

Final Technical Letter Report

prepared for

National Science Foundation

by

Georgia Institute of Technology

Atlanta, Georgia 30332

HYDROTHERMAL CIRCULATION ON MID-OCEAN RIDGE CRESTS

Grant #DES74-00513 (Formerly GA-41195)

Starting date: January 1, 1974 Completion date: December 31, 1976

Principal Investigator
Dr. Robert P. Lowell
Assistant Professor
School of Geophysical Sciences

Introduction

At the time this research program was initiated, data regarding hydrothermal circulation in the oceanic crust was somewhat limited. Bostrom and Peterson (1966, 1969) had observed that sediments on the East Pacific Rise were enriched in certain metals and suggested hydrothermal emanations at the ridge crest as the source of the metals. Heat flow data from the axial zones of the Reykjanes Ridge (Talwani et al., 1971) and the Juan de Fuca Ridge (Lister, 1972) indicated that the conductive heat flux was not an accurate measure of the total heat loss from the newly created, spreading lithosphere to the ocean floor. There were also some data on rock samples dredged from the ocean floor (Aumento et al., 1971; Corliss, 1971) which suggested the occurrence of hydrothermal processes in the oceanic crust.

Likewise, the theoretical modeling of the hypothesized thermal convection system in the oceanic crust was quite sketchy. Models were based on either (a) the fundamental linear model of convection in a homogeneous, isotropic, fluid-saturated porous layer, bounded above and below by parallel planes, and heated from below (Lapwood, 1948) or (b) the model of steady state convection in narrow, deep, widely-spaced, planar fractures, imbedded in an impermeable medium (Bodvarsson and Lowell, 1972).

Over the past few years, however, the ocean ridge hydrothermal systems and related phenomena have become one of the most active areas in marine geophysical research. The amount of data has grown and several interesting results have been obtained. Among the most important ones are:

(1) Conductive heat flow near the Galapagos Ridge exhibits a roughly sinusoidal pattern with a wave length of about 6 kilometers (Williams et al. 1974).

(2) Conductive heat flow falls below the theoretical conductive cooling curve for a uniformly spreading lithosphere to great distances from the ridge axis for all the oceans, indicating that convective losses may be important in the oceanic crust out to ages of tens of millions of years (R.N. Anderson 1976, personal communication).

(3) There is a correlation between the sediment thickness/topography ratio and the amount of apparent convective transfer (Anderson and Hobart, 1976).

(4) There are small water temperature anomalies ($\Delta T \leq 0.1^{\circ}\text{C}$) in the ocean-bottom boundary layer which may be due to hydrothermal discharge (Rona et. al., 1975; Williams et al., 1974; Crane and Normark, 1975). Such water temperature anomalies were not observed in the FAMOUS area. In addition, there is a great deal of interest in the geochemical effects of the hot seawater-basalt interaction (e.g. Wolery and Sleep, 1976).

Objectives

The initial objectives of this research were to develop models for thermal convection in permeable media which would provide useful information with regard to hydrothermal circulation in the oceanic crust. Cases in which the permeability was due to thin, widely-spaced, deep, open fractures and cases in which the permeability was due to fine-scale fracturing, so that a Darcy's law approach was valid, were to be considered. Of particular importance in this research program was to be the development of finite difference models for time dependent finite amplitude convection very near a ridge axis. In this situation, both vertical temperature gradients as well as transient horizontal temperature gradients resulting from the periodic intrusion of material at the ridge axis were to be assumed to drive the flow.

As the research progressed, and more heat flow data and the data on near-bottom water temperature anomalies became available, attempts were made to interpret the data in terms of the models which were being developed. The research program developed into essentially four research tasks, each of which is summarized below. The first three tasks bear directly on the ocean ridge problem. The fourth task is somewhat of a digression which involved the application of the numerical methods employed in the ocean ridge problem to an important problem in borehole geophysics.

The main results of the research performed under this grant have been published in or submitted to various journals (see section on papers). Therefore only brief descriptions are given below.

Research Results

A. Convection in discrete, widely-spaced, narrow fractures.

The problem of convection in a two-dimensional block of oceanic crust containing two narrow widely-spaced vertical fractures connected by a thin horizontal contact was considered (Figure 1). Sea water is presumed to descend down one fracture, move horizontally along the contact and ascend along the other vertical fracture, discharging at the sea floor. It is assumed that the only driving force is the buoyancy in the fluid which is due to the temperature gradient in the impermeable block. A steady state model, similar to that of Bodvarsson and Lowell (1972), showed that fractures of a few millimeters width could carry a substantial convective flow. Time dependent models showed the decay of the outlet temperature and flow rate with time for various fracture widths. For example, if the vertical fractures were 3 mm wide, 5 km deep and separated by 3 km, and if the geothermal gradient were initially $100^{\circ}\text{C}/\text{km}$ in the

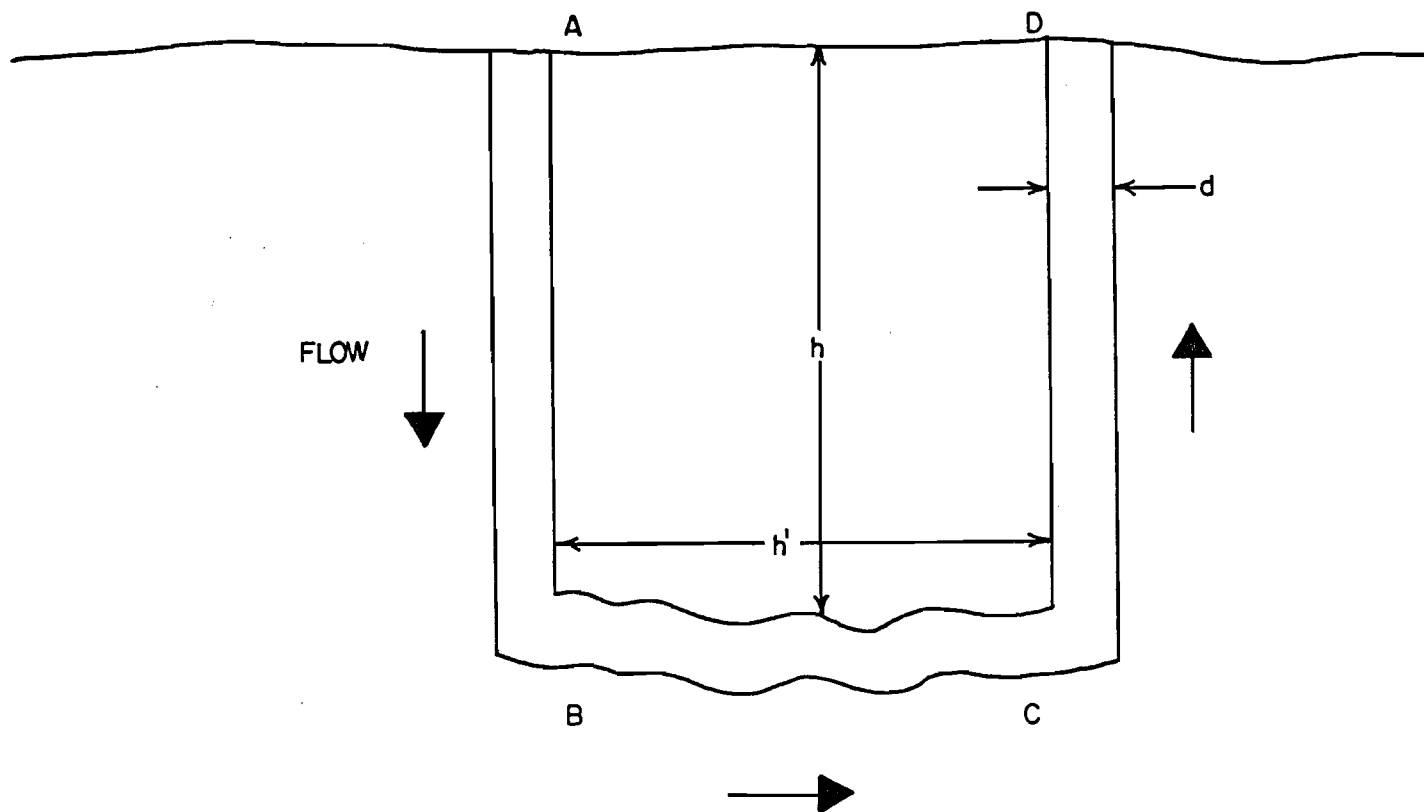


FIGURE 1 - Sketch of a transverse flow system.

block, the outlet temperature and rate of discharge at the sea floor would be $100^{\circ}\text{C}/\text{cm}$ in the block, $0.14 \text{ kg}/\text{m}\cdot\text{sec}$, respectively, at the end of 10^4 years. If the fracture were 1 km in length, the discharge would be $140 \text{ kg}/\text{sec}$, which is of the same order as the discharge in many continental thermal areas. Such a spring discharging at the sea floor may give rise to a small water temperature anomaly in the ocean-bottom boundary layer. The total convective heat transfer, over the period of 10^4 years, in the above circulation system would be about 200 times greater than the conductive transfer through the surface of the block. Thus the principal effect of the convective circulation is the efficient cooling of the oceanic block down to the depth of the fracture system. The conductive heat flow at the surface of the block would be in reasonable agreement with the data of Williams, et al. (1974) for the Galapagos.

Details of the fracture convection models are contained in Lowell (1975).

B. The interpretation of near-bottom water temperature anomalies.

The fracture circulation results discussed in the preceding section suggest that small water temperature anomalies may exist in the ocean-bottom boundary layer. Water temperature anomalies of approximately 0.1°C have been observed at heights of approximately 10 meters above the sea floor by means of towed thermistors (Williams et al., 1974; Rona et al., 1975; Crane and Normark, 1975; Weiss et al. 1976). The temperature anomaly, and its associated superdiabatic temperature gradient, in the TAG hydrothermal area (Rona et al., 1975) have been interpreted in terms of thermal plume models and in terms of turbulent heat transfer in the boundary layer. The results indicate that the thermal output from the TAG area may be of the same magnitude as some continental thermal areas and that even a small temperature anomaly in the water column may indicate a region where a significant portion of the heat loss from the cooling lithosphere occurs. Energetic considerations suggest

that such temperature anomalies are probably transient features.

Details of the discussion on interpretation of near-bottom water temperature anomalies are found in Lowell and Rona (1976).

C. Finite difference models of convection at a ridge axis.

The problem of convection in the oceanic crust, very near a ridge axis, was considered. The crust was treated as a two dimensional square block of porous material (Figure 2). At time $t < 0$, a steady state condition existed in which the temperature increased linearly with depth. At time $t = 0$, in order to simulate a single episodic intrusive event at a ridge axis, a slab of high-temperature material was emplaced at the left hand edge of the crustal block. The time development of the ensuing convection system was modeled assuming rigid, insulated vertical walls, a rigid lower boundary into which there was a constant heat flux, and a permeable upper boundary, overlain by a free-standing column of fluid which would enter and exit the porous layer. The upper boundary was held at $T = 0$. A range of constant permeability values was used giving rise to a range of Rayleigh numbers such that $2.5 \leq R \leq 250$. For $R < 17.7$, the convection was driven solely by transient horizontal temperature gradients whereas for $R \geq 17.7$, the convection was driven by both horizontal and vertical temperature gradients. The effects of permeability linearly decreasing with depth and anisotropic permeability were also considered.

The principal purposes of these models, in addition to examining the effect of different permeability conditions, were to a) determine what Rayleigh number would be required for the heat perturbation due to the intrusion at the ridge axis to be removed within the time frame of one episode (~14,000 years on the Mid-Atlantic Ridge, Moore, et al. 1974) and b) examine the redistribution of heat conducted through the upper boundary as a result of convection.

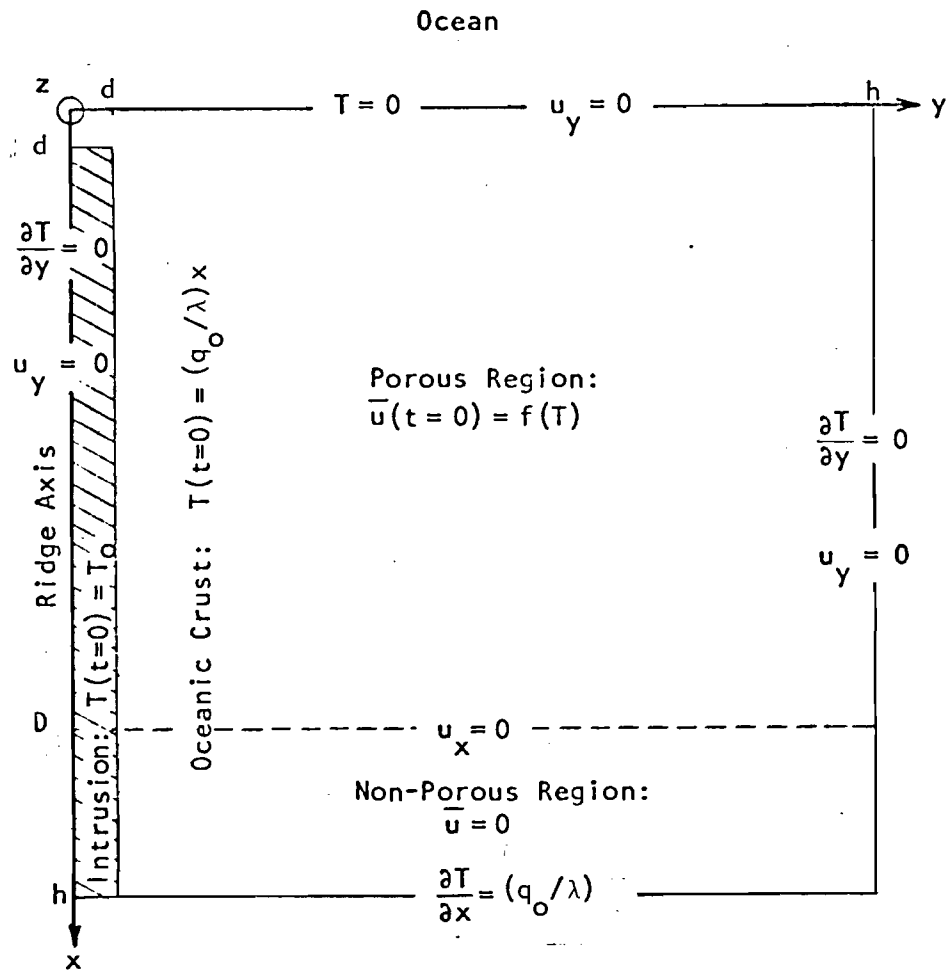


Figure 2. Basic Model with Initial and Boundary Conditions.

The results indicate that a Rayleigh number somewhat greater than $R = 250$ is required for the heat to be removed within the imposed time frame. The exact number could not be determined since the numerical calculations become unstable at high Rayleigh numbers. Moreover, the convective circulation redistributes the heat flux such as to enhance the heat flux near the axis and decrease the flux away from the axis, relative to the heat flux due to a purely conductively cooling lithosphere. This result suggests that the observed low heat flux values observed within a few tens of kilometers from ridge axis may result, in part, from convective redistribution, and the discrepancy between the observed values and the cooling curves of, for example, McKenzie (1967), may not be evidence of convective loss per se. Heat flow data within a few kilometers of a ridge axis is virtually non-existent, and it may be that the bulk of the convective losses occur there.

Details of the numerical models are contained in a manuscript which has been submitted for publication in the volume on the Benthic Boundary Layer Symposium which was held at the Joint Oceanographic Assembly in Edinburgh, United Kingdom, September 13-24, 1976. A copy of this manuscript is attached as Appendix A to this report.

D. Temperature transients in flowing boreholes.

Finite difference methods were used to model the outlet temperature of a flowing geothermal well that was subject to small temperature or flow perturbations in the fluid entering the base of the hole. The results showed that step-like changes of 1% in the flow-rate could give rise to an observable temperature perturbation at the top of the borehole. Such a temperature transient may provide useful information with regard to the structural aspects

of the geothermal system. A small step-like change in the inlet temperature also produces an observable perturbation in the outlet temperature.

These results appeared in abstract form in the program for the Second United Nations Symposium on the Development and Use of Geothermal Resources. The full paper appeared in the proceedings of this symposium (Lowell and Bodvarsson, 1977).

Comments

When this project was initiated, the ocean ridge thermal problem had just begun to receive significant attention. Now the ocean ridge problem is one of extreme interest and a great deal of experimental work is going on. New, detailed heat flow surveys are being undertaken to more clearly outline the convection patterns in the Galapagos area and to investigate the role of sediment type and thickness in sealing off the convection system. Detailed surveys off the sea floor and attempts to more accurately define water temperature anomalies by use of submersibles are currently underway. Laboratory experiments on basalt-sea water reactions are also being carried out. Because of the new geophysical, geochemical, and geological data and recent theoretical research on various oceanic hydrothermal systems, Dr. Peter Rona of NOAA and I are organizing a symposium on "Hydrothermal Systems at Oceanic Spreading Centers" to be held to the Annual Geological Society of America Meeting in Seattle, November 7-9, 1977. This symposium is the first of its kind and serves as a follow-up to the symposium on continental hydrothermal systems held at GSA Denver, 1976. It is hoped that this interaction among marine scientists will provide new insight into the nature of oceanic hydrothermal systems and perhaps lead to a broad-based coordinated effort to investigate such systems.

In order to interpret the wealth of new data, development of reasonable physical models of the convection system is necessary. The models which have been developed under this grant as well as models developed by others over the past few years (e.g. Lister, 1974), will assist in interpreting data and in devising new field and laboratory experiments. There is much that remains to be done, however. There are no models which take into account such important aspects of the real system as thermoelastic effects, chemical precipitation of minerals in fracture spaces, and variable topography and/or surface temperature and pressure conditions. Also there is little information on the structure of the ocean-bottom boundary in active ocean thermal areas. This information is needed for the accurate interpretation of water temperature anomalies.

The numerical modeling which has been initiated under this grant is being continued under NSF grant #OCE-76-81876. The new models will emphasize the effects of variable topography and surface conditions on convection in the oceanic crust as well as investigate processes in the ocean-bottom boundary layer.

BIBLIOGRAPHY

- Anderson, R.N., and M.A. Hobart, 1976, The relationship between heat flow, sediment thickness and age in the eastern Pacific, J. Geophys. Res., 81, 2968-2989.
- Aumento, F., B.O. Loncarevic, and D.R. Ross, 1971, Hudson geotraverse: geology of the Mid-Atlantic Ridge at 45°N, Phil. Trans. Roy. Soc. Lond., A, 268, 623-650.
- Bodvarsson, G. and R.P. Lowell, 1972, Ocean-floor heat flow and the circulation of interstitial waters, J. Geophys. Res., 77, 4472-4475.
- Bostrom K. and M.N.A. Peterson, 1966, Precipitates from hydrothermal exhalations on the East Pacific Rise, Econ. Geol., 61, 1158-1265.
- Bostrom K. and M.N.A. Peterson, 1969, The origin of aluminum-poor ferromanganoan sediments in areas of high heat flow on the East Pacific Rise, Marine Geology, 7, 427-447.
- Corliss J.B., 1971, The origin of metal-bearing submarine hydrothermal solutions, J. Geophys. Res., 76, 8128-8138.
- Crane K. and W.R. Normark, 1975, Ridge crest structure vs. hydrothermal activity (East Pacific Rise, 21°N), EOS, 56, 1064-1065.
- Lapwood, E.R., 1948, Convection of a fluid in a porous medium, Proc. Cambridge Phil. Soc., 44, 508-521.
- Lister, C.R.B., 1972, On the thermal balance of a mid-ocean ridge, Geophys. J. Roy. Astr. Soc., 26, 515-535.
- Lister, C.R.B., 1974, On the penetration of water into hot rock, Geophys. J. Roy. Astr. Soc., 39, 465-509.

- Lowell, R.P., 1975, Circulation in fractures, hot springs and convective heat transport on mid-ocean ridge crests, Geophys. J. Roy. Astr. Soc., 40, 351-365.
- Lowell, R.P. and G. Bodvarsson, 1976, Finite difference models for temperature transients in flowing boreholes, in Proceedings of 2nd United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, May 20-29, 1975, 3, 1733-1735.
- Lowell, R.P. and P.A. Rona, 1976, On the interpretation of near-bottom water temperature anomalies, Earth Planet. Sci. Lett. 32, 18-24.
- McKenzie, D.P., 1967, Some remarks on heat flow and gravity anomalies, J. Geophys. Res., 72, 6261-6273.
- Moore, J.G., H.S. Fleming, and J.D. Phillips, 1974, Preliminary model for extrusion and rifting at the axis of the Mid-Atlantic Ridge, $36^{\circ} 48'$ North, Geology, 2, 437-440.
- Rona, P.A., B.A. McGregor, P.R. Betzer, G.W. Bolger, and D.C. Krause, Anomalous water temperatures over the Mid-Atlantic Ridge crest at 26° N latitude, Deep-Sea Res., 22, 611-618.
- Talwani, M., C.C. Windisch, and M.G. Langseth, Jr., 1971, Reykjanes Ridge Crest: a detailed geophysical study, J. Geophys. Res. 76, 473-517.
- Weiss, R.F., J.E. Lupton, P.F. Lonsdale, A.E. Brainbridge, H. Craig, 1976, Hydrothermal plumes on the Galapagos Spreading Center, EOS, 57, 935.
- Williams, D.L., R.P. Von Herzen, J.G. Sclater, and R.N. Anderson, 1974, Lithospheric cooling and hydrothermal circulation on the Galapagos Spreading Center, Geophys. J. Roy. Astr. Soc., 38, 587-608.
- Wolery, T.J. and N.A. Sleep, 1976, Hydrothermal circulation and geochemical flux at mid-ocean ridges, J. Geol., 84, 249-275.

Publications

- Lowell, R.P., 1975, Circulation in fractures, hot springs, and convective heat transport on mid-ocean ridge crests, Geophys. J. Roy. Astr. Soc., 40, 351-365.
- Lowell, R.P. and P.A. Rona, 1976, On the interpretation of near-bottom water temperature anomalies, Earth Planet. Sci. Lett., 32, 18-24.
- Lowell, R.P. and G. Bodvarsson, 1976, Finite difference models for temperature transients in flowing boreholes, in Proceedings of 2nd United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, May 20-29, 1975, 3, 1733-1735.
- Lowell, R.P. and P.L. Patterson, 1977, Numerical models of hydrothermal circulation at an ocean ridge axis, (submitted to Benthic Boundary Layer Symposium).

Thesis

- Patterson, P.L., 1976, Numerical Modeling of Hydrothermal Circulation at Ocean Ridges, M.S. Thesis, Georgia Institute of Technology, Atlanta, Georgia, 84pp.

Papers Presented at Meetings

- Lowell, R.P., A convection model for thermal springs in the southeast, Annual Meeting, Southeastern Section, Geol. Soc. America, Atlanta, Georgia, April, 1974.

Lowell, R.P. and P.A. Rona, Thermal model for the TAG hydrothermal field, Spring Annual Meeting, AGU, Washington, D.C. April, 1976. (Abstract in EOS, 57, 265, 1976)

Lowell R.P. and P.L. Patterson, Numerical modeling of hydrothermal circulation at ocean ridges, Benthic Boundary Layer Conference of Joint Oceanographic Assembly, Edinburgh, U.K., September, 1976.

Collaborators and Students Supported

This research has opened the door for cooperation and interaction with other investigators in marine geophysics. There has been a particularly fruitful interaction with Dr. Peter Rona of NOAA and there have been very useful discussions with Dr. Clive Lister of the University of Washington, Dr. Gunnar Bodvarsson of Oregon State, and Dr. Roger N. Anderson of Lamont. This interaction has enhanced the reputation of the School of Geophysical Sciences at Georgia Tech as well as having enlightened the Principal Investigator. This important exchange of ideas would not have been possible without the support of the National Science Foundation.

Three graduate students have been supported under this grant. They were: Mr. Larry King, 1/1/75 - 4/15/75. Mr. King began to develop some of the finite difference models; however, he was forced to leave school for personal reasons.

Ms. Patricia Patterson, 9/15/75 - 8/31/76. Ms. Patterson developed the finite difference models which served as the basis for her M.S. thesis as well as for the paper presented in Edinburgh and the manuscript submitted to the symposium volume. Our frequent discussions on ocean ridge problems

and finite difference models have assisted in formulating the direction of future research in this area. She is currently employed by Exxon Company, USA in New Orleans, LA.

Mr. James Fulford, 9/15/76 - 12/31/76. Mr. Fulford is continuing the numerical work initiated by Patterson and is currently supported on the NSF continuation of the ocean ridge convection problem. He expects to finish an M.S. thesis in the summer of 1977.

Respectfully submitted,

Robert P. Lowell
Principal Investigator