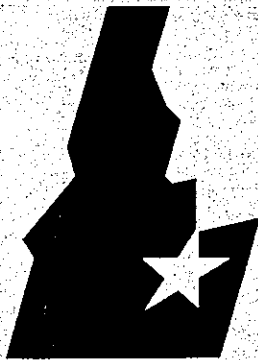


*For your retention*

EGG-NPR-10190

EGG-NPR-10790  
April 1992

*cy1*



**Idaho  
National  
Engineering  
Laboratory**

*Managed  
by the U.S.  
Department  
of Energy*

**PATENT CLAIM**

**HEAT FLOW MODELING OF THE  
SNAKE RIVER PLAIN, IDAHO**

~~APR 14 1992~~

*ILL 1-24-82*

PHOTOCOPY  
UNAUTHORIZED REPRODUCTION  
IS PROHIBITED. CONTACT  
EG&G IDAHO FOR  
FURTHER INFORMATION.



*Work performed under  
DOE Contract  
No. DE-AC07-76ID01570*

7  
8

9  
10

11  
12

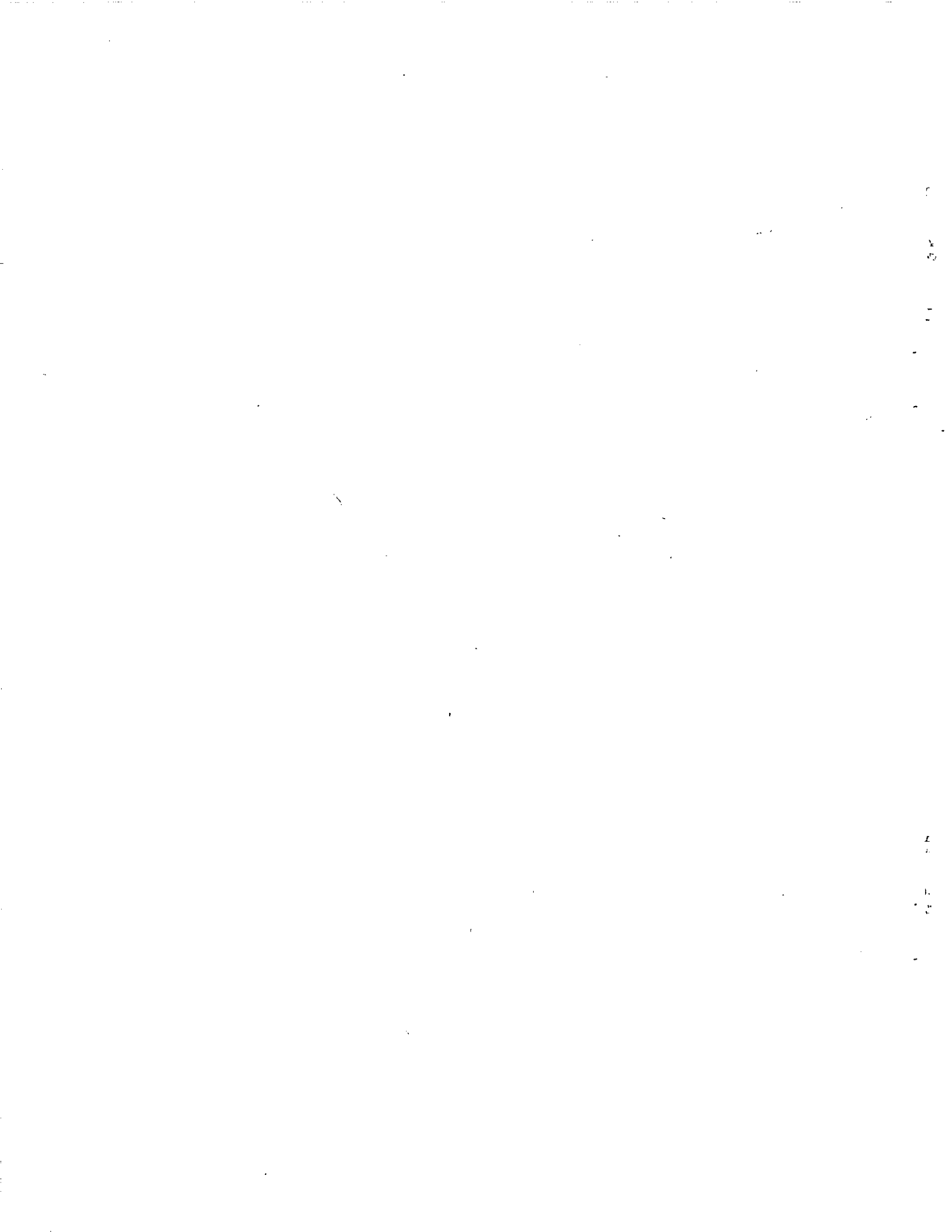
HEAT FLOW MODELING OF THE  
SNAKE RIVER PLAIN, IDAHO

by

David D. Blackwell  
Shari Kelley  
John L. Steele

Department of Geological Sciences  
Southern Methodist University  
Dallas, Texas 75275

Prepared for U.S. Department of Energy  
Office of New Production Reactors  
Under DOE Idaho Field Office  
Contract No. DE-AC07-76ID01570



HEAT FLOW MODELING OF THE  
SNAKE RIVER PLAIN, IDAHO

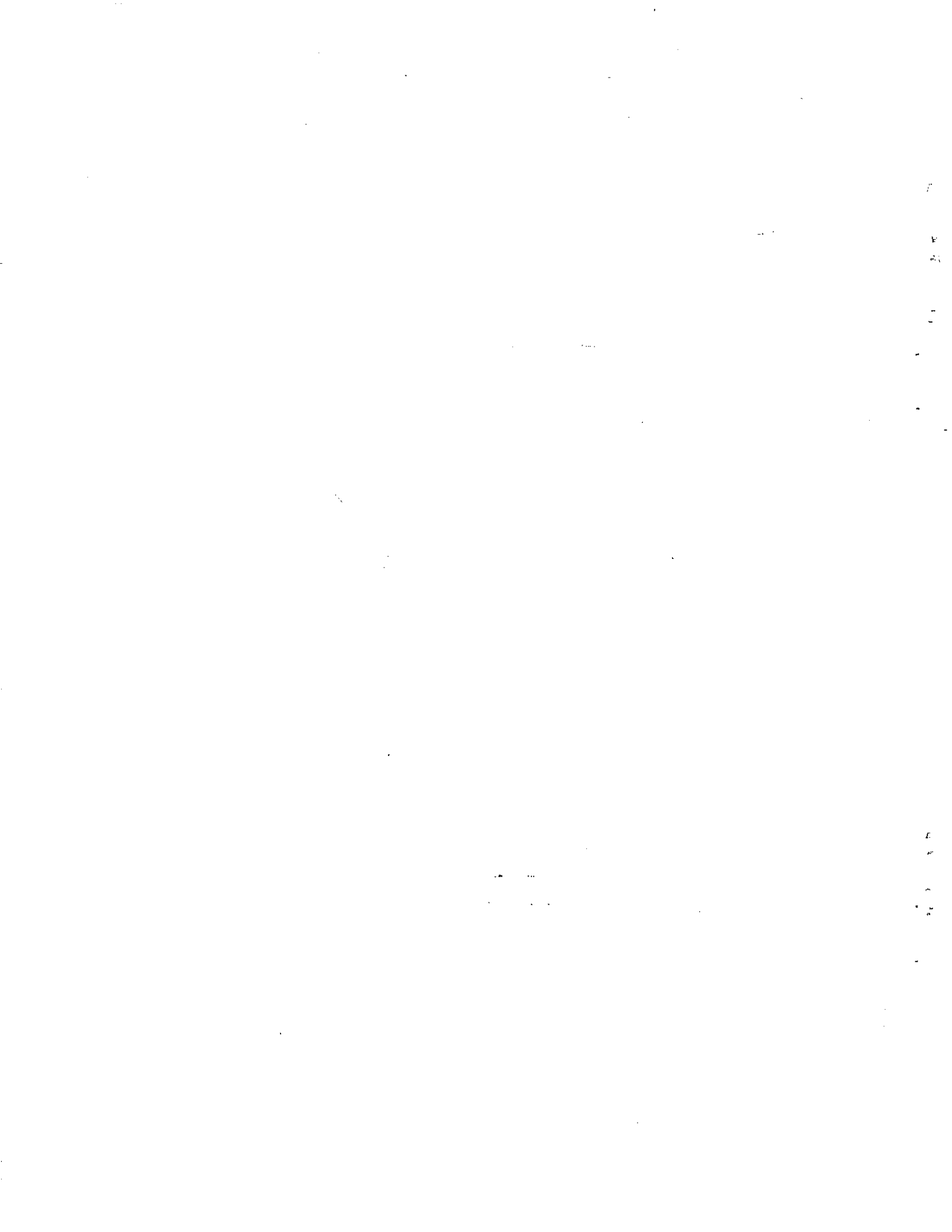
David D. Blackwell  
Shari Kelley  
John L. Steele

April, 1992

Department of Geological Sciences  
Southern Methodist University  
Dallas, Texas 75275

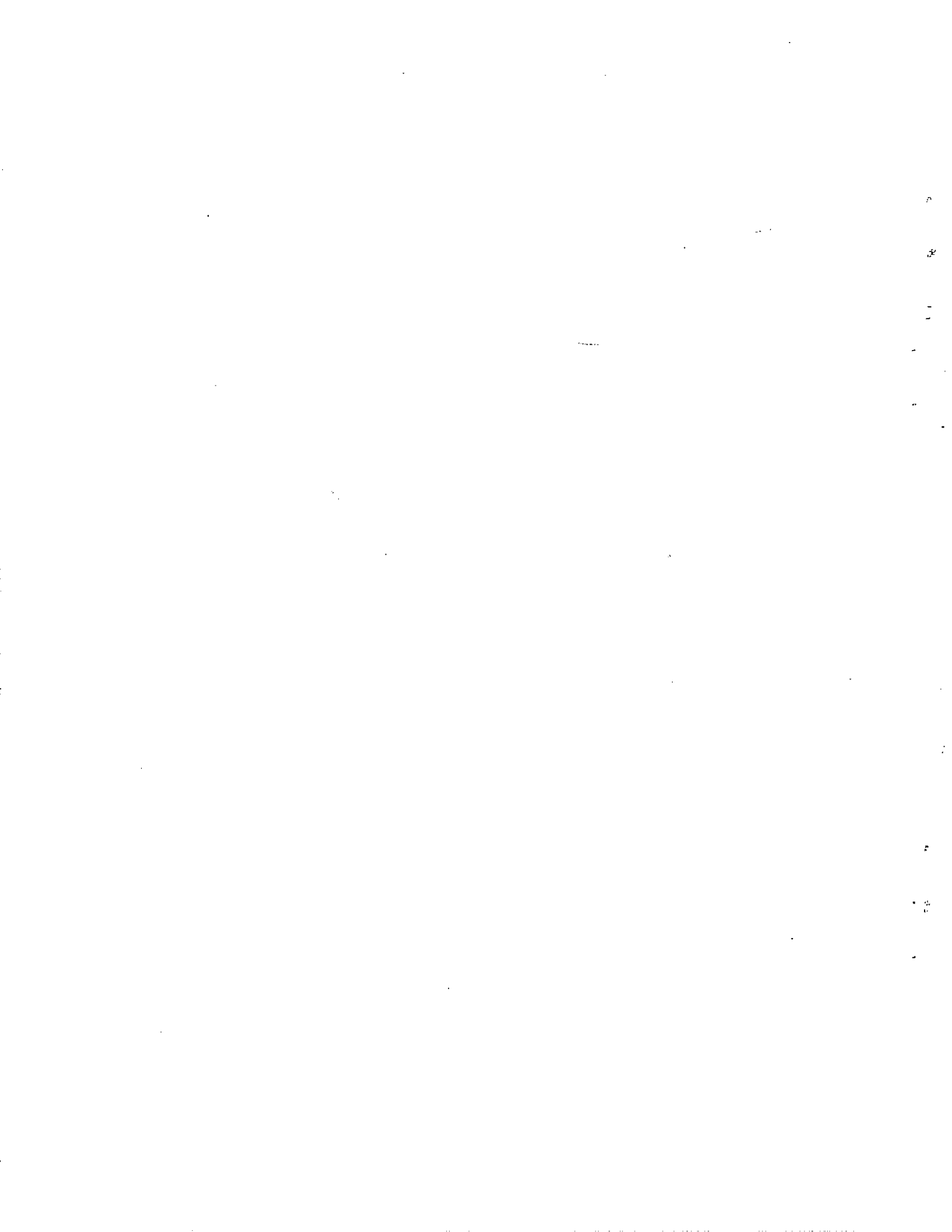


Prepared for the U. S. Department of Energy  
Office of New Production Reactors  
Under DOE Idaho field Office  
Contract DE-AC07-761DO1570



## ABSTRACT

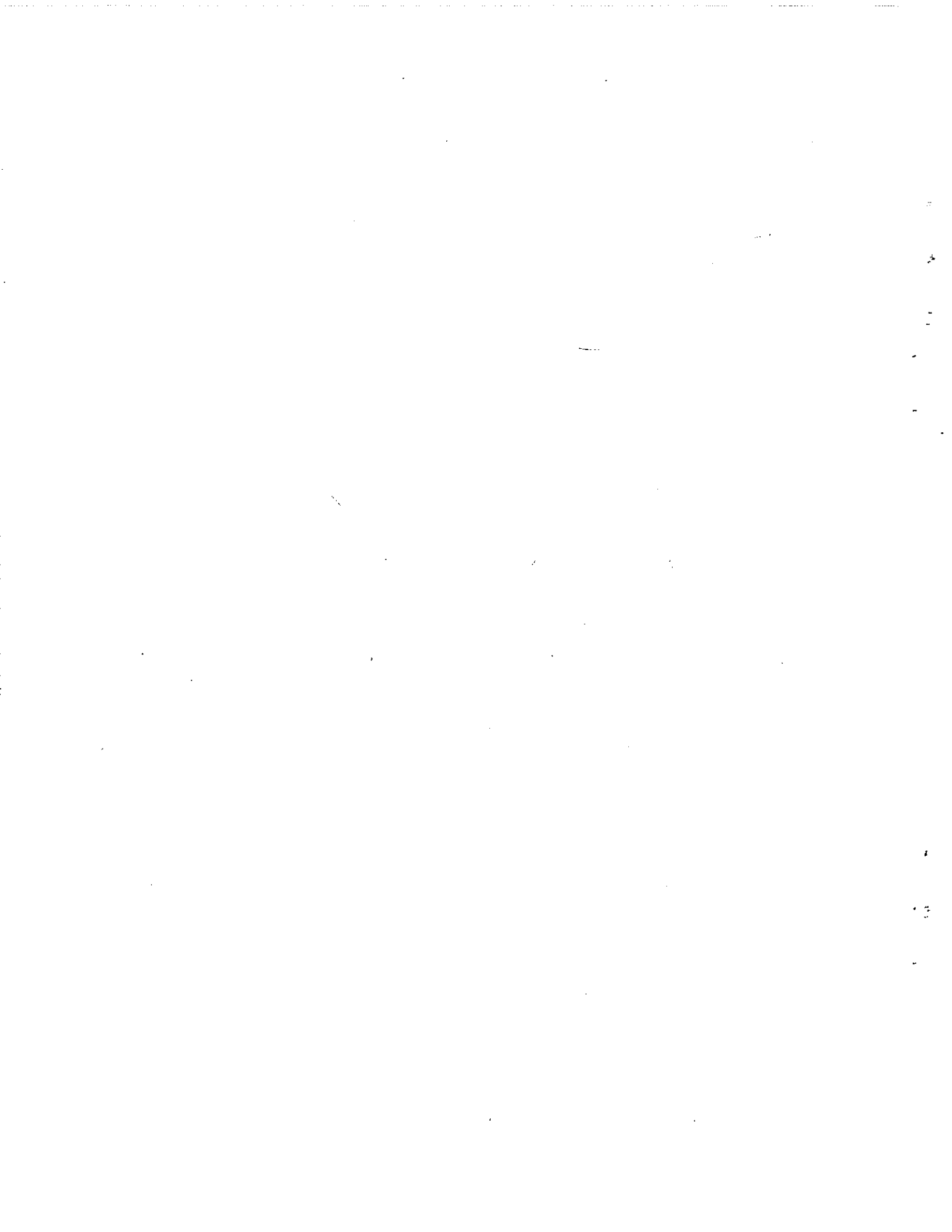
Heat flow data have been summarized for the Snake River Plain and vicinity, Idaho. In addition, new data have been collected and analyzed. The thermal data document that the heat flow and thus the crustal temperatures are higher in the Snake River Plain/Yellowstone region than in the surrounding provinces. The thermal effects of the passage of an energetic mantle hot spot beneath the region have been investigated with the aid of numerical modeling. Particular attention was focused on the lateral effects of the hot spot. The most intense thermal effects are associated with the center of the hot spot, which covers an area about 75 to 100 km in diameter and is centered at the present time on the Yellowstone region. There is evidence for thermal effects outside the apex of the hot spot, however. The heat flow data and the model results were compared with some aspects of the regional geology and geophysics. The implications of the thermal field on the rheology of the crust were investigated based on calculation of crustal strength envelopes. The weakest part of the lithosphere is the Basin and Range crust along the edge of the Snake River Plain/Yellowstone province. Because of this fact and because the stress and strain rate regimes inside the Snake River Plain/Yellowstone region are dominated by the thermal and igneous effects, stress and strain rate fields within the Basin and Range province may not have a strong influence on structures in the Snake River Plain.





## ACKNOWLEDGEMENTS

Special assistance in locating information on geothermal data was received from John Mitchell, Dennis Dunn, and Paul Castelin of the Idaho Department of Water Resources, R.E. Lewis, R.G. Whitehead and H.W. Young of the U.S. Geological Survey, Chuck Horsborough of the U.S. BLM, and William Pittman of the Idaho Department of Lands. Jack Barraclough of the U.S. Geological Survey (now at EG&G, Idaho) was a source of information on the Snake Plain aquifer in eastern Idaho. Roger Jensen of the U. S. Geological Survey made available the temperature logs for two wells at Butte City. John Knox and Edward Western of Sunedco made possible release of exploration information in southeastern Idaho. Exploration data in the eastern Snake River Plains and Island Park areas collected under the direction of Malcolm Mossman and Robert Crewdson was released by Oxy Geothermal Incorporated. Roger Bowers obtained the release of the northern margin thermal data. David Becker made the calculations of residence time versus temperature in the Snake River aquifer. Steve Mueller made the calculations of the crustal elastic effects of the Snake River Plain loading. Robert E. Spafford, Larry S. Carter, and David Crouch assisted in the various aspects of the laboratory and field studies. This study was funded by EG&G Idaho via contract EGG-C91-103450. In addition to the support for this study collection of data in central Idaho was supported by NSF-RANN Grant No. AER-76-00108 and NSF Grant No. GA-11351. Collection of data in the eastern Snake River Plains included in Table 2 was supported in part by NSF Grant No. EAR-8213156.



## CONTENTS

Introduction .....	1
Purpose and Scope .....	1
Previous Investigations.....	2
Geology of Idaho.....	2
Techniques of Heat Flow Measurement.....	7
Introduction .....	7
Water Circulation Disturbances .....	8
Data Table Description.....	8
Thermal Data North of Snake River Plain.....	14
Northern Idaho and Blue Mountains.....	14
Southern Idaho Batholith and Challis Section.....	14
Central Idaho Basin and Range .....	16
Thermal Conditions in Southwestern Idaho .....	17
Western Snake River Plain .....	17
Owyhee Uplands .....	22
Camas Prairie/Mount Bennett Hills.....	22
Thermal Conditions in the Eastern Snake River Plain .....	24
New Thermal Data.....	24
Snake River Plain Aquifer .....	25
Snake River Plain Aquifer Thermal Model.....	32
Comparison to Observed Data .....	33
Heat Flow Below Aquifer .....	40
Southeast Margin.....	44
Island Park Area.....	45
Thermal Conditions in Deep Wells .....	47
Regional Heat Flow.....	49
Thermal Conditions in the Southeastern Idaho Basin and Range.....	51
Thermal Modeling .....	57
Geological and Geophysical Constraints.....	57
Thermal Cross Sections .....	62
Other Models .....	75
Discussion .....	79
Topographic Evidence for Dimensions .....	79
Crustal Rheology.....	79

Contemporary Strain Field .....	84
Precusory Uplift.....	84
Conclusions .....	85
References .....	87
Appendix A. Temperature-Depth Plots .....	95
Appendix B. Discussion of Test Cases for RECTAN.FOR.....	102

# HEAT FLOW MODELING OF THE SNAKE RIVER PLAIN, IDAHO

## INTRODUCTION

### Purpose and Scope

A particularly important tool in the evaluation of the geothermal resources is the technique of heat flow. A heat flow study measures the heat which originates within the earth and flows out at the surface of the earth. A quantity which is measured as part of a heat flow study is the geothermal gradient or the rate of temperature increase with depth increase. Thus information relevant to the temperature in the crust is a natural outcome of the heat flow studies. In recent years it has been recognized that the temperature in the crust has a major effect on the strength of the crust and the nature of seismicity, thus the seismicity in the vicinity of the Snake River Plain will be affected by the heat flow and resultant temperatures.

As part of this study thermal data from various sources were collected and incorporated in the extensive database of heat flow and geothermal information for Idaho maintained at SMU. Between 1974 and about 1983 the geothermal resources of the State of Idaho were the subject of extensive heat flow studies to evaluate the energy potential they represent. Most of the data collected to 1980 have been published, but data collected since that time have not. In addition extensive commercial geothermal and hydrocarbon exploration took place in Idaho in the early 1980's as a result of the energy crisis. A large amount of this data was filed with various government offices and confidentiality time limits have passed and/or the data have been released by companies. Thus a large component of the new data discussed in this report is from these types of sources. Of special interest for this study are thermal data from several deep wells south and east of the Snake River Plain. In addition a program of logging of wells of opportunity was carried out. A number of wells in areas not previously studied were logged. Finally a deep well was drilled on the INEL site and preliminary thermal measurements were made in that well.

Idaho has a diverse geology and many volcanic and tectonic processes have been active within the environs of the State over the last few million years, particularly in the southern part of the State. The objectives of this study are to review existing and to process new thermal data for the eastern Snake River Plain and vicinity, and to evaluate the validity of the propagating hot spot concept as a basis for the modeling of the crustal thermal structure. Further the goals of this investigation are to evaluate the temperature conditions in the Snake River Plain compared to the surrounding Basin and Range province and to determine the possible significance of the thermal effects on the stress regime and earthquake potential of the eastern Snake River Plain. The results of this study can also be used as constraints for regional tectonic interpretations and, because of the ability of moving water to transport heat, the study

also furnishes information on flow of water in regional aquifer systems. Thermal data measured during this project and geothermal exploration data not previously published from 68 wells are presented. In addition bottom hole temperature measurements from a number of hydrocarbon exploration wells are summarized. Samples (core or cuttings) were collected from many of the holes for thermal conductivity measurements (the property of the rock which measures its ability to conduct heat) and those data are presented here also.

Some of the wells were drilled for the specific purpose of geothermal evaluation. Most of these exploration holes were drilled to depths on the order of 100 to 150 m. The holes which were drilled for geothermal studies were logged for gradients and core or cutting samples were generally obtained for thermal conductivity measurement. In addition, several deep geothermal, hydrologic, and hydrocarbon exploration tests have been drilled in Idaho during the last few years. Thermal results from some of these holes will be used because of the information they contribute to the deep thermal conditions.

#### Previous Investigations

The Snake River Plain (Figure 1) has been a focus of several heat flow studies (Brott and others, 1976, 1978, 1981; Blackwell, 1988, 1989). The other published heat flow studies dealing with Idaho have been local in nature (Sass and others, 1971; Urban and Diment, 1975; Nathenson and others, 1980). An extensive study of the western Snake River Plain was presented by Smith (1980, 1981). In addition several reports of geothermal potential emphasizing well and spring temperatures have been published (Ross, 1971, Mitchell and others, 1980). Reports dealing with specific areas will be discussed in appropriate sections of this report. The electrical resistivity of the crust has been investigated by Stanley (1982).

### GEOLOGY OF IDAHO

The State of Idaho can be divided into a number of different physiographic provinces. The relevant areas for this report are the southern provinces (solid lines) and subprovinces (dashed lines) shown in Figure 1. The provinces of interest north of the Snake River Plain are the Blue Mountains, the Southern Idaho Batholith and its Challis subdivision, and the Central Idaho Basin and Range province. The Snake River Plain is divided into four different areas consisting of the Western Snake River Plain, the Eastern Snake River Plain, the Camas Prairie/Mount Bennett Hills, and the Island Park region. South of the Snake River Plain two physiographic divisions, the Owyhee Uplands and the Southeast Idaho Basin and Range, are considered as separate areas for the purposes of this report.

The geologic features of these various provinces are well known. Within Idaho the mid-Miocene Columbia Plateau basalts lie on an older basement of Mesozoic sedimentary and igneous rocks

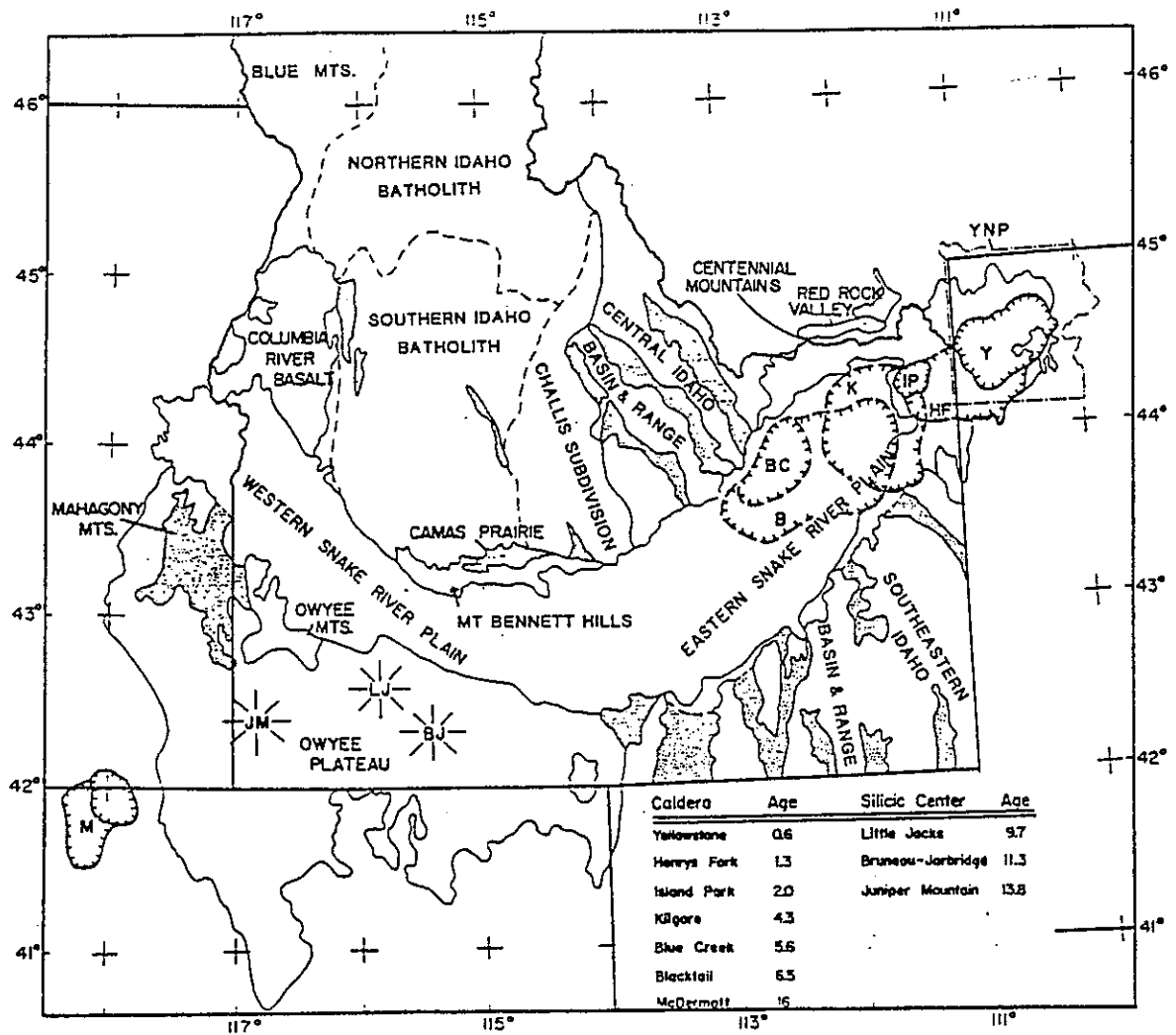


Figure 1. Physiographic province map of southern Idaho. Boundaries of major provinces are shown as solid lines, subprovinces are shown as dashed lines. The dot pattern indicates primarily alluvial-filled Basin and Range type valleys intersecting the Snake River Plain and those associated with it (Red Rock Valley, Camas Prairie and Mahogany Mountains). Location of ages of major silicic volcanic centers associated with the proposed hot spot as summarized by Malde (1991) are shown.

in the Blue Mountains and the Wallowa Mountains. The Southern Idaho batholith and the Challis sections of the Northern Rocky Mountains are composed almost exclusively of granitic and volcanic rocks. The plutonic rocks are predominantly Mesozoic in age, although an extensive early Cenozoic (Eocene) plutonic episode has also been recognized (Armstrong and others, 1975; Criss and others, 1983, 1984). The Challis region contains the eastern part of the Idaho batholith and has extensive exposures of volcanic rocks associated with this Eocene magmatic activity. These volcanic rocks sit on a complex basement of Mesozoic granitic rocks and Paleozoic to Precambrian sedimentary and metamorphic rocks. The area is crosscut by numerous linear valleys with diverse orientations. The orientation of these valleys is related to differential erosion along faults and/or zones of fracturing. This area is characterized by extensive hot spring activity that is focused along some of these major linear zones. Because of this distribution the heat flow data from the southern Idaho batholith are listed separately in Table 1.

A major portion of the Northern Rocky Mountain province in Idaho is identified as the central Idaho Basin and Range subprovince. This area is composed of Basin and Range topography and structure with high relief ranges separated by alluvial valleys. The general trend of the topography is northwest/southeast. The youthfulness of the ranges in this area is clearly indicated by the numerous young fault scraps (see summary by Crone and Haller, 1991, and paper by Turko and Knuepfer, 1991, for example) and the occurrence of the magnitude 7.3 Borah Peak earthquake beneath the Lost River valley near Mackay on October 28, 1983 (Dosier and Smith, 1985; Scott and others, 1985). The bedrock of the ranges consists of folded and thrust faulted Paleozoic and Precambrian sedimentary rocks. The structure and hydrology of this area is extremely complex.

The Snake River Plain province comprises the area of southern Idaho modified by a moving hot spot during the late Cenozoic. As a major igneous/tectonic event propagated eastward at a rate of approximately 3.5 cm/year (Christiansen and Lipman, 1972; Armstrong and others, 1975; Rogers and others, 1990), a predictable sequence of geologic events related to the response of the continental lithosphere to the passage of a very energetic thermal event (Brott and others, 1978) followed. Large scale silicic ash flows and associated caldera systems similar to those that are now characteristic of the Yellowstone Plateau formed initially. Subsequent to the passage of the hot spot, the area began to subside due to thermal contraction and basaltic volcanism became dominant. The result was an extensive plain covered by as much as 1 kilometer of basalt. This stage is represented by the eastern Snake River Plain. The site of the youngest stage of silicic volcanism now mostly covered by basalt is the area directly west of Island Park. The calderas formed during this episode of silicic volcanism between 2 and 5 MY ago have been described by Morgan and others (1984). Following continued subsidence, deposition of lacustrine and fluvatile sediments occurred in the trough resulting in the formation of a deep sedimentary basin associated with minor basaltic volcanic activity (Newton and Corcoran, 1963). This area is now represented by the Western Snake River Plain. Capture of the



TABLE 1. Average geothermal gradient and heat flow values for the various provinces. Updated from Brott and others (1981) as noted.

Province	Geothermal Gradient (°C/km)	Heat Flow (mWm <sup>-2</sup> )	Number
Northern Idaho			
Granite (14)	22±1	65±3	23
Basalt (9)	40±10		
Southern Idaho Batholith (Excluding SRP Margin and Geothermal Systems)	27±3	77±4	12
Wieser Area	56±5	79±7	19
Western Snake River Plain	69±3	99±4	80
Owyhee Plateau	51±4	98±7	23
Eastern Snake River Plain			
Northern Margin			
Brott and others	55±9	93±13	23
Present study-all data	61±11	109±16	17
Present study-highs out	50±6	90±9	15
Southern Margin			
Brott and others	71±7	113±11	80
present study-new data		88±23	8
Above Snake River Aquifer	18±2	27±4	125

Snake River in the last 2 Ma by the Columbia River drainage has resulted in lowering of the base level so that the trough is no longer collecting sediments (Malde, 1991). Within this simple framework there are many complexities, however. For example there are two "anomalous" east-west trending range and valley areas associated with the Snake River Plain. These are the Camas Prairie-Mt. Bennett Hills area in central Idaho, and the Centennial Mountains-Redrock Valley area of southwestern Montana.

These seemingly disparate physiographic areas are related to one another by their unusual crustal structure (see Blackwell, 1989). A typical crustal section, based on gravity and refraction experiments (Hill, 1963; Hill and Pakiser, 1965; Braile and others, 1982; Mabey, 1976, 1978) consists of an unusually thick lower crust and an unusually thin upper crust. The unique feature of the crust which underlies the Eastern Snake River Plain, Western Snake River Plain, the Owyhee Plateau, and which may be evolving under the Yellowstone region, is that it is unusually thick and mafic, even though the Snake River Plain has been interpreted as an extensional feature (rift valley). The crust is thicker because during passage of the continent over the hot spot a large intrusive body (probably of grabbroic composition) has been emplaced in the mid to lower crust. This mafic intrusive body has differentiated and also partially melted the lower and middle crust and as a result extensive magma chambers and calderas have formed in the upper crust (Brott and others, 1978, 1981; Leeman, 1982a). As part of this process, there may have been a small amount of extension as well as significant density changes associated with erosion, and with loss of the light granitic component of the crust due to voluminous ash flow expulsion (Brott and others, 1981). So as the crust (and underlying mantle) cools following the passage of the hot spot, thermal contraction may be responsible for as much as two to two-and-a-half km of subsidence, although simple analysis is complicated in the west by the formation of the sedimentary basin. The actual observed topographic surface west of Yellowstone is approximately exponential in form and drops over 1.5 km.

South of the Snake River Plain there are two major physiographic provinces, the Owyhee Uplands on the west and the southeastern Idaho Basin and Range province on the east. The Owyhee Uplands consists of an extensive volcanic plateau of late Cenozoic ash flows and basalts sitting on top of an essentially unknown basement. Relief is relatively subdued and tectonic activity in the last few million years has been relatively minor. Malde (1991) points out that this province represents a southwestward continuation of the Snake River Plain silicic volcanism associated with the hot spot track (the sites and ages of major silicic volcanism are shown on Figure 1).

The southeastern Idaho Basin and Range province is an area of complicated geology and active tectonics. The effects of late Cenozoic Basin and Range normal faulting are superimposed on the Northern Rocky Mountain thrust-fault terrain of late Mesozoic to early Cenozoic age. Sedimentary rocks of Mesozoic to Precambrian age are involved in the thrusting. The geology and hydrology of this area are extremely complex, and are of great interest at the moment. Several significant hydrocarbon discoveries have been made in the Utah portion of this province in recent years and several deep

exploration tests have been drilled in Idaho so that some information on the deep thermal character of the area is available (Ralston and Mayo, 1983). The province is crossed by the Intermountain Seismic Belt (Smith and Sbar, 1974; Arabaz and others, 1980; Smith and Arabaz, 1991) along its eastern margin. Very young volcanism has occurred in this province. The rocks are both basaltic and rhyolitic in composition and cover extensive areas near Grey's Lake and Blackfoot Reservoir.

## TECHNIQUES OF HEAT FLOW MEASUREMENT

### Introduction

In a thermal study of an area there are three quantities of interest. Two of these are measured and the third is calculated from measurements of the first two. The three quantities are: temperature gradient, thermal conductivity, and heat flow. In order to obtain the heat flow measurement the geothermal gradient, the rate of temperature increase with depth, and thermal conductivity of the rocks must be known. The gradient is obtained from measurements of temperature as a function of depth in drill holes. Thermal conductivity measurements must be made in the laboratory on core or cutting samples from a well or from representative outcrop samples. The laboratory technique used in this study is the divided bar measurement for core and cuttings samples (Birch, 1950; Sass and others, 1971). The units used for thermal conductivity are Watts per meter per degree Kelvin ( $\text{Wm}^{-1} \text{K}^{-1}$ ).

Disturbances to the geothermal gradients may arise from topographical features, circulation of water, temporal changes in the mean ground surface temperature, and temperature anomalies at the surface resulting from contrasts in vegetation (Blackwell and others, 1980). The geothermal gradient may also vary because of complexities in geology reflected as lateral thermal conductivity variations. In much of the Snake River Plain and the Owyhee Plateau (Figure 1), the topographical, cultural, and vegetation disturbances are moderate and do not have significant effects on the temperature gradients. In the mountainous regions of central and northern Idaho, however, such effects cause significant gradient perturbations. Terrain corrections have been made to the holes in areas where the effects are significant. In the heat flow data tables a column titled "corrected heat flow" includes values that have been adjusted for terrain effects (if needed). Most of the heat flow determinations were made in relatively flat lying rocks or in regions of homogeneous rocks such as the granite of the Idaho batholith, therefore disturbances in gradient due to geological complications are usually small.

The units used in the present report are based on the SI system. Conversions to the cgs system of units are  $41.84 \text{ mWm}^{-2}$  equal 1 HFU, etc. In SI units the worldwide average heat flow is about  $60 \text{ mWm}^{-2}$ . Typical low values of heat flow are 20 to  $40 \text{ mWm}^{-2}$  and typical high values of heat flow are 80 to  $120 \text{ mWm}^{-2}$ . Values greater than about  $120 \text{ mWm}^{-2}$  are not usually found except in geothermal areas. The sources of all of the data collected as part of this study are listed in Appendix A.

## Water Circulation Disturbances

Disturbances in geothermal gradient due to the circulation of water cannot be easily eliminated. This situation is particularly difficult because many of the holes used for heat flow determination in Idaho were originally drilled as water wells. Thus there is a possibility of water being naturally in motion in these areas. In fact the shallow thermal measurements in the eastern part of the Snake River Plain give more information on water circulation than they do on the regional temperature gradient and heat flow coming conductively from the interior of the earth.

Regional water disturbances are caused by naturally occurring water movement in and between major aquifers due to differences in piezometric levels along and between the aquifers. For example, low temperature water may enter an aquifer from the surface, causing the geothermal gradient to be decreased above the aquifer because the lower temperature water absorbs heat and transports it downward or laterally in the aquifer. In other areas down gradient the water flow may be up, i.e. the deeper aquifers may have positive potential heads. In wells where upflow occurs the geothermal gradient below the aquifer will be higher than the regional value of the geothermal gradient, while in the aquifer the gradient will be lower than the regional value (see Domenico and Palciauskus, 1973, for some simple models). Regional water circulation effects will cause similar disturbances in all wells in the same region. In other areas high temperature water from depth may enter a shallower aquifer along a fault or fracture zone and cause the geothermal gradient to be anomalously high above the shallower aquifer. These phenomena are clearly shown in some areas of the Eastern Snake River Plain discussed below.

## Data Table Description

The data are presented in two tables discussed below. Wells are identified by both township-range-section and by latitude and longitude in the tables. The township range and section numbering system used by the Idaho Department of Water Resources and the U.S. Geological Survey in Idaho is used in this report. The section number is followed by up to three letters which indicate the quarter section, the 40 acre tract, and 10 acre tract, respectively. One or more numerals representing the serial number of the well within the tract may be occasionally included. Quarter sections are lettered A, B, C, D, in counterclockwise order from the northeast quarter of each section. Within the quarter sections 40-acre and 10-acre tracts are lettered in the same manner. Well 7S/19E - 23CAC is in the SW 1/4 of the NE 1/4 of the SW 1/4 of Section 23, Township 7 South, Range 19 East.

In addition, the name of each hole as shown, as is the tectonic province. The depth interval over which the geothermal gradient and heat flow were calculated is indicated. In holes that did not have a uniform gradient with depth, gradient and heat flow over several intervals are given. In cases where the

change in gradient coincides with variations in conductivity, a higher level of confidence is assigned to the calculated heat flow value. Where variations do not correspond to changes in conductivity, non-conductive influences on the heat flow data or errors in gradient or thermal conductivity values are indicated. Average thermal conductivity values and the number of thermal conductivity measurements used to calculate the average values for some holes are also shown in the tables. Thermal conductivity values in parenthesis are assumed values based on knowledge of the rock type and/or measurements on the same rock type in nearby wells or from surface samples. Since many of the measurements of thermal conductivity were made on cuttings, a major potential error source for the thermal conductivity values is a lack of knowledge of the *in situ* porosity of the rocks (Sass and others, 1971). Columns for corrected and uncorrected gradient, and corrected heat flow are presented. The values in the corrected gradient column indicate the gradient after corrections have been made for topographic effects. Calculated standard error values are provided for the uncorrected gradient.

In cases where both the corrected heat flow and uncorrected heat flow values are the same, the topographic effects were calculated or estimated to be less than  $\pm 5\%$ . The topographic corrections were made by the technique discussed by Blackwell and others (1980). Almost all of the measurements outside the Snake River Plain required terrain corrections. The error of these corrections is approximately  $\pm 10\%$  of the correction. The total error in most cases will be less than  $\pm 5\%$  of the corrected heat flow. No statistical error is given for corrected heat flow values because it is difficult to establish reasonable error limits that take into account the many environmental factors that might affect heat flow. Overall error estimation is given qualitatively in the column to the right of the corrected heat flow. Sites which are estimated to have heat flow values with an error of  $\pm 5\%$  or less are of A quality, sites with estimated error of  $\pm 10\%$  or less are of B quality, and sites with estimated errors of  $\pm 25\%$  or less are of C quality. Data indicated by a G are within a geothermal system and do not reflect regional heat flow values. If no information was available on the lithology of the hole so that no heat flow can be calculated, the heat flow column is blank. A brief lithologic summary for each hole is included and the age of the rock units is given when known. In a few cases the data values for the sites shown in Table 2 will be different from published values due to collection of additional data and/or changes in interpretation based on new information. Thus these values supersede the results of the five published reports. Data published since the compilation of Brott and others (1981) are also included in this table.

TABLE 2. Thermal data from Urban and others (1986), (points with asterisks), and Blackwell (1988-unpublished).

TWN/RNG SECTION	N LAT DEG MIN	W LONG DEG MIN	HOLE (DATE)	COLLAR ELEV (m)	DEPTH RANGE (m)	AVG TCU <SE> (W/m/K)	UN GRAD <SE> (°C/km)	CO GRAD <SE> (°C/km)	CO H.F. <SE> (mW/m <sup>2</sup> )	Q HF	LITHOLOGY SUMMARY
13N/39E 9ACC	44-28.38	111-51.85	OXY-5B 0/ 0/77	2009	30.0 40.0 60.0 82.0	(1.88)  (1.88)	32.8 3.6 9.1 5.6	32.8  9.1	63  17	G  G	RHYOLITE
13N/40E 10CDB	44-27.80	111-43.90	OXY-6B 0/ 0/77	1981	15.0 95.0 95.0 135.0	(1.88)  (1.38)	65.5 5.5 38.2	65.5  38.2	121  54	G  G	RHY 1-82
13N/42E 22CAD	44-26.10	111-29.35	OXY-20 0/ 0/77	1951	10.0 100.0 100.0 150.0	(1.63)  (1.63)	14.6  25.5	14.6  25.5	25  42	D  D	BASALT 0-140 RHY 140-152
13N/42E 24DAD	44-26.09	111-26.25	WW-1PB2 6/24/77	1923	10.0 38.0	(1.88)	189.3 36.4	189.3	310	G	BASALT
13N/42E 25ABC	44-25.64	111-26.95	WW-1PB1 6/17/77	1926	15.0 38.0	(1.88)	121.9 9.1	121.9	201	G	SILICIC VOL
12N/44E 10BBC	44-23.00	111-15.00	OXY-18 0/ 0/77	1939	10.0 175.0 175.0 280.0	(1.88)  (1.88)	  12.7	  12.7	  25	X  D	RHYOLITE
12N/38E 19DAC	44-21.03	112- 0.92	OXY-4 0/ 0/77	1882	10.0 125.0 125.0 143.0	(1.88)  (1.88)	21.8  67.3	21.8  67.3	42  126	D  D	RHYOLITE
12N/36E 24BAD	44-20.95	112- 9.20	OXY-2 0/ 0/77	1820	60.0 150.0	(1.88)	41.9 3.6	41.9	79	C	RHY 2-90 BASALT TO TD
12N/36E 34ABC	44-19.75	112-12.13	OXY-1 0/ 0/77	1768	40.0 89.0	(1.88)	29.1	29.1	54	C	RHYOLITE
12N/42E 36CCB	44-19.20	111-27.25	OXY-19 0/ 0/77	1867	100.0 180.0 180.0 350.0	(1.63)  (1.88)	52.8  65.5 1.8	52.8  65.5	88  109	B  B	BASALT 5-274 CLAY 274-303
11N/41E 148AB	44-17.30	111-35.35	OXY-15 0/ 0/77	2070	40.0 96.0	(1.63)	9.1	9.1	17	X	NO RETURNS

TABLE 2. (continued) Thermal data from Urban and others (1986), (points with asterisks), and Blackwell (1988-unpublished).

TWN/RNG SECTION	N LAT DEG MIN	W LONG DEG MIN	HOLE (DATE)	COLLAR ELEV (m)	DEPTH RANGE (m)	AVG TCU <SE> (W/m/K)	UN GRAD <SE> (°C/km)	CO GRAD <SE> (°C/km)	CO H.F. <SE> (mW/m <sup>2</sup> )	Q HF	LITHOLOGY SUMMARY
11N/41E 15DBD	44-17.10	111-36.53	OXY-16 0/ 0/77	2060	20.0 205.0 205.0 305.0	(1.88) (1.88)	-5.6 7.3 1.8	-5.6 7.3	13	X	BASALT 5-73 RHY 73-303
11N/41E 15BDB	44-16.95	111-35.48	OXY-14 0/ 0/77	2062	20.0 200.0 200.0 290.0	(1.88) (1.88)	14.6 7.3 -5.5	14.6 -5.5	29	X	BASALT 8-61 RHY 61-290
9N/43E 11BDA	44- 7.45	111-20.78	OXY-17 0/ 0/77	1695	20.0 60.0 60.0 135.0	(1.88) (1.88)	12.7 1.8 (155.0) 64.0	12.7 (155.0) 64.0	17 ( 356) 146	X	RHYOLITE
9N/43E 11BDA	44- 6.10	111-36.53	OXY-8 0/ 0/77	1515	30.0 133.0	(1.88)	10.9 1.8	10.9	13	X	BASALT 0-50 NO RET TO TD
9N/43E 19BDC	44- 5.55	111-25.73	STURM-1 8/29/79	1602	0.0 1210.0	2.26	( 48.0)	( 48.0)	( 109)	C	SILICIC VOLCANICS
8N/35E 22ADA	44- 0.68	112-19.00	OXY-9 0/ 0/77	1487	30.0 157.0	(1.63)	3.6 7.2	3.6	4	X	BASALT 0-60 NO RET TO TD
6N/42E 20CAC	43-49.85	111-31.88	OXY-10 0/ 0/77	1926	10.0 145.0	(1.88)	3.6	36.0	8	X	RHYOLITE TUFF
6N/40E 31BBA2	43-48.65	111-47.15	GT-MCG1 9/ 3/81	1511	0.0 1495.0	(1.88)	( 11.3)	( 11.3)	( 21)	X	BASALT 0-296 RHY TO 957
6N/40E 31B	43-48.58	111-47.58	RBHTW-1 1/ 5/80	1483	100.0 250.0					X	SILICIC VOLCANICS
6N/42E 35CCD	43-47.85	111-28.40	OXY-11 0/ 0/77	1780	50.0 153.0	(1.88)	9.1	9.1	17	X	BASALT 0-79 RHY 79-152
5N/40E 5CD	43-47.10	111-46.60	RBHTW-2 6/11/80	1563	10.0 393.0					G	SILICIC VOLCANICS
5N/41E 17CCC	43-45.38	111-39.85	OXY-12 0/ 0/77	1658	10.0 153.0	(1.88)	34.6	34.6	67	C	SEDIMENTS VOLCANICS
5N/41E 25ACD	43-44.05	111-34.45	OXY-13 0/ 0/77	1911	10.0 100.0	(1.88)	-7.3	-7.3		X	RHYOLITE

TABLE 2. (continued) Thermal data from Urban and others (1986), (points with asterisks), and Blackwell (1988-unpublished).

TWN/RNG SECTION	N LAT DEG MIN	W LONG DEG MIN	HOLE (DATE)	COLLAR ELEV (m)	DEPTH RANGE (m)	AVG TCU <SE> (W/m/K)	UN GRAD <SE> (°C/km)	CO GRAD <SE> (°C/km)	CO H.F. <SE> (mW/m <sup>2</sup> )	Q HF	LITHOLOGY SUMMARY
3N/27E 9AB	43-36.50	113-14.63	WW-BUTT	1620	119.5 141.4	( 1.46)	999.0	999.0	1920	G	BASALT
2N/29E 15ACA	43-30.17	112-58.95	INEL106 8/ 6/83	1524	20.0 225.0					X	BASALT
2N/29E 24DDDA	43-28.80	112-56.13	INEL104 8/ 6/83	1517	20.0 214.0					X	BASALT
2N/29E 33DCC	43-26.97	113- 0.12	INEL105 8/ 6/83	1549	20.0 225.0					X	BASALT
2N/29E 35CCC	43-26.95	112-57.95	INEL108 8/ 6/83	1534	20.0 225.0					X	BASALT
2N/30E 16CCA	43-29.67	112-53.42	INEL107 8/ 5/83	1499	20.0 210.0					X	BASALT
2N/30E 31CCB	43-27.17	112-56.10	INEL103 8/ 6/83	1527	20.0 215.0					X	BASALT
2N/30E 35DDB	43-27.12	112-50.33	INEL110 8/ 5/83	1521	20.0 225.0					X	BASALT
4S/16E 33DA	43- 1.90	114-33.35	PALACIO1 6/ 9/80	1015	0.0 610.0	( 1.46)	( 73.2)	( 73.2)	( 107)	C	BASALT AND RHY TUFF
5S/14E 12AAA	43- 0.70	114-44.00	RWINK1 5/15/80	1098	0.0 610.0	( 1.46)	( 68.4)	( 68.4)	( 100)	C	BASALT
7S/15E 12CBA1	42-49.95	114-39.03	USGS-WTW 0/ 0/84	1097	70.0 342.0					X	BASALT
9S/18E 1DD	42-39.90	114-17.30	ANDCMPWW 3/27/86	1194	65.0 650.0	( 1.46)	62.5	62.5	92	C	BASALT 0-237 RHY&CLAY TD
	42-14.25	113-22.10	RDH G-W* 12/18/76	1350	200.0 1498.0	( 2.09)	54.0	54.0	113	C	
	42-10.10	113-25.75	USGS-ID5* 8/ 6/76	1650	76.0 128.0 140.0 216.0	1.97 2.38	63.0 45.0	61.0 43.0	120 103	A A	



TABLE 2. (continued) Thermal data from Urban and others (1986), (points with asterisks), and Blackwell (1988-unpublished).

TWN/RNG SECTION	N LAT DEG MIN	W LONG DEG MIN	HOLE (DATE)	COLLAR ELEV (m)	DEPTH RANGE (m)	AVG TCU <SE> (W/m/K)	UN GRAD <SE> (°C/km)	CO GRAD <SE> (°C/km)	CO H.F. <SE> (mW/m <sup>2</sup> )	Q HF	LITHOLOGY SUMMARY
15S/39E 6CA	42- 8.75	111-56.71	SUN-1001 6/15/78	1446	0.0 110.0	( 1.46)	857.0	857.0	1255	G	PHYLLITE AND SCHIST
15S/26E 12ACC	42- 8.00	113-21.85	USGS-ID1* 0/ 0/76	1478	50.0 260.0	1.09	120.0	120.0	131	A	CENOZOIC SEDIMENTS
15S/26E	42- 6.50	113-23.50	SCHMITT*	1500	0.0 126.0	> 1.05	63.5	63.5	> 106	G	CENOZOIC SEDIMENTS
15S/26E 22DDD	42- 5.85	113-23.61	USGS-ID3* 8/11/76	1487	20.0 330.0	1.67	200.0	200.0	335	G	CENOZOIC SEDIMENTS
15S/26E 25ABC	42- 5.55	113-21.75	USGS-ID2* 1/15/76	1475	20.0 190.0	1.30	210.0	210.0	335	G	CENOZOIC SEDIMENTS
	42- 4.95	113-36.60	USGSALM2* 8/ 8/76	1700	50.0 200.0	( 2.09)	52.0	52.0	109	C	
	42- 0.75	113-12.30	STREVELL* 10/17/75	1675	75.0 220.0	( 2.09)	56.0	56.0	117	C	

## THERMAL DATA NORTH OF SNAKE RIVER PLAIN

### Northern Idaho and Blue Mountains

A summary of the geothermal gradients and heat flow for the northern and western part of the state of Idaho is listed in Table 1 and shown in Figure 2. North of the Snake River Plain and west of the Central Idaho Basin and Range the heat flow/temperature gradient measurements indicate that heat transfer is primarily by conduction and interpretation of the results is straightforward. Histograms of geothermal gradients and heat flow are shown in Figure 2. Average gradients range from approximately 40°C/km in Columbia River basalt to 22°C/km in granite and in the Belt Series rocks. These variations reflect differences in the average thermal conductivity of the rock because the variation in heat flow values is quite small, as shown by the histogram in Figure 2. The average heat flow for this area of Idaho is  $65 \pm 3 \text{ mWm}^{-2}$  based on 23 determinations. Taking into account the low heat production due to radioactivity of the crust in this area (Swanberg and Blackwell, 1973), this value is typical of the heat flow in the Northern Rocky Mountains in the United States and Canada (Blackwell, 1978; Davis and Lewis, 1984), including areas in Washington and Montana. Furthermore, adding the heat flow component from radioactivity of typical granites (about  $20 \text{ mWm}^{-2}$ ), this average heat flow value is identical to heat flow values in the Basin and Range province (Roy and others, 1972; Blackwell, 1978). Thus this heat flow pattern is characteristic of the conductive heat flow for much of the interior part of the North American Cordillera from British Columbia to central Mexico where active volcanism has not taken place in the last 10 to 15 m.y. (Blackwell, 1978, Blackwell and others, 1991).

### Southern Idaho Batholith and Challis Section

The thermal regime in the southern part of the Idaho batholith is somewhat different than that in northern part of the Idaho batholith because there are major effects on the heat flow associated with deeply circulating groundwater. Hot springs are common in the southern part of the Idaho batholith and locally these hot springs occur along major topographic lows with a spacing of only a few kilometers. Estimates of the heat loss from the hot springs within this area using the geochemical temperatures and observed flow rates suggest a total heat loss from the hot springs that is more than  $4 \times 10^7 \text{ W}$  (Ross, 1971; Mitchell and others, 1980; and Lewis and Young, 1980a, 1982). This value corresponds to 10 to 20% of the regional heat flow in this area of Idaho, so that major effects on the conductive transport pattern can be expected.

The regional heat flow in the granitic rocks of the batholith is well characterized. The gradients and heat flow values are generally of high quality and were obtained from either cored mining exploration

holes or from holes drilled specifically to investigate the regional heat flow (Blackwell, 1989). Histograms of gradient and heat flow are shown in Figure 2. The average "background" values are about  $26^{\circ}\text{C}/\text{km}$  and about  $75 \text{ mWm}^{-2}$ . These values are consistent with the heat flow observed in the back-arc region of the western United States (Blackwell, 1978; Blackwell and others, 1991). The values are slightly higher (about  $10 \text{ mWm}^{-2}$ ) than the heat flow in Northern Idaho and along the Snake River because of the heat generation of the granitic rocks in the batholith. The holes considered to represent "background" are at least 10 km from the nearest hot spring or major topographic lineament and are not near the margin of the Snake River Plain. High heat flow values (greater than  $85 \text{ mWm}^{-2}$ ) coincide with hot spring locations/lineations or the margin of the Snake River Plain.

The Challis section as shown on Figure 1 is a subsection of the Southern Idaho batholith. Geothermal data are very sparse in this area, consisting primarily of a series of holes in the Eocene Challis volcanics and Paleozoic sediments near the town of Challis and in the Bayhorse mining district. Two holes near the Salmon River are in the east edge of the Idaho batholith. All the data sites are shown on Figures 7 and 13 below. Average heat flow values of this small data set appear to be 10-20% higher than in the Idaho batholith and gradients are significantly higher because the volcanic rocks have lower thermal conductivity than the granites. Significant high heat flow anomalies occur in the Bayhorse mining district (12N/8E) and along the Salmon River (hole 11N/14E-21ccd). The anomalous value along the Salmon River is not surprising because this part of the Salmon River flows along a major hot spring lineament. The high geothermal gradients and heat flow in the Bayhorse mining district are not near any known geothermal manifestation and suggest the presence of a blind geothermal system in this area. The data are geographically too sparse to draw detailed conclusions about the characteristic heat flow in this region at this time.

As part of this study heat flow data were obtained from two localities in this province (not including sites at the edge of the Snake River Plain to be discussed below): at Challis in two holes 750 and 600 m deep; and in the Mackay area in shallow exploration holes. The temperature-depth curve for the deepest Challis hole as well as a deep hole in the Idaho batholith (DDH-3) are shown in Figure 12 (below) for comparison to the data from the Snake River Plains to be discussed.

### Central Idaho Basin and Range

Geologically and tectonically the Central Idaho Basin and Range province differs from the remainder of the provinces north of the Snake River Plain. Because of the undeveloped nature of the area, very little is known about the hydrology and the geothermal character away from the margin of the Eastern Snake River Plain. A few low quality sites show low gradients in shallow holes drilled for mineral or water exploration. Several relatively high quality geothermal gradients and heat flow values have been obtained in the vicinity of the Gilmore Mining district (13N/26E and 27E). Heat flow values in the

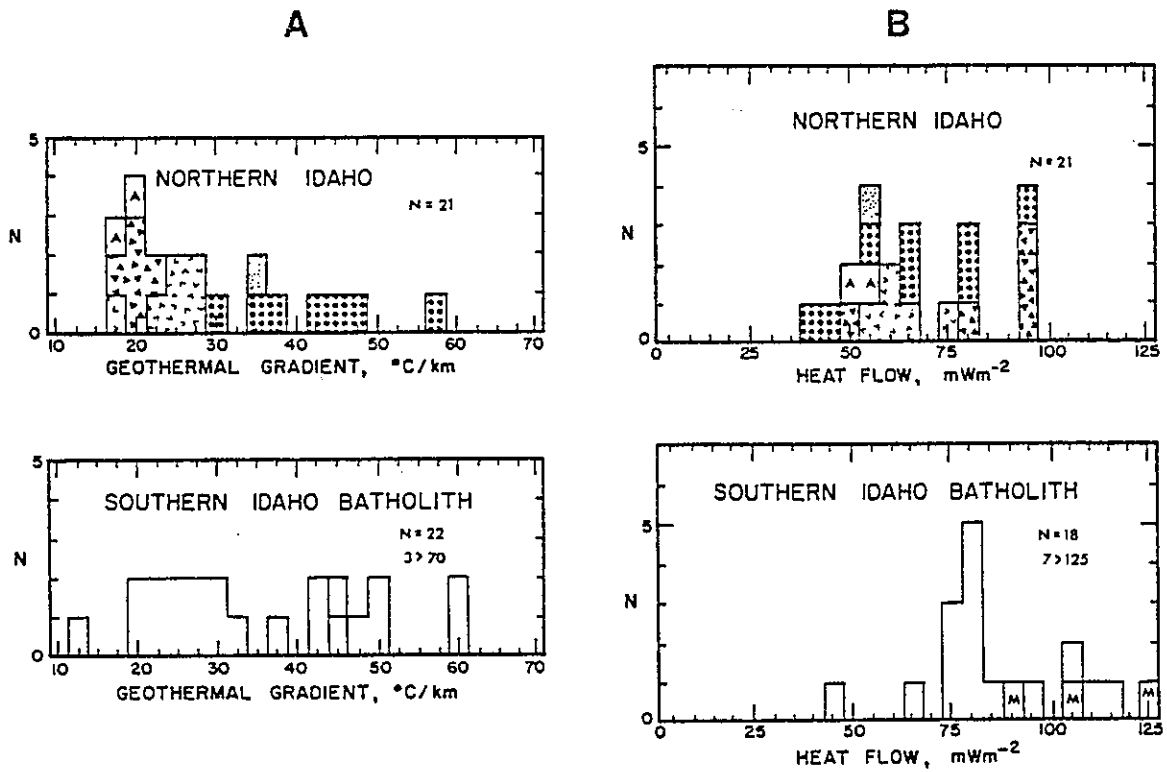


Figure 2. Figure 2a. Histograms of geothermal gradient for northern Idaho and the southern Idaho batholith. The dominant lithology at each site is shown by a pattern (granite, caret; basalt, large dots; Precambrian sediments, triangles; unconsolidated sediment, dots; andesite, A). Figure 2b. Histograms of heat flow for northern Idaho and the southern Idaho batholith. The dominant lithology of each site is shown by the same pattern as in Figure 2a. M indicates holes near the margin of the Snake River Plain. Other sites with heat flow values in excess of 80 mWm<sup>-2</sup> are associated with hot spring systems.

bedrock of the Lemhi Range are 55-59  $\text{mWm}^{-2}$ , significantly below average values elsewhere in the greater Northern Rocky Mountain province. On the other hand the gradient in a deep hole in the adjacent Lemhi River valley is  $84^\circ\text{C}/\text{km}$  and the estimated heat flow is greater than  $105 \text{ mWm}^{-2}$ . As is the case with the Southeastern Idaho Basin and Range province, deep drill holes are needed to evaluate the intrinsic thermal characteristics of this province.

The only deep thermal data are bottom hole temperature measurements (BHT) measurements from several hydrocarbon exploration wells drilled near the Idaho/Montana border in the general vicinity of the Lima anticline (Perry and others, 1983) and two wells drilled in Birch Creek and Lemhi Valleys. The average gradients are shown in Table 3 (below) for the wells in Idaho using corrected BHT's. There has not been sufficient time nor funds to complete analysis of the lithology and heat flow for these wells. Unlike some of the wells described in the Southeastern Idaho Basin and Range described in a later section, none of these wells appear to have gradients in excess of  $40^\circ\text{C}/\text{km}$ . The deepest well, the EXXON Meyers Federal Unit #1 reaches an uncorrected BHT of  $197^\circ\text{C}$  at 5.7 km.

## THERMAL CONDITIONS IN SOUTHWESTERN IDAHO

### Western Snake River Plain

The geothermal character of the Western Snake River Plain was first studied in detail by Brott and others (1976, 1978). Subsequent studies were carried out by Smith (1980, 1981). The Weiser and the Bruneau-Grand View-Oreana areas have been the object of several studies (Young and others, 1978, 1982; Lewis and Young, 1980b). New data and reinterpretations of some of the data contained in the papers by Brott and others (1976, 1978) and by Smith (1980, 1981) are included in the data tabulated by Blackwell (1988 and 1989). The broad outlines of the distribution are quite clear. The results are demonstrated by a heat flow map of the western Snake River Plain shown in Figure 3. The contours in Figure 3 near the Oregon border are based on data from the western Snake River Plain in Oregon (Blackwell and others, 1978). This map has been discussed in detail by Blackwell (1989). Areas of contrasting heat flow and geothermal gradient are shown on Figure 3 and identified by name for ease of reference in this discussion. Typical heat flow values in the high heat flow regions are  $120\text{-}150 \text{ mWm}^{-2}$ , while in the low heat flow region of the central Western Snake Plain the values are less than  $80 \text{ mWm}^{-2}$ .

There are over twenty holes in the depth range 300 to 500 m in this area. The data within the Western Snake River Plain in general fall into two categories. These categories correspond to areas of relatively high gradient and heat flow (on the order of  $100^\circ\text{C}/\text{km}$  and  $120\text{ to }150 \text{ mWm}^{-2}$ ), and areas of moderate gradients (about  $40^\circ\text{C}/\text{km}$ ) and average heat flow values ( $60\text{-}80 \text{ mWm}^{-2}$ ). Histograms of gradient and heat flow are shown in Figure 4. Most of the gradients range between 45 and  $85^\circ\text{C}/\text{km}$ .

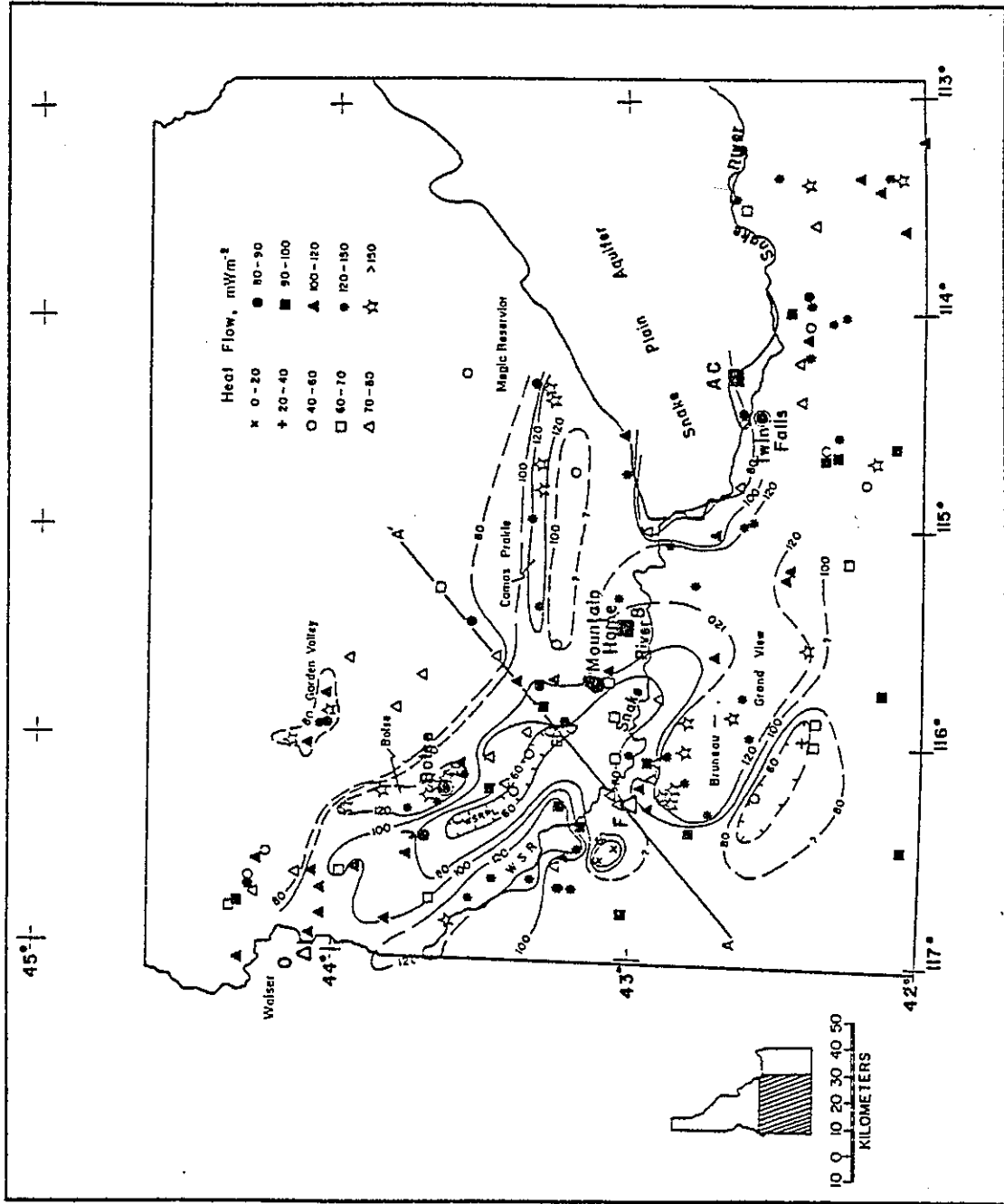


Figure 3. Detailed heat flow map of southwestern Idaho. Contours of heat flow at 20  $mWm^{-2}$  intervals are shown. Locations of deep wells discussed by Blackwell (1989) are shown (WSRPL is low heat flow band and WSR is western Snake River high heat flow anomaly). The line of the cross section (AA') in Figure 5 is shown. The deep wells discussed in the text are identified by a letter, i.e. O is Ore-Ida #1 well, B is Bostic well, J is James well and F is Federal 60-13 #1 well.

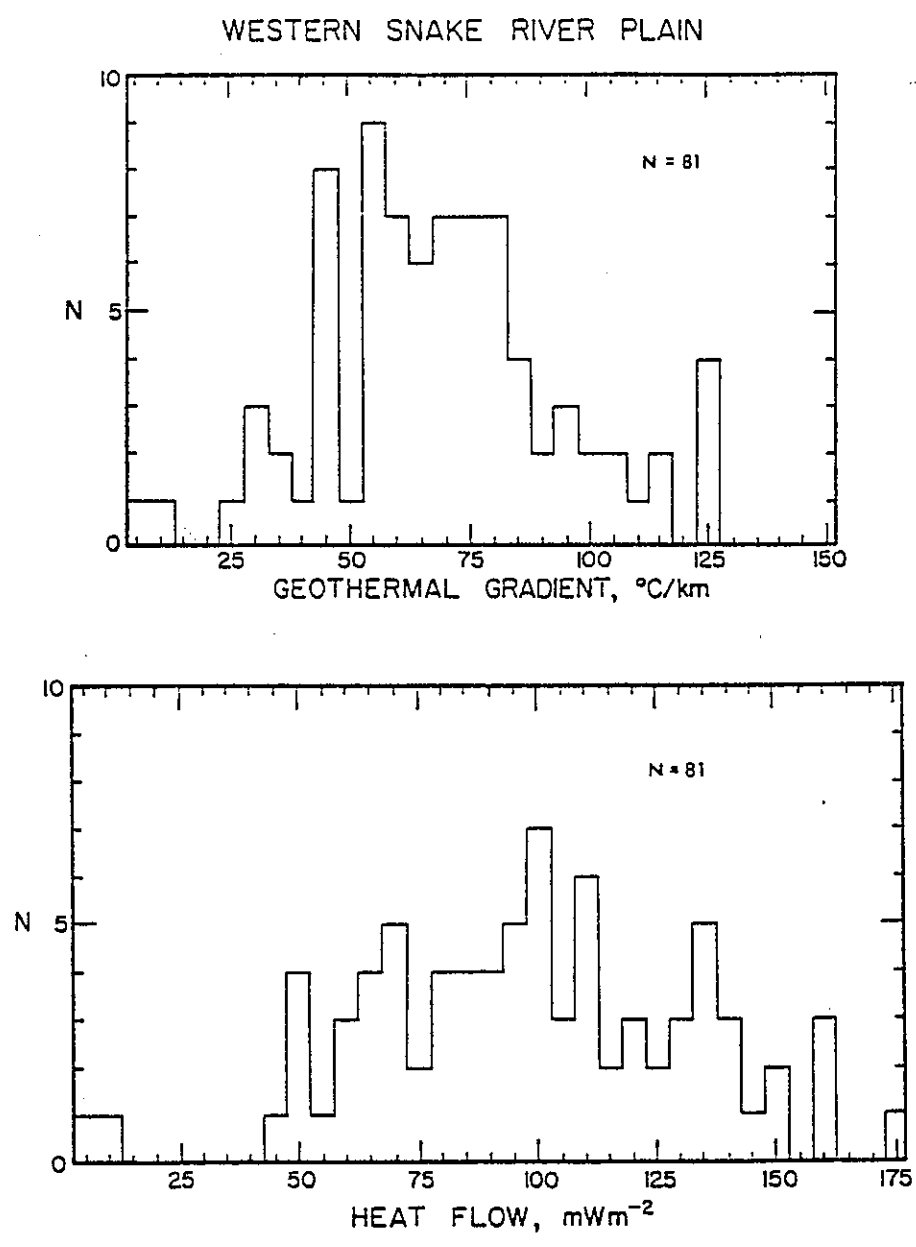


Figure 4. Histograms of geothermal gradient and heat flow for the Western Snake River Plain area. The holes are all in basalt or sedimentary rocks.

Heat flow values range from 50-150  $\text{mWm}^{-2}$  with an average of  $100 \pm 10 \text{ mWm}^{-2}$ . The lithology in most of the holes is lacustrine sediment with a few of the holes drilled in basalt. Areas of high heat flow are distributed in two bands along the northern and southern margins. Lower gradients and heat flow are found along the axis of the Snake River Plain between Caldwell and Mountain Home.

A heat-flow cross-section is shown in Figure 5. The line of the section is shown on Figure 3. The observed pattern was discussed in detail by Brott and others (1978) on the basis of a substantially smaller data set. With additional data the origin of some parts of the pattern has now become clearer. Deep drilling in the Boise area and in the Bruneau-Grand View region has demonstrated that the high heat flow values there are related to intermediate temperature (40-80°C) geothermal systems and relatively local geothermal anomalies. Typical temperature-depth curves in the Boise front geothermal system and in the Bruneau-Grand View geothermal system show isothermal or low gradient sections starting between 80 and 280 m with temperatures of 40 to 80 °C. The occurrence of warm water in wells along the Snake River has been described by Lewis and Young (1980b). Geochemistry suggests that maximum temperatures in the geothermal systems are 70-100°C. Thus the high gradients and heat flow that are measured in holes 50-200 m deep do not project to great depth. Maximum temperatures in the depth range 200-500 m in the wells range up to 80°C. This pattern of heat flow and gradient is due to systematic regional flow of groundwater toward the edges of the Snake River Plain from the higher elevation margins. Very low heat flow that may represent part of the recharge system occurs south of the Bruneau-Grand View area (see Figure 3). At the edge of the Snake River Plain hydraulic boundaries cause upflow, which gives rise to the geothermal systems at the various locations. The effects on the heat flow are generally modest, however, because the average heat flow values observed are only on the order of 50-100% above the regional background values. The approximate heat flow pattern is shown by the dashed lines on Figure 5. Outside the areas of most active fluid flow, temperature-depth curves are linear to depths of at least 400-500m, and in the case of the Bostic 1-A well (4S/3E-25cbb, Arney and others, 1982, Arney, 1982) to a depth of 2500m (see Blackwell, 1989).

High gradients and heat flow values are also found in holes drilled in granitic rocks on both margins of the Snake River Plain (Urban and Diment, 1975; Brott and others, 1978; Blackwell, 1988, 1989). The high heat flow in these rocks, presumably not associated with the regional groundwater flow systems, is related to the large scale nature of crustal disruption associated with the Snake River Plain margins (Brott and others, 1978). These holes are shown by a special symbol on Figure 3.

The heat flow values that may represent regional conductive values are connected on Figure 5 by a solid line. The regional heat flow is about  $100 \text{ mWm}^{-2}$  south of the Snake River Plain and about  $75 \text{ mWm}^{-2}$  north of the Snake River Plain. In the center of the Snake River Plain the heat flow is about  $60\text{-}75 \text{ mWm}^{-2}$ ; the heat flow on the margins is 25-50% higher than in the center because of the thermal conductivity refraction effect discussed by Brott and others (1978).



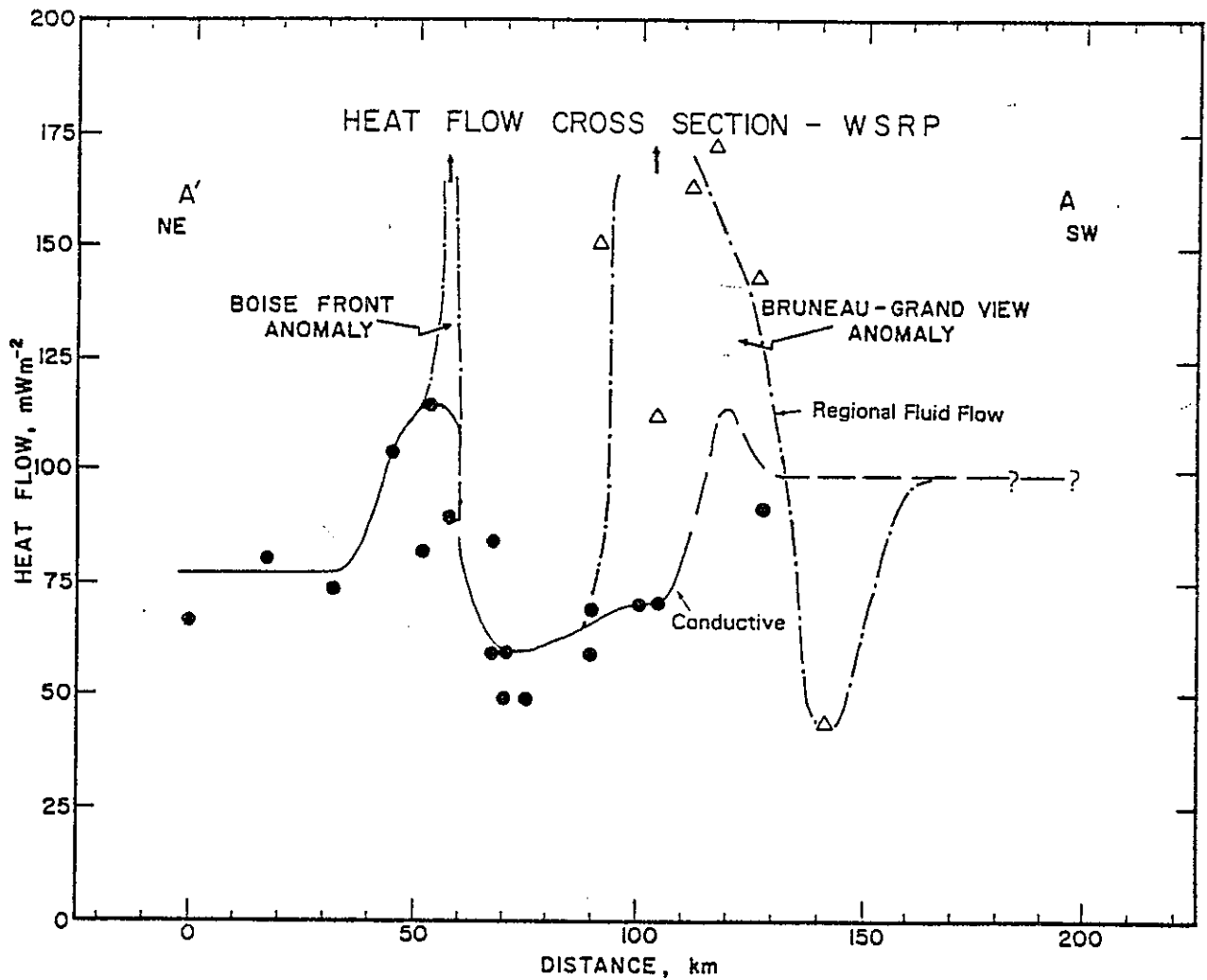


Figure 5. Heat flow cross section of the Western Snake River Plain. The line of the cross section is shown on Figure 3. Points on the cross section are shown by dots. Generalized heat flow east and west of the line of the section is shown diagrammatically and the geothermal areas identified. Dots represent heat flow values least influenced by shallow convective fluid flow, and the triangles represent heat flow values affected by convection.