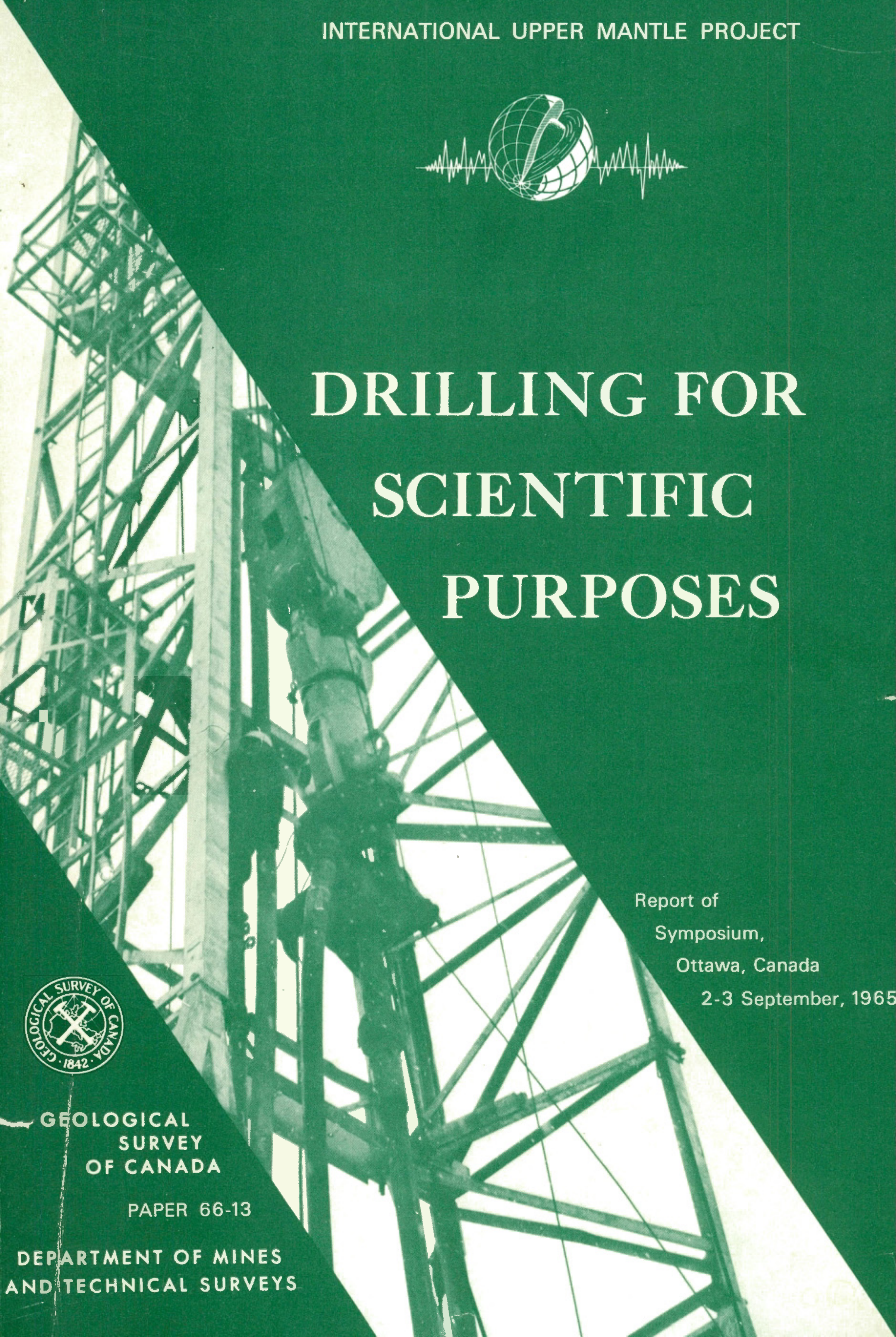
INTERNATIONAL UPPER MANTLE PROJECT

DRILLING FOR SCIENTIFIC PURPOSES

Report of
Symposium,
Ottawa, Canada
2-3 September, 1965



GEOLOGICAL
SURVEY
OF CANADA

PAPER 66-13

DEPARTMENT OF MINES
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UPPER MANTLE COMMITTEE

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Report of the International Upper Mantle Symposium Ottawa, 2-3 September, 1965

Edited by D. C. Findlay and C. H. Smith

DEPARTMENT OF MINES AND TECHNICAL SURVEYS

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D. SESSION ON SCIENTIFIC OBJECTIVES OF DEEP CRUSTAL DRILLING

E. SESSION ON DEEP DRILLING TECHNOLOGY

INTRODUCTION

During the period of September 2-9, 1965, the International Upper Mantle Committee held three Symposia in Ottawa. Their titles were - Drilling for Scientific Purposes; The World Rift System; and Continental Margins and Island Arcs. This volume is the first of three to be published containing the papers and recommendations of the sessions.

The symposium on Drilling for Scientific Purposes marked the first attempt to bring earth scientists and representatives of the drilling industry together to consider how to exploit drilling as a prime research tool in the study of a wide variety of non-economic geological and geophysical problems. For nearly a century the oil and mining industries have depended on drilling as the principal means of investigating mineral occurrences and mineral deposits at depth; more recently scientists have recognized the potential value of drilling to extend academic geological and geophysical investigations into the third dimension. However, although scientists working in various fields are becoming aware of the potential usefulness of drilling to their own work, many have not had the opportunity to become familiar with the mechanics, techniques, or economics of drilling, or with the vagaries of planning and carrying out drilling projects.

This symposium was evolved with two objectives in mind. At the 1964 Moscow meeting of the International Upper Mantle Committee, the importance of scientific drilling in connection with Upper Mantle research was affirmed and its objectives - particularly with regard to deep drilling - were defined. Countries were urged to consider drilling programs as a part of their contribution to the Upper Mantle program, within the limits of their individual resources. Thus the first objective of the Ottawa Symposium, following from the Moscow meeting, was to provide an opportunity for presentation and discussion of the plans of individual nations for drilling programs and for presentation of progress reports on projects under way or completed. It was realized that the capability of countries to carry out drilling programs would vary depending on their past history of resource development, and that the knowledge and experience possessed by some would benefit other countries wishing to develop drilling plans but lacking the experience to guide their efforts.

The second objective of the symposium was more practical - to acquaint earth scientists, through papers and discussion by invited representatives from industry, with the present state of the art of drilling, drilling equipment and techniques, drilling economics, and in-hole measuring systems and instrumentation. Particular emphasis would be placed on plans for deep and ultradeep drilling, since the major burden of the "exploration of inner space" will fall on such programs.

The papers presented in this report reflect a balance between the technical aspects of drilling and the scientific motivation for drilling. The body of the report is divided into five main sections paralleling closely the actual proceedings of the symposium. The first section – Scientific Drilling Programs – contains reports of national drilling programs, either in the planning stages as is the case in Switzerland (H.P. Laubscher) and Japan (M. Saito), or in various stages of progress as in Canada (D.C. Findlay and C.H. Smith) and U.S.A. (Gene Simmons, T. Saito).

The session on Geophysical Research in Deep Holes covers the range of measurements that are being made, and that can be made, in bore-holes. A comprehensive survey of present logging techniques is given by A.F. Bosworth and more specialized instrumentation used in bore-holes in South Africa is discussed by S.H. Haughton. A.E. Beck looks ahead to possible future developments in the measurement of terrestrial heat flow under conditions of high temperature and pressure, and G.G.R. Buchbinder, E. Nyland, and J.E. Blanchard describe experiments on the measurement of stress in bore-holes. Of topical interest is W.P. Schneider's account of the instrument and measurement program being developed for the Mohole Project. The session concludes with some preliminary results of geophysical measurements and heat flow studies from the Muskox drilling project by G.D. Hobson, A.E. Beck and D.C. Findlay.

The general philosophy of scientific drilling is discussed in the third session on the Scientific Objectives of Deep Crustal Drilling with an account of the approach to the subject in the U.S.S.R. by V.V. Fedynsky and a general paper on the reasons for scientific drilling by T.F. Gaskell. Undoubtedly a highlight of the symposium is the informative series of papers on the United States Mohole Project by H.H. Hess, W.H. Tonking, J.D. Sides, W.P. Schneider and D.L. Sims. In this session the inception and early days of the project are described and its progress to date is summarized.

The session on Technology of Deep Drilling records a variety of practical experience in the drilling of deep holes in various parts of the world with various types of equipment. W.S. Garrett describes the remarkable achievements of small diameter deep diamond drilling in South Africa and S.C. Foster presents a contrasting account of deep drilling in crystalline rocks in North America using oilwell drilling equipment and techniques. In the last of the Mohole papers, D.L. Sims discusses drilling and coring techniques developed to meet the special conditions of what V.V. Beloussov has termed "a most majestic project". To complete this session, H. Becker's account of the deepest well in Europe describes the operation of standard oilwell drilling techniques in deep sedimentary drilling.

The report concludes with an account of the discussion and recommendations arising from the papers presented during the meetings. The formal resolutions arising from this session are summarized in the front of the report.

In this report an attempt has been made to record the actual proceedings of the symposium as closely as possible. In the interests of brevity and standardization of format some sections have been shortened or modified considerably, particularly those involving discussions following many of the papers. We hope that misrepresentation of speakers' views has been avoided. In most cases delegates have had the opportunity of correcting or revising their contributions but this has not always been possible or practical in detail. In any event, for errors of commission or omission that do occur, the editors may be taken to task.

The symposia and report would not have been possible without the support and efforts of many people. Foremost, of course, are the authors and delegates who, by their active and conscientious participation, made the sessions possible. The Department of Mines and Technical Surveys and the National Research Council sponsored the meeting. The International Union of Geological Sciences defrayed part of the cost of preparation. Thanks are also due to Pembroke J. Hart, A.S. MacLaren, A.C. Hamilton, E.R. Niblett and Mrs. B.F. Thomas. Miss F.C. Aitkens provided assistance in assembling the manuscripts and Mrs. M.A. Shanks spurred them through the typing process.

D.C. Findlay
C.H. Smith

Ottawa,
January, 1966

RESOLUTIONS AND RECOMMENDATIONS ON DRILLING FOR SCIENTIFIC PURPOSES

Summary of Progress

Since the inception of the International Upper Mantle Project in 1961 various countries, including USSR, USA, Canada, Japan, South Africa, Federal Republic of Germany and Switzerland, have planned, and in some instances have carried out projects involving drilling for scientific purposes. A brief summary of these activities follows:

(1) USSR. Site selection studies, including detailed geophysical surveys have been carried out for proposed deep bore holes on the Kola Peninsula, in the Ukraine, in Azerbaijan, and in the region of southern Sakhalin and the Kuril ridge. Four deep wells are being drilled to study structural and stratigraphic sections in oil and gas-bearing regions, including the Aralsor and Bashkirskaya areas. Progress has been made in developing logging tools and cables for instrumentation of deep boreholes.

(2) USA. Progress continues on the Mohole project, including the successful completion of Phase II, the design, fabrication and field testing of the major components of the drilling, instrumentation, and deep-water vessel positioning systems and various auxiliary systems. A contract for construction of the drilling platform has been negotiated; drilling components have been tested in a hole drilled in basalt at Uvalde, Texas.

A program of continental drilling for various specific scientific purposes, including heat flow studies, isotope distribution studies, structural investigations, and studies of metamorphic rocks at depth, is planned.

(3) Canada. The Muskox drilling project has been completed. This involved the drilling of three diamond drill-holes totalling about 3 km, to investigate the large layered ultramafic-mafic Muskox intrusion. In-hole geophysical logging was completed. Detailed chemical and petrologic studies on cores from the drill-holes are in progress.

A program of drilling for heat flow studies continues. To date 7 holes, from about 500-700 metres deep, have been completed at various sites in Canada.

(4) Japan. Three potential deep drilling site areas have been chosen; Kamaishi, Izu Islands, and Oboke. Detailed geophysical site studies will begin in the Oboke area of west Japan this year. It is anticipated that drilling of a 5 km bore-hole at one of these sites will commence in 1967. Scientific studies will include, investigation of the lower layers of sialic crust, study of volcanic root zones, or investigation of the axial core of an orogenic belt, depending on which site is chosen.

(5) Federal Republic of Germany. A 6,000-metre well has been completed in the Munsterland region of West Germany for purposes of exploration of the hydrocarbon reservoirs and geologic structures of the "subvariszische Vortiefe". A second well in the Saar district is presently being drilled to a proposed depth of approximately 6,100 metres.

(6) Switzerland. A deep hole has been proposed for purposes of investigating the deepest exposed structural region of the Alps, in the area of the Lepontine Alps in southern Switzerland.

General Recommendation

Drilling for increased fundamental knowledge of the deeper parts of the crust and the upper parts of the mantle should be considered by governments and government agencies as an integral part of scientific activities sponsored by them. They should make continuing budgetary provision for such work, which would be undertaken only on a basis of adequate geological and geophysical knowledge. Holes should be made available for maximum utilization by the various scientific disciplines.

Specific Recommendations

1. Mohole

The Mohole project is most fundamental to advances in knowledge in a wide range of earth sciences and the early initiation of drilling is strongly recommended in places where the Mohorovicic discontinuity is well-established by geophysical measurements.

> Collection of rock samples above and below the Moho, and physical observations made in the bore-hole will permit the modification and strengthening of theories in earth sciences in a manner that no other method allows.

The Mohole project is already developing the tools and techniques associated with deep drilling and will, therefore, be of great value in improving the economics of drilling as well as in pioneering the methods.

2. Oceanic Areas

Countries are urged to drill into the ocean floor and oceanic islands so that basic information may be obtained on the structure and history of ocean basins.

Bore-holes through the sediments of ocean floors promise to elucidate at least the more recent history of the oceans and could test various hypotheses on the origin and/or movement of continents and ocean basins; the nature and origin of oceanic linear magnetic anomalies; the age of the basins, etc. Drilling on oceanic islands would elucidate petrologic problems, and drilling on atolls would clarify both stratigraphic and structural problems.

3. Continental Margins

Holes for scientific purposes should be drilled in the transition area between continents and ocean basins.

The transition areas are extremely attractive targets, not only for scientific data but for the economic deposits they may contain. Verification of the ideas derived from abundant geophysical data depends on sampling the sedimentary and basement rocks. Such information is fundamental not only to an understanding of the important structures but also to basic geological theory on continents and oceans.

4. Continents

Drilling should be particularly considered where essential information can reasonably be expected concerning those parts of the crust that cannot be directly observed at the surface.

Deep drilling is needed to advance significantly our understanding of several problems such as the Conrad discontinuity, granitic and basaltic layers, roots of mountains, distribution of isotopes, heat flow, differentiation of intrusions, etc. Logging tools need to be

> developed to take advantage of bore-holes of small diameter and techniques devised for the better interpretation of logs obtained in crystalline rocks.

5. Island Arcs

Carefully selected sites should be drilled so as to reveal the deep structure of island arcs and to supplement abundant geophysical information already available.

> Island arcs are of two types. The first type exemplified by Japan and New Zealand, appears to have continental structures. The second type is exemplified by Izu-Mariana, Tonga and West Indies, and appears to be part of the oceanic crust. Drilling should provide important data on their character and may give some clues to the origin of continents.

6. The International Upper Mantle Committee would appreciate learning of all holes being drilled for scientific purposes. It expects also that the drilling of some holes might be undertaken as an international enterprise by a group of nations. The Committee would be glad to receive proposals for such projects.

Ed. Note

The above recommendations were prepared and approved by the International Upper Mantle Committee, meeting on September 10, 1965. The detailed discussions and resolutions presented by the assembled delegates, which formed the basis for the above general recommendations, are found in Section F of the Proceedings recorded in this volume.

PROCEEDINGS OF THE SYMPOSIUM

A. OPENING REMARKS

Prof. R.J. Uffen introduced Dr. W.E. van Steenburgh, Deputy Minister, Department of Mines and Technical Surveys.

Dr. van Steenburgh: "Ladies and gentlemen, it gives me great pleasure this morning, on behalf of the Department and myself, to welcome the delegates to this symposium. We consider this a milestone in the scientific endeavours of Canada, and we feel that when these organizations decided to meet here in Canada, they paid us a great compliment. My purpose in being here this morning is a pleasant one. I have been asked to introduce our Minister, the Hon. J. Watson MacNaught. Our Minister has shown great interest in the scientific activities of this Department and is very pleased also, that you are here. At this time, I would like to present my Minister the Hon J. Watson MacNaught."

Mr. MacNaught: "Distinguished delegates, it gives me much pleasure to welcome you on behalf of the Government of Canada and to tell you that we are honoured to have you gather in Ottawa to discuss research progress of the International Upper Mantle Project. Canadian scientists have played an active role in the Upper Mantle Project and their enthusiasm has affected those of us engaged in other sectors of Canadian affairs as well. As you may know, Canadian research on the Upper Mantle Project got off to an early start. Some critics, who were perhaps not quite serious, have even suggested that our scientists were too successful in getting their projects approved and accomplished. They fear that they are now cast in the role of the child who has eaten his cake while the other children are still happily munching theirs.

"My government is not only aware of the scientific benefits which will arise from these studies, but is also acutely aware of the potential economic benefits which may evolve from your studies of deep drilling, continental drift and other matters related to the deeper parts of the earth. Speaking of continental drift, it is hard to resist various analogies. I have even heard it said that Prince Edward Island, which happens to be my home province out on the Atlantic seaboard, is threatening to drift away from the rest of Canada, and that to prevent this, it has been found necessary to anchor it to the mainland with a causeway. Well, I believe that some of the talk about drifting apart that is heard today is greatly overrated and that whatever the continents may be doing, the people inhabiting them are steadily drawing together. No better proof of this could be found than this gathering itself; in which representatives from the most distant nations, both geographically and politically, sit down together to pool their research and knowledge for the common good. These international human contacts, I think, are valuable in themselves and further enhance the importance of the present symposium. I join with the members of the Departmental staff and indeed the entire community in hoping and wishing that your stay here may be pleasant and fruitful, and that this city may act as an effective catalyst in furthering your work. I am also looking forward to meeting you informally at the reception at Kingsmere tomorrow night.

"It is now my pleasure to declare this meeting officially open."

Prof. Uffen: "We had expected at this time to hear some opening remarks from Professor Beloussov, Chairman of the International Upper Mantle Committee. Unfortunately he will not be here until this afternoon. However, I feel it appropriate at this point to make a few remarks on his behalf. I would like you to recall that it was Professor Beloussov who proposed the project at the 12th General Assembly of the International Union of Geodesy and Geophysics in Helsinki in 1960, and at that time he was President of the I.U.G.G. He proposed an international program analogous to the International Geophysical Year, which we all know has been quite successful—but in which the attention would be directed towards the earth's interior and in particular to the Upper Mantle, and its influence on the development of the crust. Now, the Upper Mantle Project was originally to have taken place from January 1962 until December 1964, but because the international planning took a little longer than was first expected, the program date has been extended to December 1967. The Upper Mantle Project has received the active support of the International Union of Geological Sciences. I think this was a major event—when the I.U.G.S. agreed to participate as well. As a result of this, the original organizing community was enlarged to include representation of geologists in 1963. In June 1964 the executive council of the International Council of Scientific Unions endorsed the project and invited member countries to participate. At present there are 43 countries participating to various degrees. Some of you will have had the privilege of attending the I.U.G.G. meetings in Berkeley in 1963, and at that time you would have heard Professor Beloussov address the general assembly. I would like to quote some of the interesting remarks he made at that time.

> 'What is the Upper Mantle Project? On the one hand it is a scientific trend, which means united geological, geophysical, geochemical, and geodetic studies of the deep structure (of the earth).'

(Prof. Beloussov coined a new word for these combined studies - "geonomic".)

> 'On the other hand, it is a program of cooperative geonomic research tied to different tectonic realms, or in some cases, to the whole globe. There is also a third part of the project which may be called, if you wish "philosophic". The Upper Mantle Project tries to create equality between geosciences in those researches which are aimed at the study of deep (earth) processes.

> 'The Project endeavours to bring about mutual respect between different geosciences which are entering the free union with equal rights. The Project makes an attempt to teach the representatives of different geosciences to work, think, and understand together and to arrive at conclusions that could be supported equally well by each of them. We tried to form a new psychology of the researcher, who, while remaining a specialist in his own field, would be also a geonomist— that is a man who can intelligently evaluate and apply data of bordering sciences. And in this connection it is necessary to reconsider seriously the methods used in training young specialists in our fields of science.'

"Those are some of the words of Professor Beloussov and I thought they were worth repeating. Now there remains only for me to welcome you to these symposia on behalf of the National Research Council of Canada, which is co-sponsoring the symposia and which is the agency in Canada which provides the financial assistance to Universities, the primary agency, but not the sole one."

B. SESSION ON SCIENTIFIC DRILLING PROGRAMS

DEEP DRILLING PROGRAM OF JAPAN

M. Saito

Geological Survey of Japan

Abstract

Deep drill-holes to 4,500 or 5,000 metres will be necessary to obtain useful information on the nature of the crust in Japan. Such holes are being planned in connection with Japanese participation in the Upper Mantle Project.

Three potential drilling sites are presently being considered; (a) the Kamaishi area in northern Japan where gravity and seismic studies suggest that the sialic crust is thin; (b) the Izu volcanic islands south of central Japan, where geophysical studies indicate that a drill-hole several kilometres deep might penetrate through the Quaternary volcanic section and the Tertiary or Cretaceous continental deposits to the suboceanic layers, such as unconsolidated sediments and basalt; and, (c) the Oboke area in west Japan where the axial core and basement rocks of a typical Palaeozoic orogenic belt paralleling an island arc structure could be examined by drilling.

Geophysical surveys will be carried out this year in the Oboke area for further assessment of deep drilling sites.

INTRODUCTION

Drill-holes to depths of 3,000 to 4,000 metres in the sedimentary rocks of the Tertiary oil and natural gas fields, and to depths of 1,000 to 1,500 metres in the crystalline rocks of mining areas are fairly common in Japan. They have contributed much data on the physical properties of the rocks of those areas through well-logging methods and many such existing bore-holes could be conveniently utilized for additional deep-seated in-hole geophysical observations. As far as Japanese drilling projects in connection with Upper Mantle studies are concerned, we hold to the principle that scientific drill-holes should be as deep as possible to obtain data from depths deeper than that normally attained by exploration drilling. We also believe that one deep drill-hole is probably preferable to a number of shallow holes. At the present time depths of about 4,500 to 5,000 metres appear to be about the limit of the drilling facilities now available in Japan. Although these depths are not very great, if drilling sites are carefully selected, they should be sufficient to provide useful information on the nature of the crust and the influence of the upper mantle on it in Japan.

POTENTIAL DRILLING SITES

Three possible sites for deep drilling in Japan are being considered at the present. These are; the Kamaishi area in northern Japan; the Izu volcanic islands south of central Japan; and, the Oboke area in western Japan.

Kamaishi Area

This area borders on the Pacific Ocean in which the Japan Trench lies about 200 kilometres off the Japanese island arc. A Bouguer gravity anomaly shows one of the highest values so far measured on the Japanese islands, suggesting the sialic crust to be thin. An explosion seismic profile on land has revealed successive crustal layers having wave velocities of 5.8 km/sec and 6.1 km/sec in descending order, with the boundary between them lying 0.5 to 2.5 kilometres below the land surface at Kamaishi. The velocity boundary and the deeper layer are probably both accessible by current drilling techniques and the investigation of those features would be the main objectives of deep drilling here. Terrestrial heat flow values are low in the area and no difficulties are expected from high temperatures at depth.

Izu Volcanic Islands

Various geophysical studies have estimated the crustal thickness in the Japanese main islands and the fringing continental shelf as 20 to 37 kilometres, so that penetration to the Moho is beyond our present scope. However, if we try in Japan to approach most closely to the Moho, one of the volcanic islands, for instance Hachijojima (140°E, 33°N) resting on the Izu-Mariana oceanic ridge, should provide the most suitable site. This conclusion is supported by marine gravity and seismic data. With luck, a bore-hole several kilometres deep would reach to the crustal layer transitional to the oceanic floor; that is, from the overlying Quaternary volcanic section and its basement of Tertiary or Cretaceous continental deposits to the suboceanic layers such as unconsolidated sediments and basalt.

Because the islands are volcanic, a rapid increase in temperature with depth may make drilling difficult. On the other hand however, we may expect to obtain useful information about volcanic roots. Air-borne magnetic data support such interpretations, suggesting that the objectives could be reached within a depth of 5 kilometres.

Oboke Area

This area represents the axial core of a typical orogenic belt of old geologic age, running parallel with the island arc. The rocks exposed are Palaeozoic geosynclinal deposits that have been strongly folded and regionally metamorphosed into crystalline schists. No acid intrusives occur in association with the folded rocks, whereas basic and ultrabasic intrusions, possibly arisen from the mantle in the past, are common. The main objectives of drilling here are to penetrate the interior and the basement of the metamorphosed geosynclinal section.

The proposed site for drilling (34°N, 133.5°E) is located on a broad anticline. The lithology of the schistose rocks occurring in the anticline suggest that the original rocks are early Devonian or late Silurian in age, which are the oldest ages so far palaeontologically dated in Japan. It is hoped that deep drilling here will reveal the nature of the lower Palaeozoic and older rocks, which are very incompletely known.

Gravity data from the area indicates a thick crust, and the heat flow is rather small. However, other geophysical information such as seismic data are meagre.

PLANS FOR DRILLING

Almost all geophysical information concerning the proposed drilling areas is based on reconnaissance surveys over broad regions. Prior to actual drilling, detailed surveys and research with the specialized objectives of examining the local geology and structure and of verifying the present data are of vital importance. This year a seismic survey will be carried out in the Oboke area in order to determine the actual structure to depths of more than 5 kilometres. Similar geophysical surveys are planned for the other proposed areas in the coming years. It is hoped that the first drilling can begin in 1967 at the earliest, but hasty undertaking of drilling without sufficient detailed examination and preparation should be avoided. The expenditure of hundreds of million yen and a duration of 2 years are estimated to be required to drill one hole about 5 kilometres deep, with nearly continuous coring in hard rocks, and accompanied by a complete logging program. Long term observations obtained from instruments installed in the bore-hole and laboratory investigations of cores will follow the completion of drilling.

Recent activities in the exploration for petroleum, natural gas, and natural steam have considerably advanced our drilling techniques and measuring methods, particularly in holes drilled under conditions of high temperatures and pressures; however, many technical difficulties remain to be overcome before drilling to depths of several kilometres can be accomplished in Japan.

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DISCUSSION

Prof. R.J. Uffen (Can.)

Which one of the three sites do you propose to drill first?

Dr. Saito

That is a problem that has not been settled, since the criteria for selection in each area are quite different. We must collect more data and consider the feasibility of the drilling.

Prof. Uffen

So you have not made a decision yet?

Dr. Saito

I think deep drilling must be controlled by geophysical rather than geological data. But the data on our proposed areas is mostly based on reconnaissance surveys and special local geophysical investigations must still be made. The first work will begin in the Oboke area this year.

THE PROJECT FOR DEEP SCIENTIFIC DRILLING IN THE SWISS ALPS

H.P. Laubscher
Geologisch-paläontologisches Institut der Universität Basel

GENERAL PURPOSE

The principal purpose of a drilling program in the Swiss Alps would be to extend surface information about the Alpine orogeny beyond the lowermost structural levels exposed at the surface.

SITE SELECTION

The core of the Alps is formed by the Pennine nappes. Below the Pennine nappes proper the Lepontine nappes ("Lower Pennine nappes" of some authors) emerge to the surface in the Lepontine Alps of southern Switzerland and northern Italy. This latter is an area of axial culmination of the nappe edifice. This general area will be the location of the proposed bore-hole,preferably at a point where the lowermost structural levels are exposed. Within this general area the best actual site will have to be chosen on the basis of other factors, particularly accessibility. Two local site areas are of particular interest; the first is in Italy close to the Swiss border; the second is in the central Ticino Valley of Switzerland. The latter site is more accessible, being on the St. Gotthard route – one of the most important north-south road and rail arteries of western Europe.

GENERAL SCIENTIFIC PROGRAM

Regional metamorphism in the Alps reaches its highest grade in the Lepontine area where the rocks contain kyanite-sillimanite and plagioclase (An_{70}-An_{100})-calcite assemblages. In this area numerous Rb/Sr age determinations on biotite yielded the youngest ages (<20 m.y.) obtained in the Swiss Alps. They are thought to represent the time of cooling to 300°C.

The metamorphic facies and biotite age determinations thus suggest either that the Lepontine Alps were a heat dome during a comparatively recent time, or that they were recently uplifted from a level of higher temperatures, or both.

A drill-hole at the proposed site may help to extend understanding of Alpine mineral facies to levels of wholesale anatexis and by means of biotite age determinations may provide three-dimensional control on the time and rate of cooling in this thermally active part.

The drill-hole would further aid in extending surface geophysical information, and the usual down-hole geophysical surveys are planned. Seismic fan shooting into the hole might help in resolving the deep structure of the area, particularly the behaviour of the Insubric fault zone. Generally the region is difficult for seismic exploration, and some experimentation is anticipated before a definite program can be established.

EXPLANATION OF FIGURES

Figure 1

This illustration is based mainly on the Geologische Generalkarte der Schweiz, 1 : 200,000 – in particular on the tectonic sketch maps 1 : 750,000 accompanying it. The key numbers are as follows:

1. Rhine Graben, flanked by Vosges and Black Forest;
2. Jura fold belt (mainly Jurassic);
3. Tertiary Molasse basin;
4. Subalpine Molasse (overthrust slices, imbrics – mainly Chattian);
5. Unmetamorphosed sedimentary décollement nappes; essentially Helvetic and Ultrahelvetic nappes, and Prealps;
6. Aar Massif;
7. Gotthard Massif;
8. Metamorphosed Mesozoic sediments of the southern Gotthard Massif and the Lepontine area (black);
9. Lepontine area;
10. Pennine nappes, exclusive of Lepontine area;
11. Austro-alpine nappes;
12. Ivrea zone;
13. Southern Alps;
14. Tertiary granitic and granodioritic rocks;
15. Insubric fault zone;

A-A. Location of profile of Figure 2.

The triangle within unit 9 indicates the best general location for the proposed deep bore-hole.

Figure 2

This is a simplified and slightly modified version of a 1 : 250,000 scale cross-section accompanying the Geologische Generalkarte

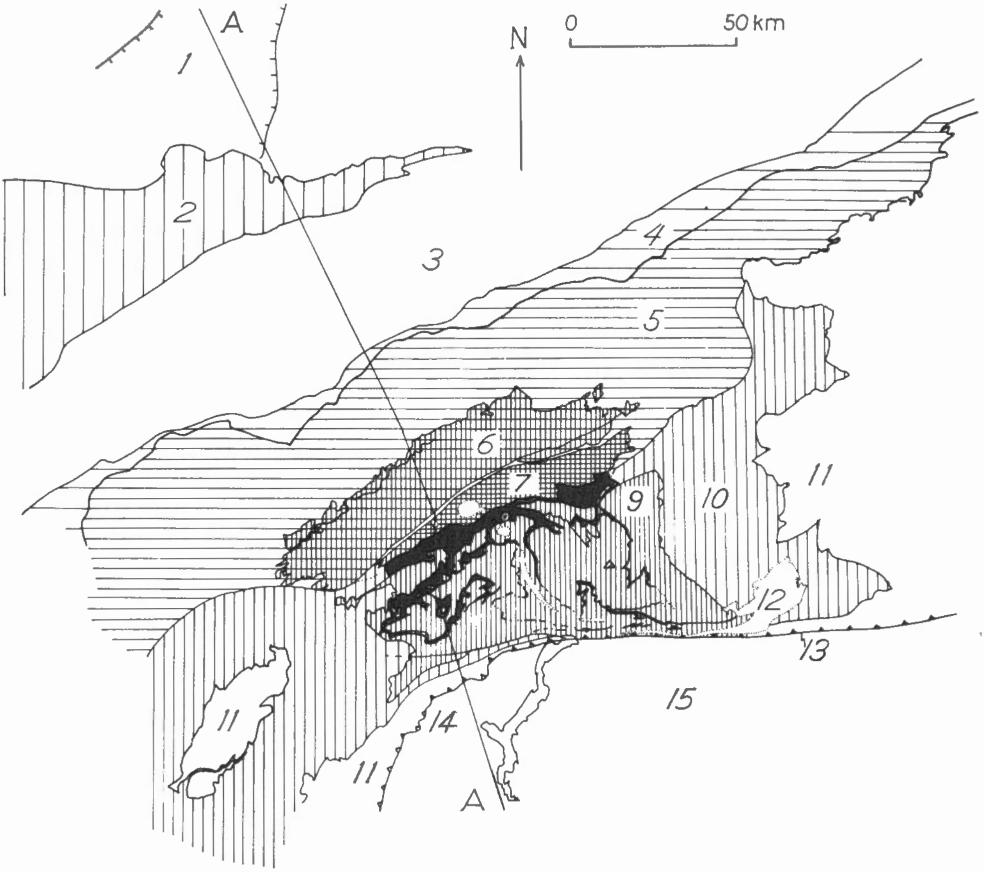

Figure 1. Tectonic sketch map of the Central Swiss Alps and their surroundings (see text for explanation of key numbers).

der Schweiz, 1 : 200,000 scale. It has been extended through the crust into the upper mantle by projecting various geophysical data onto the section (Closs, 1963; German Research Group for Explosion Seismology, 1964; Fuchs et al., 1963; Gassman and Prosen, 1948; Liebscher, 1964; and, Wanner, 1948). The exact boundaries of the main rock units are thus somewhat arbitrary, but they are believed to correctly indicate the present state of knowledge.

In Figure 2 the positions of the Conrad (C) and Mohorovicic (M) discontinuities and of the Ivrea body (I) have been approximately interpolated from data to the east and west of the present section. The limits of the Tertiary body of axatexis and homogenization (G) are conjectural and are defined by outcrops of younger, massive granitic bodies and by palaeotemperature determinations.

The Verampio window (V) is the deepest structural level exposed, and the position of a proposed 6 km deep bore-hole in this area is shown. The Tertiary anatectic body (G) has been a source of controversy amongst Swiss petrologists for some years. The interpretation shown here is based on estimates of palaeotemperatures at the surface, assuming what are believed to be reasonable palaeotemperature gradients around large thermally active bodies. The latter have been taken as an average of 20°C/km in the peripheral parts, and up to 100°C/km in the roof rocks of the granitic body. The irregular shape of body G is based partly on surface outcrops, and partly on the geometry of other granitic bodies in a similar setting. Possible relics of different rock types and of preexisting nappe structure, such as those of the similar Bergell granite farther to the east have been omitted because of lack of knowledge. The offshoot shown at depth to the south beyond the Insubric fault zone is the projection of a structurally similar occurrence in the Adamello Massif. The relation between body G and the basal part of the crust is unknown and the interpretation shown to complete the picture here is arbitrary.

In addition to a general structural picture, Figure 2 also provides insight into relations between the upper mantle and Alpine orogeny. Four aspects of these relations may be stressed in particular:

(1) The largest structural unit is the Ivrea body (I). The important positive isostatic gravity anomaly associated with the Ivrea zone, in which basic and ultrabasic rocks are common, has been known for many years (cf. Niggli, 1947). More recently, extensive explosion refraction work (Fuchs et al., 1963; Closs, 1963) has been added to the gravity data. It appears now that the Ivrea body extends down to the Mohorovicic discontinuity with a root exceeding 50 km deep in places. In addition, it apparently plunges along the Insubric fault zone, northwesterly below the Pennine backbone, in the western Alps at least.

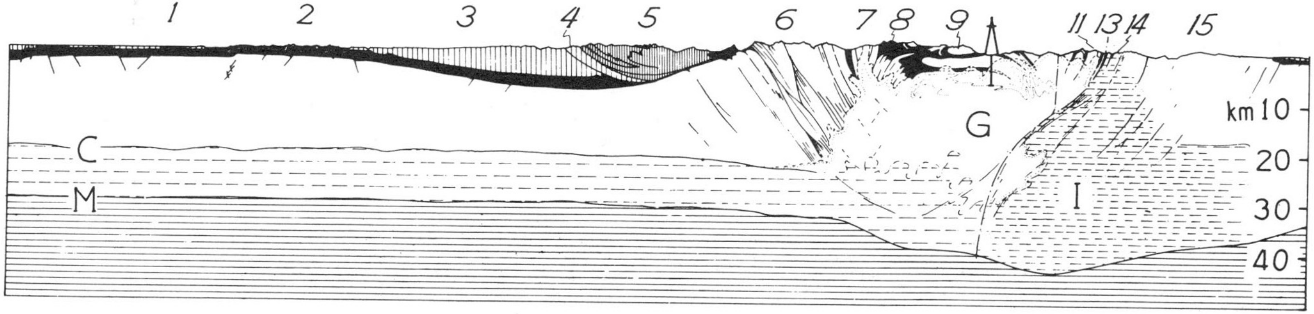

Figure 2. Tectonic profile through Central Switzerland, including parts of France (left side of diagram) and Italy (right side). Key numbers as in Figure 1.

(2) A large body of anatectic granitic material is centred below the Pennine zone and extends to the north into the Central Massifs, and to the south into the "roots" along the Insubric fault zone and beyond it. This body apparently post-dates most of the tectonic activity of the region. Infrequent outcrops of intrusive acidic rocks occur, but over most of the region medium to high grade metamorphic rocks are exposed. Rubidium-strontium age determinations on biotite have yielded ages (believed to represent times of cooling to 300°C) as young as 13 m.y. (Jäger, 1962; Jäger and Niggli, 1964). A study of this body and its peripheral effects might provide insight into the history of mantle heat involved in crustal deformation (cf. Shimazu and Kohno, 1964). In general, data of this type support the view that heat transfer has been slower than crustal movement.

(3) The crustal roots - the "bulges" of the M-discontinuity - are not related to the structural roots which are the source areas of the nappes. The crustal roots seem to be young and ephemeral features. Reconstruction of depositional basins whose sediments are now mostly piled up as the décollement nappes reveals structural shortening of several hundred kilometres. Particularly clear is the case of the Helvetic nappes which have been derived from a trough originally about 50 km wide and whose basement is now shortened to perhaps 5-10 km. This implies that a crust originally 20 km thick ought to be now about 100 to 200 km thick. Actually, crustal thickness in the Central Massifs, including the part now removed by erosion, does not appear to exceed a maximum of about 40 km. It thus appears that a large part of the crust has disappeared at depth, removed by some unknown process to an unknown destination. This is another puzzling connection between upper mantle activity and crustal deformation.

(4) Beneath the Molasse basin the crystalline crust appears attenuated. For the section shown on Figure 2 this interpretation is the result of extrapolation from the east where such attenuation is a feature peculiar to the south German Molasse basin (German Research Group for Explosion Seismology, 1964, pp. 221-223).

Figure 3

In Figure 3, the dashed lines outline areas of the same anorthite content of plagioclase in equilibrium with calcite; dotted lines indicate Alpine mineral facies zones as follows: ST - stilpnomelane only; CH - chloritoid, stilpnomelane; KY - kyanite (and staurolite); SI - kyanite, sillimanite (and staurolite). A further refinement of isograds and determinations of palaeotemperatures is in progress. The black triangle marks the location of the proposed deep bore-hole.

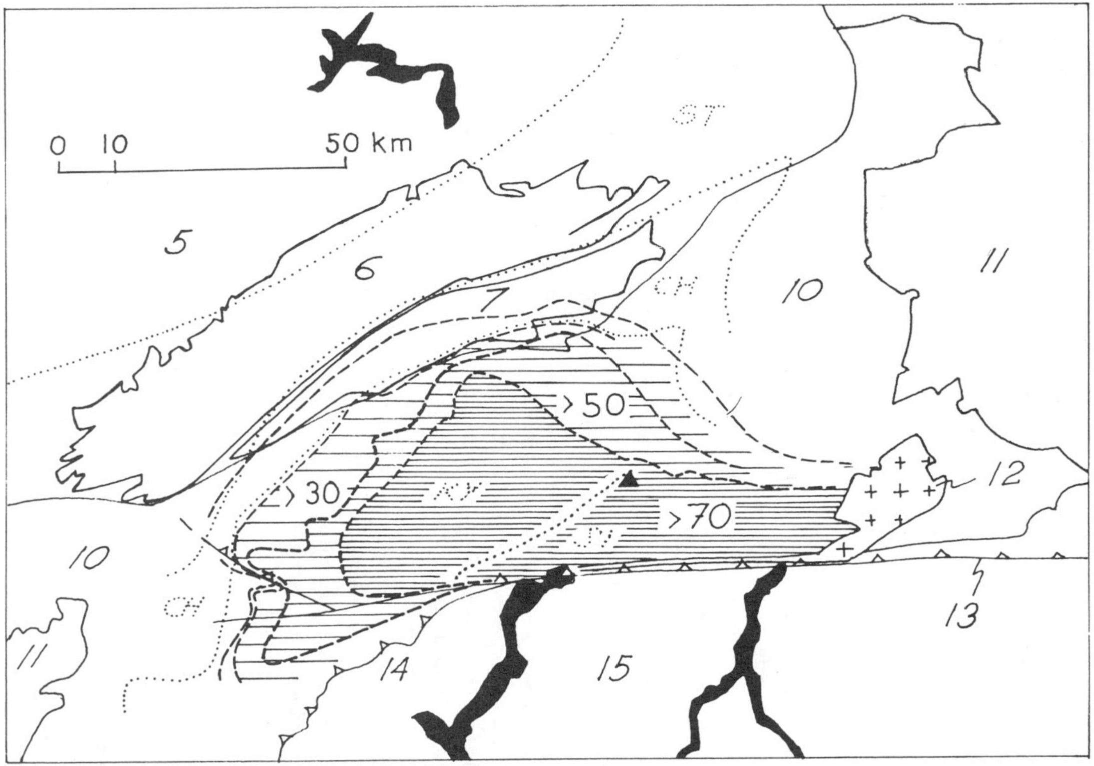

Figure 3. Mineral facies zones of the Lepontine area, after Wenk, 1962, and Niggli (Jäger, 1962). See text for explanation of symbols.

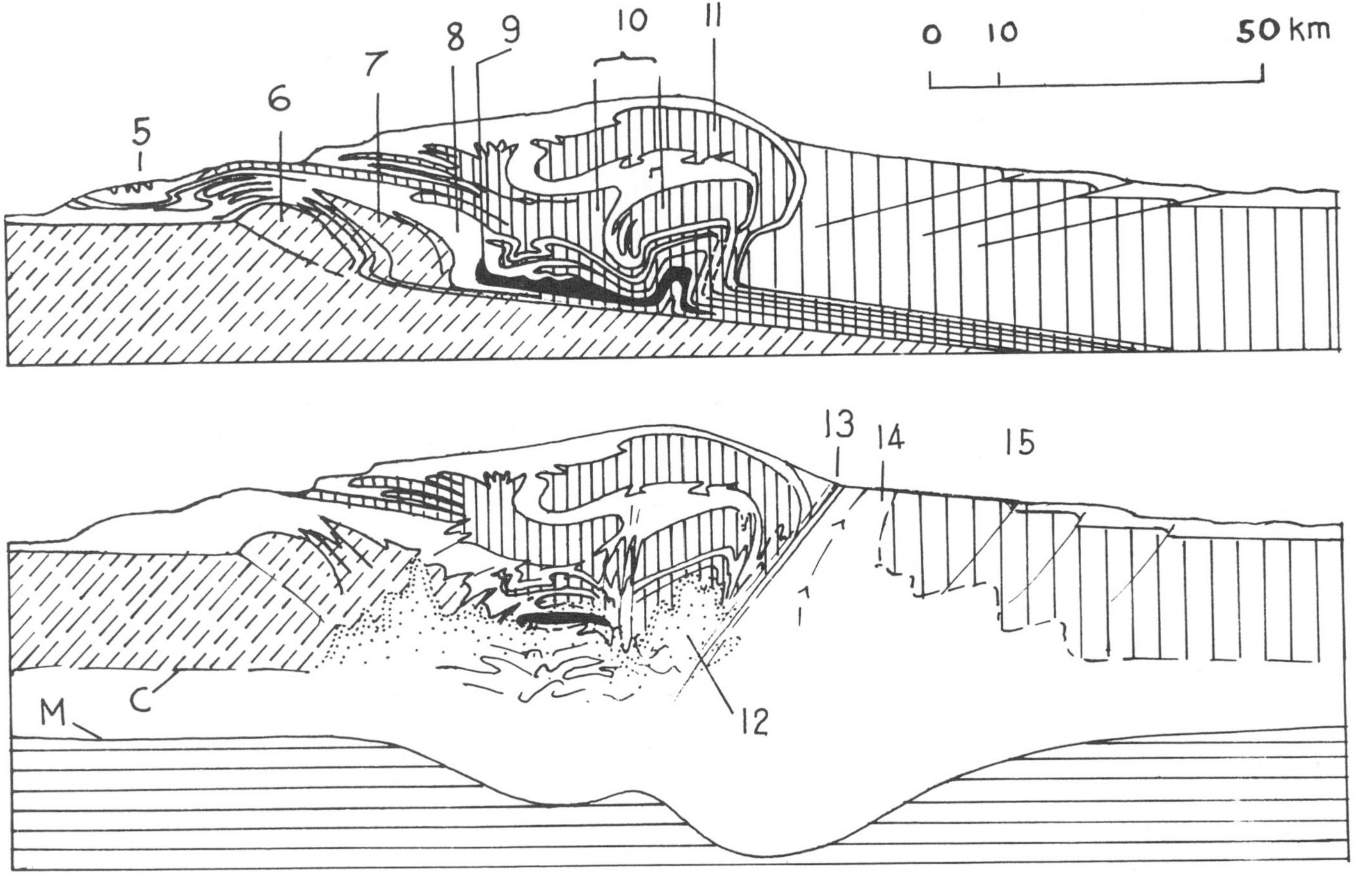

Figure 4. Schematic cross-sections through the Western Alps (after Argand, 1916, Bearth and Lombard, 1964, Wenk 1962b, and others).

Figure 4

This figure serves two purposes. First, it illustrates the lowermost structural unit exposed in the Alps – the Verampio body (black) – within the intricate framework of Alpine nappes. Here the classical interpretation of Argand, although out of date in many respects, still provides the easiest means of orientation. Secondly, Figure 4 provides a general impression of the present structure of the different levels of the Alpine orogen. This cannot be shown in Figure 2 because in that area the main part of the pile of nappes has been removed by erosion. No precision in detail has been attempted.

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DISCUSSION

Prof. R.J. Uffen (Can.)

As a geophysicist, I find it refreshing to learn that a textbook area in geology that I once studied, is apparently still open to reinterpretation. It does not look at all like what I was taught.

Prof. H.H. Hess (U.S.A.)

What do you think you are going to find when you drill this hole?

Prof. Laubscher

There are differences of opinion about this. Some people hope that we will go first into a zone of wholesale anatexis, and beyond that, perhaps into a water-free granulite facies. Others think that we will get slowly and gradually into deeper mineral zones without encountering anatexis for a long while. Ideas on the area, as has been said, have certainly changed since the classical time of alpine "nappism", and I am sure that the drill-hole will change the interpretation again.

Prof. Uffen

Do you have any ideas of the cost of this proposed hole? Could you guess at the cost of, say, the first 2,000 feet?

Prof. Laubscher

I do not think that 2,000 feet would cost very much. At any rate it probably would not be worth while to drill to less than about 3 km or about 10,000 feet.

Prof. Uffen

There was an estimate from the floor of 3/4 million dollars.

Prof. Lauscher

Yes, a minimum of 3/4 million. I have talked to some of the South African delegates and they describe drilling to 15 to 18,000 feet under very favourable circumstances. Do they have anything to offer about the possible costs to go to these depths?

Mr. W.S. Garrett (S. Africa)

The price range is a bit of a guess. Under South African conditions of ruling labour rates, materials, and costs, a 10,000 foot hole would probably cost about £40,000 – say $120,000. But this is under conditions where we have been drilling these holes for years, we know exactly what we are doing, and we have a very good idea of what we are going to go through.

PROGRESS AND PLANS FOR SCIENTIFIC DRILLING IN CANADA

D.C. Findlay and C.H. Smith,*
Geological Survey of Canada, Ottawa

Abstract

During the initial period of the International Upper Mantle Project, diamond drilling programs were organized to drill to depths up to 10,000 feet for scientific purposes. The principal fields of interest include:

(a) drilling of igneous intrusions;
(b) drilling for heat flow studies;
(c) drilling to investigate circular crustal structures.

Because of limitations imposed by drilling costs, available equipment and technical requirements, actual drilling projects carried out to date have involved holes less than 5,000 feet deep. Drilling to investigate the large, layered Muskox Intrusion in the Northwest Territories has been completed and the results published. The experience gained from this project has provided a useful basis for the planning of more ambitious, deep hole programs.

Site evaluation studies for 10,000 foot holes have been carried out in alpine-type ultramafic intrusions, and recommendations have been made for drilling in connection with other geological and geophysical research projects. The principal problems in initiating drilling programs for earth science studies are not unique to Canada. They involve an acceptable balance between cost and scientific benefit, and these factors are still being weighed in the light of new technological advances and scientific techniques.

INTRODUCTION

This paper reports on the status of drilling programs undertaken in Canada since the start of the International Upper Mantle Project. The need to drill for geologic knowledge as opposed to drilling for direct economic benefit is a concept that Canadian scientists have been interested in for some time, and the advent of the Upper Mantle Project gave some added impetus to these drilling ambitions.

To date, scientific drilling in Canada has been confined to relatively modest projects, related to three main fields of investigation.

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*Speaker

These are:

i) holes drilled for heat flow studies;
ii) drilling to investigate circular crustal structures believed to be ancient meteorite craters;
iii) drilling to investigate the large, layered Muskox intrusion in the Northwest Territories.

Originally, a number of deeper holes were planned, particularly in connection with the study of ultramafic intrusions. However, as feasibility studies for the drilling progressed, it rapidly became evident that the deep holes were beyond our immediate capability because of cost, and the lack of diamond drilling equipment in Canada capable of continuous core drilling to depths greater than 10,000 feet. For these reasons it was necessary to limit the initial projects to shallower holes — less than 5,000 feet deep — in order to explore geological problems where maximum vertical penetration was not a critical factor.

The Muskox Project has been the single most ambitious project to date. A complete description of the project has been published (Findlay and Smith, 1965) and the present report only summarizes the planning, logistics, and operational stages of the project briefly and then concludes with a few remarks concerning possible future drilling plans.

THE MUSKOX DRILLING PROJECT

The Muskox Intrusion is a well differentiated mafic-ultramafic layered complex that outcrops in the Canadian Shield, about 300 miles north of Yellowknife, Northwest Territories. It is exposed for 75 miles along strike, and gravity data indicate it probably extends an additional 75 miles to the north beneath cover rocks. By 1961 much geological information had been obtained from surface studies (Smith, 1962; Smith and Kapp, 1963) but it was apparent that drilling would be necessary to provide a complete three-dimensional structural, petrographic and geochemical picture of the intrusion, which is interpreted as composed of mantle-derived material emplaced in the crust — obviously not a part of the present mantle. Drilling was required for three main reasons:

i) to define the internal shape and structure of the intrusion;
ii) to provide precise thicknesses and volumes of separate rock units;
iii) to provide complete core sections across each rock unit for petrographic and chemical studies.

Figure 1 summarizes the geology and structure of the intrusion and shows the location of the drill-holes. Structurally the intrusion is fairly simple, consisting of a main body which is trough-shaped in cross-section and a feeder which forms a dyke-like keel beneath the trough. The feeder contains bronzite gabbro and picrite in vertical zones parallel to the walls; the main body comprises a variety of gently-dipping layers ranging from dunite and pyroxenite to various types of gabbros, forming the gravity-differentiated Central Layered Series. The Layered Series is bounded by the inward-dipping Marginal Zones containing rocks ranging from bronzite gabbro to peridotite, and is overlain by an Upper Border Zone containing granophyric rocks.

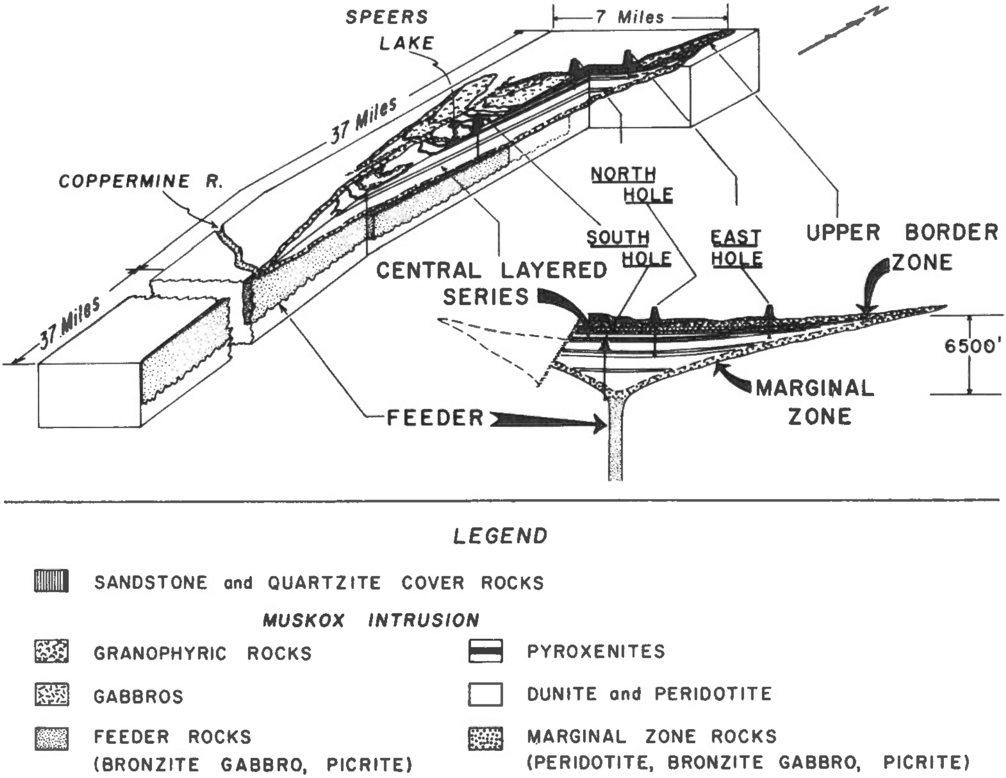


Figure 1. Summary of the geology and structure of the Muskox Intrusion, showing the location of the drill-holes.

Three holes were drilled in the intrusion, totalling slightly over 10,000 feet. The depths of individual holes were 4,000 feet, 3,593 feet and 2,496 feet. The sites were chosen so that the South and North holes would overlap in the stratigraphic section and thus provide a complete core section from the roof of the intrusion through to its floor. The third hole was located near the eastern margin of the body to provide information on the lateral variations in layers from the centre toward the margin of the intrusion.

The drilling was carried out over a $5\frac{1}{2}$ month period from mid-April to the end of September, 1963. Materials, equipment, and supplies were transported by air from Yellowknife to Speers Lake, Northwest Territories, which served as the main base for the drilling operations.

Figure 2 shows the DC-6 freighter aircraft used during the airlift, unloading diesel fuel. Operating into a prepared ice-strip at Speers Lake, this aircraft carried slightly over 27,000 lb. per trip over the 320 mile distance from Yellowknife to Speers Lake. It proved to be an efficient and relatively economical means of bulk air transportation. About 25,000 gallons of diesel fuel were flown in for the operation. It was used in all drilling equipment engines, generating plants, and for heating purposes. The total fuel consumption for the operation was 19,300 gallons.

Figure 2. The DC-6 freighter aircraft unloading part of the 25,000 gallons of diesel fuel airlifted to Speers Lake, Northwest Territories, for the Muskox Drilling Project.

Figure 3 shows the south drill rig operating during the summer. The hole was collared in 45 feet of overburden overlying soft, highly serpentinized dunite. The top of the ridge in the background is formed by one of the resistant pyroxenite layers of the Central Layered Series.

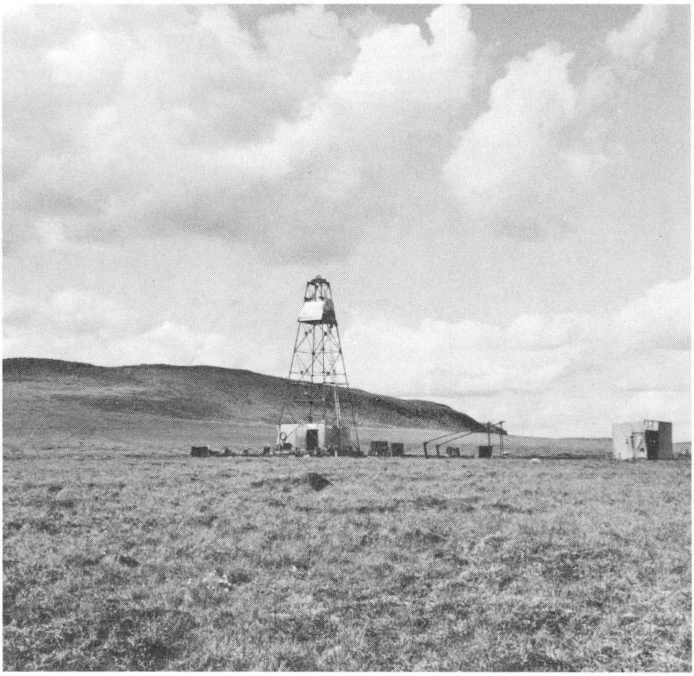


Figure 3. The Muskox South drill site at Speers Lake. The top of the ridge in the background is formed by a resistant pyroxenite layer dipping north (away from the drill). The base of the hill and foreground are underlain by soft serpentinite formed from dunite.

After geological logging, drill cores were washed, sampled with a portable diamond saw and then packed in 2-foot cardboard core boxes for air shipment to Yellowknife. Figure 4 shows the final stages of field core processing where boxes are being marked for identification prior to shipment.

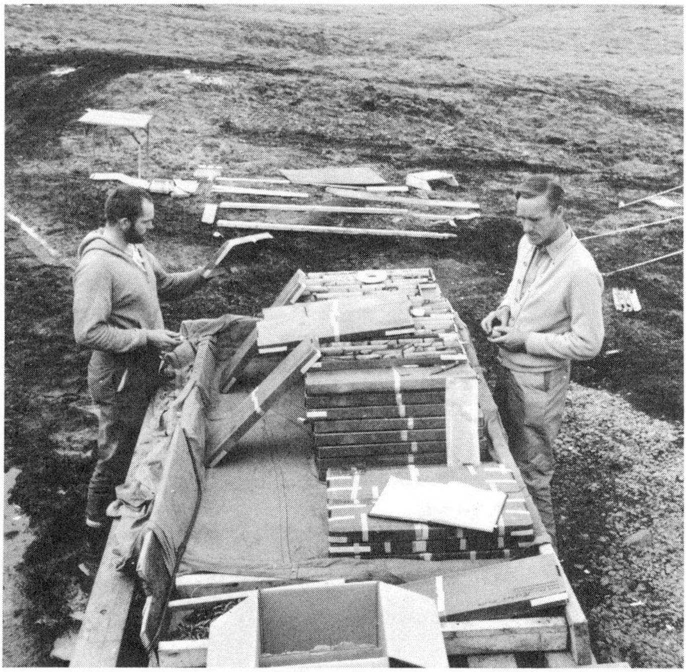
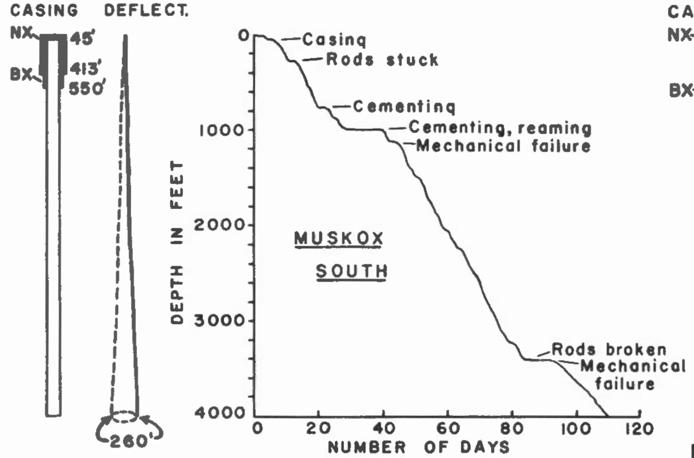
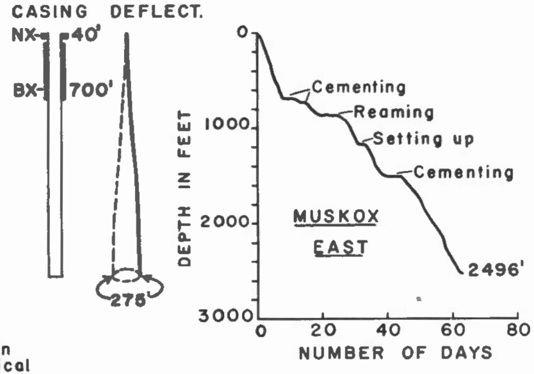


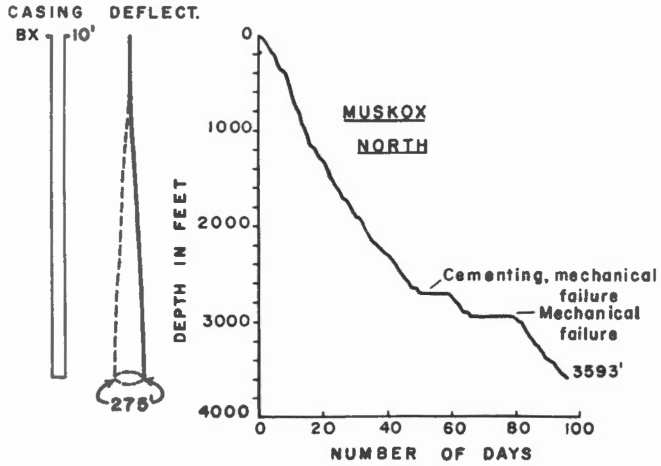
Figure 4. Final packing of drill cores in waterproofed cardboard boxes prior to air shipment. The boxes are 2 feet long and contain 10 feet of BX-size core.

The performance records for the three holes, and some of their vital statistics are summarized in Figure 5.

The principal objectives of the drilling and the results achieved are summarized in Figure 6. The main objectives were to obtain a completely cored section through the intrusion for petrographic and chemical studies, to confirm or refine the structural interpretations based on surface geology, and to allow the measurement of properties of the rocks with geophysical logging instruments, for correlation with similar measurements made on drill cores in the laboratory. All the objectives were achieved in that nearly 10,000 feet of core was recovered, the structural picture was confirmed with valuable additional detail on internal correlation of layers, and geophysical logs, including gamma and neutron radiation, self-potential,







SUMMARY

	SOUTH	NORTH	EAST
SITE	45' Ovrb.	Bedrock	Bedrock
COLLAR ELEV.	1759.6'	1682.8'	1893.5'
PERMAFROST DEPTH	660'	700'	
HOLE DEPTH	4000'	3593'	2496'
CASING	413' NX 550' BX 46' H	4' NX 10' BX	40' NX 90' Gap 570' BX
MAX. DEPARTURE	130'	138'	138'
DRILLING DAYS	110	97	63
AV. ADVANCE/DAY	36.4'	37.0'	39.6'
AV. PENETRATION RATE (FEET/HR)	3.77	2.80	3.40
AV. BIT FOOTAGE	43.0	49.2	55.5
CORE RECOVERY(%)	97.3	98±1	98.7

Figure 5. Progress records and summary of performance data for the Muskox drill-holes.

resistivity, and velocity, were obtained from two of the holes (see Hobson, Beck and Findlay, this volume). The third hole became blocked during temperature profile measurements, and logging could not be completed. The South drill-hole was filled with fuel oil to prevent the inflow of water and freezing of the drill-hole. This summer, 2 years after drilling, the hole was still open and available for heat flow measurements.

PRIMARY OBJECTIVES	*RESULTS*
1. To obtain a complete sample section through the intrusion for chemical and petrographic studies.	1. 10,000 feet of BX (1.625" dia.) core recovered.
2. To provide additional data on the shape and internal structures of the intrusion.	2. Major structures confirmed; plus additional correlation detail on layers. Volumetric proportions of rock types determined.
3. To provide in-hole geophysical data for correlation with geological logs and with properties of drill cores measured in the laboratory.	3. Neutron, gamma, self-potential, and resistivity logs of two holes. Temperature profile from one hole.

Figure 6. Summary of objectives and results of the Muskox Drilling Project.

PLANNING FOR FUTURE DRILLING PROJECTS

From the experience with the Muskox Project some of the factors that will require attention in planning for future, deeper-hole projects can be outlined. Figure 7 shows the principal steps in drilling project design, exclusive of laboratory follow-up studies.

The definition of specific drilling objectives is important in choosing the drilling methods, depths and equipment to do the job with minimum cost. Such factors as making use of readily available equipment, reducing the hole diameter and depth, partial coring, minimum casing, etc. can be closely assessed when the objectives are well-defined, and these factors will have an important bearing on deciding whether a project is financially practical. Particularly with regard to deeper holes, the higher costs involved make it essential that multi-purpose holes — that is, holes designed for a number of geological and geophysical studies by different groups of scientists or agencies — be carefully planned to ensure maximum scientific benefits.

1. *CHOICE OF PRIMARY OBJECTIVES*	2. *SITE SELECTION*	3. *DRILLING EQUIPMENT*	4. *IN-HOLE INSTRUMENTATION*
a) SPECIFIC OBJECTIVES -sampling an igneous intrusion -heat flow study -regional stratigraphic /structural data -etc. b) MULTIPLE PURPOSE HOLES Combined geological and geophysical studies. Use of holes for many years for long term in-hole measurements.	a) GEOLOGICAL SURVEYS b) GEOPHYSICAL SURVEYS c) OPERATIONAL SURVEYS -access -topography -water supply -etc. d) SYNTHESIS	a) PRIME EQUIPMENT i) Oil-Well Rig ii) Diamond Drill b) INSTRUMENTATION FOR DRILLING DATA c) CONTRACTS	a) GEOPHYSICAL LOGGING -velocity -electrical -radiation -magnetic -thermal b) LONG TERM IN-HOLE MEASUREMENTS -seismic -earth currents -etc.

Figure 7. Factors in drilling project design.

It is of prime importance that all possible surface data be collected before choosing the final drill sites. The completion of detailed geological and geophysical surveys is time consuming, but since site selection involves a definite commitment of money and personnel, "instant" drilling projects are neither desirable nor practical.

Each country will have its own limitations on the availability of drilling equipment based on its past opportunity to develop a drilling industry for economic purposes. For holes less than 10,000 feet (about 3 km), diamond drilling equipment is less expensive to operate, has greater flexibility and is particularly suited for use in inaccessible areas. Oil-well equipment, modified for continuous coring, may be preferable for deeper holes because of its ruggedness and ability to reach great depths; however, this equipment will increase costs considerably. These holes are larger in size and facilitate the use of larger, more complex, in-hole instruments.

In larger drilling programs an attempt should be made to record all drilling data and to improve the performance of the equipment. This will require the use of accurate data-recording instruments on drills and auxiliary equipment. Parameters affecting drilling performance such as bit load, fluid pressure, temperature and flow rate, drilling R.P.M. and torque, penetration rate and time data need to be accurately recorded. Analysis of this type of data will facilitate the future planning of holes. In smaller drilling projects this may not be practical, but in larger projects supported by governmental funds it appears desirable to couple a program of drilling for earth science research with a long range program of drilling research itself.

FUTURE DRILLING PROJECTS IN CANADA

Since material of the earth's mantle may be ultramafic in composition, the study of ultramafic intrusions now exposed at the earth's surface may yield valuable data on the physical and chemical properties of the mantle, and provide clues to the processes operating within it. For this reason, large ultramafic-mafic intrusions (such as Muskox) are one prime target for deep drilling. As an extension of the Muskox Project, the Geological Survey has carried out site selection studies for 10,000 foot holes in peridotite intrusions. Two potential sites have been considered for this proposed project — the Mount Albert pluton, Gaspé, Quebec, and the Bay of Islands Complex of western Newfoundland. Preliminary site selection work, including detailed geological and geophysical surveys has been completed in these areas.

Perhaps one of the most challenging potential sites for deep drilling in Canada is the Sudbury nickel irruptive. In spite of its long and controversial history of geological studies, and the thorough investigation and exploitation of its rich ore deposits, the Sudbury Irruptive persists as a geological enigma of controversial origin. Its shape has been investigated to depths down to over 8,000 feet in the search for nickel deposits but a single ultradeep drill-hole, sunk through the basin into the basal zones of the Irruptive would greatly clarify its petrological history and perhaps provide additional information on the presence and origin of its ore deposits.

The Flemish Cap area off eastern Newfoundland is another extremely interesting potential site for shallow drilling (Fig. 8). It lies about 160 miles off the east coast of Newfoundland and is the easternmost physiographic extension of the North American continent. However, its bedrock geology is unknown, and it has been suggested that it is made up of oceanic rather than continental material. Minimum water depth over the Cap is about 100 fathoms, and drilling a series of shallow holes to obtain cores from it could be accomplished from a floating offshore oil well drilling platform. From a geological and geophysical point of view, data on the composition, age and origin of the Flemish Cap may contribute to our understanding of the transition zone between oceanic and continental geological environments and it may also provide additional knowledge of the Appalachian tectonic belt.

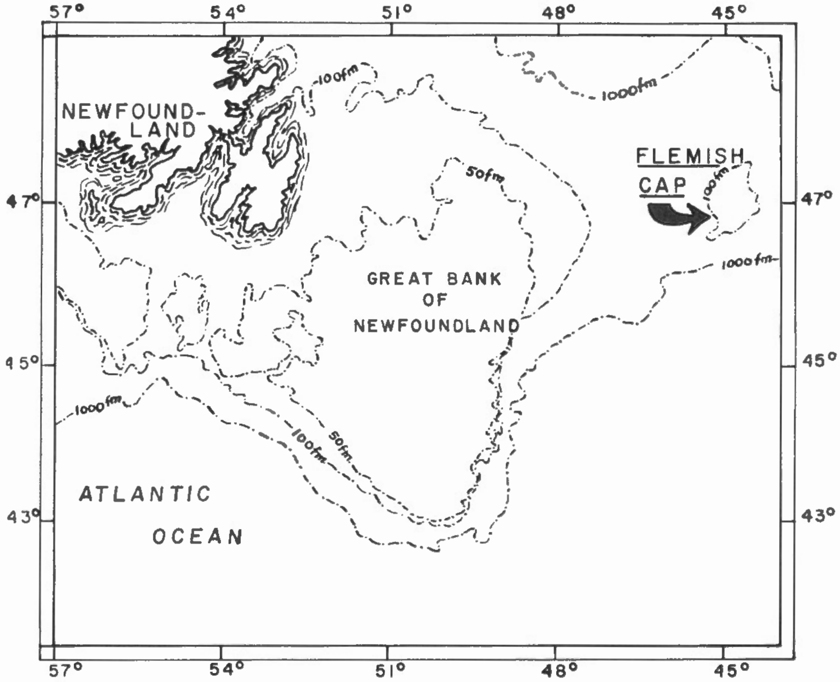


Figure 8. The Flemish Cap; a possible future site for offshore drilling (after Hood and Godby, 1965).

At an Upper Mantle Workshop Meeting held in Ottawa last February to discuss research programs bearing on Upper Mantle studies, a number of other recommendations for drilling as an aid to solving geological problems were presented. A summary of the recommended targets is given in the Appendix to this paper.

CONCLUSIONS

In conclusion, there is little doubt that drilling can be an effective and useful tool in a wide range of earth science studies. This conclusion holds not only in connection with major deep hole projects, but also in more humble shallow hole programs. Although the costs of any drilling project are significant, and on first impression may seem to be a true case of pouring money down the drain, drilling will provide direct information which cannot be obtained by any other means. The justification of each project depends on establishing an acceptable balance between cost and scientific return. It must be accepted that drilling is expensive, but if we are to ever explore our planet earth we must get started on more extensive programs than now exist.

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DISCUSSION

Mr. W. Schneider (U.S.A.)

Could you summarize the heat flow work that was done in conjunction with this project?

Dr. Smith

Prof. Alan Beck supervised the heat flow studies and perhaps he would like to answer your question.

Prof. A.E. Beck (Can.)

During the drilling we sent someone out to take measurements as the drilling progressed, making bottom hole measurements and ordinary (temperature) logs, because we were not too sure how long these holes would stay open when they were filled with oil. So we had some information from this. We could not get back to the North hole, because as Dr. Smith mentioned, the probe froze in. I went up again this summer to measure temperatures in the South hole. We do not have conductivity measurements on the cores yet. The gradient does not appear too different from the gradient in the North hole that we had measured two years earlier. I was just comparing my gradients versus depth with this chart (of Muskox geophysical logs) over there on the display board, and about the only correlation I can get is with the drilling rate — and I do not know what this means. As the rock gets harder the gradient goes down — that is all I can get out of that. But we still have to do detailed conductivity measurements.

Dr. T. Sorgenfrei (Den.)

I would like to ask how you decide what locations one should drill? I imagine that you have subdivided your areas in accordance with geological evidence or for whatever objectives you would like to drill — that you have some subdivision of the area, and that you give some of the areas priority in comparison with other areas. I would like to know how many categories or geological provinces you work with in planning your well?

Dr. Smith

You are talking about planning in the future now, and not in the past?

Dr. Sorgenfrei

Yes. The other question is: When do you expect to publish the data, in what form, and where?

Dr. Smith

If I can start with publishing data, the complete record of the drilling project that I described is published. Of course, this is the operational aspect of the drilling program. There is also a laboratory stage which is a much longer operation than the actual drilling part. We have a great deal of geochemical data from the cores now, and petrographic data. These are being put on cards and we are trying to find a fast way of interpreting them. We are being swamped with data at the moment.

In terms of selection of other drill sites, this is more difficult in Canada because we have a large number of geologic provinces or tectonic provinces and it is very difficult, for instance, to make a decision between drilling in the Appalachians versus drilling in the Cordillera. They are each separate problems and one cannot draw a comparable evaluation. In terms of the availability of money in Canada, though, if any deeper drilling is done, it seems that it will be done by the Federal government. This seems to be about the only agency in Canada that could conceive of putting up the money for this sort of thing. At the moment it has not, but it might, and if this were done, then I must admit that at this stage we have different groups within our Federal government who have different interests. Some are interested in igneous rocks, as we are, others are interested in tectonic problems such as the one that was described from Switzerland. And it is very difficult to compare these two problems. I should not say that it depends on who gets the money first — this is not true — but it is very difficult to compare the two. So we cannot come down, logically, to a prime target.

Dr. Sorgenfrei

I think you have to.

Dr. Smith

We have to in order to start, yes. However, at the moment, the money still is not available for coming to a prime target and so I think we are in the same position as Dr. Saito from Japan — we can still entertain a number of possibilities. If we felt we could justify the drilling solely for geophysical purposes, why then it would be simple to say we could put it down in area "A", because we can neglect the surface geology to some extent. But it is not feasible to put a deep hole down just for heat flow. If we could, it would be simple — we would forget about the geology of Canada and just work on a geographic grid. But if we try and work the geology and the geophysics into a combined program, then there is not a unique solution. That is the situation now.

Prof. P.J. Uffen (Can.)

Is it fair for me to point out that we have made that decision; the hole has been drilled. We went through this agonizing process two years ago in Canada and it was not easy — a few people's feelings were badly hurt. But one hole has been drilled. Dr. Smith has not been talking about something that is going to be done; it has been done.

Dr. Smith

Yes, but we were talking about the next hole.

Prof. Uffen

I was just drawing attention to the fact that we have already made such a crucial decision, and it will be much easier to do it the next time.

Dr. Sorgenfrei

I thank you very much for this comment because I think that is just what is needed — the cooperation of the various people of various standing and interests, because it is quite likely you cannot drill just for one purpose. Now I am talking generally, and mixing into your own problems in Canada. However, I think this is a very important point.

APPENDIX

RECOMMENDATIONS FOR SCIENTIFIC DRILLING PROPOSED AT THE CANADIAN UPPER MANTLE WORKSHOP MEETINGS, OTTAWA, FEBRUARY, 1965

GENERAL

An Upper Mantle Workshop held in Ottawa, February 24-26, 1965, consisted of four simultaneous informal sessions in which scientists from Canadian universities and government agencies discussed research projects concerned with the Upper Mantle Project. For purposes of the Workshop, Canada and its continental shelves were divided into 4 sections — Arctic, Western, Central and Appalachian — which provided a convenient geographical and geological framework for discussion of various topics. Recommendations for continuing research included a number of drilling proposals which are summarized below.

RECOMMENDATIONS

1. Appalachian Section

   (a) Drilling the eastern edge of the continental shelf near Sable Island. (dormant)

   (b) Drilling of the gravity anomaly over the Black Lake peridotite body, Eastern Townships. (dormant)

   (c) Shallow offshore drilling of the Flemish Cap, off the east coast of Newfoundland.

2. Central Section

   (a) Drilling a network of heat flow holes in the Western Shield region, between Moosonee and the Rocky Mountain Foothills, Edmonton and Norman Wells, Hudson Bay and the Alaska border, and across the Nelson River gravity anomaly. (dormant)

(b) Drilling of a deep hole (approx. 8 km) to the Conrad discontinuity in the Nelson River area of Manitoba. (dormant)

3. Western Section

(a) Drilling a 2,000 foot hole at a location in Alberta in which to make continuous recordings of magnetotelluric data. (dormant)

(b) Drilling of three shallow holes for heat flow measurements in the Stikine Plateau area of British Columbia. (plans in hand)

4. Arctic Section

Drilling the north flank of the Franklinian geosyncline to determine its extent beneath the cover rocks. (dormant)

CRUSTAL DRILLING IN THE UNITED STATES

Gene Simmons*
Professor of Geophysics,
Massachusetts Institute of Technology

Abstract

The oil and gas industry drills about 200 million feet of hole per year in the United States and the mining industry drills several million feet. The scientific output from these holes has been good but considerably more data of non-economic value are available than are being used currently. A good example of the cooperation afforded university scientists is the current work on geothermal flux. Similar opportunities exist in other fields of science.

But there are significant problems that can be solved only by drilling holes solely for scientific purposes. Such holes should be drilled in areas not drilled by the petroleum or mining industries and they may solve local structural or geologic problems while providing answers to petrologic, geochemical and geophysical problems.

A twenty-five thousand foot hole in a deeply eroded igneous-metamorphic terrain would permit examination of a significant part of the crust. It would provide data on the identification and distribution of heat sources, equilibration of minerals and fluids held at elevated pressures and temperatures for long times, and the variation with depth of several geophysical parameters. But most important, such holes would provide, for the first time, opportunities to test certain scientific hypotheses.

INTRODUCTION

Billions of feet of hole have been drilled in the United States by industry in the search for oil and gas. A natural consequence of this large effort has been the steady, sometimes spectacular, advance of many areas of science; micropalaeontology, exploration geophysics, and petroleum geology may be cited as examples. Other areas of science have not been influenced by the results of this vast, uncoordinated drilling program. These "other areas" — frequently termed "pure science" — usually do not offer

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*Formerly with Southern Methodist University.

immediate economic rewards and so have not been pursued by industry but rather have been developed by individuals working in either academic or government environments. It happens that many of the scientific problems explored by this group need data that can be obtained only by drilling. Potential benefits to science, and ultimately to industry in terms of profits, from the drilling of a number of holes for scientific purposes are large indeed. Recommendations to drill such holes have been made in the past by the International Upper Mantle Committee and by the Panel on Solid Earth Geophysics of the (U.S.) National Academy of Science. Drilling, as a part of the Upper Mantle program, has already received attention in several countries, particularly Canada and Russia.

In this brief report I wish to discuss the status of crustal drilling in the United States. For many years, the oil and gas industry has been engaged in extensive research on parts of the earth's crust, primarily through drilling. A few statistics will serve to emphasize the magnitude of this effort. In addition to the research in industry, there are several projects not related to petroleum currently underway; brief mention will be made of these. And finally, plans will be sketched for crustal drilling specifically for scientific purposes.

DRILLING BY INDUSTRY

As suggested above, the oil and gas industry has drilled many holes in the United States. Figures 1 and 2 show the footage and new wells, respectively, drilled in the past few years. I submit that these data are impressive! Figures 3 and 4 show the distribution by states of the footage and wells, respectively, forecast to be drilled in 1965. These data were obtained from World Oil (161, No. 3) and modified slightly. Not shown on these figures are data for holes drilled by industry other than oil and gas. The mining industry annually drills several million feet, mostly in areas not drilled by the oil and gas industry. Additional holes are drilled each year for gas storage, fluid disposal, and water wells. The few holes drilled each year in new areas are especially important to science.

Because so many holes have been drilled by now, it is likely for a given scientific study that at least a few suitable, and possibly ideal, holes already exist. To find such holes may not be easy but in view of the expense of drilling new holes it is obviously worth the effort. If one wishes to use existing holes, it is necessary first to locate the holes and then obtain permission from the owner. To obtain permission, one must usually convince the owner that the hole will remain open and unharmed after the experiment or measurements are finished. To be engaged in research that has at least some indirect interest for the well owner is helpful, of course.

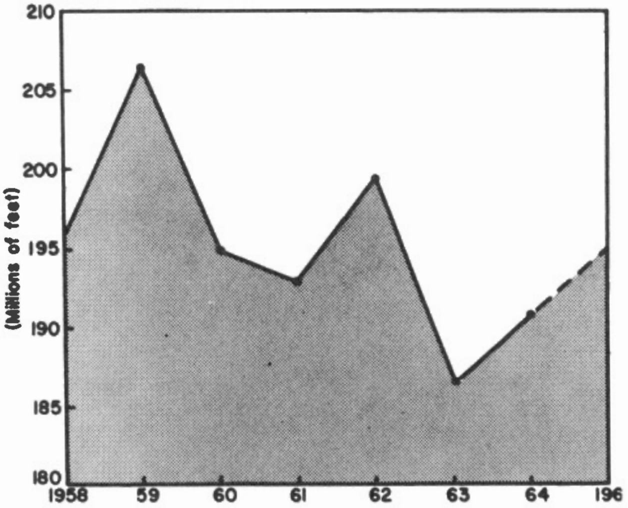

Figure 1. Footage, in millions of feet, drilled annually in the United States in new wells by the oil and gas industry. (After World Oil Aug. 15, 1965.)

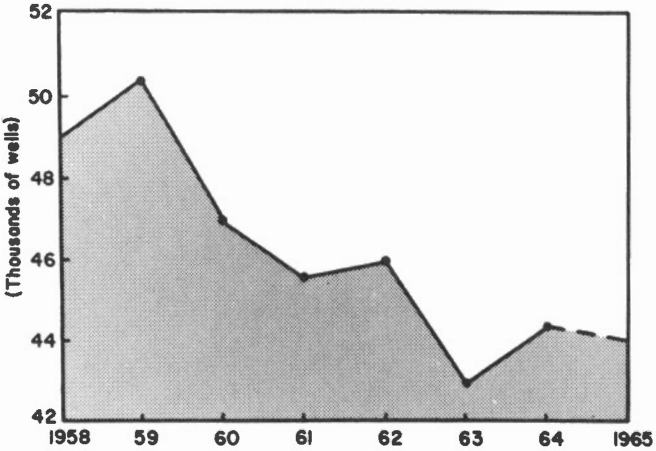

Figure 2. New wells, in thousands, drilled annually in the United States by the oil and gas industry. (After World Oil Aug. 15, 1965.)

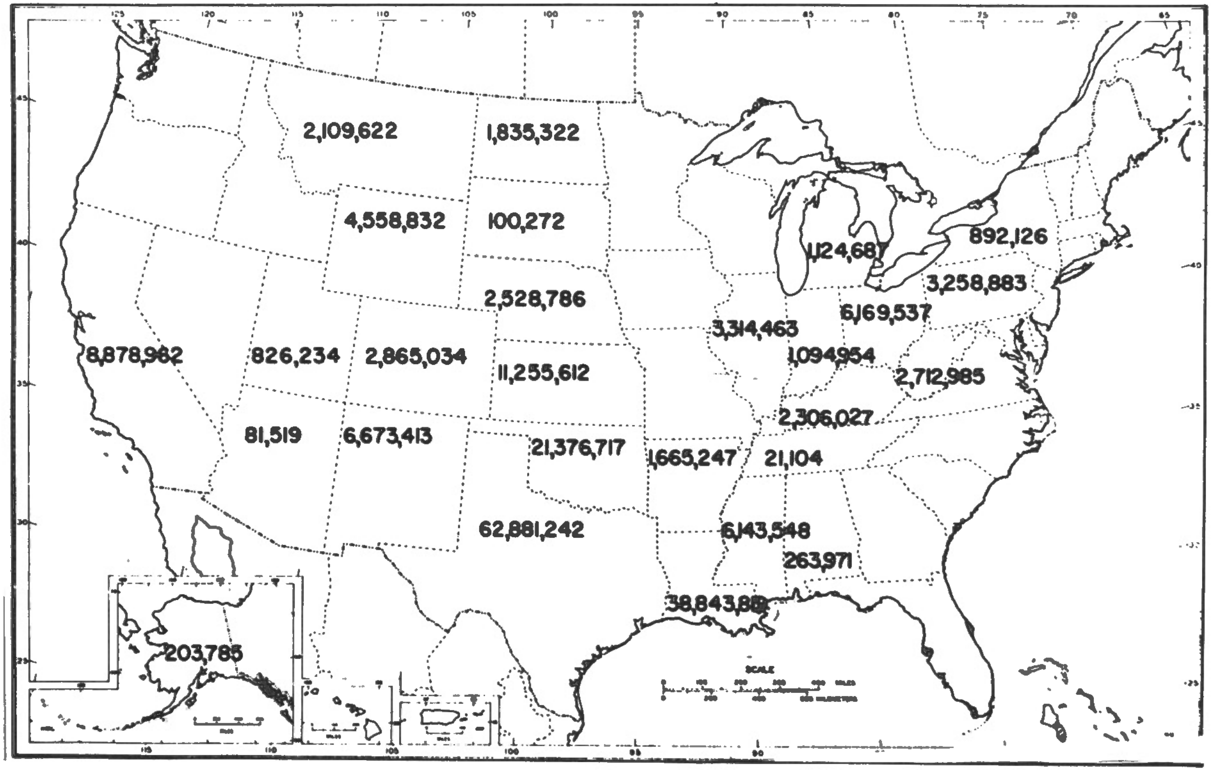

Figure 3. Forecast of footage to be drilled in 1965. (Data from World Oil Aug. 15, 1965.)

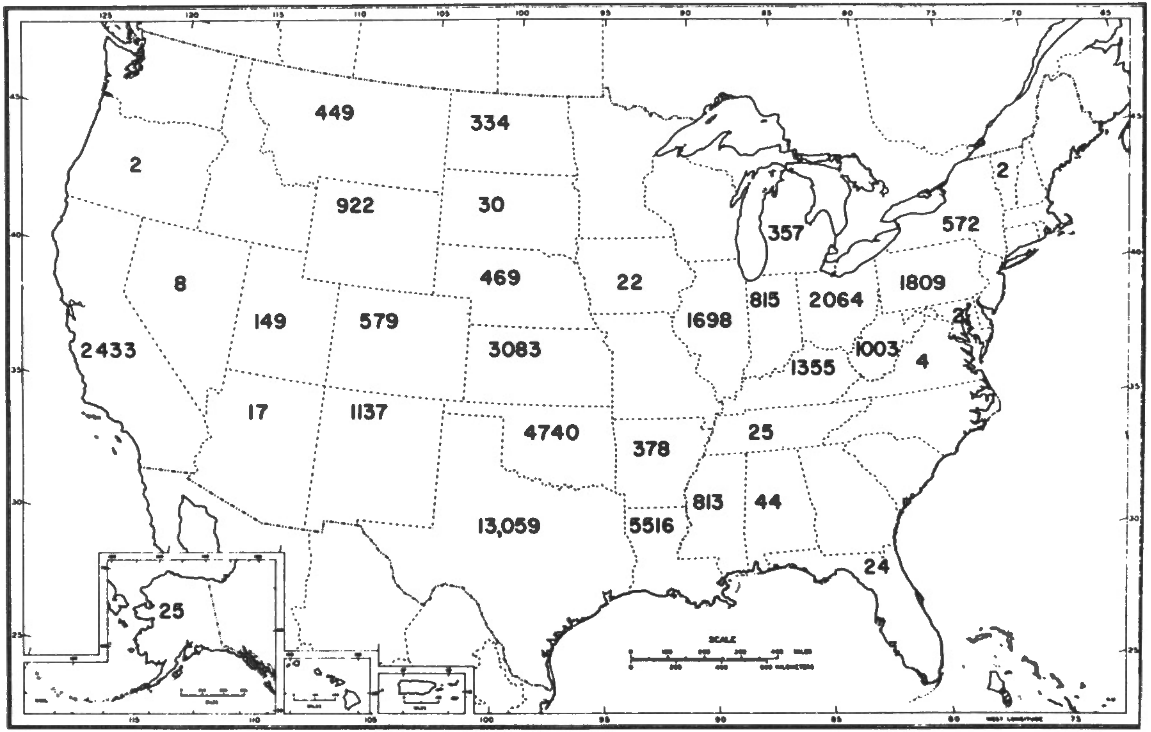

Figure 4. Forecast of U.S. wells to be drilled in 1965. (Data from World Oil Aug. 15, 1965.)

Industry has been most helpful in the work on heat flow in the earth. Figure 5 shows the status as of July 1, 1965, of the measurements in the United States of heat flowing from the interior to the surface of the earth. All of the points shown for Simmons were obtained in existing holes provided by various oil and gas companies. R.F. Roy, of Harvard University, drilled holes in northeastern United States but elsewhere used existing holes provided by various mining companies. The other investigators shown on the figure also used existing holes. I submit that this heat flow project is a fine example of the excellent cooperation furnished by industry! This is an important point for science and should be emphasized: cooperation by industry in providing holes for scientific projects has been excellent and deserves high tribute.

CURRENT SCIENTIFIC DRILLING PROJECTS

Current projects that are underway in the United States can be summarized in a few statements. Figure 6 shows the Hawaiian chain where drilling solely for scientific purposes is now underway. One project is drilling on Oahu and another on Midway Island to examine the sequence of rocks and hence learn about the history of this interesting chain.

Several holes have been drilled off the coast of Florida under the JOIDES (Joint Oceanographic Institutions' Deep Earth Sampling) program organized by the directors of the Woods Hole Oceanographic Institution, the Lamont Geological Observatory, the Institute of Marine Science, and the Scripps Institution of Oceanography. The locations are shown in Figure 7. These holes were drilled for the purpose of examining the structure and stratigraphy of continental margins to depths of several hundred metres (see T. Saito, this volume).

A number of other holes has been drilled recently in the United States for scientific purposes. The Mohole Project is described elsewhere in this volume but let me mention here a hole drilled recently as part of this project through about 3,000 feet of basalt in southwest Texas for the purpose of testing equipment. It is my understanding that several scientific experiments are planned for that hole.

A hole was deepened recently near Wells Creek, Tennessee, by Prof. Richard Stearns to investigate the cryptovolcanic structure. Many holes are in use by the Ground Water Branch of the U.S. Geological Survey to study the movement of groundwater. In recent years, a large number of shallow holes, no deeper than about 1,000 feet, have been drilled in the states of Tennessee, Kentucky, Iowa, and probably other states, specifically

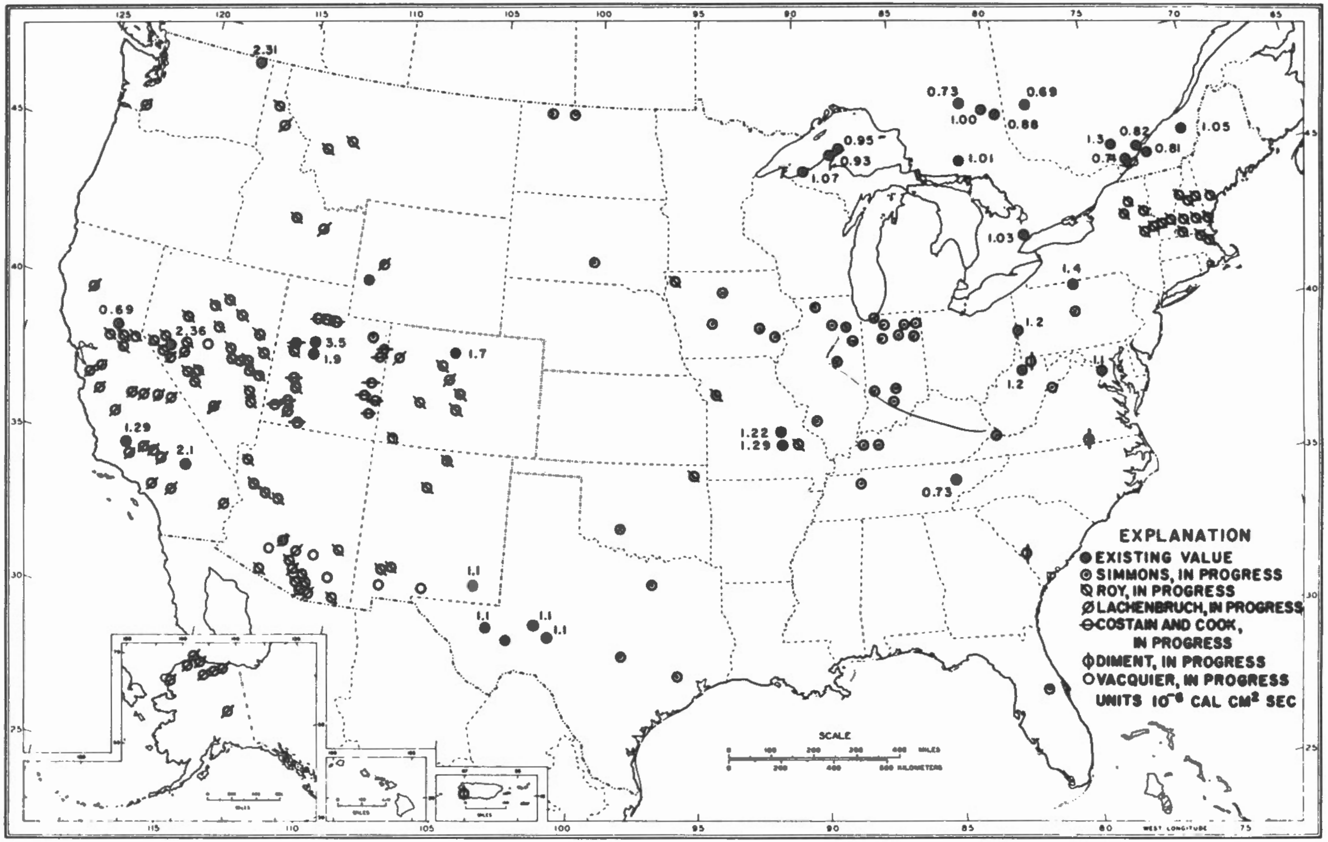

Figure 5. Status of projects to measure heat flow in the United States.

for hydrologic studies. At the present time (Sept. 1965), a hole is being drilled to 3,200 feet in northeastern Arkansas for scientific studies.

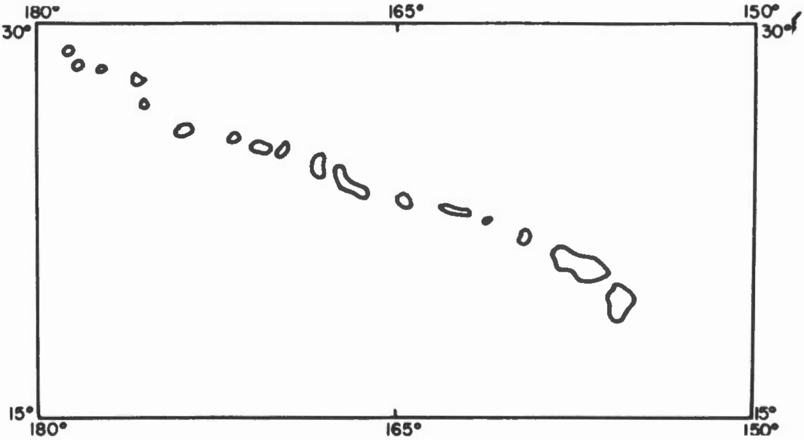

Figure 6. The Hawaiian Chain.

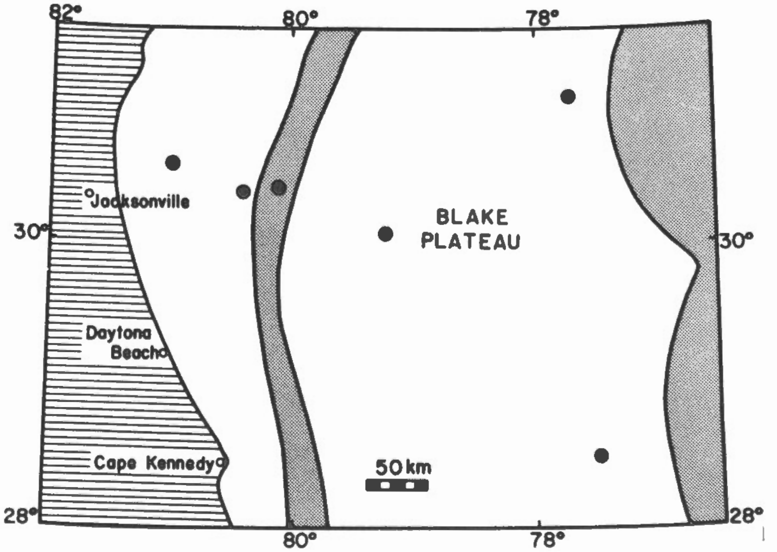

Figure 7. Location of holes drilled in the JOIDES program.

The heat flow project, illustrated in Figure 5, included a number of holes drilled specifically for heat flow work. Many of these holes are being used also for other studies. The U.S. Geological Survey and the Bureau of Mines also drill a few holes each year for specific scientific studies. The U.S. Air Force, under the Vela Program, recompleted several deep holes (about 10,000 feet) for seismological studies.

FUTURE SCIENTIFIC DRILLING PROJECTS

Several possible areas in the United States are being considered for drilling projects for scientific purposes. The geothermal area of California contains some hot igneous bodies recently emplaced with tops no deeper than 2 or 3 km. With a 10,000 foot hole, one would likely reach a magma chamber which would provide much data on many problems. Other possibilities exist in southern Oklahoma and in the Appalachian Mountains where there are a number of fundamental structural problems. One of the most intriguing problems is the structure of the anorthosite body in northern New York state. The study of the three-dimensional relations of the very high metamorphic gradients near Iron River, Michigan is important to petrology. The most important scientific results, however, are probably to be derived from a very deep hole — say 25,000 feet — drilled in a deeply eroded granitic terrain. Such a hole would sample a significant part of the thickness of the earth's continental crust and provide data that can be obtained in no other way.

ACKNOWLEDGMENTS

I wish to acknowledge the help of Pembroke J. Hart, of Charles L. Drake in supplying the location of the JOIDES holes, and of Winnifred Holtz in drafting the figures.

DISCUSSION

Mr. L.S. Collett (Can.).

The hole drilled in Arkansas for groundwater purposes; was it drilled into crystalline basement rocks?

Prof. Simmons

Maybe I did not make this clear. The hole is now being drilled. It is down perhaps to 200 feet, at present. (Prof. Simmons explained that the hole was being drilled by the United States Geological Survey, Groundwater Branch at Memphis, Tenn., and remarked that he was not personally familiar enough with the geology of the area in which the hole is being drilled, to know if basement rocks would be reached before 3,200 feet, the proposed hole depth. Prof. Simmons asked if anyone in the audience could help with this question; no help was offered.)

Prof. A.E. Beck (Can.)

I would like to support Prof. Simmons' comments about the availability of holes drilled for industrial purposes. The big problem now is not connected with the companies. Somebody needs to collect the information as to where the holes are, how to get to them, etc. This is something that might be included in the recommendations tonight — that some central agency collect and distribute this information. Some of this work is already being done by the provincial governments, but it is by no means complete. It has to be done for the oil and gas industry also.

Prof. R.J. Uffen (Can.)

Would you like to raise that question again? We have one more paper this morning to finish this program, and then we will throw it open for general discussion, and I suspect that there will be a great deal of interest in this point.

J.E. Husted (U.S.A.)

Where in Tennessee is the hole being drilled?

Prof. Simmons

I must apologize for confusing this issue. The people in charge of drilling the hole are located in Memphis, Tennessee, but the hole is being drilled in northeastern Arkansas.

I would like to make one comment on Prof. Beck's question. Really, I think the problem at the moment is not with industry's cooperation, but it is simply in finding out where suitable holes exist. The cooperation is available, once one is aware of the existence of the hole, and once one contacts the proper people. My chief interest in holes at the moment is for heat flow purposes. It turns out that a few days ago I came across a company that had collected temperature data from 65 wells in the Los Angeles area each year for the last five years. And they have cores, but have never worked out the data for heat flow.

I think that the real burden is essentially on us to find the holes and make use of them.

OCEAN DRILLING OFF THE COAST OF EASTERN FLORIDA

Tsunemasa Saito
Lamont Geological Observatory

Summary

As the first program of the Joint Oceanographic Institutions' Deep Earth Sampling (JOIDES)* project, a series of holes was drilled in the ocean floor off the east coast of Florida on the Blake Plateau in April and May of 1965. The purpose of the drilling was to investigate the relations between sediments and sedimentation processes on land and those on the continental shelf and Blake Plateau.

The drilling operations summarized in the accompanying table involved 14 cored holes totalling 2,052 metres, drilled at 6 sites in water depths ranging from 25 to 1,032 metres. Penetrations of 120 to 320 metres into the bottom were attained and over 500 metres of cores were recovered.

The cores recovered provide an excellent composite stratigraphic section from the Paleocene upward. Land formations were found to extend beneath the continental shelf. Artesian fresh-water aquifers, characteristic of Eocene calcareous beds of the adjacent land, were encountered on the inner shelf.

Studies on the cores suggest that shelf conditions existed at near shore sites during the Tertiary; particularly that a shallow water environment prevailed during the Eocene age. On the other hand, sediments from offshore sites indicated a water depth similar to that in which they are presently found. Major unconformities were observed in the submarine sedimentary record, being post-Oligocene on the landward part of the area, and Middle-to-Late Eocene on the seaward part.

The picture which emerges from borings and seismic profiles shows the continental margin in this area to be a wedge-shaped constructional feature, thinning seaward.

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*The JOIDES group comprises Woods Hole Oceanographic Institution, Lamont Geological Observatory, Institute of Marine Science at the University of Miami, and the Scripps Institution of Oceanography.

Table — Summary of Drilling on the Blake Plateau, April-May, 1965[1]

Site	Position		Ocean bottom	Hole	Interval	Interval
No.	N. Lat.	W. Long.	depth (m)	No.	drilled (m)	cored (m)
1	30°33'	81°00'	25	1	0- 7.6	7.6-135.6
				1a	0-121.9	121.9-277.4
2	30°21'	80°20'	42	2	0- 19.8	
				2a	0- 17.4	17.4-173.4
	30°20'	80°20'	46	2b	0- 15.2	15.2- 68.6
					68.6- 76.2	76.2- 88.4
					88.4-146.3	146.3-152.4
					152.4-158.5	158.5-320.2
5	30°23'	80°08'	190	5	0- 9.1	9.1- 30.5
				5a	0- 17.7	17.7- 57.3
				5b	0- 50.6	50.6-100.6
				5c	0- 97.5	97.5-171.6
						171.6-245.0 Intermittent
6	30°05'	79°15'	805	6		0-119.7
4	31°03'	77°45'	885	4		0- 91.4
				4a		(surface)
	31°02'	77°43'	892	4b		0-178.3
3	28°30'	77°31'	1032	3		0-178.3
				3a	0-170.7	170.7-173.7

[1] From JOIDES Report, 1965, p. 711.

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JOIDES Group. 1965. Ocean drilling on the continental margin, Science, 150, 709-716.

DISCUSSION

Prof. H. Kuno (Japan) asked Dr. Saito what depth of holes could be drilled from the ship used in the JOIDES project.

Dr. Saito answered about 1,032 metres — 3,000 feet.

Dr. C.L. Drake (U.S.A.) commented that this was not the maximum capacity of the drilling ship.

Dr. Saito

Well, Dr. Drake would you mind answering the question? I think you might know better than I about the maximum capacity of the drilling ship.

Dr. Drake

About 6,000 feet using 4½ inch pipe; that is the maximum capacity.

Dr. H. Berckhemer (W. Germany)

I would like to know if there were bore-hole measurements too, and if so, can you tell us something about the results?

Dr. Saito

We made some velocity measurements and we also ran some electric logs.

Prof. R.J. Uffen (Can.)

The results presumably will be made available?

Dr. Saito

Yes, they will be published shortly in the journal "Science".

GENERAL DISCUSSION ON SCIENTIFIC DRILLING PROGRAMS

Mr. L.R. McDonald (Can.) commented that diamond drilling contractors would be glad to assist the Geological Survey in providing access to holes that they might be able to make use of. If the Geological Survey would provide the various drilling contractors in Canada with criteria as to what they require in various types of holes, he felt that the contractors would be willing to advise the Survey when such holes were going to be drilled and that perhaps a cooperative approach to the utilization of holes drilled for industry but useful for scientific studies could be worked out.

Dr. A.M. Jessop (Can.)

I suggest that this would be an extemely good idea as far as heat flow is concerned. Our main problem is just as much finding out about holes as obtaining cooperation. Cooperation is always forthcoming.

Mr. McDonald

This is what I mean. If you let us know what kind of a hole you are looking for, then when one comes up we can contact you.

Dr. Jessop

The main problem is getting to know about these holes in time to make arrangements to do work in them. It is a communications problem, really. However, I think that it is something that can easily be worked out amongst ourselves — between the scientists concerned and the people doing the drilling.

Prof. R.J. Uffen (Can.)

I have a comment on this communication problem. It would seem to me that in most countries there is either in existence, or ought to be, a joint committee of the people who are representing these two groups who will make information available quickly to their counterparts. I know that we have one such committee here in Canada that just needs to be rejuvenated – we should do this. May I make a personal observation? In most of these things, what it really boils down to is that there must be individual scientists who really want to do the work. The holes are available and everyone wants to cooperate; however you have to find the man who really wants to use them. Once you find the man everything else will follow. You can get money, if you have a scientist with a good project. This is a subject which has not been touched on today — perhaps it will come up later on. Our problem now is that we may not have enough people to do all the projects that are proposed.

Prof. H. Kuno (Japan)

From the viewpoint of volcanology and petrology, the most interesting topics would be to determine the total volume of basaltic or other volcanic material, erupted during the Tertiary period. And also what kind of magma was erupted in different geologic ages ranging from Recent to oldest Precambrian time. In this connection, I would like to know whether United States or Canadian scientists have any plans for drilling holes through the oldest Precambrian volcanic rocks such as the Ely greenstones of the northern part of Minnesota or in the equivalent volcanic rocks of Manitoba, and also whether United States scientists have a plan to determine the maximum thickness of the Columbia Plateau basalts?

Prof. H.H. Hess (U.S.A.) commented that he knew of no plans for this.

Prof. Uffen

Earlier in the meeting we touched briefly on costs of drilling, but we did not pursue the subject very far. Would you like to discuss this any further today? Sometimes it is difficult for people to publish costs that they can talk about informally at a meeting like this.

Dr. P.J. Hart (U.S.A.)

I would like to comment on the remarks that Prof. Simmons made in discussing the question of a, say, 10,000 foot hole or a 25,000 foot hole mentioned by several people. In a rough way, it is supposed that in hard rock a 25,000 foot hole might cost perhaps ten times as much as a 10,000 foot hole. Assume this is a reasonable approximation, perhaps an order of magnitude increase in expense. If it could be agreed to drill a 25,000 foot hole this should, in any case,be preceded by a 10,000 foot hole, since the cost is relatively so small. This would allow you to determine from the 10,000 foot hole whether you are in as interesting an area as all your other studies said you should be. If you decide at the end of 10,000 feet that perhaps it is not so interesting, your investment is, on a percentage basis, still rather small, although it may not be small in terms of dollars.

Prof. Hess

On that last point, I think one of the great benefits that has come out of the Mohole technology is the increase in understanding of how to drill, better equipment to drill, and much faster drilling. We should certainly aim to cut down the cost of the 25,000 foot hole very appreciably. The greatest expense of the Mohole project to date has gone into the engineering of the ship. But something very good has come out of this in the end, in that the drilling will be very much less expensive and very much faster with this type of hole.

C. SESSION ON GEOPHYSICAL RESEARCH IN DEEP HOLES

Chairman: T.F. Gaskell (U.K.)
Reporter: E.R. Niblett (Can.)

Dr. T.F. Gaskell: "Ladies and gentlemen, we have been hearing about drilling programs in various parts of the world this morning. This afternoon we are getting into that interesting subject of what you do with a bore-hole while you are drilling it. Well-logging of various sorts is really geophysics, considered in a vertical position instead of horizontally as it is usually applied on the surface. There are many logging operations that can be done already and our program this afternoon will be a survey of the sort of instruments that have been used to a large extent by the oil industry. We shall obviously have to remember that much of the information that one gets from bore-holes is in the form of direct geological information from rock chips that are brought to the surface, and from the cores that one recovers. Towards the end of the session today, we shall take a forward look with regard to the type of tools which may be available for improving well-logging in the future. There are many different ways of finding what sort of things exist down a bore-hole, ranging from taking direct photographs in some cases to all the electrical, magnetic, seismic, and radioactive measurements that one makes in ordinary surface prospecting. Well, I do not want to steal anyone's thunder by explaining anything in detail; so I will ask Mr. Bosworth of Schlumberger Canada to set the ball rolling, and no one could be better qualified for this task. Those who know the subject of well-logging will give great credit to the Schlumberger brothers who started the whole business, by realizing that useful information could be obtained by applying surface electrical measurements down a vertical bore-hole. Another essential thing is that it is no use having an idea without making the tools to do it. The Schlumberger brothers made a cable that would operate in a deep bore-hole, and therefore made it possible to do all these elegant things that we manage these days.

"Now, Mr. Bosworth would you start off and explain some of these for us?"

LOGGING TECHNIQUES IN THE OIL INDUSTRY

A.F. Bosworth
Division Engineer
Schlumberger of Canada

Abstract

Electrical logging has progressed from the simple resistivity curve recorded by Conrad and Marcel Schlumberger thirty-eight years ago, to the sophisticated devices in use today. However, the objectives of well logging remain essentially the same; that is, to provide those who explore for petroleum resources accurate information relating to:

- formation correlation,
- identification of productive zones,
- evaluation of productive zones,
- accurate depth control.

This variety of information is available from groups of logging tools, the selection of which depends on formation characteristics and drilling practises. In this paper the types of logging equipment available to the industry are briefly discussed. Included are resistivity and porosity devices, auxiliary equipment, their types of measurements, and the physical limitations of the equipment.

INTRODUCTION

The first electrical log was recorded thirty-eight years ago by Conrad Schlumberger at Pechelbronn, France, on September 5, 1927 (Fig. 1). This crude log was made by plotting many point by point resistivity measurements versus depths. The variations in formation resistivities were immediately recognized as a valuable aid to correlation between wells. From this beginning, a new science was evolved.

The depression initially slowed development but progress was made in both instrumentation and interpretation. The spontaneous potential or S.P. curve was identified by Conrad Schlumberger in 1929 and by 1931 was being recorded simultaneously with resistivity measurements. The standard electrical log then consisted of an S.P. plus short normal.

By 1936, electrical logs were improved to include two normal spacings, a lateral and S.P. This, combined with photographic recording, greatly speeded up logging operations. Other companies entered the electrical logging field and the development of new aids to oil exploration continued at a competitive and rapid pace.

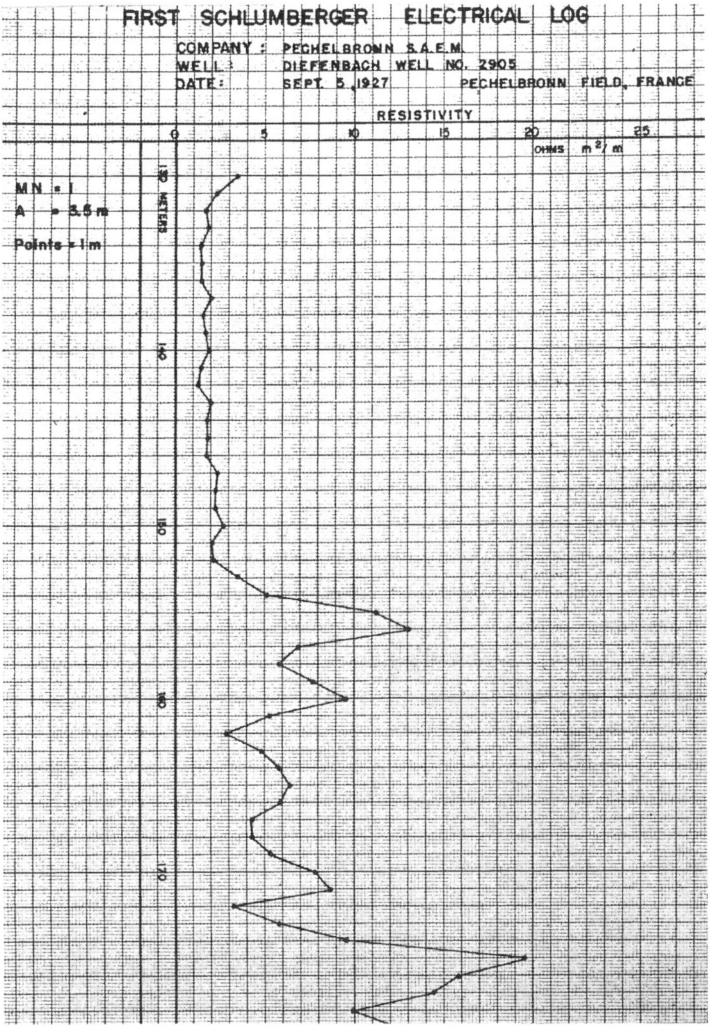

Figure 1. The first electric log; Pechelbronn Field, France, September 5, 1927.

FORMATION CHARACTERISTICS AND RESISTIVITY RELATIONSHIPS

In the search for oil, knowledge of several reservoir characteristics is desired and measured. Some years ago, Archie (1942) postulated these relationships:

$$Sw^n = \frac{F \times Rw}{Rt} = \frac{Ro}{Rt}$$

where: Sw = percentage of pore space occupied by formation water
F = formation resistivity factor
Rw = formation water resistivity
Rt = undisturbed formation resistivity
Ro = formation resistivity when fully saturated with formation water
n = an empirically derived exponent, commonly taken as 2.

Archie also proposed that:

$$F = a/\phi^m$$

where a = a constant
ϕ = porosity
m = cementation factor, ranging from 1.8 to 2.2.

Thus, to calculate formation water saturation (Sw), measurements of Rt, ϕ or F, and Rw, are required and it was to this end that many logging devices were developed.

RESISTIVITY MEASURING DEVICES

1. Induction Log

The original E-log has now been superseded by the Induction log (Fig. 2), which measures formation conductivity rather than resistivity. A 20 KC a.c. current is fed to a transmitter coil. The magnetic field produced by the transmitter induces eddy currents into the formation which in turn induce signals in the receiver coils (Fig. 3). The formation current density, and hence receiver signal strength, are proportional to the formation conductivity. A reciprocal computer is used to convert conductivity values to the more commonly used resistivity. The Induction log was first developed for logging in non-conductive (oil-base) muds but now, combined with an S.P. curve, it is used in almost all environments.

2. Laterolog

When the original E-log was run in wells with salty (very conductive) muds, the survey current would course up or down the borehole, especially when opposite resistive beds. The readings obtained were thus depressed and not representative of formation resistivity. A focussed current device called a Laterolog was developed. By using this tool, survey

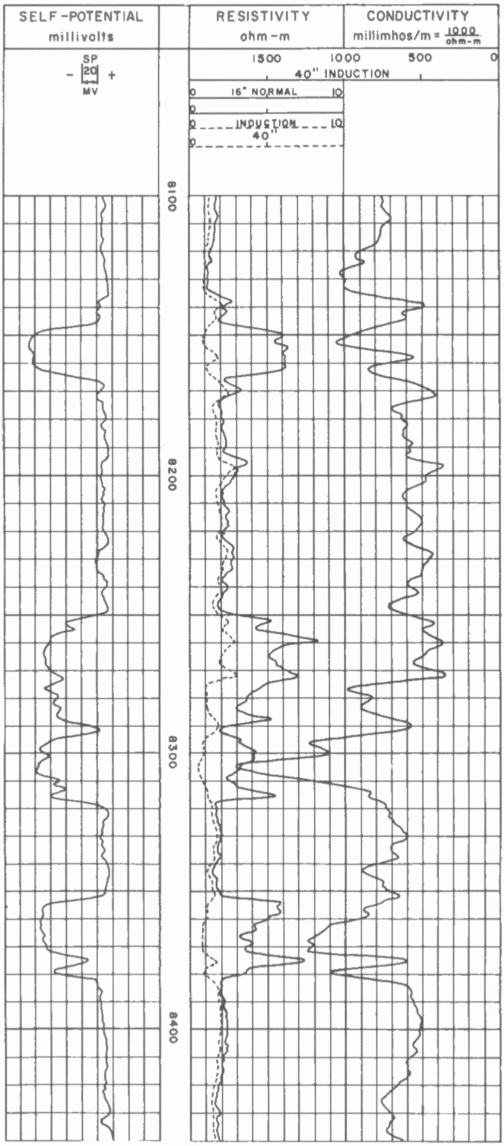

Figure 2. Induction-electric log, combining the S.P., 16" normal resistivity, and induction (conductivity) logs.

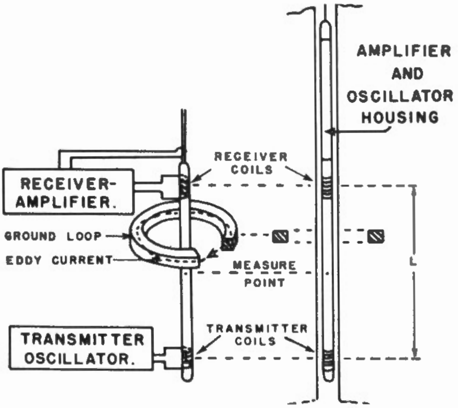

Figure 3. Induction log equipment.

current is forced into the formation to provide a detailed record of resistivities. Figure 4 gives a schematic comparison of Laterolog and normal E-log behaviour.

A recently developed tool, called the Dual Induction Laterolog combines, in one unit, two Induction systems, plus a Laterolog and an S.P. curve. Thus a detailed analysis of formation resistivities is possible from one log.

POROSITY MEASURING DEVICES

In order to determine the potential oil reserves of a formation, an indication of formation porosity must be obtained. Several tools that measure porosity directly are available.

1. Sonic or Acoustic Equipment

Originally designed primarily as an aid to seismic surveys, the sonic log has become one of the most popular porosity measuring devices. A transmitter and two receivers are commonly used to provide a log of the travel time (in micro-seconds) of sound through a formation. The use of two receivers cancels out the effect of travel time in the mud column.

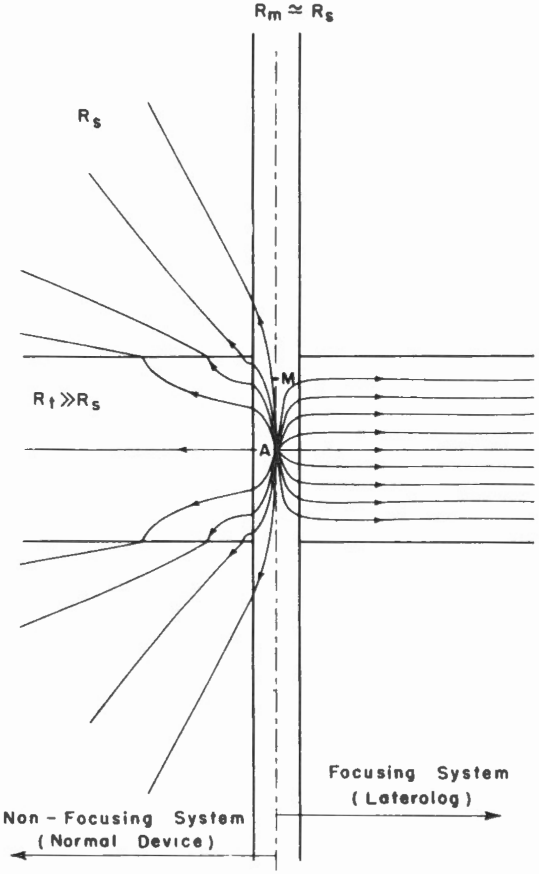

Figure 4. Comparative distribution of current lines for normal device (left) and Laterolog (right) opposite a thin, resistive bed — Schematic.

Wylie (1957) proposed a relationship where:

$$\phi = \frac{V_{Log} - V_{Fluid}}{V_{Log} - V_{Matrix}}$$

Assuming knowledge of fluid and matrix velocities, the porosity may be calculated from the above relationship.

The Schlumberger "BHC" (Bore-Hole Compensated) Sonic log is currently being introduced to the industry. In this application, two transmitters and four receivers combine to produce a single Δ T measurement. Greater accuracy is obtained by minimizing sonde tilt and bore-hole size changes.

T, as measured with the "BHC" log

$$= \frac{\Delta T + \Delta T2}{2 \text{ x } \text{span}}$$

The span in use today is 2 feet. Future plans include a sonde with 1 foot span. It is common practise to record a scintillation gamma ray and caliper log simultaneously with the "BHC" log.

Today, considerable research is being conducted into the utilization of the complete sonic wave train, including both shear and compressional waves. Fracture location and cased hole cement quality are only two of the many topics under study.

2. Density Logs

Density measuring devices have been available to the industry for some time, but only recently have refinements been made to provide accurate measurements under bore-hole conditions.

In operation, a source of gamma rays and a detector are placed in a metal pad which is pressed against the bore-hole wall (Fig. 5). The detector count rate (output) is proportional to electron density which, for most practical purposes, is closely allied to bulk density. Porosity may be derived using the following relationship:

$$\phi = \frac{Dg - Db}{Dg - Df}$$

Knowledge of fluid density (Df) and grain density (Dg) is required. Density logs are especially valuable in determining shaly formation effective porosity.

3. Neutron Logs

To obtain these surveys the formation is bombarded by a source of fast neutrons, usually radium-beryllium, plutonium-beryllium, or actinium-beryllium. Epi-thermal or thermal neutron, or neutron-gamma capture type logs may be recorded. Each log reflects the presence of hydrogen in the formation and by the use of appropriate charts a hydrogen

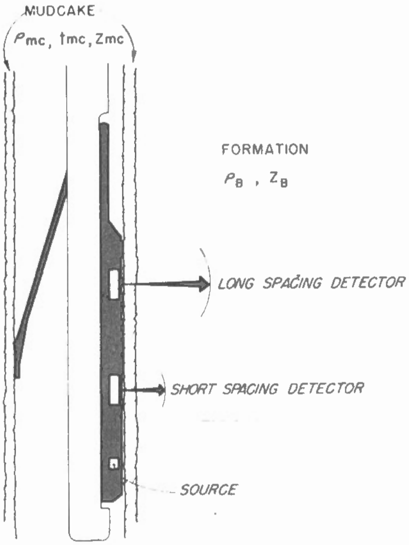

Figure 5. Schematic drawing of the dual-spacing Formation Density Logging device (FDC).

index can be calculated. This, in turn, can be expressed in terms of per cent porosity. Neutron logs are best suited to formations of low porosity. A gamma ray log is customarily run simultaneously as a lithology identifier. Figure 6 is an example of a combined gamma ray-neutron log.

Recent developments in interpretation techniques have determined that by cross plotting sonic, neutron and density surveys, more accurate porosity values are obtained as well as knowledge of the minerals comprising the rock matrix. This approach to lithology identification may be of use in Upper Mantle studies.

FORMATION FACTOR OR INDIRECT POROSITY LOGS

Microlog

The Microlog was originally developed to delineate permeable sections of hard formations—these are not readily distinguished by the S.P. curve. Small electrodes are mounted on an insulated pad and pressed against the bore-hole wall. The resistivity of a very small volume of material is measured. Using appropriate charts, an apparent formation factor may be calculated where:

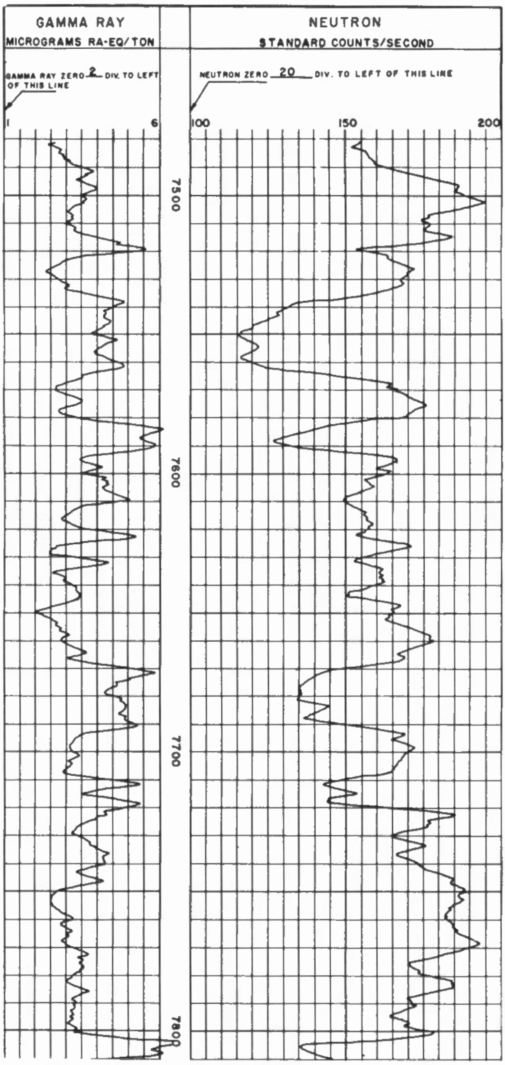

Figure 6. Gamma Ray-Neutron Log.

$$Fa = Rxo/Rmf \qquad \text{(analogous to } F = \frac{Ro}{Rw}\text{)}$$

where: Rxo = Flushed Zone Resistivity
Rmf = Mud Filtrate Resistivity

A similar device, the Microlaterolog was developed for salt mud and/or high resistivity beds. The survey current is focussed into the formation and the formation factor is calculated from:

$$F = RmLL/Rmf$$

or

$$\phi = \sqrt{Rmf/RmLL}$$

The recently developed Proximity log is a deeper reading microlaterolog and finds its application in zones deeply penetrated by either fresh or salt muds.

OTHER WIRELINE DEVICES

1. Dipmeter

A knowledge of the angle and direction of formation dips is important to the petroleum industry and as early as 1933 a form of dipmeter was available. The newest type of equipment provides a continuous record of bore-hole deviation and direction plus three micro-resistivity curves from which formation dips may be computed (Fig. 7). The dipmeter is adaptable to machine computation and in some areas surveys are now recorded on magnetic tape that can be fed directly to a computer.

2. Sampling Devices

The recovery of actual samples of formation by a cheaper means than continuous coring led to the early development of various sampling devices. The most common tool today is a gun that drives "bullets" into the formation by detonating a powder charge. Samples of formation are retained within the bullet and retrieved by suitable connectors. Soft formations are easily cored by gun samplers but improved bullet design has led to usable recoveries in extremely hard formations. New models of guns that can be connected in tandem allow as many as 66 shots to be attempted during one trip in a well. Core sizes, depending on bullets used, vary from 51/64 to 1 3/32 inches in diameter and maximum lengths are 1 3/4 inches. Equipment is also available to obtain azimuth-positioned cores for dip and sedimentation studies.

3. Formation Tester

This instrument was developed to retrieve samples of formation fluids. The tool is positioned accurately by comparing S.P. and gamma

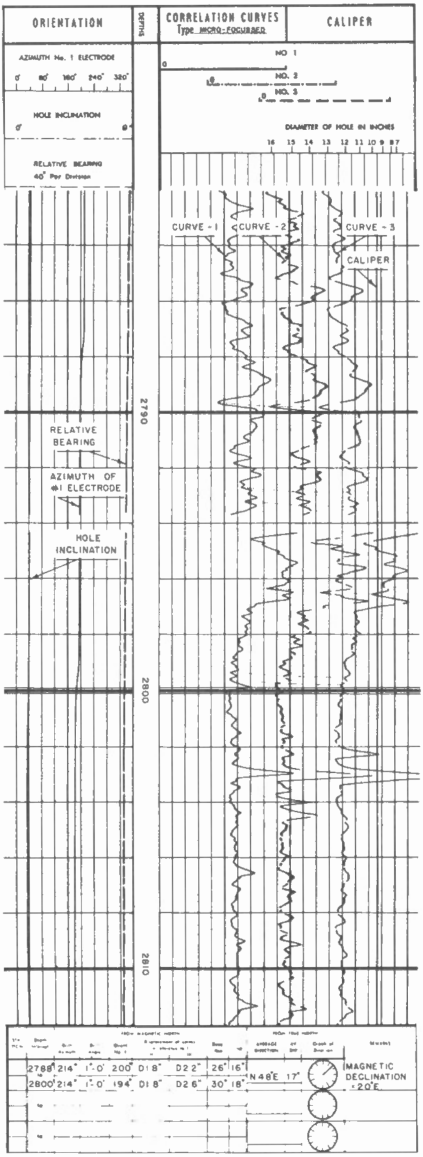

Figure 7. Dipmeter Log on a well in Canada.

ray logs run with the formation tester to logs previously recorded. The tool is set by admitting hydrostatic pressure to a seal pad and back-up shoe which press against the hole wall. One to four shots may be fired into the formation and from these perforations, formation fluids are admitted to a reservoir. When the tank is filled, or after some selected interval, the unit is sealed; the tool retracted, and brought to surface. The complete process is recorded on film at the surface. From pressure recordings and buildup times, calculations of formation permeability and production may be made.

4. Caliper Surveys

Caliper surveys are run simultaneously with many tools as an aid to interpretation—examples are Microlog, Microlaterolog, Dipmeter, Sonic, and Density equipment. Other applications are:

as permeability indicators,
to provide information for calculating cement volumes,
to assist in casing corrosion studies, and
to assist in study of efficient drilling practises.

Special calipers are the Section Gauge for large diameter holes and the Through Tubing Caliper for small diameter applications. The latter is usually run in cased wells and its small diameter allows entry through 2 inch tubing.

5. Temperature Measuring Equipment

Temperature surveys have been available to the industry for many years. A popular use was to locate cement tops behind casing by running surveys shortly after cement was set. Other applications are:

to establish thermal gradients,
to locate gas producing zones,
to locate thief or lost circulation zones, and
to determine formation production characteristics following stimulation treatments.

Magnetic casing collar locators are usually run in simultaneously with both temperature and caliper surveys. Maximum reading thermometers are included in every downhole survey. Their readings are required for accurate log interpretation and they can be used to establish formation thermal characteristics.

LOGGING PROGRAMS

There is presently no universal device that will completely evaluate a formation. We can, however, recommend a group of surveys that will best evaluate a particular type of formation. The choice of combinations depends on both the bore-hole and formation environments. Bore-hole conditions refer primarily to the type of drilling fluid, while formations are defined as to the type and degree of porosity, and the salinity of interstitial water. The various logging programs available, and their application to different bore-hole conditions are summarized in Table I.

Table I

Recommended Logging Services for Various Bore-Hole Conditions

BORE-HOLE CONDITIONS	DATA DESIRED	SOFT FORMATIONS**	HARD FORMATIONS**
Fresh muds (Salinity is less than 20,000 ppm. chlorides, or Rmf/Rw > 4)*	Resistivity and Lithology	Induction-Electrical Log***	Induction-Electrical Log*** Laterolog Gamma Ray may be used for lithology
	Porosity	Formation Density Log Sonic Log Microlog-Caliper	Formation Density Log Sonic Log Neutron Log Microlaterolog-Caliper
	Permeability Indication	Microlog-Caliper Formation Tester	Microlog-Caliper Microlaterolog-Caliper Formation Tester
Salt muds (Salinity is greater than 20,000 ppm. chlorides, or Rmf/Rw < 4)*	Resistivity and Lithology	Induction-Electrical Log*** Laterolog Gamma Ray Log may be needed for lithology	Laterolog and Gamma Ray Log
	Porosity	Formation Density Log Sonic Log Microlaterolog-Caliper Microlog-Caliper	Formation Density Log Sonic Log Neutron Log Microlaterolog-Caliper
	Permeability Indication	Microlog-Caliper Microlaterolog-Caliper Formation Tester	Microlog-Caliper Microlaterolog-Caliper Formation Tester
Oil-Base (non-conducting) Muds	Resistivity	Induction Log	Induction Log
	Lithology	Gamma Ray-Sonic Logs with Formation Density Log Formation Density-Neutron Log	Formation Density Log with Gamma Ray-Neutron Log
	Porosity	Formation Density Log Sonic Log Neutron Log	Formation Density Log Sonic Log Neutron Log
	Permeability Indication	Formation Tester	Formation Tester
Empty or Gas-Drilled Holes	Resistivity and Lithology	Same as for Oil-Base Muds, except no Sonic Logs.	
	Porosity	Formation Density Log Neutron Log	Formation Density Log Neutron Log
	Permeability Indication	Temperature Log	Temperature Log
Cased Holes	Resistivity	none	none
	Lithology	Gamma Ray-Neutron Log	Gamma Ray-Neutron Log
	Porosity	Neutron Log	Neutron Log
	Permeability Indication	Formation Tester	Formation Tester

* Rmf is resistivity of mud filtrate.
Rw is resistivity of formation water.

** Soft Formations - reservoir beds have porosities greater than about 15%.
Hard Formations - reservoir beds have porosities less than about 15%.

*** Although largely obsolete, an Electrical log may be substituted for an I-E log.

FIELD EQUIPMENT

1. Trucks

Electrical logging trucks contain an instrument cab, a large winch for survey cable, a power generator, a photographic recorder, plus developing and printing facilities. Skid type units are available for remote or offshore locations.

2. Cable

Survey cable in common use today contains seven insulated conductors protected by two layers of counter-wound armor wire. Where extreme temperatures are expected, teflon or glass insulated cables are available.

3. Operational Limits

The operational limits of Schlumberger wireline equipment are shown in Table II. The minimum hole sizes are for open hole sections longer than 5,000 feet in unconsolidated formations. For other conditions, the hole size may be decreased as much as one inch. The maximum sizes take into consideration the quantitative use of the log, or the ability of a tool to remain properly oriented with respect to the bore-hole. Maximum temperature ratings are for exposures of three hours for tools in excellent condition. Repeated exposure to high temperatures will eventually cause electrical circuits to fail.

FUTURE DEVELOPMENTS

Following present industry trends it is conceivable that exploratory wells will reach 50,000 feet by 1990. It is expected that bottom hole temperatures will be between 450° and 850°F, at pressures of about 35,000 psi. In anticipation of this, laboratory facilities are already available to test equipment at pressures of 30,000 psi and temperatures of 450°F.

Much research is directed to improving the reliability of present equipment while other investigations are aimed at producing tools that will assist the oil industry in exploration and development. Well site data (log) recording on magnetic tapes compatible with computers is now under investigation and will contribute rapid evaluation of log information. The transmission of log data by microwave from offshore locations to produce a simultaneous log at a land location has already been accomplished. It is reasonable to assume that the challenges of formation evaluation by electrical means will continue to be met by the electrical logging industry.

Table II

Equipment Specifications

Equipment	Tool Outside Diameter	Hole Size Min.	Hole Size Max.	Max. Press. psi	Max. Temp. °F
A. Resistivity Devices:					
1. Induction Std. 6FF40	3 7/8"	6 1/2"	12"	20,000	300°F
Hi-Temp 6FF40	3 7/8"	6 1/2"	12"	20,000	400°F
Dual Induction Laterolog	3 7/8"	6 1/2"	12"	20,000	285°F
2. Laterolog	3 7/8"	6 1/2"	18"	20,000	300°F
3. Electrical log	3 5/8" 1 1/2"	5 1/2" —[1]	12" 6"	20,000 20,000	350°F 350°F
B. Porosity Devices:					
1. Sonic VLT	3 5/8"	6"	12"	20,000	350°F
BHC[2]	3 5/8"	6"	15"	20,000	350°F
2. Density FDC	3 5/8"	5"	15"	20,000	350°F
3. Microlog[3], Microlaterolog	5 1/16"	6 1/2"	20"	20,000	350°F

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[1] Determined by drill pipe inside diameter

[2] Newer models will operate to 425°F; both include simultaneous gamma ray and caliper loop.

[3] Can log to 4 3/4" hole size with a special pad.

Equipment	Tool Outside Diameter	Hole Size Min.	Hole Size Max.	Max. Press. psi	Max. Temp. °F
C. Radiation Devices:					
1. Gamma Ray with Scintillation Detector	3 3/8"	4"	—	20,000	350°F
2. GR-Neutron with GR Scint. Detector	1 11/16" 2"	2" Tubing 2 1/2" Tubing	10" 10"	12,000 20,000	300°F 300°F
with G-M GR Detector		As above			350°F
GR-N Scint. GR Detector	3 5/8"	6 3/4"	14"	20,000	400°F[1]
D. Sample Taker:					
1. CST-C (30 Shot)	5 3/8"	8 1/2"	13"	20,000	275°F[2]
2. CST-U & V (24, 21 Shot)	4 3/8"	6 1/8"	9 7/8"	20,000	275°F[2]
3. CST-W (12 Shot)	4 3/8"	4 3/4"	9 7/8"	20,000	275°F[2]
E. Formation Tester:					
FIM-A	4.4"[3]	5 1/2" Casing 6" Open Hole	12 1/4"	20,000	250°F[4]
F. Dipmeter:					
CDM (Includes continuous directional or hole deviation survey)	4"[5]	4 3/4"	16"	20,000	350°F

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[1] 350°F with transistorized cartridge.

[2] Can be extended to 350°F with special powder and igniter. By connecting guns in tandem, 66 shots may be attempted per trip in a well.

[3] Sizes variable to suit hole conditions.

[4] Can go to 340°F with special powder.

[5] Small diameter sonde required.

Equipment	Tool Outside Diameter	Hole Size Min.	Hole Size Max.	Max. Press. psi	Max. Temp. °F
G. Caliper:					
1. Section Gauge	5 1/2"	6"	36"	20,000	350°F
2. Thru-Tubing Caliper	1 11/16"	2"	12"	10,000	285°F
H. Temperature Tools:					
1. DWT	3 3/8"	6"	—	15,000	300°F
2. HRT	1 11/16"	2" Tubing	—	15,000	350°F Min. - 0°F.

Tools are under development to measure temperatures to 600°F.

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INSTRUMENTATION IN DEEP DIAMOND BORE-HOLES IN SOUTH AFRICA

S.H. Haughton
Geological Survey of South Africa

INTRODUCTION

A considerable number of deep bore-holes have been sunk in South Africa, particularly in connection with the exploration for gold. The deepest has reached to over 14,000 feet and had a diameter of 2 inches at the bottom. In 1961, R. Borchers listed over 200 holes, the longest of which reached a depth of 10,456 feet, all within the greater Witwatersrand basin. But additional deeper holes have since been sunk in the search for gold (see W.S. Garrett, this volume); and others have been or will be drilled in the exploration for strategic minerals, including oil, in other parts of South Africa. All these holes are drilled with diamond bits, so that when they are completed both the holes themselves, and the cores that have been obtained, are available for study.

IN-HOLE MEASUREMENTS

In-hole instrumentation has been progressively developed both in South Africa and overseas. Multiple probes with surface registration are now used in a routine manner by exploration companies and specific probes have been in use for a number of years by the Geological Survey and the National Physical Laboratory of the Council for Scientific and Industrial Research. Naturally, one of the first measurement objectives is the investigation of the deviation from the vertical and the declination of small-diameter holes drilled to depth, which can be affected by such factors as pressure on the drilling rods, the occurrence of alternating layers of hard and soft strata, crevices in the rocks, bedding or fracture planes, and the ratio between the diameters of the rods and the drilling bits. Designers of probe equipment recognize that, at a depth of 14,000 feet, pressure on the probe is likely to be over 6,000 p.s.i.

One company—Boart and Hard Metal Industries—has been successful in designing equipment which can withstand pressures of this magnitude, is non-magnetic, and can measure inclination from 0° to 40° to ±0.1°, compass direction to within 5°, temperatures up to 70°C, and record radioactivity. It is capable of taking a virtually unlimited number of readings, and can transmit them to surface recorders, all with a probe diameter not exceeding 1.9 inches.

In exploration programs as well as in scientific studies in bore-holes it is necessary to plot an accurate trace of the hole from a knowledge of both declination and deviation. This is now done as a matter of routine in the case of all cored holes.

Apart from these geometric observations, most attention in the recording of in-hole measurements has been given to radioactivity and temperature, the former because of the occurrence of uranium ore in the sediments of the Witwatersrand system.

Systematic radiometric logging in bore-holes was first undertaken by D.J. Simpson, using specially designed equipment that was described by Guelke, Heydenrych and Anderson (1949). Some of Simpson's results were published in a series of papers between 1950 and 1952, in which he concluded that the intensity curves obtained could be used for geological correlation—the variations in radioactive intensity depending on the amounts of uraniferous material present in each horizon in the succession. The same equipment is still in use by the Geological Survey which has to date logged about 400 holes; in addition, certain mineral companies possess another 200 or so radioactive logs.

At about the same time as Simpson's work, Bouwer of the Geological Survey utilized an "electronic thermometer" constructed by the National Physical Laboratory to make temperature measurements in many of the same bore-holes. The accuracy of this instrument is about 0.5°C, much less than that of mercury maximum thermometers in pressure-tight steel tubes (± 0.002°C). Its advantage lies in the fact that it is self-recording and can be used as a single shot in each hole. Geothermic steps sufficiently reliable for mining purposes could be calculated and compared with stratification. Mining companies on the Witwatersrand undertake routine temperature measurements and the Council for Scientific and Industrial Research has placed orders for equipment capable of recording to depths of 20,000 feet.

FUTURE STUDIES

The Geological Survey is planning to drill two holes in the Bushveld Igneous Complex to obtain more data on the succession of rocks down to its floor; each hole will probably be 8,000 feet deep. It is also contemplating sinking much deeper holes in connection with the national search for oil—the Director of the Survey envisages depths of 12,000 to 14,000 feet. The same organization is undertaking detailed geological and gravity surveys in two areas in which the Upper Mantle Committee is specifically interested—one along an east-west belt of gravity highs along which carbonatite intrusions lie, and the other in the area containing the Palabora carbonatite plug and its surrounding ring of pyroxenite and syenite. The Committee is of the opinion that one or other of these areas may provide a site for a deep hole—for which, however, no financial support has yet been arranged.

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PROBLEMS IN MEASURING TEMPERATURE AND TERRESTRIAL HEAT FLOW IN DEEP BORE-HOLES

A.E. Beck
Department of Geophysics
University of Western Ontario

Abstract

This paper deals mainly with problems in extending existing bore-hole temperature measuring techniques to high temperature regions such as might be encountered in very deep bore-holes, volcanic regions and geothermal areas.

1. INTRODUCTION

1.1 When asked to give a paper on temperature measurements in deep bore-holes, I felt that a discussion of present day accomplishments would not be very helpful. Since we are entering upon a new era of great interest in geothermal power, volcanological regions, and bore-holes that will penetrate the Mohorovicic discontinuity beneath the oceans and eventually, we hope, beneath the continents, it occurred to me that we should at least start thinking about the problems of measuring temperature and terrestrial heat flow in high temperature regions. In this paper therefore, I propose discussing, quite briefly, the present day techniques, the problems in extending these techniques for use in high temperature regions, and one or two new techniques that may be worth further investigation.

1.2 The first thing to be decided is the maximum temperature at which the equipment should operate and the precision of the readings required. In areas of 'normal' (about 1.5 μ cal/cm^2/sec) heat flow, temperatures as high as 200°C have been recorded in bore-holes; in volcanological areas and geothermal fields, temperatures in excess of 300°C have been reported. We should therefore be thinking in terms of equipment capable of operating at 500°C and possibly higher.

1.3 In present day work it is fairly easy to obtain temperatures with a precision of 0.01°C; direct differential temperature measurements over small depth intervals can give temperature gradients that are an order of magnitude better than those obtained from absolute temperature measurements. Although it would be pleasant to have similar precision in higher temperature equipment, it is not only rather impractical but also, in view of how little we know about the temperature distribution at great depths or in volcanic regions, not really necessary. In regions of high temperature gradient, and in very deep bore-holes where temperatures can be measured over larger depth intervals than is usually the case now, a precision of 1 or 2°C seems quite adequate.

1.4 My own approach to the problem would be to try and design equipment to operate at 800°C with a precision of 1°C but I would not be too dissatisfied if I could only achieve an operational temperature of 500°C and a precision of 3 or 4°C.

1.5 With these basic objectives I shall now briefly examine the problems likely to be encountered in achieving the goal.

2. PROBES ELECTRICALLY CONNECTED TO THE SURFACE

2.1 The first thing one considers is to modify an existing technique. Since most of my own work has been over land the first thing I think of is to examine the possibility of modifying one of the methods using a probe electrically connected to equipment at the surface. The advantage of these techniques is their great flexibility. They can be used for continuous recording (Schlumberger et al., 1937; Simmons, 1965); for readings at given intervals (Misener and Beck, 1960) which can be varied at will during the logging process so that sections of the bore-hole of particular interest can be studied in detail; various types of probes can be readily interchanged so that with the same basic equipment either temperatures or temperature gradients can be recorded; and, if the probe becomes jammed in a bore-hole the only loss is a small and inexpensive probe.

2.2 Because of its high temperature coefficient of resistance the thermistor is widely used in present day temperature measuring equipment. However, this advantage becomes a severe disadvantage for temperature measurement over a wide range; for instance, even if it is assumed that a thermistor with an ice point resistance of 1 megohm could survive at 500°C, its resistance at this high temperature would be less than 1 ohm. The problems are obvious and will not be discussed further. Stability is one of the principal requirements of a temperature sensitive element at high temperatures and this factor suggests the use of a platinum, nickel, or quartz element.

2.3 If a resistance thermometer is used in a fairly simple bridge circuit, one of the problems is to reduce the errors introduced by the lead resistance of the connecting wires (which is recorded by the bridge at the surface as a resistance in series with the resistance thermometer) and the inter-lead insulation resistance of the cable (which is recorded by the bridge at the surface as a shunt resistance across the resistance thermometer).

2.4 As an example, if a platinum resistance thermometer is used, then in order to make the problem of the series resistance of the leads reasonably easy to deal with, we might choose an element with an ice point resistance of 1,000 ohms. A 1°C increase in temperature would give a 4 ohm increase in resistance or at 500°C the resistance would be about 3,000 ohms. To avoid resistance errors equivalent to 1°C error in temperature, the variations in the insulation resistance of the cable, which will be under strain in the high temperature-high pressure fluid environment (with the possibility of the fluid being a moderate electrical conductor), should be less than 4 ohms. This means that to be reasonably safe, the ratio of insulation resistance to element resistance should at all times exceed 3,000, thus indicating the need for an inter-lead insulation resistance of at least 10 megohms for this type of element. Similarly the series resistance of the connecting conductors should not vary by more than 4 ohms. Both of these requirements may be difficult to achieve without some form of compensation or correction; however, the requirements can be reduced considerably by one of three methods.

2.5 The first method requires a four lead cable which can be connected in such a way (Beck, 1963) that the series resistance, the shunt resistance and the variations of these with temperature and strain are automatically compensated; only a simple bridge is needed at the surface. The great advantage of this method is that the only item in the probe is the temperature sensitive element.

2.6 The second method (Jessop, 1964) requires two latching relays in the probe and only a three lead cable. The latching relays are connected in such a way that they provide four separate circuits in the probe so that the shunt resistance, the series resistance and two other resistance measurements can be made. The resistance of the temperature sensitive element is therefore corrected on the basis of the measured series and shunt resistances of the cable. The computation can be reduced by having a double balancing bridge, the first balance being made so that the shunt resistance of the cable is measured by a variable shunt resistance across the resistance box used to measure the element (plus series) resistance in the second balancing operation. This method has the advantage of being able to keep track of the cable behaviour at all times.

2.7 In the third method the probe can be lowered on only one, but preferably two, insulated leads. However, since the temperature sensitive element is now part of a temperature sensitive oscillator (Doig et al., 1961; Von Herzen and Maxwell, 1964) the probe must also contain electronic components such as transistors, vacuum tubes, capacitors etc. To build such components to withstand temperatures as high as 500°C is probably beyond present day technology, although it may be possible to overcome the problems by a suitable design incorporating heat pumps (which themselves may not be able to withstand the high temperatures).

2.8 Even if suitable components do become available there still remains the problem of providing a suitable cable. Cables have been used under a wide variety of environments. Great lengths of them can be buried underground or laid across the ocean, both of which can be regarded as fluid environments; very high temperatures can be measured using short lengths of suitably designed cable provided there is no fluid about. However, it will be an extremely difficult problem to design a cable with the required characteristics for use in a fluid (possibly conducting) at high temperatures and pressures and hanging under its own weight. The cable would presumably be made with some form of ceramic insulation and it may be possible to reduce the problem of strain by making the cable almost buoyant. Such a cable could probably be developed over the next few years but it is likely to be difficult to handle and very expensive to produce.

3. PROBES MECHANICALLY CONNECTED TO THE SURFACE

3.1 While such a cable is being developed, and to guard against the possibility that it may turn out to be impractical, we should be prepared to investigate the use of methods that do not require electrical connections to the surface. In these both the thermometer and any required associated equipment, such as recorders and amplifiers, are housed in a pressure proof container.

3.2 The most straightforward approach, at the sacrifice of some convenience, would be to use maximum thermometers. I do not know if these have ever been built for high temperatures but, since ordinary mercury-in-glass thermometers have been designed for use to over 600°C, presumably they could be designed quite easily. If one is prepared to sacrifice both precision and convenience, temperature sensitive paints could be used. In this case the probe would have to be lowered and raised to various given depths in much the same way that maximum thermometers are lowered and raised. To save time, a string of such probes could be used in the same manner as the equipment for maximum thermometers designed by Mossop (1950). This method requires very little development and could be used now.

3.3 For a recording thermometer, probably the simplest approach would be to modify the bathythermograph, an instrument much used by oceanographers, or a similar recording vapour pressure thermometer of the type much used by the oil industry. Both these instruments are basically mechanical types with the record of temperature being scratched by a stylus on a blackened slide or pressure sensitive paper; they are extremely simple and I do not see any great problem in getting them to operate at high temperatures. However, there may be some difficulty in presenting the data with the required precision over a wide range of temperature. Much will depend on the amount of space available in the probe which in turn depends on other factors such as the diameter of the hole in which it is lowered.

3.4 To be able to read temperatures to 1°C over the temperature range would require more sophisticated recording techniques than are presently used with these instruments. It is important that as far as possible any required improvements be carried out mechanically so as to avoid the problems that will arise if electronic components have to be used; this might be achieved by recording on a slowly rotating cylinder which can also be moved in discrete steps parallel to its axis using a spring operated motor.

3.5 A change in present techniques may help to simplify some of the problems. The normal method is to lower a probe and either record continuously the temperature versus depth, or else the probe is lowered to a given depth and the temperature noted, the probe lowered to another depth and the temperature again noted. In other words the datum interval is a unit of depth. The problem of recording might be considerably simplified if the datum interval is made a unit of temperature rather than depth and the depth noted every time the temperature changes by, say, 1°C. If the temperature sensitive element is a resistance thermometer, the simplest thing would be to make the datum interval a unit of resistance. It may even be possible to use our old friend the mercury-in-glass thermometer.

Electrical contacts could be inserted at intervals along the column so that the datum interval would be a unit of length of the mercury column. Thus what I have in mind is an electromechanical device whereby every time the resistance, or mercury column, increases by a pre-set amount, a high voltage or acoustic pulse is signalled to the surface through the lowering cable or bore-hole fluid, on receipt of which the operator notes the depth. The instrument should either have a small time constant or else the time constant should be well known so that corrections can be made. The absence of any recording device in the probe will clearly simplify its construction in this respect, but without a more detailed examination of the electrical and mechanical requirements of such a method it is difficult to say whether or not some equally difficult problem might arise.

3.6 Other alternatives, such as modifying the type of heat flow probe used in oceanographic work, present the problems mentioned earlier of packaging electronic components in such a way that they can withstand high temperatures. Naturally, if these problems can be overcome a much wider range of instruments, having higher precision, becomes possible. New techniques could be tried. For instance, could an optical pyrometer be built into a probe? If so, then by judicious use of various filters, some information might be obtained about the dominant wavelengths transmitted by radiation within the earth; this in turn would help towards solving the problem of how much thermal energy is transmitted by lattice conduction and how much by radiation. Unfortunately, at the present time adequate protection of the components does not seem practical.

3.7 So far, I have dealt mainly with methods that appear to me to be well within the bounds of possibility. I would now like to make a few suggestions which cannot be so classified, but which I feel could nevertheless bear further discussion even if they are ultimately rejected.

4. RECOVERABLE UNCONNECTED PROBES

4.1 Is it possible to design a probe that does not require any sort of lowering cable? Such a probe could contain any of the types of temperature sensitive equipment discussed earlier, complete with recording equipment if necessary, and could be made either recoverable or non-recoverable. The probe could be made buoyant but instead of tying it to the surface with a cable, the probe could be weighted with material designed either to melt and drop off at a pre-selected temperature or to drop off at a pre-selected pressure, and allow the probe to rise to the surface again where the records could be recovered. The tremendous advantage of not requiring a lowering cable needs no discussion. However the big problems would be the depth measurement, which has to be tied to the temperature measurement, and the large number of angry geophysicists if the probe becomes stuck at some unknown depth.

5. EXPENDABLE UNCONNECTED PROBES

5.1 In this case the probe would be expendable and therefore not buoyant. The instrument package might be similar to that discussed in 3.5, or consist of a temperature sensitive oscillator, with the temperature information being telemetered or transmitted directly through the bore-hole fluid. This idea is, of course, suggested by Sonar techniques and could presumably be used for oceanographic temperature measurement. The problems here are the same as in 4.1 with the addition of the unknown transmission characteristics of sound waves through a fluid column with a large temperature and pressure gradient, and (if a temperature sensitive oscillator is used) a Doppler effect due to a falling sound source. This latter might be put to good use and give information about the fluid by having a second, fixed frequency, oscillator in the probe.

6. IN SITU THERMAL CONDUCTIVITY MEASUREMENT

6.1 The advantage of measuring thermal conductivities at the natural temperatures and pressures encountered, which may be very difficult to reproduce in the laboratory, probably needs no discussion. Some thought should therefore be given to methods of measuring conductivities in situ.

6.2 For relatively shallow uncased bore-holes the method is fairly well established and consists basically of matching the temperature-time curve from an electrically heated cylinder with various theoretical curves (Beck, 1965). At the present time the possibility of using cased bore-holes is being investigated, the main modification being to add a guard ring at each end of the probe. This of course adds to the complication of the equipment which is separate from the temperature measuring equipment. If a cable suitable for use in high temperature bore-holes can be developed, there does not appear to be any serious difficulty in using this technique at high temperatures.

6.3 It may be possible to combine both a temperature (or temperature gradient) log with measurements of conductivity at several points going down the hole, and eliminate the need of an electrical heater. If the probe is massive enough it will not be able to reach equilibrium with the temperature of the bore-hole as it is lowered. Thus, when a stop is made to measure thermal conductivity the probe must absorb heat from the bore-hole; therefore the temperature rise versus time is again recorded and compared with theoretical curves. If existing curves are to be used some rather complicated corrections which depend on the rate of lowering and the temperature gradient will be needed; alternatively new families of theoretical curves could be computed taking these two variables into account. From experiments along these lines a few years ago, I believe that it may not be too difficult to get values accurate to within 20 or 25%. This relatively large error may not seem too large when the advantages of making the conductivity measurements under natural conditions are considered. The method would probably be useless in cased bore-holes.

6.4 In both cases the biggest problem would be in measuring the temperature rise to the required precision which would need to be at least one, and possibly two, orders of magnitude better than that which is required for the actual measurement of temperature in the bore-hole.

7. SUMMARY

7.1 Maximum thermometers might be used for temperatures to 500 or 600°C. Above (and up to) these temperatures fairly crude measurements could be made with temperature sensitive paints.

7.2 Within a reasonable period of time a mechanical recording, vapour pressure type thermometer could be developed for use at high temperatures with a precision of 2 or 3°C.

7.3 A cable capable of maintaining good mechanical and electrical characteristics in a high pressure-high temperature fluid (possibly electrically conducting) environment appears to be feasible, but requires much development at great cost. However, such a cable would make the extension of present day bore-hole temperature measuring techniques a relatively simple matter.

7.4 Use of electronic components in probes at high temperatures does not appear to be feasible. Nevertheless, if it was found possible to enclose the instrument package (except for the temperature sensitive element) in a controlled temperature chamber, a whole range of existing and new techniques could be used.

7.5 Extension of in situ methods of measuring thermal conductivities to high temperature bore-holes depends upon the development of a suitable bore-hole cable.

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MEASUREMENT OF STRESS IN BORE-HOLES

G.G.R. Buchbinder, E. Nyland and J.E. Blanchard*
Dalhousie University

Abstract

The various methods of measuring absolute stress in the crust of the earth are reviewed.

A recent experiment to measure absolute stress at Wawa, Ontario, using displacement meters in a bore-hole is described. The principal stresses at Wawa have been determined to be compressive.

The results are:

Minimum 2×10^7 newtons/metres^2 ± 50%
4×10^7 newtons/metres^2 ± 50%
6×10^7 newtons/metres^2 ± 50%

Modifications of existing equipment to make measurements from deep bore-holes are suggested.

INTRODUCTION

One of the most important influences on the crust of the earth is the stress that has acted on it. Geologists have been mapping the past and present effects of the stress on the surface of the earth. Seismologists record the time and the place where these forces have become strong enough to cause fractures or faults in the crust of the earth.

As our demand for the economic minerals in the crust of the earth has risen, the conditions under which these minerals have to be exploited are placing greater demands on the mining engineer to understand the stresses in the rocks around mines. The measurement of the stress in rocks _in situ_ is attracting increasing attention among mining engineers. Various methods have been devised to carry out these measurements. It is the purpose of this paper to review work done by graduate students at Dalhousie University, with the assistance of the Mines Branch of the Department of Mines and Technical Surveys, in assessing various methods of measuring absolute stress.

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*Speaker

MEASUREMENT OF STRESS

There are various ways one might measure stress in rock in situ. For example, one might measure the velocity of sound in the rock and, from a knowledge of the variation of the elastic constants with pressure, determine the state of stress. Unfortunately the elastic constants are too constant for this. The successful methods of measuring absolute stress depend on some means of stress relief in the rock so that a measurement may be made while the rock is under stress, and again when there is no stress. There are a number of names associated with this work. For example Professor Nils Hast of Sweden has been active in this field for many years.

Figure 1 shows a number of ways the stress around a bore-hole could be changed. No. 1 in Figure 1—in which a concentric hole is drilled around a bore-hole thus relieving the stress on the bore-hole — is the method we shall be concerned with. At present, in order to minimize the effects of the surface of the earth, measurements have been made in bore-holes from mine workings. The mine working will have an effect on the stress distribution in the rocks around it. Figure 2 shows the effect of an idealized mine working, an infinite cylindrical hole, on the stress field. From Figure 2 one sees that if the measurements are made a diameter away from the working, the effect is small. Figure 3 shows a measuring device in the bore-hole. The measuring device may be a displacement meter. It may be a solid elastic inclusion inserted within the bore-hole so that it exerts a known pressure and is then cemented in place. Theoretically this method could measure stresses directly, or, the measuring device could exert a pressure over equal and opposite arcs of the hole. The first method is directly dependent on Young's modulus; the last method is partially dependent on Young's small modulus. More recently Leeman in South Africa has placed strain gauges on the end of the bore-hole and overcored this.

For any of these devices to be successful the rock must behave as a perfectly elastic material while the measurements are made.

RESULTS

The first part of our work consisted of evaluating these methods. For example, Figures 4 and 5 show the effect of the size of the overcoring hole on the displacement of the uneven surface of the rock when a prestressing device such as Professor Hast uses is inserted in a bore-hole. From our studies the solid inclusion type appeared the least useful for our purposes and the displacement meter developed by Merrill of the U.S. Bureau of Mines, the simplest. Leeman's measuring technique has the advantage of using the same diamond bit to cut the strain gauges out as was used to drill the hole. The displacement meter used in our work is shown in Figure 6.

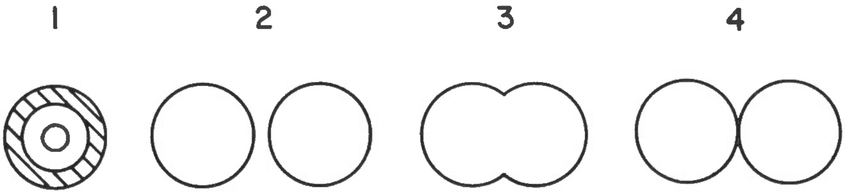


Figure 1. Possible methods of relieving stress around boreholes.

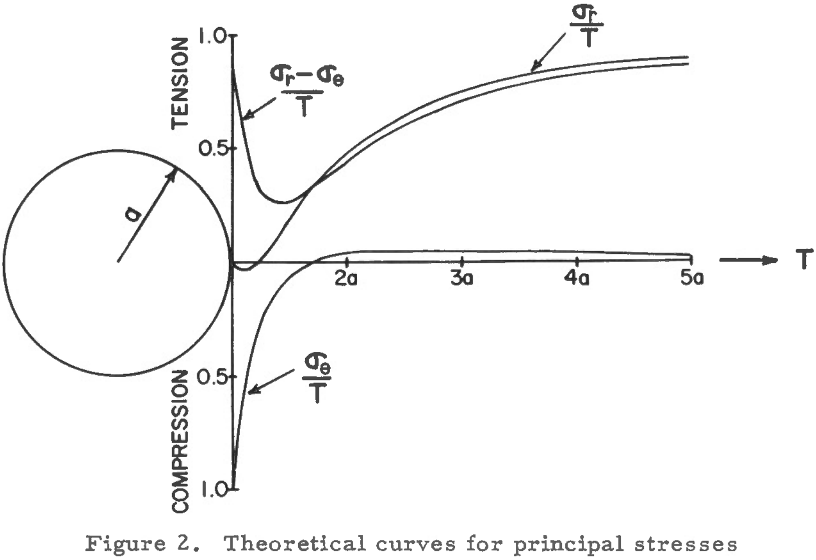
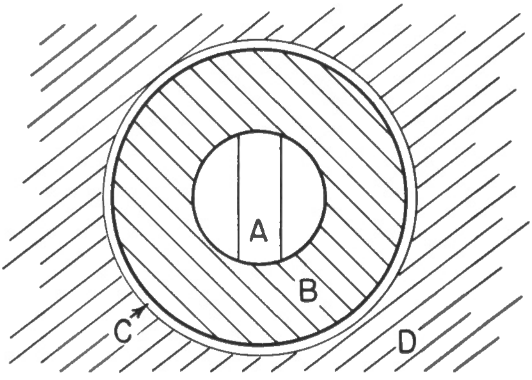


Figure 2. Theoretical curves for principal stresses around circular cylindrical holes at 0 degrees with applied tension.



A. STRESS MEASURING DEVICE
B. ISOLATED ROCK
C. STRESS RELEASE HOLE
D. STRESSED ROCK

Figure 3. Stress relief by overcoring.

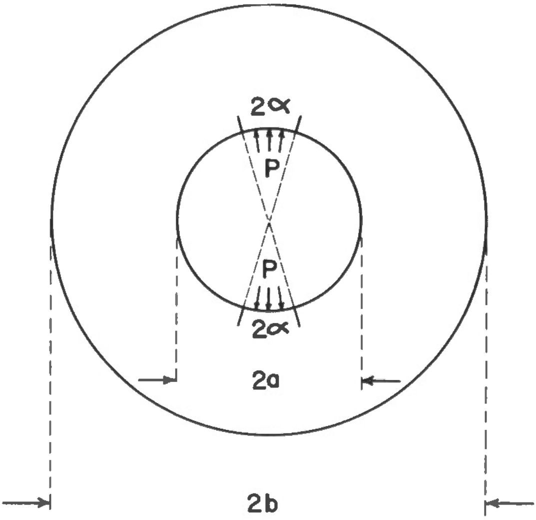


Figure 4. Idealization of Hast's method of measuring stress cylinder with pressure P exerted along equal and opposite arcs.

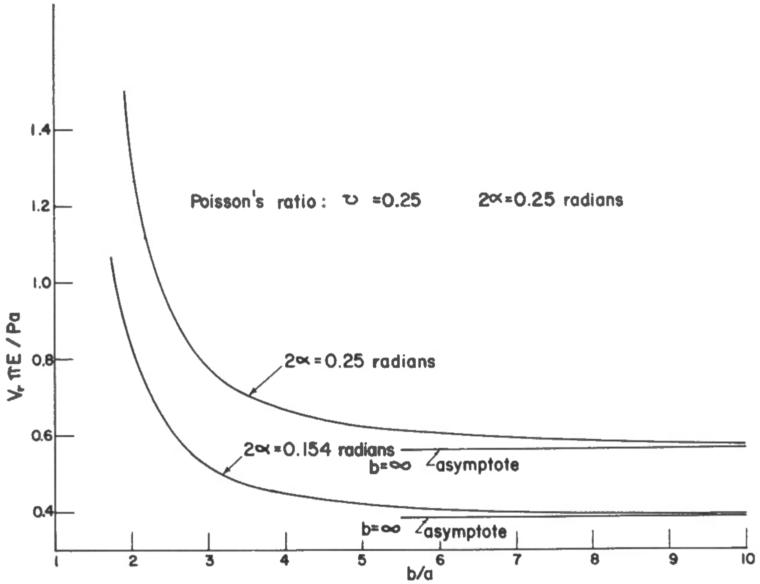


Figure 5. Effect of overcore diameter in Hast's method. Displacement of inner boundary of a cylinder under pressure P along equal and opposite arcs.

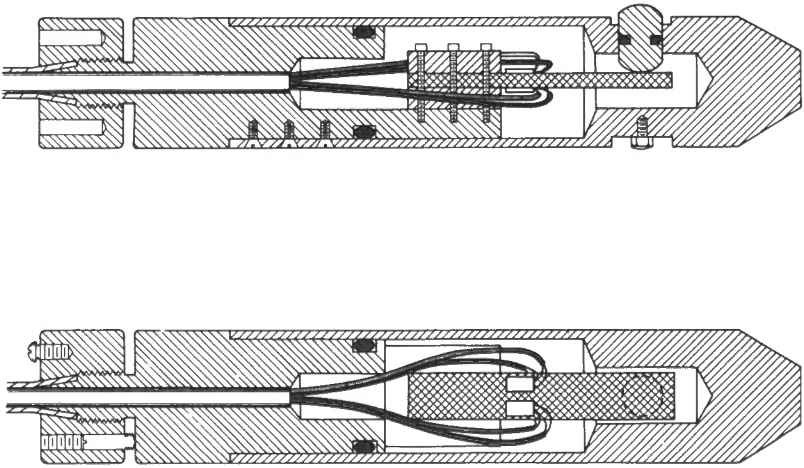


Figure 6. The U.S. Bureau of Mines deformation meter (after Obert et al.).

The next problem is to find an area for suitable measurements. To date we have not had much choice in this. One has to go where one is welcome when funds are limited. Figure 7 shows the geology around an iron mine at Wawa, Ontario where we were fortunate to be able to make some measurements. Figure 8 shows the mine workings at a depth of 350 metres and the location of the two bore-holes in which measurements were made. The measurement of the change in dimensions of the bore-hole as the stress is relieved, together with a value of Young's modulus, permit one to determine the principal stresses perpendicular to the bore-hole.

The holes here are parallel. One of the authors (Nyland) worked out a method of determining stress parallel to the hole by the way stress was relieved as the overcoring proceeded. The results are shown in Figure 9. Young's modulus was determined statically in the laboratory, and velocity of sound measurements were also made at various intervals from one hole to the other, during the experiment. It will be noted that the value of Young's modulus is not constant over the length of the hole and that the value of the stresses measured vary with Young's modulus. From the results the value of the stresses here are:

Minimum	2×10^7 newtons/metre^2 $\pm$ 50%
Intermediate	4×10^7 newtons/metre^2 $\pm$ 50%
Maximum	6×10^7 newtons/metre^2 $\pm$ 50%

The vertical stress, which is the minimum, is about twice what one would expect from gravitational loading. The horizontal components are ten to fifteen times what one might expect from gravitational loading. A great many more measurements are required to assess the significance of these results; however, we believe them to be such as to warrant a great deal more work in this field of research.

The results were obtained in a bore-hole a few tens of metres in length. If the method is to be extended to depth, considerable modification is warranted. Figure 10 shows the existing equipment. Certainly, one will have to modify the drilling technique and re-design the electrical leads to the recorder if measurements are to be made in deeper bore-holes.

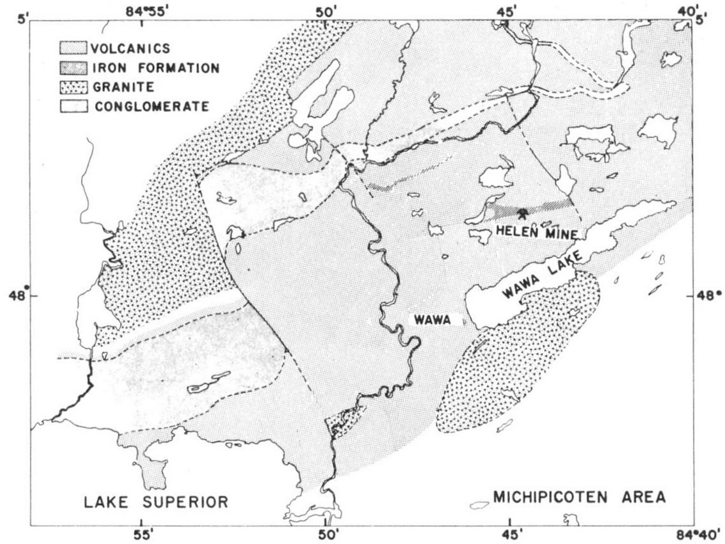


Figure 7. Geology of Michipicoten area.

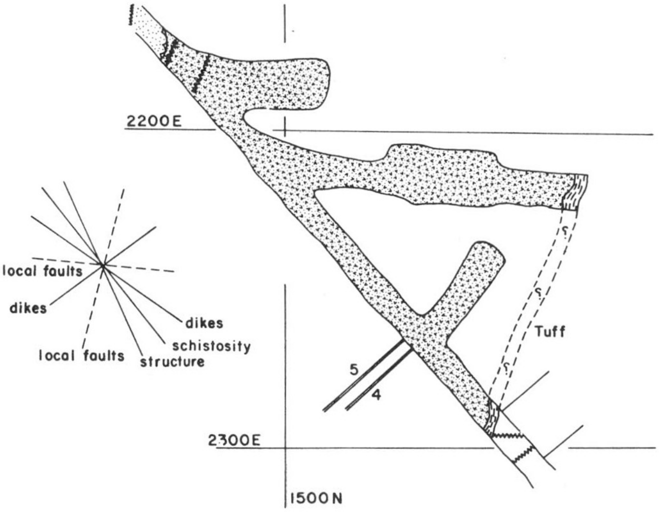


Figure 8. Site for bore-hole deformation measurements, Wawa.

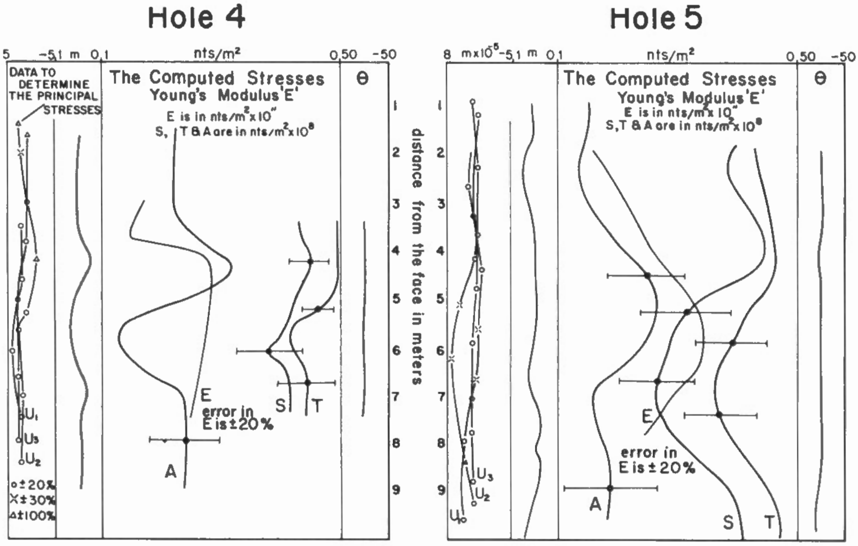


Figure 9. Bore-hole deformation, Helen Mine, Wawa.

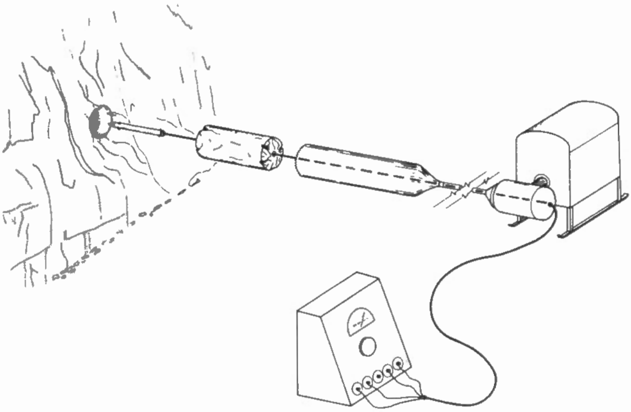


Figure 10. Existing equipment for measuring bore-hole deformation.

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DEEP HOLE SCIENTIFIC INSTRUMENTS AND MEASUREMENTS FOR PROJECT MOHOLE

William P. Schneider
Brown and Root Inc.

Abstract

A comprehensive instrumentation program has been developed to assist in obtaining the scientific objectives of the Mohole Project. This program includes the development, modification and general upgrading of instruments, not only to measure in situ properties of the earth, but to assist in the drilling and operation of the drilling platform. Topics discussed in this paper include the in situ measurement program designed for the Project, pressure and temperature conditions expected in the bore-hole, instrument handling equipment, bore-hole re-entry system and instrumentation of the turbo drill. The newly-developed sidewall coring tool is described and measurement of other parameters such as rock stress and subsurface ocean currents are discussed.

INTRODUCTION

The major scientific objective of the Mohole Project is to obtain a core record through the layers of the earth's crust and the upper part of the underlying mantle. In addition, important information will be acquired from various measurements made in the hole during and after the completion of the drilling, and it is intended that this information will be of the highest quality and in amounts that will allow reliable and realistic interpretation. A comprehensive instrumentation program has been developed to assist in attaining the scientific objectives of the Project. This program includes the development, modification, and general upgrading of instruments intended not only for measuring in situ properties of the earth but also to assist in the drilling and platform operations. For operational purposes, the parameters that must be monitored cover a wide spectrum. This includes such information as the position of the drilling platform with respect to the sea floor, deep ocean currents, the stresses in the drill pipe due to its frequent bending, the condition of the drill bit and the hole while drilling, and the depth from the sea floor at which the various measurements are made. This list is not complete, but is given merely to point out the problems, parameters, and associated environments that must be considered. To discuss the complete instrumentation program is beyond the scope of this paper.

IN SITU MEASUREMENT PROGRAM

In the following section some of the contemplated in situ measurements, and some of the results that have been obtained with the equipment that we have investigated are discussed. Table 1 lists the principal measurements that will be performed. Some of these are for scientific measurements whereas others will be used to aid in drilling and in determining the condition of the hole. The first measurement will be the bore-hole diameter and cross-section using the caliper and various caliper tools. The next instrument will be used to obtain a standard resistivity measurement. For this Project, we will be measuring resistivities greater than 10^4. I may mention here that in the oil industry the maximum values measured are in the order of 1,000 ohmmeter. We are interested in resistivities from 10,000 to 1 megohmmeter. The dipmeter will be used for measuring any formation dip if measurable dips exist. Formation fluid pressure will be measured if applicable. Temperature surveys will be run at regular periods, and accurate measurements of the thermal gradient will be made.

Table 1

In Situ Measurement Program and Down-hole Instruments

(1) Caliper
(2) Resistivity ($\rho > 10^4$ Ohm-meters)
(3) Dipmeter
(4) Formation Fluid Pressure
(5) Temperature
(6) Seismic Record (Geophones)
(7) Gamma Ray-Neutron
(8) Gamma-Gamma (Density)
(9) Sonic-Acoustic Velocity
(10) Side-Wall Coring
(11) Core Orientation
(12) Magnetic Field Intensity
(13) Magnetic Susceptibility
(14) Thermal Conductivity
(15) Rock Stress

In an effort to increase the reliability and accuracy of the seismic survey data, velocity profiles will be measured from geophones lowered in the hole. The gamma ray-neutron is an instrument from which correlation data can be obtained and will provide information that will become increasingly valuable as later holes are drilled. The gamma-gamma log uses radioactivity effects to measure in situ rock density. Sonic acoustic velocity is a method for determining the in situ compressional velocity of the material; it may also be used to obtain the total travel time for use with the seismic records. The sidewall coring tool, which is discussed in more detail later, is a wireline device for supplementing the normal coring operations carried out during the drilling. While we are interested in obtaining sidewall cores per se, we are also interested in knowing the geometrical orientation of these cores. We anticipate measuring the magnetic field intensity as a function of depth, and the magnetic susceptibility of the formations that are penetrated. The thermal conductivity of the section is intimately associated with temperature measurements, and this information is needed to extrapolate the anticipated bottom-hole temperature. Lastly, we have a program for developing equipment to measure in situ rock stress as was discussed earlier by Prof. Blanchard (Buchbinder, Nyland and Blanchard, this volume).

ENVIRONMENTAL CONDITIONS

The measurement program discussed above is rather ambitious, even under ideal situations; now I would like to discuss some of the environmental conditions under which these measurements are to be made. These are probably somewhat more pessimistic than we are led to believe by the logging industry. As Mr. Bosworth pointed out (Bosworth, this volume), they have many tools and we have made good use of them. These instruments are our point of departure in designing most of these programs; however, our programs are not quite as simple as those used in oil well logging. On the other hand, we hope that our environmental conditions are not quite as severe as those Prof. Beck has predicted (Beck, this volume). I will discuss some of our temperature extrapolations later but here it is sufficient to say that from present information it is felt that 800°C is a much higher temperature than anticipated. In any case, the environmental conditions are as follows: a minimum 6 5/8-inch diameter hole down to the mantle (the upper part of the hole will be larger than this, but it is planned to have an open hole never smaller than 6 5/8 inches); a total depth of about 35,000 feet; a fluid weight in the hole that will range from about 8 to 12 pounds per gallon; fluid column pressures that may reach as high as 25,000 p.s.i. at the bottom; and, temperatures at the bottom of about 200°C. All instruments must operate through a 7-conductor Teflon-covered armored cable 40,000 feet in length.

To determine the maximum anticipated bore-hole temperature, an extrapolation was obtained by simplifying the heat equation. The equation ((1) below) is a familiar one and is non-linear. We do not know what the heat sources will be, or the volume distribution that is of interest to us.

Furthermore, since the thermal conductivity is a function of both depth and temperature, the differential equation that must be solved is a non-linear one. In order to make the equation useful for engineering purposes, it has been simplified to the linear differential equation (2) by neglecting the heat sources and assuming that the thermal conductivity is a constant.

(1) $$q - S_X X = - k(X, T) \frac{dT}{dx}$$

T = temperature in C°
q = heat flow in cal/cm^2-sec
S_X = heat source distribution in cal/cm^3-sec
k(X, T) = thermal conductivity in cal/deg.-cm-sec
X = distance from the surface toward the centre of the earth

(2) $$q = - K \frac{dT}{dx}$$

To make the values obtained meaningful, a realistic average heat-flow value was used with a typical value of thermal conductivity for igneous rocks at 200°C. Solving this simplified equation the curves shown in Figure 1 were obtained. These curves indicate that 200°C is a reasonable value to use for the purposes of the instrumentation program.

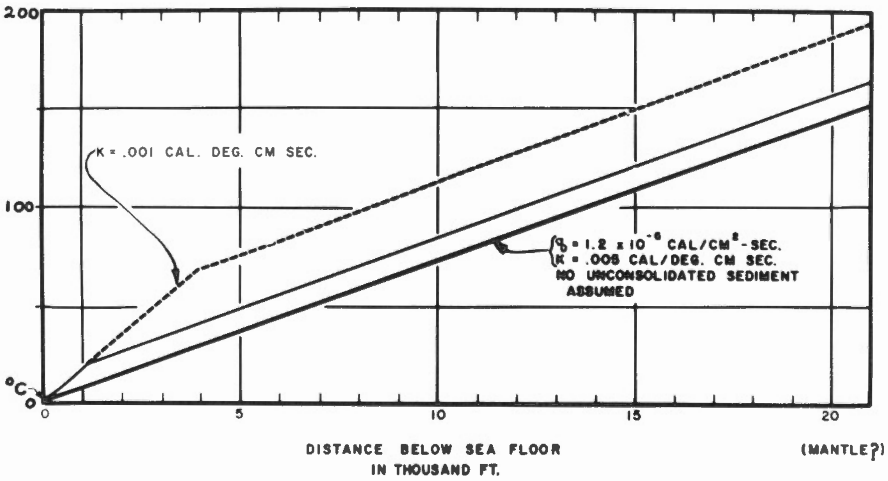

Figure 1. Curves for calculated temperatures vs. depth below sea floor.

This temperature is at about the top limit of the equipment presently in use in the logging industry. This is the basic reason for using this figure besides the fact that it is a fairly good extrapolated value. The first measurements in the hole will be heat flow. If the heat flow is significantly larger than the average value of 1.2 microcalories/cm^2- sec, efforts will be made to try to find a less anomalous location. As drilling proceeds, measurements of the thermal conductivity of the material drilled will be made, and if a revised extrapolation indicates higher bottom-hole temperatures, the instruments and measurement program will be redesigned to be compatible with the expected higher temperatures.

INSTRUMENT HANDLING EQUIPMENT

Instrument handling is as important as the environmental conditions. The components shown in Figure 2 are similar to those used in oil well logging equipment. The main difference is the handling capacity. This equipment must handle about 40,000 feet of cable, whereas the longest cable in use in the logging industry is about 25,000 feet. Forty thousand feet is needed since we are contemplating depths to 35,000 feet, and a few thousand feet of extra cable has to be in reserve on the drum. An important difference between the Mohole equipment and normal logging equipment is the cable compensator. We do not have a fixed horizontal plane of reference because the drilling vessel is continually moving due to wave action and swells. As a result, to make measurements that are meaningful and capable of being accurately correlated with depth, this motion must not be transmitted to the logging instrument. A device that will compensate for ship movement is now being designed.

Other differences from standard logging practices are in the data-recording equipment. Besides the normal film record, the data will be recorded as digital information on tape. The tape system will permit analysis of the data and also allow various computations to be performed with this information at a later date.

The logging unit designed for the Project is of modular construction with the drum and cable being separate from the winch equipment. This allows a cable change during the program if it is found that a better cable has been developed or that some characteristics of the cable in use should be changed. The present cable has the following characteristics; length 40,000 feet, diameter 9/16 inch; breaking strength (new) about 22,000 pounds. It has seven Teflon covered conductors, which are comparable to No. 22 copper conductors. The Teflon insulation allows the cable to be used under temperature conditions well in excess of 200°C.

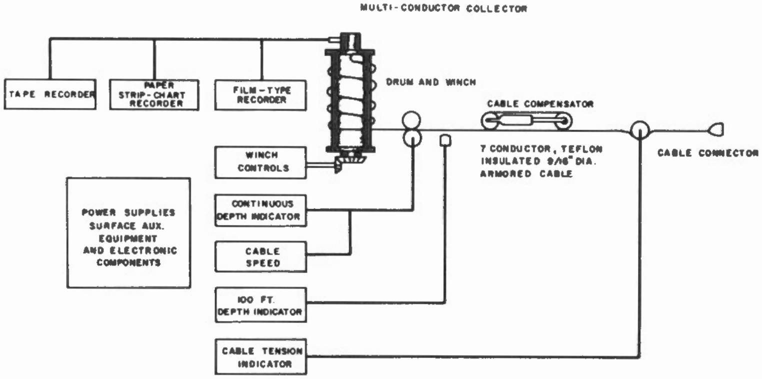

Figure 2. Schematic diagram illustrating the components of the logging instrument handling system.

HOLE RE-ENTRY SYSTEM

In addition to in situ measurements of the rock properties, other instrumentation will aid in re-entering the hole after the drilling program is started. Figure 3 shows the essential components that are used to perform the re-entry operation. The technique involves the use of a sonar scanner projecting out of the bottom of the drill string, a jet which is an integral part of the drill string, and a funnel-shaped landing base which will be about 25 feet in diameter. The high resolution sonar has a scanning range of about 250 feet. In operation, the sonar scanner package is lowered in the drill string by the logging line; and then the sonar is operated after the package is seated in its proper position. The sonar reflection information is relayed to the surface and displayed to the driller in a display similar to that used in radar systems. When the landing base is detected, the driller rotates the jet to the proper direction and moves the bottom of the drill string over the landing base by the controlled thrust produced by pumping fluid through the jet nozzle. Final guidance into the hole is accomplished by the mechanical centring action of the funnel.

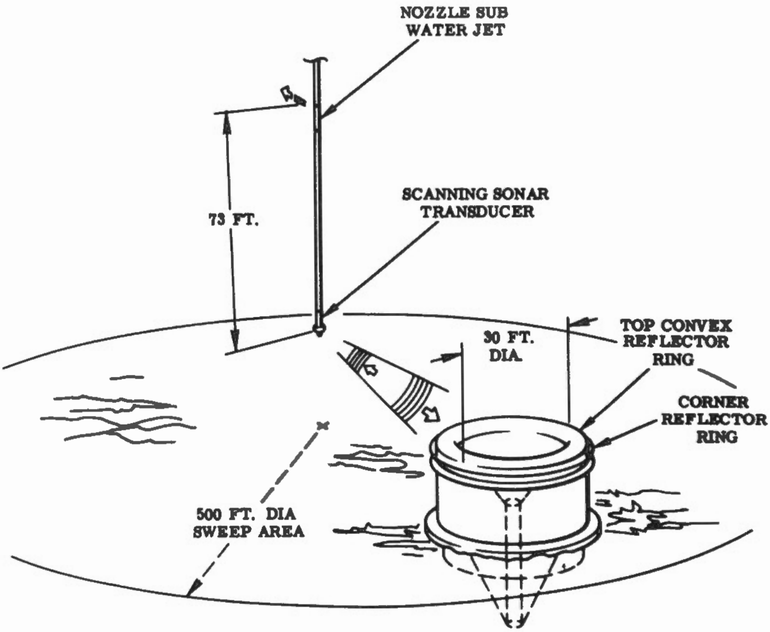

Figure 3. Components of the bore-hole re-entry system.

DRILLING INSTRUMENTATION

The primary objective of the drilling instrumentation system is to measure the dynamic parameters during drilling and turbocoring and transmit this information directly to the surface. The signal transmission problem has been investigated from the standpoint of electromagnetic radiation, acoustic energy, hydrodynamics, and transmission lines. Because a conductor cable is needed for logging and re-entry, this cable will be available and can also be used for transmitting the drilling information to the surface. In examining the other methods, we found that although they are very good in principle, they have a numer of serious problems that have to be overcome before they can be considered practical solutions. At this stage, the problems appeared greater than the gain that would be effected by their use. Consequently, the turbocorer contains an instrument package that is connected to the surface by the logging line.

Turbocorer Instrumentation

Figure 4 shows the instrument package that fits inside the turbocorer. It contains an electrical multiconductor swivel to allow for counter-rotation of the drill pipe. The upper portion is the electronic section, housed under atmospheric pressure and containing the power supply, the sensor amplifiers, the output amplifiers, the pulse generator, the inclinometer sensor, and other devices. The next section is the latching assembly which keeps the package in place in the turbocorer. Below this is the lower-sensing assembly which is maintained at well pressure and which contains sensors that are pressure compensated to operate under high ambient pressures. The instrument package also carries a core barrel. In operation, the instrument package with a fresh core barrel is lowered into the drill pipe and latched in place. When the turbocorer is started, with the logging cable in the pipe, the various parameters (r.p.m., inclination, bearing wear, downhole power, amount of core coming into the core barrel, etc.) are measured.

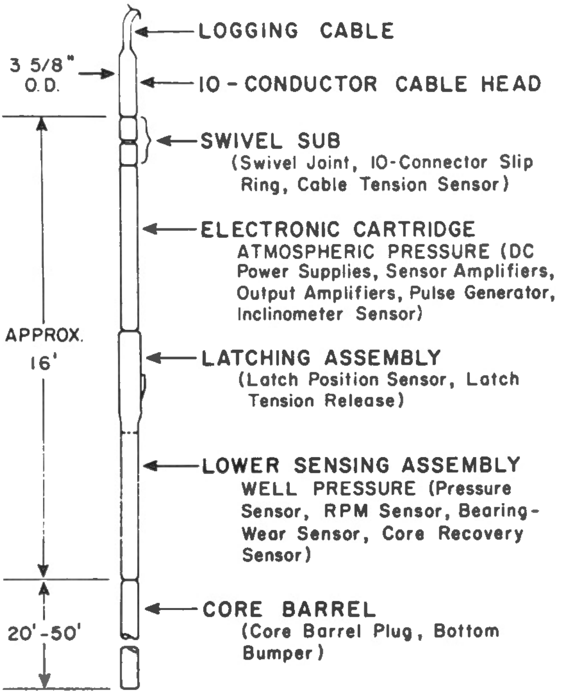

Figure 4. Turbocorer instrument package sub-assemblies. During operation of the turbocorer this package monitors r.p.m., inclination, bearing wear, downhole power and other data and transmits this information to surface via the logging cable.

The turbocorer and instrument package were tried in a test hole drilled at Uvalde, Texas. The operating parameters of the turbocorer were recorded and provided interesting information on the operation and handling characteristics of the system. As an example, Figure 5 shows an

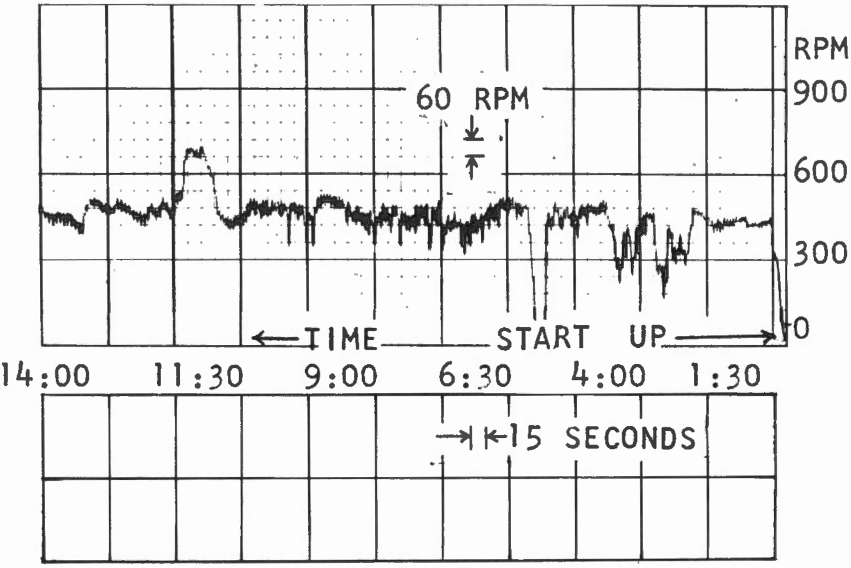

Figure 5. R.p.m. record of a turbocorer run at Uvalde, Texas.

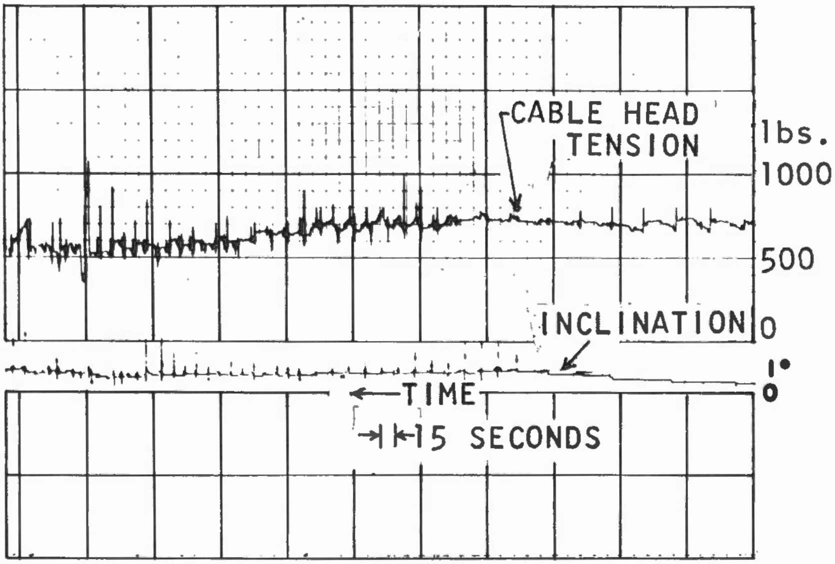

Figure 6. Cable-head tension record while running the turbocorer instrument package into the test well at Uvalde, Texas.

r.p.m. record of a run at Uvalde. The record shows the rapid start up of the turbocorer and the continuous r.p.m. variations. The rapid change in r.p.m. of the turbocorer is notable. Another example is given in Figure 6 which shows the cable-head tension record while lowering the instrument package inside the pipe. The sharp peaks on the tension record are the result of the instrument package hitting the drill collars; thus part of the problem associated with the instrument package, in addition to the high-pressure and high-temperature environment, is the handling or mishandling that it must withstand when it is being lowered into the hole. During tests of the instrument package in the Uvalde well, certain operational problems were encountered. This was the first time that a turbodrill had ever been instrumented, and as might be expected, on the first field test there were features of the system that worked very well; however, there were also some that worked not so well. At present, we are modifying the instrument package to eliminate the problems which were brought to light by the field test.

Sidewall Coring Tool

Also tested at Uvalde was a new sidewall coring tool. In a previous discussion (Bosworth, this volume), a bullet method of taking sidewall cores was discussed; however, it must be realized that there is a difference between what the oil industry calls "hard" rock and what we call "hard" rock. In oil industry usage, "hard" refers to rocks having densities of about 2 to 2.5 gm/cm^3, whereas we are concerned with rock densities of about 3 to 3.1 gm/cm^3. The so-called "hard" rock sidewall corers or bullet guns are not effective for coring rocks such as basalt, and core recovery by these devices in such rock types is extremely poor. As a result, a different system was required to obtain these cores.

The sidewall corer considered for our program contains a pair of diamond-cutting wheels that cut a triangular section of core. It is a wire-line device that is lowered on the end of the logging cable to the required depth. The diamond-cutting blades are rotated and forced into the rock in much the same way that a snow plow operates. The cutting wheels penetrate the formation about 1 $\frac{1}{2}$ inches and then travel up the hole for a distance of 5 feet, cutting a vertical core of this length. At the upper limit of travel, the rotating blades are retracted into the tool, releasing the triangular-shaped core from the sidewall.

Figure 7 shows the sidewall tool. Note the two retractable back-up shoes that "set" the tool in the hole. Figure 8 shows a close-up view of the cutting wheels, photographed just prior to the test runs at Uvalde. After the core is cut, the back-up shoes are retracted, and the instrument with its 5-foot piece of core is brought to the surface by the logging line.

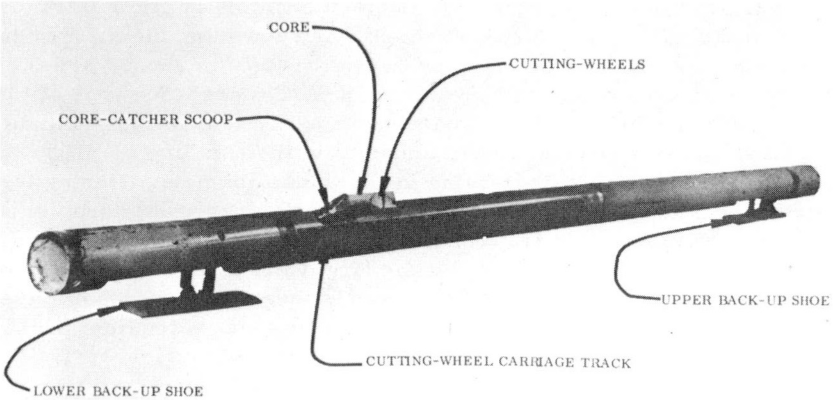

Figure 7. The sidewall coring tool showing the upper and lower back-up shoes which lock the tool in the correct position in the hole, prior to the coring operation.

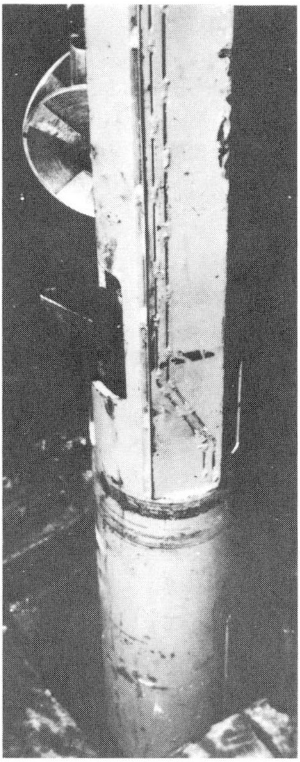

Figure 8. A view of the two inclined cutting wheels of the sidewall corer. The photograph was taken during testing of the instrument at the Uvalde, Texas site.

OTHER MEASUREMENTS

Rock Stress

The present technique being considered for measuring rock stress is based on the overcoring method that was mentioned in Prof. Blanchard's discussion (Buchbinder, Nyland and Blanchard, this volume). At the depth at which the rock stress is to be measured, a small pilot hole is drilled from the bottom of the main hole. An instrument package is lowered into this small hole and continuously measures the change in the hole diameter as the pilot hole is overcored. The diameter change is measured at six points around the circumference of the hole, and the information is read out at the surface during the overcoring process. Investigations of this technique, as well as other methods, are still underway.

Subsurface Ocean Currents

Another interesting measurement problem concerns the determination of the subsurface currents in water over the site. The riser casing is a self-buoyed system, connected at the sea floor and to the vessel at the surface. As such, it will be affected by the behaviour of the subsurface currents. An instrumented buoy string has been designed and is presently being built. This system (Fig. 9) will measure the subsurface currents from the sea floor to the surface at 17 strategically located points. This buoy system will be installed at the general site area with the hope that it will remain in place for a year to provide records of currents. The subsurface and surface information will be continuously telemetered back to Hawaii so that, if the system does not survive the full year, all of the information gathered up to the time the system is destroyed will be obtained.

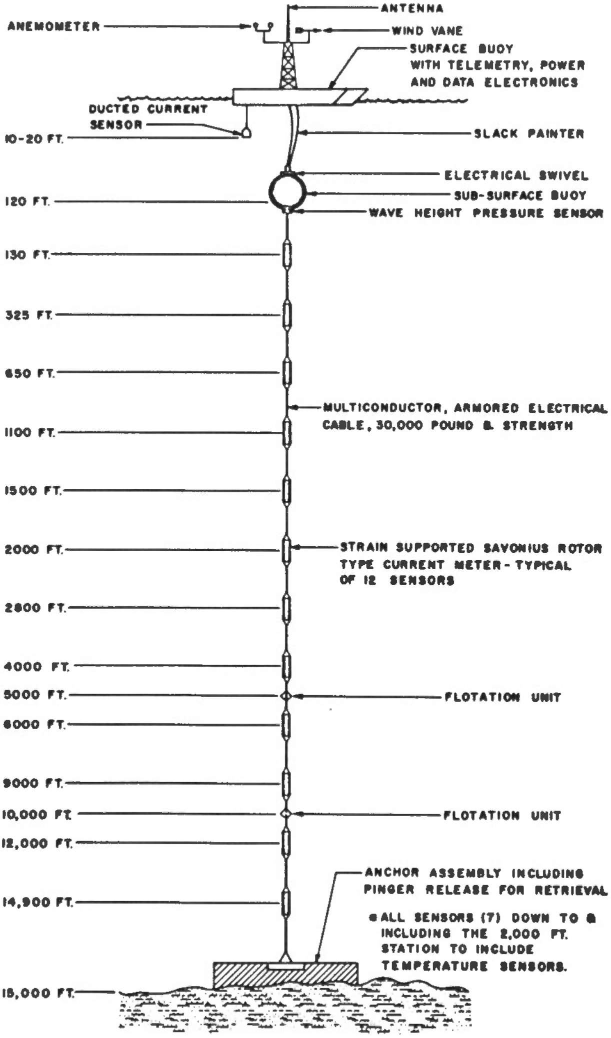

Figure 9. The sensor profile for the deep ocean untended data acquisition system.

DISCUSSION

Prof. A.E. Beck (Can.)
Will the hole be cased to bottom?

Mr. Schneider
No, it will be an open hole.

Dr. A.H. Lachenbruch (U.S.A.) asked if stress measurements could be made while coring with the sidewall corer, both before and after cutting out the core.

Mr. Schneider remarked that the method had not been tried, but that one problem would be the positioning of the strain gauges on the bore-hole wall precisely at the position where the core would be cut.

Prof. J.E. Blanchard (Can.) commented that measurement of stress on triangular cores or samples with sharp angles at the corners, such as would be recovered by the sidewall corer, would be more difficult than measurements made on round core. He also commented that overcoring from 1 inch to 6 5/8 inches means that very accurate measurements of changes in dimension are necessary.

Mr. Schneider agreed with Prof. Blanchard, but felt that they could accomplish this.

Prof. Beck (Can.) asked what type of temperature probes would be used.

Mr. Schneider replied that they would basically be thermistors, bridge-type.

Prof. Beck (Can.) asked what sort of back-up temperature probe system would be used.

Mr. Schneider replied that they hoped to be able to simplify their temperature measuring systems and were presently investigating several different possibilities. He added that he hoped they would not have to use a back-up system.

Dr. Lachenbruch (U.S.A.) suggested that both absolute temperature and changes in temperature in the bore-hole be recorded, because this information was necessary for accurate heat flow data.

Mr. Schneider agreed with Dr. Lachenbruch and said that they intended to make both types of measurements.

NOTES ON GEOPHYSICAL LOGS AND BORE-HOLE TEMPERATURE MEASUREMENTS FROM THE MUSKOX DRILLING PROJECT

G.D. Hobson,* A.E. Beck,** and D.C. Findlay*

Abstract

A limited logging program carried out in conjunction with the Muskox drilling project included S.P., resistivity, gamma-ray, and neutron measurements and a geophone velocity survey. Preliminary correlations indicate that the most useful log in igneous rocks such as the Muskox sequence is the neutron log. Such features as pyroxenite-dunite contacts and changes in the degree of serpentinization in dunite are clearly indicated on this log.

Two temperature profiles have been measured from the Muskox drill-holes; one in the Muskox North hole about two weeks after completion of drilling; the other, in the Muskox South hole about two years after drilling. The profiles are similar, except for the upper part of the north hole profile within the permafrost section (0-700 feet) which shows disequilibrium effects due to drilling. Maximum temperatures recorded were 17.3°C and 17.9°C in the North and South holes respectively, both at depths of about 3,400 feet. Minimum temperature was -6.9°C at 68 feet in the South hole. Based on conductivity measurements on a limited number of samples, a preliminary heat flow value of 1.3 μ cals/cm^2/sec is obtained for the bottom part of the South hole.

INTRODUCTION

The Muskox drilling project is described in this volume and to supplement that account, it may be useful to present a few notes concerning a limited geophysical logging program carried out as a part of the project. The logging program was undertaken on a test basis since very little information is available about in-hole logging of igneous rock in small diameter drill-holes. It is desirable to determine to what extent these methods can provide data that could be correlated directly with rock properties and structures determined from the drill cores. Any such correlations, if they exist, would be extremely useful for interpreting the geology in future deep drill-holes

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*Geological Survey of Canada

**Department of Geophysics, University of Western Ontario

where continuous coring might be impractical for economic or other reasons. In addition to the geophysical logs, temperature measurements were made in one of the three holes about two weeks after drilling was completed in 1963. In 1965, about two years after completion of the drilling, temperature measurements were made in a second hole which had been kept open during this period by displacing the drilling fluid with fuel oil to a depth well below permafrost level (about 500 feet). Thermal conductivity measurements on cores from the holes have not been completed and thus reliable values for heat flow cannot be presented at this stage; however, over the bottom 1,500 feet of the South hole the temperature profiles and rock conductivities for 7 samples give a heat flow value of 1.3 μ cals/cm^2/sec — a fairly typical Precambrian Shield value. Conductivity values for 3 rock samples from the upper 1,000 feet, combined with gradients that are higher than normally found in the shield, suggest a heat flow value that is significantly higher than in the lower section.

LOGGING PROGRAM

One of the main problems in planning a logging program for the Muskox holes was that most existing equipment is designed for use in large diameter bore-holes. Thus, the program was limited to logs obtainable with probes available for use in the 2 3/4 inch diameter B-size holes. The following logs were run in the Muskox South and East holes: S.P., resistivity (16" and 64" normal), gamma-ray, neutron, and geophone velocity survey. A blockage, near the top of the north hole due to icing in during withdrawal of a temperature probe, prevented further logging in that hole. All tools were 1½ inch diameter except the neutron tool which was 1 3/4 inch. The logging was carried out by Birdwell Division of Seismograph Service Corporation, Tulsa, Oklahoma under contract with the Geological Survey of Canada.

RESULTS

Detailed interpretations and correlations between geophysics and geology in the Muskox holes are not complete, but on the basis of preliminary studies, a few general observations about the effectiveness of the various logs may be made. One important factor concerning the Muskox logs is that they apparently cannot be interpreted according to the established practices of well-log interpretation in sedimentary sections. Although the relationships between various logs have been defined for sedimentary rocks, apparently little has been done toward establishing similar relationships for igneous and metamorphic rocks.

S.P. Log

According to the concept of S.P. behaviour in general acceptance until quite recently, the Muskox holes should show no appreciable S.P. development. In general, this is true in both holes; however, in the Muskox East hole, there is greater variation in activity on the S.P. log particularly in the peridotite and serpentinized dunite formations in the lower part of the hole.

Resistivity Logs

Both 16" and 64" normal resistivity logs were run. Unfortunately, there were equipment problems with this log and the recorders were not capable of handling the extreme variations in resistivity encountered in the holes. Equipment for resistivity measurements in such formations must be capable of recording resistivities of 100 K ohm m^2/m. Based on the part of the record on scale, the serpentinized peridotite and dunite appear to have higher resistivity values than the harder, denser pyroxenite layers; however, the distinction is not very well defined. It may be mentioned here that auroral activity was not at a high level at the time these logs were being run, since it has been suggested that such activity may contribute to extreme and erratic resistivity values in a hole.

Figure 1 illustrates part of the S.P. and resistivity (64 inch normal) record from 1,200 to 1,600 feet in the Muskox East hole. The S.P. log shows considerable activity in this section and the lower values appear to correlate approximately with the feldspathic peridotite layers. The resistivity log suggests a poorly defined inverse correlation, with higher resistivity values occurring in the peridotite zones.

Gamma Ray Log

This log is a measure of the natural gamma ray emanation from the formation. In the case of Muskox, it correlates poorly with geology in both holes. There are several minor "hot spots" indicated on both logs but as yet it has not been possible to match them with any unusual features in the drill core, including natural radioactivity checks on the core at these anomalous intervals. The log shows increased activity in the marginal zone below 3,100 feet in the South hole, where the rock type changes from fresh dunite through peridotite, and picrite to bronzite gabbro. Figure 2 shows a typical "hot spot" in the interval 1,800 to 2,100 feet in the South hole.

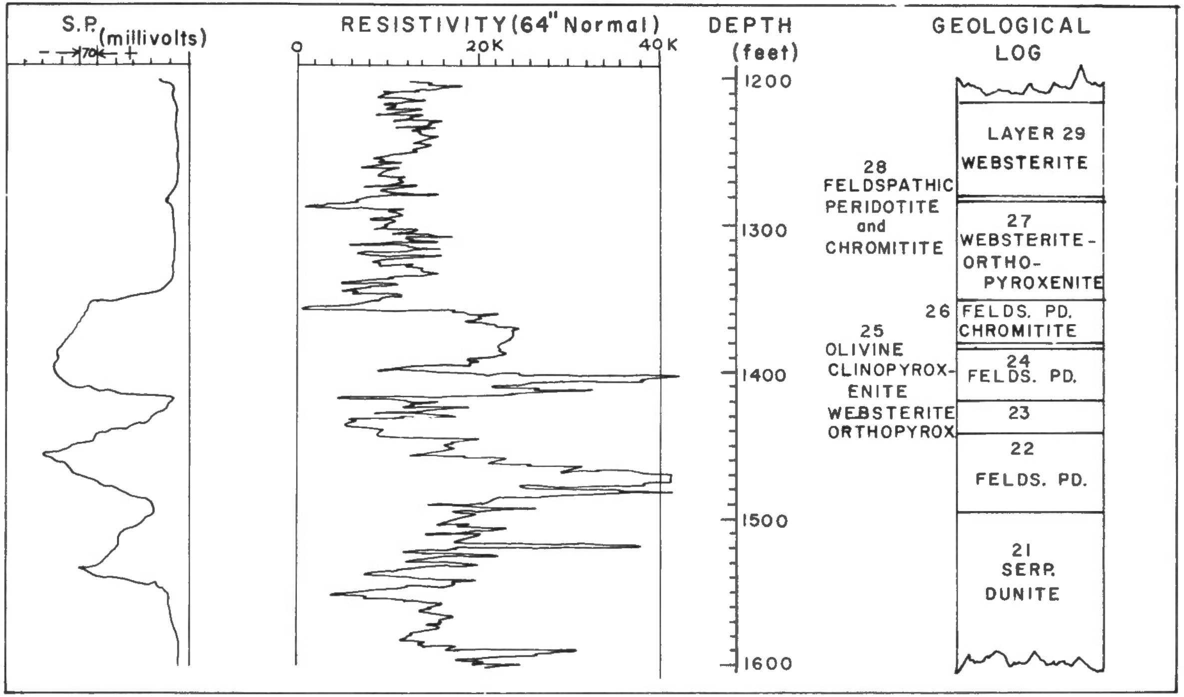

Figure 1. A part of the S.P. and resistivity log record from 1,200 to 1,600 feet, Muskox East hole.

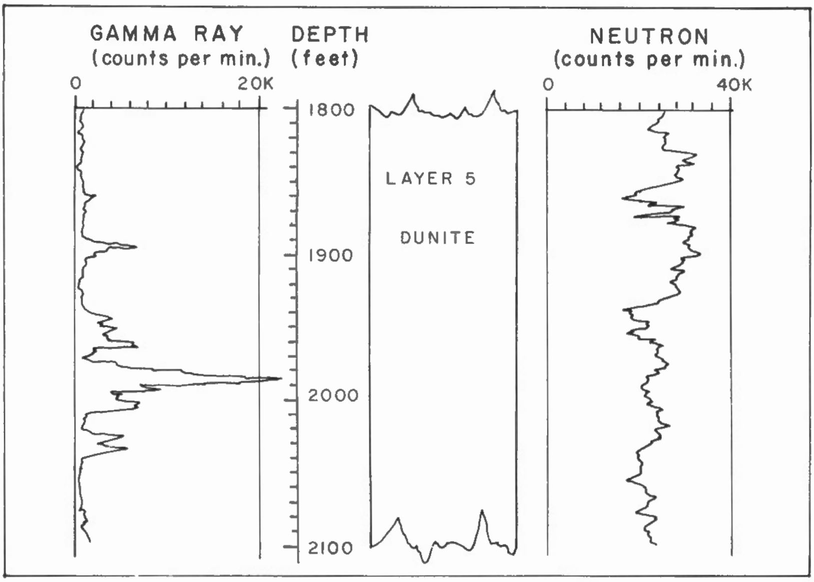

Figure 2. Gamma ray and neutron logs from 1,800 to 2,100 feet, Muskox South hole. Note the anomalous gamma ray activity just above 2,000 feet.

Neutron Log

The neutron source used was radium-beryllium with a measured neutron output of 4.36×10^6 u/sec. As far as our results are concerned, this log was the most profitable and shows the most promise for future applications.

One of the features of the Muskox intrusion is that the degree of serpentinization in dunite and peridotite decreases with depth. There is a marked transition between rocks containing over 75 per cent serpentine and those containing less than 25 per cent serpentine occurring between depths of about 1,500 and 1,700 feet in the South hole. This change is reflected in the neutron log by a gradual but obvious increase in activity through the transition zone. This is an indirect measure of the water content of the rocks; the serpentinite or serpentinized dunite may contain up to 12 per cent water thus providing an abundant supply of H-ions for capture of neutron emission and resulting in low return counts at the receiver.

The neutron log also shows formation boundaries more accurately than any other log, particularly where abrupt changes in composition and physical properties occur. Pyroxenite-dunite and pyroxenite-peridotite contacts are fairly distinct on the logs. Figure 3 shows selected portions of the neutron log in the South hole and illustrates the increase in activity through the transition zone into fresh dunite and the well defined correlation with the olivine clinopyroxenite layers.

In addition, the neutron log provides an accurate check on the position of the casing in the hole and thus is useful for locating broken and displaced sections of casing.

There is some hope that detailed correlation between neutron activity and minor structures such as fractures, alteration seams, etc., may also be possible.

Geophone Velocity Survey

From Figures 4A and 4B, it may be noted that average velocities in the South hole to a total depth of 3,433 feet are less than the average velocities in the East hole to a depth of 2,400 feet. This reflects the smaller amount of highly serpentinized dunite in the latter hole. Average velocity in the South hole increases gradually from 11,300 ft/sec. or 3.4 km/sec. to about 16,900 ft/sec. or 5.1 km/sec. reflecting the decrease in serpentinization of the dunite member which forms the main part of the section in this hole. Interval velocities as high as 22,700 ft/sec. or 7.0 km/sec. were recorded in the fresh dunite in the lower portions of this hole.

In the East hole, average velocity increases from 16,700 ft/sec. or 5.1 km/sec. to 19,500 ft/sec. or 6.0 km/sec. Interval velocities as high as 24,400 ft/sec. or 7.4 km/sec. were observed in the gabbros in the upper parts of this hole.

Interval velocities correlate in a general way with the physical properties of the layered rocks, but resolution is not detailed enough to locate contacts. A sonic or continuous velocity log should be the type of velocity log run in such holes.

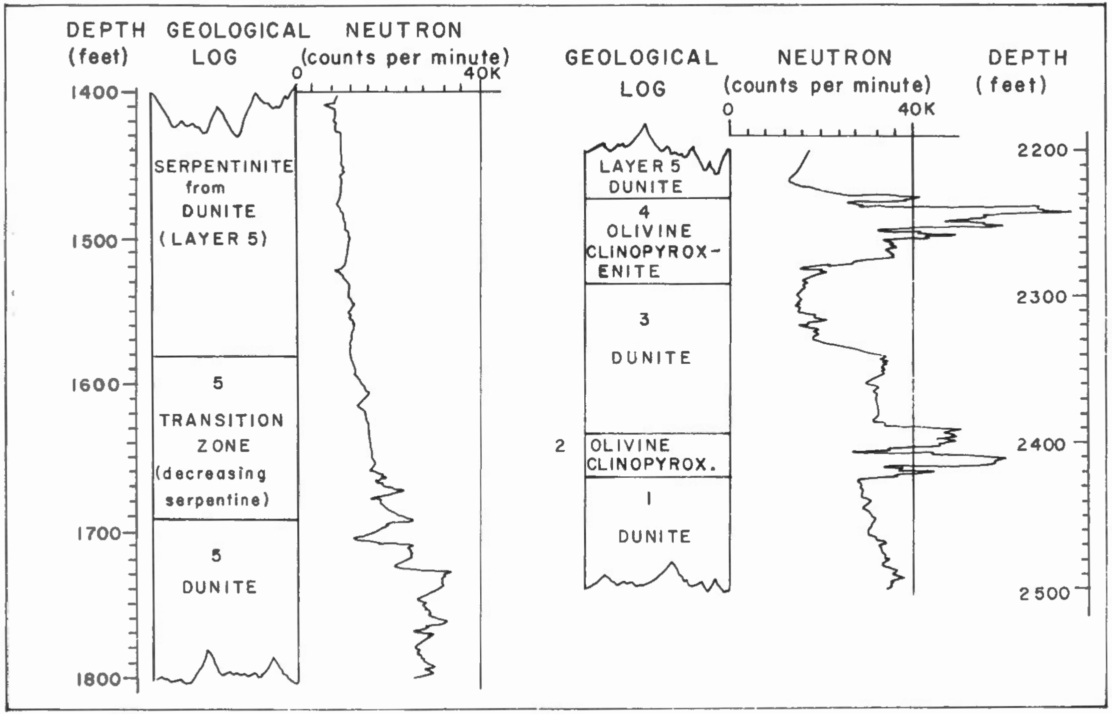

Figure 3. Parts of the neutron log from the Muskox South hole illustrating the correlation between neutron activity and the amount of serpentine in dunite, and the positive definition of olivine clinopyroxenite layers.

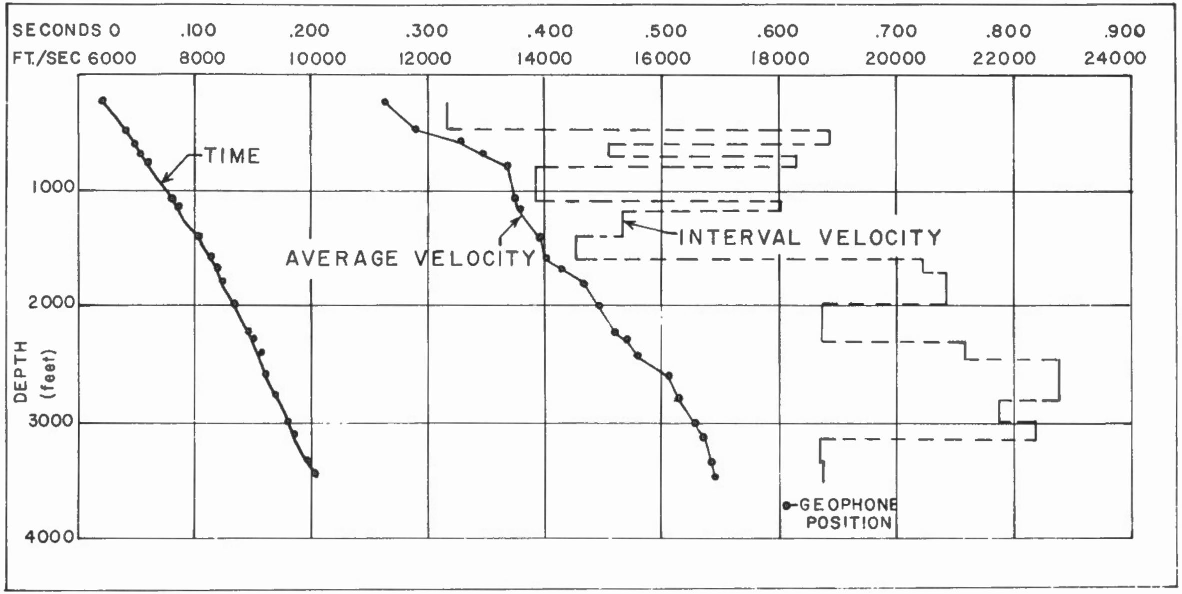

Figure 4(A). Velocity curves for the Muskox South hole.

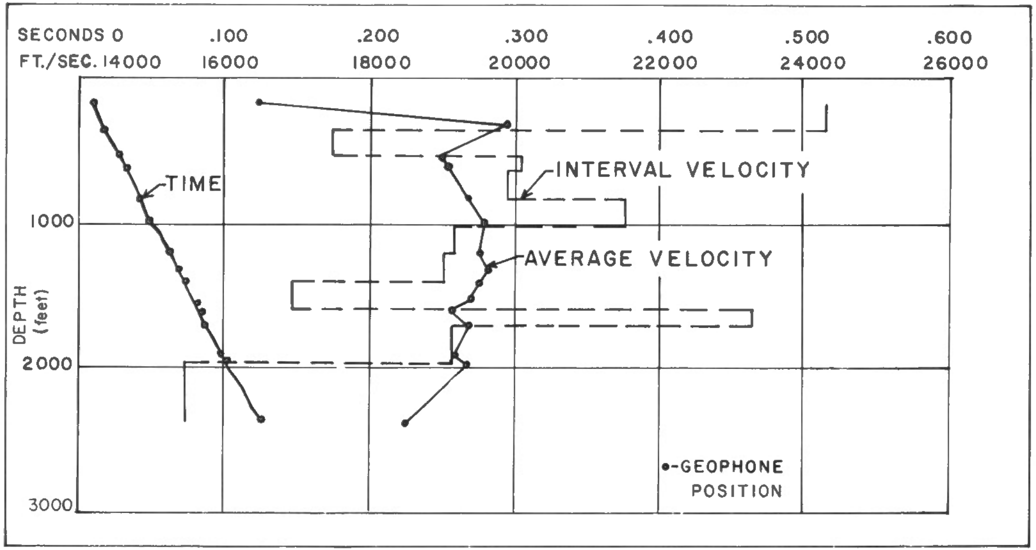

Figure 4(B). Velocity curves for the Muskox East hole.

TEMPERATURE MEASUREMENTS

Two weeks after completion of drilling in August, 1963, A. Judge* measured temperatures at 100 foot intervals from 100 to 3,400 feet in the Muskox North drill-hole. Measurements were made using a thermistor probe and bore-hole equipment described by Beck (1963) and shown in Figure 5. After logging from top to bottom the probe unfortunately became jammed at a depth of 550 feet on the return trip and could not be recovered. A spare probe was not available at the site in time to log the other two holes after completion of drilling and plans for further work that year had to be abandoned. However, the Muskox East and South holes were filled with fuel oil to depths well below permafrost level in the hope that they would remain unfrozen for future work. This proved successful in the case of the South hole at least, and a temperature profile was obtained from this hole in August, 1965, 23 months after completion of drilling. The equipment was an improved and lighter weight version of that used in the 1963 measurements.

Figure 5. Portable temperature measuring equipment used for logging the Muskox North drill-hole.

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*Graduate student, University of Western Ontario.

TABLE 1

Summary of Temperature Data from Muskox South and North Holes

	Muskox South			Muskox North			
Depth (Ft)	Resistance (Ohms)	Temp. (°C)	Gradient (°C/km)	Depth (Ft)	Resistance (Ohms)	Temp. (°C)	Gradient (°C/km)
68.0	18130.0	-6.860	0.00	100	29660	2.15	
168.0	16181.0	-4.459	78.78	202	31469	1.19	-34.2
268.0	15231.0	-3.154	42.82	300.5	32340	0.65	-17.7
368.0	14318.0	-1.816	43.89	400	33350	0.1	-18.1
468.0	13485.0	-0.524	42.38	500	33395	0.08	-0.65
568.0	12843.0	0.518	34.18	600	33405	0.03	- 1.6
668.0	12285.0	1.495	32.06	700	33465	0.00	- 1.0
768.0	11882.0	2.227	24.04	801	33401	0.07	2.3
868.0	11414.0	3.124	29.41	901	32949	0.32	8.2
968.0	11009.0	3.939	26.74	1000	32302	0.68	11.8
1068.0	10620.0	4.756	26.82	1101	31453	1.15	15.4
1168.0	10283.0	5.492	24.13	1200	No result		
1268.0	9934.0	6.280	25.87	1300	29755	2.08	15.4
1368.0	9573.0	7.125	27.70	1402	29032	2.58	16.4
1468.0	9290.0	7.809	22.44	1499.5	28105	3.20	20.4
1568.0	9033.0	8.435	20.54	1601.5	27191	3.86	21.6
1668.0	8760.0	9.131	22.84	1700	26640	4.28	13.8
1768.0	8526.0	9.753	20.41	1799	26442	4.42	14.6
1868.0	8321.00	10.817	18.51	1899	24949	5.58	38.1
1968.0	8137.0	10.839	17.12	1999	24002	6.32	24.3
2068.0	7938.0	11.420	19.05	2099.5	23123	7.08	25.0
2168.0	7738.0	12.021	19.71	2200	22224	7.94	28.2
2268.0	7552.0	12.595	18.84	2300	21359	8.74	26.3
2368.0	7381.0	13.136	17.75	2400	20589	9.47	24.0
2468.0	7240.0	13.591	14.94	2500	20001	10.05	19.0
2568.0	7102.0	14.045	14.90	2600	19320	10.78	24.0
2668.0	6968.0	14.494	14.72	2700	18605	11.58	26.3
2768.0	6843.5	14.918	13.90	2800	17879	12.42	27.6
2868.0	6714.0	15.373	14.93	2900	17224	13.18	25.0
2968.0	6587.0	15.828	14.95	3000	16626	13.93	24.6
3068.0	6460.0	16.296	15.34	3100	16228	14.43	16.4
3168.0	6325.5	16.804	16.68	3200	15738	15.05	20.4
3268.0	6198.0	17.299	16.22	3300	14703	16.58	17.4
3368.0	6074.0	17.791	16.16	3400	14190	17.35	25.3
3420.0	6040.0	17.928	0.00				

Temperature data, including interval gradients are listed in Table 1 and Figure 6 shows the profiles for the two holes. In general they are similar, with the exception of the upper 700 feet or so – the permafrost region. The reverse gradient of the Muskox North hole profile above the 0°C level (-700 feet) reflects disequilibrium conditions due to the effects of drilling. The Muskox South hole has had two years to recover from the disturbances due to drilling so that the temperatures in the lower half of the hole are probably close to the undisturbed temperatures, whereas those in the upper section of the hole may not be. However, this point will be resolved in one or two years' time when another complete temperature log of the hole is made.

Because of heat exchange between the drilling fluid and the rocks in the North hole the depth of permafrost may be as much as 100 feet in error if the 0°C inflection point in the profile at 700 feet is taken as an indicator; the depth of permafrost is about 500 feet for the South hole. The shallower permafrost depth in the South hole is probably due to the presence of a large lake (Speers Lake) adjacent to the site. The proximity of large bodies of water is known to inhibit permafrost development and, in fact, during drilling of the South hole a gap in the permafrost section was encountered that corresponded approximately with the water depth in Speers Lake (Findlay and Smith, 1965).

The Muskox drill-hole temperature gradients appear to be high in comparison with the available data for Shield areas. Lee and Uyeda (1965) give values from 6 to 19°C/km; for Canada the range is 9 to 16°C/km (Hodgson et al., 1964). However, as noted earlier, the preliminary heat flow value from the Muskox South hole is a typical Shield value and until a more detailed analysis of rock conductivities has been carried out (as well as a repeat of the temperature log) further comment on the results is not warranted.

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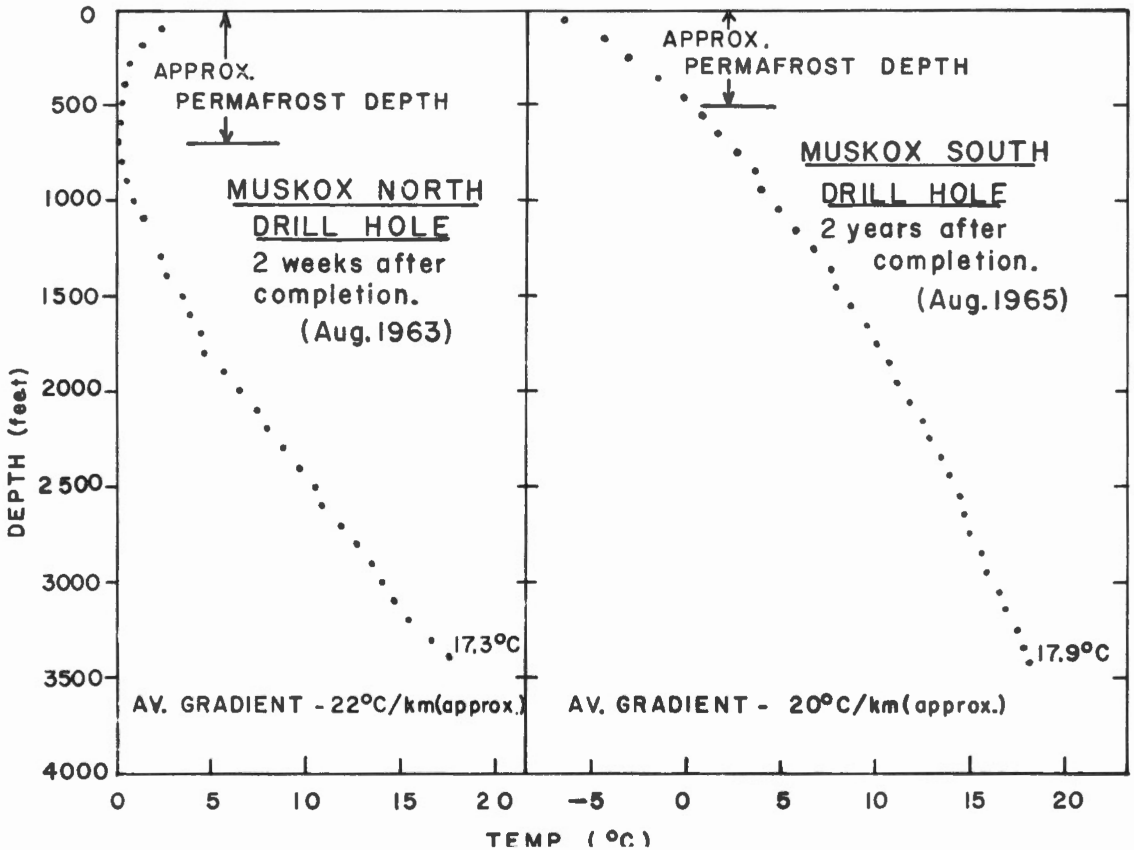

Figure 6. Temperature profiles for Muskox North and South drill-holes.

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DISCUSSION

Dr. T.F. Gaskell (Chairman)

I don't think I would worry too much about interpreting these logs in crystalline rocks. It has taken the oil companies more than 30 years to make sense from what some cynics call an empirical art. The correlation part of well-logging is very good, but the actual absolute measurements of such parameters as porosity and whether it is a porous rock containing oil or a non-porous rock full of rock – well we are not too good at this unless we know what has been obtained in a neighbour's bore-hole. And so, I think you are doing a very great service to the scientific bore-hole project by at least tackling the problem of seeing what these logs mean in crystalline rocks and perhaps shopping around a bit more to see if something can be specially built for this type of research. The instruments available "on the shelf" were really made for sedimentary rocks and for reservoir investigations.

Dr. C.L. Drake (U.S.A.)

Did you ask the Birdwell people to make you a continuous velocity log tool?

Mr. Hobson

To our knowledge no one had one on the shelf for this diameter bore-hole. As a matter of fact Birdwell built the geophone for us, for that job. Shell Oil had one made out of small phones but Birdwell did not at the time. There are a few phones available now that will fit in small holes but they are not continuous.

Dr. T. Sorgenfrei (Denmark)

I have only one remark regarding publication. I would also salute this desire to publish. But I would also like to have the interpretation regardless of how good or bad it is, because it gives us the theories of those who have worked with the subject. I would certainly invite you to publish.

Mr. A.F. Bosworth (Can.)

What variations in density would you say there were in these bore-holes.

Dr. Findlay

Densities range from about 2.6 to 3.3.

Mr. Bosworth

We have used an annular density type tool of small diameter to distinguish oil-water or oil-gas contacts within the pipe. I am curious whether there would be enough definition here to do the job. There would be no guarantee of results though.

D. SESSION ON SCIENTIFIC OBJECTIVES OF DEEP CRUSTAL DRILLING

Chairman: J.M. Harrison (Can.)
Reporters: C.H. Smith and D.C. Findlay (Can.)

Dr. J.M. Harrison: "Ladies and gentlemen, this evening's program is basically concerned with the scientific aspects of deep crustal drilling. The first speaker is Professor V.V. Beloussov who originated the idea of the Upper Mantle Project and who unfortunately could not be with us this morning to open the symposium of deep drilling. I do not think Professor Beloussov needs much introduction to this group. He is, of course, the president of the Soviet Geophysical Committee, has been president of the I.U.G.G., and is now the chairman of the I.U.M.C. I take much pleasure in asking Professor Beloussov to present a paper which includes principally the ideas of Professor V.V. Fedynsky, who is the reporter of the I.U.M.C. Working Group on Deep Drilling."

DEEP DRILLING IN THE U.S.S.R. FOR SCIENTIFIC PURPOSES

V.V. Fedynsky*
Soviet Geophysical Committee, Moscow

Abstract

Drilling for scientific purposes is recognized as an important tool for deep geological and geophysical research in the U.S.S.R. Although the development of major drilling programs is still in a preparatory stage, four important structural and tectonic regions have been chosen for investigation of the nature of the crust and upper mantle through deep and superdeep drilling. These are: The Baltic Shield, the Ukraine, the Azerbaijan region, and Far Eastern U.S.S.R. Since 1962, extensive geophysical investigations, including deep seismic, gravity and magnetic surveys, have been in progress in these different tectonic regions. On the basis of crustal and upper mantle sections compiled from the geophysical data, sites for drill holes ranging in depth from 5 to 15 km will be established.

In addition to geophysical and geological studies of regions for potential deep and superdeep drilling programs, research in drilling

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*Read by V.V. Beloussov

equipment and techniques is currently in progress in a number of shallower experimental wells. Also, an extensive laboratory program to investigate the physical properties of rocks under the conditions of high temperatures and pressures anticipated in superdeep wells is being carried out. Geophysical apparatus for in-hole measurements is being developed, with particular emphasis on acoustical and radiometric devices and methods.

INTRODUCTION

The problem of deep drilling for scientific purposes is considered to be one of the most important problems in the earth sciences in the U.S.S.R. at the present. Due to numerous technical difficulties and the high cost of experimental work the solution of this problem requires considerable preparation and a long period of time. At the moment of this report (September, 1965) research on the problem of deep drilling in our country is still in a preparation stage.

The main objective of deep drilling, according to the conceptions of Soviet scientists, consists of studying the composition and physical state of the earth's crust down to its lower boundary and, in particular, of studying the nature of the underlying layers of the upper mantle. This problem may be solved by the drilling of a number of wells on the continent and in the ocean under different geological conditions. A study and comparison of their sections should give a conception on the structure of the earth's crust and its interrelation with the upper mantle.

Geological conditions in the regions of deep wells are to be chosen in such a way that drilling may help to answer the following questions:

(1) the mode of occurrence of volatile components in the strata;
(2) the distribution of temperature in the earth's crust and the possibilities of making use of hot waters for industrial and other purposes;
(3) the nature of oil and gas present at depths greater than 5 km;
(4) the migration of underground water solutions and associated gases in relation to the problem of formation of underground waters and the origin of hydrothermal ore deposits;
(5) the processes of deep metamorphism;
(6) the character of deep tectonics and types of deformation;
(7) the nature of faults;
(8) the nature of the "granite" and "basaltic" layers of the earth's crust;
(9) the formation of magma, movement and differentiation of

magmatic melts, genesis of minerals and the formation of ore solutions; and

(10) the nature of upper mantle material and the Mohorovicic discontinuity.

SOVIET PLANS AND OBJECTIVES FOR SCIENTIFIC DRILLING

As has already been reported (Belyaevsky and Fedynsky, 1961), preparation for deep drilling in the U.S.S.R. is being carried out in the five following regions:

1. Deep depressions of platform regions. Studies in these areas are aimed at investigating the total thickness of sedimentary rock masses in regional oil and gas-bearing depressions. Regions for possible study include North-Caspian depression and Azerbaijan.

2. Palaeozoic geosynclinal regions. Work will be carried out in these regions for the purpose of studying processes typical of deep zones. Possible regions are the Urals and Northern Kazakhstan.

3. Ancient shields. Studies here are to investigate the most ancient Archaean formations composing the granite layer, and to reach its "basaltic" layer in order to study its influence on the formation of ore deposits. Possible regions include Karelia and the Ukraine.

4. Regions of the earth's crust of the type transitional to oceanic. Here the aim is to reach the "basaltic" layer under sedimentary rocks. Azerbaijan is a potential region for such studies.

5. Island arcs and oceanic crust regions. Studies should be undertaken in these regions to reach the Moho and to sample the upper mantle. Possible regions are the Kuril Islands and southern Sakhalin.

To serve a useful purpose deep wells must be located in carefully selected typical places, preliminarily well-studied by geological and especially by geophysical methods. In all the above-mentioned regions relatively detailed geophysical surveys are being carried out including deep seismic soundings and gravitational and magnetic surveys. From the results of these investigations the sections of the deep structure of the earth's crust are being compiled. These sections are designed for the most rational selection of the location of deep wells. In their turn these predicted sections will be modified and attached to the actual section as the well data are being obtained.

The depth of wells which might solve the postulated problems must be from 5 to 15 km. At present the only technical means of deep drilling is rotary drilling. The deepest well was drilled by rotary method in the U.S.A. — I-EE University well, West Texas. This well reached a depth of 7,724 m and a temperature of 180° C was recorded at the bottom of the well. In the U.S.S.R. the greatest depth of 5,940 m was reached in 1965 in the Aralsor well No. 1, West Kazakhstan, with a bottom-hole temperature of 150°C. The drilling of Aralsor well No. 1 encountered difficulties at this depth due to the presence of steeply dipping strata of sedimentary rocks. However in spite of this the deepening of the well is going on. Such is the initial basis for further improvement of technology of deep rotary drilling, with the aim of reaching the depths of 10-15 km on land. We may anticipate the possibility of drilling of such deep wells during the next 5-10 years. Therefore it is proposed to start drilling in the most interesting places first down to depths of 7-8 km by means of ordinary oilwell drilling equipment, and later, as the necessary experience is achieved and special more powerful equipment is developed, to drill in the same places down to 10-15 km.

From 1962 to 1965 special geophysical projects were carried out to study the deep structure of possible deep drilling regions on the Baltic shield, in the Ukraine, in Azerbaijan and in the Far East of the U.S.S.R. Deep seismic sounding was the main method used in a complex of geophysical surveys. Soviet scientists have considerable experience in carrying them out, on the basis of which conceptions on the nature of observed seismic waves and of the mechanics of their propagation are accurately determined. Along with the improvement of deep seismic methods, interesting new data are continuously obtained on the deep structure of the earth's crust. Besides this the deep seismic results allow us to interpret gravitational and magnetic anomalies over large areas around the seismic profiles.

The deep structure of the ancient Baltic shield was studied along two regional deep seismic profiles by different geophysical methods (Litvinenko, 1965). The profiles are located in Northern Karelia and in the northwest part of the Kola Peninsula. They cross various structural zones of the Baltic shield and are the first detailed studies on an ancient shield carried out in the world. As a result of these studies it is found that the earth's crust here has a stratified structure according to its elastic properties. Its total thickness is comparatively constant at 35-40 km. The crustal substructure in different structural zones is unequal. Seismic boundaries within the crust are discordant, with inclination angles sometimes reaching 5-10°.

The terms "granite" and "basaltic" layer of the earth's crust do not reflect their complex and variable bulk compositions. On the Baltic shield inhomogeneities were first discovered in the "basaltic" layer.

Block structures in the crust result in the development of different structural zones, which are most distinctly displayed in the upper parts of the section down to 5-8 km. In the "basaltic" layer physical properties of rocks are evidently more homogeneous due to processes of regional metamorphism. The anomalously shallow position of the Conrad boundary on the Baltic shield as compared with the Barents Sea and the Russian platform is evidently the result of continuous uplift of the shield and erosion of a considerable part of the crustal section.

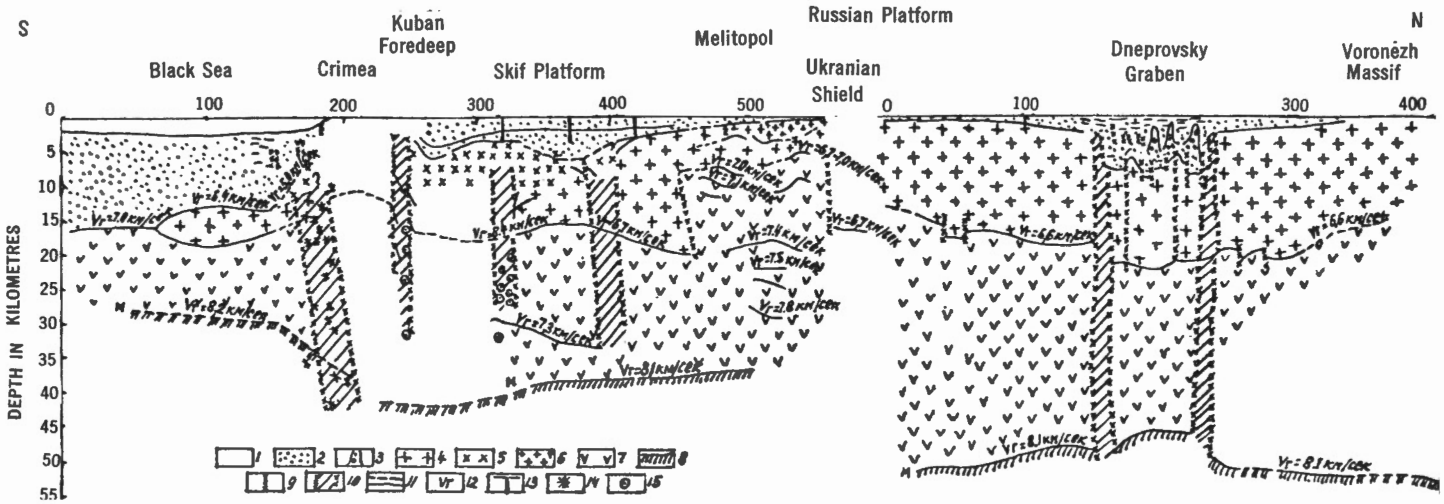
Zones of deep faults are developed at the junctions of different structural elements, penetrating the complete thickness of the shield crust and characterized by late stages of magmatism.

The shallow position of the "basaltic" layer, with a velocity of propagation of the longitudinal elastic waves of 6.4-7.0 km/sec, on the Baltic shield creates uniquely favourable conditions for carrying out deep drilling for scientific purposes in this region.

In the Ukraine, nearly all the major structures — the Dnieper-Donetz basin, the Ukrainian shield, the Ante-Black Sea depression, and the Black Sea basin were studied by deep seismic soundings in combination with other geophysical methods (Subbotin et al., 1965). Figure 1 gives a schematic section across the Ukrainian territory and the Black Sea basin from north to south. We can see on this section the complex block structure of the earth's crust and the differences in thickness of the crust and of the layers composing it, as well as the existence of deep faults displayed in different horizons above the Mohorovicic discontinuity. A sharp distinction begins to show on the section between the structures of the continental and "suboceanic" crust of the Black Sea. The earth's crust is of a considerably smaller thickness (22-30 km) under the Black Sea than it is on the continent (35-50 km).

In the central part of the Black Sea the "granite" layer wedges out and a thick mass of sediments lies directly on the "basaltic layer". The thickness of the continental crust under the depressions is thinnest where the amplitude of subsidence is greatest. Thus in the northwest part of the Dnieper-Donetz basin the Moho ascends to a depth of about 45 km subsiding northwards under the Voronezh massif and southwards under the Ukrainian shield to a depth of 50 km. The Conrad surface forms a depression at the same place imitating the behaviour of the basement surface in a qualitative respect.

Under the ancient (Proterozoic) synclinal depression of the Belozersky region on the Ukrainian shield, the Conrad boundary is elevated. In this region the "basaltic" layer approaches the surface most closely, lying at a depth of the order of 10 km. Within the limits of the Ukrainian shield in the "granite" layer, at depths of 1.5-10 km, several nearly horizontal



1-water layer; 2-sedimentary formations; 3-salt diapirs; 4-"granite" layer; 5-metamorphic rocks of Palaeozoic-Triassic-Jurassic(?) age in "granite" layer; 6-metamorphic rocks of Proterozoic age in "granite" layer; 7-"basalt" layer; 8-Mohorovičič surface; 9-faults; 10-deep faults; 11-refracting and reflecting horizons; 12-maximum velocity; 13-bore-holes; 14-earthquakes epicenters; 15-points of diffraction.

Figure 1. Schematic north-south section across Ukrainian territory and Black Sea basin, showing variations in the depth to the Mohorovičič, Conrad and other seismic discontinuities in passing from continental crust (right) to "suboceanic" crust (left).

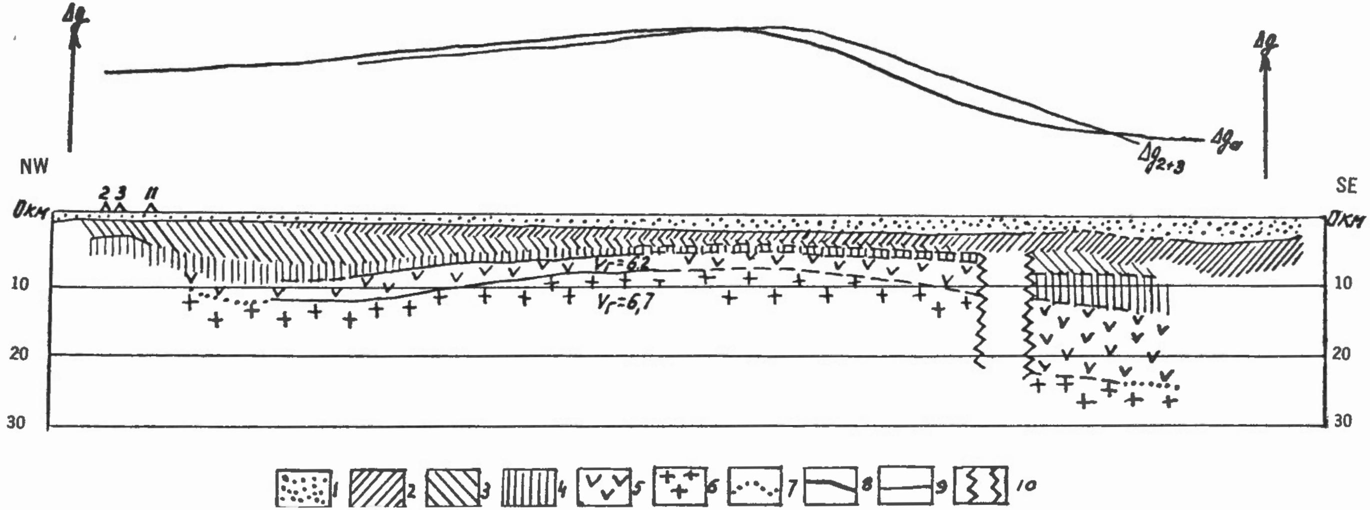
seismic boundaries are found as well. In places they are characterized by very high boundary velocities up to 8.0 km/sec. These boundaries evidently separate rock complexes of different petrographic composition. We believe that within the limits of the Ukrainian shield we can reach the basaltic layer by wells having depths of 10-12 km.

The Kura depression in the Azerbaijan S.S.R. region is of great interest from the viewpoint of superdeep drilling. As a result of studies by deep seismic soundings (Ali-Zade, Ahmedov, and Kulikov, 1965) in the eastern part of the Kura depression a transitional type of crust was determined, characterized by a thin "granite" layer and a sharply increased thickness of the "basaltic" layer, with total thickness of the earth's crust of the order of 45-50 km. Approaching to within 7-8 km of the surface the "basaltic" layer, with a boundary velocity of 6.7-7.0 km/sec occurs in the region of buried Lower Kura sediment (Fig. 2). The gravitational maximum observed in this area is connected with the elevation of the consolidated crust along the surface. The basalt is overlain by sedimentary-effusive complexes, in the basement of which the "granite" layer is either missing or is very thin.

A study of the Azerbaijan region by means of drilling may reveal the conditions and possibility of oil and gas concentration in a sedimentary formation at great depths. The composition of the "basaltic" layer playing a special role in depressions of the Mediterranean type will be determined. In addition, this well may reveal the peculiarities of migration of matter and ore-bearing fluids within the "basaltic" layer. Finally data will be obtained for solution of the problem of mobilization of the "basaltic" layer and for determination of its absolute age — problems which are being actively pursued at the present.

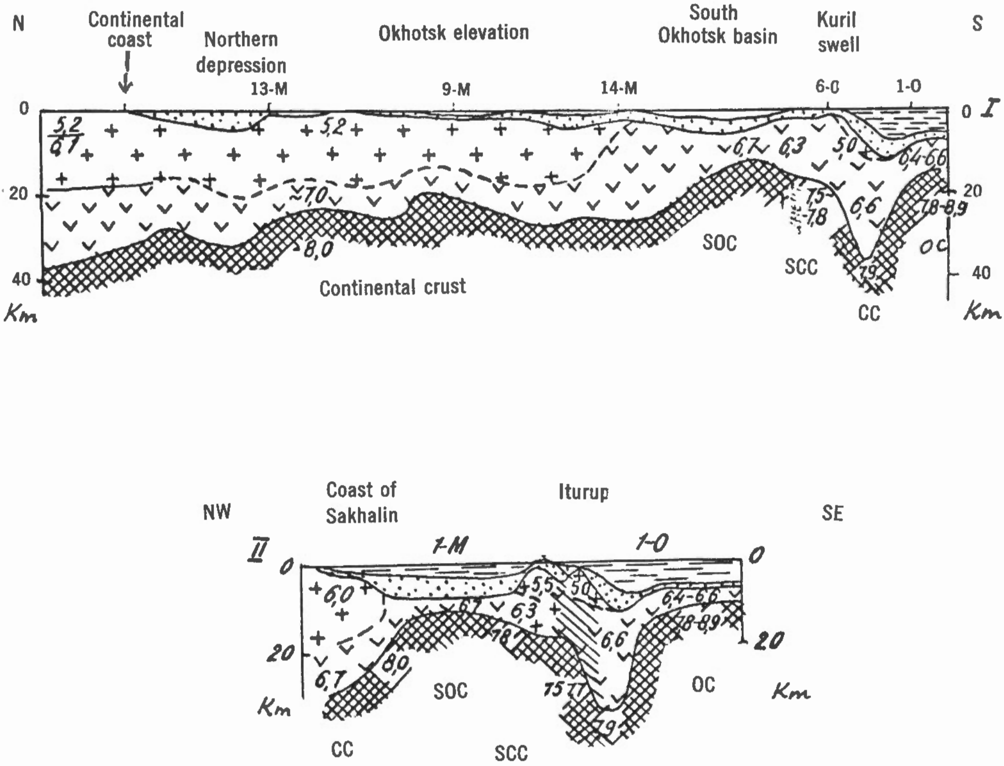
In studying the nature of the Mohorovicic boundary and of upper mantle matter, the region of transition from the Asian Continent to the Pacific Ocean is of particular interest. At this place extensive deep seismic soundings were carried out during the last few years (Galperin et al., 1964). As a result of this work four large regional sections of the earth's crust were made, crossing the Okhotsk Sea, the Kuril Island arc, the deep-water trench and bottom of the Pacific Ocean in latitudinal and meridional directions (Fig. 3). In addition, a schematic map of equal thicknesses of the earth's crust, and a map of the Mohorovicic surface relief were compiled for this whole region.

A combined analysis of gravity, magnetic and seismic data showed inhomogeneity of the upper mantle matter. This matter is of lower density in the Kuril uplift zone (island arc) and of higher density in the Kuril-Kamchatka depression (trench). A sharp distinction in deep structure



1-Upper Pliocene and Quaternary sedimentation; 2-Middle and Lower Pliocene; 3-Miocene and Palaeocene; 4-Mesozoic; 5-metamorphosed basement; 6-basalt; 7-assumed contacts; 8-curve of gravity observations; 9-total curve; 10-zone of possible rupture according to DSS data.

Figure 2. Cross-section of the Kura depression in the Azerbayan S.S.R. region, showing a transitional type of crust characterized by a thin "granite" layer and a thick "basalt" layer. Total crustal thickness is 45-50 km.



▤ Water

⛆ Sedimentary layer, average velocity less 3.5 km/sec

⊞ Granite layer, velocities 5.2-6.4 km/sec

∨ Basalt layer, velocities 6.4-7.0 km/sec

▩ Subcrustal layer, velocities 7.5-9.4 km/sec

▧ Region of modern seismic activity

Figure 3. Cross-sections showing the transition from continental to oceanic crust in eastern U.S.S.R.; CC-continental crust; SCC-subcontinental crust; OC-oceanic crust; SOC-suboceanic crust.

of north Kuril and south Kuril structural — tectonic zones was revealed (Lifshits, 1965).

An analysis of magnetic anomalies along seismic profiles shows a qualitative difference in density change on the Mohorovicic boundary under continents and oceans (Gainanov and Solovyev, 1964). On the basis of seismic data obtained by the method of reflected waves and deep seismic sounding a schematic section crossing the coast of Soviet Primorye, the deep-water basin of the Sea of Japan, the northern part of the Honshu Island, the Japanese trench and the bed of the Pacific Ocean was plotted in an NE-SW direction (Kovylin and Neprochnov, 1965).

The studies of volcanism within the Kuril-Kamchatka region showed that the location of volcanoes is controlled by comparatively shallow faults, feathering off the deep faults (Rivosh and Steinburg, 1964).

The depth of the Mohorovicic surface within the islands of the Kuril arc and of the Southern Sakhalin appears to be of the order of 16-18 km which is deeper than it was believed to be before detailed geophysical studies were carried out. For the time being it is evidently beyond the limits of technical possibilities of deep drilling.

OTHER RESEARCH IN CONNECTION WITH DEEP DRILLING PROGRAMS

Along with the study of regions for possible drilling of deep research wells, an analysis of questions of drilling technology is being carried out. Experimental well No. 2000, being drilled in Bashkiria with standard oil equipment, is presently at a depth of 3,800 m, having passed through about 2 km of sedimentary rocks and more than 1,800 m of granites of the crystalline basement of the Russian platform. In addition to the previously-mentioned Aralsor well No. 1 drilling is proceeding on two more wells with designed depths of 6-7 km; one in western Kazakhstan and another in Azerbaijan.

In 1966-1967 deep drilling will be started in one or two additional areas.

An extensive series of scientific research studies on physical properties of rocks at high pressures and temperatures anticipated at depths of 5-15 km is being carried out and development of geophysical apparatus for studying well sections under these conditions is progressing.

In the high pressure laboratory physical parameters are being measured at pressures up to 4,000 atm (Volarovich, 1962 and Volarovich et al., 1962). It has been found that the velocity of longitudinal seismic waves varies with pressure up to 800-900 kg/cm^2; however, with a further increase of pressure they remain practically invariable. In the interval 1,000-4,000 kg/cm^2 the velocities are as follows: for sedimentary rocks — 2-4 km/sec; for granites — 5.5-6 km/sec; for basic rocks (gabbro, diabase, basalt) — 6.5-7 km/sec; for ultrabasic rocks — 8 km/sec. As pressure increases (up to 1,000 atm) electrical resistance of rocks sharply decreases— by 1.5-3 times.

Up to 800 atm some physical properties (porosity, electrical conductivity) of the rocks were studied under laboratory conditions (Dubrynin and Morozovich, 1965; Morozovich, 1965). The rock samples from the Aralsor well No. 1 were taken from depths deeper than 4 km. With an increase of pressure up to 700-800 atm, porosity of limestone decreases by 1-5 times, and aleurolite by 5 times. Resistance falls by 2-5 times. Research is planned at pressures up to 2,000 kg/cm^2 under conditions of increased temperatures and rock pressures. A review of geothermal data was prepared (Geothermal Studies, 1964) from which it is seen that the heat flux on the shields is lower than in depressions and mountainous regions; $0.6\text{-}0.7\times10^{-6}$ cal/cm^2 sec for the Ukraine in contrast to $1.0\text{-}1.2\times10^{-6}$ cal/cm^2 sec for the Caucasus.

Geophysical studies in deep wells drilled in various places of the Soviet Union are continuing.

In developing geophysical apparatus for studying the sections of deep wells drilled for scientific purposes it is important to choose fundamental methods of research and to determine what parameters are required. As the depth increases and temperature and pressure rise, the electrical resistance of rocks decreases and differentiation of resistance curves decreases. At the same time elastic properties and nuclear parameters of the rocks vary insignificantly or do not vary at all. Therefore the main emphasis was placed on working out acoustical and radiometric devices and methods. To measure the composition of rocks in their natural position it is also necessary to use nuclear-physical methods. Well geophysical apparatus must be hermetic, designed for pressures up to 2,000 kg per cm^2 and temperatures up to 300°C. At the present, electro-thermometer and radiometric well logging devices are being developed for temperatures up to 200°C and pressures up to 1,200 kg/cm^2 (Nedostup and Migunov, 1965).

DEEP DRILLING PROGRESS IN OTHER COUNTRIES

Development of deep drilling programs in the U.S.S.R. is, as well as in other countries, only in the initial period. However, even the small amount of information which is being provided by different countries, i.e. Canada, U.S.A., Germany, Japan and South Africa, gives data on different approaches to the problems of deep drilling.

The scientists of the U.S.A. consider reaching the Mohorovicic discontinuity and obtaining information on the upper mantle matter to be their main task. For this purpose they undertook a practical attempt to drill in deep water in the ocean from a floating base. This attempt is of great interest from many standpoints, although it was not completely accomplished due to a number of technical difficulties. In addition, it is intended to drill a few wells to depths of 6-8 km during the next 10 years and a number of wells of shallower depths on the continent as well. Gravitational anomalies indicate the presence of heavy material, perhaps of the upper mantle, at shallow depths in some regions. Drilling, even to relatively shallow depths in these regions should provide important results. In addition, in the process of such drilling technical problems of superdeep drilling will be worked out, the nature of layers distinguished according to geophysical data will be studied, and the heat flux and distribution of radioactive elements in well sections will be measured (Solid Earth Geophysics, 1964).

In 1963 the Geological Survey of Canada carried out a small scale drilling project for scientific purposes — the so-called Muskox drilling project (Findlay and Smith, 1965). This experiment undoubtedly deserves high consideration. Three wells, from 830 m to 1,380 m deep, were sunk by diamond drilling through a buried part of the ultrabasic Muskox Intrusion, located east of Great Bear Lake at 66°-67°N. The information obtained is of great importance for studying the nature of the intrusion and mineralization associated with it. Canadian scientists intend in the future to continue drilling of comparatively shallow wells within the limits of the Precambrian crystalline shield for similar purposes. Geophysical instruments being developed include a vibrating string gravimeter which may have application as a bore-hole gravimeter.

Less definite information is received from other countries. The Federal Republic of Germany plans to drill a well in the northwest part of the country, evidently to a depth of 8-10 km for the purpose of studying oil and gas presence in sedimentary rocks at great depths (see H. Becker, this volume). Japan has declared its intention to drill wells for research purposes to depths of 2-3 km in regions of volcanic activity to study the roots of volcanoes. In South Africa they will evidently make use of their experience in deep diamond drilling in carrying out drilling projects for scientific purposes.

EXCHANGE OF DEEP DRILLING DATA

As the experience grows and the first results of deep drilling for scientific purposes, especially of superdeep wells, are obtained the international exchange of these data becomes more and more necessary. Therefore, the International Upper Mantle Committee should plan to hold symposia in deep drilling, similar to the Ottawa meeting, regularly every 2 to 3 years.

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THE MERITS OF SCIENTIFIC DRILLING

T.F. Gaskell
British Petroleum Limited, Great Britain

I am sure that in talking to you tonight there is no need for me to make any excuses for curiosity about what the inside of the earth is made of. We can read recorded curiosity about the inside of the earth, right from the beginning of any history books that I find. The earth, the solar system, the universe—all the things that are common to all human beings—are attracting even more attention today now that we are probing outside our planet and infiltrating into some of the other members of the solar system. The very work that people are doing to investigate the moon, Mars, and so on, is underlining the fact that we do not really know very much about our own planet at all. We have, of course, learned from early Babylonian writings about ideas of an earth rather like this room with the stars hanging from the ceiling and the sun and moon performing their various functions suspended above us. We left that flat earth system a long time ago. However we did have a long period of "hollow earth" theories. Jules Verne was one of the hollow earth experts and had his professor disappearing down a geyser in Iceland. After a certain amount of wandering among peculiar vegetation and so on, inside the earth, the professor came up in the Mediterranean. It is difficult to see how he managed it because he came up through the volcano Stromboli.

A rival school of writers supposed that the earth had something inside it. Conan Doyle's earth, if you will recall, in one of his short stories was an earth rather like a giant animal. It had a thin outer skin and it had a big jelly-like inside. And his professor, being a resolute character, engaged a drilling firm to drill a hole through this thin outer crust. Well, the professor prodded the animal and the story was called "The Day the Earth Screamed"—and it sort of blew up on him.

But Doyle did have one point which is pertinent to our thoughts these days—if you want to find out about the inside of the earth, you should drill a hole into it.

Figure 1 shows what the ancient world was like. You can see that they had the sun, and moon, and stars very conveniently suspended from the bedposts, and it had four corners. This must have been an earth belonging to one of the Middle East writers; one of the good things about all these old writers was that always their own home town was the centre. Well, we have since progressed from the earth of Figure 1 to a spherical earth. In fact, it was quite a long time ago that we determined its size by measuring the angular distance of two points which were a known distance along a circumference of the earth. About a hundred years ago we also obtained a measure of the mass of the earth through a combination of Newton's theories and Cavendish's experiment. We also learned about the moment of inertia of the earth by observations of perturbations of the orbits of the moon and earth. The final main pieces of evidence about the earth, we obtained by studies of earthquake waves, which provided the sort of picture shown in Figure 2.

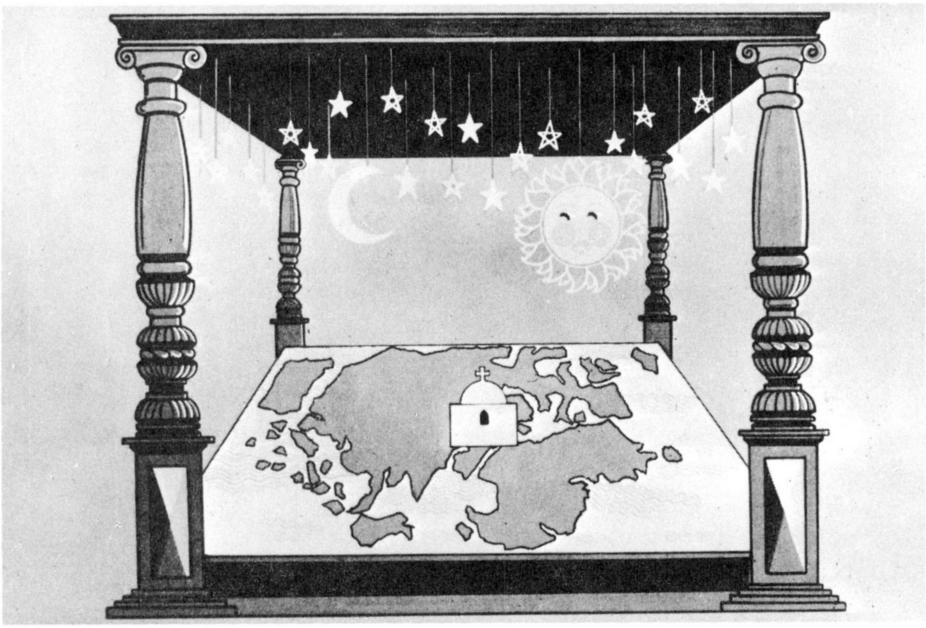


Figure 1. A 'home-town'-oriented viewpoint of the Ancient World.

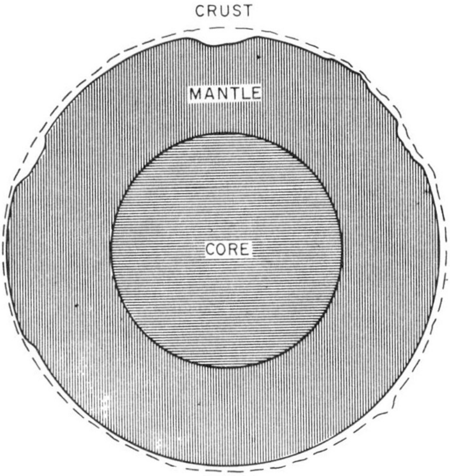


Figure 2. The modern picture of the earth's structure, derived mainly from seismic studies. Crustal thickness greatly exaggerated.

Figure 2 shows the earth approximately as we interpret it today. It has an outer crust which is only 20 miles thick in an 8, 000 mile diameter of the earth. Below this there is the mantle which goes half-way to the centre of the earth, and then a liquid core. Some people believe in a solid inner core, and possibly this may be demonstrated one day. We are not proposing any experiment to drill down to the core; what we are proposing to do in some of our experiments is to drill through at least into the upper part of the mantle which forms about 80% of the earth.

There are very good reasons why we should learn more about the inside of the earth, apart from our natural curiosity to know what sort of a planet we live on. One important thing we do not know is the abundance of elements in the earth. If we could determine this we would learn more practical facts about the whole of the solar system, than we would by finding what the moon is made of. Then again, the thin outer crust of the earth is affected by what goes on inside the body of the earth. It is affected in particular by the heat being produced inside the earth—the heat which associates itself with all sorts of changes on the outside skin. Some people believe that we have an earth which is warming up. For many years, it was believed that the earth was cooling down. It would be useful to know which of these possibilities is true, and to do this we have to find out how much heat is being produced inside the earth.

It is most important, in many ways, for us in the practical mining industries to increase our knowledge of the earth; the more we can understand how mountains are built or determine whether or not continents have wandered apart, the better we can carry out our exploration work. There is a great deal of talk now, about wandering continents and I know that many people believe that continents have changed their position in times past. But to be sure of this one has to, if possible, find a mechanism. To find a mechanism one wants to determine the physical properties, at least to a few tens of miles below the Mohorovicic discontinuity. One wants to know if it is possible, for example, to have convection currents which could explain the movement of large land masses. So we would like a sample from a bit further down inside the earth to test in the laboratory under conditions of high temperatures and pressures.

There are additional good reasons why we should embark on various deep drilling projects. In the oil business we have always been aware of the importance of drilling holes, partly of course, because we cannot get our oil up without drilling holes in the ground. But apart from that, geological and geophysical interpretations have to be checked, and this can only be done by drilling. Now, it will have a most salutary effect on many people who produce theories about what the inside of the earth is made of if they have someone — and someone seems to be coming along now—who is going to drill a hole and check up on what they say should be there. There is another thing about drilling in the oil business—when we do geophysical experiments we make a certain interpretation and sometimes it is right, but sometimes it is wrong. By drilling holes, and by drilling quite a lot of holes in many cases, we learn a great deal more about our geophysics. In fact, geophysical methods have been improved by going back afterwards and seeing how they match up with the evidence we get from bore-holes. We have also tried drilling a large number of holes at comparatively close spacing and learned quite a lot more about geological environments and how various sedimentary rocks were laid down. This sort of drilling also has been demonstrated to be most useful, and I am quite sure that it would have been used much more extensively in what I might call "university" geological and geophysical research if it had not been so expensive. Well, in point of fact bore-holes have been used for quite a long time for specific scientific purposes, not such deep ones as you will be hearing about later on tonight, but shallow bore-holes.

There have been some special bore-hole projects in Britain recently. Drilling was used to investigate volcanic extrusions in the north of England a few years ago. Professor Wager is currently trying to get some holes drilled in his favourite hunting ground at Skaergaard in Greenland. Bore-holes have been usefully employed in the ice of the Arctic and Antarctic, not so much to learn about the geology of the earth, but about the record of the earth's climate over the past 50 to 100 or more years. There was a famous bore-hole drilled in 1901 on Funafuti, a Pacific coral atoll to test a very heated geological controversy. This was to test whether Darwin's idea of atolls being formed by growing of coral rock on a sinking volcanic platform was true, or whether on the other hand, Murray was right, and the coral rock grew up on a fixed platform which happened to have been worn away below the sea surface. Well, the bore-hole went about 1,000 feet through coral rock and since coral, of the kind that built these atolls, does not grow in depths greater than about 200 feet, the Darwin school claimed that they were right. But it was pointed out that since they were drilling on the edge of the atoll, then the coral could represent the tip-over slope of the debris on the Murray theory. Well, anyone who knows anything about atolls knows that both sides were right—they were arguing about two different types of atolls. However the sad thing was, that here was a case of a deep scientific bore-hole which did not prove anything at all.

This morning we heard something about scientific drilling projects that are planned, or are going on in various parts of the world. Later this evening we will be hearing about the Mohole project, and I would like to say here that I think it is easily the most exciting and worthwhile project yet conceived. Apart from everything else, the tools that are being produced for this project are going to be very useful for everyone else's projects. Not only the tools for measuring what goes on down the bore-hole but also the tools that are being used to improve the speed—and therefore decrease the cost—of drilling these deep holes.

Another series of holes of great interest are those that will be drilled in the next few years, I suppose, through the complete sedimentary column of the deep oceans. Here is a place where many people have done quite good geophysical work and they find that there are 1,000 to 1,500 feet of soft sediments on the deep ocean floors in most parts of the world. This is assumed because one can take cores of the top 50 to 100 feet of this sediment, and from the seismic results the same layer should continue for a thousand feet or so. Then we get another much harder layer the so-called "layer 2". This has been a very vexing question to us for some time. From its velocity it could be some sort of consolidated sediment—say a hard band of limestone, or baked clay which has turned into shale of some sort—or it could be a volcanic layer a few hundred feet thick. All these things, unfortunately, would give the same seismic velocity.

Thus, some of the useful things that will be determined when holes are drilled through the complete sedimentary column on the ocean floors will be first of all to find what "layer 2" is, and then to allow a check-back and a reinterpretation of the geophysical results. But much more interesting geologically will be the collection of what may prove to be, in some parts of the oceans at least, a fairly undisturbed column of sediments that existed from the time the ocean basin was formed. That is, if one believes that oceans do not move around as some people would like them to do now. If one believes in the floor of the oceans continually shifting then, of course, there are no very old sediments anywhere. They have all been gradually swept under the continents in the course of time. Drilling through this complete sedimentary column in several places should show one or the other of these ideas to be right. It will contribute new facts so that we can carry on a little further from there. You have heard already this evening about the deep holes to be drilled on land. This should tell us many things, especially more about geological processes in the past, and, from a practical point of view, a lot more about mineralization processes. Possibly we shall gain more clues to go and find useful concentrations of things that the human race needs.

One thing that we have to watch for in collecting all these cores is that someone will have to get busy quickly to obtain useful information from the very long series of core samples that these drilling operations will produce. For example, there are still some cores from the 1872 Challenger Expedition lying in the British Museum. They have become so old and valuable now that no one is even allowed to look at them.

Today is a very good time for carrying out these drilling operations, because there are good new tools available. Also, which is just as important, there are quite large amounts of money available for large scale scientific projects. For both these reasons we can now do things that we could not have done about 30 years ago. However, we have been drilling holes in the earth for much longer than I had suspected, as I discovered in reading some old books a little while ago.

About 1,500 years ago the Chinese were in the drilling business (Fig. 3). Drilling then took much longer than we would like it to—a well was a family affair and it was handed down from one generation to another. The object was to drill down to get salt water—the reverse of what we do in the oil industry; if we found salt water we would burst into tears and call it a dry hole. But the Chinese were trying to get salt and they would drill holes up to 2,000 feet deep by the laborious process of using a percussion instrument down the hole and jumping on a board to give it a jerk up and down. One generation with a hard formation to penetrate might only make a few tens of feet. But they did, in fact, manage to reach 2,000 feet eventually. So we have not improved so very much with our 25,000 feet, which is the record depth at the present time.

Although things have changed since the days of the Chinese drilling methods shown in Figure 3, some of the changes were very slow in coming about. In the early drilling days of the oil industry, cable-tool percussion methods were still in use and it was not until the 20th century that rotary drilling was introduced.

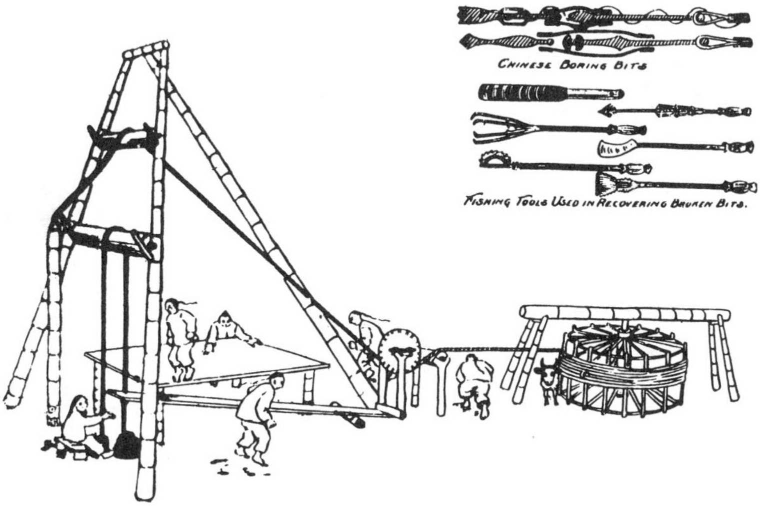


Figure 3. A Chinese drilling rig in use over 1500 years ago.

It is difficult to imagine how they ever did change because to try and get any driller to change his technique at all is one of the most difficult things—I have tried it for many years—and how they ever did manage this transition from cable-drill to rotary method always surprises me. However, this is the way it is done now, and as you will hear this evening and tomorrow, there are some new little tricks coming along in the way of improved turbodrills, more automation, and so on.

One of our main occupations these days is off-shore drilling. Figure 4, shows one of the most famous off-shore drilling ships. This is the "Cuss I" that did the preliminary Guadaloupe Mohole trials.

Figure 5, shows a type of drilling platform that has been very popular in water up to about 120 feet in depth. It is a floating barge that floats along and when it gets into position jacks itself up out of the reach of waves on legs to drill a hole.

Figure 6, is an artists impression of a semi-submersible. I show this to lead you into the next talk, because it is a semi-submersible that the Mohole project will use. The great advantage of this type of platform is that it has its flotation at about 70 feet below the surface in its large "feet".

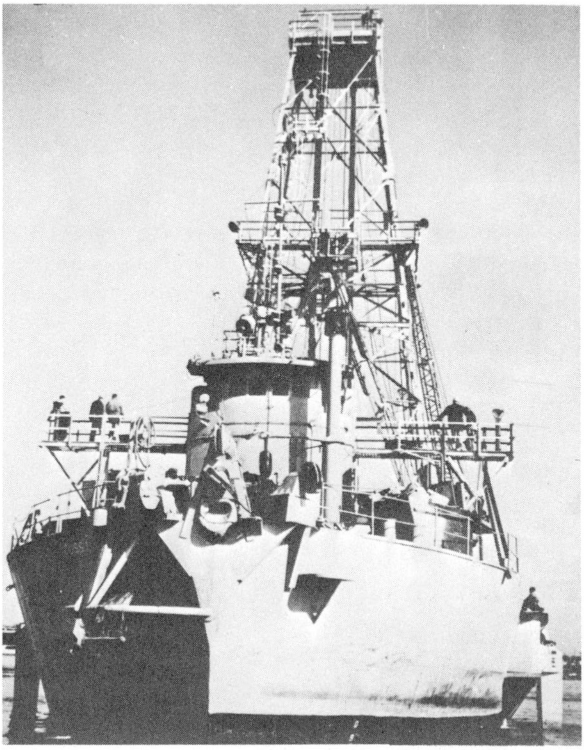
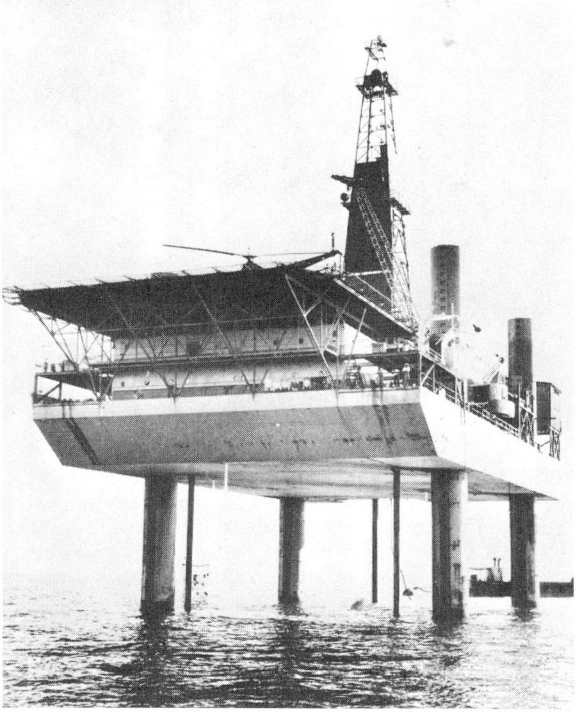


Figure 4. The off-shore drilling ship "Cuss I". This vessel was used to drill the preliminary Guadeloupe test holes for the Mohole Project.

Figure 5. A popular type of off-shore drilling platform that has been used to drill in water depths up to 120 feet.



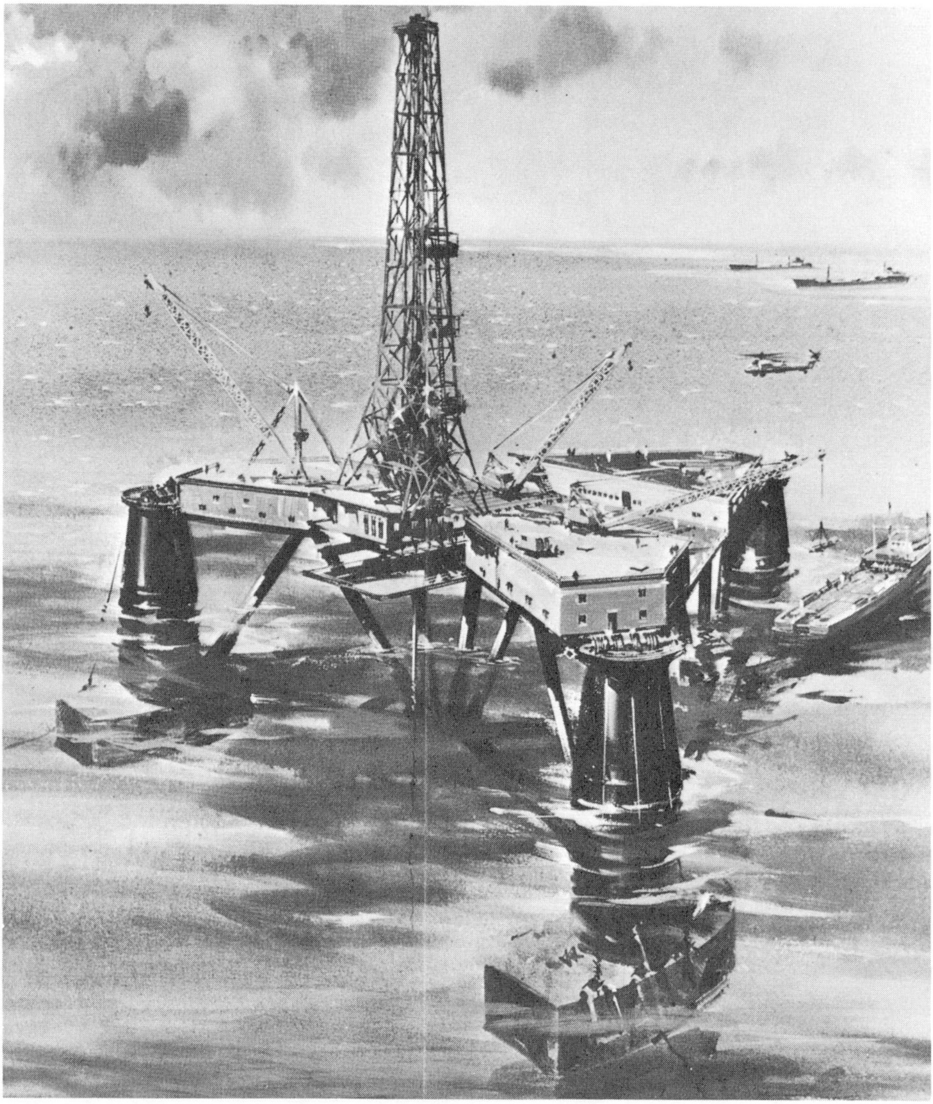


Figure 6. Artist's impression of the new semi-submersible drilling platform "Sea Quest" presently under construction for drilling in the North Sea.

This means that any wave action at the surface does not result in severe vertical motion to the whole craft, because the wave motion 70 feet below the surface is much less than it is at surface itself. The platform shown in Figure 6, is one that will be employed shortly in the North Sea, which is a very active area of exploration for oil and gas these days. But whether or not we find any oil or gas we can count some of those bore-holes or at least a part of the value of them as scientific holes, because we shall learn a great deal more about the geology of Northern Europe from them.

In addition to the improved drilling tools there has been a great improvement in the well-logging methods we use, and in the amount of information we can get from bore-holes. A particular case, and to my mind a thing that should have been invented years ago, is the Sidewall Corer that was demonstrated today. (See Schneider, and Sims this volume.) This means, that instead of just having one core, with this tool one can always go back and cut another. And of course if you have two rival geological schools, they can both have cores from the same interval, thereby keeping both schools happy.

I would like to mention one final point and I was pleased to hear several people raise this subject today. Although we are going ahead and starting all these drilling projects, we must be very careful in our choice of sites. Drilling is an expensive process and we must, therefore, try and make our money go as far as possible by spending it carefully—by choosing places where specific questions can be answered and where the geology and the geophysics have been well established. We do not want to do what they did at Funafuti some years ago.

In conclusion I would like to say that I am very pleased that we are all getting into the drilling business. I think, quite honestly, that many of us have lived far too long in a sort of fool's paradise where we have been basing too much theory on a too limited set of facts. Now we have an opportunity to show to future generations that we were sensible enough to use what tools we had available and to collect a few more facts before we start making too many wild guesses.

THE MOHOLE PROJECT, PHASE II

H.H. Hess, J.D. Sides and W.H. Tonking (U.S.A.)

Chairman's Introduction

Dr. J.M. Harrison (Can.): 'If there is any single project that has caught the imagination of people it is the Mohole project, which began a few years ago. We have now reached the point where government is prepared to spend large sums of money in order to conduct this sort of scientific project. We are extremely fortunate in that we have here the representatives of the three different components of the team that will, we hope, be able to drill the Mohole. Prof. Hess represents the non-governmental scientists. Dr. Sides represents the governmental scientists from the National Science Foundation. Dr. Tonking is the consulting engineer for Brown & Root Inc., the prime contractor for the project. Prof. Hess will lead off with a discussion and description of activities in the past and future stages of the project.'

Prof. H.H. Hess: Thank you Mr. Chairman.

I usually like to appear on a program after three very dull speakers. This is the only way I can make my way in the world. However, it is rather unfortunate tonight that I am following my friends V. Beloussov and Tom Gaskell. But I will do the best I can, and I will not speak for very long. I would like to go back and remind you how this project originally got started. I will not deal with the technical situation very much; I will leave that to my colleagues, one of whom you heard this afternoon—Mr. Schneider—and three more, whom you will hear this evening, and tomorrow.

The Mohole project started in March, 1957, at a National Science Foundation panel meeting where eight scientists were gathered to analyze projects submitted from earth scientists of the country. We had something like sixty projects to review in two days. A week's work was involved in reading these projects before we met. At the end of a two-day session we were rather tired and Walter Munk mentioned that none of these proposals was really fundamental to an understanding of the earth, although many of them were very good. If someone wanted to study the clay minerals of such and such a formation to find out about its diagenesis, well, this was a good thing to do; however, it would not solve a major problem about the earth. If someone wanted to study the stability of anthophyllite, well, yes, I would like to know about its stability too. But still, it is a relatively small point. We had gone through sixty of these proposals, most of which we rated as being very good projects; they should be supported. Walter Munk commented that we should have projects in earth science — geology, geophysics, geochemistry — which would arouse the imagination of the public, and which would attract more young men into our science. We are very short of geophysicists, for example, and we were very short of oceanographers also at that time. It is necessary at times to have a really exciting project. I think that Dr. Beloussov realizes this too. Thinking of his own country he had proposed, I believe, the Upper Mantle Project because this was exciting to the imagination of the people and you must have people behind you if you are going to carry out major scientific projects. Thus, I was very pleased with Dr. Beloussov's original suggestion at the I.U.G.G. because it was an attempt at the same sort of thing that we had been trying to do, starting a few months earlier.

Now to look at the Mohole project specifically. Walter Munk suggested that we drill a hole through the crust of the earth. I took him up and said let's do it; let's not drop it here, and we did go on. But it has been a hard fight, and if some two or three or five people had not fought for the project every year since it was started, it would have crashed several times. It might even crash now. We had a crisis only a week ago when the cost was looked upon with dismay by some people who wanted to do more seismology. They wanted to take the money from the Mohole project and put it into seismological studies. However, you cannot really do this. Money that is not spent is not available for some other project. The way to raise funds for these important and large projects, some of which you must have, is to make a strong case for your own project. In this case, if you can make a strong case, and you get public support, you can do these things.

Now, why did we start a Mohole? What were the questions to be asked? I will repeat a few of these. We were looking at an earth model invented in 1850 by a very ingenious Frenchman named Boisse, who is usually forgotten. He said the earth must be just like meteorites. This was a brilliant idea for that time, before we had any seismological information. He postulated that the iron meteorites represented the earth's core and the stony meteorites the earth's mantle. Now this is a good analogy in a gross way, but some geochemists take it so seriously that they look at the average rubidium content of meteorites and conclude that the earth's mantle must also have this rubidium content. Well, it probably does not hold true to that degree. All one has to do is to look at the great variety of, say, chondritic meteorites. They have different trace element contents. It is a very interesting problem why they are not all the same, but evidently processes early in their history, or in the primordial body in which they were formed, were varied and there was differentiation of one sort or another. Certain gaseous elements were concentrated in some meteorites. Certain elements were depleted in others. Certain elements which might be volatile at high temperatures show discrepancies. The average composition of the solar system, as judged by spectrographic work on the sun, does not agree exactly with meteorites. There are rather major discrepancies with regard to iron and potassium, for example. And potassium is a particularly important element because it is the K content of the earth that contributes a large part of the internal heat. If you knew the K of the earth you could solve many of the thermal problems regarding the earth because this is the main radioactive constituent which influences what has happened in the last $4\frac{1}{2}$ billion years.

When we started out we had a list of the things that we wanted to determine. We wanted to determine the density of the upper mantle materials, the radioactivity, and the age. Age, I thought, could not be done, but Dr. Hart, of the Carnegie Laboratory has approximately determined the age of St. Paul's rock as 4.5 billion years. Using similar methods one could determine the age of mantle rocks if they could be retrieved. I think that St. Paul's rock is mantle material, relatively undifferentiated, and I suspect, that this is what will be found, at least at some places, when we drill the Mohole. The first thing we would want to know about this sample would be its chemical and mineralogical composition. Today, a vast amount of research is going on in the U.S.A. and I think, in Russia, and I know, in Australia, on chemical systems which might represent mantle materials. But I do not believe that this research is progressing as well as it should, because there are just too many possiblities. If you had one sample of the mantle, even if it was not representative I think this would still give you 75 per cent of the information required. If it was not representative you might make a good guess at what it would be if it was representative. One Mohole, I think, will give a large fraction of all the information wanted. However, you certainly must drill quite a few holes to determine the reliability of this sample. This sample, of course, would not be a hand specimen; it might be 1,000 feet of core; perhaps a ton of rock. We want to determine the isotope composition, the relative isotope ratios, say, of the leads and the strontiums because this would give us a better understanding of age determinations and what the primordial constituents were. We would like to know more about rubidium, uranium and thorium in the mantle. This may require many samples to get a reliable understanding of the variation. We already know there are variations by sampling the basalts that came from the mantle and these are complex — we know that they are not all the same. In my original statement eight years ago, I said we ought to try somehow or other to sample the gases and fluids that might be coming out of the mantle at the bottom of this hole. How much free water, how much argon, how much neon is coming out? I felt at the time it might be extremely difficult — I still think it might be extremely difficult — to avoid contamination from the upper part of the hole. But this has become enormously more important in the last year or so, because people have generated ideas on the origin of the atmosphere, and these hypotheses are highly dependent on what gases are leaking from the earth. What is the ratio between nitrogen and argon, or neon, or water?

If you knew this then you could construct a good model of the origin and development of the earth's atmosphere.

We would like to know what "layer 2" is, as Dr. Gaskell has mentioned. I think we can guess at this. We have samples that probably represent it, such as the basalt at the bottom of the Guadaloupe well. Hard rock outcrops on the ocean floor are usually basalt and I think that "layer 2" is predominantly basalt. Material that is very magnetic is required to account for the magnetic anomalies. If you take my hypothesis on what "layer 3" is; serpentinized peridotite — you cannot derive the large magnetic anomalies from this material. The serpentines do not have enough remanent magnetism to produce the anomalies we now see at the surface. Also, from the character of the anomalies we know they are generated in the upper 10 km. So that one hole penetrating "layer 2" into "layer 3" would give one a basis for further work, and for controlling what experiments are going to be done in the laboratory. This is very necessary because we are doing experiments now on a great variety of chemical and mineralogical systems, and we have to narrow these down to a more confined range of possiblities to make the laboratory work effective.

In the hole we also want to measure thermal conductivity and heat flow, seismic velocity, and magnetic properties including oriented magnetic properties to correlate with the palaeomagnetic measurements. We want to measure electrical conductivity and radioactivity. There are many other minor things which we should measure but the above are the main parameters which we need to understand at this time.

As for the rest of the program, it is now four years since we drilled the Guadaloupe holes. Five holes were drilled in three thousand feet off San Diego, looking at sediments and getting to learn how to use the drilling vessel. Five more holes were drilled between Guadaloupe Island and the coast of Mexico. These penetrated about 500 feet of sediments, from which we got a complete core and penetrated about 50 feet of basalt. The sediments ranged from Recent to Miocene; the basalt at the bottom of the well had an age of 35 million years, which is Miocene also. One thing I learned here, is that a basalt flow coming out on very soft sediments would spread as a sill underneath the sediments. This is apparently what has happened at the Guadaloupe site. There is evidence of contact metamorphism in the sediments just above the basalt; since it came out on this very weak material, it is reasonable that it would flow underneath the ooze rather than on top of it. I do not think that anyone had thought of such a situation before, but a drillhole brought this obvious thing to light. Following the Guadaloupe holes we drilled a 1,000-foot hole on the island of Puerto Rico. This was in the basement rocks of Puerto Rico — all in peridotitic material, which I would guess, is altered mantle material immediately below the surface in an island arc. If you dehydrate the Puerto Rico cores you get something of almost the same composition as St. Paul's rock.

This year a well was drilled at Uvalde, Texas to test drilling conditions in basalt and Dr. Tonking will probably say more about this. Also, we have completed site surveys — geophysical surveys — in three areas; one north of Puerto Rico on the rise immediately beyond the trench. This area we found to be structurally very complicated, and we gave it up for that reason, although we had done an enormous amount of work there. Next we did surveys over the Barracuda Fault which displaces the crust about 2 km upwards. This looked very promising structurally, but it turns out that the crust is thicker here than it is in some other places. Here we have a 10 km depth to the Moho — a minimum of 10 km. It might be somewhat greater since this is a matter of interpretation of seismic data along the Barracuda Fault. Thirdly, we surveyed the area north of Hawaii, and this gives a depth of about 9.6 km to the Moho based on the present seismic information and looks slightly better, from the point of view of thickness of the crust, simplicity of structure, and weather conditions — we have a hurricane once every five years around the Barracuda Fault, and we have no storms of that intensity north of Hawaii.

THE SELECTION OF THE MOHOLE DRILL SITE

J.D. Sides
National Science Foundation, Washington

Abstract

A site at which it is planned to perform the drilling of the Mohole, to penetrate through the crust of the earth into the mantle, has been tentatively selected. It is located on the Hawaiian Arch. The selection followed the determination of relevant scientific and technologic criteria. Geophysical investigations were undertaken especially to determine the total depth to mantle at three areas: the Puerto Rico Outer Ridge, the Barracuda Fault area, and the Hawaiian Arch.

INTRODUCTION

In January of this year the National Science Foundation announced the selection of a site, located on the Hawaiian Arch northeast of the island of Maui, at which it is planned to perform the ultimate drilling of the Mohole to penetrate the entire crust of the earth into the underlying mantle. This site was chosen after its recommendation by a Site Selection Panel acting, under the auspices of the National Academy of Sciences, as advisor to the Foundation. Dr. H.H. Hess has served continuously as Chairman of that Panel. The choice of a drilling location was made at this time for planning purposes, especially in order to specify in which ocean the platform must be delivered. The decision could be changed in the event that some as yet unidentified site would better fulfill the scientific objectives or afford substantially increased odds for success.

SITE SELECTION CRITERIA

The various considerations relevant to the site selection are as follows:

(a) Scientific considerations
    Nature of the crust and upper mantle;
(b) Technological and economic considerations
    Projected temperatures
    Proximity to port facilities
    Weather conditions
    Total depth to the mantle.

Scientific Considerations

The single exigent scientific consideration consists of the nature of the crust and upper mantle. The ultimate goal of the Project is defined as the penetration of the crust of the earth into the underlying mantle. Implicitly, the aim is to sample a normal crustal layer sequence and normal upper mantle, as these terms have become at least approximately defined by general consensus. Thus, the sampling of rocks of hypothecated mantle composition by either pick, dredge or drill where they may occur very anomalously situated has not been regarded as satisfying the ultimate goal of the Project.

Technological and Economic Considerations

Among the technological and economic considerations, high temperatures projected from abnormal heat-flow measurements ruled out, in the initial analysis, some potential site areas which might otherwise have been regarded as satisfactory. The requirement for logistical support facilities for the drilling operation demands a proximity to a suitable port of no more than a very few hundred miles at most, and preferably within helicopter range. Of the remaining two considerations, depth and weather, the total depth to mantle has been regarded as the more important. That is, while the design of the drilling platform includes ability to survive even hurricane conditions, with provision made for emergency abandonment of the hole and subsequent re-entry, the difficulty of drilling may be expected to increase exponentially with increasingly greater depths.

SITE INVESTIGATIONS

Following the establishment of the above criteria, the Site Selection Panel recommended three areas as being worthy of intensive investigation — the Puerto Rico Outer Ridge and the Barracuda Fault areas in the Atlantic Ocean, and the Hawaiian Arch in the Pacific Ocean. Site investigations were then performed by both academic institutions and industrial geophysical contractors. The investigations were undertaken to assess the relative merits of the three potential site areas, especially to measure the total depth to mantle with the highest attainable degree of accuracy at each. For that purpose seismic data, particularly, were recorded in great density in comparison to conventional marine crustal determinations. Not only were a number of profiles recorded in relatively areally restricted locations, but also the multi-detector equipment of industrial techniques afforded, where employed, much denser spacing of refraction arrivals along any one profile than has been common in crustal studies. By virtue of this density, then, these data may possess interest and value beyond the immediate purpose which they have served.

Puerto Rico Outer Ridge Area

The Puerto Rico Outer Ridge comprises that area between the Puerto Rico Trench to the south and the Nares Abyssal Plain to the north (Fig. 1). Prior to 1962 when the earnest search for a Mohole site was initiated, a substantial volume of geophysical information already existed on this one area. I refer especially to the refraction survey conducted jointly by Hudson Laboratories, Lamont Geological Observatory, Woods Hole Oceanographic Institution, and A & M College of Texas (Northrop and Ransone, 1962; Nafe and Drake, 1960; Bunce and Fahlquist, 1962; Dehlinger and Antoine, 1962); and, reflection surveys (Hersey, 1962 and J. and M. Ewing, 1962), to cite only the more recent work performed in the area. Subsequently, an industrial geophysical contractor, Western Geophysical Company, undertook detailed reflection and refraction investigations there. Their reflection profiles along Outer Ridge clearly manifest very frequent

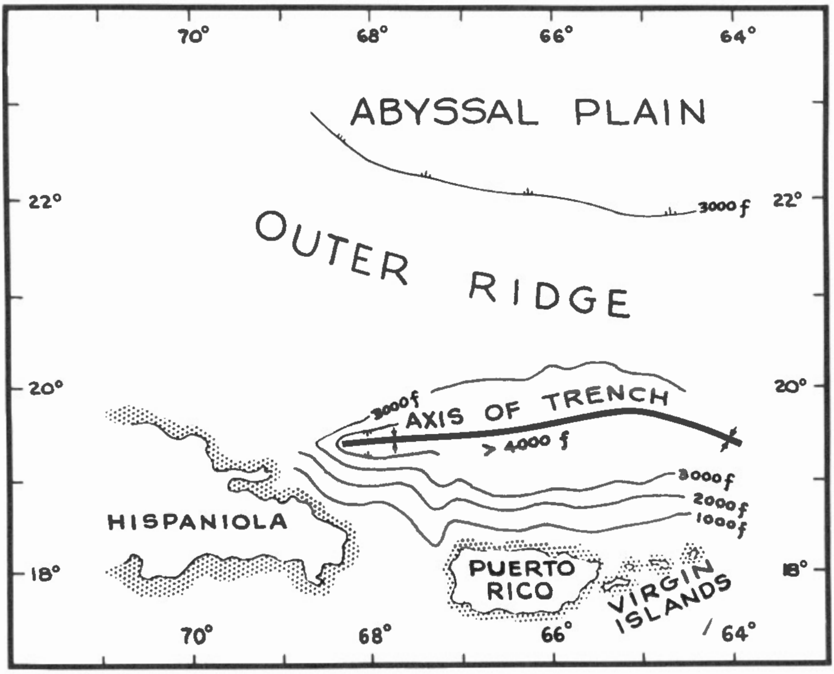


Figure 1. The Puerto Rico Outer Ridge area.

structural complexities extending at least as deep as the base of the sediments (Savit, et al., 1964). Additionally, their refraction profiles, recorded using 100 meter detector stations along the extent of the profiles (Western Geophysical Co., 1963) strongly suggested that those structural aberrations in many cases extend deep into the crust. It was judged that a precise calculation of total crustal thickness, and hence depth to Moho, at any given point is unattainable where such structural complexities prevail.

Barracuda Fault Area

At the time the Barracuda Fault area was originally proposed as a potential Mohole drill site, it was known only from its bathymetry. It consists of a feature trending east, rising about two kilometres above the surrounding abyssal depths, highly asymmetrical with its steep flank or scarp to the north, and located about 200 miles east of the Lesser Antillean island arc (Fig. 2). At the conclusion of their work at the Puerto Rico Outer Ridge in 1963, Western Geophysical Co. proceeded to this area and recorded a few reflection lines along with three refraction profiles. The reflection

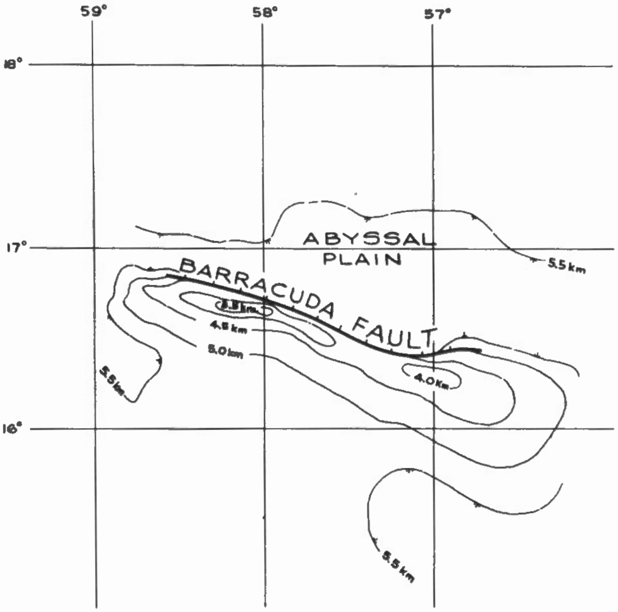


Figure 2. The Barracuda Fault area.

data (Paitson, et al., 1964) disclosed the structure of the sedimentary section and the top of the crystalline basement to be of relatively simple configuration on the up-thrown fault block. The refraction data indicated that subsedimentary layer interfaces were generally parallel to the top of the crystalline basement. This supported the hypothesis that an entire crustal block has been up-thrown, perhaps to afford a substantially less than average total depth to mantle. Therefore, detailed geophysical surveys were planned and executed in 1964. Woods Hole Oceanographic Institute conducted gravimetric and magnetic surveys there, while Offshore Exploration Group, Inc. performed the seismic program. The refraction program consisted of five profiles on the up-thrown block and one north of the escarpment. These data disclosed the average subsedimentary crustal thickness on the up-thrown block to be about 7.75 kilometres, and in no case was a total depth to mantle of less than ten kilometres measured (Sides, 1965). While it is believed that the geophysical data recorded in this area may prove of more extensive interest, the immediate purpose for Mohole site selection considerations is thus served by the determination of the indicated mantle depths.

Hawaiian Arch

The Hawaiian Islands are located on that broad feature referred to as the Hawaiian Swell (Figs. 3, 4). The Swell includes the Ridge (the supermarine portions of which, of course, comprise the islands), the Deep, and the Arch. These subfeatures are best expressed on the north half of the Swell. The literature contains descriptions of the geology of the islands too numerous to mention individually. Suffice to say that the Ridge is composed of a mass of volcanics, the weight of which has apparently depressed the sea floor to produce the Deep. The formation of the Arch is thought to be the result of either the up-welling of subcrustal convection currents diverging beneath the Ridge antecedent to, or contemporaneous with, the earliest vulcanism (Dietz and Menard, 1953), or the yielding of the crust, elastically and/or plastically, in subsequent response to the great weight of the extrusives (Hamilton, 1957). Two seismic surveys were performed on the Arch north of the island of Maui: one by Scripps Institute of Oceanography in 1962 and the other by Western Geophysical Company in 1963. A fairly dense distribution of data is thereby afforded with a total of 18 reversed profiles recorded in a quadrangle about two degrees on a side. The two sets of data are in some respects mutually complementary. The Scripps' data provides the very long range refraction arrivals necessary for adequate reversal of Moho first arrivals to define the thickness of the deepest crustal layer. The Western multi-detector recordings define the upper crustal layers with good resolution. These data indicate a total mantle depth of about $9\frac{1}{2}$ kilometres to exist on the Arch, the greatest density of dependable data being at the approximate coordinates 22°20'N, 155°30'W. This point is near Scripps'

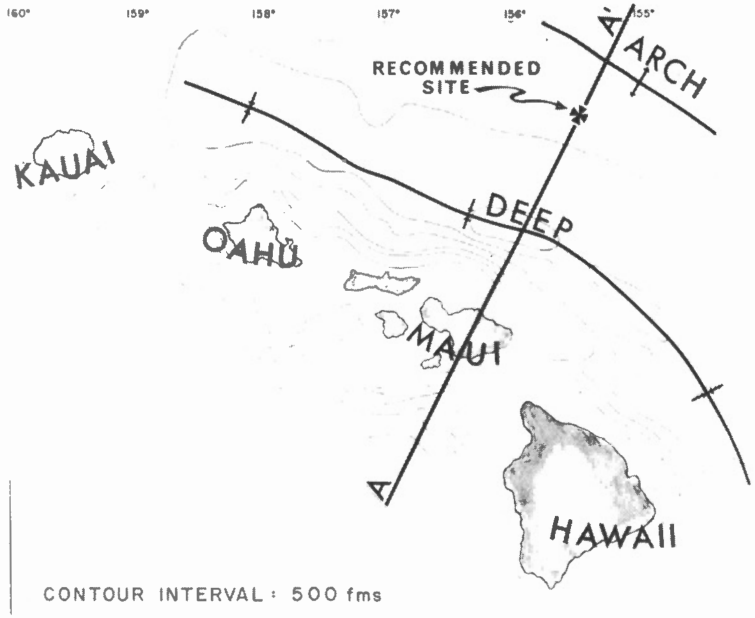


Figure 3. The recommended Mohole site northeast of the Hawaiian Archipellago.

Station 29 (Shor and Pollard, 1963 and 1964). The investigators originally computed the reversed and split profiles according to a number of methods of solution, of which five out of six yielded a total depth to mantle, at that Station, substantially less than 10 kilometres. Also, I believe it is worth noting that the reversed profile pair between Stations 28 and 29, alone of all the reversed pairs in the area, manifest a total mantle depth of less than ten kilometres at the profile mid-point, since that average or mid-point depth is less sensitive to deviations from the conventional assumptions of plane dipping interfaces and laterally constant intra-layer velocities. The data recorded by Western Geophysical Company (1964) corroborate the indication of relatively thin crustal layers on the Arch, especially about the referenced point. The Hawaii Institute of Geophysics has compiled and collated the existing gravity data available from several sources and supplemented them with gravity profiles across the immediate area of interest (Woollard, 1964). The gravity measurements were reported to be wholly compatible with a mantle depth of less than 10 kilometres over that portion of the Arch. In brief, the geophysical data establish a location on the Hawaiian Arch at which the most probable total depth to mantle is about $9\frac{1}{2}$ kilometres with about as high a degree of reliability as conventional methods allow. Additional geophysical investigations will be undertaken on the Arch.

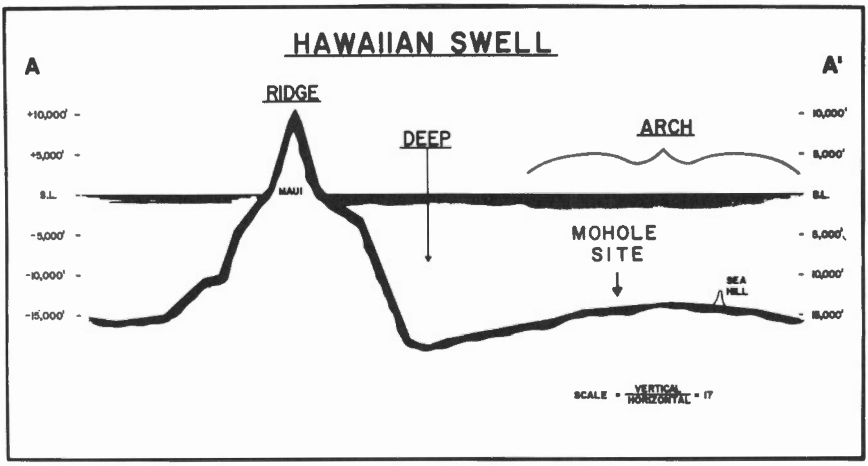


Figure 4. Profile across the Hawaiian Archipellago showing the position of the Mohole site in relation to the Ridge, Deep, and Arch.

SUMMARY

The choice from amongst the three potential Mohole drill site areas thus was made principally from considerations of total depth. Happily, the area so chosen also affords optimum weather conditions, including freedom from severe tropical storms, plus maximum proximity to suitable ports. As regards scientific ends, the great volume of geophysical, geochemical and geologic information already available from the many investigations of the Hawaiian Archipelago should permit a most comprehensive analysis of the Mohole data, especially as they relate to processes of magmatic differentiation and crustal petrogenesis.

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STATUS AND ACCOMPLISHMENTS OF THE MOHOLE PROJECT, PHASE II

W.H. Tonking
Brown and Root Inc.

Abstract

Since 1962 when the Mohole staff was formally organized, extensive research and evaluation studies have been carried out on the major components of the complete Mohole drilling system. These major subsystems include: the drilling platform; positioning control devices for the platform; drilling equipment and instrumentation, including the turbocorer and its associated components, logging winches, sidewall coring tool, and retractable diamond coring bit; equipment connected with the hole re-entry system, including landing pad and re-entry cone, riser sytem and riser latching and buoyancy control mechanisms; and a manned underwater inspection capsule for maintenance of the upper part of the riser system.

The engineering of most of these various subsystems has been accomplished. Most of the components have been designed, and in many cases have been fabricated or are in the process of fabrication. Drilling equipment such as the turbocorer and sidewall coring tool has been field tested in a well drilled at Uvalde, Texas as a part of the testing and development program.

INTRODUCTION

The great effort expended on Phase II of Project Mohole has resulted in accomplishment and achievement. Today, three and one-half years after this program was implemented by the National Science Foundation a great mobile sea-going research centre that will bring us fundamental data from the deep ocean basins is well on the way to becoming a reality. This has come about only through the expenditure of much effort. Our staff has been rather small, and our budget has been rigid and somewhat limited.

Our staff of naval architects and marine engineers have worked with naval research centres and model test basins to design a drilling vessel of unique characteristics. This prototype vessel is well suited for the many different types of deep ocean operations that inevitably will come in the future, when the nations represented here today endeavour to exploit the seas for the good of all mankind.

The accomplishment of the task of drilling into the mantle calls for a giant step ahead in drilling technology, in vessel design, and in downhole logging and sampling techniques. In order to penetrate all the layers of the earth's crust and the upper part of the mantle at any of the sites considered favourable for this effort, the drilling rig must be capable of attaining a depth of about 35,000 feet below sea-level while operating in 12,000 to 18,000 feet of water. At the time the Mohole staff was organized in mid 1962, technical problems made it impossible to drill to such depths even on land. This overall depth of 35,000 feet is forty per cent deeper than the world's deepest well which was drilled some years ago in West Texas. Of course, this well was drilled under conditions much less severe than those anticipated for the Mohole.

It might be useful to briefly review the general criteria for all the equipment and instruments concerned with the Mohole. The first criterion is ruggedness — all this equipment has to be resistant to shock, vibration, corrosion, and to extreme humidity. The second is reliability — we will be out there for days in and days out, months in and months out, for years; so we have to have very reliable systems. Thirdly, because so much of the operation is remote from us — it is under the water, two or three miles below us — the simplicity of operation and maintenance is extremely important.

UVALDE TEST WELL

We have drilled a well in Uvalde, central Texas to test different drilling equipment, core barrels, bits, logging equipment etc. (Fig. 1). For these tests we wanted to find a buried plug of basalt, in order to allow us to put some weight on our bits before we could obtain realistic drilling tests in the basalt. We ran ground magnetics and gravity in four or five areas and chose this one as a plug that we should intersect at about 500 feet. We actually started coring at around 450 feet, cored the contact at 485 feet and then penetrated about 3,000 feet of basalt where we stopped the hole. The primary objectives of this hole were to gain the maximum information on diamond bit coring and diamond drilling in basaltic rock.

Figure 2 shows one of the diamond bit types that we used on our turbodrill at Uvalde. This is a 9 7/8-inch O.D. bit that cuts 2-inch core. We were also very interested in determining the effectiveness of mud-treating equipment for the removal of basaltic cuttings — the abrasiveness of these cuttings can raise havoc with the equipment.

In the Uvalde well we also wanted to determine the response, in basaltic rock, of present logging equipment, so we could determine the

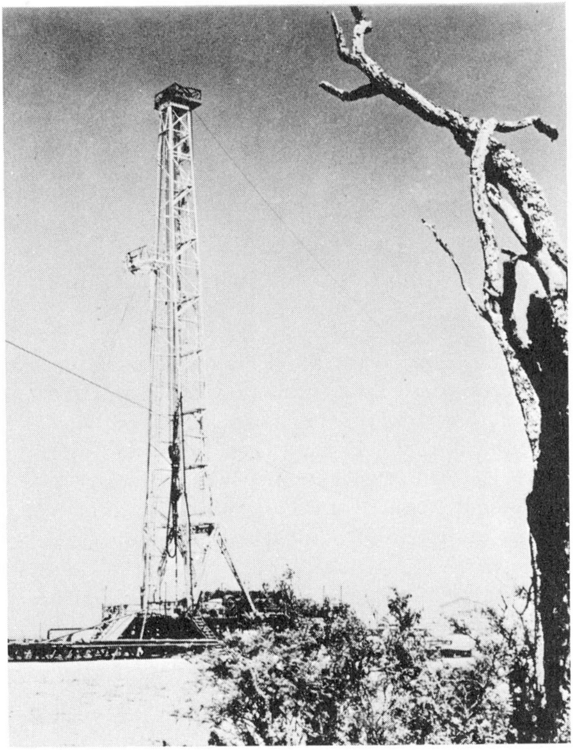
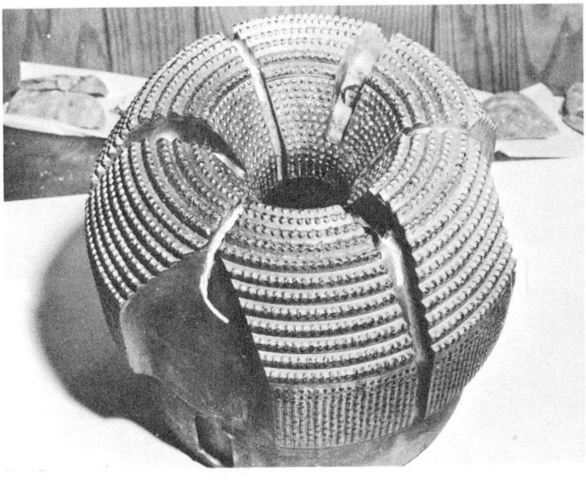


Figure 1. Drilling the test well at Uvalde, Texas, for field evaluation of Project Mohole drilling equipment and instruments.

Figure 2. A 9 7/8 inch stepped diamond core bit tested on the turbocorer at Uvalde, Texas. The bit cuts a 2-inch diameter core.



necessary modifications, and decide what new tools we actually have to design — what development programs we have to go into. The results from this equipment test well were extremely encouraging. Our turbocorer performed beyond the design criteria, and you will hear more about this tomorrow morning from Mr. Sims (see D.L. Sims, this volume). We had hoped that we could get 100 hours out of our bearings and seals and as it turned out we got over 200 hours. We also had extremely fine core recovery— about 95 per cent — at a penetration rate of $5\frac{1}{2}$ feet an hour. The turbocorer instrumentation package that Mr. Schneider discussed this afternoon proved very feasible (see W.P. Schneider, this volume). The bits and core barrels also performed very satisfactorily.

We found that through a cyclone system we can remove abrasive solids from our fluid down to ten microns and thus increase the life of the turbocorer as well as our mud pumps. An interesting sidelight here was that the contractor on the well had been drilling in this area for many years, and was getting only about 250 to 270 hours out of his mud pumps before he had to replace his expendables. The last time I was out at the rig, just before it shut down, he had 950 hours on his mud pumps, an increase which was mainly due to removal of the abrasives from the mud system. We found that spraying metallized zinc on the walls of the drill pipe is very effective in preventing corrosion. Of course, in our salt water environment this will be much more important than in this land environment. Further, the sidewall coring tool was proven to be feasible, as Mr. Schneider mentioned. Also the logs that we ran correlated very well with each other, particularly the density, acoustic, and gamma ray-neutron logs.

THE MOHOLE DRILLING PLATFORM

From the outset, it was obvious that the task of designing a drilling vessel for this project would be a complicated one. Both the depth of the hole and the depth of the water were without precedent in the drilling industry. During drilling operations, the heave, roll, and pitch of the vessel must be minimal to prevent damage to the drill pipe or to other strings of pipe required to complete the hole. To achieve a satisfactory level of efficiency, drilling operations must be carried on around the clock, even in fairly heavy seas, and when the weather reaches hurricane proportions the vessel must survive without loss of life, equipment, or Project progress.

Following preliminary studies, the Mohole staff established design criteria for the vessel. We specified that the vessel's response to normal wave motion of the water must be minimal and that drilling operations must continue during seas likely to be encountered in sustained winds up to 33 knots. Maximum design criteria specify that for a severe storm, the drilling platform may be buffeted by steady winds of 140 knots with gusts up to 200 knots and waves up to 100 feet in height.

Naval architects and marine engineers associated with the Project evaluated all known types of vessels: these included barges, catamarans, outrigger vessels, spar buoys or "flip" ships, seadromes, column-stabilized semi-submersible platforms, and various types of ship hulls. Some are shown in Figure 3, including a Russian vessel which the Czar built for the Czarina back in the late nineteenth century, the Popoffka. The result of the preliminary investigation was to eliminate all but the platforms and ship hulls and a number of preliminary designs for both types of vessel were made. The reason for eliminating most of the vessels was either that their motions were too quick, or that they were very difficult to position dynamically over the hole.

The ship hulls had one primary advantage over the platforms — they were initially less expensive. However, ship-motion and response to waves was two to four times that of semi-submersible platforms. The explanation is that the ship has a large water-plane area — that is the area of the hull at the waterline — and tends to be highly responsive to wave action. On the other hand, the general configuration of the platform is such that most of its buoyancy is provided by the twin hulls submerged well down in the water where wave action is less severe than at the surface. The water-plane area is small, amounting to the cross-sectional area of the vertical columns which pierce the surface of the water. In addition, the platform is much easier to position over the hole, requiring less horsepower for positioning motors than a ship.

The design of the Mohole drilling platform has been evolved to meet the exacting criteria that accompany a deep ocean drilling program. The resulting structure will afford a safe and efficient working platform for day-to-day drilling operations, will exhibit minimum response to wind and sea conditions, and will have the ability to survive, without severe damage, extreme weather conditions.

Figure 4 shows a model of the presently designed platform that will, we hope, drill the Mohole. It is a type that we call the column-stabilized semi-submersible platform. It has twin lower hulls, very similar to submarines. These hulls are 390 feet long and 35 feet in diameter. The six columns that connect the platform or upper deck to the lower hulls are 31 feet in diameter. The upper hull is 279 feet by 234 feet, and is watertight — so that this is a buoyant three deck upper hull. The derrick is approximately 200 feet high and the total height from the top of the derrick to the keel of one of the lower hulls is 335 feet, keel to top deck being 135 feet. The normal drilling draft (shown by the gray and white boundary in Fig. 4) is approximately 60 feet. In severe seas, this draft will be reduced

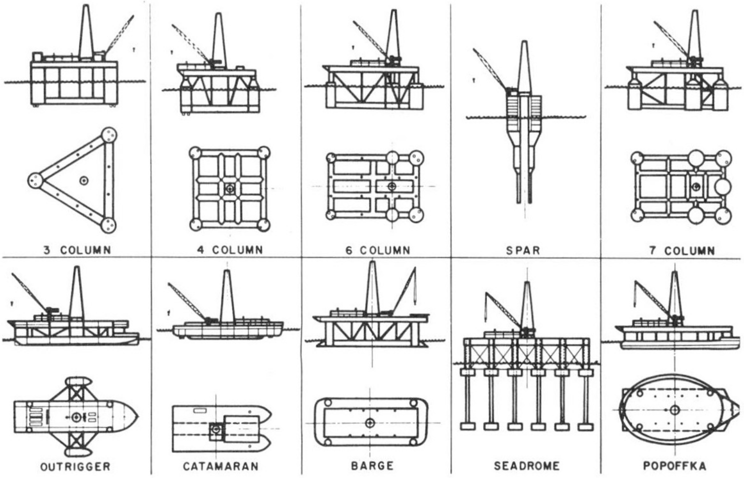


Figure 3. Various types of vessels evaluated in the search for a suitable drilling platform for Project Mohole.

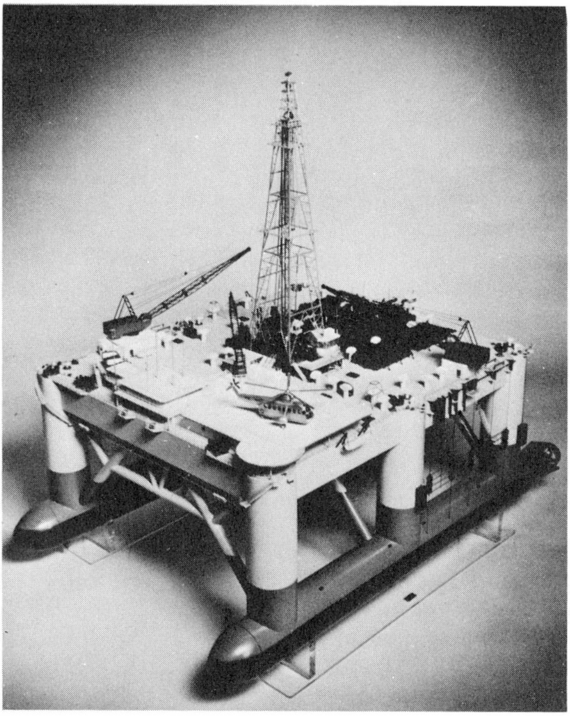


Figure 4. A model of the drilling vessel selected for the project. This column-stabilized semi-submersible platform rides on twin 390 foot hulls and has a total height of 335 feet.

to about 45 feet so that we have more clearance under our platform from wave slapping. The transit speed is about ten knots at the 29-foot draft (shown by the boundary between black and grey along the hulls in Fig. 4).

DRILLING PLATFORM ENVIRONMENTAL STUDIES

Extensive experimental and analytical studies have been carried out to investigate response of the platform under a wide variety of environmental conditions. The resulting information has been applied to the estimates that have been made of wind and wave conditions at the Mohole site to give long range estimates of platform heave and inclination.

Figure 5 shows histograms of the wind conditions at the Hawaiian drilling site — this is the distribution of wind speed by daily occurrence. Here the cumulative occurrence graph shows that over 95 per cent of the time wind speeds will be less than 30 knots. Recall that we can stay on position and continue drilling in wind speeds up to 33 knots. Actually, 98 per cent of the time the wind speeds will be less than 35 knots.

Figure 6 illustrates the same type of information for waves. Again, over 95 per cent of the time, the wave-height at the chosen site will be less than 13 feet. Only 4 or 5 days of the year will we have wave-heights greater than 20 feet.

Estimates of maximum heave are given in Figure 7. Maximum heave refers to the total travel or the double amplitude — the up and down motion — on a daily occurrence basis. Here again we are up into the ninety per cents, as far as double amplitude heave being less than 5 feet is concerned. We will have this condition 97 to 98 per cent of the time. Only on 3 or 4 days during the year will we have amplitudes greater than 8 feet.

Figure 8 gives similar information for the inclination or pitch and roll. It tells the same story. About 97 per cent of the time, either the pitch angle or the roll will be less than 2 degrees, and only 3 or 4 days out of the year will we run into a condition where we have a pitch or roll up to 5 degrees.

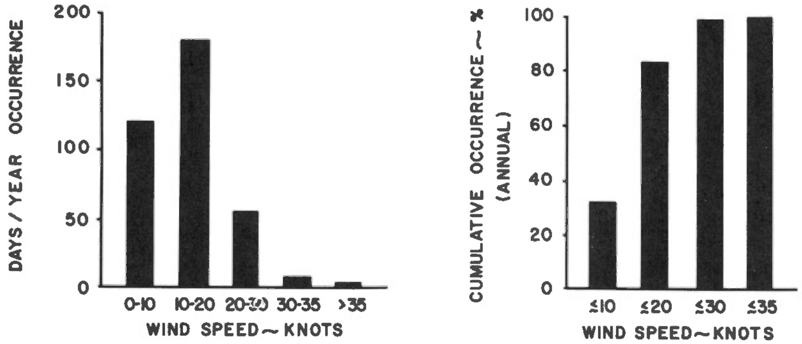


Figure 5. Distribution of wind speed by daily occurrence – long term averages for the Hawaiian drilling site area.

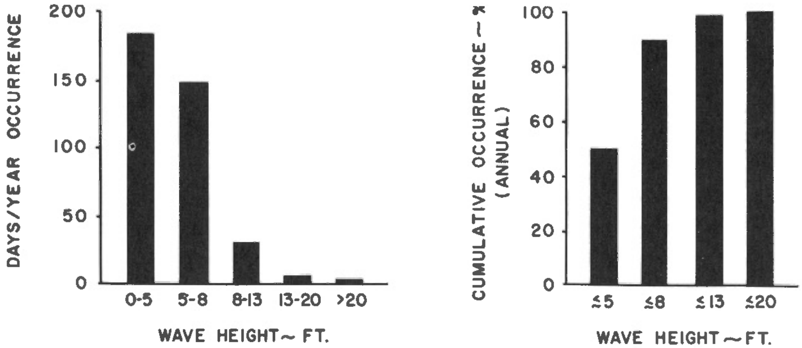


Figure 6. Distribution of wave height by daily occurrence – long term averages for the Hawaiian drilling site area.

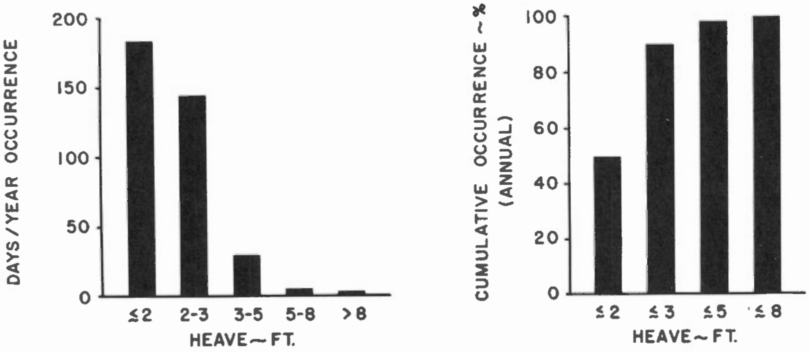


Figure 7. Distribution of maximum heave travel by daily occurrence - long term averages for Hawaiian drilling site.

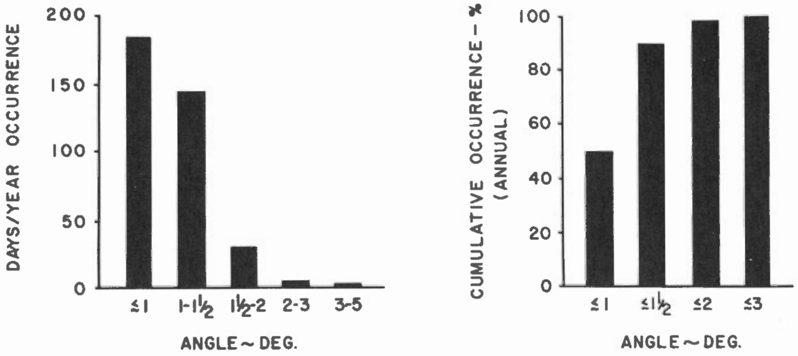


Figure 8. Distribution of maximum roll or pitch angle by daily occurrence - long term averages for the Hawaiian drilling site.

In Figure 9 the heave and wave data are combined. Here the wave periods are plotted against the ratio - heave amplitude over wave amplitude. In 95 per cent of the cases we will have wave periods of less than 10 seconds. For example, a 10-foot wave of 10 second period is not unusual except that it only occurs less than 5 per cent of the time. That would give us 2/10 on our heave amplitude-wave amplitude ratio. Thus we would have 2 feet of heave in a 10-foot wave of a 10 second period. On the other hand, in an 8 second wave — and 7 to 9 seconds are extremely common wave periods — we do get waves up to 15 to 18 feet and we would have no measurable heave. This is one of the major reasons that we have chosen the platform, rather than using a ship hull or combination of ship hulls.

DRILLING PLATFORM POSITIONING SYSTEM

I would like to discuss briefly the platform positioning system. The water is much too deep for conventional static anchoring, and thus a dynamic system had to be devised. The problem of maintaining accurate position on station consists of determining at all times, the lateral distance and direction of the platform from the vertical axis of the hole, and of providing the desired thrust to move back to the hole against prevailing wind, currents, and waves. An automatic dynamic positioning system has been developed to determine the platform's relative position, calculate the required correction, and generate the control signals to the propulsion units. The system is designed to hold the platform within a circle of radius 400 feet centred on the indicated position of the Mohole, under prevailing conditions of a 3 knot surface current and a 33 knot wind, for a period of 3 years. The maximum allowable deviation of the platform is related to water depth and is specified as a 350-foot radius circle for 12,000 feet of water depth, and a 500-foot radius for 18,000 feet of water. Below 10,000 feet you can use a rule of thumb which is 3 per cent of the water depth for the radius of excursion on the surface of the ocean.

Six directional propeller positioning units are employed under each of the columns. To augment these positioning units there are twin screws, one for each of the lower hulls, which are used for transit as well, but can be used for positioning under severe conditions.

A number of position sensing systems were considered including Loran, radar, sonar, inertial, and taut-wire. Considering the vital nature of this system, the extreme water depths and the required accuracy, sonar was selected. The system actually involves three separate sonar subsystems. First, we have our primary system which is a long base line system (Fig. 10). We plant 4 transponders on the ocean floor in a square pattern. Each side of the square is the same as the depth of water. Thus

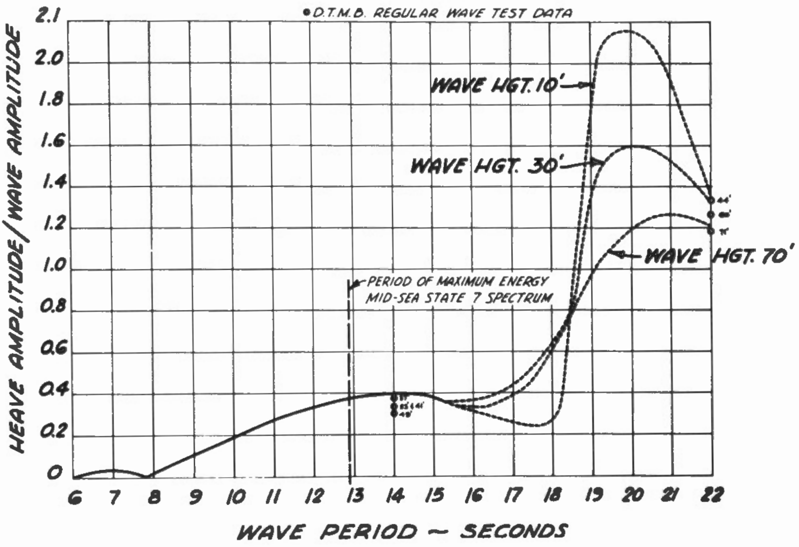


Figure 9. Heave amplitude-wave amplitude ratio plotted against wave period to give double amplitude heave response ratio of drilling platform for a given wave period.

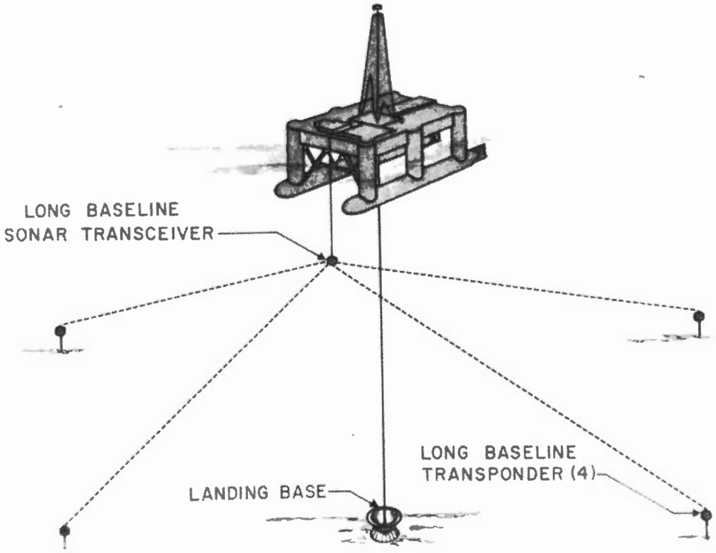


Figure 10. The primary platform position sensing system. This is known as the long baseline system.

we have a 45 degree transmitting angle. Information is then picked up by a transponder suspended from the vessel. To back this up, as a secondary system, we just flip the arrangement the other way around and put a transponder on the bottom as close to the landing base funnel as we can and have hydrophones receiving from the transponder on the ends of each of the lower submarine hulls (Fig. 11). This is a time-difference system. Furthermore, for an additional sonar back-up, another transponder is placed on the bottom close to the landing base and transmits on a different frequency in a continuous manner to the same 4 hydrophones. This information is fed into computers aboard the vessel in a phase-comparison manner. In addition, but not tied into our automatic system, we have radar targets on taut-line buoys. We will have 4 of these about a mile from the vessel as a manual back-up to the automatic system. Briefly, the system operates as follows: after receiving the positioning system signals the positioning computers solve the geometric problem and determine the platform's location; these data are displayed for the operator's information, although he would normally not take action; the computers then calculate the magnitude and direction or thrust required for each propeller.

The steerable propellers are used in pairs to provide control over heading and location. Under normal weather conditions, 2 positioning units are activated. As conditions demand, additional pairs of units would be added. The main propellers can also be controlled by the computer. The six positioning units are electrically powered right-angle drive propellers equipped with Kort nozzles to improve thrust at low speeds. Each propeller is powered by a 750 h.p. DC traction-type motor. The motor and gears are enclosed in a watertight capsule, which is inserted into a vertical trunk in the column. In use, the propeller projects below the bottom of the hull, and can be trained continuously in any direction. The units may be withdrawn into the trunk or brought out on deck for inspection or repair. The main propellers are driven by twin armature DC motors rated at 7500 shaft h.p. It is not anticipated that the full power of the main shaft will ever be used for positioning. These units were designed to provide the greatest practicable amount of power for severe storm conditions.

RISER SYSTEM

I would like to turn to the riser system, which is vital to this whole project — it is the link between the drilling platform and the drill-hole at the sea floor. The system is being designed to provide a reliable and convenient means for making normal working trips in and out of the hole with drill pipe and wire-line equipment, and to provide return mud circulation. Incidentally, this is one of the most difficult problems connected with Mohole. Only after more than two years of engineering study on the part of

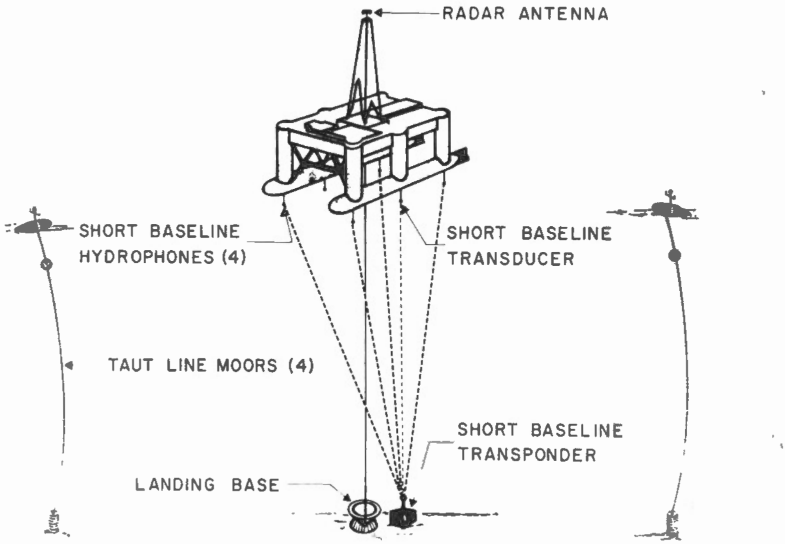


Figure 11. The secondary platform position reference system, called the short baseline system.

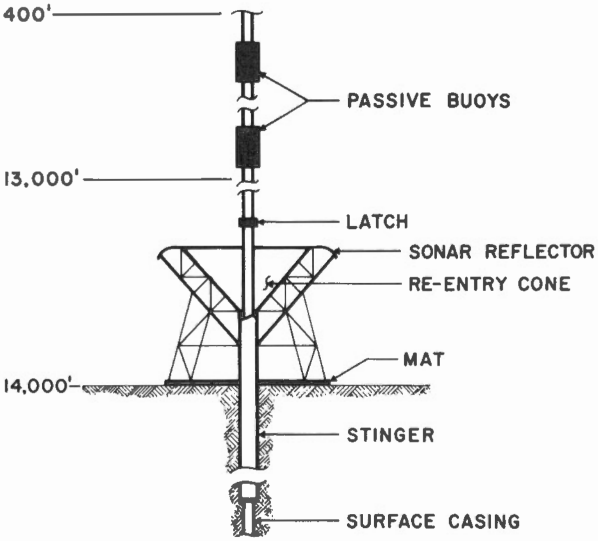


Figure 12. The landing base and lower riser components of the complex riser system that provides the vital link between the drilling platform and the sea floor.

the staff and a highly capable consulting firm as well, have we concluded that this system is feasible. The riser is also being designed to provide a means of re-entry should it become necessary for the platform to move off station, and to provide emergency support of the drill pipe and the riser with or without the platform on station. The 14,000-foot length of riser is dictated by the site water depth, while the inside diameter is dictated by clearance for 9 7/8" O.D. tools. Stresses will be induced in the riser and drill pipe by currents, waves, platform motion and maneuvers, riser and drill string weights and motions, buoyancy arrangements and mud pressures. A detailed stress study of all configurations was necessary to ensure adequate and reliable design of a suitable riser system. The basic system consists of a riser-to-base latch, riser buoyancy system, upper riser assemblies, and riser-to-vessel connection. Details of the landing base and subsurface casing are also relevant to the riser system.

A landing base will be provided at the sea floor (Fig. 12). Design of the base incorporates the flexibility necessary to accommodate the varying bottom conditions which may be encountered. The base will have a large diameter cone-opening which is compatible with the riser-to-base latch and casing hanger system, and will contain the necessary sonar targets for re-entry. A large diameter pipe "stinger" will be integral with and extend below the base. A special running tool will allow the landing base to be lowered on the drill string and be either washed or drilled into its final position on the sea floor. Casing hangers within the funnel will allow a number of casing strings of varying diameter to be installed, suspended, and cemented below the landing base. The casing program to be adopted will depend, to a large extent, on the nature of the subsurface formations but will in any event provide sufficient weight and/or bond to resist the tension at the bottom of the riser under all normal conditions and configurations. Bottom connection of the riser will be effected by means of a riser-to-base latch — this is also in the funnel with the riser extending up from the cone. The latching mechanism will be operated by vertical motion of the riser pipe and will be proof against accidental release. The riser will mainly comprise coupled 11 3/4" O.D., 80,000 p.s.i. yield pipe weighing 54 to 60 lbs per linear foot. Pipe dimensions will be increased in the areas of higher stress in the vicinity of the drilling platform and adjacent to the sea floor.

Figure 13 illustrates the upper riser system at the drilling platform. A constant tension slip joint will be incorporated in the upper riser to isolate the effect of tides, vessel heave, changes in draft, and elongation due to movement off-station from the main length of the riser. Immediately below the riser-to-vessel connection a guide-shoe will be provided to reduce the magnitude of the maximum bending stresses induced at the top of the riser by platform inclinations and by positioning maneuvers. The upper riser will normally be "fixed" to the platform; however, it will be possible to convert to a "pinned" or gimballed connection in the event of excessive riser stresses or vessel motions. During the pinned phase, any drill pipe within the riser will be hung from a seat provided in the riser at the gimballed connection. A second drill pipe seat will be provided within the riser immediately below the rigid buoy to provide emergency support of the drill string.

Inflation of emergency buoys in the upper riser system will be controlled to provide the requisite amount of buoyancy as the weight of the drill string is transferred from drilling platform to riser. Two upper riser disconnect points are provided to allow the platform to move off-station. One is above the inflatable buoys and one is immediately above the rigid buoy.

To avoid placing all loads through the slipjoint, buoyancy in various forms will be provided along the length of the riser. The overall buoyancy system is designed to: (a) support the submerged weight of the riser pipe — 14,000 feet of this pipe without any buoyancy would collapse under its own weight in the ocean; (b) supply a predetermined tension in the riser to reduce curvatures in the vicinity of the seabed — we want to take as much catenary out of it as we can; (c) compensate for the difference in weight between the drilling fluid column and seawater; and (d) in emergency conditions, support the submerged weight of any drill pipe hung in the riser. The basic components of the buoyancy system comprise passive buoys from 13,000 feet to 500 feet, variable capacity buoys on the upper riser (shown inflated in Fig. 13), and the buoyancy activation and destruction systems. The passive buoys will provide support for approximately 90 per cent of the submerged weight of the riser; in other words, it is still negatively buoyant with passive buoyancy only on it.

A major effort has been made to determine materials and/or systems which will reliably provide buoyancy throughout the design water depths. Of the 18 methods studied or tested, 2 reliable methods have been found for the full design-pressure range of 0 to 6200 p.s.i. These two methods are syntactic foams, a solid material which consists of glass microballoons in an epoxy resin, and flexible shells filled with a high flash-point, low specific-gravity oil. Also, metal spheres are feasible for water depths to approximately 3,000 feet.

Variable capacity buoys of two different types, placed on the riser over the depth range of 200 to 400 feet, will be used to provide the balance of the riser weight, pretensioning, and emergency buoyancy. Variable capacity buoys of both rigid (spherical, fixed displacement, and maximum diameter of 25 feet) and flexible (variable displacement) types for emergency situations will be used. Normally, the flexible buoys which provide the additional capacity to support the weight of any drill pipe being hung off on the riser during emergency conditions will be deflated.

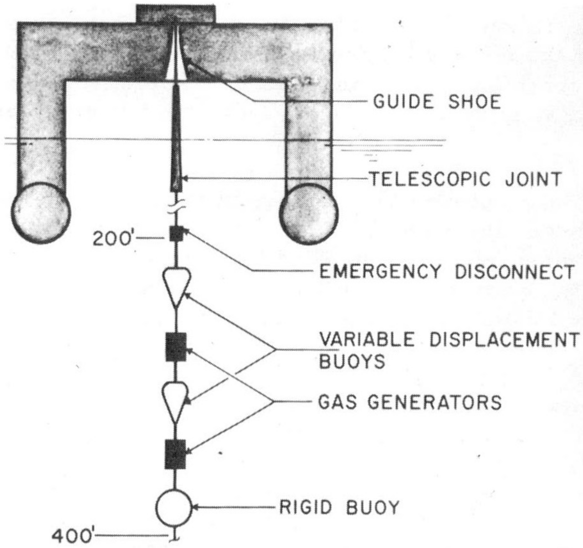


Figure 13. The upper riser system illustrating the riser-to-vessel connection and the riser buoyancy-control mechanisms.

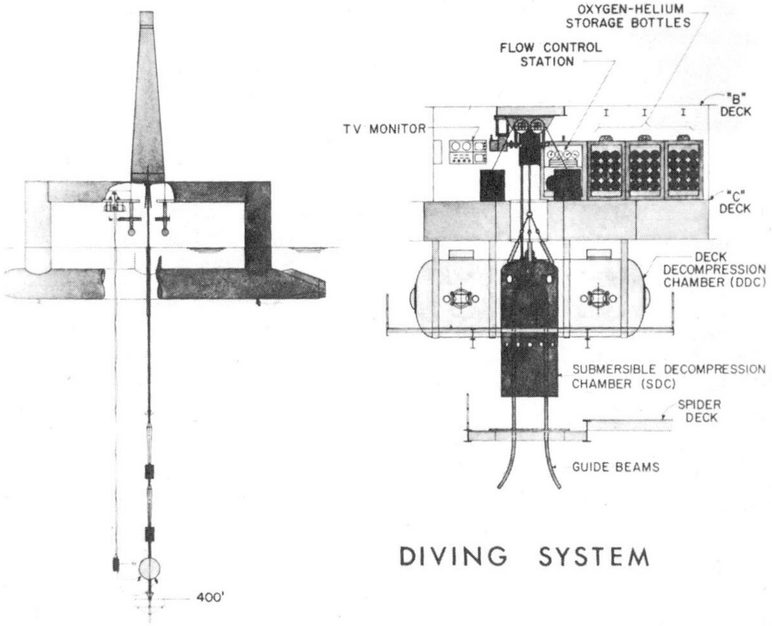


Figure 14. The helium and oxygen manned diving capsule designed for inspection and maintenance of the upper part of the riser system.

The capacity of the rigid buoy which can be varied by changing the amount of water ballast within the buoy will be adjustable from time to time to suit changes in the weight of drilling fluid and so forth.

Primary and secondary charging systems will be used to activate the variable capacity buoys. The primary system, located aboard the drilling platform, will be connected to each of the buoys with piping and armoured flexible hose. This system comprises a compressed air unit for day to day adjustment of riser pretensioning requirements. The primary system for charging the inflatable buoys utilizes a cryogenic nitrogen regenerator unit for supplying high volume displacement in the relatively short time intervals required for emergency operations. A secondary charging system will comprise underwater gas generators to be used only in extreme emergencies. This system will be used only in the event of failure of the primary inflation system or if an extremely rapid rate of inflation should be required. Two generators will be provided, one adjacent to each buoy. Each generator is an assembly of modules containing solid-fluid propellant and liquid refrigerant which mix together to generate the required volume of gas. The system is similar to that used for the Polaris missile launchings.

A buoyancy destruction system will prevent damage to the drilling platform in the event of riser failure. This system will consist of sensing devices on the riser, recording and actuating instrumentation aboard the platform, and explosive destruction devices on the buoys. The system will be capable of automatic activation if necessary.

INSPECTION AND MAINTENANCE SYSTEM

A helium and oxygen diving system has been provided to inspect and maintain all instrumentation and equipment in the upper 400 feet of water (Fig. 14). This system will also be utilized to replace any spent gas generator modules, to install the upper riser and to assist in reconnecting the riser after a move off location. All equipment below this depth will be maintenance free. The system consists of a three-man diving bell, an onboard 3 compartment decompression chamber, and all necessary life support and monitoring systems.

SUMMARY

To recapitulate briefly and summarize the present state of the Project, first, the platform has been designed and the bids for its construction contract are in and evaluated. We have until October 8th to make an award for the construction.* Construction will take 725 days which is very close to two years. The positioning system has been designed and is presently being fabricated — it is about two-thirds completed at present. The tremendous logging winches have been designed, are being fabricated, and we will take delivery on both of them this year. The turbocorer has been designed, fabricated, and field tested. The same applies to the turbocorer instrument package, as well as the sidewall corer. A thousand feet of serpentine was successfully cored in Puerto Rico and a report has been published (NAS-NRC, 1964). The riser system has proven feasible. Tomorrow you will hear about a retractable diamond core bit which also has proven feasible (see D.L. Sims , this volume). Commercial seismograph techniques have been successfully applied to deep ocean geophysics. We have an adequate communications system, designed to tie in the platform to the shore base, to the helicopters, to the supply boats, to the mainland, and to Washington. This morning you heard about the deep ocean untended digital data acquisition system which is being fabricated now (see W.P. Schneider, this volume). The underwater gas generator system has been designed, a model has been fabricated, and it was tested in 400 feet of water in Lake Tahoe last week. Additionally, there has been a fatigue testing machine designed which will be the first of its kind. It is a destructive machine that will accommodate full lengths of drill pipe. This development is in conjunction with a continuing program of steel investigation as well as the possibilities of using a titanium alloy drill string for the deeper parts of our hole.

REFERENCE

NAS-NRC. 1964. A study of serpentine, ed. C.A. Burk. Nat. Acad. Sci. Nat. Res. Council, Rept. 1188, Washington.

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*(Ed. note) In early October, 1965, the National Science Foundation announced that award of a contract for construction of the drilling platform to the National Steel and Shipbuilding Company, San Diego, California had been authorized. National's winning bid was $29.9 million, and construction will begin in January, 1966 (Science, 150, 195).

E. SESSION ON DEEP DRILLING TECHNOLOGY

Chairman: W.H. Tonking (U.S.A.)
Reporter: D.C. Findlay (Can.)

CORE DRILLING IN SOUTH AFRICA

W.S. Garrett,
The Cementation Company (Africa) (Pty.) Ltd.

Abstract

In South Africa, more than 545 bore-holes have been drilled to depths of between 5,000 and 8,000 feet, over 126 between 8,000 and 12,000 feet, and a few to greater depths, the deepest being 14,505 feet. This paper summarizes technical aspects of this type of diamond drilling carried out in South Africa for purposes of mineral exploration that may provide useful guides for drilling projects in other parts of the world undertaken in connection with Upper Mantle Project investigations.

Technical features of the design and performance of drilling equipment presently in use are outlined, including coring equipment, drill rods, bits, fluid systems, drilling instrumentation, wedges and wedging operations, drilling machines, derricks and various auxiliary equipment. Measurement and control of deviation and direction of bore-holes has not been a serious problem in most South African deep drilling, but several areas are known in which persistent severe deviations occur that cannot be uniquely explained by known geological conditions.

Drilling to depths of 18,000 feet can probably be carried out using existing equipment with only minor modifications, including the introduction of improved N-size drill rods in the upper part of the drilling string. Below 18,000 feet, efficient drilling performance will require considerable redesign and modification of existing equipment. Major improvements will be required in rod design and strength, and sturdier core barrels, bits, and reaming shells; however, the engineering problems involved are not insurmountable.

INTRODUCTION

This paper is mainly concerned with technical aspects of diamond drilling as carried out in South Africa for purposes of mineral exploration. Since the essential purpose of the work done is exploration, much attention has been paid to core recovery, and since the country is rich in gold deposits there has been justification for a considerable amount of boring to depths in excess of 10,000 feet.

The purpose of the paper is to set forth features of deep bore-holes in South Africa that might be of use when consideration is being given to deep holes in other parts of the world in connection with Upper Mantle studies. The design of machinery to drill deep holes is not difficult, but it is the behaviour of the drilling tools at depth and the imponderables connected with them that are of most interest.

More than 545 bore-holes have been drilled to depths between 5,000 and 8,000 feet, 126 to depths between 8,000 and 12,000 feet and a few to greater depths, the deepest being 14,505 feet. The great bulk of this drilling has been in search of gold-bearing ores in the Witwatersrand system, but in the process of looking for the formation in outlying areas a few holes have been drilled to considerable depths in lavas. The deepest such holes are in the Western Transvaal where a depth of 12,074 feet has been reached and in the Northern Free state where a depth of 12,836 feet has been reached. A few holes have been drilled for geological information in the search for oil in the sedimentary rocks of the Karroo system in the Cape, and in the Free State, Natal, and Zululand. The deepest of these holes near Laingsburg in the Cape, was 9,439 feet.

Extensive development work has been done on various aspects of the process of drilling, but no fundamental departures have been made from well-established world-wide techniques. Rather, development has been along the lines of multiple minor advances occasioned by the requirement to reach greater depths.

SIZE OF BORE-HOLES

In all this drilling an essential fact has been that the rock penetrated has, with a few exceptions, been hard and competent. There are of course, a variety of problems in penetrating the upper 1,000 feet at surface but once the lavas or Witwatersrand Formations have been entered, difficulties with caving holes have been rare. As a consequence of this fact, it has been possible to drill small slim holes, with the governing factor being the strength of the rod line to support the weight of the rod string. With very few exceptions all deep holes have been drilled B (2.10" O.D.) or BX (2.36" O.D.) size with NX (2.98" O.D.) used on relatively few occasions. Even in the few borings that have been made in Karroo measures, it has been possible to drill to depth using the same slim hole techniques, although some difficulties have been experienced in Zululand recently.

Occasionally, at any depths, bands of rock which disintegrate to sand have been encountered that have held up drilling for months. In some cases it has been possible to hold the caving by cementing, but more often it has been necessary to ream and case off the troublesome formation.

Since small holes have been drilled, the use of a drilling mud has not been necessary, and because of the small annular clearances involved, the use of a mud fluid is, in fact, hardly possible.

PENETRATION OF SURFACE MEASURES

The normal drilling techniques for penetrating surface measures — loose soils and decomposed rock etc. — such as the use of casing strings, mud, and the like, which are almost universal, are in common use in South Africa and need not be discussed here. One feature which is of interest, however is the penetration of cavernous dolomite occasionally encountered at depths down to 3,000 feet. This problem, although it may not be unique, is a serious one in the Republic because the gold bearing Witwatersrand rocks commonly underlie blankets of dolomite, sometimes up to 5,000 feet thick.

In the west Witwatersrand area in particular it is not uncommon to find enormous caverns in the 400 feet of rock above water table level, and these may be open or partly filled with loose chert rubble. No means of rotary drilling has yet been developed to cope with these conditions, and as some such caverns have been known to accept $2\frac{1}{2}$ million tons of slimes without filling up, the use of mud is precluded. The means of penetrating such ground is either by Jumper drilling or by air operated "down-the-hole" machines working inside successively reduced casing strings.

Below the water table the caverns rapidly reduce in size to fissures, but these occasionally persist to depths approaching 3,000 feet. Near water-table level they always contain mud and often chert rubble, and again present considerable obstacles to drilling. On a few occasions these fissures have been so extensive and so difficult to penetrate that holes have been abandoned. Fortunately, however, it is frequently possible to forecast the strike of such fissures and a hole can be re-sited to avoid the hazard.

Generally, however, it is possible to deal with dolomite fissures below water-table by cementation or the use of successive casing strings. The most effective cementation treatment is to seal the hole above the troublesome point by means of a packer (Fig. 1) and inject grout through the rod line under pressure. If the hole above the packer is water filled and can be pressurized during injection, there is little risk of the grout seizing the rod line. If, however, the hole is losing water, there is a real risk while injecting grout under pressure that it will bypass the packer and seize the rod line. Under these conditions the practice is to withdraw the rod string as grout is pumped into the hole so that only a few feet of rods are within the grout.

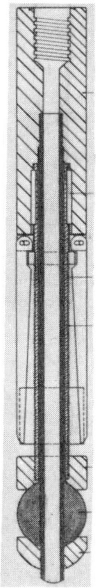


Figure 1. Bore-hole cementation plug.

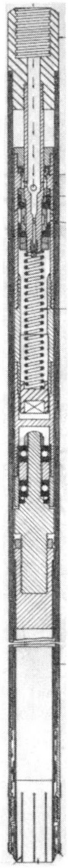


Figure 2. Improved double tube core barrel.

DRILLING PRACTICE

Coring:

Omitting any details of operations down to hard and competent rock, the general practice in South Africa is to drill small holes, rarely above NX (2.98" O.D.) size.

On holes of considerable depth the invariable method of control of bit pressure and feeds is hydraulic, and although attempts have been made to arrange automatic feeds to give constant bit pressure, manual control under a skilled operator is still the rule.

As the rock is nearly always hard, bit life is not long, often 20 to 50 feet, sometimes as low as 4 feet, and rarely as much as 100 feet; and since it is necessary to pull the rod strings to replace bits the use of wire lines for extracting core is not favoured.

Penetration speeds in normal hard rock conditions (quartzite) are of the order of 0.6 in./min., but length of runs which it is possible to get before core becomes blocked by wedging in the barrel or the barrel is full can vary from a few inches to as much as 60 feet. In very good ground it is common practice to use single tube core barrels, but as soon as ground is broken, or, in fact, if it is anything but very good, double tube core barrels are favoured and are usually 20 feet in length.

For normal drilling double tube core barrels are of the standard type, in which the core lifter or spring is free in the bit and rides tightly on the core. There is no doubt that the spring in this position has a tendency to break up core, and this has led to the more satisfactory but delicate arrangement of mounting the spring on the inner tube. This type of core barrel is always used in doubtful ground even at very great depth.

Some interesting and highly effective core barrels for special core recovery problems were developed in the late 1940s, and are described by G.A.P. Low (1950). The essential feature of both the two special core barrels (the Blair and the Garrett) is that the core spring is designed to be larger than the core size when in an uncompressed position. During drilling the inner barrel is lifted clear of the core spring which therefore rides up with the core till it becomes completely disengaged. In this position the spring provides no obstruction to coring. When it is desired to break off and withdraw core, the inner barrel is forced downwards compressing the core spring and bringing it into firm contact with the core.

Recently a further improvement has been made by W.M. Adamson using hydraulic pressure to lift the inner tube to which the core spring is attached during drilling (Fig. 2). This improvement ensures that the core spring is never in contact with the core until it is desired to grip, and the spring can be mounted so that it grips almost at the very bottom of the hole.

The bits or crowns are of standard design and very similar to those in use in other parts of the world. Much research has been done on bit performance at the Diamond Research Laboratory, and the subject is covered in a paper by J.F.H. Custers, C.R. Elliott and R.S. Young (1952).

The cutting clearances are kept small, and for a deep BX hole average 0.07" to 0.10" between core and core barrel, and 0.11" between core barrel and hole (Table 1).

Table I

Crown and Core Barrel Sizes *

SIZE	SINGLE TUBE CROWN		SHELL	CORE BARRELS					
				Single Tube		Double Tube			
						Inner		Outer	
	O.D.	I.D.	O.D.	O.D.	I.D.	O.D.	I.D.	O.D.	I.D.
B	2.100 2.090	1.400 1.390	2.110 2.100	2	1½	1.9/16	1.7/16	2	1.21/32
BX	2.355 2.345	1.660 1.650	2.365 2.355	2 1/4	1 3/4	1 7/8	1.23/32	2.9/32	2
NX	2.975 2.965	2.160 2.150	2.985 2.975	2.29/32	2 3/8	2.7/16	2 1/4	2.29/32	2.9/16

* All dimensions given in inches.

Because diamond drilling in this country started with American equipment and men and has been used on a large scale since the turn of the century, the old B (2.10" O.D.) size came into common use. More recently, as holes got deeper, the very considerable advantage of having a rod string only just smaller than the core barrel has been responsible for the continued use of this size.

Drill Rods:

As already mentioned, the old type B rod imported from America has served South Africa well for many years, but as depths became greater the maximum stress in the couplings became the critical factor. The highest tensile stress is developed in the minimum section of the coupling during deceleration due to braking in the process of lowering rods. Lowering speeds reach peaks of 24 ft./second, and under severe braking the deceleration takes place over 2.4 seconds. With, say, 8,000 feet of rods being lowered under these conditions, the maximum stress approaches 37,500 lbs./sq. in.

These figures are derived from actual observation of the speed of lowering under normal working conditions using a derrick 136 feet high and lowering rods in 120 foot lengths. The buoyancy effect of water in the hole has been taken into account in estimating the rod weight, but there is an additional factor during braking produced by the effort required to displace water past the core barrel acting as a piston. Since the actual lowering speeds have been observed, this braking effort was at least partially effective, but it is known to be of greatest assistance when holes are deep and when the core barrel size is close to hole size. To ensure the full braking effect it is the usual practice to fit a non-return valve in the rod line just above core barrels.

During drilling at, say, 8,000 feet, the static tensile stress would be approximately 32,500 lbs./sq. in., but to this must be added torsion stress. Much of this torsion stress is taken on the full rod diameter by reason of tightness of the joints, and, due to the number of variables, it is difficult to assess in practice. It is a fact, however, that rod strings do not often break in torsion even when seized up at the bottom of a hole. Breakages usually occur during drilling, and it is probable that the combination of direct weight, torsion and bending, coupled with fatigue, produce the limiting conditions, and trial and error has indicated that a sound practical limit to the use of B rods is about 8,000 feet. Depths very much greater than 8,000 feet have been reached with B rods, but at a risk of failure.

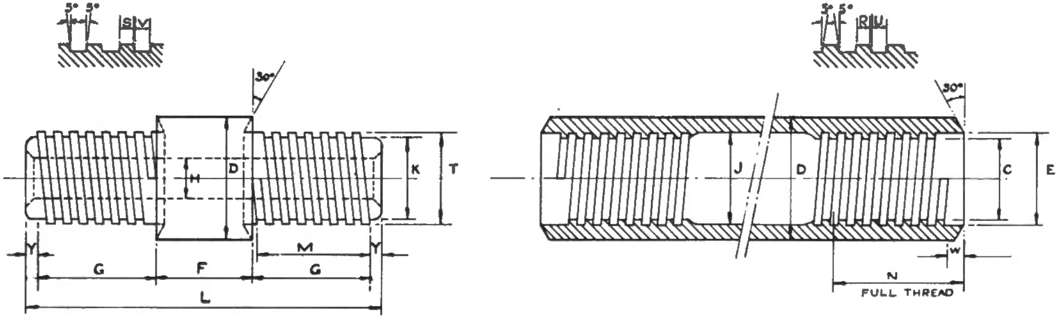
Rod and coupling size details are given on Figure 3, and specifications for two types of coupling steel in use are given in the Appendix.

A point of great importance in the manufacture of couplings has been found to be that heat treatment should never be used after final machining.

To provide extra strength for deeper drilling, what is known as a BX rod has been developed, which is slightly different from the world BW standards. Steel specification is the same as that generally used for B couplings, but research is under way to improve performance. These rods are used as a single string from surface, or alternatively they are used for the upper portion of a rod line below which a B hole is drilled using an 8,000 foot string of B rods.

By analogy with the apparent reasonable safe depth for the use of B rods, it might be expected that a safe limit to the use of BX rods by themselves might be 10,000 feet, and as a composite string with 8,000 feet of B rods, 13,500 feet.

These BX rods and couplings have been in service now for about five years, and have been entirely satisfactory to depths of 14,000 feet and more as composite strings, but trial and error have not yet confirmed that the figures indicated above are entirely satisfactory.



	THREADS PER INCH	C	D	E	F	G	H	J	K	L	M	N	R	S	T	U	V	W	Y
B	5	1·283 1·282	$1\frac{29}{32}$	1·408 1·407	$1\frac{1}{2}$	$1\frac{7}{8}$	·625	$1\frac{13}{32}$	1·280 1·275	$5\frac{1}{2}$	$1\frac{13}{16}$	2	0·094 0·088	0·094 0·090	1·405 1·404	0·101 0·095	0·099 0·095	$\frac{1}{4}$	$\frac{1}{8}$
BX	4	1·444 1·443	2·165	1·600 1·599	2	$2\frac{1}{8}$	·725	1·6	1·440 1·435	7	$2\frac{1}{16}$	$2\frac{1}{8}$	0·121 0·117	0·121 0·117	1·597 1·596	0·124 0·117	0·121 0·117	$\frac{3}{8}$	$\frac{3}{8}$
NX	4	1·954 1·952	2·685	2·141 2·139	2	$2\frac{5}{8}$	1·125	2·140	1·950 1·945	8	$2\frac{1}{2}$	3	0·116 0·114	0·118 0·116	2·138 2·137	0·120 0·118	0·118 0·116	$\frac{3}{8}$	$\frac{3}{8}$

Figure 3. Rod and coupling sizes.

Control of Bore-holes:

The problem of deviation of holes from the vertical is always a serious one, and in a very deep hole can be excessive, but fortunately the tendency to drift has not been serious in most holes in the Republic. All over the country and at various depths there have, of course, been some holes that deviate for exceptional reasons, possibly due to bad drilling in one form or another, or possibly forced off line by hard layers such as chert bands in the dolomites. These odd cases may be considered to be due to bad luck or bad operation and are bound to occur from time to time. They are therefore accepted as a hazard, but there are areas of persistent deviation which present a more serious problem in the drilling of very deep holes. This is a most puzzling phenomenon, however, as the three following cases indicate:

(1) On the East Witwatersrand, in the vicinity of Sub Nigel mine, the succession of quartzites dips very gently at about 5°, and in this area where drilling conditions are otherwise excellent, holes deviate at about 3° to 4° per 100 feet advanced and continue to deviate. This happens with all sizes of hole up to NX, and only by careful drilling with the use of heavy, stiff rods and core barrels, very small clearances and very careful load on sharp bits, is it possible to get holes down. One uncontrolled hole in this area deviated 68° from vertical at 4,000 feet, and yet another required 63 Hall Row wedges to keep it reasonably vertical. Just a few miles away, in the same horizons and with about the same formation dips, no trouble whatever is experienced.

(2) On the Central Rand, in the vicinity of Durban Deep mine where the dip of the Witwatersrand rocks is 35°, the same phenomenon is found; however in exactly the same horizons at much the same dip only a few miles away no trouble at all is experienced.

(3) On the Far West Rand where the dolomites are overlain by Pretoria shales and quartzites dipping at about 8°, the same phenomenon of rapid deviation is encountered, but in this area it is confined to the shales which are within 1,000 feet of surface.

Numerous explanations have been put forward for the deviation of bore-holes by A.F. Skirl (1933), G.A.P. Low (1950), W.S. Garrett(1952), and W.M. Adamson (1961). The hypothesis that deviation is usually due to ground conditions fits with the observed facts on deep borings in South Africa. Basically, it postulates an eccentric load on the bit face due to the cutting edge entering or leaving harder or softer layers, leading to the drilling bit having in effect, a component of horizontal travel direction as well as its axial direction of travel. The magnitude of this component depends on rock conditions and torsional effects.

If the above hypothesis is correct, then a continuous tendency to deflect can only be produced by a condition of the rock becoming harder or softer continuously over a considerable thickness, and not just by a sudden change into or out of a hard layer. Such a condition is quite possible, and could be produced by peculiar circumstances during the laying down of sediments, or by the influence of an igneous intrusion indurating surrounding rocks with maximum effect near the intrusion and gradually decreasing effect away from it. Whatever the cause of deviation, the problem is a serious one and is an ever present hazard to deep holes, but actually in South Africa it has not generally been enough of a hazard to prevent very deep drilling.

If a hole is deviating there is not a great deal that can be done, except to ensure that core barrels and rods just above them are as heavy and rigid as possible, that clearances are kept to a minimum, particularly just above the cutting edge, and that bits are used only so long as they are cutting freely with light bit loadings. These precautions will minimize deviation, but to correct holes some form of wedging is necessary.

The commonest of all wedging techniques is of course the Hall Row wedging system. There is no doubt that this system is effective; however, it is very tedious in application. The technique is too well known to need further description, and while effective, the system has the very material disadvantage that it puts a series of kinks in a hole and leaves a wedge of steel at each kink. If a great many wedges are needed, the hole in the end becomes troublesome, friction increases to a marked degree and occasionally a sliver of steel is torn off a wedge with disastrous results. Finally, due to friction and wear a wedge may become loosened and then the hole is lost. Nevertheless, large numbers of directional wedges have been set in deep holes, and the holes thereby kept within the desired limits. A particular application of this technique has been widely applied in drilling pregrouting holes for the treatment of ground prior to shaft sinking.

One of the best alternate devices used is the Weldon Whitehead, patented in 1945. Basically, this system uses a small turbine mounted in the bottom of a normal tool string to drill a pilot hole deviating from the line of the original hole. The pilot hole is then reamed out to full gauge. The pilot is a gravity-controlled device that falls to the lower side of an inclined hole and thus sets a correction in the direction of vertical. The method unquestionably produces a correction, but the process is slow and tedious; however, it has the advantage that no steel is left in the hole.

Numerous other devices for correcting holes, many using universal joints of various types, have been tried and have occasionally produced a correction, but generally they have been too unreliable and too tedious in operation to be successful.

A more recent attempt at deviation correction has been made by the introduction of the Clappison wedge designed and patented in Australia. In this device the wedge is lowered into the hole on the rod string and locked in by downward pressure. After drilling a pilot hole the wedge is withdrawn and reaming out of the pilot to full size proceeds. To date, the orientation of the wedge has been determined by orienting the rod string as it is lowered. While this is practical at shallow depth it is always difficult to determine if the actual position of the wedge is correct, and at considerable depth it becomes quite impossible. Some thought has been given to electrical means of checking the wedge orientation from surface, and if this can be done a greatly improved tool for the control of holes will be in our possession.

Fluid Circulation and Drilling Speed:

Due to the small clearances around the core barrel string, and the small size of rods used in slim holes, the circulating fluid is most commonly water. Normal circulation down through the rods and up the outside is the invariable practice, and pumping pressures are of the order of 600 – 800 lbs./sq. in. at a depth of 10,000 feet, most of which is needed to overcome frictional resistance to flow. Pressure across the bit is of the order of 100 lbs./sq. in. Although control of the flow is commonly by pressure gauges, a much better control is given by meters registering the actual flow down the rod line.

Soluble cutting oils and soft soaps have been used extensively in the circulating water from time to time, frequently with excellent results on bit life. There is some uncertainty as to why these better results are obtained, but it is generally thought that vibration is reduced and a smoother cutting action is obtained. It is quite common in the Republic, however, for holes to be drilled in formations, notably the dolomites, where water return is difficult or impossible, and in these circumstances the use of additives in the circulating water becomes costly. Where it is possible to use additives with the circulating water, no other rod lubrication is necessary, and hole friction is materially lower than when rod greases are used.

For over 50 years rod lubrication has been by means of heavy grease smeared on during the process of lowering. Without doing this or using soluble oils mixed with the water, intense vibration in rod lines is apt to develop, usually with disastrous results. Over-greasing can also be troublesome as grease transferred to the wall of a hole gradually picks up cuttings until it either makes the hole tight, or comes off in lumps. Washing out from time to time is therefore good practice.

These practices regarding fluid circulation are probably in common use, but it is of interest that they appear to be effective, at least in the Republic, down to 14,000 feet. At this depth heat does not yet appear to be a critical factor.

Rotational speed is a function of the rock type being cut, and of clearances, fluid circulation, and lubrication, as illustrated by the slow speed (about 200 r.p.m.) used to cut soft shales. At shallow depths and in small holes in hard rock speeds of 2,000 — 3,000 r.p.m. are often used, but these speeds are not possible in deep drilling. Since the rock at depth is usually hard in most deep borings in this country, rotation speeds of 300 — 500 r.p.m. are the rule. Speeds above this have been tried but the advantages gained are outweighed by the risk in rotating a long string of rods at high speed.

Pumping equipment for the small flows of 400 to 1,000 gallons per hour circulated is no problem, and numerous alternate systems are possible. Common practice is to use Duplex piston pumps of the Gardner-Denver type, or three throw ram pumps, driven by 15 to 20 H.P. diesel engines through gear boxes in order to provide some variablity to the flow if it is required. It is usually considered essential to have a separate pumping unit so that fluid flow is not dependent on any other functions.

INSTRUMENTATION

This subject, where it deals with recordings taken on completion of a bore-hole, is best left to my colleague, Dr. Haughton (see S.H. Haughton, this volume). However, during the process of drilling, it is necessary to survey holes for direction and magnitude of deviation, and for this a wide variety of instruments is used. Because of the small size of holes the more sophisticated bore-hole logging instruments of the oil industry are not used, and basically, the instruments in common use are of the type in which photographic records are made of compass and clinometer readings. They are reasonably accurate for the purposes of controlling holes within the practical limits of deep drilling. A locally-developed instrument of this type is the "Marland", and a well known imported tool which is much in favour is the "Docenette", made by Leutert of Western Germany. This latter instrument is capable of reading angles of 0 to 120° from vertical. Currently, attempts are being made to develop electronic instruments, but as yet these have not passed the development stage.

At one time it was considered safer to lower instruments on a rod string, but this has given place in recent practice to dropping instruments down holes on a wire line.

While final control of bore-holes is thus determined by fairly accurate instruments, field control and testing is still carried out by the simple process of etching a glass tube with hydrofluoric acid. It is common practice to mount the glass tube with its acid in the head of the core barrel, lower it to the point at which a test is required, allow it to stand for about an hour to etch the line of the meniscus at the surface of the acid, and then proceed with the drilling. On withdrawal, the etch line on the tube gives a reasonable check on verticality of the bore-hole. The system is crude, but is very useful as a field test for deviation.

The control of drilling weight and fluid circulation has already been mentioned, and for these factors the essential instruments on the machine are pressure gauges on the hydraulic cylinders, and flow meters and pressure gauges on the circulating water system. Additional instruments which are not essential, but which make an important contribution to efficiency, are revolution counters on the drilling head and tachometers on the machine to record round the clock operation.

DRILLING EQUIPMENT

The equipment required on the surface to produce the functions of drilling at depth is relatively much less important than the actual drilling mechanism, with its remoteness down the hole and all the imponderables connected with it. The surface machinery designed to cope with loads and conditions which can be calculated within reasonable limits can be worked out to produce the results by normal design techniques, and is therefore discussed only briefly in the following section.

General Assemblies of Machines:

The machine most commonly in use in South Africa is the Joy-Sullivan 50 drill built in South Africa and illustrated in Figure 4. It is a simple "in line" arrangement of Caterpillar 96 H.P. engine driving directly through a gear box to either the rotating head or the hoist. The drilling drive is via bevel gears to a hollow hexagon drive rod which carries the chuck and which has a vertical movement range of 33 inches controlled by 8-inch diameter hydraulic cylinders. The weight of the rod string is carried through the chuck to the hydraulic cylinders through a heavy thrust race. All controls are manual, and the hoist is operated by two levers, one controlling the clutch and the other the brakes. It should be noted that as lowering of rods takes slightly less time than hoisting, a very large amount of heat must be dissipated in the process, particularly as depth increases.

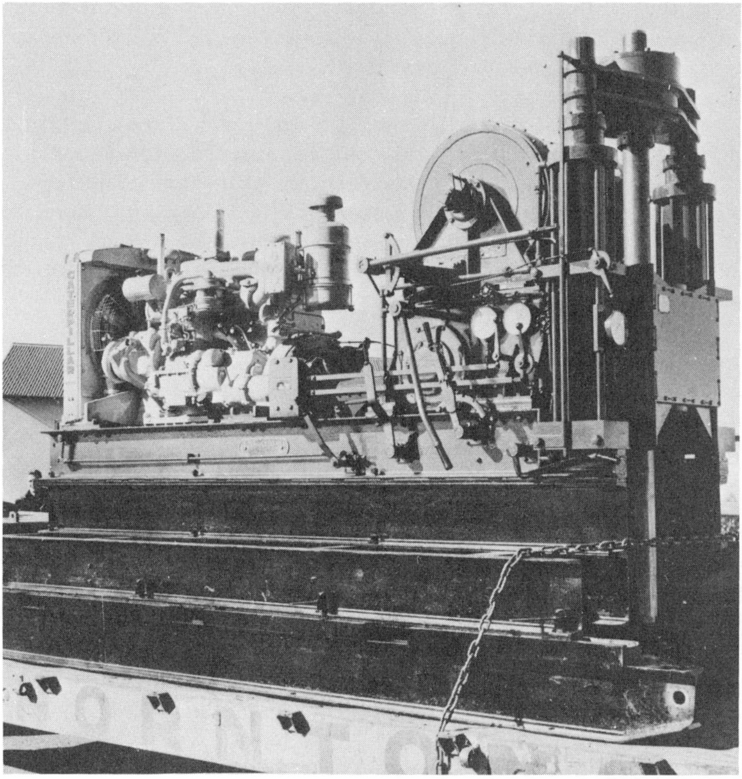


Figure 4. Joy-Sullivan "50" diamond drill.

At a depth of 10,000 feet the dissipation of heat energy is about 80,000 B.T.U. per hour which can most conveniently be handled by the use of water cooled brakes.

The hoist unit is mounted along the axis of the machine and is an 18 inch diameter drum, 12 inches long and having water cooled brake paths on both cheek plates. It is operated by a chain drive direct through a clutch. The Joy-Sullivan 50 is an extremely versatile and robust rig, and although it was designed to drill with B rods to a depth of 10,000 feet, it has in fact been used down to 14,505 feet. By any standards, this is a gross overload and is testimony to the durability of the machine.

The Sullivan 55 drill (Fig. 5), of which there is only one in the country, was designed before the war, and has a basic capacity for very deep work. This unit has a large 24-inch dia. by 30-inch long hoist which is mounted independently of the drilling head. Originally the drive to both hoist and head was by steam engine, but this has been rebuilt and it now operates with two separate diesel engine drives working entirely independently. The hoist, which is now mounted as a separate unit, is driven by a 200 H.P. Caterpillar engine, and the head is driven by a separate 52 H.P. engine.

Another rig, the Gold Fields 10 (Fig. 6), was designed and built in South Africa along the lines of the Sullivan 55, but is driven by a single 200 H.P. Caterpillar engine. This unit has a particularly satisfactory hoist similar in size to the Sullivan 55. Having been designed for depths of 10,000 feet it uses a very heavy thrust race to carry the load onto 10-inch hydraulic cylinders.

There is another variation of equipment used on deep holes which has much to commend it. This system uses a Sullivan 50 for the start of a hole, and as depth increases the Sullivan machine is used purely as a drilling unit, and a separate and much heavier "Draw Works" is brought in to do the hoisting. This separate hoist unit is made by the Joy-Sullivan Company and is designed to handle rod strings of 12,000 feet. It is powered by a 290 H.P. Rolls-Royce engine, and is fitted with torque converter and compressed air controlled clutch (Fig. 7).

Drilling Control

Speed variation during drilling is controlled through the gear box and engine throttle. While this system is generally effective, it is not particularly sensitive and has the disadvantage that in most cases an engine of 96 H.P. is being used while throttled back, and the momentum of power

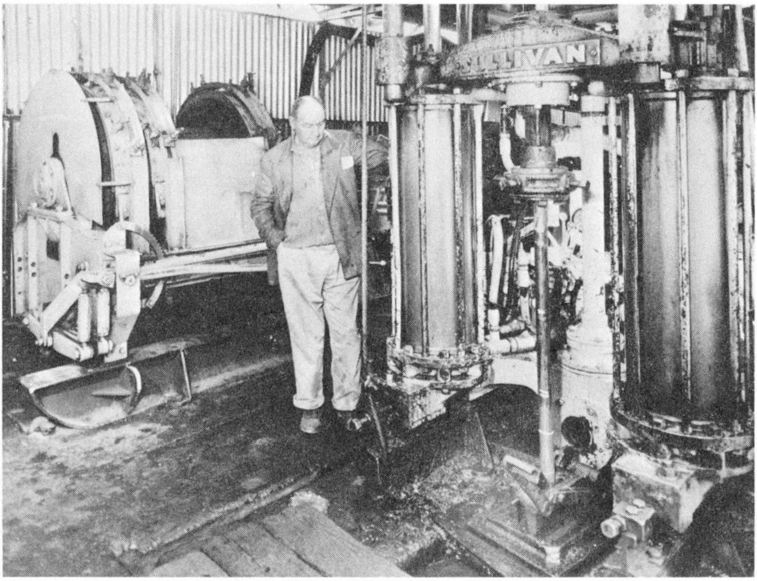


Figure 5. Sullivan "55" diamond drill. The separate hoist on this machine is driven by a 200 h.p. Caterpillar diesel engine and the head by an independent 52 h.p. engine.

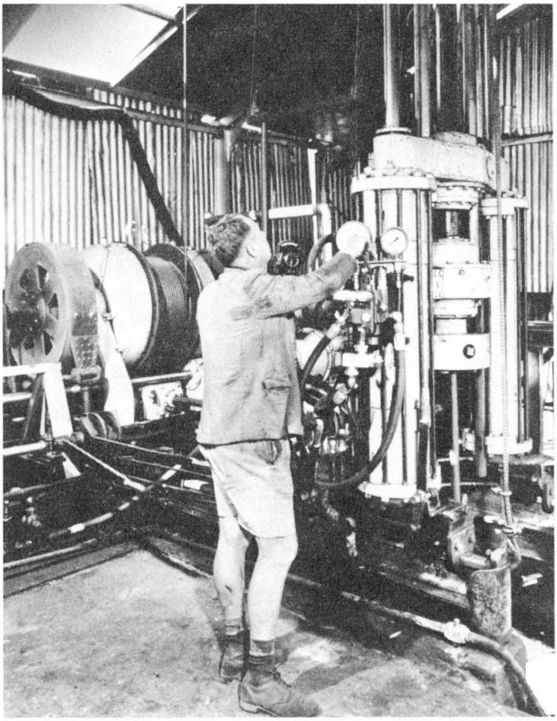


Figure 6. The Gold Fields "10" diamond drill was designed for depths of 10,000 feet and is powered by a single 200 h.p. engine.

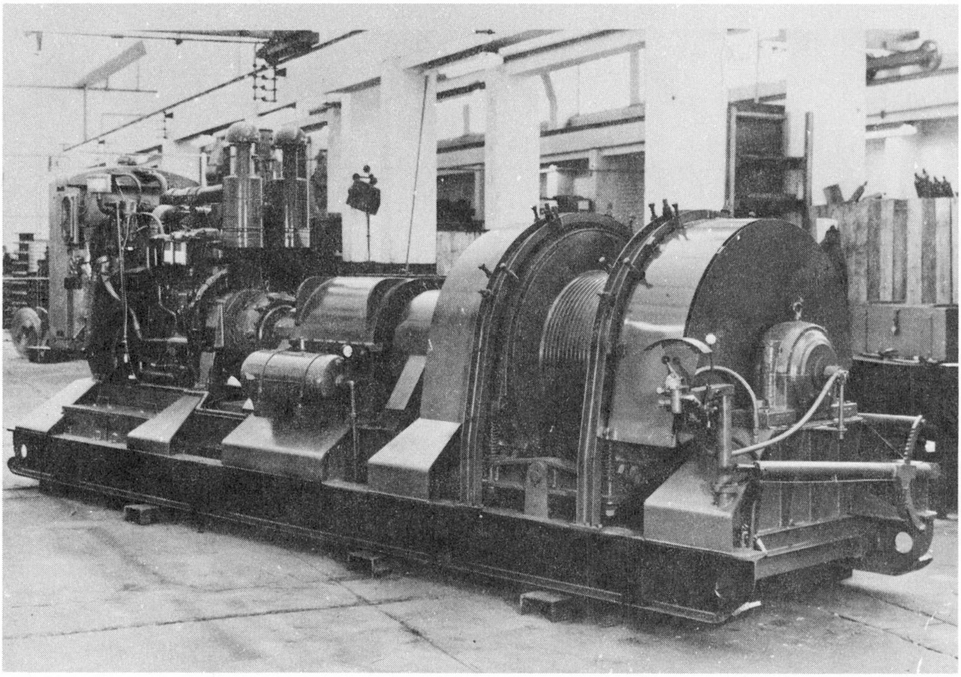


Figure 7. Joy-Sullivan draw works powered by 290 h.p. Rolls Royce Engine.

behind it is such that there is very little warning between the time that something goes wrong in the hole and a smash-up.

A 10,000 foot rod string hanging in a wet hole weighs not less than 35,000 lbs., a weight which it is obviously inadvisable to rest on a thin-wall core barrel standing on the bottom of a hole. It is therefore the invariable practice to carry the rod weight, and during drilling the load is carried through the chuck and thrust race onto hydraulic cylinders. Thus, a very delicate weight control is possible even at great depth. Feed is provided by bleeding oil from the cylinders through a needle valve.

Drill head chucks in use are the normal 4 jaw manual type with each jaw gripping an arc of 48° over a length of 2 3/4 inches; however they are rather slow in operation and have reached about the limit of their present capacity. A newer type of chuck is based on the use of tapered jaws drawn into place by the actual rod weight. This type is much faster in operation, is self centring and is now used almost universally (Fig. 8).

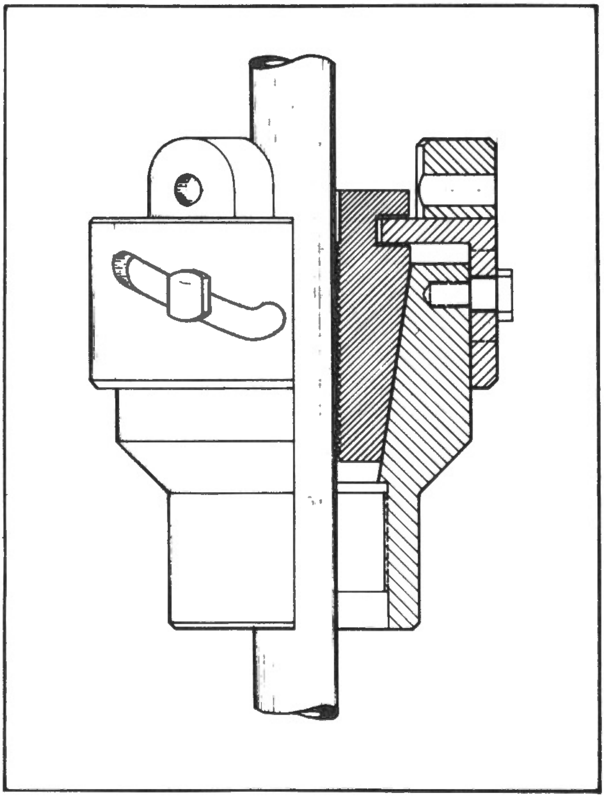


Figure 8. Tapered jaw self-centring chuck that is automatically activated by the weight of the rod string.

Foot clamps are invariably what is known as a "Macnamara Clamp" (Fig. 9), which uses only two jaws with removable high grade steel insert grips covering an arc of 120° with a contact length of 6½ inches. They are highly effective and rarely cause trouble.

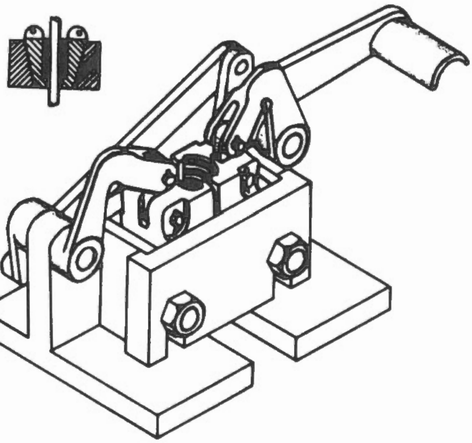


Figure 9. Macnamara foot clamp.

Hoisting Systems

Figure 10 shows progress records of two recent holes drilled in fair but broken ground, giving short runs, and therefore requiring frequent raising and lowering of rods. Although the drilling conditions were comparable, both holes having been drilled in dolomite, the faster hole was drilled with a Gold Fields 10 rig and the other with a Sullivan 50. In the case of the Gold Fields 10 machine, raising and lowering rods required from 35 per cent of the total time at 1,000 feet to 50 per cent at 6,000 feet, whereas the figures for the Sullivan 50 were 45 per cent at 1,000 feet to 80 per cent at 10,000 feet. Hoisting and lowering is thus a matter of paramount importance at depth, and the time required for these operations is directly affected by the two main factors of hoist horsepower and the length of the rod string pulled in each stand.

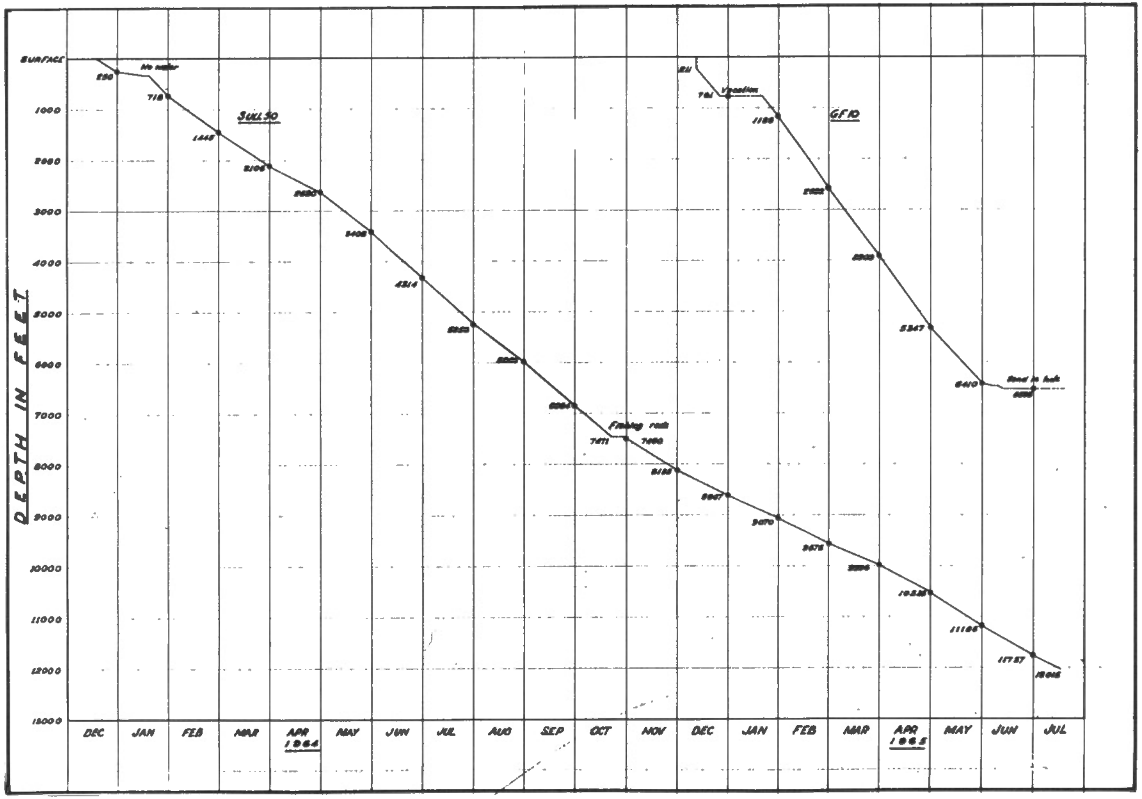


Figure 10. Progress records comparing two holes drilled with different machines. The shorter hole (upper right) was drilled with a Gold Fields 10 rig; the other with a Sullivan 50 machine.

The actual hoist, rope and sheave arrangements, and brakes are therefore solely matters of academic design having regard particularly to the two main factors noted above. A common arrangement at 10,000 feet on a Sullivan 50 rig is to use five falls of 13/16-inch rope winding onto an 18-inch diameter by 12-inch drum and pulling 60 foot stands of rods. With this assembly a normal time to pull out 10,000 feet of rods is about $6\frac{1}{2}$ hours, while lowering time is about $5\frac{1}{2}$ hours.

A 60 foot stand is about the maximum length that B rods will stand without buckling. With bigger drums on the hoists, 136 foot derricks can be used with advantage, pulling rods in 120 foot lengths which are hung in the derrick from slings. These extra lengths of stand are of great assistance in hoisting from deep holes.

The invariable practice of handling rods is by means of loose elevator plugs made from the same material as the couplings and Wilson elevators. Screwing and unscrewing is done by hand.

Derricks:

A few jack knife derricks are in use and they are particularly valuable on the shallower holes where their mobility is of great advantage, but for most very deep holes standard framed steel derricks are favoured. For the 60 foot rod stands, 84 foot Lee Moore derricks are very common, but for the 120 foot stands, locally made 136 foot angle-iron derricks are used (Fig. 11). Their design presents no unusual features in terms of normal structural engineering practice.

DEEPER DRILLING

The possibilities of deeper drilling should be considered in two categories; the first utilizing existing equipment, and the second involving major redesign of existing equipment. The first category would involve the use of existing equipment with only the addition of a further string of N rods of better quality than currently in use now. In such a design, the hole might be NX size to 4,000 feet, BX size thereafter to 10,000 feet, and B size to 18,000 feet. This string of rods in a wet hole would weigh about 80,000 lbs., and with some overload this could probably be carried on the existing thrust races used on either the Sullivan 55 or Gold Fields 10 drilling heads. An improved N rod for this particular duty would have to weigh about $8\frac{1}{2}$ lbs. per foot and be capable of carrying the overall load of 80,000 lbs. This would require a steel of higher grade than that now specified for standard rods.

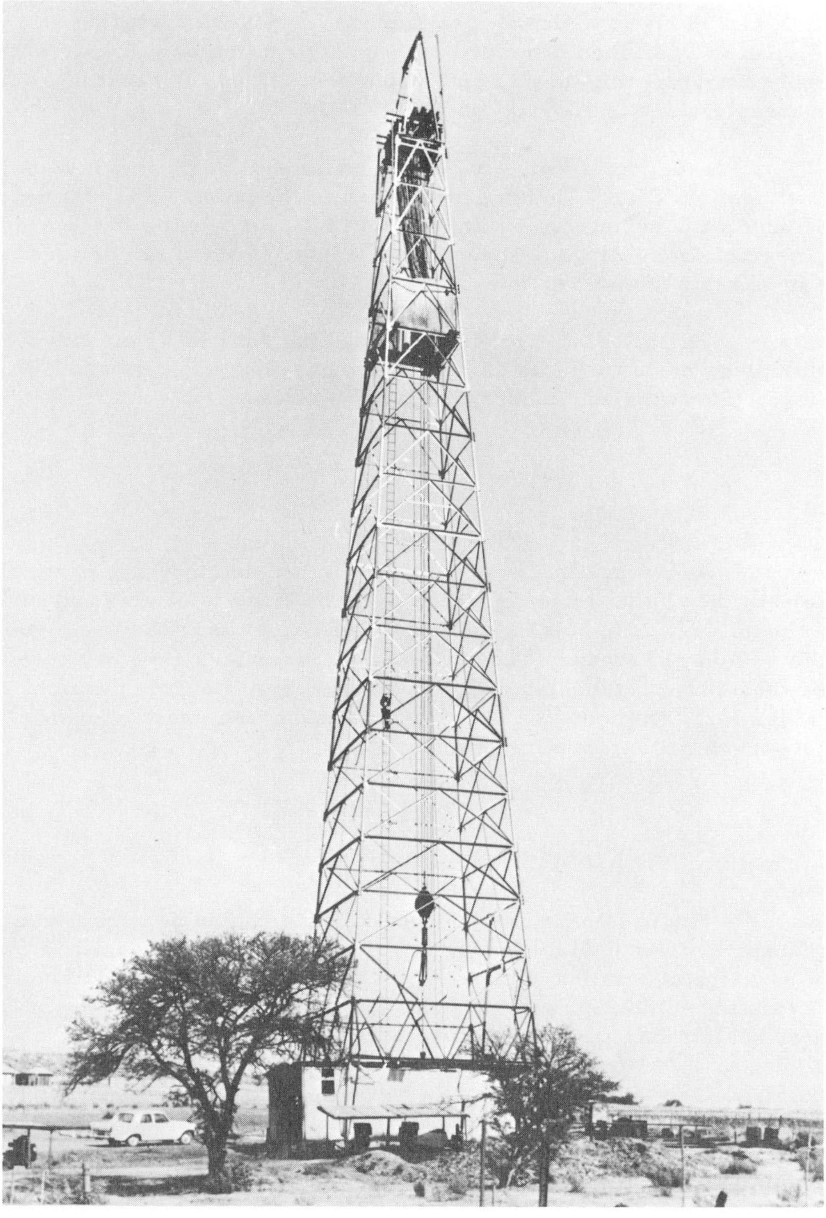


Figure 11. Locally built 136 foot derrick used with 120 foot rod stands on deep holes.

Sufficient coupling strength with this diameter of rod could be obtained with the steels in use at the present time and the production of such rods should not present a serious or costly problem.

The Joy-Sullivan type separate hoist unit powered by a 290 H.P. Rolls Royce engine would probably do the hoisting, provided extra falls were introduced which the present drum has the capacity to take. It would undoubtedly be necessary to duplicate chucks and to increase the size of the Macnamara clamps, but these are small units and could be produced as relatively minor modifications. With an increase in the number of falls and the design of heavier sheaves and Wilson elevators, the alterations to the running gear would be minor.

It is thus reasonable to assume that with very minor alterations to existing gear and the introduction of a limited quantity of new special N rods, we could drill to depths of the order of 18,000 feet. The machines used would, in fact, be adaptations of the Sullivan 55 drill.

At depths of 18,000 feet the B core barrel equipment at the bottom of a hole would not be able to stand any sort of ill treatment, and it would seem likely that to go any deeper much sturdier bottom-hole equipment would be needed. There is reason to suppose that core from very deep holes may tend to break up as a result of stress relief (J.C. Jaeger and N.G.W. Cook, 1963) and as depth increases this phenomenon could reach the stage where very much larger clearances would be necessary if excessive pulling and lowering for short runs is to be avoided. It is a fact that at depths of the order of 12,000 — 14,000 feet it is possible to drill an initial hole with very little trouble, but a deflection very close to the original hole can give considerable trouble with broken core. This can only be due to fracturing of the rock due to stress relief, even in so small an excavation as a 2-inch hole. There are, however, practical indications that this is not a serious problem, as reports from all very deep holes indicate a steady improvement of the coring conditions with depth.

The temperature gradient in the Witwatersrand quartzites is of the order of 5°F per 1,000 feet of depth, and in the lavas the figure is 7.5°F per 1,000 feet, whereas it might be as high as 15°F per 1,000 feet in banded shales. In a deep bore-hole in lava the rock temperature at 14,000 feet would be of the order of 170°F with a surface temperature of 65°F. At 18,000 feet this would be 200°F, and at 25,000 feet it would be 250°F. At this depth, however, the water pressure would be far higher than the critical pressure at which the water would vaporize. Furthermore, an initial mean rate of heat transfer from the rock could be of the order of 9 B.T.U. per hour per sq.ft. of hole surface per 1°F difference in temperature between rock wall and circulating water. On the basis of a $2\frac{1}{2}$ inch diameter hole 25,000 feet deep, this would represent 1,500,000 B.T.U. per hour transferred to the water. With a circulation of 1,000 gallons per hour this means a rise in water temperature of only 150°F. In point of fact the rate of heat transfer would drop off sharply to about 1/10th of the above figure in a week of pumping. It is clear therefore that temperature is unlikely to present any great difficulty to deep drilling in South Africa.

Finally as depth continued to increase, raising and lowering times would increase. This would mean very slow progress at depth, even assuming reasonable coring conditions, and disastrously slow if the core was tending to break up due to stress relief.

If we are to consider going to depths greater than about 18,000 feet, some major redesign and changes would be necessary, involving a very considerable expenditure. The problems of derricks, ropes, sheaves, clamps and chucks, could be solved simply by increasing sizes to cope with the heavier loads. Similarly, hoist design would present no difficulty, but it would be desirable to increase horsepower considerably to reduce raising and lowering times. The design of drilling heads would not present insurmountable problems, but a material advantage in speed and rod control could be obtained by driving the head hydraulically. An arrangement such as this would give infinite speed range control, but more important, it would give a continuous check on torque applied, and therefore resistance in the hole.

The major change in equipment for deeper drilling would have to be in the direction of lighter rods made from high tensile material, much sturdier core barrels, greater clearances and more robust bits and reaming shells. There would also have to be much improved fluid circulation with infinitely variable pump speed control, and improved casing or sealing of the upper hole to ensure water return. While the design of rods and coupling would follow normal lines of development, factors such as clearances and bit design would probably have to be matters of judgement. In fact, whether it would be possible to core at all at depths of the order of 25,000 feet, would depend entirely on the rock condition and the improvement of equipment by trial and error as depths increased.

ACKNOWLEDGMENTS

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APPENDIX

Steel Specifications

Couplings

(1) Firth Browns F.65. Imported

Chemical Analysis:

C.	0.25
Si.	0.25
Mn.	0.55
Mo.	0.45
Va.	0.20
Cr.	1.20

Yield Point:	75 tons per sq. in.
Elongation:	18%
Izod Value:	50 lbs. ft.

(2) E.N.23 Mova S.A. Manufacture

Chemical Analysis:

C.	0.20 to 0.30
Si.	0.350 Maximum
Mn.	0.45 to 0.65
S.	0.05 Maximum
P.	0.05 Maximum
Ni.	2.75 – 3.52
Mo.	0.65 Maximum
Va.	0.25 Maximum
Cr.	0.90 to 1.30

Physical Properties:

Oil Quench 830°C and tempered at 640°C.

Rods

South Africa Manufactured Steels

Chemical Composition:

The steel shall conform to the following chemical composition:

Table I

	Medium Carbon Steel (TAC)	Alloy Steel (N80)
Carbon	0.40% to 0.55%	0.40% to 0.47%
Manganese	0.70% to 1.00%	1.20% to 1.50%
Sulphur	0.06% Maximum	0.04% Maximum
Phosphorus	0.06% Maximum	0.04% Maximum
Silicon	0.35% Maximum	0.35% Maximum
Molybdenum	Nil	0.15% to 0.25%

Mechanical Properties:

(a) Cold Drawn and normalized Drill Rod Tubing, either upset or plain, will develop the minimum mechanical properties as shown in Table II. Cold Drawn stress relieved plain end drill rod tubing is available in the medium carbon steel only and will develop the minimum mechanical properties as shown in Table III.

(b) If mechanical tests are required and specified on the order, the number of tests and the costs of same are subject to negotiation between the purchaser and the manufacturer.

Table II

Minimum Mechanical Properties as Normalized

Grade	Tensile Strength lbs. per sq. inch	Elongation	V.P.N. Hardness
Medium Carbon Steel (TAC)	85,000	15% on 2"	190
Alloy Steel (N80)	100,000	15% on 2"	210

Table III

Minimum Mechanical Properties As Stress Relieved

Grade	Tensile Strength lbs. per sq. inch	Elongation	V.P.N. Hardness
Medium Grade (TAC)	100,000	10% on 2"	230

A DISCUSSION OF ROTARY DRILLING IN IGNEOUS ROCKS OF WESTERN U.S.A. AND ALASKA IN THE 5,000'-10,000' DEPTH RANGE

S.C. Foster
Brinkerhoff Drilling Co. and Shaft Drillers, Inc.

Abstract

This paper discusses experiences in the U.S.A., in drilling igneous rocks using oilwell equipment, and draws comparisons between normal oilwell drilling practices and those necessary for successful penetration of igneous rocks. Penetration rates in igneous rocks are usually lower than in sedimentary rocks by factors of 4 to 35; costs may be higher by factors of 2 to 10.

The two most important variables affecting drilling rate in igneous rocks are the weight on the bit and the type of circulating medium used. Air is the most efficient circulating medium, but highly fractured or faulted igneous rocks commonly carry too much water to permit the use of air.

INTRODUCTION

This paper is primarily concerned with our experiences in drilling igneous rocks with land-type drilling rigs in the western U.S.A., western Canada, and Alaska. As you will see in the film that I will show later,* the drill pipe that we use in the large 72 inch holes is 13 3/8 inches in diameter as compared with the normal oil field pipe size range of $3\frac{1}{2}$ to 6 5/8 inches, with most holes drilled with $4\frac{1}{2}$ inch pipe. The typical hole sizes in sedimentary rocks range from approximately 6 inches to 12 1/4 inches in diameter, with the most common sizes being 7 7/8 to 9 inches. These latter two sizes are probably the most economic to drill in sedimentary or igneous rocks. Standard oilwell rigs using this type of equipment have drilled to depths of nearly 26,000 feet in sedimentary rocks.

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*A film produced by the United States Atomic Energy Commission entitled "Big Hole Drilling on Pahute Mesa" was shown following Mr. Foster's paper.

Prior to 1963 there had been approximately 7,000 feet of igneous rock drilled with oil field equipment in the western U.S.A.; however, since then there has been considerable igneous rock drilling, both in the eastern and western parts of the country. In 1964, two 10,000 foot holes were drilled in granite in the east, one in West Virginia and one in Pennsylvania; in the west five 12 1/4 inch holes to 1,500 feet were drilled in northern Nevada, also in granite. In the same year a 10,000 foot hole was drilled in granite in western Wyoming, being 12 1/4 inch to 4,500 feet and 8 3/4 inch from 4,500 to 10,000 feet. I believe that this latter hole is the record for continuous drilling in granite in western U.S.A. Also in 1964, a 3,000 foot 12 1/4 inch hole was drilled in northern Manitoba and this hole was later opened to 48 inches in diameter down to 3,000 feet. At the present, there is a 10,000 foot hole being drilled in Alaska, having an upper section 12 1/4 inches in diameter and a lower section (below 4,500 feet) 8 3/4 inches in diameter. This latter hole is being drilled in volcanic schists. It may be noted that, until three or four years ago, very little footage had been drilled by the oilwell industry in volcanics. However, during the past few years there has been about 150,000 feet drilled in volcanics in southern Nevada, mainly in tuffs and rhyolite. One hole in southern Nevada was drilled to 14,000 feet, exclusively in volcanics.

The rock types drilled in the holes mentioned above have been highly variable, but the most common formations have been pink quartzite, diorite, gabbro and biotite schists.

COSTS OF DRILLING IGNEOUS ROCKS

The chief comment that can be made concerning the costs of drilling igneous rocks is that they are highly variable. Typical costs of drilling sedimentary rocks in the oil fields range from as low as $1.00 per foot up to $15.00 per foot, with rare instances of higher footage prices. However, it requires a very productive oil field to justify costs greater than $15.00 per foot. On the other hand, igneous rocks are much more costly to drill because of the slow penetration rates realized, and footage costs here may range from $10.00 to as high as $100.00.

In the oilwell drilling industry there are approximately 8 or 9 rig classifications, starting with a 1-2,000 foot rig costing about $400 per day, up through a 7-10,000 foot rig costing about $1,300 per day, to a 25,000 foot land rig costing approximately $1,800-2,000 per day. Then of course there are the offshore rigs that can cost up to $6,000-7,000 per day. These are only the costs of operating the equipment on the drilling rig, and do not include costs of bits, drilling mud or air, logging, coring or rig mobilization; however, they illustrate part of the reason why drilling costs below 10,000 feet increase exponentially.

Factors affecting costs include remoteness of the site, depth of hole, rock drillability, lost circulation problems, deviation problems, sloughing holes, and high pressures.

BITS

Prior to 1956 there had been practically no drilling done in igneous rocks with rotary equipment; however, the advent of the tricone tungsten carbide button bit at about that time provided an economic means for penetrating these rocks. The normal oil field bits are called milled tooth bits, and they penetrate the rock through the cutting action of sets of rotating teeth. The button bit, on the other hand, has circular tungsten carbide inserts or buttons instead of teeth mounted on three cutting cones. It penetrates the rock as a result of the crushing action imparted by the carbide buttons, which exceeds the compressive strength of the rock, causing chips to be broken out.

DRILLABILITY OF IGNEOUS ROCKS

In a general way, as rock density and ultimate strength increase, drillability decreases; however, there does not appear to be a rigid correlation between these variables. We have often drilled rocks with ultimate strengths of 45-50,000 p.s.i. much faster than we can drill rocks of lower ultimate strengths and densities.

Penetration rates in igneous rocks are highly variable but probably range from a low of 1 foot per hour up to 12 feet per hour. This compares with penetration rates in sedimentary rocks such as sandstone, limestone, shale and dolomite that may reach as high as 350 to 400 feet per hour. In the 10,000 foot hole in granite of western Wyoming the penetration rate varied greatly, but averaged about 4 feet per hour. The ultimate strengths of the rocks in this hole ranged from approximately 25,000 to 45,000 p.s.i.

There are three general concepts on the drillability of igneous rocks. The first is that the finer the grain size the slower the drillability; second, as the total quartz content of the rock increases, the drillability decreases; and thirdly, the type and size of material cementing the grains probably has the greatest effect on drillability. In sedimentary rocks, two other factors affecting drillability are porosity and permeability; however, as igneous rocks are relatively non-porous and non-permeable, these factors probably do not exert much influence.

The drilling rates in igneous rocks can be greatly influenced by the choice of drilling technique and equipment. I do not refer here to the use of exotic tools such as the turobdrill, dyna drill, or hammer drill, but rather to variations in conventional techniques employing direct circulation of the fluid medium down the drill pipe to clean the face of the bit and return the cuttings to the surface through the annulus. In this connection, variables that may influence penetration rates include the type of bit – as previously mentioned button insert bits are used almost exclusively – weight on the bit, and rotary speed. Optimum weights for igneous drilling are about 6 to 8,000 pounds per inch of bit diameter, which would mean that on a 9 inch bit, weights of the order of 70,000 pounds would be carried. In contrast to drilling in soft sedimentary rocks where we usually have low bit weights and very high rotary speeds, the best results are obtained in igneous rocks or hard sedimentary formations by using high bit weights and very slow rotary speeds. In sedimentary rock drilling the general rule is that the weight on the bit is in direct proportion to the penetration rate — in other words, if drilling with 10,000 pounds of bit weight gives a penetration rate of 5 feet per hour, a bit weight of 20,000 pounds should increase the penetration rate to about 10 feet per hour. However, this only holds true up to the point where the circulation medium lags and can no longer keep the bit face clean. These rules apply in general to igneous rock drilling, although the optimum weight on the bit (6-8,000 pounds per inch of bit diameter) is usually greater than in sedimentary drilling (about 5,000 pounds per inch of bit diameter on button-type bits).

CIRCULATING MEDIUM

Probably the most important consideration in drilling either sedimentary or igneous rocks is the proper selection of the circulating medium, be it air, aerated water, air mist, water or mud. In drilling sedimentary rocks, penetration rates can be increased 2 to 4 times by using air as the circulating medium rather than mud. Unfortunately, in several holes drilled in igneous rock that I have mentioned we encountered large water-bearing zones and this, of course, practically eliminated the use of air. However, in a water-free hole in igneous rocks it is probable that air drilling could result in greatly increased penetration rates.

DEVIATION OF HOLES

In our experience in drilling oil field size holes in igneous rocks, we have had considerable problems with hole deviation, and this is probably due to the relatively high degree of faulting and fracturing in these rocks. We have found that when a hole penetrates fracture or fault zones, it commonly results in an abrupt change in deviation.

CONCLUSION

In conclusion, I would comment that the land-type oilwell drilling equipment, both in North America and overseas is probably capable of drilling in igneous or metamorphic rocks to depths of 25-26,000 feet without any major modifications to drilling equipment or bit design. However, total drilling costs would be high, probably $150 to $250 per foot.

DISCUSSION

Prof. H.P. Laubscher (Switz.)

How expensive are those large 72 inch holes (illustrated in the film)?

Mr. Foster

They cost approximately $2 million each.

Dr. T.F. Gaskell (U.K.)

Could you tell us how deep you think you could drill a 48 inch hole?

Mr. Foster

The limiting factor would probably be the hole condition rather than the drilling equipment. As you saw in the film, most of the weight is provided by the large donut drill collars and adding additional joints of drill pipe to go deeper does not appreciably increase the total weight of the drill string. So I think that the drilling equipment could go considerably deeper; however, as I say, it would probably depend a lot on the hole condition. In these holes, we do not run intermediate casing strings the way we do in oil field drilling, and this means that if you are going deep you may have several thousand feet of open hole behind the bit. Whether this hole would stay open to allow you to continue drilling would depend on the condition of the rock formation.

Conversely, the depth would affect the total amount of casing that could be run with the drilling rig. As seen in the film, these large drilling rigs can run approximately 700,000 to 800,000 pounds of casing. The balance would have to be run with hydraulic casing jacks.

DIAMOND CORING TECHNIQUES FOR PROJECT MOHOLE

Darrel Sims,
Brown and Root Inc.

Abstract

This paper presents a discussion of the drilling tools being developed to core the Mohole, and of the hoisting and pipe handling systems necessary to operate them. Systems discussed include: surface drilling equipment; turbocoring; conventional coring; diamond bit performance; and, retractable diamond bit.

INTRODUCTION

A number of unusual design considerations have been incorporated in the drilling tools and equipment being assembled for Project Mohole. Some of the more important ones are:

(1) The hole will be carried to an overall depth of 32,000 to 35,000 feet. The latter depth is about 10,000 feet deeper than the world's deepest well;

(2) The drilling operations will be carried out from a floating vessel operating in ocean water at an unprecedented depth of 14,000-15,000 feet;

(3) The hole will be cored continuously from the ocean bottom down through all the layers of the earth's crust and into the underlying mantle rock.

Project Mohole has been defined as a research program directed toward the study of the earth as a planet — rather than as a system of continents, oceans and mountains — and the efficiency of the coring and logging programs is highly important to the project.

A broad geophysical exploration program was carried out prior to the selection of an area in the Pacific 170 miles northeast of Hawaii as the drill site. Although this was satisfactory in providing the site selection committee with data, additional exploratory work must be completed before drilling operations can commence. The ocean bottom must be sampled with available oceanographic equipment and with samplers such as a jet-powered core sampler. This latter tool utilizes a partial vacuum in the inner core tube to increase core recovery. All circulation around the core is upward to urge the core into the barrel. In addition, a sample chamber will be used to catch sections of the core which are too soft to be retained by a catcher.

The drilling of deep holes with normal rotary methods is rapidly approaching its maximum depth. Thus, any drilling program projected to a 40 per cent greater depth must look to all facets of drilling technology for aid. In its search for better tools and techniques, the Mohole staff has utilized the research facilities and creative minds of the oil industry and its supply and service companies. Perhaps one of the most significant tools to come from this effort has been the turbocorer — an axial flow hydraulic turbine coring tool. This will be our primary coring tool.

The tool will be introduced into the hole after the landing base, riser pipe and liner have been run. The use of this down hole motor to supply torque to the bit minimizes the role of the drill pipe in bit rotation. Surface rotation equipment will be used only to the extent necessary to prevent pipe sticking and to maintain a straight and vertical hole.

SURFACE DRILLING EQUIPMENT

With the prospect of such a long string of pipe necessary for this project, we have designed a pipe handling system as nearly automated as is operationally practical.

Hoisting System

The hoisting system design criteria were predicated on the assumption of hoisting a 650,000 lb. hook load at 125 feet per minute. This dictates a 4,000 h.p. electric powered drawworks spooling a 1 3/4 inch drilling line. The travelling block is a box design with a 7 inch hole through the centre to allow coring with the conductor cable in the drill pipe. The crown block is matched to the travelling block, and supports two logging or coring sheaves. Block sheaves are 72 inches in diameter. The system carries a very conservative 500 ton rating, as our design cellar depth is 14,000 feet. The travelling blocks are tracked to prevent swinging.

Pipe Rotation

Pipe rotation can be accomplished by either an individually electrically powered 500 h.p. rotary table, or a power sub driven by two

150 h.p. motors geared to maintain a rotating speed of less than 10 r.p.m. This slow rotation will be used while turbocoring to reduce riser and drill pipe wear, and yet prevent wall sticking.

Pipe Handling System

The pipe handling system is designed around the automatic pipe racker (Fig. 1). This racker will either run or rack a tapered drill string. Sets of identical racks are placed on each side of the centre track. The pipe grabs can be programmed for either automatic or manual selection. The two sides are identical, and are fed alternately to allow time to inspect each stand of doubles with the air-driven pipe inspection sondes. The stand is positioned immediately parallel to the centre track for this operation. Inspection will consist of magnetic, sonic and backscatter gamma ray methods.

The pipe is fed by the centre track conveyor to the derrick floor where the automatic elevators are rotated and positioned to receive it. After the elevators are closed, the stand is picked up and made up with power tongs.

Drilling Fluid System

The drilling fluid system is designed to a maximum operating pressure of over 5,000 p.s.i. The pressure requirement for the $8\frac{1}{2}$ inch turbocorer at 550 g.p.m. fluid flow is 3,700 p.s.i. at 31,000 feet. If the hole is reduced, pressure requirement for the 6 5/8 inch turbocorer would be 4,300 p.s.i. at the same depth. From these figures it is obvious that an appreciable amount of the pumping is above 3,500 p.s.i., which is now normally accepted as plunger pump area.

One of the most important factors relating to the mud system is the removal of abrasives which can shorten bearing life in the turbocorer. At Uvalde (see below), our mechanical mud treating tests proved that we can keep mud with basaltic cuttings in excellent shape with commercially available desilting equipment.

TURBOCORER

The prototype turbocorer is $8\frac{1}{2}$ inch O.D. and 68 feet long (Figs. 2 and 3). It is a modification of a field proven production model. The thrust bearing stack, large lower radial bearing, and face seal have been

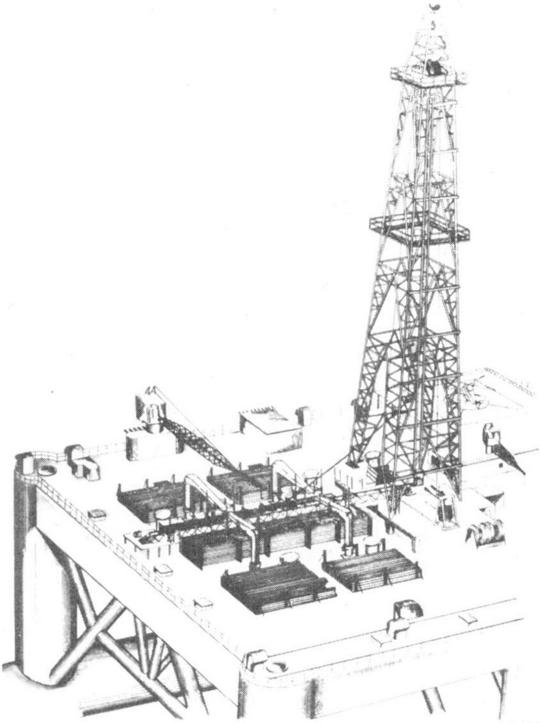
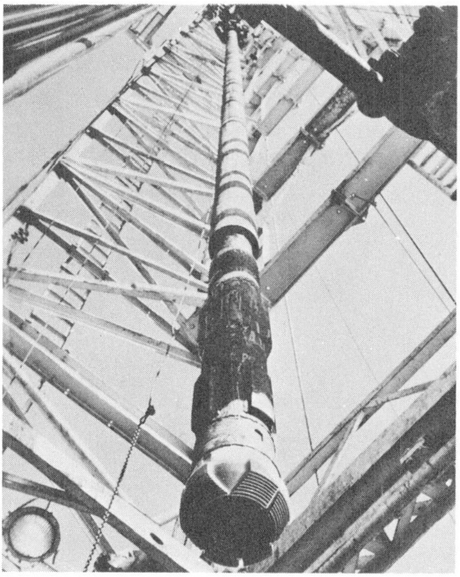


Figure 1. Automatic pipe racker, designed to handle pipe at high speed. Twin grabs on either side of a centre track can be programmed for automatic or manual selection. Each stand of doubles will be inspected with magnetic, sonic and backscatter gamma ray techniques.

Figure 2. Turbocorer hanging in derrick. Diamond core bit on bottom measures 9 7/8 inches by 2 inches. Turbocorer is $8\frac{1}{2}$ inches in diameter, 58 feet long and has a 155-stage turbine.



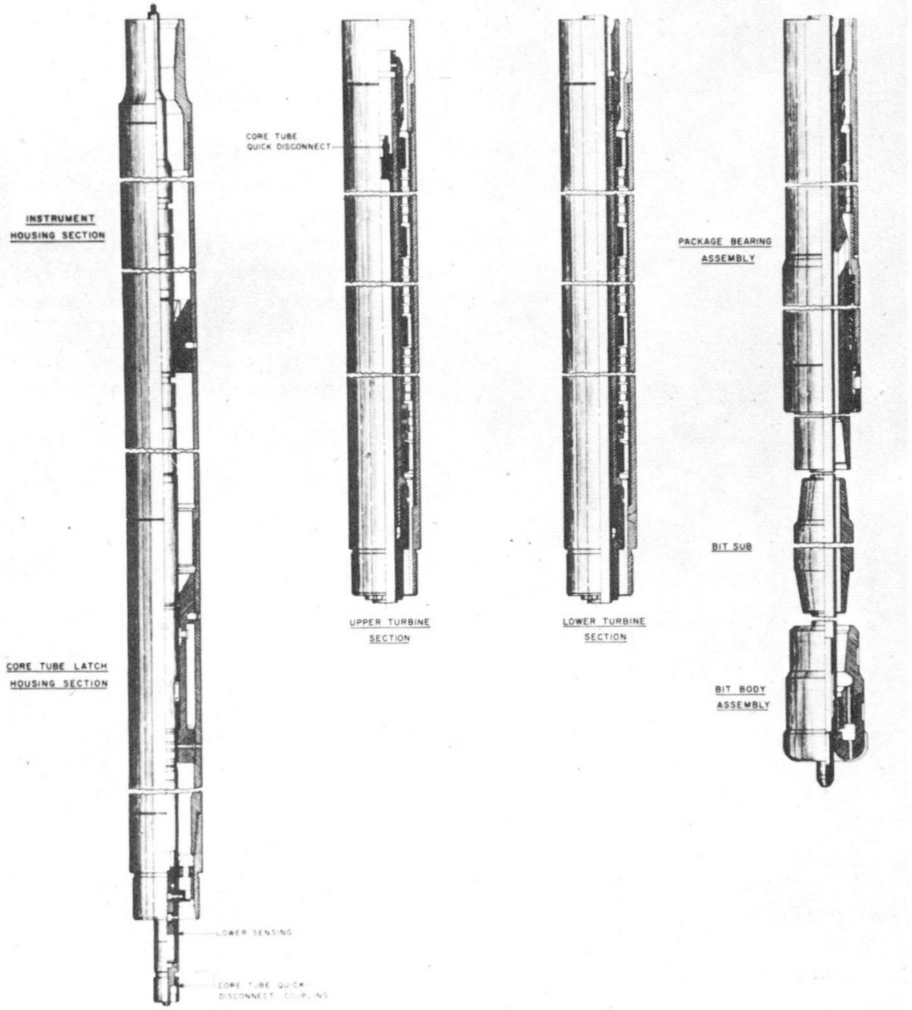


Figure 3. Sections showing the major components of the turbocorer. Rotation speed is 550 to 600 rpm. Downhole instrument package makes it possible for the driller to exercise precise control of penetration rate, which is vital to bit life.

placed in a removable section below the turbine cases for increased rotor stability and ease of maintenance. The rotors and stators (Fig. 4), which are designed to operate at 550-600 r.p.m. are assembled in two sections of 68 stages each. An extra radial and two thrust bearings were added to each section for stability. The upper section houses and positions the instrument package used to monitor the turbocorer.

All bearings are molded of Viton 10, an elastomer that will withstand continuous operation at our design temperature of 200°C. In addition to the laboratory tests used to select this compound, these bearings have been tested for over 200 hours in a turbodrill test stand at Dallas, Texas. The tests included runs with all drilling fluids expected to be used in our program.

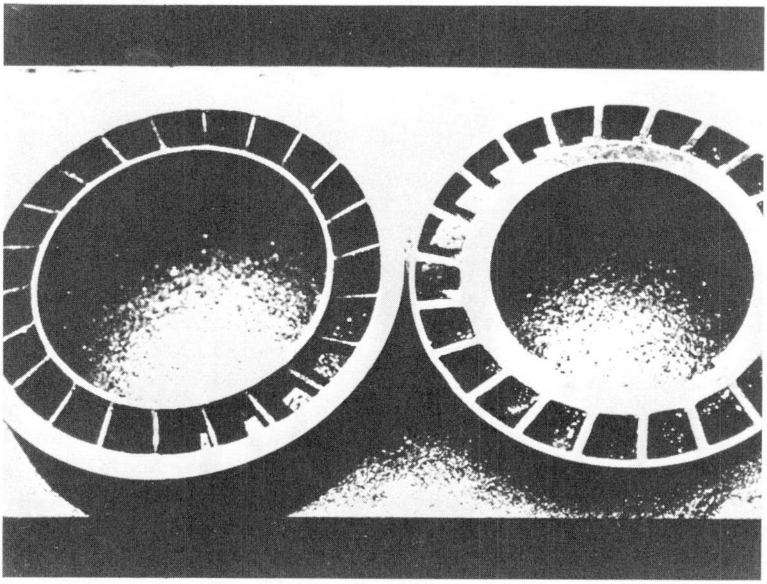


Figure 4. Rotators and stators to provide torque to the bit are assembled in two sections of 68 stages each.

FIELD EVALUATION WELL

In September, 1964, an extensive test drilling program was commenced on a ranch near Uvalde, Texas. The purpose was to evaluate new drilling tools and techniques developed for Project Mohole by drilling into a subsurface basaltic plug lying 485 feet below the surface. This dense rock has properties similar to rock that may be encountered in drilling the Mohole. Also, it was the toughest test medium available for the program that was located near oilfield supplies and services.

Once the plug was reached, the tests continued for about 3,000 feet into the basalt.

Turbocorer Tests

The performance of the turbocorer in the evaluation drilling was highly satisfactory. In 200 hours of actual drilling in basaltic rock, the thrust bearings' wear was only a small fraction of the 1/8 inch allowable. However, the lower radial bearing was ready for replacement after operating for 200 hours. The face seal, which increases bit life when coring with diamonds, also had additional running time left. The purpose of the face seal is to carefully control the volume of fluid from bypassing the bit face. The radial bearing is being redesigned to increase its life to that of the other bearings.

DIAMOND BIT PERFORMANCE

Our Uvalde cored footage also proved the compatibility of diamond core bits and a 600 r.p.m. turbocorer drilling in basaltic rock. During these tests, conventional, wireline and turbocorer bits from five suppliers, each having their own design, were tested. The variance in bit design is illustrated in Figures 5A, B and C. One bit (Fig. 5A) feeds the mud to its face and is built with a double taper and steps between diamond rows to stabilize the bit. Another (Fig. 5B) has a more conventional face pattern, and feeds the bit face from centre water courses. A third design (Fig. 5C) also feeds the bit face from centre water courses, but is unique in that the centrifugal force of the drilling fluid, rather than the pressure drop across the water courses, is used to flush the bit.

Early in the turbocorer tests we found that a diamond reamer and stabilizer were necessary to keep the hole from spiraling and to reduce hole deviation. This also increased bit life by reducing lateral bit movement.

Bit Life

The fact that all bits performed satisfactorily on the turbocorer, with no burning or lost diamonds, indicates that turbocorer diamond bit design is not the cause of short bit life. Instead, control of bit operation

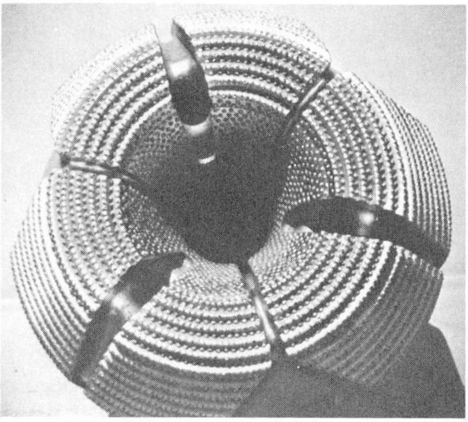


Figure 5A. Stepped diamond bit.

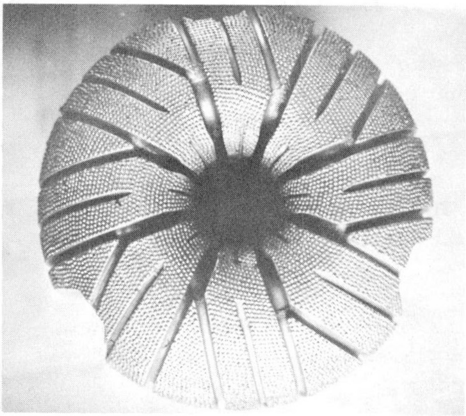


Figure 5B. Conventional face diamond bit.

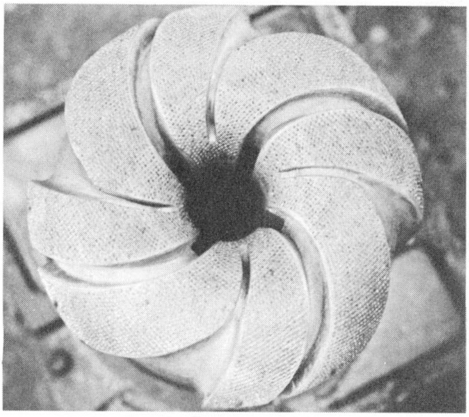


Figure 5C. In this bit, the centrifugal force on the drilling fluid is utilized to flush the bit face, rather than the pressure drop across the water courses.

Figure 5. Three of the diamond bits used with the turbocorer. The thousands of diamonds in each bit penetrate about .002 inch per revolution. At 600 rpm this results in a rate of advance of about 5 1/2 feet per hour.

determines whether the bit fails prematurely. With accurate r.p.m. and other down-hole information provided as a surface readout, we are able to closely control bit operating conditions. Keeping the r.p.m.,weight on bit, and flow rate constant resulted in the maximum rate of penetration commensurate with bit life. A total of 1,194 feet of basalt was successfully cored with the turbocorer, using the assembly shown hanging in the derrick in Figure 2. Starting at the bottom of the string, we ran the diamond core bit, full gauge diamond blade reamer, a square stabilizer 1/32 inch under bit gauge, and the changeover sub to the rotor shaft. This assembly kept the hole in excellent shape, and we were able to follow it with the very stiff conventional rotary coring assemblies. Several 40-45 inch cores were cut and recovered, which is the maximum length the present inner core barrel design will allow. Core recovery was about 95 per cent which included highly fractured basalt. As an illustration of the excellent bit performance obtained one of the diamond bits was run 129 hours, coring more than 650 feet of basaltic rock — yet we estimated that the limit of its useful life had not been reached.

Figure 6, which shows the turbocorer running at surface was taken at 1/15 of a second, with the turbocorer unrestrained in the derrick. The absence of wobble indicates its stability. Incidentally, this was late in the tests and the bearings are worn.

The turbocorer will be our primary tool. However, for coring the softer ocean bottom sediments and for any rocks encountered that are not adapted to turbocoring, we plan to use either conventional or wireline coring.

Following the theory of maximum stabilization for core recovery, bit life, and deviation control, we tested an outer core barrel utilizing a square spiral section (Fig. 7). This outer barrel is 1/16 inch under bit gauge and spirals 540 degrees in 26 feet. Square stabilizers, 1/32 inch under bit gauge, were run above and below the spiral section. The conventional barrel can be lengthened to cut a 90 inch core by adding 15 foot long round outer barrels and stabilizers. We believe this stabilization to be instrumental in making it possible to recover fractured cores.

Five different conventional 9 7/8 inch x 4 7/8 inch bits were tested, for a total penetration of 740 feet. All bits performed satisfactorily. The same square spiral outer barrel and bits used on the turbocorer were run for testing rotary wireline coring to compare rotary and turbocorer rates of penetration. During this part of the test, 105 feet of core was cut. The rate of penetration for rotary wireline was 1.9 feet per hour as compared to 5.5 feet per hour for turbocoring. This obviously will decrease hole costs where rig costs are high.

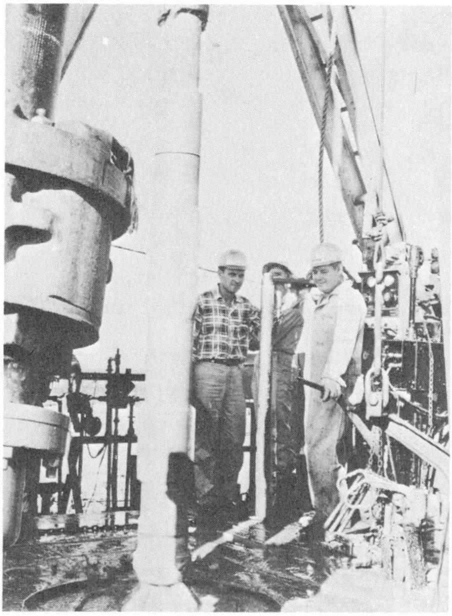
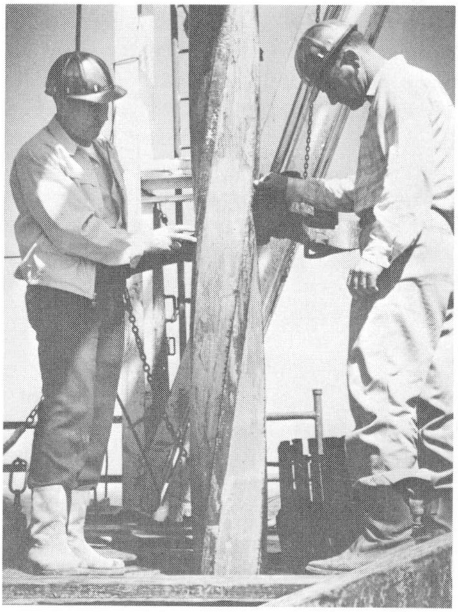


Figure 6. The stability of the turbocorer is demonstrated here. The bit, reamer and stabilizer leave a steady blur when photographed at a slow speed, indicating the absence of wobble in the rotating part of the tool. The leakage below the turbine section at top is metered by a face seal to lubricate the cluster of thrust bearings.

Figure 7. Square spiral outer core barrel which provides a high degree of stabilization was tested at Uvalde. The barrel is 1/16-inch under bit gauge and is 26 feet long. Stabilizers were run immediately above and below the barrel.



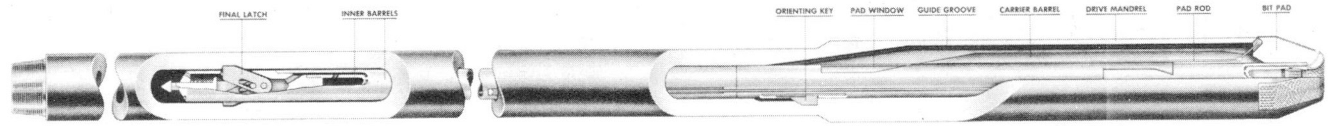
A carbide insert rotary core bit also was tested. This bit was built similar to conventional roller cutter core bits using 6 cutters. The smaller cutters reduce bit life, but this bit, run on the conventional wireline core barrel, cut 55 feet of basalt in 28 hours with 100 per cent recovery.

RETRACTABLE DIAMOND CORE HEAD

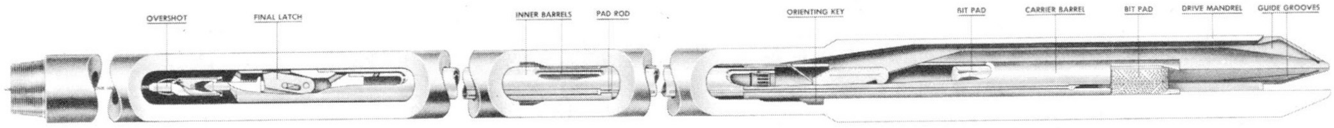
In addition to these tools which have been field tested, we are developing other techniques to use in Mohole. One promising tool under development is a retractable diamond core bit.

The upper cross-section in Figure 8 shows the bit pads locked in drilling position in the mandrel, making a 9 7/8 inch x 2 inch core bit. The bit pads and core barrels are run through 4 inch or larger tool joints. An orienting device lines up the leading bit pad with a slot in the mandrel and the following pads are lined up with their respective slots from this pad. Continued lowering of the wireline seats the carrier barrel, sealing off mud flow to the inner barrel, and locking the bit pads in place. The inner floating core barrel and catcher are of conventional design. The latch assembly incorporates a signalling device that signals position of the latch to the surface if a conductor cable is used. The core barrel is retrieved by running in with the conductor cable and latching on to the spear-point with the over-shot. The latch will signal through the conductor cable when unlatched, and will continue to signal as long as the two are connected. This will prevent pulling the cable out of the pipe without the core barrel; otherwise, with a long line in the drill pipe it would be quite difficult to tell whether or not the core barrel had been retrieved. The bit is retracted in the reverse order of running. Picking up the inner barrel and carrier tube allows the bit pads to be retracted into the outer core barrel. The slots in the mandrel are narrower than any cross dimension of the bit pads, so even if a pad is dropped, it cannot get out in the open hole. As the bit pads are tripped out with each core, the pads can be inspected for wear or damage. This would keep a sharp bit on bottom. The wireline pack off on the swivel allows us to circulate while pulling the core to equalize the drill pipe and annulus and this will eliminate back flow and reduce contamination of the mandrel from bit cuttings.

Our subcontractor set up a computer program to evaluate the economics of this retractable bit as compared to conventional rotary and the turbocorer. The program was written in such a way that the loading of the individual diamonds in all bit configurations was the same. Formation characteristics were based on information we obtained at Uvalde and on the results of the seismic work done at the proposed drilling site. These runs show the retractable design has a decided advantage over the conventional



CORING POSITION



TRIPPING POSITION

Figure 8. Cutaway illustration of the retractable bit presently under development.

wireline. Runs were also made to check the effect of the retractable bit and turbocorer combination and the results indicated that this combination will produce the best results.

The retractable bit idea is still in the model stage and we plan to build a prototype and test it before making the necessary modifications in the turbocorer to allow running the bit through it.

The retractable bit, run on conventional rotary equipment, will enable us to core an appreciable distance into the ocean floor in a number of holes in the site area without setting a landing base. We can select the optimum site and then refine and finalize the design of a casing program for maximum protection.

We are also pursuing the applications of the electrodrill to the project. The present configurations of the electrodrills we have studied do not lend themselves to continuous coring operations. However, there are other operations where this very versatile tool can be of assistance, such as drilling in the landing base, cutting short, large diameter cores, cleaning up core stubs, and the like.

Other down-hole tools such as reamers, hole openers, and hydraulically balanced bumper subs will be industry standard, or modifications of standard tools.

PLANNING AND DRILLING THE DEEPEST WELL OF EUROPE - MÜNSTERLAND 1

H. Becker
(Presented by H. Berckhemer, Federal Republic of Germany)

Abstract

The Münsterland No. 1 well was started July 10, 1961 and completed to a depth of 19,680 feet after 495 days. The well, located in the Münsterland area (Nordrhein-Westphalen) of the Federal Republic of Western Germany was designed to explore hydrocarbon reservoirs and little known geological structures of the "subvariszishe Vortiefe". This paper gives technical details of the planning and execution of the drilling, including casing program and drill string design, drilling rig and auxiliary equipment, and performance data from the actual drilling operations.

INTRODUCTION

Preparations for drilling the deepest well in Europe were started in 1960 in the Federal Republic of Western Germany. The purpose of the drilling was to explore hydrocarbon reservoirs and as yet unknown geological structures of the "subvariszische Vortiefe" in the area of Münsterland (Nordrhein-Westphalen). The Federal State Nordrhein-Westphalen, together with eight oil companies, participated in financing and carrying out the project. After a thorough study by reflection and refraction seismic methods, an anticlinal structure in Carboniferous rocks near Münster (Westphalen) was selected as the drilling location.

PLANNING FOR THE PROJECT

Technical planning (1963) of the Münsterland No. 1 well was based on geological cross-sections, which were constructed on the basis of geophysical data and information from wells previously drilled in the surrounding area. Münsterland No. 1 was designed to reach a maximum depth of 16,400 feet and the drilling equipment selected was capable of drilling to depths greater than 18,040 feet. The well was expected to penetrate the following geological sections:

0 - 5,450 feet, Upper Cretaceous
- 9,840 feet, Westphalian) Upper Carboniferous
- 11,500 feet, Namurian)
- 13,120 feet, Lower Carboniferous
- 16,400 feet, Devonian.

Casing Program

As the geological structure and hydrocarbon content of the deeper part of the Vortiefe were completely unknown, the casing program had to be planned with maximum flexibility and safety. The best casing combination was considered to be 18 5/8 - 13 3/8 inch, 9 5/8 - 7 inch, and 5 inch and the planned program is shown in Figure 1. The 18 5/8 inch casing was to be set to a depth of about 650 feet in the upper part of the Lower Campanian Formation to prevent inflow of fresh water from the Upper Campanian rocks. Before running the 13 3/8 inch casing, the 18 5/8 inch pipe was to be cemented to surface to act as an anchor pipe. The 13 3/8 inch casing was designed to reach one third of the final depth and would be landed at a depth of 6,000 feet in the Upper Carboniferous (Westphalian) to case off the Upper Cretaceous. For deeper drilling this casing would have to be the anchor pipe and thus it was to be cemented to surface. The 9 5/8 inch pipe was to be used to case the Carboniferous to a depth of 13,120 feet. Two strings of 7 inch and 5 inch pipe would be used for casing the Devonian and the 5 inch casing was selected for lining the 7 inch casing from a depth of 9,840 feet. The 5 inch liner would be extended to surface, in the event of oil or gas production from the well. The heaviest casing in the program is the 9 5/8 inch string with a total weight of 273,800 pounds (in air).

Drill Pipe and Collar Program

The drill pipe and collar program (Fig. 2) was selected on the basis of past experience and the casing program. From surface to the setting depth of the 13 3/8 inch casing, drilling would be with 6 inch, Grade E pipe and $5\frac{1}{2}$ inch IF joints made from 34 Cr Mo 4 quality steel. At a depth of 6,000 feet the 6 inch pipe was to be replaced with 5 inch Grade P-105 pipe. For safety reasons, $4\frac{1}{2}$ inch IF joints of 36 Cr NiMo4 quality steel were planned to a depth of 6,560 feet. After running the 9 5/8 inch casing, drilling was to be completed with a combination string of 5 and 4 inch pipe. The drill collars were chosen to provide a maximum bit load of 30,000 pounds. Generally, combined drill collars were selected in order to minimize bending strain at the stem and pipe joint.

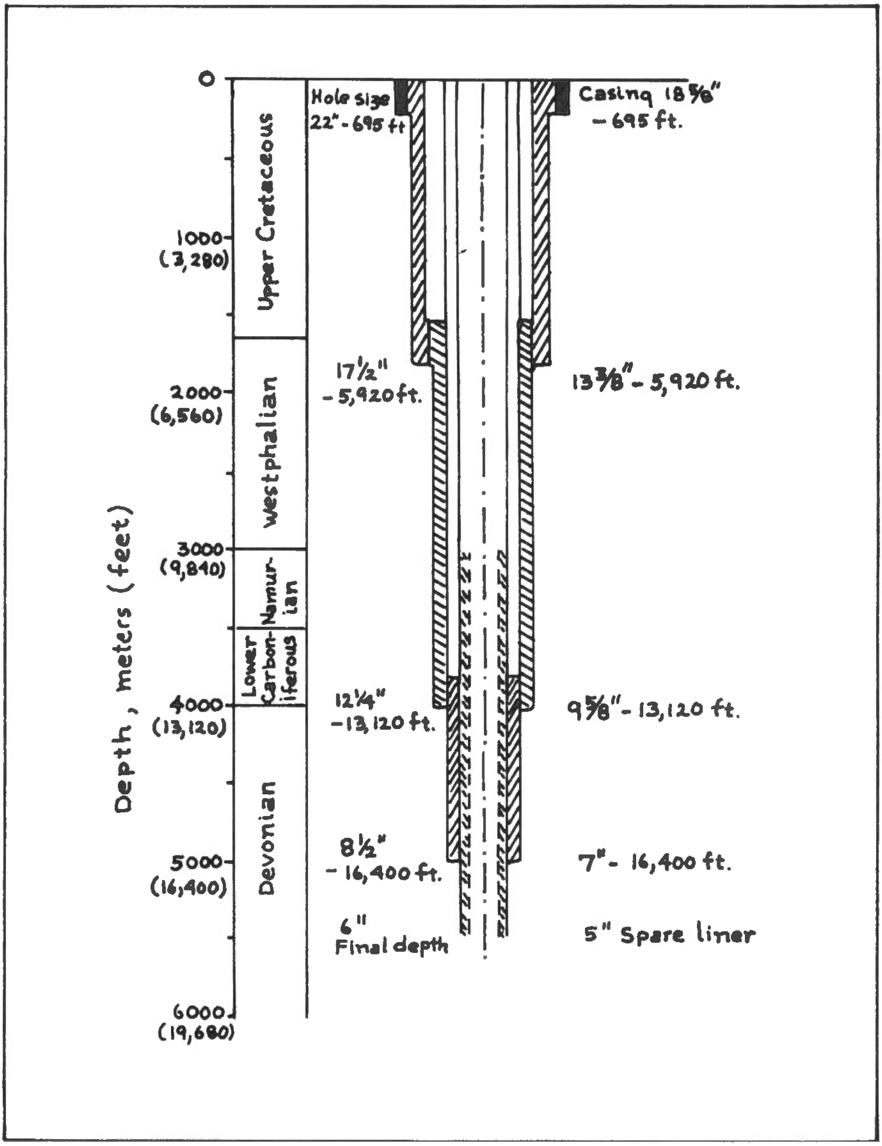


Figure 1. Planned casing program for Münsterland No. 1 well.

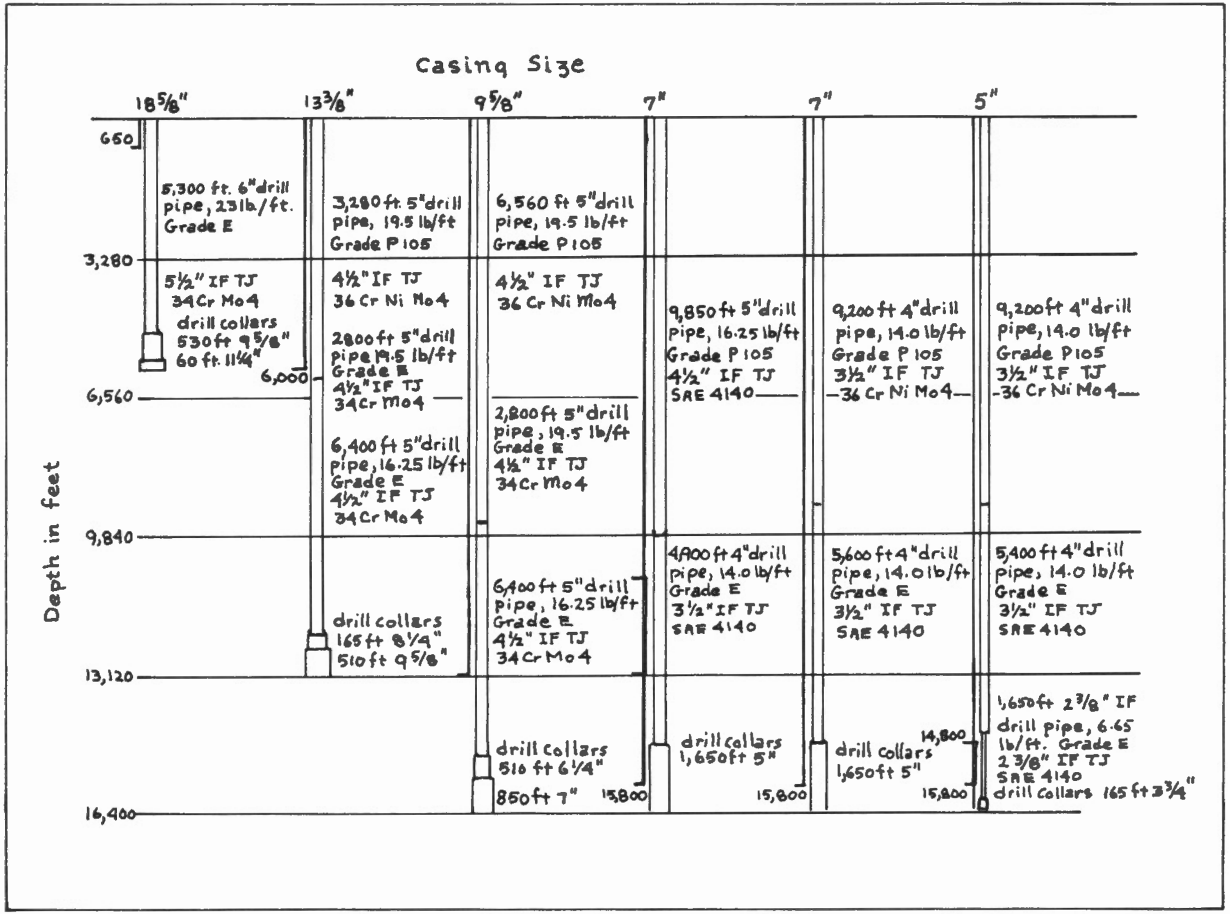


Figure 2. Planned drill pipe and collar program for Münsterland No. 1 well.

Factors Affecting the Choice of the Drilling Rig

The capacity of the drilling rig was determined by the weight of the 9 5/8 inch casing - 273,000 pounds - and the theoretical power requirements of the mud pumps. If the 9 5/8 inch pipe should stick during running in, a rig load of more than 300,000 pounds could be reached. Power requirements of the rig were determined by the mud pumps. Considering an efficiency of 80 per cent the mud pumps would have to be powered with 1,970 h.p., with an additional power output of 195-295 h.p. for the rotary table. Thus the total power requirements for the rig were about 2,270 h.p.

DRILLING RIG AND AUXILIARY EQUIPMENT

In addition to the maximum rig load and the power requirements, as discussed above, the following factors had to be considered:

(a) The rig must be designed with the maximum possible safety factors;
(b) the equipment should be capable of drilling to depths greater than 18,040 feet.

For these reasons the drilling contractor, Deutsche Schachtbau und Tiefbohr G.m.b.H. put its largest rig on the operation.

Derrick

Münsterland No. 1 was drilled with a derrick that had already successfully completed deep wells in the northern part of Germany. This rig (Liehman, 1961), using a four-pylon derrick, was designed and constructed by Gewerkschaft Elwerath, DEMAG and EIKOMAG. The four-pylon derrick was mounted on a floor 33 by 33 feet and had a total height of 158 feet above the rotary table. Its permissible working crown load was 500,000 pounds although in exceptional cases a maximum load up to 650,000 was possible. The capacity of the travelling block was 500,000 pounds when rigged with a 12-line cable. The derrick substructure consisted of 4 boxes each with a height of 7.4 feet. Two of these were bolted together to give an overall height of about 15 feet. The derrick floor was strengthened by supports and the total braking load of the rotary table was 450,000 pounds when up to 150,000 pounds of drill pipes and drill collars were racked on both sides of the floor.

The draw works substructure also consisted of two boxes bolted together to give the same height as the working platform. The engine platform was constructed from three boxes of 7.4 feet high, placed one beside another. The derrick was equipped with a Wirth RKS 63017 crown block for a maximum load of 500,000 pounds, and a Wirth RBZ 500/6 travelling block with National Triplex hook block for a maximum load of 500,000 pounds. The rotary line, with a diameter of $1\frac{1}{2}$ inches had a calculated ultimate strength of 124,300 pounds. With a four-fold safety factor the permissible load of the string was 31,080 pounds with an exceptional load of 41,400 pounds allowed. Thus, the total capacity of the derrick was limited by the permissible exceptional load of the rotary line.

Draw Works

The rig was equipped with a Wirth GH 1400 draw works, which is the largest built in Germany at the present. It is chain geared and has an input power capacity of 1,380 h.p. While running with a Wülfel air cushion coupling the maximum pull of the hoisting drum is 45,000 pounds. By locking the coupling, the hoisting load can be increased to 55,000 pounds.

Engines and Transmissions

Mud pumps and draw works were driven by a Wirth 4/400 chain drive compound with a power input of 2,220 h.p. provided by three type GTO 6A Maybach diesel engines, each delivering 740 h.p. Each of the engines could be independently clutched to the draw works and/or the mud pumps. A spare engine of the same type powered a standby pump.

Mud Pumps

The rig was equipped with three 6 3/4 inch by 12 inch Wirth mud pumps, two being connected with the power compound and the third on standby. With 6 3/4 inch, 5 3/4 inch and 5 inch liners the pumping rate of each mud pump was 64.9 cu. ft./min, 47 cu. ft./min, and 34.8 cu. ft./min respectively, at 70 r.p.m. At these pumping rates the maximum pressures obtained were 1,480 p.s.i., 2,078 p.s.i., and 2,730 p.s.i.

Additional Equipment

For blow-out prevention a Hydril was installed for four hydraulic preventers. The drilling operations were controlled by a Martin Decker Type E Drillometer with automatic hook load, mud pressure, and rotary table torque recorders. A mud laboratory, sampling laboratory, and a mud logging service to detect gas, especially CH_4 to C_3H_8, CO_2 and H_2, were located on site.

DRILLING OPERATIONS

Drilling of Münsterland No. 1 commenced July 10, 1961. At that time the large rig as described above was not yet available and a Salzgitter Gulliver Type AS 300/40 derrick with GH 900 draw works was used until the 13 3/8 inch casing was run. The drilling operation can be divided in four periods, as follows:

(a) 0 - 685 feet, running 18 5/8 inch casing;
(b) 685 - 6,200 feet, running 13 3/8 inch casing;
(c) 6,200 - 13,360 feet, running 9 5/8 inch casing;
(d) 13,360 - 19,500 feet, drilling to final depth.

The drilling, casing, and cementing operations are shown in Table 1. Due to the unexpected greater thickness of the Namurian (Carboniferous) rocks the final depth of the well was extended to nearly 19,680 feet. Because of the very hard nature of the rocks it was possible to leave the section below 13,360 feet uncased. This change also allowed some divergence from the intended drill pipe program. The actual casing and drill pipe programs are shown in Figures 3 and 4. Except for some minor repairs only one extensive fishing job was necessary, and this occurred when a 7 5/8 inch core barrel became stuck while running in the hole at a depth of 14,650 feet. The fishing operation required 22 days, and the core barrel was eventually freed with a pull of 170,000 pounds.

The geological objective was reached at the depth of 19,500 feet where drilling was stopped. Total drilling time was 495 days (Fig. 5). The average drilling rate was about 39.5 feet per day. With a net drilling time of 41.27 per cent (Fig. 6), the overall drilling rate was about 4 feet per hour. This fast drilling rate was due to very short round trip time (Fig. 7). Although the bit load was very high at times (see Fig. 7) the horizontal deviation of the well at its final depth was only 1,200 feet.

The mud program used during drilling is given in Table 2. Bottom hole temperatures up to 200°C below 13,120 feet resulted in high mud costs. The construction of the final geological section (Table 3) was based on the study of samples as well as on data from electrical and acoustic logs. To a depth of 19,500 feet a total of 1,050 feet of coring was done.

Table 1

Drilling, casing, and cementing data for Münsterland No. 1 well

Depth (ft) Draw works	0 - 680 GH 900	680 - 6,200 GH 900	6,200 - 13,200 GH 1400	13,200 - 19,700 GH 1400
Drilling time				
from	7.10.61	7.19.61	10. 7.61	5.2.62
to	7.16.61	9.10.61	4.15.62	12.5.62
Bit O.D.	12 1/4" (22")†	17½"	12 1/4"	8½"
Bit load (Mp)*	---	15 - 30	15 - 30	13 - 15
Drill string				
pipe O.D.	6"	6"	6"	5"
length ft	---	5,700	12,700	18,750
weight Mp	---	69.8	148.2	163.9
Collars O.D.	---	11 1/4"/ 9 5/8"	9 5/8"/ 8 1/4"	6½"
score	---	2/ 16	9/9	24
weight (Mp)	---	50.3	41.4	21.8
Drill string total weight (Mp)	---	120.1	189.6	185.7
Pumping rate (gal/min)	---	990	440	265
Mud pressure (p.s.i.)	---	50 - 100	50 - 100	90 - 130
Annular mud velocity (ft/sec)	---	1.85	1.97	1.97
Casing	18 5/8"	13 3/8"	9 5/8"	---
Landing depth	665	6,220	13,200	---
Cement composition	TZ 275 (Class N)	TZ II (Class E/D) Diatomite Bentonite	Poz. A 140 Diatomite Retarder ZL CMHEC	---
No. of sacks	500	3800	---	---
Weight (Mp)	25	190.26	190	---
Slurry (gal)	---	45,000	---	---
Cementing time (h)	---	3	15	---
Average drilling rate (ft/d)	76.5	97.8	50.6	39.5

†Hole opened with 22" Security hole-opener.

*Thousands of pounds.

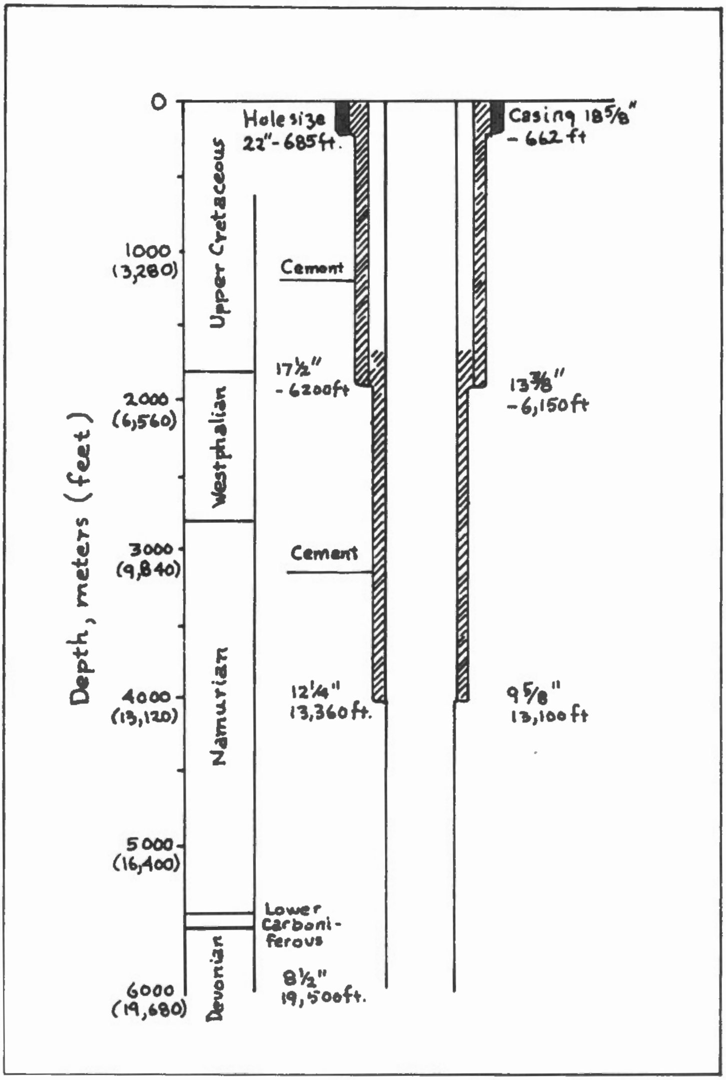


Figure 3. Actual casing program for Münsterland No. 1 well

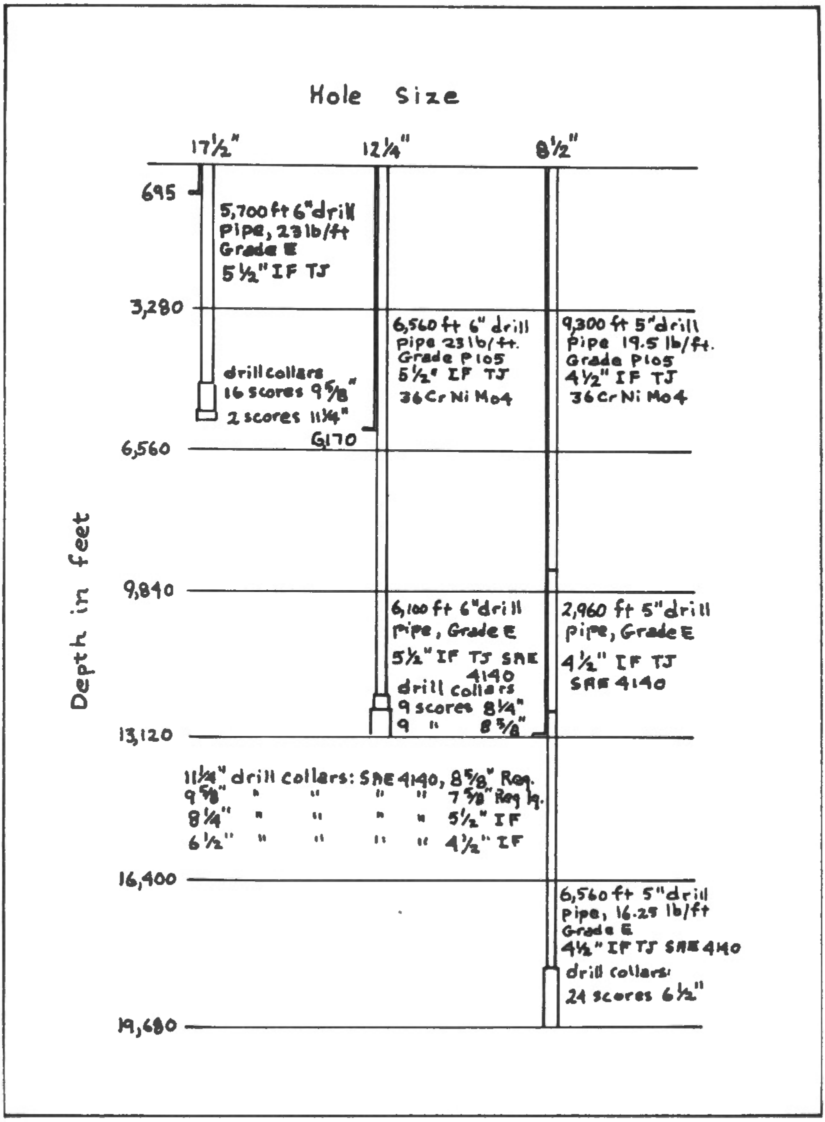


Figure 4. Actual drill pipe and collar program for Münsterland No. 1 well.

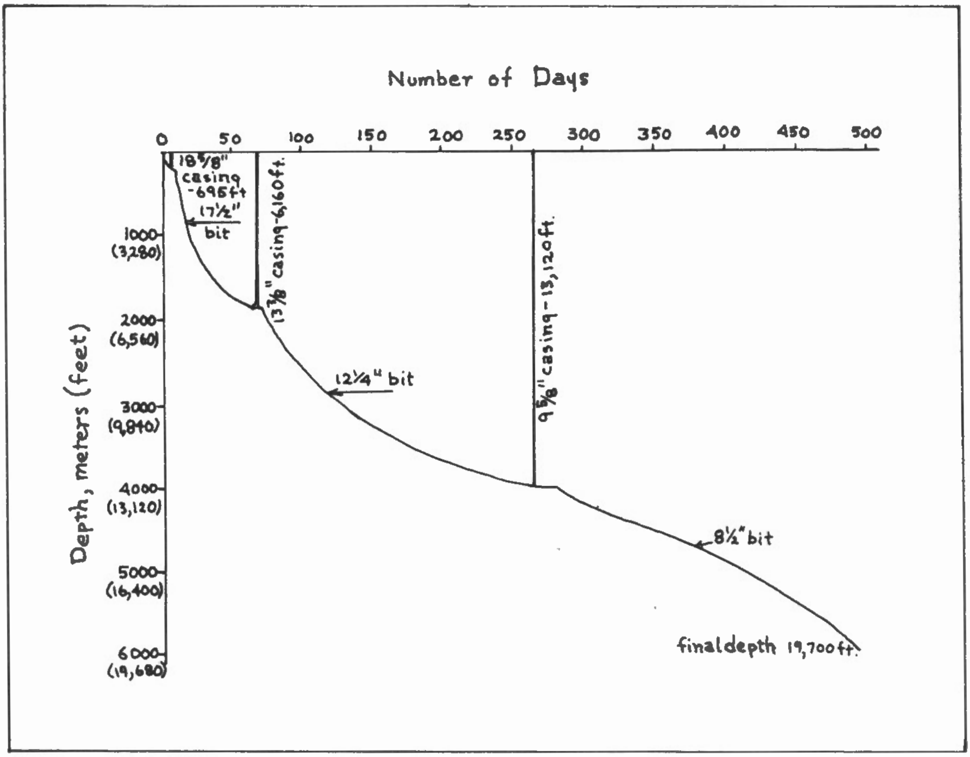


Figure 5. Performance chart for Münsterland No. 1 well

TECHNICAL DATA FROM THE MÜNSTERLAND WELL

In spite of unfavourable rock formations, the Münsterland No. 1 well has proved the feasibility of drilling to a depth of nearly 19,680 feet without great difficulties, and probably even greater depths could be reached. Modifications to the planned program were made by drilling with 6 inch pipe and 5½ inch IF joints until running in the 9 5/8 inch casing. Final depth was reached using 5 inch pipe and 4½ inch IF joints. It is probable that by using the planned combined 5 inch and 4 inch string, depths of 23,000 feet could be reached with a hoisting reserve of 40,000 pounds.

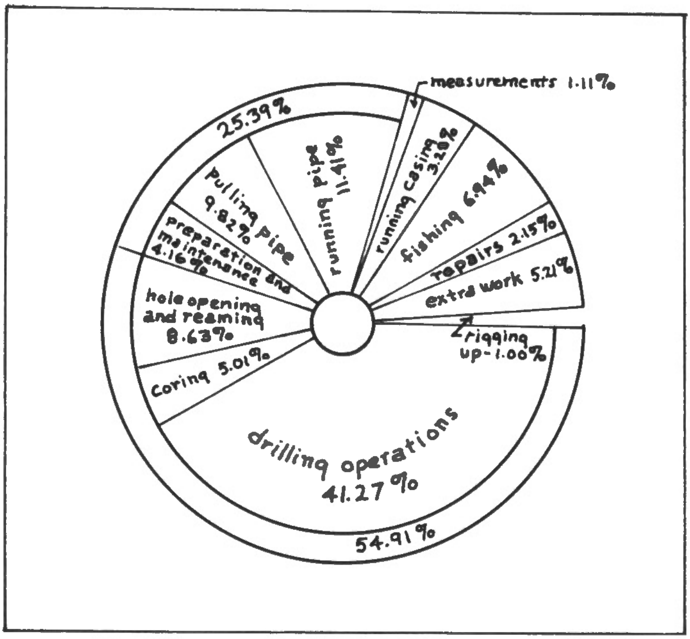


Figure 6. Time distribution diagram for Münsterland No. 1 well

Inspection of drill collars was carried out after a drilling period of 200-300 hours. Thirty-three failures, mainly located in joints were detected during the drilling. Detection of these incipient failures prevented fishing jobs which certainly would have occurred otherwise. Duplicate collar strings were used to reduce the time lost due to inspection. Drill collars with releasing grooves were used with good result. With this collar type the time between inspections could be increased to 600 hours.

The well was drilled mainly with jet bits. For drilling hard quartzite and brittle sandstones, and at depths below 16,400 feet, chert bits were run in the hole. Logging was difficult because of high temperatures encountered in the hole and instruments became damaged. The depth limitations for the different logs are given in Table 4.

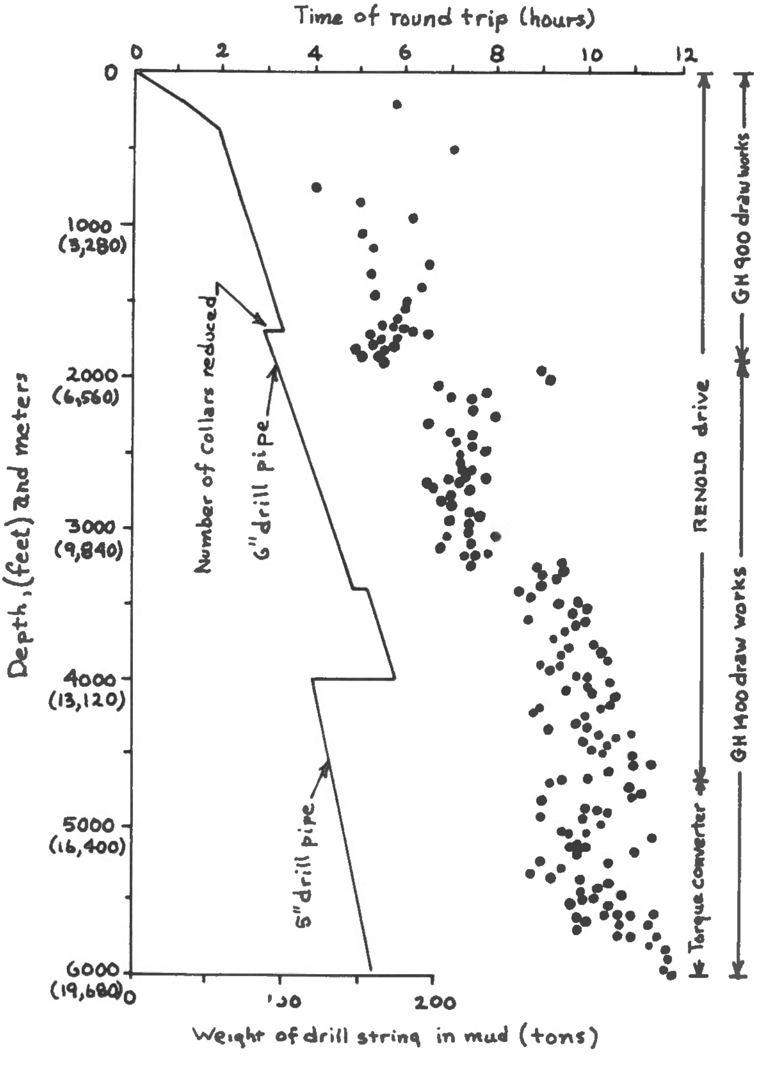


Figure 7. Round trip times and variations in weight of drill string during drilling of Münsterland No. 1 well

Table 2

Mud program for Münsterland No. 1 well

Depth (feet)	Mud Type	Spec. Gravity (Kp/l)	Marsh Funnel Viscosity (sec.)	Fluid Loss (ml)	Circulating Volume (U.S. gal.)	Costs total $/ft	Rel.* $/ft	Remarks
0- 680	natural mud	1.08 - 1.20	50 - 70	-----	-------	2.6	2.6	high thixotropy
- 1,740	fresh water mud	1.08 - 1.25	40 - 55					mud plugging due to bentonite hydration
- 6,170	caustic Quebracho mud	1.24 - 1.30	40 - 75	7.5	105,600	1.6	1.7	low mud loss
-10,500	caustic Quebracho mud	1.25 - 1.30	50 - 70	5.0				
-12,200	caustic Quebracho mud	1.20	80 - 100	5.0		0.9	0.8	low mud loss, thickening due to high temperature
-12,270	X-P-20-Spersene mud	1.17 - 1.20	50 - 180	8-10		1.4	1.1	difficulties in changing mud
-13,300	alkaline water mud	1.25 - 1.30	110 - 130	2-3.5	116,160	2.0	1.3	increasing spec. gravity
-14,000	alkaline water mud	1.25 - 1.35	60 - 80	3-4				viscosity loss due to cracking CMC (bore-hole temperatures up to 328°F)
-19,520	alkaline water mud	1.45	100 - 200	2.5-5	92,400	21.6	9.8	

*Related to respective depth zones

Table 3

Geological profile – Münsterland No. 1 well

0 - 5,850 ft Cretaceous

- ca. 1,000 ft Campanian
- 2,870 ft Upper and Middle Santonian
- 4,460/4,620 ft Lower Santonian and Coniacian
- 5,310 ft Turonian
- 5,660 ft Cenomanian
- 5,820 ft Upper Albian
- 5,850 ft Middle Albian

Transgression

5,850 - 18,280 ft Carboniferous

- 6,260 ft Westphalian B
- 9,160 ft Westphalian A
- 12,080 ft barren coal measures Namurian
- 17,810 ft seamless Namurian
- 18,280 ft Dinantian

18,280 - 19,520 ft Devonian

- 18,200 ft Strunian
- 18,450 ft Condroz Sandstone
- 18,800 ft Famennian and Frasnian Shale
- 18,900 ft Frasnian Limestone
- 19,400 ft Givetian Limestone
- 19,480 ft Lime sandstone of Middle Devonian
- 19,520 ft Quartzite

Table 4

Logging depth limits due to high bore-hole temperatures

Log	Final depth of measuring	Temperature when instrument was damaged
Conductivity Laterolog	18,000 ft	180 °C
Soniclog-caliper	final depth	(197 °C)
Temperature	18,700 ft	191 °C
Dipmeter	17,900 ft	196 °C

Gas measuring instruments, particularly the gaschromatograph, proved to be useful in locating very thin coals seams. As far as is known, this is a new application for the instrument. A quantitative interpretation of the data was not possible, however, as no correlation was found between coal seam thickness and gas content.

CONCLUSIONS

The Münsterland No. 1 well has shown that drilling to depths of 19,680 feet or more is possible without great difficulties. The difficulties which arose were more financial than technical. The costs of planning and drilling the well totalled about $2.25 million. Although the well did not penetrate gas or oil traps, a large amount of technical and geological knowledge has been obtained that is of significant value in the exploration of reservoirs at great depths. At the present a new well in the Saar district is being drilled, also to a planned target depth of 19,680 feet.

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F. GENERAL SESSION - RESOLUTIONS AND RECOMMENDATIONS

Chairman: J.M. Harrison (Can.) and H.H. Hess (U.S.A.)
Reporters: D.C. Findlay and C.H. Smith (Can.)

Dr. J.M. Harrison "In our discussions to date during this Symposium, we have talked about plans for drilling, places to drill, and the techniques of drilling. Now it is time to crystallize our discussions into specific recommendations. Many of the delegates here will have problems that are characteristic of a country or region, or perhaps unique to it, and which should provide much useful information to the whole concept of deep drilling for scientific purposes. We hope that some of these proposals will be put forward this afternoon.

At the Moscow meeting in 1963, the Deep Drilling Committee of the U.M.C. defined the basic objectives of deep drilling as a program to obtain specific geological and geophysical data on the upper mantle and the deeper layers of the earth's crust. In addition, the collection and analysis of data on the distribution of economic elements in the crust and upper mantle was emphasized as an important first step toward ultimate discovery and exploitation of deep-level mineral deposits. Prof. V.V. Fedynsky, who is chairman of the U.M.C. working group on deep drilling, was unfortunately unable to attend this Symposium. However he has submitted certain specific recommendations and I will ask Prof. V.V. Beloussov to present them, and lead off the discussion on recommendations arising from this Symposium."

Prof. V.V. Beloussov (U.S.S.R.) I wish to read the report and recommendations on drilling for scientific purposes prepared by V.V. Fedynsky, Reporter of the Working Group, who was unable to attend this meeting.

"In 1964-65 deep drilling projects for scientific purposes were being planned and partly carried out in the U.S.S.R., Canada, U.S.A., Japan, Federal Republic of Germany, and the Union of South Africa. The efforts of these countries in the field of deep drilling for scientific purposes are commendable. The International Upper Mantle Committee should urge governmental and other scientific organizations of these and other countries to develop programs in deep drilling for scientific purposes, and stress once again that these programs are a very important part of the Upper Mantle Project. The main objective of deep drilling for scientific purposes is the study of the upper mantle and its interaction with the earth's crust. In connection with this the International Upper Mantle Committee confirms the recommendations on the types of deep wells, research projects in deep drilling, and criteria for site selection of wells as approved in 1964 by the Committee.

"The following programs were planned or completed in 1964-1965:

U.S.S.R.

Complex geophysical studies, especially deep seismic soundings have been carried out to determine precisely the best sites for deep drill-hole locations on the Kola Peninsula, in the Ukraine, in Azerbaijan and in the region of southern Sakhalin and Kuril ridge. Four deep wells are being drilled by rotary methods to study sections in oil-and gas-bearing regions. Of these, the Aralsor well No. 1 reached a depth of 5,940 m. in 1965, and the Bashkirskaya well No. 2000 passed 3,800 m., 2,000 m. of which were in crystalline rocks. Programs for developing thermo-resistant well devices and a cable for studying deep well sections are in progress.

Canada

The Muskox drilling project involving 3 wells ranging from 760 m. to 1,220 m. deep in an ultrabasic intrusion was completed within the crystalline shield near the Arctic Circle east of Great Bear Lake. A program of further drilling of scientific wells of moderate depth (1-4 km) in crystalline rocks is being considered.

U.S.A.

Considerable progress has been made on the Mohole Project, designed to drill a well in the open ocean to reach the Mohorovicic discontinuity and sample mantle material. In addition, a program of drilling to intermediate depths on the continent in crystalline rocks is being planned.

Japan

A program of scientific drilling to intermediate depths (3-5 km) to study volcanic roots is in the planning stages.

Germany

A deep hole (6 km) to investigate an oil-and gas-bearing region has been completed, and additional holes are in progress.

"The most urgent problems in the field of deep drilling for scientific purposes are as follows:

(a) Technological improvements for drilling wells in crystalline and sedimentary rocks to a depth of 8-10 km with the most complete recovery of rock samples by means of the available equipment;
(b) Development of technique for drilling in the open sea to the depth of 5-6 km under the ocean floor;
(c) Development of new methods of well drilling;

(d) Improvement of well logging apparatus, surface equipment, and the design of logging cables for studying superdeep wells under high temperature and pressure conditions, and also for use in small diameter diamond drill-holes;

(e) Further study of sites most characteristic and valuable for drilling deep wells;

(f) Thorough analysis of the data obtained and publication of the results.

For the purpose of further exchange of information it is recommended that the next symposium on deep drilling be convened in 1968."

Prof. V.V. Beloussov Now I would like to make some remarks on my own behalf. These will concern the definition of deep drilling for scientific purposes about which I think there might be some misunderstanding. For example, the deep bore-hole in Kamchatka, which reached a depth of over 7 km certainly is a very deep hole; however, it seems to me that for the purposes of our Upper Mantle Project it does not qualify as a hole drilled for scientific purposes. From our point of view I think that drilling for scientific purposes is such drilling that will bring us quite new information about the composition and the structure of the earth's crust and certainly, the upper mantle. For instance, if a very deep hole is drilled completely in sedimentary rocks it is very useful from a practical point of view, but from the point of view of obtaining new information this kind of well probably cannot give us specific new data, because in other areas we might observe the same, or almost the same sedimentary rocks on the surface of the earth, and thus we would already know what the sedimentary section was, before drilling. Therefore, I think that we should limit the definition of drilling for scientific purposes only to such projects where we can reach some layer of the earth's crust which cannot be studied directly at the surface. For example, it seems to me that some wells may be relatively shallow, and yet provide valuable scientific data. In this category would be wells drilled for specific purposes, such as those of the Muskox project. They may be only 1 or 2 kilometres deep, but they may provide us with extremely valuable information about parts of the earth's crust which we cannot examine anywhere in outcrops.

I think that the general objectives in drilling the continental crust should be targets such as the basaltic layer for instance, since we do not know exactly what this layer actually is. Also of course in the oceans, we want not only a well which will reach the upper mantle but any holes which might penetrate the sedimentary horizons which cover the ocean floor. We know very little about the deep ocean rocks and we can be certain that such holes will lead to extremely important information about the heat flow of ocean basins. I do not want to suggest that the Mohole is not a valuable program – I think that some more modest drilling programs should be undertaken to study the sedimentary section of the ocean bottom.

Dr. S. Thorarinsson (Iceland) I wish to make a recommendation for a drill-hole into the "P-6.3 km/sec" layer beneath Iceland.

The seismic refraction measurements started in Iceland by Bath and Tryggvason in 1960 have been continued by G. Palmason and his collaborators. They have measured many tens of profiles in an area embracing the neovolcanic zone – which is a part of the mid-Atlantic rift zone – and adjacent Tertiary districts. Four layers were found with the following P-velocities: 2.8 (layer 0), 4.2 (layer 1), 5.1 (layer 2) and 6.3 (layer 3) km/sec. Layer 0 is interpreted as Quaternary volcanic products with a thickness less than 1 km. Layers 1 and 2 are Tertiary flood basalts with an aggregate thickness of about 3 km. Layer 3 has a P-velocity of 6.3 km/sec., an S-velocity of 3.5 km/sec and a Poissons ratio of 0.27. It extends down to a layer with a P-velocity of 7.4 km/sec at a depth of 10 to 16 km. Refraction measurements in the Faroe Islands revealed the existence of this layer beneath the Faroe plateau basalts but it is absent beneath the mid-Atlantic ridge north and south of Iceland.

Opinions differ as to the nature of this layer. Many students of the problem are inclined to deny the existence of any continental substratum beneath Iceland; others maintain that the petrography of Iceland and the recent volcanism cannot be explained without assuming the existence of a sialic substratum. The nature of the P-6.4 km/sec layer has played an important role in the discussion of crustal drift in Iceland. Consequently it is highly desirable to achieve a better knowledge of this layer. Recent extensive refraction measurements combined with gravity and magnetic data have revealed that in a restricted area in northern Iceland, the upper limit of the P-6.3 km/sec layer is at a depth of only 0.6 km. A drill hole about 1,000 metres deep might add considerably to our knowledge of this layer and it is therefore recommended that such a drilling project be carried out.

Dr. T.F. Gaskell (U.K.) I agree with Prof. Beloussov and Dr. Thorarinsson that there are many places where one can do shallow drilling, but I have been most impressed by two things over these past few days. The first is that the Mohole Project has progressed to a much greater and more technically possible stage than one had ever hoped possible. It is also leading to much more economic ways of drilling through crystalline rocks for all the other projects. Therefore, I think that our first resolution should be to do as was done a few years ago – say that one of the most important objectives in studying the upper mantle is in fact to get a piece of the upper mantle. To put a corollary to this, we know that the Mohorovicic discontinuity, which we talk about so much, is the boundary between the crust and the mantle. But we only know it as a manifestation of the peculiar behaviour of earthquake waves. We would like to know, as geophysicists, what really happens when you go through what seismic waves tell us is a discontinuity. Therefore, I can see no more important project ahead than the Mohole.

In this connection I would like to present a recommendation along these lines:

> We recommend that samples of rocks be collected from above and below the Moho discontinuity, in places where this feature is well established by geophysical measurements, and that physical observations be made in the bore-hole. The Mohole Project is most fundamental to advances in knowledge in a wide range of earth sciences at the present time.

Dr. T. Sorgenfrei (Denmark) I would like to support this recommendation because I think that we are now at a stage, as has been pointed out, where we are able to undertake such a project both financially and technically. Also in the future we may want to drill even deeper holes, so it is best to start drilling this hole as soon as possible. For our general understanding of the crust and what is below, we need to have holes such as the Mohole now. I am afraid that if we do not emphasize this, our governments may think that we could get by with drilling only shallow holes. We need such shallower holes also, of course, to provide data from the ocean basins and the continents, but it is of fundamental importance to drill deep holes such as Mohole. I would therefore like to support this resolution.

Dr. H.H. Hess (U.S.A.) I would like to elaborate on Prof. Beloussov's statements regarding ocean drilling. I agree that this is also extremely important. I think that holes should be drilled through ocean sediments in many places; it can be done quickly and,if you have a drilling vessel, not too expensively. The purpose of these holes would be to try and work out the stratigraphic column of the ocean floor and to find out at least the more recent history of the ocean basins. In this way ideas of continental drift and ocean spreading could be tested.

I would also recommend shallow drilling (1,000-3,000 feet) on oceanic islands, mainly for petrologic information. This is the sort of drilling that could be useful in the Hawaiian Islands, Iceland and many other places. Data on seismic velocities and petrology of the rocks in these holes will be essential for an understanding of oceanic islands in general.

Combined stratigraphic and petrologic objectives might be met by drilling on atolls. Such a hole has already been started on Midway Atoll. This was initially planned to determine the stratigraphy of the calcareous sediments of the atoll, but the hole will penetrate into the basalt, and will give us oriented cores of the basalt.

Finally, a project that would be most exciting to me would be drilling into the top of layer 2, to determine the cause of the linear magnetic anomalies in oceans. If Dr. Matthews and Dr. Vine are correct, and we showed that the positive anomalies are due to normally magnetized basalt, and the negative anomalies due to reversely magnetized basalt, we might be able to determine how fast the ocean floor has spread based upon radioactive age determinations on the basalts. In summary, I would propose that a program by many nations of drilling the sediments and layer 2 of the ocean floor for a variety of geophysical, stratigraphic, petrological and historical purposes be recommended by this group.

Dr. C.L. Drake (U.S.A.) I would like to second Prof. Hess's recommendation. I think that drilling the sediments in the ocean is one of the most fruitful experiments that could be carried out at the present time. I would suggest that drilling programs on the continental margins would be very useful. These are extremely critical areas in connection with present theories of continental drift or continental accretion, and any information that could be obtained on these areas through drilling would be extremely valuable. There has been considerable geophysical work done on the continental margins, and we are now almost at the point where, in order to learn anything further, we will have to actually sample the rocks. Also, the political picture concerning the continental shelves and continental margins has become clarified in the last few months with the ratification of the convention on the continental shelves. Therefore I would like to offer a resolution worded something as follows:

> The transition areas between continents and oceans offer extremely attractive target areas for oceanic drilling. Considering the geophysical work that has been done on many margins which has resulted in speculation about their nature, their history, and their permanency, the verification of these ideas depends on actual sampling of the sedimentary rocks as well as the basement rocks beneath them. Since the information gained would be fundamental to understanding not only these important structures, but such basic theories as continental drift and continental accretion as well, it is urged that every effort be made to drill such holes for scientific purposes.

Prof. Beloussov I agree with all these proposals, but I also think we should say something about drilling on continents in our resolutions. As has been mentioned, the study of the Conrad discontinuity, or a definition of the composition and structure of the supposed basaltic layer 2 in the regions where it is not deep, would be very useful. Also I think that countries that cannot allocate large funds for deep drilling could usefully participate in this program by concentrating on shallower wells, provided such wells are located properly.

Prof. R.J. Uffen (Can.) I would like to support this last resolution, and mention specifically the drilling of holes for heat flow studies. We hope that we can establish an extensive network of drill holes for this purpose in Canada, and a start has already been made in this program. One of the Canadian proposals in connection with the Upper Mantle Project was to have a network of 25 to 30 seismic stations across the country. These would be shallow holes but in line with what Prof. Beloussov has said they would provide valuable scientific information and serve as a network into which we could tie measurements made in bore-holes drilled by the oil, gas and mining industries. I would like to recommend that we re-affirm the desirability of drilling holes in continental areas for the purpose of heat flow measurements.

Prof. Hess (U.S.A.) I would second this recommendation. A strong recommendation on continental drilling is important.

Prof. H.P. Laubscher (Switz.) Having previously recommended drilling in the Alps I would like to expand on the subject here since Prof. Hess has said that we should not forget the continents. Recent seismic exploration of the Alps has determined the rather startling fact that the deepest roots of the Alps are not below the central, most intensely deformed part, but below the southern Alps which are relatively undeformed. The seismic measurements seem to indicate that this most important – from a seismic standpoint – part of the Alps, is not composed of any of the regular crustal layers, but is of the mixed-layer type with a velocity of 7.4 km/sec. From published seismic sections it would appear that this is the single most important rock body in the Alps, and therefore it ought to be explored by deep drilling.

A second point of interest concerns the disappearance of the Alpine chain at the border of the Mediterranean, and its reappearance again on some of the islands. Neither seismic measurements nor topographic soundings have uncovered any facts about the missing links between the different pieces of the Alpine chain, which are now buried under water depths of 1,000 to 3,000 metres. I think that it would be worth while exploring these missing links by drilling.

Much has been said here about testing theories such as continental drift and ocean bottom spreading by shallow drilling in the ocean. But the ideas of Prof. Beloussov concerning the "oceanization" of a former continental crust have not been mentioned. This could be a very important concept in connection with the disappearance of the Alpine chain in the Mediterranean. There is palaeogeographic evidence that continental rocks exposed at the surface at some time during the Tertiary, now underlie the

Mediterranean Sea at a depth of 3,000 metres. It would be a useful project to drill through the Upper Tertiary-Quaternary sediments of, for example, the Tyrrhenian Sea to determine whether there are continental deposits of Tertiary age there. Since the gravity measurements show that the area is in isostatic equilibrium, the presence of Tertiary continental deposits would indicate that a former continental crust has subsided by isostatic movement to a depth of almost 3,000 km. Such a subsidence would have to be achieved by some method of condensing the crust.

Prof. Gene Simmons (U.S.A.) Following the lead of Prof. Hess, I would like to present on behalf of Dr. Diment and myself, the following recommendations:

1. A few very deep holes (8-10 km) drilled on the continents are necessary at this time if we are to advance significantly the scientific understanding of several problems, including the distribution of certain isotopes in the earth's crust;
2. Advantage should be taken of slim-hole diamond drilling to depths of 3-4 km, for such studies as heat flow measurements, the examination of interesting geothermal areas, and the investigation of geological problems of outstanding importance. This clearly applies to the investigation of some very important structural problems such as Prof. Laubscher has just mentioned.
3. Logging tools should be developed for use in small diameter bore-holes, and techniques for the better interpretation of logs obtained in non-sedimentary rocks should be encouraged.

I think that this last recommendation ties in with all the other recommendations that people have made here this afternoon. One of the most fruitful sources of information from bore-holes drilled in sedimentary rocks by the oil industry has been provided by geophysical logging. And yet, we are in the somewhat anomalous situation of recommending drilling holes in crystalline rocks for which we do not have adequate instrumentation to obtain the same type and quality of data.

Prof. H. Kuno (Japan) At the Upper Mantle Committee meeting in Moscow last year, one of the three general recommendations regarding drilling, concerned the drilling of island arcs. The phrase "island arcs" may have two meanings. One refers to island arcs that are very close to continents, such as the Japanese Islands or Indonesia. However, I would like to call attention to another kind of island arc which has a unique structure and petrologic character of its lavas. Island arcs of this type include the

Izu-Marianas Islands, Tonga Islands, South Sandwich Islands and perhaps the Aleutians and West Indies. I am not completely familiar with the petrology and the structure of the West Indies but, so far as the petrographic character of the volcanics of the other islands is described in the literature, we know that their lavas have a very unique character. They are low in alkalies, and rather high in silica, compared with volcanic rocks of the typical oceanic islands such as Tahiti and Samoa. Although the Tonga Islands are very close to the Samoa Islands, the petrographic character of the two island groups is very different. The rocks of the Samoa group are typical alkali volcanics, but those of the Tongas, especially of the islands at the northern end of the Tonga chain, have a quite different character – they are typical tholeiitic basalts, low in alkalies. It is well known that most of the volcanic islands in the oceans are characterized by basalt and trachyte of the alkali rock series, but here we have island arcs that are capped by tholeiitic rocks ranging in composition from basalt to dacite.

In addition to their petrologic differences, there are also structural differences. On one side of these island arcs there are deep trenches, such as the deep trenches on the east side of the Marianas, the Tongas, and the South Sandwich Islands. On both sides of these island arcs there may be oceanic crust and oceanic mantle, but the physical character of the oceanic mantle on either side of the arcs may be different. For instance, there is some indication of a difference between the seismic velocities in the upper mantle of the Philippine Sea and those of the main part of the Pacific Ocean. The Mariana Islands lie between these two major units of the oceanic mantle. Unfortunately, detailed geological and geophysical studies of these island arcs have never been done. I would strongly recommend that drilling be done in several of these island arcs in order to determine whether they are simple volcanic piles and also to determine what rocks underlie these island arcs.

Dr. G.H. Charlewood (Can.) Speaking as a member of the diamond drilling industry in Canada, I would like to comment on a subject that appears to me to be of prime importance if scientific drilling projects are to proceed logically and with some continuity. Several recommendations covering specific earth science problems have been made today and the matter of financing has been mentioned frequently. I think that this latter subject deserves some concrete suggestions.

Governments have been committed to earth science expenditures for many years, for economic purposes as well as for fundamental scientific knowledge. This work has defined many two-dimensional problems which need clarification in the third dimension. The best means to achieve this is by drilling. Thus it would seem to follow naturally that funds for earth science research should include an annual budget for drilling, for without drilling the solution to many problems is not possible.

It is recommended therefore that granting agencies be urged to consider that drilling is a logical part of the scientific research program.

Dr. S.H. Haughton (South Africa) In South Africa, as I said yesterday, we would like to drill in some of the most ancient rocks of the earth's crust. These rocks, by their very nature, must be fairly low down in the crust. Our problem of course is to get the necessary funds to drill holes for what one might call purely scientific purposes. Therefore, I think that if strong resolutions could come from this symposium, urging governmental support for drilling, then we should certainly have ammunition with which to approach the South African government and ask for further assistance. I do not want to leave the impression that the South African government is not sympathetic to these projects, because it has already provided funds for this coming year to enable us to carry out a program which we think is an initial step in this international investigation of the lower crust and upper mantle. I will not go into details of this program, but it concerns the northeast part of South Africa where ancient granitic gneisses are bordered by Triassic basalts. These basaltic outflows as well as others that occur to the north in Rhodesia, may be a result of a "geothermal wave" from the basaltic layer in Triassic time. Work recently carried out by the Leeds Research Laboratory suggests that a succession of rhyolites and basalts occurring in the area just north of the South African Republic has been due to an uprising of heat, followed by a static condition, and then a lowering of heat, resulting in repeated generation of basalt from the basaltic layer as the geothermal level rose. This hypothesis may have some bearing on the possibility of finding the basaltic layer at a comparatively shallow depth below these Archean granitic rocks.

Dr. Sorgenfrei First of all I would like to emphasize the great progress that has been achieved when we compare the first papers given at the meeting in Berkeley (Calif.) with those that we have heard here. But I would also like to emphasize the practical and financial implications. As we know, up to now few countries have actually carried out drilling projects. If we really want to have more countries participate in these projects then we should have a general idea of what financial and mechanical implications are involved. Therefore, I would recommend that those papers that have dealt with these problems during this session be published as soon as possible. It will be extremely valuable to many countries to have data regarding the footage prices and about the various types of drilling equipment and techniques. Up to now, only those countries which have a mining industry or an oil industry have some knowledge about the costs involved.

Dr. P.J. Hart (U.S.A.) emphasized the importance of collecting suggestions and recommendations from people at the meeting and outside and publishing them – perhaps even a catalogue of specific sites and projects – so that priorities could be documented.

Dr. A.H. Lachenbruch I do not think that the question of optimum utilization of holes drilled for scientific purposes has been discussed today. There are many scientific purposes for drilling, although often a single scientific purpose motivates the drilling of a hole. It seems to me that we should urge that the institution, or the people responsible for drilling a hole, contact their colleagues with peripheral interests to make sure that the hole is utilized in the best way possible for the geophysical community. I mention this specifically because I do not think it is a hypothetical problem. I know of several holes that would fall into the category of holes drilled for scientific purposes in the last year, where the scientific purposes were rather restricted and many other studies, including heat flow work,could have been done, but were not.

Dr. Hart urged that attempts be made to learn where and when holes are being drilled for commercial purposes, so that they can be utilized for scientific purposes.

Dr. Hess remarked that holes are often drilled and abandoned because the costs of keeping them open are too high.

Dr. D.H. Matthews (U.K.) I wonder if it would be possible for geological surveys in Europe to combine to make use of the considerable quantity of drilling machinery gathered in the North Sea at the present? It might be possible for European countries, particularly those with access to the continental margins such as Portugal, France, Germany, Norway etc. to provide funds to contract some of this equipment to carry out drilling projects on the Atlantic continental margin.

Dr. Gaskell remarked that not much saving in cost could be realized by this since transportation or mobilization costs of drilling ships are relatively minor in comparison to the costs of actual drilling.

Dr. Hess You could save a little. If there happens to be a ship near the site, costs can be reduced. There was a hole drilled off Jamaica in this way. The barge happened to be going from Panama to the U.S. and they drilled a hole for the University of Miami on the way.

Dr. Drake noted that holes were drilled for Woods Hole, Scripps Institute, University of Miami and Lamont by Caldrill at relatively low costs because the ship was passing by the area (proceeding from Panama to the Grand Banks off Newfoundland) and transportation or mobilization costs, which were considerable, were assumed by the Pan American Petroleum Corp. for whom it was under contract.

Prof. Hess agreed that it might be useful to make a recommendation in line with Dr. Matthews' suggestion that use could be made of equipment presently in the North Sea area for drilling for scientific purposes.

Dr. Gaskell re-emphasized his earlier remarks concerning the probability of little cost savings by using equipment in the North Sea but said he would be pleased to make enquiries regarding any specific suggestion.

APPENDIX I

PROGRAM

SYMPOSIUM ON DRILLING FOR SCIENTIFIC PURPOSES
OTTAWA, CANADA

2 September A.M.

Chairman: R.J. UFFEN Reporter: D.C. FINDLAY
Opening Remarks: W.E. VAN STEENBURGH
J. WATSON MacNAUGHT
R.J. UFFEN (on behalf of V.V. BELOUSSOV)
C.H. SMITH

DISCUSSION OF SCIENTIFIC DRILLING PROGRAMS

M. SAITO (Japan): Deep Drilling Program of Japan.
H.P. LAUBSCHER (Switzerland): The Project for Scientific Deep Drilling in the Swiss Alps.
D.C. FINDLAY and C.H. SMITH* (Canada): Drilling for Scientific Purposes in Canada.
G. SIMMONS (USA): Crustal Drilling in the U.S.A.
T. SAITO (Japan): Ocean Drilling off the Coast of Eastern Florida.

2 September P.M.

GEOPHYSICAL RESEARCH IN DEEP HOLES

Chairman: T.F. GASKELL Reporter: E.R. NIBLETT

T.F. GASKELL (UK): Opening Remarks.
A.F. BOSWORTH (Canada): Logging Techniques in the Oil Industry.
S.H. HAUGHTON (South Africa): Instrumentation in Deep Diamond Drill Holes in South Africa.
A.E. BECK (Canada): Problems in Measuring Temperature and Terrestrial Heat Flow in Deep Bore-holes.
G.G.R. BUCHBINDER, E. NYLAND and E. BLANCHARD* (Canada): Measurement of Stress in Bore-holes.

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*Speaker

W.P. SCHNEIDER (USA): Deep-hole Scientific Instruments and Measurements for Project Mohole.

G.D. HOBSON*, A.E. BECK and D.C. FINDLAY (Canada): Notes on Geophysical Logs and Bore-hole Temperature Measurements from the Muskox Drilling Project.

2 September Eve.

SCIENTIFIC OBJECTIVES OF DEEP CRUSTAL DRILLING

Chairman: J.M. HARRISON

J.M. HARRISON (Canada): Opening Remarks.

V.V. FEDYNSKY (USSR): Deep Drilling in the USSR for Scientific Purposes (presented by V.V. BELOUSSOV).

T.F. GASKELL (UK): The Merits of Scientific Drilling.

H.H. HESS, J.D. SIDES and W.F. TONKING (USA): Status and Accomplishments of the Mohole Project, Phase II.

3 September A.M.

DEEP DRILLING TECHNOLOGY

Chairman: W.H. TONKING   Reporter: D.C. FINDLAY

W.H. TONKING (USA): Opening Remarks.

W.S. GARRETT (South Africa): Core Drilling in South Africa.

S.C. FOSTER (USA): A Discussion of Rotary Drilling in Igneous Rocks of Western U.S.A. and Alaska in the 5,000'-10,000' Depth Range.

D.L. SIMS (USA): Diamond Coring Techniques for Project Mohole.

FILM: Testing Equipment for Mohole Project at the Uvalde, Texas Site.

H. BECKER (Federal Republic of Germany): Planning and Drilling the Deepest Well in Europe (by title).

FILM: U.S.A. Atomic Energy Film: Big Hole Drilling in Pahute Mesa - shown by Brinkerhoff Drilling Inc.

3 September P.M.

DISCUSSION OF RECOMMENDATIONS

Joint Chairmen: J.M. HARRISON and H.H. HESS
Joint Reporters: D.C. FINDLAY and C.H. SMITH

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*Speaker

Recommendations were submitted and read by: V.V. BELOUSSOV (USSR)

a) for FEDYNSKY
b) for himself
S. THORARINSSON (Iceland)
T.F. GASKELL (UK)
H.H. HESS (USA)
C.L. DRAKE (USA)
H.P. LAUBSCHER (Switzerland)
G. SIMMONS (USA)
H. KUNO (Japan)
G.H. CHARLEWOOD (Canada)
S.H. HAUGHTON (South Africa)
T. SORGENFREI (Denmark)
A.H. LACHENBRUCH (USA)

Comments on recommendations were made by:

V.V. BELOUSSOV (USSR)
R.J. UFFEN (Canada)
H.H. HESS (USA)
J.M. HARRISON (Canada)
P.J. HART (USA)
D.H. MATTHEWS (UK)
T.F. GASKELL (UK)
C.L. DRAKE (USA)

Appendix II

LIST OF PARTICIPANTS

J. Banks	Brinkerhoff Drilling Co., Ltd., Postal Station L., Box 5110, S. Edmonton, Alberta, Canada.
A.E. Beck	Department of Geophysics, University of Western Ontario, London, Ontario, Canada.
H. Becker*	Institut für Tiefbohrkunde und Erdölgewinnung der Bergakademie Clausthal Technische Hochschule 3392 Clausthal-Zellerfeld, Federal Republic of Germany.
E. Bederke	Georg August University, Berliner Str. 28, Göttingen, Germany.
V.V. Beloussov	Soviet Geophysical Committee, Molodezhnaya 3, Moscow B-296, U.S.S.R.
H. Berckhemer	Institut fur Meteorologie and Geophysik, Frankfurt / Main, Feldbergstrasse 47, Germany.
J.E. Blanchard	Dalhousie Institute of Oceanography, Halifax, Nova Scotia, Canada.
A.F. Bosworth	Schlumberger of Canada, 335 Elveden House, Calgary, Alberta, Canada.

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*In absentia

W.C. Brisbin	Department of Geology, University of Manitoba, Winnipeg, Manitoba, Canada.
B.B. Brock	Bosky Dell D., Grant Ave., Simon's Town, South Africa.
C.A. Burk	Socony Mobile Oil Co., Inc., 150 East 42nd St., New York, U.S.A.
J.F. Caley	Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, Canada.
G.H. Charlewood	Heath and Sherwood Diamond Drilling Company Ltd., 6 Hudson Bay Avenue, Kirkland Lake, Ontario, Canada.
D.W. Coates	Midwest Diamond Drilling Company, 866 King Edward Street, Winnipeg, Manitoba, Canada.
L.S. Collett	Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, Canada.
W.H. Diment	Department of Geology, University of Rochester, Rochester, New York, U.S.A.
C.L. Drake	Lamont Geological Observatory, Palisades, New York, U.S.A.

V.V. Fedynsky*	Soviet Geophysical Committee, Molodezhnaya 3, Moscow B-296, U.S.S.R.
D.C. Findlay	Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, Canada.
Y.O. Fortier	Director, Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, Canada.
S. Foster	Brinkerhoff Drilling Company, 870 Denver Club Bldg., Denver, Colorado, U.S.A.
W.S. Garrett	Managing Director, Cementation Co. (Africa) Ltd., P.O. Box 1128, Johannesburg, South Africa.
T.F. Gaskell	British Petroleum Limited, Britannic House, Finsbury Circus, London E. C. 2, Great Britain.
M.J. Gleason	E.J. Longyear Company, Minneapolis, Minnesota, U.S.A.
K. Graber	Inspiration Limited, P.O. Box 477, North Bay, Ontario, Canada.
W.M. Gray	Mines Branch, Department of Mines and Technical Surveys, Booth Street, Ottawa, Ontario, Canada.

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*In absentia

J.M. Harrison
Department of Mines and Technical Surveys,
588 Booth Street,
Ottawa, Ontario,
Canada.

P.J. Hart
National Academy of Sciences,
2101 Constitution Avenue, NW,
Washington D.C. 20418,
U.S.A.

S.H. Haughton
P.O. Box 401,
Pretoria,
South Africa.

H.H. Hess
Department of Geology,
Princeton University,
Princeton, New Jersey,
U.S.A.

M.L. Hill
Richfield Oil Corporation,
555 South Flower Street,
Los Angeles 17, California,
U.S.A.

G.D. Hobson
Geological Survey of Canada,
601 Booth Street,
Ottawa, Ontario,
Canada.

J. Hooks
Brinkerhoff Drilling Company, Ltd.,
Postal Station L, Box 5110,
S. Edmonton, Alberta,
Canada.

J.E. Husted
Georgia Institute of Technology,
Engineering Experiment Station,
Atlanta, Georgia 30332,
U.S.A.

R.K. Irvine
Peter Bawden Drilling Ltd.,
10th Floor,
707-7th Avenue, S.W.,
Calgary, Alberta,
Canada.

T.N. Irvine
Geological Survey of Canada,
601 Booth Street,
Ottawa, Ontario,
Canada.

A.M. Jessop
Observatories Branch,
Department of Mines and Technical Surveys,
Carling Avenue,
Ottawa, Ontario,
Canada.

H. Kuno
Geological Institute,
University of Tokyo,
Tokyo, Japan.

A.H. Lachenbruch
U.S. Geological Survey,
345 Middlefield Road,
Menlo Park, California,
U.S.A.

A. Larochelle
Geological Survey of Canada,
601 Booth Street,
Ottawa, Ontario,
Canada.

H.P. Laubscher
Geological Institute of the University of Basel,
Bernoullistrasse 32,
4000 Basel, Switzerland.

W.H.K. Lee
Institute of Geophysics,
University of California,
Los Angeles, California,
U.S.A.

A.S. MacLaren
Geological Survey of Canada,
601 Booth Street,
Ottawa, Ontario,
Canada.

V.A. Magnitsky
Soviet Geophysical Committee,
Molodezhnaya 3,
Moscow B-296,
U.S.S.R.

M. Maldonado-Koerdell	Pan American Committee of Geophysical Sciences, PAIGH Ex-Arzobispado 29, Mexico 18, D.F. Mexico.
M. Maska	Department of Physical Geology, Czechoslovakian Academy of Science, Praha 4, Spirilov, Bocni 2, Czechoslovakia.
L.R. McDonald	Midwest Diamond Drilling Company, 705-80 Richmond Street W., Toronto, Ontario, Canada.
M.J. McKenna	Inspiration Limited, P.O. Box 477, North Bay, Ontario, Canada.
H.O. Militzer	Institut für Angewandte, Geophysik Bergakademie, Freiberg, Germany DDR.
L.W. Morley	Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, Canada.
P.S. Naidu	Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, Canada.
E.R. Niblett	Observatories Branch, Department of Mines and Technical Surveys, Carling Avenue, Ottawa, Ontario, Canada.
R.S. Parsons	J.K. Smit & Sons, Diamond Products Ltd., 81 Tycos Drive, Toronto 19, Ontario, Canada.

W.L. Petrie	National Academy of Sciences, 2101 Constitution Avenue, N.W., Washington, D.C., U.S.A.
L. Picard	Department of Geology, Hebrew University, Jerusalem, Israel.
S.C. Robinson	Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, Canada.
M. Saito	Geological Survey of Japan, 8 Kawada-cho, Shinjiku, Tokyo, Japan.
T. Saito	Lamont Geological Observatory, Palisades, New York, U.S.A.
W. Schneider	Brown and Root Incorporated, San Jacinto Building, Houston, Texas, U.S.A.
G.W. Shipley	Mine Equipment Company, Montreal, Quebec, Canada.
J.D. Sides	National Science Foundation, 800 San Jacinto Building, Houston, Texas, U.S.A.
G. Simmons	Geophysics Department, M.I.T., Cambridge, Massachusetts, U.S.A.
D. Sims	Brown and Root Incorporated, San Jacinto Building, Houston, Texas, U.S.A.

C.H. Smith	Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, Canada.
T. Sorgenfrei	Instituttet for Teknisk Geologi, Lyngby, Denmark.
J.G.A. Stevenson	Canadian Longyear Ltd., P.O. Box 330, North Bay, Ontario, Canada.
A. Sugimura*	Geological Institute, Faculty of Science, University of Tokyo, Hongā, Tokyo, Japan.
A.J. Surkan	System Research & Development Centre, IBM Corporation, 590 Madison Ave., New York, U.S.A.
H. Sydor	8625 Basswood, Montreal 2, Quebec, Canada.
S. Thorarinsson	Department of Geology and Geography, Museum of Natural History, Reykjavik, Iceland.
W.H. Tonking	Brown and Root Incorporated, San Jacinto Building, Houston, Texas, U.S.A.
R.J. Uffen	College of Science, University of Western Ontario, London, Ontario, Canada.

---

*In absentia

W.E. van Steenburgh
Deputy Minister,
Department of Mines and Technical Surveys,
588 Booth Street,
Ottawa, Ontario,
Canada.