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GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF RESEARCH ADMINISTRATION

RESEARCH PROJECT INITIATION

Date: December 13, 1973

Project Title: "Interaction Between a Cooling Intrusion and a Circulating Hydrothermal System — Application to Mid-Ocean Ridges"

Project No: G-35-611

Principal Investigator: Dr. Robert P. Lowell

Sponsor: National Science Foundation

Agreement Period: From Jan. 1, 1974 Until June 30, 1975

Type Agreement: Grant GA-41195

Amount: $14,100 NSF
3,817 GIT cost-sharing (G-35-316)
$17,917

Reports Required: Final Technical Report. If renewal of grant is anticipated, a progress report is due on the anniversary of the project. Progress report may appear as part of renewal proposal.

Sponsor Contact Person (s):

Gaylord L. Ellis
Grants Officer
National Science Foundation
Washington, D. C. 20550

Assigned to: Geophysical Science

COPIES TO:

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RA-3 (6-71)

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION

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Date: April 28, 1977

Project Title: "Interaction Between A Cooling Intrusion and a Circulating Hydrothermal System - Application to Mid-Ocean Ridges"

Project No: G-35-611

Project Director: Dr. Robert P. Lowell

Sponsor: National Science Foundation

Effective Termination Date: 12/31/76

Clearance of Accounting Charges: 12/31/76

Grant/Contract Closeout Actions Remaining: none

- _ Final Invoice and Closing Documents
- _ Final Fiscal Report
- _ Final Report of Inventions
- _ Govt. Property Inventory & Related Certificate
- _ Classified Material Certificate
- _ Other ______

Assigned to: Geophysical Sciences (School/Laboratory)

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CA—4 (3/76)

G-35-611

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF GEOPHYSICAL SCIENCES

Atlanta, Georgia 30332
(404) 894-2857

December 15, 1975

Central Processing Station
National Science Foundation
Washington, D.C. 20550

Attention: Dr. Robert E. Wall, Director
Submarine Geology and Geophysics Program
Oceanography Section
Division of Environmental Sciences

Subject: Annual Technical Letter Report on research proposal entitled "Hydrothermal Circulation on Mid-Ocean Ridge Crests" for the period January 1, 1975 to December 31, 1975. Grant # DES 74-00513

Dear Dr. Wall:

The following briefly summarizes research accomplished during the past year, personnel supported, and papers written and published.

RESEARCH

During the past year, three principal tasks have been undertaken.

TASK I. Application of the fracture convection model (Lowell,1975) to the TAG hydrothermal System.

A positive water temperature anomaly of 0.11°C has been measured over the TAG hydrothermal field (Rona, *et al*., 1975). Assuming that this anomaly was due to hydrothermal discharge, a thermal plume model for the discharge was constructed. The heat transfer by such a two dimensional plume compares favorably with heat transfer due to open hydrothermal convection in fractured rocks. The heat transfer, $Q \cong 4 \times 10^4$ watts/m, is a significant fraction of the total heat loss in the crustal zone of ocean ridges.

Rona, P.A., *et al*, 1975, Anomalous water temperatures over mid-Atlantic ridge crest at 26°N. latitude, *Deep Sea Res*. (in press).

The results of this work have been submitted to *Earth and Planetary Science Letters* (see section on Papers). Reprints of the Lowell (1975) paper are enclosed.

TASK II. Development of finite difference models for hydrothermal circulation on ridge crests.

The development of a finite difference model for time dependent convection in a homogeneous, saturated, porous rock driven by a cooling intrusive dike has continued from the preceeding year. We have been trying to develop models in which the permeability is large (large Rayleigh number) as well as models in which there is uneven surface topography and/or sediment cover. This work has not been progressing as well as expected, however. This is partly due to the fact that the Georgia Tech Computer Center changed from a UNIVAC 1108 to a CDC Cyber 74 computer system in June, 1975. This has caused some inefficiency in computer operations which has only recently been overcome. There has also been a change in graduate student research assistants which has caused delay (see Students Supported section below). It is expected that sufficient progress will be made on these problems so that a paper can be presented at the April meeting of the American Geophysical Union.

TASK III. Development of finite difference models for flowing boreholes.

During the past year a problem of considerable geothermal interest arose in which finite difference modeling was required. The computer funds for this work were derived from this grant. This problem involved the temperature transients resulting from a change of either the temperature or the flow rate of the fluid entering the base of a geothermal borehole. The results showed that in a typical producing borehole, a step-like change of 1% in the flow rate could give rise to an observable temperature pertubation at the top of the hole. Such temperature transients may provide useful information regarding the structural and connectivity aspects of geothermal reservoirs. Observable temperature at the surface also arise in the case in which fluid temperature at the base of the borehole changes. Those temperature transients may provide useful information regarding subsurface temperature conditions in the reservoir.

The results of this work have appeared in abstract form in the program for the Second United Nations Symposium on the Development and Use of Geothermal Resources., San Francisco, California, May 20-29, 1975. The complete manuscript will appear in the symposium proceedings (see section on papers).

STUDENTS SUPPORTED

Mr. Larry King, January 1, 1975 to April 15, 1975. Mr. King had to leave school for personal reasons.

Ms. Patricia Patterson, September 15, 1975-present. Ms. Patterson is currently developing numerical convection models. She expects to receive an M.S. degree in June, 1975.

PAPERS

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. (3 reprints enclosed)

Lowell, R.P. and Bodvarsson, G., 1975. Finite difference models for temperature transients in flowing boreholes, Proceedings of Second United Nations Sympossium on the Development and Use of Geothermal Resources May 20-29, 1975, San Francisco, California, (in press).

Lowell, R.P. and Rona, P.A., 1976. Thermal model for the TAG hydrothermal field, Earth Planet. Sci. Letters. (in review)

Respectfully submitted,

Robert P. Lowell
Assistant Professor

RPL:jg

Enclosed: reprints of Circulation in Fractures

G-35-611
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GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

OFFICE OF
THE DIRECTOR OF
FINANCIAL AFFAIRS

March 1, 1977

Grants and Contracts Office
National Science Foundation
Washington, D. C. 20550

Gentlemen:

Enclosed is the original and two copies of the final fiscal report for grant number DES74-00513-A01.

If you have any questions or desire additional information, please let me know.

Sincerely yours,

C. Evan Crosby
Associate Director of
Financial Affairs

CEC/bs
enclosures:
Dr. C. E. Weaver
cc: Dr. R. P. Lowell
Mr. E. E. Renfro
Mr. A. H. Becker
File G-35-611

NATIONAL SCIENCE FOUNDATION
Washington, D.C. 20550

RESEARCH GRANT BUDGET & FISCAL REPORT

Form Approved
Budget Bureau No. 99-R0013

Please read instructions on reverse side carefully before completing this form.

INSTITUTION AND ADDRESS Georgia Institute of Tech. Atlanta, Georgia	NSF PROGRAM Submarine Geophysics	GRANT PERIOD from 1/1/74 to 12/31/76 REPORTING PERIOD from 1/1/74 to 2/23/77
GRANT NUMBER DES74-00513 A01 / BUDGET DUR. (MOS.) ~~12~~ 36	PRINCIPAL INVESTIGATOR(S) Lowell	GRANTEE ACCOUNT NUMBER G-35-611*

	NSF Funded Man Months Cal.	Acad.	Summ.	NSF AWARD BUDGET	CUMULATIVE GRANT EXPENDITURES *Do Not Round*
A. SALARIES AND WAGES					
1. Senior Personnel					
a. 1 (Co)Principal Investigator(s)			2	$ 2,915	
b. Faculty Associates					
Sub-Total				$ 2,915	$ 8,737.00
2. Other Personnel (Non-Faculty)					
a. Research Associates—Postdoctoral					
b. Non-Faculty Professionals				-	
c. 1 Graduate Students				4,000	
d. Pre-Baccalaureate Students					
e. Secretarial—Clerical					
f. 1 Technical, Shop, and Other				300	
TOTAL SALARIES AND WAGES				$ 7,215	$ 14,396.04
B. STAFF BENEFITS IF CHARGED AS DIRECT COST				256	781.22
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)				$ 7,471	$ 15,177.26
D. PERMANENT EQUIPMENT					-
E. EXPENDABLE EQUIPMENT AND SUPPLIES				300	420.74
F. TRAVEL 1. DOMESTIC (INCLUDING CANADA)				300	680.95
2. FOREIGN					-
G. PUBLICATION COSTS					142.77
H. COMPUTER COSTS IF CHARGED AS DIRECT COST				800	1,078.25
I. OTHER DIRECT COSTS					-
J. TOTAL DIRECT COSTS (C through I)				$ 8,871	$ 17,499.97
K. INDIRECT COSTS 65% of salaries and wages				4,690	** 9,673.43
L. TOTAL COSTS (J plus K)				$ 13,561	$ 27,173.40
M. AMOUNT OF THIS AWARD (ROUNDED)				$ 13,600	
N. CUMULATIVE GRANT AMOUNT				$ 27,700	
O. UNEXPENDED BALANCE (N. BUDGET MINUS L. EXPENDITURE)					$ 526.60

REMARKS: Use extra sheet if necessary

*No obligations were incurred outside the grant period of 1/1/74 thru 12/31/76.

**65% of	$ 3,862.63	=	$ 2,510.71
68% of	$10,533.41	=	$ 7,162.72
	$14,396.04		$ 9,673.43

FOR NSF USE ONLY
Final Fiscal Report Accepted
Grant Closed ______ Remains Open ______
By ______ Date ______
Grants Administration Section, Area ______

SIGNATURE OF PRINCIPAL INVESTIGATOR	TYPED OR PRINTED NAME	DATE
	Robert P. Lowell	2/24/77

I CERTIFY THAT ALL EXPENDITURES REPORTED ARE FOR APPROPRIATE PURPOSES AND IN ACCORDANCE WITH THE AGREEMENTS SET FORTH IN THE APPLICATION AND AWARD DOCUMENTS

SIGNATURE OF AUTHORIZED OFFICIAL	TYPED OR PRINTED NAME & TITLE	DATE
	C. Evan Crosby, Associate Director of Financial Affairs	3/1/77

FOR NSF USE ONLY

Organ. Code	F.Y.	Fund ID	Prog. Code	Ob. Class	O/Dres.	Award No.	Amd.	Inst. Code	Unexpended Balance	Trans.	Lot
									$		

NSF Form 98, JULY 1971

SUPERSEDES ALL PREVIOUS EDITIONS

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

OFFICE OF
THE DIRECTOR OF
FINANCIAL AFFAIRS

August 2, 1977

Division of Grants and Contracts
National Science Foundation
Washington, D. C. 20550

Gentlemen:

Enclosed in triplicate is the final fiscal report for Grant Number DES74-00513 A01.

If you have any questions or desire additional information, please let us know.

Sincerely yours,

Evan Crosby
Associate Director of
Financial Affairs

EC/bs
enclosure:

cc: Dr. R. P. Lowell
Dr. C. E. Weaver
Mr. E. E. Renfro
Mr. A. H. Becker ✓
File G-35-611, G-35-316

NATIONAL SCIENCE FOUNDATION
Washington, D.C. 20550

RESEARCH GRANT BUDGET & FISCAL REPORT (REVISED)

Form Approved
Budget Bureau No. 99-R0013

Please read instructions on reverse side carefully before completing this form.

INSTITUTION AND ADDRESS	NSF PROGRAM	GRANT PERIOD
Georgia Institute of Tech. Atlanta, Georgia	Submarine Geophysics	from 1/1/74 to 12/31/76 REPORTING PERIOD from 1/1/74 to 2/23/77*

GRANT NUMBER	BUDGET DUR. (MOS.)	PRINCIPAL INVESTIGATOR(S)	GRANTEE ACCOUNT NUMBER
DES74-00513 A01	36 ~~12~~	Lowell	G-35-611

	NSF Funded Man Months Cal.	Acad.	Summ.	NSF AWARD BUDGET	CUMULATIVE GRANT EXPENDITURES Do Not Round
A. SALARIES AND WAGES					
1. Senior Personnel					
a. 1 (Co)Principal Investigator(s)			2	$ 2,915	
b. Faculty Associates					
Sub-Total				$ 2,915	$ 8,737.00
2. Other Personnel (Non-Faculty)					
a. Research Associates—Postdoctoral					
b. Non-Faculty Professionals				-	
c. 1 Graduate Students				4,000	
d. Pre-Baccalaureate Students					
e. Secretarial—Clerical					
f. 1 Technical, Shop, and Other				300	
TOTAL SALARIES AND WAGES				$ 7,215	$ 14,396.04
B. STAFF BENEFITS IF CHARGED AS DIRECT COST				256	781.22
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A + B)				$ 7,471	$ 15,177.26
D. PERMANENT EQUIPMENT					-
E. EXPENDABLE EQUIPMENT AND SUPPLIES				300	420.74
F. TRAVEL 1. DOMESTIC (INCLUDING CANADA)				300	680.95
2. FOREIGN					-
G. PUBLICATION COSTS					142.77
H. COMPUTER COSTS IF CHARGED AS DIRECT COST				800	991.47
I. OTHER DIRECT COSTS					
J. TOTAL DIRECT COSTS (C through I)				$ 8,871	$ 17,413.19
K. INDIRECT COSTS 65% of salaries and wages				4,690	9,673.43 **
L. TOTAL COSTS (J plus K)				$ 13,561	$ 27,086.62
M. AMOUNT OF THIS AWARD (ROUNDED)				$ 13,600	
N. CUMULATIVE GRANT AMOUNT				$ 27,700	
O. UNEXPENDED BALANCE (N. BUDGET MINUS L. EXPENDITURE)					$ 613.38

REMARKS: Use extra sheet if necessary

* No obligations were incurred outside the grant period of 11/1/74 through 12/31/76.

**65% of	$ 3,862.63	=	$2,510.71
68% of	$10,533.41	=	$7,162.72
	$14,396.04		$9,673.43

FOR NSF USE ONLY
Final Fiscal Report Accepted
Grant Closed ______ Remains Open ______
By ______ Date ______
Grants Administration Section, Area ______

SIGNATURE OF PRINCIPAL INVESTIGATOR	TYPED OR PRINTED NAME	DATE
	Robert P. Lowell	7/28/77

I CERTIFY THAT ALL EXPENDITURES REPORTED ARE FOR APPROPRIATE PURPOSES AND IN ACCORDANCE WITH THE AGREEMENTS SET FORTH IN THE APPLICATION AND AWARD DOCUMENTS

SIGNATURE OF AUTHORIZED OFFICIAL	TYPED OR PRINTED NAME & TITLE	DATE
	Evan Crosby Associate Director of Fin. Affairs	8/1/77

FOR NSF USE ONLY

Organ. Code	F.Y.	Fund ID	Prog. Code	Ob. Class	O/Dres.	Award No.	Amd.	Inst. Code	Unexpended Balance	Trans.	Lot
									$		

NSF Form 98, JULY 1971

SUPERSEDES ALL PREVIOUS EDITIONS

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF GEOPHYSICAL SCIENCES
Atlanta, Georgia 30332
(404) 894-2857

March 25, 1977

Central Processing Section
National Science Foundation
Washington, D.C. 20550

Attention: Dr. Donald F. Heinrichs, Director
Submarine Geology and Geophysics Program
Oceanography Section
Division of Ocean Sciences

Subject: Final Technical Letter Report on "Hydrothermal Circulation on Mid-Ocean Ridge Crests" (NSF Grant #DES 74-00513, Formerly GA-41195)

Dear Dr. Heinrichs:

Enclosed is the Final Technical Letter Report on the NSF supported research grant entitled "Hydrothermal Circulation on Mid-Ocean Ridge Crests." This research support came at a critical time with regard to the development of the geophysics program of the School of Geophysical Sciences at Georgia Tech. Moreover, the support was scientifically timely. The scientific community has just become greatly interested in marine hydrothermal systems, and consequently this program led to a fruitful interaction between the Principal Investigator and other marine scientists. The NSF support of this research project is gratefully acknowledged and deeply appreciated.

Sincerely yours,

Robert P. Lowell
Principal Investigator

RPL:cma

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 ($\Delta T \leq 0.1^{o}C$) 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 $100^{o}C/km$ in the

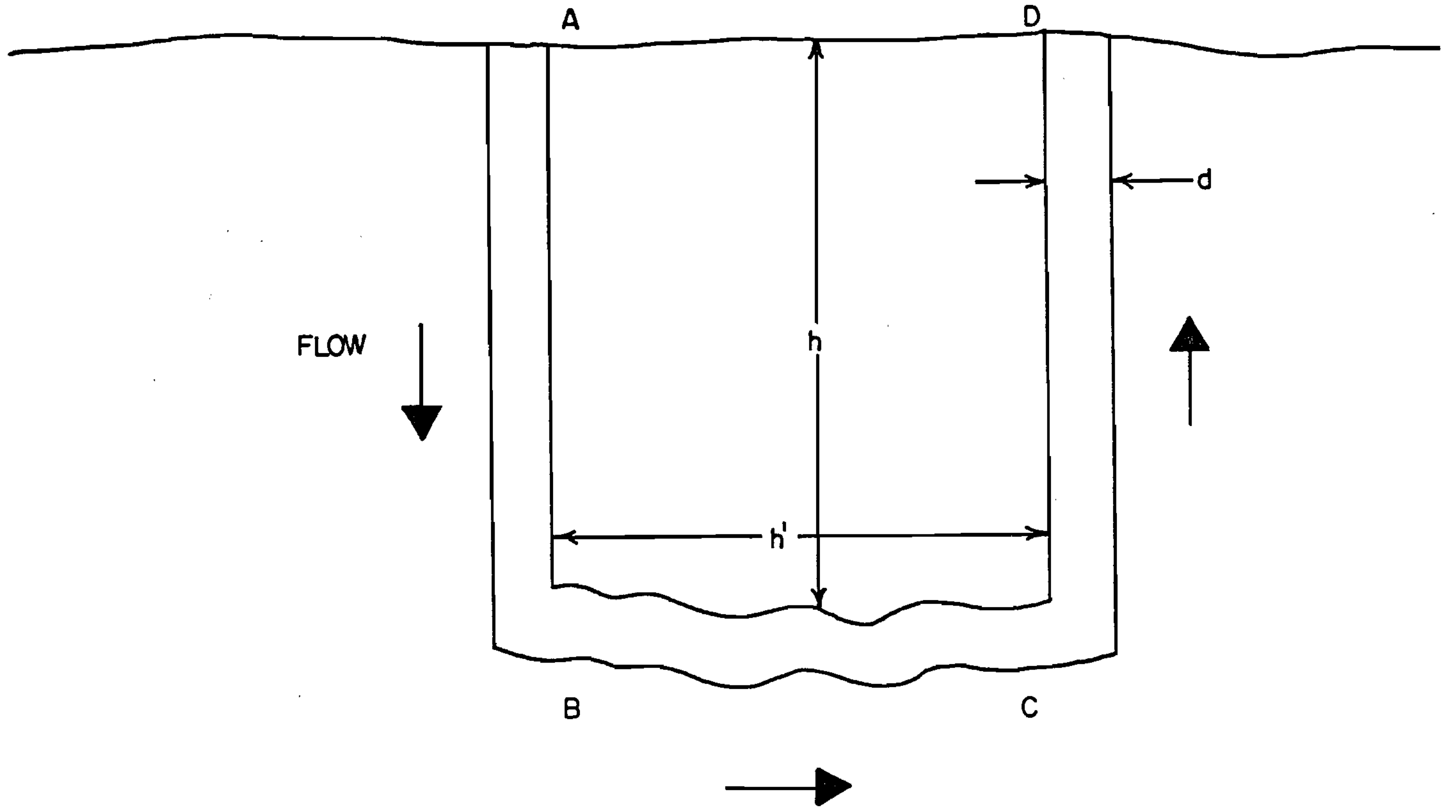

FIGURE I — Sketch of a transverse flow system.

block, the outlet temperature and rate of discharge at the sea floor would be $100^{o}C/cm$ in the block, 0.14 kg/m-sec, repsectively, at the end of 10^4 years. If the fracture were 1 km in length, the discharge would be 140 kg/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 ^{o}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.

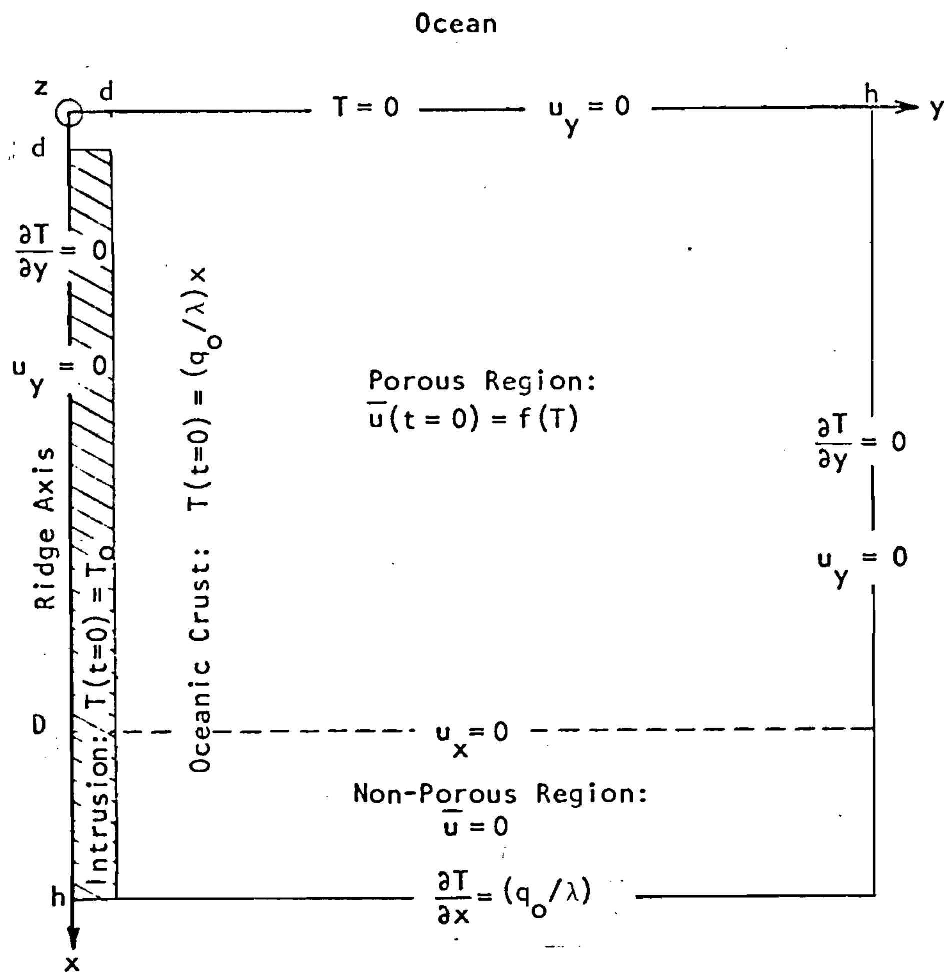

Figure 2. Basic Model with Initial and Boundary Conditions.

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 descrepancy 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

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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

APPENDIX A

NUMERICAL MODELS OF HYDROTHERMAL CIRCULATION AT AN OCEAN RIDGE AXIS

by

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Abstract

Hydrothermal circulation in the oceanic crust at a ridge axis is modeled numerically using finite differences. Episodic emplacement of new crustal material at the axis is assumed. The circualtion is driven by the transient, horizontal temperature gradients arising after one episodic emplacement and by an assumed uniform heat flux from below. The oceanic crust is treated as a porous medium for various cases of permeability conditions. Although the ocean bottom is considered to be a permeable boundary, convective heat transfer across this boundary is not considered.

Conductive heat transfer through the ocean bottom resulting from fluid circulation within the crust is found to be directly proportional to crustal permeability for cases of homogeneous, isotropic permeability, and conductive heat transfer through the ocean bottom becomes more concentrated at the ridge axis with increasing permeability. Changes in permeability conditions from homogeneous, isotropic distributions do not alter flow patterns or cooling effects significantly. Based on these flow patterns and cooling effects a new conductive heat-flow curve is postulated for qualitative comparison of measured heat-flow distributions near ocean ridges.

Introduction

Ocean-floor heat flow values in the vicinity of ocean ridge crests exhibit a high degree of scatter, and often values close to zero occur. In some cases, the distribution of values is opposite to that expected from topographic refraction effects (LISTER, 1972). TALWANI, WINDISCH, and LANGSETH (1971) have noted that the average heat flux measured on the Reykjanes Ridge crest is less than the average flux that would be generated by a cooling lithospheric plate originating at and moving with constant speed from the ridge axis (e.g. MCKENZIE, 1967; SCLATER and FRANCHETEAU, 1970; PARKER and OLDENBURG, 1973; SLEEP, 1974). A similar observation has been made for the Galapagos Spreading Center (WILLIAMS, VON HERZEN, SCLATER, and ANDERSON, 1974) where, in fact, the heat flow exhibits a roughly sinusoidal pattern with a wavelength of approximately 6 kilometers. Recent compilation of heat-flow data from the world ocean shows that the mean heat fluxes to a considerable distance from ridge axes are less than those predicted by models of a conductively cooling crust (ANDERSON, 1976, personal communication). The distance, or age of the sea floor, at which the observed heat flux begins to match the theoretical prediction varies from ridge to ridge and is thought to be a function of sediment thickness and/or type, or the ratio of sediment thickness to topographic roughness (ANDERSON and HOBART, 1976).

To account for the discrepancy between the observed and theoretically predicted heat flow distributions, circulation of sea water in the oceanic crust with convective heat transfer across the ocean bottom has been proposed (e.g. PALMASON, 1967; TALWANI, WINDISCH, and LANGSETH, 1971; WILLIAMS, VON HERZEN, SCLATER, and ANDERSON, 1974; and LISTER, 1972).

The existence of hydrothermally altered rock (AUMENTO, LONCAREVIC, and ROSS, 1971) and hydrothermal deposits (CORLISS, 1971, SCOTT, SCOTT, RONA, AND NALWALK, 1974), near-bottom photographs of cracks on the Mid-Atlantic Ridge (BALLARD, 1975), and measurements of water temperature anomalies near the sea floor (RONA, MCGREGOR, BETZER, BOLGER, and KRAUSE, 1975) are evidence that such large scale hydrothermal circulation occurs.

Theoretical models for hydrothermal circulation in the oceanic crust have been based on convection in narrow, deep, widely spaced vertical fractures (BODVARSSON and LOWELL, 1972; LOWELL, 1975), as well as on steady-state convection in a porous layer with constant temperature or constant heat flux at the lower boundary (LAPWOOD, 1948; RIBANDO, TORRANCE, and TURCOTTE, 1976). These models have given widely divergent results with regard to convective heat losses at the sea floor. Based on his fracture models, LOWELL (1975) has concluded that a significant portion of lithospheric heat is lost by convection, the heat being carried by hot springs discharging at the sea floor. On the other hand, RIBANDO, TORRANCE, and TURCOTTE (1976) have suggested that little heat is lost by convection and that the heat-flow measurements reported by WILLIAMS, VON HERZEN, SCLATER, and ANDERSON (1974) on the Galapagos Spreading Center are indicative of the true heat flux. None of the above mentioned models, however, has considered conditions at ridge axes, where intrusions must give rise to transient, horizontal temperature gradients.

The purpose of this paper is to examine the effects of some of the conditions not included in the earlier works of others. The oceanic crust is treated as a porous layer, and the hydrothermal environment of a single convection cell at a ridge axis is modeled following the emplacement of a high-temperature intrusion into the layer. Different cases of crustal permeability conditions are considered, including: homogeneous, isotropic permeabilities; non-homogeneous, isotropic permeabilities; and homogeneous, anisotropic permeabilities. The results provide insight into possible cooling histories of the oceanic crust, of interest not only for the explanation of measured heat fluxes, but also for the prediction of environments for hydrothermal reactions with crustal rocks.

The Basic Model

The basic model (Figure 1) consists of a block of oceanic crust of linear extent h in the x and y directions and infinite extent in the z direction. There is a uniform heat flux q_o across the lower boundary. The block is overlain by sea water, assumed to act as a perfect conductor at temperature $T = 0$, and the vertical sides of the block are insulated. The block is permeable to depth D, where D may be less than or equal to h, the vertical boundaries are impermeable; and the upper boundary is permeable, so that sea water may enter and exit, circulating through the permeable region. For time $t<0$, no circulation occurs, and a steady-state conductive temperature field exists: $T(x,y,t<0) = (q_o/\lambda)x$, where λ is the thermal conductivity of the rock. At time $t = 0$, a rectangular intrusion of width d and temperature T_o is emplaced to a depth d at the left side of the oceanic block. This event represents the sudden emplacement of a dike or dike swarm at the ridge axis, leading to the formation of new oceanic crust. The crust is impermeable for $T \geq T_r$, where T_r is the cracking temperature, and permeable for $T < T_r$. (This is a much simplified treatment of the thermally induced rock fracturing process given by LISTER (1974).)

Assuming the rock and fluid to be in thermal equilibrium and the fluid to be incompressible, the pertinent equations of conservation of fluid mass, fluid momentum, and thermal energy and the equation of state for the fluid are (LAPWOOD, 1948):

$$\nabla \cdot \vec{u} = 0 \tag{1}$$

$$-\nabla P - \rho_f \, \nu \, \underset{\sim}{K}^{-1} \cdot \vec{u} + \rho_f \, \vec{g} = 0 \tag{2}$$

$$\rho c \, \partial T/\partial t + \rho_f s \, \vec{u} \cdot \nabla T = \lambda \nabla^2 T \tag{3}$$

$$\rho_f = \rho_{f_o} (1 - \alpha T) \tag{4}$$

where u is the Darcy velocity of the fluid, p its pressure, ρ_f its density, ν its kinematic viscosity, $\underset{\sim}{K}^{-1}$ the inverse of the permeability tensor, g the acceleration of gravity, ρc the heat capacity of the rock, s the specific heat of the fluid, α its coefficient of thermal expansion, and ρ_{f_o} its density at T = 0. In equation (2) the inertial terms are omitted, being much smaller than the viscous term (STRAUS, 1974). To allow for anisotropies in permeability (LISTER, 1974), permeability is written as a tensor.

Conditions at $t \geq 0$ are treated as perturbations on the conditions existing at $t < 0$, so that:

$$\begin{aligned} T &= T^o + T' \\ \vec{u} &= \vec{u}' \\ P &= P^o + P' \\ \rho_f &= \rho_f^o + \rho_f' \end{aligned} \tag{5}$$

where the superscripts designate the unperturbed values at $t < 0$, and the primes designate the perturbations to these values at $t \geq 0$. Equations (5) are substituted into equations (1) through (4), employing the Boussinesq approximation; the pressure term of the momentum equation is eliminated by taking the curl of this equation; and the resulting equations are non-dimensionalized by measuring length in units of h, velocity in units of $\lambda/(\rho_{fo} sh)$, time in units of $\rho ch^2/\lambda$, and temperature in units of T_o. A stream function is introduced, given by:

$$v_x = -\partial\psi/\partial Y$$
$$v_y = \partial\psi/\partial X \qquad (6)$$

where v_x and v_y are the dimensionless velocity components and X and Y are dimensionless coordinates. The resulting dimensionless equations are:

$$\partial^2\psi/\partial Y^2 - (K_x/K_y{}^2)\partial K_y/\partial X\ \partial\psi/\partial X + (K_x/K_y)\ \partial^2\psi/\partial X^2 - R(K_x/K_o)\ \partial\theta/\partial Y = 0 \qquad (7)$$

$$\partial\theta/\partial\tau + \vec{v}\cdot\nabla\theta + v_x R_q/R = \nabla^2\theta \qquad (8)$$

Where θ and τ are dimensionless temperature and time, respectively, $\underset{\sim}{K}$ is a function of depth only, $K_o = K_x(x = 0)$, and R and R_q are Rayleigh parameters given by:

$$R = \rho_{fo}\ s\alpha\ gT_oK_oh/\nu\lambda$$
$$R_q = \rho_{fo}\ s\alpha\ gq_oK_o\ h^2/\nu\lambda^2$$

The initial temperature conditions are:

$$\theta = 1-(R_q/R)X \quad \text{at and inside the intrusion}$$
$$\theta = 0 \quad \text{outside the intrusion,} \qquad (9)$$

and the boundary conditions are:

$$\theta(0,Y) = \partial\theta(X,0)/\partial Y = \partial\theta(X,1)/\partial Y = \partial\theta(1,Y)/\partial X = 0 \qquad (10)$$

$$\partial\psi(0,Y)/\partial X = \psi(X,0) = \psi(X,1) = \psi(D/h,Y) = 0 \qquad (11)$$

Equations (6) through (8) with conditions (9) through (11) were solved numerically using finite difference methods. The finite difference scheme was carried out on a 20 by 20 grid of equally spaced points. The procedure was to (1) solve the finite difference representation of equation (7) for the stream function field using the known (initial) temperature field, (2) use this solution to solve the finite difference representations of equations (6) for the velocity field, (3) use this velocity field and the known temperature field to solve the finite difference representation of (8) for the temperature field at time $\Delta\tau$, and (4) repeat these steps using the new temperature field as the known temperature field and thusly advance through time, obtaining solutions at each grid point at discrete time multiples of $\Delta\tau$.

The surface heat conduction through the top boundary, the total heat conducted out of the system, and the volume of water circulated through the system as functions of time were calculated also. Details of the numerical methods are given in PATTERSON (1976).

Results

Solutions were obtained from time t = 0 to t = 15,000 years for linear extent of the model h = 4 km, intrusion width d = 200 m, initial temperature of intrusion T_o = 1200°C, cracking temperature T_r = 690°C, and a bottom heat flux q_o = 10 μcal/ cm^2-s . Values of other parameters were ρ_f^o = 1 cal/cm^3-°C, $\alpha = 1.6 \times 10^{-4}$/°C, λ = 0.01 cal/°cal/C-cm-s, and ρc = 0.75 cal/cm^3-°C. The depth of the permeable layer D and the permeability function $\underset{\sim}{K}$ were varied according to Table 1 for different models. Case 1 is a conductive model, involving no hydrothermal circulation.

The emplacement of an intrusion with a 200 km width every 15,000 years corresponds to a half spreading rate of the sea floor of

1.33 cm/year. These conditions roughly approximate those at the Mid-Atlantic Ridge, where the average half spreading rate is 1.1 cm/year and where the eruption of pillow basalts at the ridge axis on 14,000 year cycles has been proposed by MOORE, FLEMING, and PHILLIPS (1974).

The range of permeability conditions modeled centers around 0.01 Darcy (D.). This value lies roughly between the estimate of 4.5×10^{-4} D. given by RIBANDO, TORRANCE, and TURCOTTE (1976) and the estimate of 10 D. given by LISTER (1974). Moreover, PALMASON (1967) has estimated the horizontal permeability of the Reykjavik thermal area to be 0.03 D., with the vertical permeability estimated to be somewhat smaller, and WOODING (1963) has estimated the bulk permeability of the Wairakei hydrothermal field to be 0.01 D.

Rayleigh parameters for the models lie in the ranges:

$$7.53 \leq R \leq 753$$

$$2.50 \leq R_q \leq 250$$

The critical Rayleigh number R_{qcr} for a porous medium with a homogeneous, isotropic permeability distribution, a constant heat flux across the lower boundary, and a permeable upper boundary is 17.7 (NIELD, 1968). For cases 2, therefore, convection ranges from sub-critical, where it is driven solely by horizontal temperature gradients, to super-critical, finite-amplitude, where it is driven by both horizontal and vertical gradients.

The principal results are shown in Figures 2 through 7. Figure 2a shows how the temperature field in the presence of hydrothermal circulation differs from that in its absence. The isotherms are displaced in the direction of fluid flow so that at the surface of the model higher temperature gradients exist near the intrusion, but lower gradients away from it.

Figure 2b shows the time development of the hydrothermal system in the case of a uniform, isotropic permeability of 0.01 D. The convection cell is asymmetric, with the center of the cell displaced toward the intrusion. As cooling progresses, the cell becomes more symmetric, but by the end of 15,000 years, full symmetry has not been attained, indicating that the steady state has not been attained. Note that after 1,000 years about one-half of the intrusion is still at temperatures greater than $T_r = 690^{\circ}C$. The approximate rate at which water penetrates the intrusion is therefore 2 m/year. This is somewhat slower than LISTER'S (1974) estimate, probably partially because of the low permeability assumed here. For the case where $K_o = 0.1$ D., the entire intrusion has cooled below T_r in less than 1,000 years.

Figure 3 (a, b, c, and d) shows the thermal and flow regimes at 15,000 years for most of the models. The figures are fairly self-explanatory. For the cases of constant, isotropic permeability (Figure 3a) the velocity at 15,000 years varies approximately as $1.5K_o$. For the cases of anisotropic permeability (Figure 3d) flow is more concentrated near the intrusion. For the case of linear decreases in permeability with depth (Figure 3b) flow is more concentrated near the surface.

Figure 4 shows the perturbation surface heat flux after 15,000 years for most of the models. (The actual surface heat flux includes the uniform heat flux q_o.) Note how hydrothermal circulation redistributes the heat flux conducted through the upper surface relative to that of the non-convective model. Near the axis the heat flux is greater, while at distances greater than 1 to 1.5 km the heat flux is lower.

Figure 5 shows the total volume of fluid circulated through the system as a function of time for the models. The slopes of the curves indicate that for all cases the rate of fluid circulation reaches a maximum early in the cooling history and then gradually decreases with time. The average rates of fluid circulation for all the models fall within the range estimated by WOLERY and SLEEP (1976).

Figure 6 shows the excess heat conducted out in 15,000 years over that for the conductive case and the total volume of fluid circulated by the end of 15,000 years as functions of permeability for models 2b through 2f, which have homogeneous, isotropic permeability distributions. (The value for case 2a are excluded because of instabilities in the numerical solution.) For this range of permeabilities (0.0275 to 0.001 D.) both functions are roughly linear. The values of excess heat output and volume of fluid circulated for the other models are superimposed on these functions.

Figure 7 shows the total perturbation heat conducted out of the models as functions of time. The slopes for all convective cases are at all times greater than that for the conductive case, indicating that the average heat flux over the surface of convective models is always greater than that over the surface of the conductive model. Except for case 2a, for which the solution became unstable, the heat conducted out in excess of that for the conductive model for cases 2b through 2f appears to be linearly proportional to permeability at all times.

Discussion

Convective heat transfer across the ocean bottom

Since the ocean bottom was assumed to be an isotherm and perfect thermal contact was assumed to exist between the circulating fluid and the rock, the models considered in this study did not allow the possibility of convective heat transfer through the ocean bottom. For the range of permeabilities involved in the models, however, the maximum Darcy velocity that occurred was 5×10^{-6} cm/sec (for $K_o = 0.1$ D.). Assuming an intercrack spacing of 100 cm in the crust, LISTER'S (1974) theory gives a crack width of 0.045 cm. The actual fluid velocity in cracks of this width would be about 0.01 cm/sec. For this and lower velocities, the assumption of perfect thermal contact seems reasonable. The assumption that the ocean bottom remains an isotherm, however, cannot be easily justified. In veiw of the very high surface temperature gradients upon emplacement of the intrusion (see Figure 2b), it is expected that the ocean above the intrusion will be heated and that convective heat transfer will occur across the ocean bottom.

The case of a radiation boundary condition at the upper surface has been treated by RIBANDO, TORRANCE, and TURCOTTE (1976), and they suggest that the effect of this boundary condition is small. After 15,000 years, however, the conductive heat flux over the ridge axis for the models presented here, even excluding the uniform heat flux, q_o, from below (see Figure 4), greatly exceeds the value of 4 $\mu cal/cm^2$-sec measured at the axis of the Juan de Fuca Ridge (LISTER, 1970). This is the only known measurement within the range of our models; and if it is representative of the conductive heat flow at a ridge axis (in particular the heat flux along the Mid-Atlantic Ridge axis), it may be concluded that convective heat losses must occur over ridge axes. The models presented here must then be modified to include convective heat losses. It may be important to consider models in which convective losses near ridge axes take place as a result of hot springs discharging in zones of high permeability.

Conductive heat transfer across the ocean bottom

For no model in this paper was the heat perturbation introduced by the intrusion reduced by as much as 50% by the end of the 15,000 year cycle.

Thus only a portion of the transient conditions, building up to an equilibrium oscillatory state were modeled. Since excess heat conducted out in convective cases with homogeneous, isotropic permeability distributions over that in the conductive case was directly proportional to permeability, the curve of Figure 6a can be extrapolated to the value of the original heat perturbation. This extrapolation leads to the prediction that a convective system with $K_o \geq 0.150D$. could conceivably reduce the heat perturbation introduced into the upper 4 km of the crust within the expanse of a single wavelength of hydrothermal flow before the end of the 15,000 cycle. For $K_o < 0.15$ modeling with periodic intrusions should be carried out until equilibrium cooling is attained, i.e., until the long term rate of heat perturbation equals the rate of its removal through the ocean floor. Such a calculation would involve lateral extension of the model away from the axis, the lower the permeability of the model, the greater the extension. In all cases oscillations in the surface heat conduction would occur at the axis with a period equal to 15,000 years. The amplitude of these oscillations would increase with K_o, and for $K_o \geq 0.15$ the amplitude would be zero for part of the cycle. The overall heat flux for convective cases would compare to that for the conductive case in the manner shown in Figure 8.

The redistribution of conductive heat flux due to convection as shown qualitatively (by curve b of Figure 8) could account, at least partially, for the fact the mean values of conductive heat flux near ridge axes have been observed to be lower than those predicted by models of a conductively cooling crust. It may be, then, that conductive heat fluxes within short distances for ridge axes, perhaps of the order of 10 km, nearly represent to total flux through ocean bottom (see RIBANDO, TORRANCE, and TURCOTTE, 1976). Convective heat losses may be confined to regions very near ridge axes.

Permeability conditions in the oceanic crust

For cases of homogeneous, isotropic permeability the ratio of the functions of Figure 6 is approximately constant and equal to 70 cal/cm^3. Thus about 70 cal of heat in excess of the number when no circulation occurs, are conducted out of the model for every gram of water entering. For cases of other permeability distributions, fewer calories are absorbed per gram of water. In most cases, however, the difference is very small. Case 5a (with $K_x/K_y = 2$) is more efficient than case 3 (with linear decrease of permeability with depth), requiring less circulation to remove the same amount of heat. This is true since in case 3 water does not move as freely into the higher temperature regions (deeper and closer to the axis) as it does in case 5a. For a given temperature distribution, however, velocities are higher for case 3 than for case 4a since viscous effects in case 3 are lower near the surface, and in all models more fluid flows near the surface than in other regions. Each of these two cases therefore affords about the same cooling rate (see Figure 7), and this cooling rate would be about the same as that of a model with a homogeneous, isotropic permeability distribution with $K_o = 0.009$ (see Figure 6). Therefore, when modeling the oceanic crust as a porous medium for the purpose of determining gross surface fluxes and overall heat removel, models with homogeneous, isotropic permeability distributions should be sufficient. When considering small scale fluid-rock interactions, however, consideration of other permeability distributions may be meaningful.

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Table 1. Cases Modeled

Case	D	K_o	$\frac{\partial K_y}{\partial x}$	$\frac{K_x}{K_y}$
1	0			
2	4		0	1
a		0.1		
b		0.0275		
c		0.01		
d		0.0075		
e		0.005		
f		0.001		
3	4	0.01	$-\frac{0.01}{4}$	1
4		0.01	0	1
a	2			
b	3			
5	4	0.01	0	
a				2
b				3
c				10

Explanation:

D is depth of porous layer in km.

K_o is permeability to vertical flow at top boundary in Darcies (1 Darcy = $0.987 \cdot 10^{-8}$ cm^2).

$\frac{\partial K_y}{\partial x}$ is change in permeability with depth in Darcies/km.

$\frac{K_x}{K_y}$ is ratio of permeability to vertical flow to permeability to horizontal flow.

List of Figures

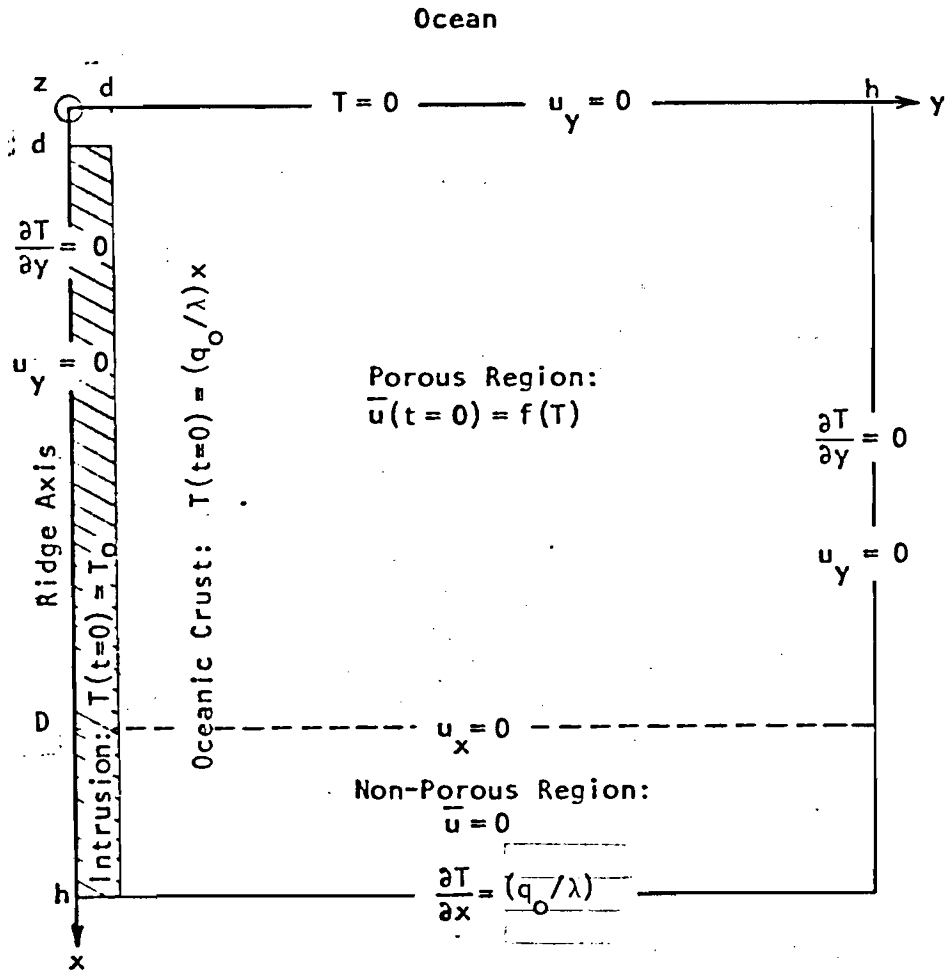

Figure 1. Basic Model with Initial and Boundary Conditions.

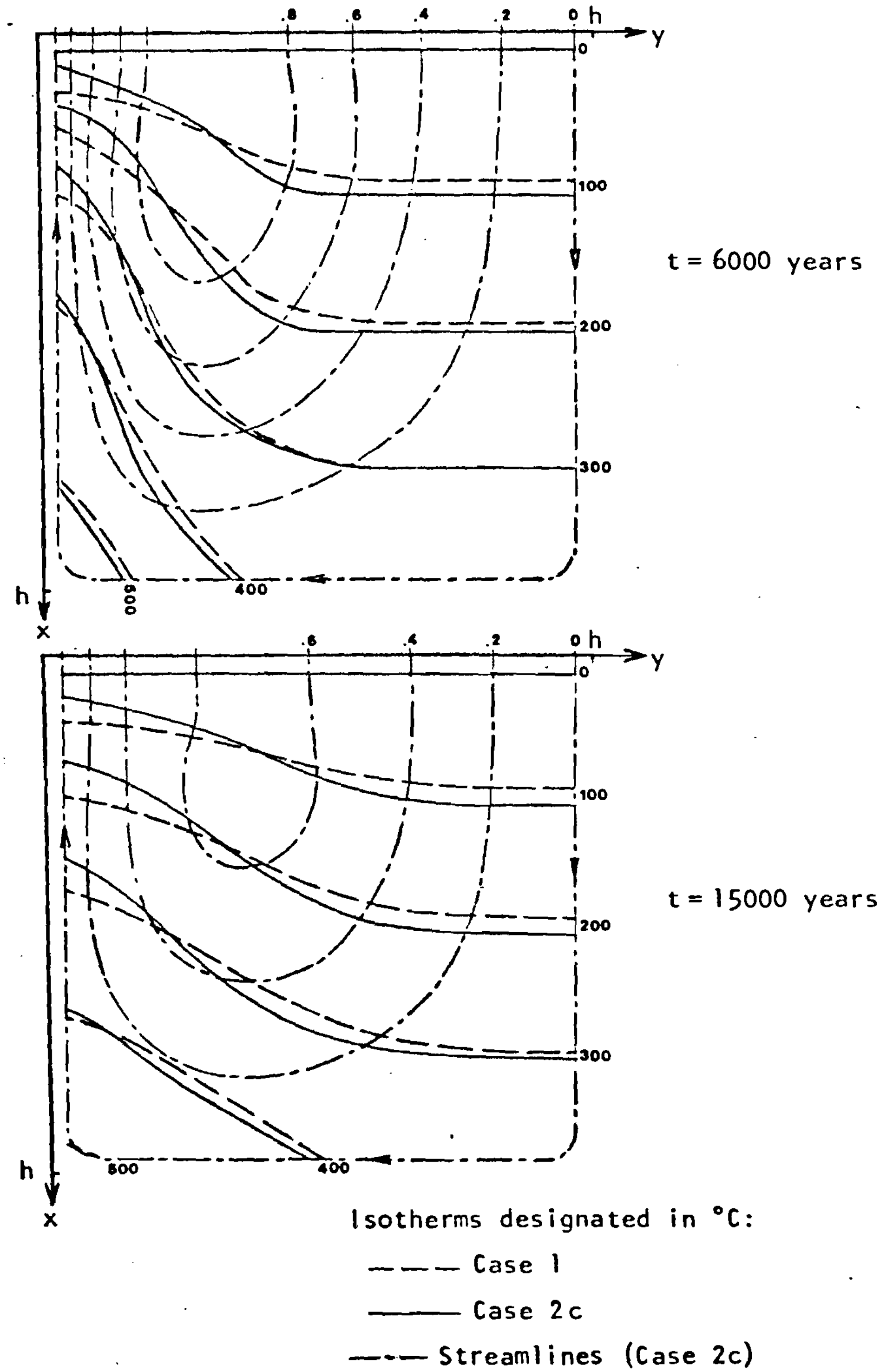

Figure 2a. Comparison of Temperature Fields for Conductive Case (Case 1) with Those for Typical Convective Case (Case 2c).

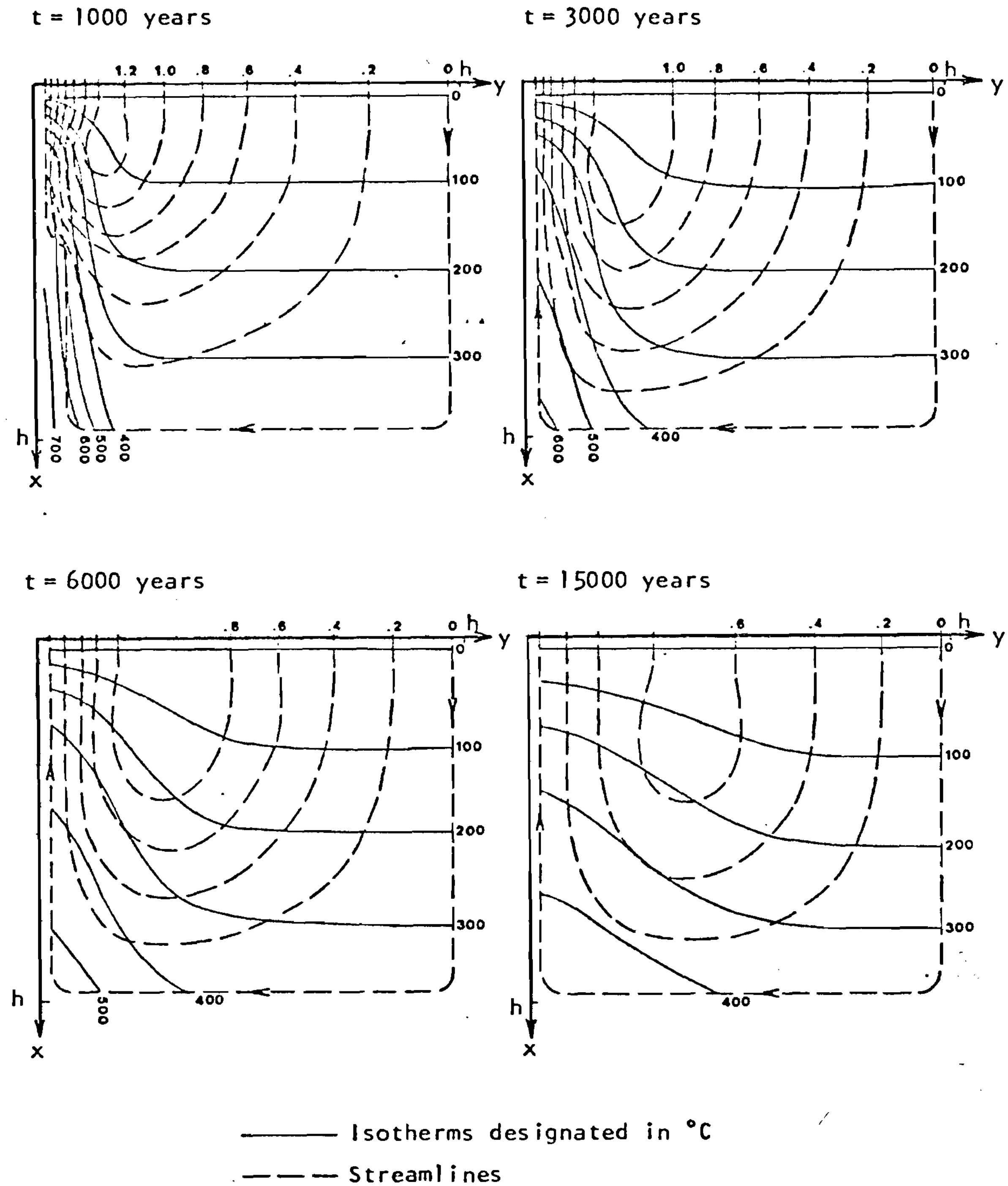

Figure 2b. Typical Time Development of Hydrothermal Field (Case 2c).

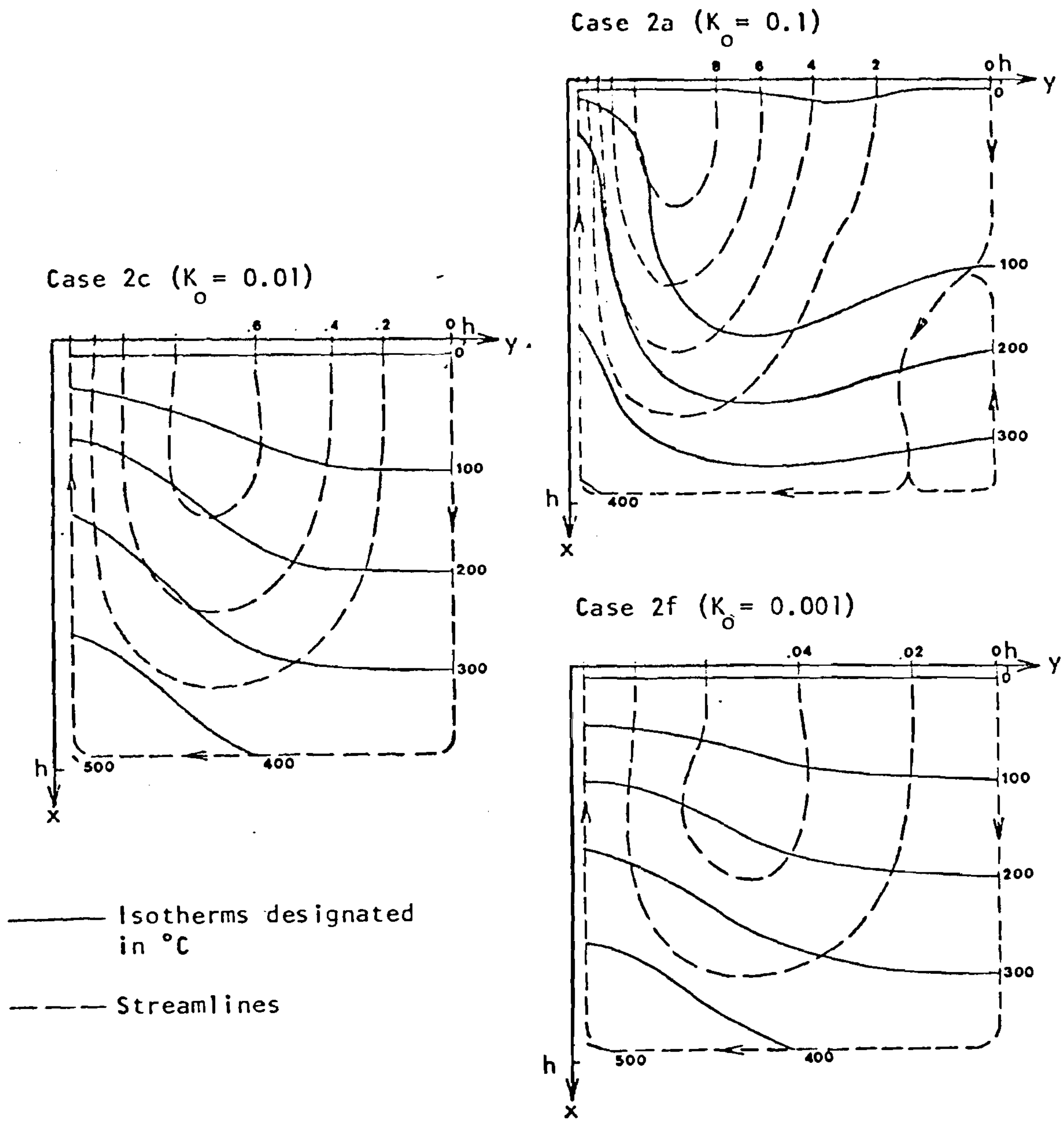

Figure 3a. Hydrothermal Fields for Three Cases of Homogeneous, Isotropic Permeability at t = 15000 Years.

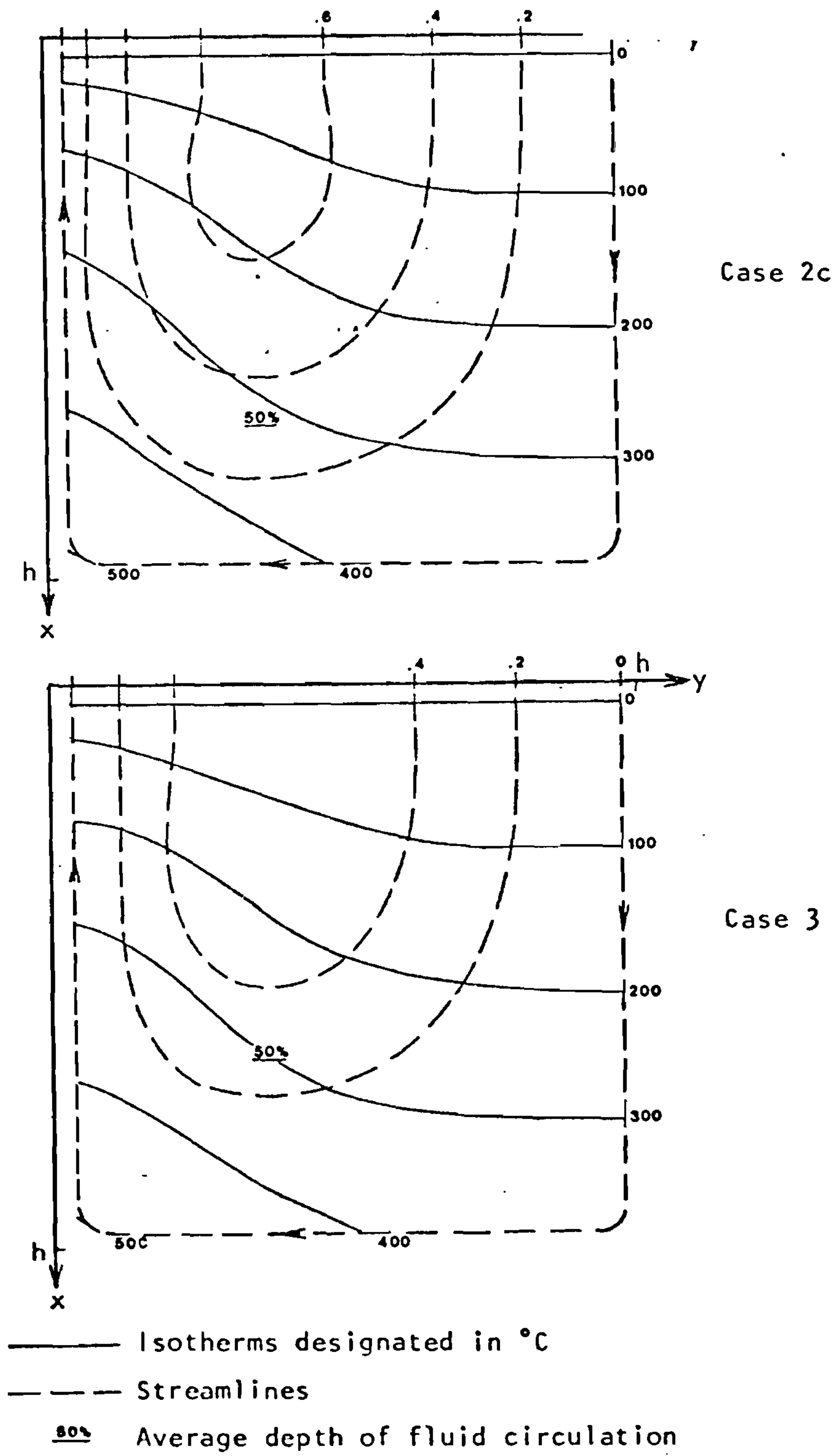

Figure 3b. Hydrothermal Fields for Cases of Homogeneous (Case 2c) and Inhomogeneous (Case 3), Isotropic Permeability at t = 15000 Years.

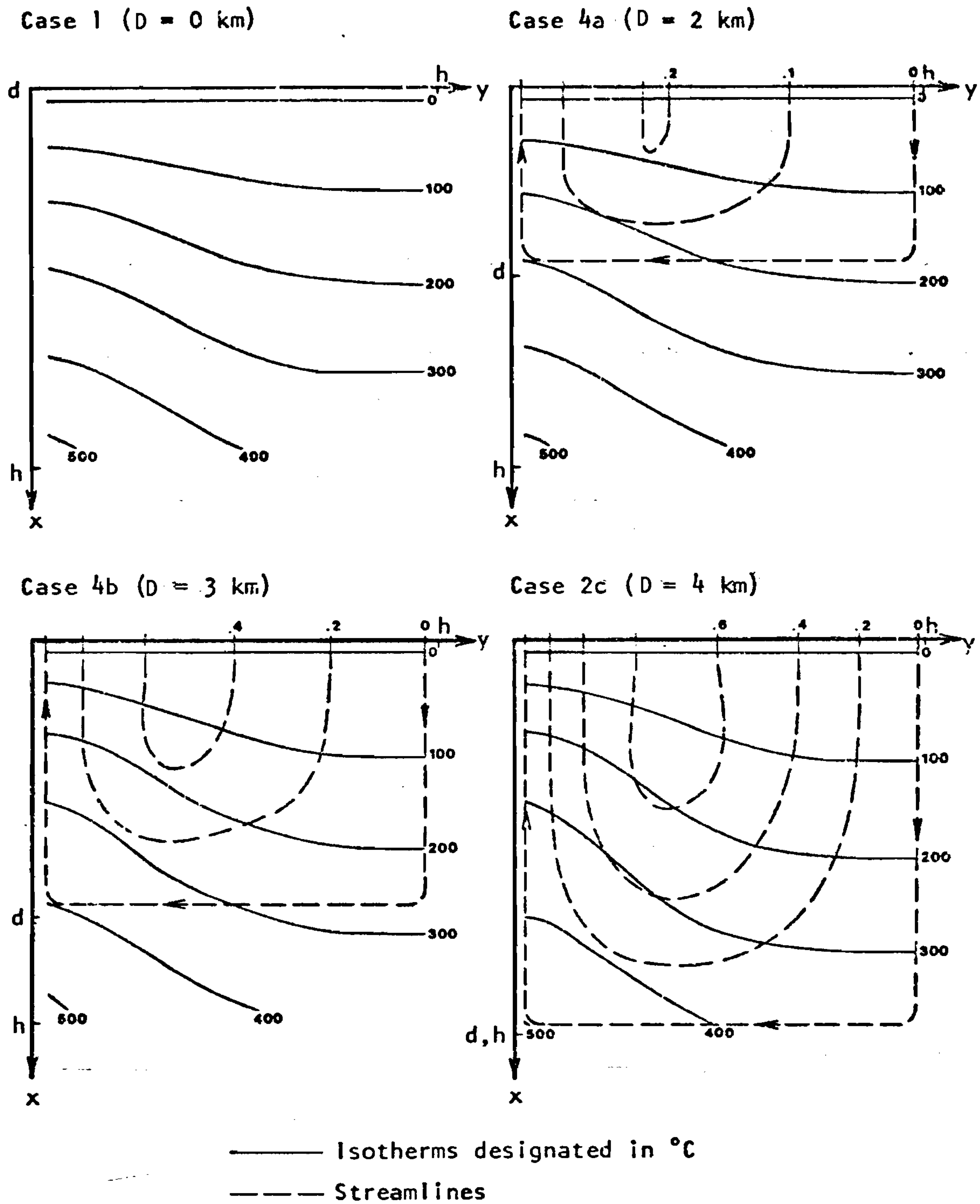

Figure 3c. Hydrothermal Fields for Four Thicknesses of Permeable Layer at t = 15000 Years.

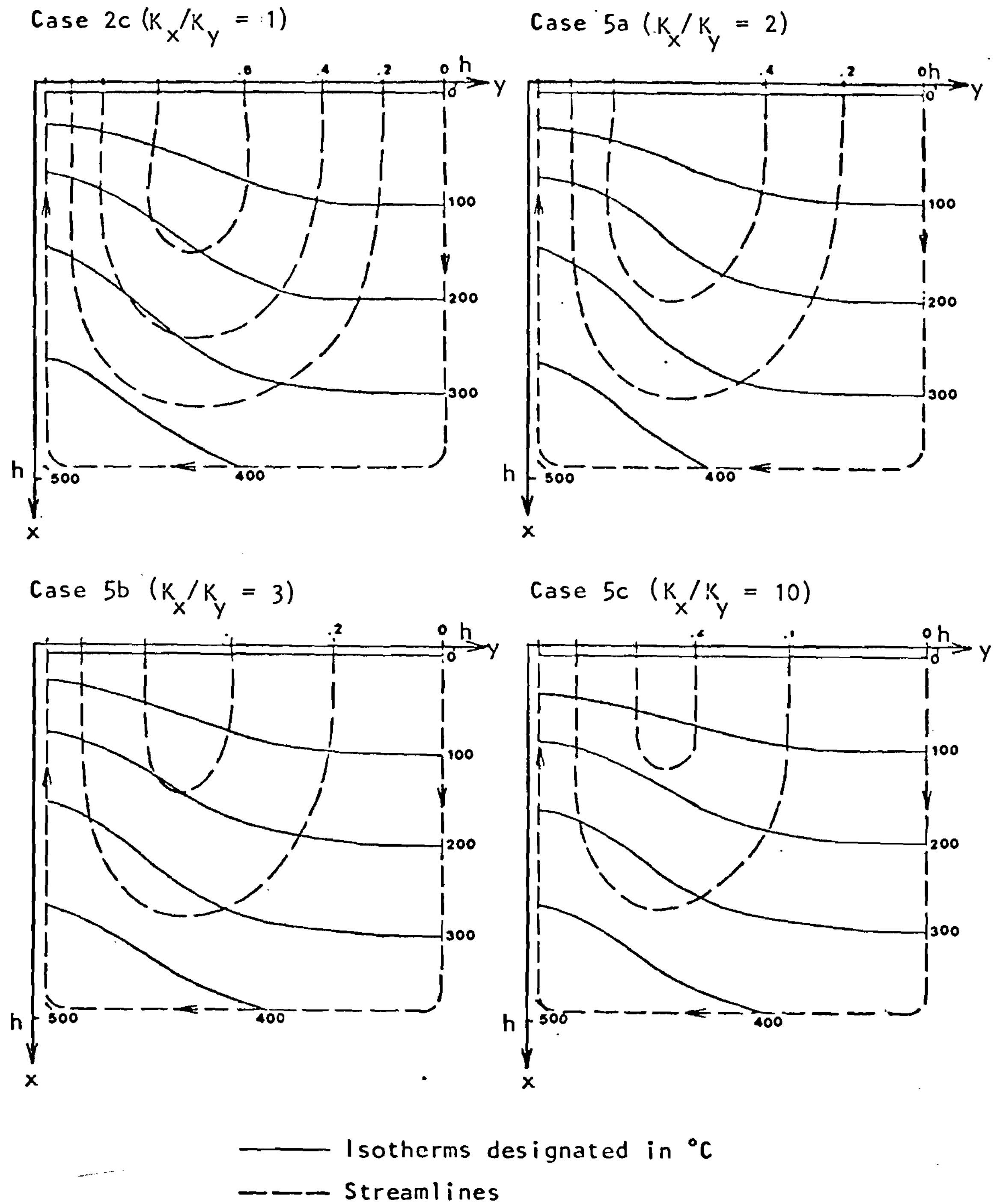

Figure 3d. Hydrothermal Fields for Four Values of Horizontal Permeability at t = 15000 Years.

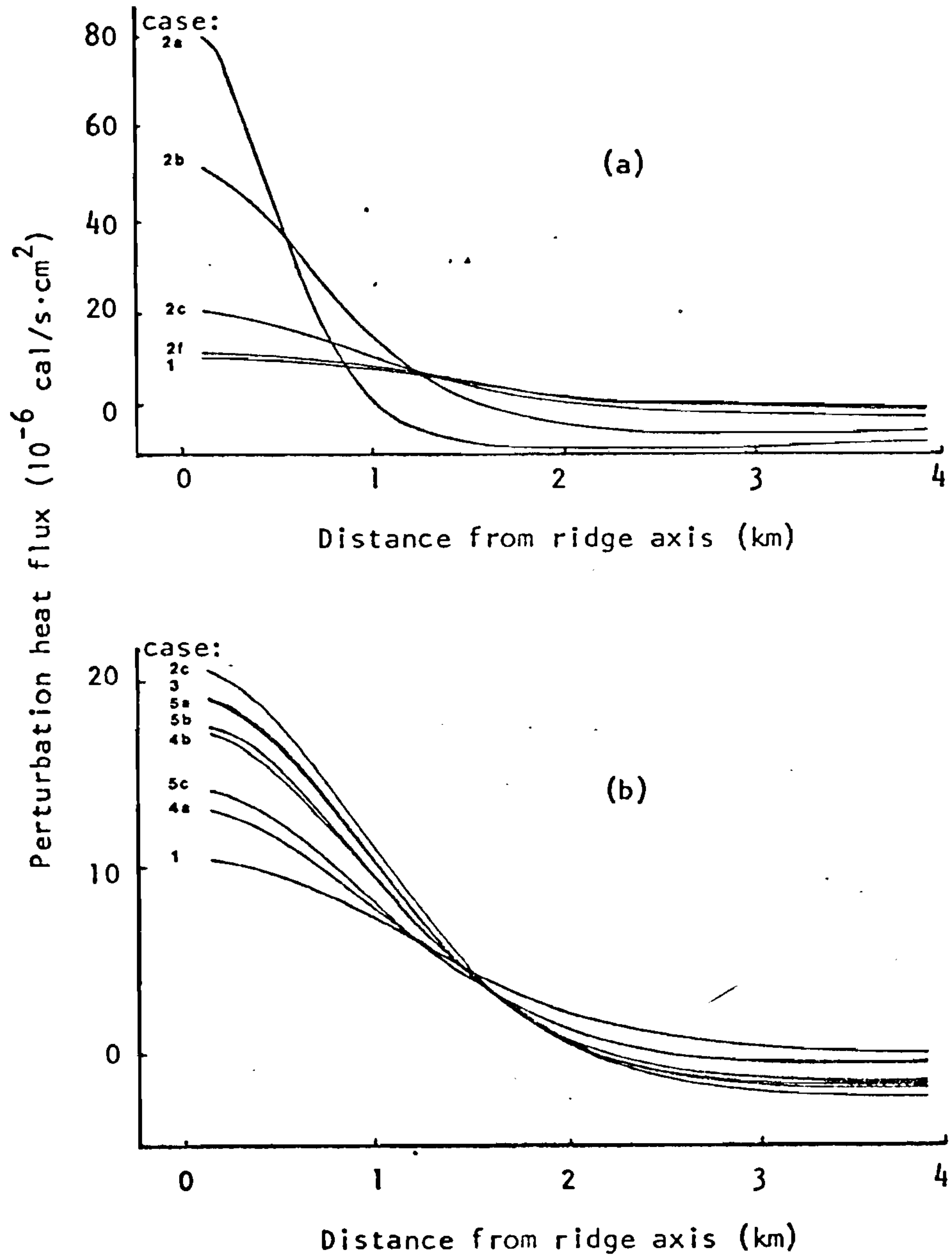

Figure 4. Perburbation Heat Flux through Top Boundary at t = 15000 Years.

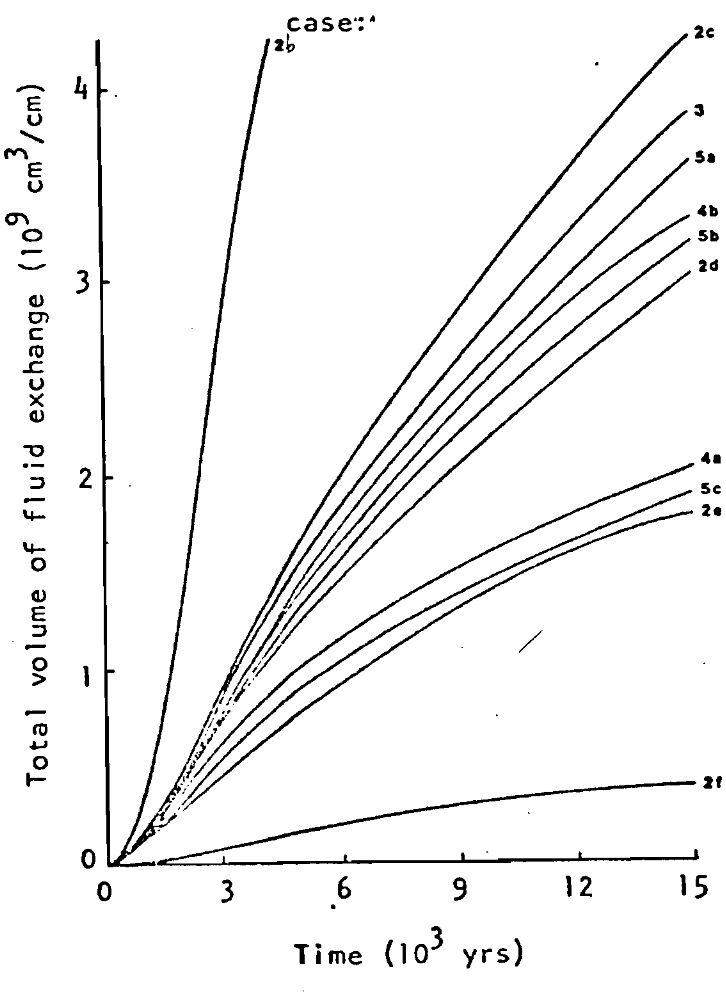

Figure 5. Total Volume of Fluid Exchange as Function of Time.

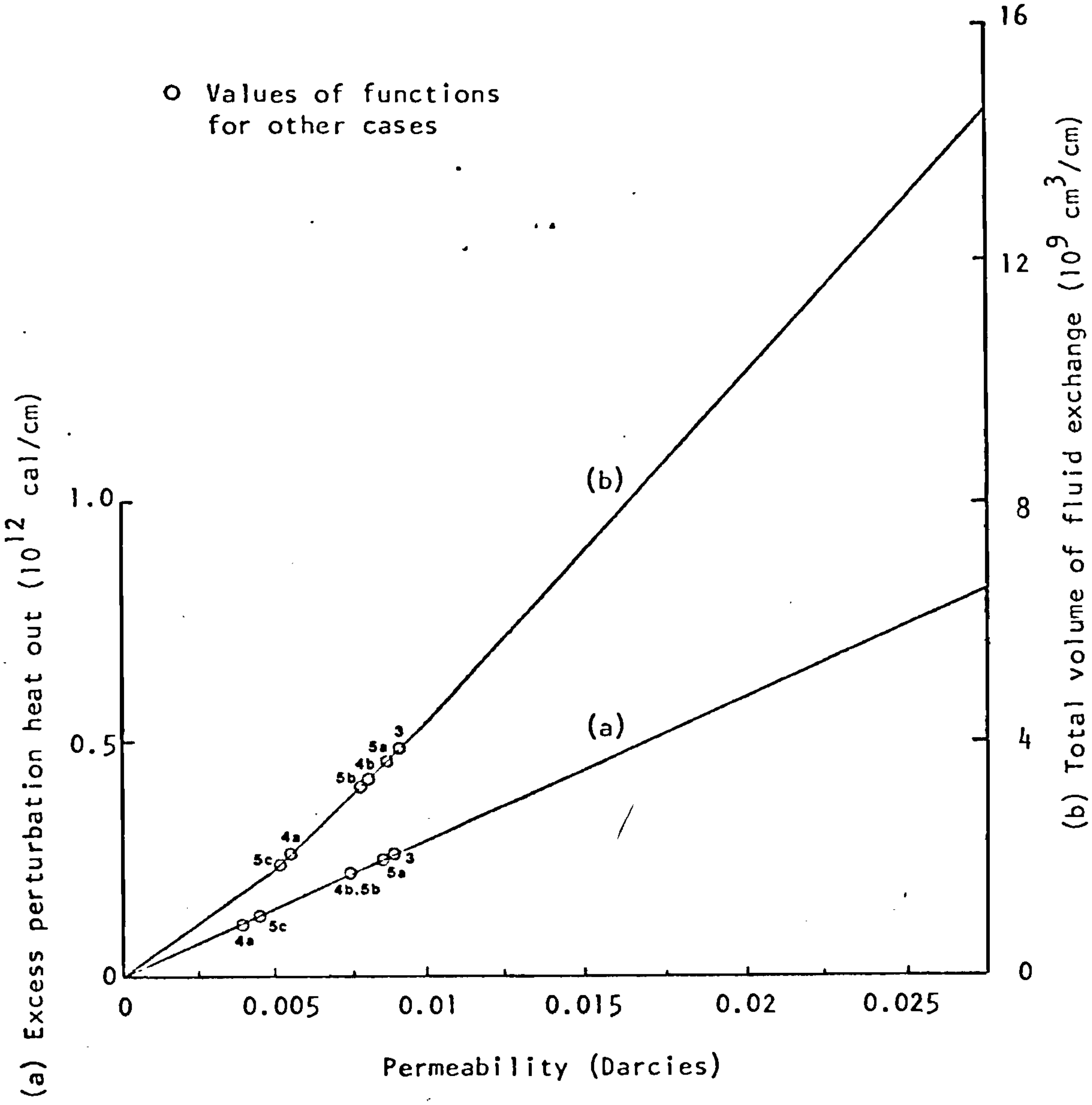

Figure 6. Perturbation Heat Conducted Out in Excess of That for Conductive Case and Total Volume of Fluid Exchange as Functions of Permeability for Cases 2b-f at t = 15000 Years.

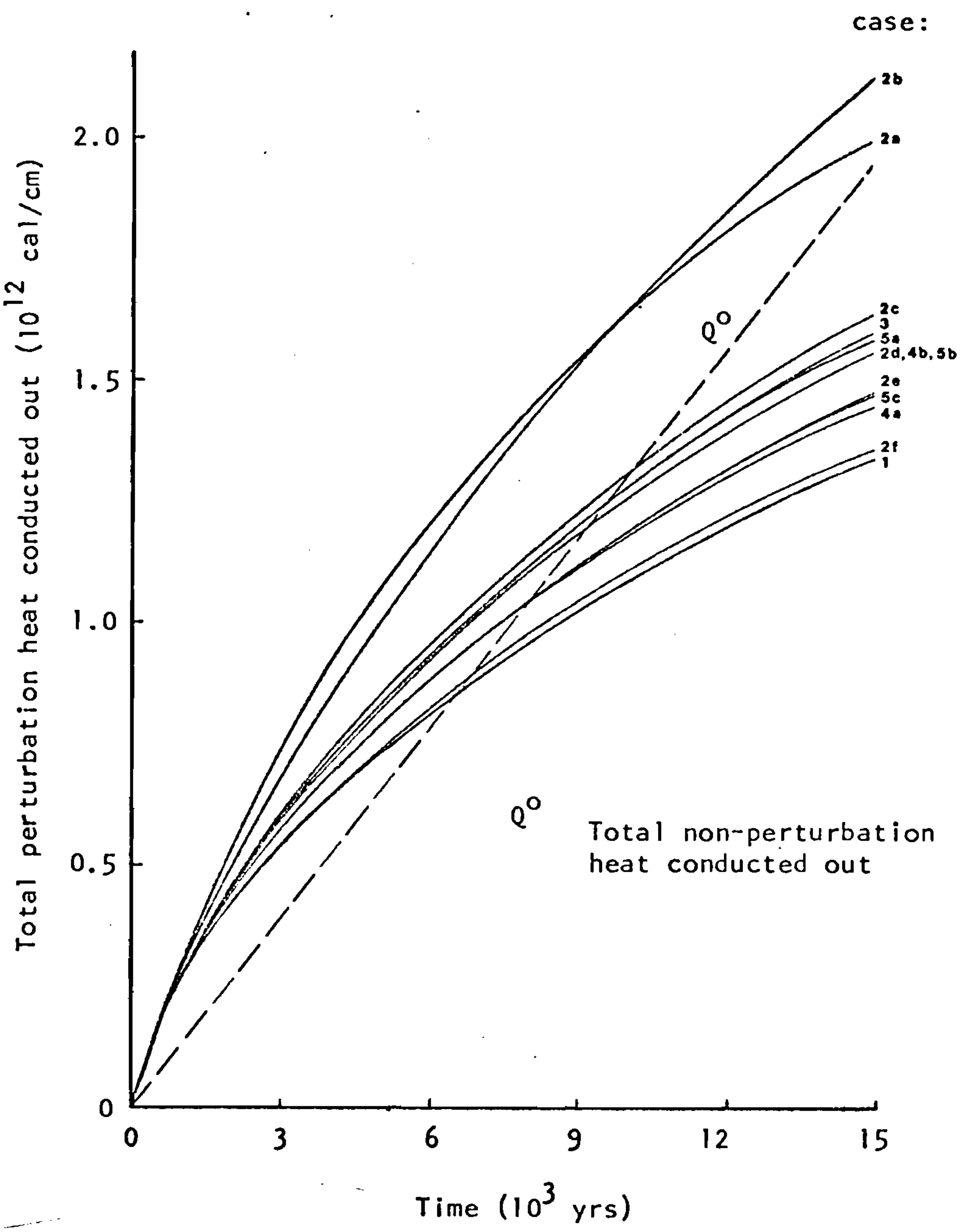

Figure 7. Total Perturbation Heat Conducted through Top Boundary as Function of Time. Total heat perturbation introduced by the intrusion is 5.64×10^{12} cal/cm.

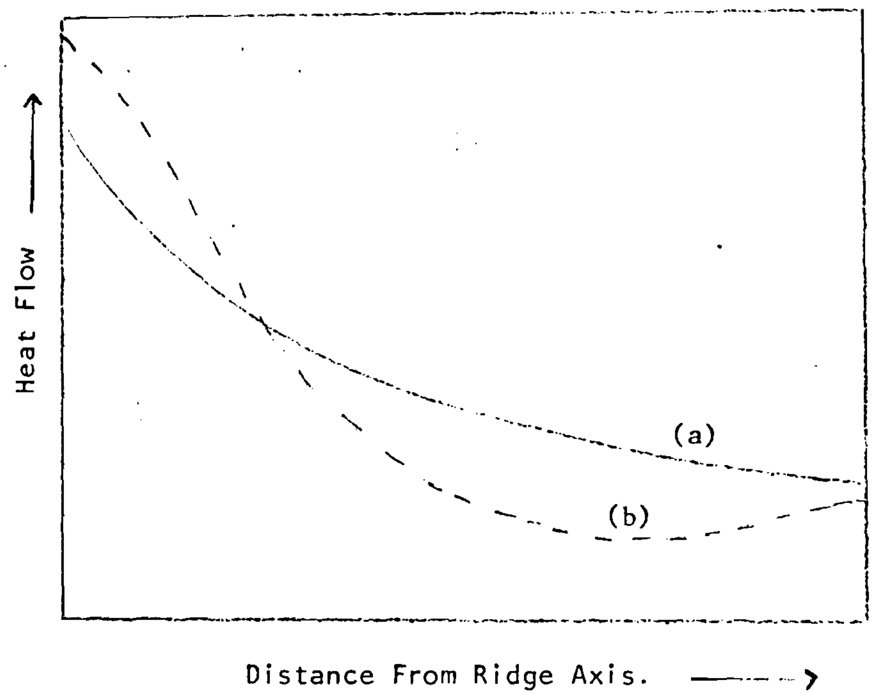

Figure 8. Qualitative comparison of surface heat conduction: a) conductive cooling case, b) general convective cooling case.

G-35-611

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF GEOPHYSICAL SCIENCES

Atlanta, Georgia 30332
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April 12, 1977

Central Processing Section
National Science Foundation
Washington, D. C. 20550

Attention: Dr. Donald F. Heinrichs, Director
Submarine Geology and Geophysics Program
Oceanography Section
Division of Ocean Sciences

Subject: Final Technical Letter Report on "Hydrothermal Circulation on Mid-Ocean Ridge Crests" (NSF Grant # DES 74-00513, Formerly GA-41195)

Dear Dr. Heinrichs:

Enclosed are 3 copies of NSF form 98-A, Summary of Completed Project, which should have been attached to the Final Technical Letter Report. I apologize for this oversight and hope that it has not caused great inconvenience.

Sincerely yours,

Robert P. Lowell
Assistant Professor

dc

Posted
SKB

NATIONAL SCIENCE FOUNDATION
Washington, D.C. 20550

SUMMARY OF COMPLETED PROJECT

Form Approved
OMB No 99R0013

Please read instructions on reverse carefully before completing this form:

1. INSTITUTION AND ADDRESS		2. NSF PROGRAM	3. GRANT PERIOD
Georgia Inst. of Technology		Submarine Geophysics	from 1/1/74 to 12/31/76
4. GRANT NUMBER	5. BUDGET DUR. (MOS)	6. PRINCIPAL INVESTIGATOR(S)	7. GRANTEE ACCOUNT NUMBER
DES74-00513 A01	36	Lowell	G35-611

8. SUMMARY (Attach list of publications to form)

Geological, geochemical, and geophysical data all have suggested that heat is transferred to the sea floor from young oceanic crust as a result of both conductive and convective processes. A significant amount of research had been done on conductive models; consequently, the purpose of this research has been to develop theoretical heat transport models involving convection of sea water in young oceanic crust.

The models have involved time-dependent finite-amplitude convection in permeable rock. The driving forces have included vertical temperature gradients and a combination of vertical and horizontal temperature gradients. Two extreme cases of permeability have been considered. In one case, the permeability has been assumed to be due to thin, widely-spaced, vertical fractures, connected by a horizontal contact zone. Such a fracture system, imbedded in impermeable rock, and opened to the sea floor, provided a circuit through which the sea water could circulate and transfer heat. In the second case, the permeability has been assumed to be due to very fine-scale fracturing so that a Darcy's Law approach to the fluid flow could be used. In this case, a range of constant permeability values, vertically decreasing permeability and anisotropic permeability have been considered. For both permeability models, the pertinent equations have been solved by the method of finite differences.

In the case of discrete fracture-controlled permeability the results have shown that thin fractures can carry a substantial convective flow and that the main effect of the circulation is to cool the crust down to the depth of the fracture system. A periodic arrangement of deep ($\sim$ 5 km), widely-spaced ($\sim$ 3 km) fractures a few millimeters wide and circulating for times of the order of 10^4 years could give rise to heat flow distribution similar to that observed on the Galapagos Spreading Center.

In the case of fine-scale permeability, the calculations have been focused on heat transfer within a few kilometers of a ridge axis and on the effects of periodic intrusions of hot material at the axis on thermal convection. The results have shown that if the periodicity of intrusions is 1.5×10^4 years (corresponding to slow spreading ridges), the Rayleigh number must be in excess of 250 to remove the added heat within 1.5×10^4 years. Moreover, one of the effects of convection is to redistribute the heat conducted through the upper surface; so that the conductive heat flux is enhanced near the axis and reduced away from the axis, relative to pure conductive cooling models. Thus low observed heat flow values may be partially due to redistribution of heat by convective flow.

Finally, in this project, the nature of small water temperature anomalies and their associated superadiabatic gradients in the ocean-bottom boundary layer have been interpreted in terms of a) buoyant thermal plume models and b) heat transfer in a turbulent boundary layer. The results have indicated that the thermal output of the TAG hydorthermal area may be of the same order of magnitude as some continental thermal zones and that even a small water temperature anomaly may indicate a significant convective heat loss from the cooling lithosphere. Energetic considerations have suggested that such temperature anomalies are probably transient phenomena.

9. SIGNATURE OF PRINCIPAL INVESTIGATOR/ PROJECT DIRECTOR	TYPED OR PRINTED NAME	DATE
	Robert P. Lowell	4/12/77

NSF Form 98A (5-76)

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).