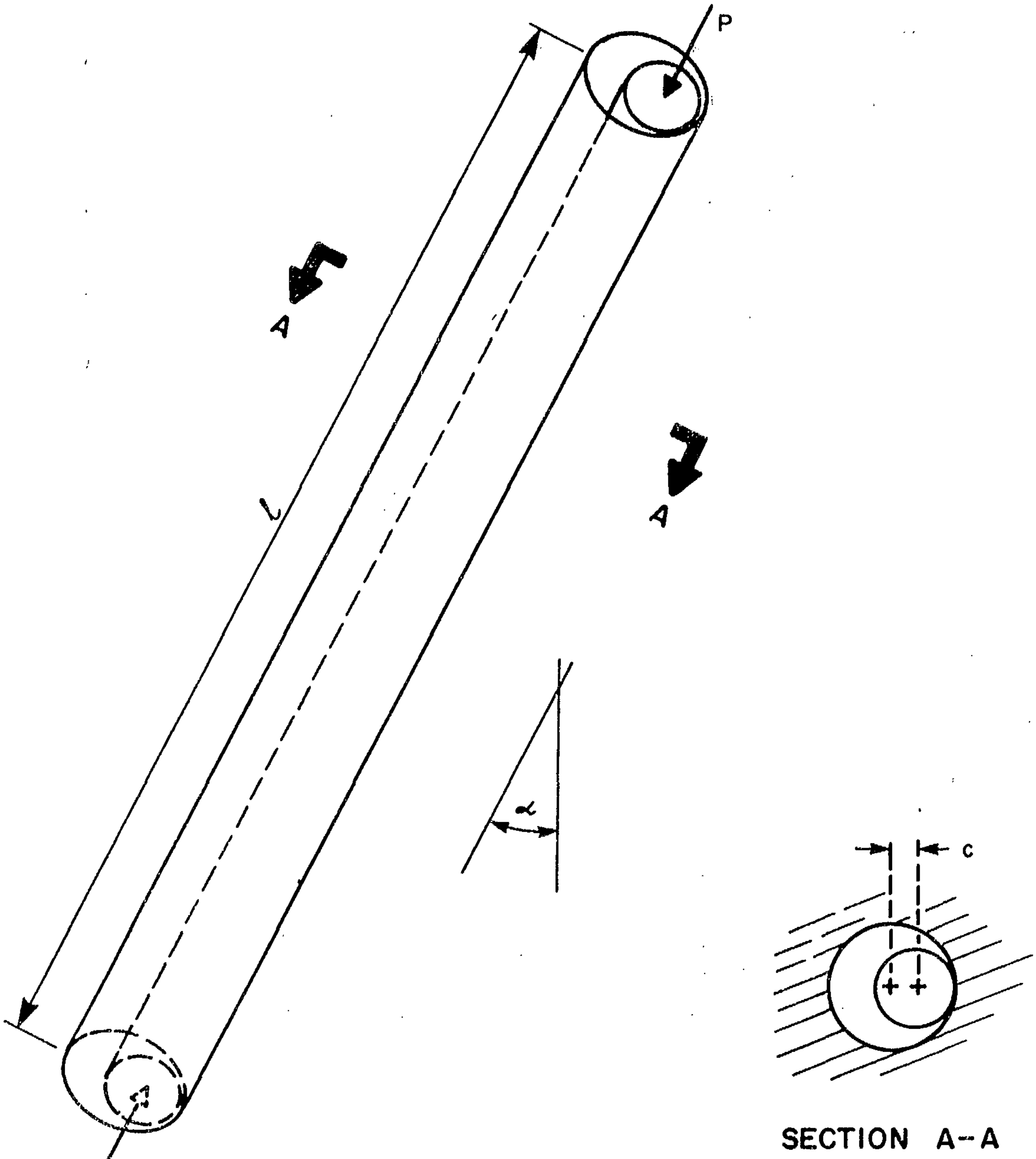

FIG. D1

MINING RESEARCH CENTRE, DEPARTMENT OF ENERGY, MINES AND RESOURCES

A STUDY OF HOLE DEVIATION IN DIAMOND DRILLING

IDEALIZATION OF DRILL STRING FOR HELICAL BUCKLING

ACRES

APPENDIX E

BIBLIOGRAPHY

NOTE: The references listed here were collected in the course of the literature search. Although not specifically referred to in the text, the material was used to provide background information on drill hole deviation.

Allen, R. H. (1962). "Operational Improvements Experienced with a Square Drill Collar in Various Drilling Fluids". *Drilling and Production Practice, API.* pp 75 – 79.

API Mid-Continent District Study Committee on Straight Hole Drilling. (1963). "Determination of Maximum Permissible Dog-Legs from Field Data". *Drilling and Production Practice, API.* pp 106 – 111.

Appl, F. S., D. S. Rowley, and H. C. Bridwell. (1967). "Theoretical Analysis of Cutting and Wear of Surface Set Diamond Cutting Tools". *Christensen Diamond Products.* Internal publication. June.

Boyarko, Yu. L. (1961). "Mechanics of the Cutting of the Hole Bottom in Anisotropic Rocks and the Process of Hole Deviation in Such Rocks During Shot Drilling". (Translated from Russian) *Izv. Tomsk. Politekhnicheskogo In-ta.* Vol. 120. pp 175 – 179.

Campbell, R. C. (1963). "Bore-Hole Surveying and Directional Drilling". *Proceedings, 11th Drilling Symposium.* Golden, Colorado. pp 185 – 193.

Colorado School of Mines. (1966). *Annotated Bibliography on Selected Mining Subjects.* CSM. Vol 61. No. 2. April.

Copley, J. D. and S. C. Jones. (1966). "Developments in Diamond Drilling Deflection Equipment and Techniques at Broken Hill South Ltd.". *Aust. Inst. Min. and Metall.* Proceedings No 220, pp 59 – 63. December.

Cullen, J. P. (1958). "The Thompson Retrievable Wedge and Arc Cutter". *Canadian Diamond Drilling Association.* Annual Convention.

Davies, S.G.G., C. Perkins and E Popplewell. (1967). "Diamond Drilling on the Zambian Copperbelt with Notes on Deep Slim Hole Drilling in South Africa". *Science and Technology of Industrial Diamonds.* Vol 2. Technology. pp 143 – 150.

Dellinger, T. B. and B. J. Livesay. (1972). "Diamond Bit Research Provides Basic Drilling Parameters". *Oil and Gas Journal.* Vol. 70. No. 38, pp 87 – 95. September 18.

Dubnie, A. (1969). "A Selected Bibliography on Drilling and Blasting". *Department of Energy, Mines and Resources, Mines Branch.* Int. Report No. MR 69/4-LD.

__________. (1972). "A Preliminary Examination of Research on Diamond Drilling in Canada". *Department of Energy, Mines and Resources, Mines Branch.* Int. Report No. 72/138.

Dubnie, A. and M. Gyenge. (1972). "Studies of Long-Hole Drilling". *Canadian Mining Journal.* pp 44 – 53. December.

Emery, M. M. (1973). "The Dyna-Drill and In-Hole Drilling Motor". *Canadian Diamond Drilling Association.* Annual Convention.

Everell, M. D., et al. (1973). "A Preliminary Control Strategy for the Automatic Control of an Instrumented Diamond Drill". *6th Conference Drilling and Rock Mechanics.* Austin, Texas. pp 55 – 65.

Galle, E. M. and H. B. Woods. (1963). "Best Constant Weight and Rotary Speed for Rotary Rock Bits". *Drilling and Production Practice, API.* pp 48 – 73.

Garret, W. S. (1952). "A Review of Diamond Drilling done in the Exploration of West Wits Areas". *Journal of the Chemical, Metallurgical and Mining Society of South Africa.* pp 497 – 515. April.

Gauvin, P. L. (1973). "Control of Verticality in 6-3/4" Diamond Drill Holes." *Canadian Diamond Drilling Association.* Annual Convention.

Gutkin, E. S. and B. G. Antropov. (1957). *"Means of Dealing with Hole Deviation During Shot Drilling".* Razvedka i Okhrana Nedr. No. 12, pp 56 – 57.

Hall, P. B. (1958). "Diamond Drilling as Applied to the Removal of Ripple Rock". *Canadian Diamond Drilling Association.* Annual Convention.

Harrington, A. T. (1960). "The Design and Application of the Turbo-Drill". *Can. Min. and Metall. Bulletin.* Transactions. Montreal. Vol. LXIII, pp 581 – 589. November.

Houghton, S. B. and C. M. Cole. (1970). "Emplacement Hole Displacement". *U.S.A. Atomic Energy Commission.* Nevada Operations Office, Las Vegas. Report NVO-38-25.

Hughes, M. D. (1972). "Direction Control Practice in Australian Diamond Drilling 1972". *Australian Diamond Drilling Association.*

__________. (1965). "Diamond Drilling in 1964". *Min. and Chem. Eng. Rev.* pp 14 – 15. February 15.

Jeffers, J. P. (1966). "Core Barrels Designed for Maximum Core Recovery and Drilling Performance". *Diamond Drilling Symposium Adelaide.* Paper 15. August.

Kempe, W. F. (1966). "Mohole Project ––Phase II". *Canadian Diamond Drilling Association.* Annual Convention.

Klinkenberg, A. (1951). The Neutral Zones in Drill-Pipe and Casing and Their Significance in Relation to Buckling and Collapse". *Drilling and Production Practice, API.* pp 64 – 79.

Logn, Av. Ø . (1965). "Retsningskontrollert Diamant Boring". *Tidskrift for Kjemi, Bergverk og Metallurgi.* Vol. 25, No. 4. April.

Lubinski, A. and K. A. Blenkarn. (1956). "Usefulness of Dip Information in Drilling 'Crooked' Formations". *World Oil.* pp 141 – 148. November.

Lubinski, A. and H. B. Woods. (1953). "Cut Costs in Crooked Hole Areas". *World Oil.* pp 135 – 142. July.

MacDonald, G. C. and A. Lubinski. (1962). "Straight Hole Drilling in Crooked Hole Country". *Drilling and Production Practice, API.* pp 15 – 26.

Metcalf, J. R. (1965). " An Investigation on the Scrolled Drill Rod–1". *Colliery Engineering.* pp 251 – 258. June.

__________. (1965). "An Investigation on the Scrolled Drill Rod–2". *Colliery Engineering.* pp 399 – 407. September.

Mindrill Ltd. (1970). "Description and Operating Instructions for the Mindrill 'S' and 'SM' Series Core Barrels". *Mindrill Ltd.* Australia.

Palmer, W. T. (1968). "Wedging Procedures at North Broken Hill Ltd.". *Aust. Inst. Min. and Metall.* Monograph Series No. 3. pp 63 – 65.

Peters, R. I. (1962) "Diamond Coring Technology's Contribution to the Moho Project". *Canadian Diamond Drilling Association.* Annual Convention.

Reinhold, W. B. (1965). "The API–AAODC Drill-Pipe Grading System in Relation to Drill-String Design and Use". *Drilling and Production Practice, API.* pp 57 – 65.

Rollins, H. M. (1956). "Studies of Straight Hole Drilling Practice 1952 – 1956". *Drilling and Production Practice, API.* **pp 37 – 74.**

___________. (1956). "New Tables for Woods-Lubinski Data .... Here's How to Use Them". *World Oil.* pp 142 – 149. May.

Speer, J. W. and G. H. Holliday. (1955). "Influence of Drill Collar Size and Stabilizers in Deviation Control". *Drilling and Production Practice, API.* pp 247 – 265.

U. S. Bureau of Mines. "Bibliography on Mineral and Oil Drilling". *Twin Cities Mining Research Center* Minneapolis.

van Eeden, G. J. (1956). "Deep Hole Drilling in S. Africa". *Canadian Diamond Drilling Association.* Annual Convention.

Walker, B. H. (1973). "Some Technical and Economic Aspects of Stabilizer Placement". *Journal of Petr. Tech.* pp 663 – 672. June.

Walsham, B. T. (1967). "Exploration by Diamond Drilling for Tin in West Cornwall". *Inst. Min. and Metall. Trans.* Vol.76, pp A49 – A56.

Woodhall, R. J. and J.C. Schillereff. (1962). "Reduction in Drilling Costs with Relaxed Deviation Requirements. Big Horn Basin, Wyoming". *Drilling and Production Practice, API.* pp 80 – 90.

SER #883 C212r
622(21)
Canada. Mines branch.
Monograph ; no. 883. Study of hole
deviation in diamond drilling.