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The Iceland Research Drilling Project

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This issue of the *Journal of Geophysical Research* contains the collected results of the initial studies of a 3-km vertical section of Icelandic crust. The material described in these papers was largely presented at a meeting of the investigators working in this project held in Reykjavík, Iceland, from May 13 to May 15, 1980

Iceland presents a very well exposed example of crust formed at an accretional plate margin, the crest of the Mid-Atlantic Ridge. The desirability of a detailed study of a long vertical section of Icelandic crust by deep drilling has been expressed in proposals and recommendations of scientists and international scientific committees since the early 1960's. A formal proposal with descriptions of several alternative drill sites was presented in 1975 [*Working Group on Deep Crustal Drilling in Iceland,* 1975], but difficulties in financing a drill hole that would penetrate into crustal layer 3 (Vp = 6.5 km/s) delayed implementation of the recommendations.

Again, investigation of oceanic crust through the use of D.V. *Glomar Challenger*, started in 1973, appeared to be limited for a number of reasons to the uppermost 600 m. Since the necessary technology, in the form of D.V. *Glomar Explorer*, for penetration into lower oceanic crust, would probably not be available until after 1985, investigators sought other approaches to the problem. In the latter half of 1977 a small group of scientists from several countries decided to try to finance an intermediate depth drilling project in Iceland. While this would not foreseeably reach layer 3, it would give a thicker continuous succession through crust of oceanic affinity than had ever been sampled before. While it was well known that Iceland is a geologically special part of the oceanic crust, it seemed likely that there would be sufficient features in common with more typical crust to make an investigation in Iceland worthwhile. Among many such features the variation of temperature, petrology, alteration, minor intrusion density, physical properties, and in situ stress with depth provide examples that seemed likely to be similar in the two types of crust.

Although the Icelandic crust has been extensively drilled in connection with geothermal research and utilization, with over 120 wells deeper than 1000 m and the deepest well 3085 m, only drill cuttings have normally been available for study [*Pálmason et al.,* 1979]. Since the Iceland Research Drilling Project was thus to be the first drilling-based investigation with continuous coring of the Icelandic crust and was to be mounted rather quickly, a relatively inexpensive means of sampling a long section was devised. Advantage was taken of the deep glacial erosion of the geologically well-known Tertiary lava pile in eastern Iceland to provide a 1-km exposed component at the top of the section. Below this a continuously cored slim hole drilled by the high-speed diamond technique would provide the balance of a 3-km crustal section that extended from 0.5 km to 3.5 km beneath the original top of the crust. A site at latitude 65°01′N, longitude 14°21′W was selected near sea level at the head of Reydarfjordur, 8 km east of the center of the Thingmuli central volcano at a location within a dyke swarm where crustal dilation by north-south dykes is 10%. The site is within a large area of anomalously high temperature gradient (80°C/km) that had been outlined by a series of 100-m temperature gradient wells drilled by the National Energy Authority of Iceland. Final site selection was made with the aid of unpublished gravity data (G. Pálmason, personal communication, 1977) which were used to identify a location where the regional gravity anomaly was of average value.

The organization of the project was facilitated by contacts between the principals made through mutual involvement in the Deep Sea Drilling Project and by long standing relationships with scientists at Orkustofnun, the National Energy Authority of Iceland. A steering committee, set up in the latter part of 1977, consisted of one or more individuals from Canada, United States, Iceland, West Germany, United Kingdom, and Denmark. Members of this committee accepted the task of raising funds and organizing scientific groups in their respective nations. It was agreed that sampling of the crustal section should take place during the summer of 1978.

Work on the crustal section during the summer of 1978 can be divided into four areas. Of these the most technically and financially demanding was the drilling operation. It was decided that initial core description and routine sampling would take place at Reydarfjordur concurrently with drilling, much as is done during *Glomar Challenger* operations. This required establishment of a temporary geological laboratory in the area, together with accommodation for a scientific team which would consist of members of the national groups. With drilling staff, scientists, and support staff there were on average 25 people at Reydarfjordur at any one time. Contact was made daily with the head office of Orkustofnun from where contact was made by telex with members of the steering committee. The third part of the operation consisted of sampling the exposed section. Conventional methods involving a relatively small number of people were used. Poor weather and the priority given to work on the drill core led to this part of the work being finished during the summer of 1979. The fourth area comprised surveys in the vicinity of

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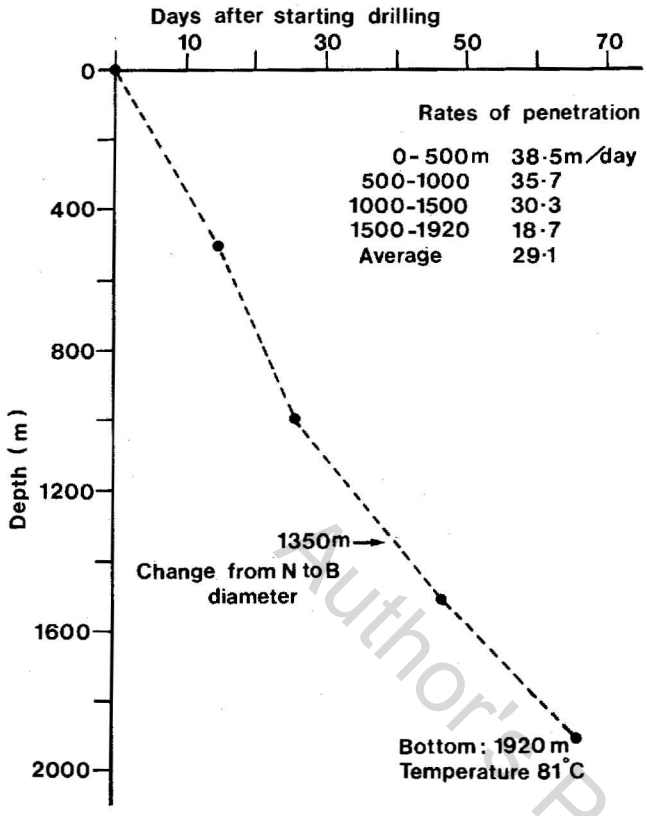

Fig. 1. Progress with time of the Iceland Drilling Project Reydarfjordur drill hole.

the drill site and includes seismic and other geophysical surveys carried out in the summers of 1978 and 1979, together with continuing work on the relationship between the IRDP crustal section and the surrounding surface geology.

The drilling operation was carried out by Bradley Bros. Ltd., Contract Diamond Drillers of Noranda, Quebec, Canada. A ten-man team consisting of a foreman, three shift runners and six helpers, working for three shifts per day and 6 days a week, completed the drill hole to 1920 m in 66 days overall (Figure 1). One of the helper positions was occupied by an Icelandic drilling engineer with long experience of drilling in volcanic strata. Complete temperature profiles of the hole were taken at the end of each weekly 24-hour break in drilling. The rate of penetration dropped by approximately half as drilling proceeded but still averaged 18.7 m/d over the lowermost 420 m of the hole. Core recovery overall was 99.7%. The core was held at Dalhousie University for 3 years and is now in the keeping of the National Energy Authority of Iceland. Applications to examine or sample the core should be addressed to I. B. Fridleifsson, National Energy Authority, Grensasvegur 9, 108, Reykjavík, Iceland. The uppermost 1350 m of the hole was drilled at NQ size (7.6 cm hole diameter, 4.7 cm core diameter) and the lowermost 570 m at BQ size (6.0 cm, 3.6 cm, respectively). The NQ drill rod was used as casing during the deeper, BQ drilling. After termination of drilling the uppermost 580 m of the casing was removed. Drilling was terminated after two drill rod breakages, probably resulting from the difficulty experienced in flushing heavy, green, sand size cuttings (mostly epidote) from the hole. Influx of warm water in the 517 to 628 m depth interval, leading to a maximum surface flow of 0.8 l s^{-1} and continuing temperature increase with depth to a bottom hole temperature of 81°C, caused no difficulties during drilling. At the termination of drilling, extensive geophysical logging of the hole, both before and after the removal of the uppermost 580 m of casing, together with water sampling at various depth intervals were carried out by Orkustofnun. Further logging runs and water sampling together with hydrofracturing and in situ permeability tests were carried out during 1979. Most of the budget for work on the crustal section during 1978 was abosrbed by the drilling operations. Of a total budget of U.S. $336,000, $306,000 was utilized for drilling and associated costs such as shipping and logging. While it should be kept in mind that interval costs increase rapidly with depth, it may be a useful reference to visualize the recovery of the drill core, together with geophysical log information as having cost an average of U.S. $153/m in 1978 dollars. The remaining scientific operations, work in the core laboratory, and sampling of the exposed section accounted for the remaining U.S. $30,000 of the budget.

With the information already given, it will be appropriate at this point to consider the project as a whole. Figure 2 is a summary of the project in which significant events are plotted in temporal order.

Between inception of the project in July 1977 and the beginning of work on the section in late May 1978, applications for funding were prepared and submitted to 10 agencies: Natural Sciences and Environmental Research Council and Dalhousie University (Canada), National Science Foundation and Office of Naval Research (United States), Iceland Energy Fund (Iceland), Natural Environmental Research Council (United Kingdom), Bundesministerium für Forschungs und Technologie and Deutsche Forschungsgemeinschaft (Federal Republic of Germany), Statens Naturvidenskabelige Forskningsråd (Denmark), and NATO. All of these applications were successful, and in addition, several agencies were prepared to look sympathetically at requests for changes in funding arrangements as the drilling work proceeded successfully.

The principal period of description and sampling of the crustal section, which was, of course, dominated by the drilling operation, occupied a very small fraction of the overall project duration, 2 1/2 months (or 4%) of 4 3/4 years from project inception to publication of this initial set of results.

Laboratory work on material from the section, the geophysical logs, and other data occupied the period from October 1978 to October 1980, culminating in publication of this initial report. It is anticipated that a number of studies will continue beyond the time of publication of this report, for example, those based on problems arising from the initial studies. A short publication describing the main results of the examination of the section in Reydarfjordur was edited by *Gibson* [1979]. This publication, together with graphic logs of the whole section prepared by J. Mehegan, a volume giving brief descriptions of each unit in the drill core prepared by P. T. Robinson and H.-U. Schimincke, several volumes of the detailed core log and a report on the geophysical logging by V. Stefansson, were circulated

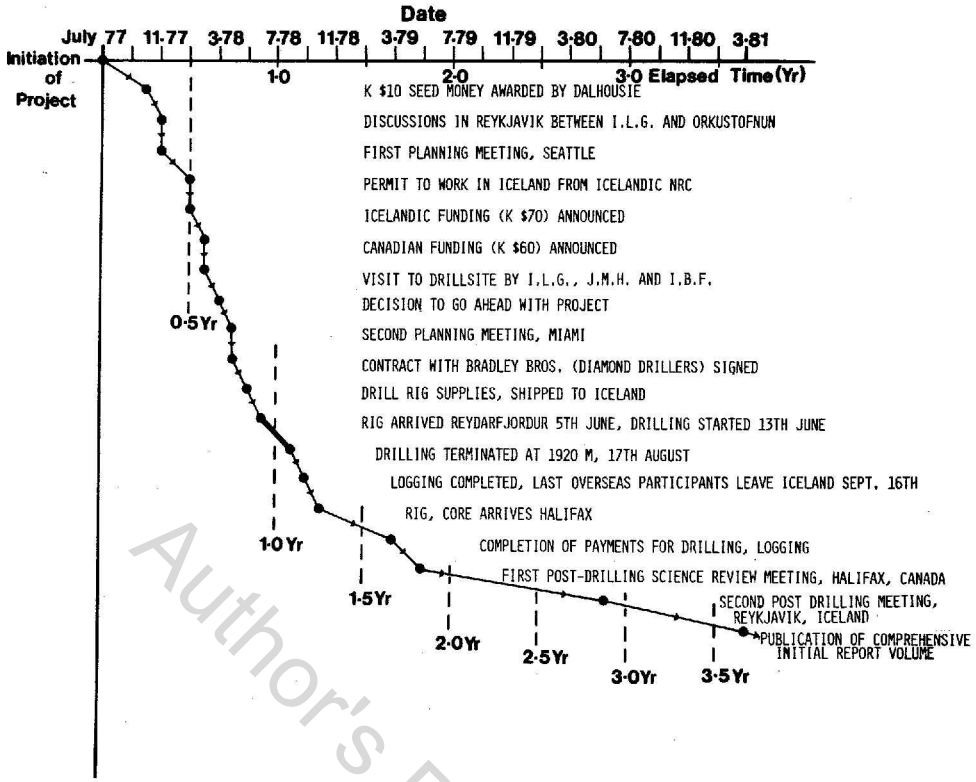

Fig. 2. Historical development of the Iceland Research Drilling Project Reydarfjordur crustal study.

among participating scientists to provide basic information for their investigations. In May 1979, 8 months after the completion of the main field investigations in Iceland, a first review of the results of laboratory investigations was held at Dalhousie University, Halifax. A year later, in May 1980, a second review meeting was held in Reykjavík, Iceland, at which the results of the largely completed initial investigations were described. Both meetings gave essential opportunities for discussion and planning by teams working in areas such as geochemistry and paleomagnetism, in addition to presentation of results to the group as a whole.

It is a pleasure to note the wide interest in the IRDP investigation in the geological community at large and to report that further crustal investigations, using the technology, much of the organization, and many of the participants of IRDP, are in hand.

Acknowledgments. The success of a complex project such as IRDP has depended on the support of many agencies and individuals, and we should like to acknowledge this support here. Permission to carry out the project was kindly granted by the National Research Council of Iceland. Financial support from 10 agencies is described above. This was often given at relatively short notice and provided an essential, secure basis for the project. Specific grants were from the Iceland Energy Fund, NSERC (Strategic Grant Program in Ocean Sciences, grant G0063), and Dalhousie University (Canada); NERC (United Kingdom), NSF (grant EAR 78-11725) and ONR (grant N000-14-78-C-0389) (United States), BMFT (grant ET 4248) and DFG (grant SCHM 250/21) (West Germany), SNF (Denmark) (grant 511-10147), and NATO (grant 1652). We thank the people of Reydarfjordur for their considerable assistance. We thank the landowners and the farmer at Areyjar, Kjartan Petursson, for permission to drill and to work on the land in the vicinity of the drill site. The intricate organization involved in taking a Canadian drilling rig and a large international group of scientists to Iceland for a crustal investigation involved enthusiastic collaboration between the drilling company, Bradley Bros. Ltd. of Noranda, Quebec, and in particular, Wallace Bradley, President of the company, and Réjean Clement, leader of the field party; many of the staff of Orkustofnun, the National Energy Authority of Iceland, and, in particular, Stefan Sigurmundsson, Sigurdur Sveinsson, and Einar Sigurdsson and the officials of the community of Reydarfjordur, in particular, Vigfus Olafsson, Chairman of the District Council, Hordur Thorhallson, Town Manager, and Fridjon Vigfusson, Shipping Agent. Facilities and coverage for the heavy traffic of communications between Reydarfjordur and the countries involved in the project during the drilling operations were generously provided by Orkustofnun. In addition, those members of the project who worked in Reydarfjordur particularly wish to thank the many citizens of the town who tolerantly accepted a large group of overseas scientists into their small community and who went out of their way to show warm friendship and to open their homes to the visitors.

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