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SCIENTIFIC DRILLING AT THE EARTH PHYSICS BRANCH - PAST ACHIEVEMENTS AND PRESENT POSSIBILITIES

Malcolm J. Drury and Alan M. Jessop

Division of Gravity, Geothermics and Geodynamics
Earth Physics Branch
Energy, Mines and Resources Canada

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Introduction

The Earth Physics Branch is currently involved in a major exercise in crustal seismology, the "lithoprobe" project. Several major reflection and refraction surveys are anticipated - some have already been completed. Other geophysical techniques, such as magneto-telluric surveys, are also being used. The justification for the major expense both in time and money is that such surveys provide information on the earth's crust to depths of many kilometres below surface. The seismic reflection component of the project - line surveys - does not give information in three dimensions, but only in two. By careful choice of survey lines the importance of that information can be substantial, but it is still severely restricted areally. Potential field geophysical surveys are able to provide much greater areal coverage, but their interpretation is often more difficult because of the non-uniqueness of the solutions. Multidisciplinary studies can help to reduce this problem if different potential field techniques, with different resolving powers, are used. By combining the two types of survey a clearer picture of the structure of the crust is possible.

Ultimately there is only one way to gain exact knowledge of the nature, composition and structure of the crust, and that is to drill into it. Drilling provides the only means of verifying the interpretations of surveys conducted from the earth's surface. Many countries are either already drilling or are about to drill deep holes. The Russian deep hole in the Kola peninsula is now about 12 km deep, and it has produced some scientific surprises (Kozlovsky 1984). The Americans appear poised to drill a 10 km hole in the southern Appalachians to test the hypothesis that there is a vast crystalline overthrust zone overlying ancient sediments; a report in EOS (October 23rd., 1984) suggests that U.S. government support for scientific drilling is "running at an all-time high". The Appalachian project would cost approximately $M40 U.S. for the drilling and a further $M20 U.S. for scientific work.

The Earth Physics Branch (E.P.B.) and its previous incarnation as the Dominion Observatory (D.O.), has a long history of scientific drilling. It is the purpose of this report to describe briefly that history and to present some ideas for present scientific needs for a renewed drilling effort. Both small scale, basically single-purpose programmes, involving one or two scientists, and large scale ones, involving multidisciplinary studies by diverse groups of scientists, are considered. The suggestions of various members of E.P.B. have been solicited. Any major scientific drilling programme would require the opinions and expertise of members of all aspects of the solid earth sciences, as was done in planning the lithoprobe project.

History of drilling at D.O. and E.P.B.

The first scientific drilling by the D.O. was at Resolute Bay in 1950, when eight holes were drilled to obtain temperature data for heat flow and analysis of climatic change (Bremner 1955). That project lasted until 1953. Total drilling was 2126 m. Drilling for the crater studies programme began in 1955, when two holes were drilled in the Brent crater in Ontario. Drilling at that and other sites continued until 1967, when two more holes were drilled at Brent. The geothermics programme benefitted greatly from that drilling. The total amount of drilling of 32 holes was 13050 m. Drilling for the formal geothermics programme of the D.O. began in 1962 when a 602 m hole was sunk on its Ottawa campus. That drilling programme continued until 1969, with a total of 17 holes and 9486 m. The most recent drilling has been for geothermal studies in Nova Scotia, a hole having been

Table 1. Holes drilled for scientific purposes by the Dominion Observatory and its successor, the Earth Physics Branch

Year	Location	No. of holes	Total drilled (m)	Purpose
1950	Resolute Bay	8	165	Geothermics
1951	"	6	663	"
1952	"	4	791	"
1953	"	3	507	"
1955	Brent	2	231	Crater studies
1957	Holleford	3	932	"
1959	Brent	1	1064	"
1961	"	7	2210	"
1962	Ottawa	1	602	Geothermics
1962	Deep Bay	2	614	Crater studies
1962	Neilsen I.	1	1041	"
1962	Franktown	1	305	"
1962	Clearwater L.	5	2391	"
1963	Clearwater L.	1	220	"
1963	Halifax	1	366	Geothermics
1963	Penticton	1	611	"
1963	London	1	594	"
1964	Clearwater L.	1	1010	Crater studies
1964	St. Jerome	1	760	Geothermics
1964	Roberval	1	611	"
1964	Winnipeg	1	610	"
1965	West Hawk L.	1	727	Crater studies
1965	Deep Bay	1	483	"
1966	West Hawk L.	3	746	"
1966	Deep Bay	1	471	"
1966	Dease L.	1	291	Geothermics
1966	Hotailuh	1	428	"
1966	Buckley L.	1	427	"
1967	Cochrane	1	474	"
1967	Kapuskasing	1	607	"
1967	Brent	2	1783	Crater studies
1968	Hearst	1	658	Geothermics
1968	Jackfish	1	611	"
1968	Otoskwin R.	1	612	"
1969	Minchin L.	1	610	"
1969	English R.	1	614	"
1979	Charlevoix	2	100	Geodynamics
1981	"	1	125	"
1985	Wedgeport	1	483*	Geothermics

* partly funded from geothermal energy programme

drilled in January, 1985 into the anomalously radiogenic Wedgeport granite, but it is being funded partly from the geothermal energy programme, and so is not a hole for purely basic research. The authors hope that it represents a return towards drilling for the sake of answering geophysical problems rather than of answering those of applied programmes only. Holes drilled under such programmes are, of course, extremely valuable scientifically, but, like industrial holes, they are drilled in areas specific to the programmes.

Since 1969 the only drilling done by the E.P.B. has been in support of two major programmes of directed research, the northern energy and the geothermal energy programmes. The bulk of the northern energy drilling was very shallow holes, drilled between 1976 and 1979. Drilling for the geothermal energy programme began in 1974, when two holes were drilled at Mt. Meager, B.C. Although there was no formal geothermal energy programme at that time, those holes are here classified as belonging to the programme. It might be argued that they were in fact truly for basic scientific purposes. In the early 1980s a substantial drilling programme by Trevor Lewis at P.G.C. considerably boosted the number of holes being drilled for the geothermal programme. Many of these were shallow holes, less than 100 m deep. Fig.1 shows in histogram form the history of drilling at the D.O. and E.P.B. Only those holes greater than 30 m deep have been counted; the choice of that value is arbitrary, and designed to filter out shallow holes drilled very cheaply without contracted drillers.

Sources of data for the geothermics programmes

The geothermics programmes at E.P.B. are heavily dependent on obtaining data from boreholes. This section is a summary of the sources of those data. To date the geothermics group has gathered temperature data from 744 holes at 366 distinct sites across Canada. It has drilled 162 holes greater than 30 m in depth, with only 80 of 100 m or more. The majority of holes from which data have been obtained have been holes of opportunity - those drilled by mineral exploration companies, the oil and gas industry, provincial governments, and in recent years by Atomic Energy of Canada Ltd. The group has also been able to obtain data from some holes drilled by the federal government, including some of the crater studies holes.

The distribution of data sources is shown in Fig. 2, which emphasises the dependence on outside sources, whether the divisions be considered by total number of holes or by the total number of distinct sites. All holes drilled by the group and listed in the computer file of hole information, including those less than 30 m deep in the northern energy programme, have been counted in Fig. 2. This has been done to highlight the different approaches to data gathering, which reflect different requirements of the programmes. For some programmes, many holes have been drilled at relatively few distinct sites. The northern energy programme, for example, has produced 127 holes at only 12 sites. Its representation in Fig. 2 is substantial in the pie chart for holes, but minor in terms of sites. The holes drilled under E.M.R. (and its precedent) scientific programmes were at separate sites, so their representation in Fig 2 is greater for the sites chart than for the holes. By far the greatest source of data is industry. Although the group owes an enormous debt of gratitude to those industry, provincial government and other personnel who have made their holes available, there is a serious flaw in such restrictive dependence: the group has no control over the siting of such holes. The impact of this restriction is probably least for the northern energy programme, the work being immediately aimed at providing scientific support to the very industry that provides holes. The most serious impact is on scientific heat flow studies. Mineral exploration holes are usually drilled to examine geophysical anomalies. While the relevance of geothermics to such studies is substantial, it is often difficult, if not impossible, to obtain data from normal sites that are more properly representative of the study area as a whole, or from features of scientific interest such as craters. Industry is unlikely to drill in areas that have no potential economic significance, so vast areas of the country remain unexplored below the surface.

The use of industrial boreholes has been extremely important, having enabled the geothermics group to carry out thermal studies in many parts of the country that otherwise could not have been considered. However, the heavy reliance on such holes is undesirable. Other government agencies carry out drilling, but it is not easy to maintain an awareness of such activities. For example, some of the deep (up to 800 m) holes drilled for the Nuclear Fuel Waste Management Programme (N.F.W.M.P.) were not announced to all earth scientists in the programme as being available. Cooperation among federal and provincial earth scientists is erratic. Holes drilled by the Geological Survey of Canada at Kelly Cross, Russell and Picton were made available to the group. A request by Drury to the Ontario Geological Survey for information on some of their boreholes was not answered. On the other hand, provincial geophysicists in New Brunswick and Nova Scotia, for example, have been exceptionally helpful in directing us to boreholes.

Industry earth scientists are generally very helpful in allowing access to boreholes and core, but they may be prevented by company policy from providing useful data such as lithological logs. Success rates in logging trips varies, but an average of approximately 20% of boreholes located yielding useful data would be considered excellent. The geothermics group is, with regard to its purely scientific operations, attempting to gain as much as possible from a situation that is far from ideal. The crater studies and geodynamics (Charlevoix) groups are not presently involved in drilling programmes.

Brief overview of international scientific drilling programmes

In May 1984 Jessop attended the International Symposium on Observation of the Continental Crust through Drilling, held in Tarrytown, New York. A report (Jessop 1984) summarised the proceedings.

It is appropriate to list here some of the major international drilling projects without going into detail, in order to present a basis for comparison with the Canadian situation. Major projects are:

1. U.S.S.R. Kola Peninsula - to obtain a better understanding of the distribution of mineral resources at great depth. The hole is presently approximately 12 km deep, and the final depth is planned to be 15 km. Major scientific surprises included an increase in geothermal gradient from 10 mK/m to 25 mK/m at 3 km, a zone of free water, possibly water of crystallisation, between 4.5 and 9 km, and the observation that a seismic wave velocity discontinuity at 9 km, thought to be the Conrad discontinuity, was the base of a 4.5 thick zone of hydraulic disaggregation of the metamorphic rock (Kozlovsky,

1984).

2. U.S.S.R. Saatly - the second super-deep hole in the Soviet Union has presently reached a depth of 8500 m, with a planned total depth of 15 km (Kozlovsky 1984). The hole is in an area of oil production near the Caspian Sea.

3. U.S.S.R. Three other super-deep holes (7000+ m) are planned. Six other deep (4000+ m) holes are also planned (Kozlovsky 1984) but no details are available at present.

4. U.S.A. Michigan Basin - In 1975 a 5.3 km deep hole was completed, by a consortium of petroleum companies, in the Michigan Basin. Members of the U.S. Geodynamics Project were able to arrange National Science Foundation funding for adding scientific experiments to the drilling programme. As a result, scientific investigations were undertaken in the fields of determining the age, origin and thermal development of the basin, in measurement of geophysical parameters such as heat flow that might be perturbed by near surface effects in shallow experiments, and measurement of *in situ* properties of the rocks at depth. A summary report was given by Sleep and Sloss (1978).

5. U.S.A. Appalachians - as mentioned above a 10 km hole is planned for the southern Appalachians thrust zone. If successfully drilled, the hole should shed light on several problems in tectonics. The presence of a zone that is interpreted to be a sediment layer underlying allochthonous crystalline material has been strongly suggested by several geophysical studies, including geomagnetic deep sounding, seismic reflection and geodynamics of basin loading.

6. Iceland Reydarfjordur - a 2 km hole was drilled in eastern Iceland in 1979 by the Iceland Research Drilling Project, to study the geology and development of an axial rift zone. The hole was drilled by a Canadian company. It was one in a natural progression of drilling programmes led in part by Dr. J.M. Hall of Dalhousie University to study oceanic islands. Holes had previously been drilled in Bermuda (802 m, 1972) and the Azores (981 m, 1973). Drury has been associated indirectly with all three programmes, measuring physical properties of core material.

7. Cyprus A major drilling project in the Troodos ophiolites of Cyprus began in 1982. The project is under the auspices of the International Crustal Research Drilling Group with a major part being played by Dalhousie earth scientists. A total of 5 km of drilling in separate holes is planned, with total drilling costs anticipated to be approximately $M1.1.

8. Germany Present plans are for a 10 km deep hole in the Black Forest area on the edge of the Bohemian Massif.

9. Sweden Drilling of a 5-7 km hole in the Siljan ring structure, believed to be an ancient meteorite impact site, is to begin in 1986 or 1987.

Other targets for continental drilling in the U.S.A. were identified at two sessions of the December 1984 meeting of the American Geophysical Union; abstracts are given in Eos of November 6, 1984.

The philosophy of scientific drilling

The purpose of scientific drilling, whether it be shallow or very deep, is to obtain information on the nature of the earth's crust at a particular location. Drilling is not cheap, so that very careful consideration must be given to the choice of that location. Scientists in the U.S. have chosen to put all their funds into drilling one very deep hole. In the Cyprus project it was decided not to use this approach, but instead to make use of the structural nature of the ophiolite suite to be studied and drill several holes at carefully chosen locations such that the full vertical section of the suite would be drilled. These approaches are both valid for the problems they address. The Appalachian hole is intended to penetrate a sub-horizontal crustal layer of well estimated thickness, and the Cyprus holes are designed to sample a crustal section that is sub-vertical. As drilling costs per metre increase with depth drilled, it is sensible to drill several relatively shallow holes at different locations if they collectively sample fully the layer of interest.

The needs of scientific programmes must also be carefully considered before a drilling project is begun. Two approaches are possible. The project could be on a fairly small scale, with few scientists involved. Alternatively, it could incorporate large numbers of scientists from both government agencies and from universities. The scientific drilling of the D.O./E.P.B. geothermics group was undertaken using the former approach. An example of a project that involves many people from diverse institutions is "lithoprobe". Both approaches have advantages and disadvantages. The former attracts fewer funds but can be kept under the control of a few people, committees are not needed, and results can be presented individually at suitable conferences. The latter, by being bigger, attracts much more funding but requires committees to run it, and formal theme meetings are usually needed. Small programmes are flexible, large programmes may not be. Whatever the scale of the programme, its management must be kept as straightforward as possible, and overall control must remain with the group or individual most directly concerned.

The geothermics group at E.P.B. has traditionally attempted to obtain data from as many holes as possible at each study site, mainly to ensure that the statistical significance of the heat flow determinations can be checked. In some cases this has led to some unexpected results. For example, from analysis of data from a large number of boreholes around Lac Dufault, Lewis (1975) postulated the existence of large scale water movement in the crystalline rock. Drury has also examined the thermal phenomena of water flows in crystalline rocks, using data from N.F.W.M.P. research areas, at each of which several holes have been drilled, some to depths of 1200 m. The thermal effects of the flow of fluids in the earth's crust are not fully understood. The observation from the Kola hole that open fractures and free water exist at depths to 9 km or more was a major surprise. Previously, most earth scientists held that all cracks would be closed at depths greater than 2-3 km. The Kola results call into question all published heat flow results from crystalline rocks - do they really represent the heat flowing conductively from the mantle and lower crust, and being enhanced by radiogenic heat in the upper crust? Recently Drury (1985) has analysed heat flow results from the Proterozoic mobile belts near the Churchill-Superior boundary in northern Manitoba, and suggested that the tectonic development of the region might have resulted in a major redistribution vertically of radiogenic - and presumably other - elements by hydrothermal circulation.

This interpretation implies that large movements of water are possible in crystalline crust. The Kola work demonstrates it.

A 500 m uncased hole into competent crystalline rock, fully cored to 45 mm diameter costs at present approximately $25,000, excluding mobilisation charges. A 1000 m hole in a remote area might cost up to $100k. The costs must be balanced carefully against the anticipated scientific returns. The authors feel, however, that E.P.B. should return to drilling in support of some of its scientific programmes, and that such drilling must be undertaken for its own merit. It should be funded separately from any existing drilling projects that are supported by applied programmes. It may be that a drilling target is identified from lithoprobe surveys; if so then we should respond accordingly, but being careful to retain scientific and managerial control. Lithoprobe is not the only potential source of drilling targets, and we should give equal consideration to drilling in support of other programmes. Management of drilling projects should be kept as simple as possible. The Wedgeport project in Nova Scotia is being handled entirely by one person (Drury). That would be impossible with a deep drilling project.

Some possible drilling targets in Canada

This part has been developed with the benefit of suggestions from other scientists of the Earth Physics Branch. The aim is to show what are some of the scientific needs for drilling as seen by the members of a diverse group. We have arbitrarily divided potential holes into shallow (up to 500 m), intermediate (500-2000 m) and deep (greater than 2000 m). We have not considered ocean floor drilling because other members of the Canadian geoscience establishment are doing so. There is no inherent reason for

E.P.B. Ottawa not to be involved with ocean drilling, but most of our activities are concerned with the continental crust. Canadian scientists, mainly from Dalhousie, have had a long-standing association with the Deep Sea Drilling Project. Drury has worked on physical properties of cored and dredged samples from many D.S.D.P. sites, and he retains an interest in its successor, the Ocean Drilling Programme, being the Ottawa campus E.P.B. liasion person.

The suggested drilling targets of immediate interest, with a brief primary scientific justification, are given in Table 2. No ranking is implied. In cases where suggestions were duplicated, all proponents are named. A list of those invited to contribute ideas is given in the Appendix.

Table 2. Possible targets for scientific drilling in Canada
Costs are estimated

Location	Number	Cost ($)	Proponent(s)	Primary purpose(s)
A. Shallow holes (to 500 m)				
Plutons of Atlantic margin	5x500 m	200k	Drury Goodacre	Heat flow province study using data from plutons of different radiogenic heat production, gravity models; in-situ stress.
Plutons of Churchill Province	5x300 m	300k	Drury	Heat flow/heat generation relationship; dating.
Pikwitonei gneisses	3x400 m	200k	Drury	Heat flow/heat generation on Superior side of Superior-Churchill boundary.
Kisseynew gneiss belt	3x400 m	200k	Drury	Test hypothesis of hydrothermal redistribution of radiogenic elements.
Hudson Bay lowlands	2x500 m	100k	Jessop Drury	Extension of Superior Province heat flow work in low heat flow area.
Manicougan	5x500 m	250k	Grieve Robertson	Nature of central magnetic anomaly; third dimension of recorded shock attenuation; distribution of radiogenic elements.
Carswell	5x500 m	400k	Grieve Robertson Drury	Distribution of shock features; distribution of radiogenic elements in central uplift.

Charlevoix	1x500 m	30k	Lambert Drury Goodacre	Heat flow; in-situ stress.
Yukon plutons	3x300 m	100k	Judge	Geothermics; palaeoclimatic analysis in unglaciated region.
Bear Province	10x300 m	500k	Drury Judge	Establish heat flow/ heat generation relationship; dating.
Cape Smith fold belt	3x300 m	100k	Drury	Heat flow near Superior-Churchill boundary on Superior side.
Baffin granites	3x300 m	150k	Judge Drury	Geothermics of northern Churchill Province; modelling of ice sheets.
South Inuvik	1x400 m	100k	Judge	High precision heat flow measurement.
Labrador Trough	3x300 m	250k	Judge	Geothermics in trough and adjacent gneissic crust.
Grenville anorthosite complexes	5x500 m	150k	Jessop Drury Goodacre Feininger	Heat flow in low heat production environment; in-situ stress; petrology.
Monteregian Hills	2x500 m	60k	Goodacre	Physical properties; geothermics; gravity models.
Regina	200 m	100k	Jessop Drury	Deepen existing hole to sample basement.

B. Intermediate holes (500 to 2000 m)

Yukon granites	1x1000 m	150k	Judge	Geothermics; palaeoclimatic analysis in unglaciated region.
Mackenzie/ Richardson mountains	2x1000 m	250k	Judge	Thermal origin of non-density compensation.
Manicougan	1x2000 m	150k	Grieve Robertson	See entry for shallow holes.
Haughton	1x1800 m 2x 700 m		Grieve Robertson	Structural/topographic relationships in inner ring; distribution of allochthonous breccias; nature of gravity and magnetic anomalies.
New Quebec crater	3x1000 m	200k	Grieve Robertson Pilon	Recovery of shocked material for radiometric dating; comparison with Brent structure; physical properties of crater floor and crater filling materials; Arctic sedimentation rates, palaeoclimates and glacial history using a closed, deep basin.
Sept-Isles	1x2000 m	150k	Feininger	Igneous stratigraphy of horizontally-layered intrusion.
Plutons of Atlantic margin	3x2000 m	450k	Goodacre Drury	See entry for shallow holes.
Darnley Bay N.W.T.	1x1000 m	75k	Goodacre	Study nature of magnetic and gravity highs.
Brandon	1x1500 m	100k	Jessop	Test thermal anomaly suggested by industrial data.

C. Deep holes (2000+ m)

Summerside P.E.I.	1x3000 m	500k	Menzel-Jones Drury	Investigate nature of sediment-volcanics contact; nature of gravity high.
Lac du Bonnet batholith	1x5000 m	2M	Drury	Test model of thin (less than 4 km) surface layer of anomalously high radiogenic heat production.
Kapuskasing structure	2x5000 m	4M	Jessop Goodacre	Nature of magnetic and gravity highs; deep heat flow.
Sutton Mt. Quebec	1x 8 km	30M	Thomas	Test hypothesis that thick wedge of rift volcanics underlies the region; provide information on style of tectonic structure.
Ellesmere Island	1x 15 km	100M	Menzel-Jones	Investigate nature of Alert/Lake Hazen electrical conductivity anomaly.
Central Manitoba (?)	1x 15 km	70M	Menzel-Jones	Investigate North American Central Plains electrical conductivity anomaly.

Discussion

Each potential drilling target identified in Table 2 has been justified in terms of its primary scientific objectives. Any drilling programme should, however, be made available to researchers from all disciplines of the earth sciences; most of the international programmes listed earlier are examples of multidisciplinary studies. For example, the Wedgeport batholith drilling is primarily for the geothermics programme, but magnetic properties of the drill-core will be studied in support of programmes in geomagnetism.

Some geophysical and geological studies would be appropriate for any drilling programme, for example, geothermics, physical properties and mineralogical analyses of recovered core. Borehole seismometry, in-situ stress measurements and other borehole geophysics techniques also have wide ranging applications. Gravity studies associated with drilling in plutons, using density data from the drilled core, would be very useful.

There is clearly no shortage of ideas among crustal studies scientists of E.P.B. for drilling programmes. Although Table 2 identifies particular drilling sites and purposes, some people solicited for ideas suggested less well-defined targets. For instance A.G. Green mentioned drilling in support of lithoprobe programmes, and D.R. Bower felt there might be a need for drilling in the near future when his aquifer tide monitoring techniques are fully developed. A.K. Goodacre suggested that borehole seismometry might be used for tomographic studies in plutons. The possibility of joint projects with other government agencies, universities or industry should also be considered; for example, it might be possible to provide funds for holes being drilled by industry to be deepened to penetrate basement under the western sedimentary basin.

Most of the proposed holes are in the shallow or intermediate range and therefore not particularly expensive. Any deep drilling of the 5 km+ range should be with international consultations, if not collaboration, and the target should be one that is "uniquely" offered by the Canadian crust, for example, old shield, the Grenville province, major craters, the Kapuskasing zone. Whereas shallow drilling might be in support of single programme, deep drilling must be for multidisciplinary studies.

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Appendix

This is a list of people invited to contribute suggestions for drilling sites. Draft copies of the report were circulated to the small groups identified. In some cases, one person responded on behalf of both or all members of their group.

A.S. Judge, J.A. Pilon

M.M. Burgess, A.E. Taylor

R.A. Grieve, P.B. Robertson

T.G. Feininger, L.W. Sobczak, M.D. Thomas

A.G. Green

R.D. Kurtz, A.G. Menzel-Jones, E.R. Niblett

A.K. Goodacre

D.R. Bower, A. Lambert

T.J. Lewis, W. Bentkowski

P.L. Lapointe, E.I. Tanczyk

We thank all those who responded with drilling suggestions and comments.

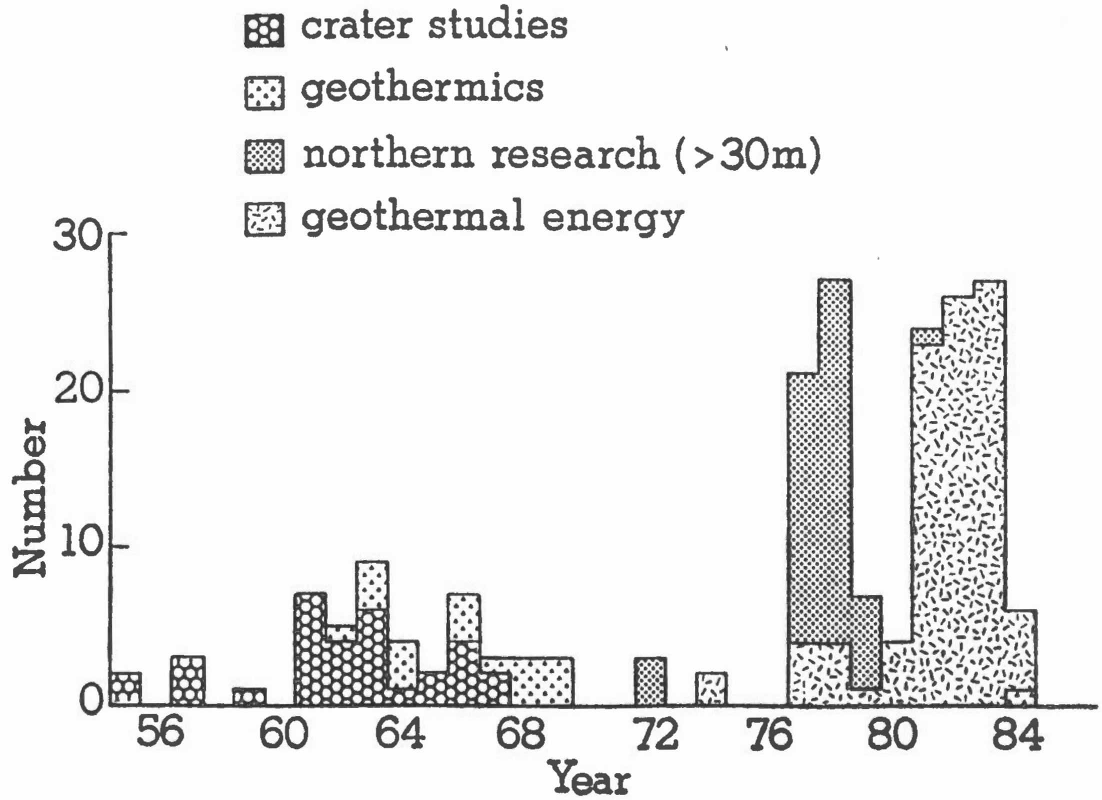

Fig. 1 Histogram to show number of holes drilled by D.O./E.P.B. for the four main scientific programmes. The drilling at Resolute Bay between 1950 and 1953 is not shown. Note that the geothermics drilling indicated for 1984 was not completed until January 1985.

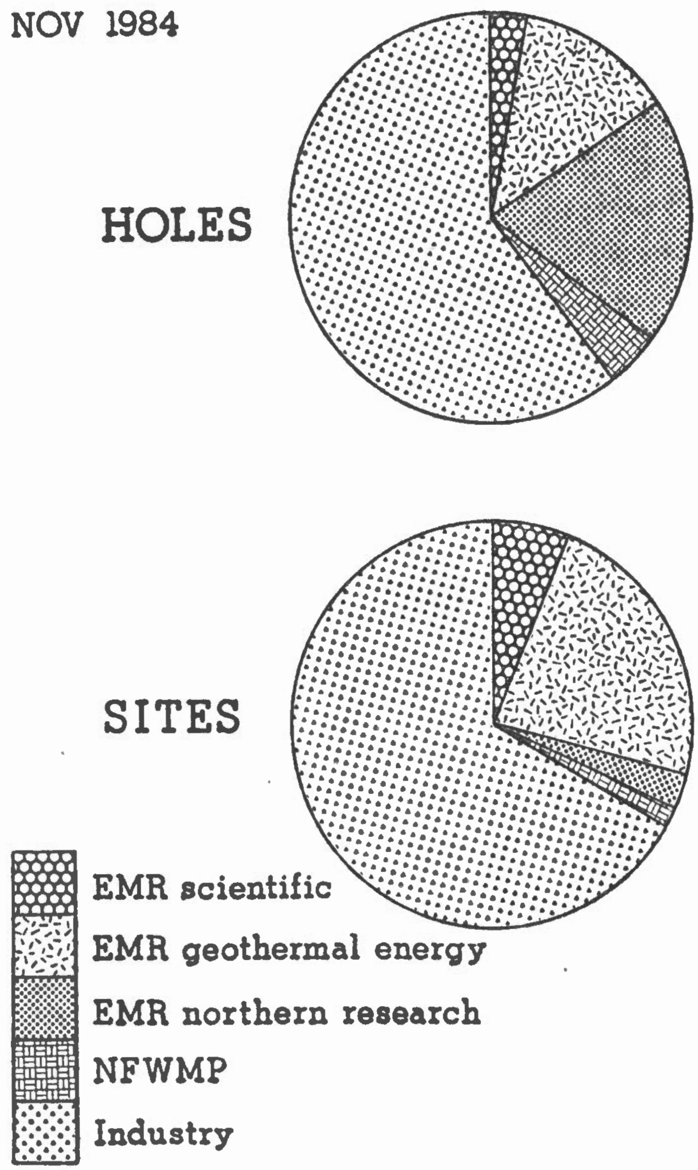

Fig. 2 Pie charts to show distribution of data sources for the D.O./E.P.B. geothermics programmes.The upper chart shows the distribution for separate holes, and the lower chart shows the distribution for separate sites, some of which include more than one hole.