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Department of Geology and Geophysics

University of Utah

December 15, 1975

Technical Proposal

Regional Heat Flow and Geochemical Studies in S.W. Utah

Submitted to

U.S. Geological Survey
Branch of Procurement and Contracts
National Center M.S. 205A
Reston, Virginia 22092

Period of Grant: June 1, 1976 through May 31, 1977

S.H. Ward

S.H. Ward, Principal Investigator
S.S. No. 552-62-7140
Tel. No. (801) 581-7162

Co-Investigators:

David D. Blackwell

David D. Blackwell
S.S. No. 449-62-6377

William T. Parry

William T. Parry
S.S. No. 529-42-9103

William R. Sill

William R. Sill
S.S. No. 137-30-2178

James A. Whelan

James A. Whelan
S.S. No. 472-22-8465

Lawrence H. Lattman

L.H. Lattman, Dean
College of Mines and Mineral Industries
Tel. No. (801) 581-8767

University of Utah
Authorized Signature
Tel. No. (801) 581-6903

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Regional Heat Flow and Geochemical Studies in S.W. Utah

1.0 Statement of Work

We propose to complete the following tasks in that portion of Utah within the hachured outline shown in Figure 1. Our emphasis will be the Basin and Range Province but we will attempt to obtain data on areas east of the Basin-Range/Colorado Plateau physiographic boundary in order to locate the possible heat flow boundary. However, it must be pointed out at this time, that it is not clear, that there is a heat flow boundary and that high heat flow values may actually occur in the Colorado Plateau. If this high heat flow exists we certainly want to determine this fact as it will be very important in terms of the regional geothermal evaluation.

1.1 Measure Heat Flow, Available Holes

Measure heat flow in available water wells, oil wells, and mining exploration drill holes where thermal gradients can be measured and where cores or chips are available or may be readily obtained for thermal conductivity measurements.

1.2 Apply Geothermometry to Available Water Chemistry

Retrieve from all available sources, including computer data banks chemical analyses of waters of all water wells, oil wells, and mining exploration drill holes for which chemical analyses have been obtained, and then estimate the temperature of last wall rock equilibration via available geothermometers.

1.3 Drill Eight New Holes for Heat Flow

Drill eight 200 ft. holes to provide heat flow measurements and petrology/lithology/alteration information in areas where heat flow data is scarce and the need is critical.

1.4 Construct Preliminary Heat Flow Contour Map

From heat flow measured in the proposed program and from those already available, construct a preliminary heat flow contour map of S.W. Utah.

1.5 Assess Geothermal Resource Potential

Assess the heat flow, water chemistry and other data in terms of regions possibly suitable for steam, hot water, or warm water occurrence in relation to electrical energy, agricultural, space heating and other uses of geothermal fluids.

2.0 Previous, Current, and Proposed Related Investigations

2.1 Heat Flow

Costain and Wright (1974) report 12 heat flow values in Utah, 6 in the Basin and Range and 6 in the Colorado Plateau; these values are coupled via assumptions concerning thermal conductivity and hence they are not all independent. Monroe and Sass (1974) report 9 heat flow values in Utah, 8 in the Basin and Range and 1 in the Colorado Plateau. Roy et al, (1968) report 2 heat flow values for the Basin and Range in Utah. Lovering and Goode (1963) noted exceptionally high thermal gradients in the East Tintic District. Lovering and Morris (1965) reported heat flow in well over 100 drill holes in the East Tintic District with values as high as 7.5 hfu. David D. Blackwell has information sufficient for heat flow determinations at two sites in western Utah and these will be included as part of this study. Additionally, W. R. Sill of the University of Utah has measured thermal gradients and obtained cores for thermal conductivity measurements in 6 holes extending from Monroe Hot Springs on the east to Roosevelt Hot Springs on the west. Heat flow values from these latter holes are expected to be available early in 1976. We present Figure 2 (after Diment et al, 1975) to show the accepted observed heat flow values in the western U.S. and in Utah [8 in the Basin and Range and 6 in the Colorado Plateau] excepting those measured by Lovering and Morris (1965).

2.2 Geochemistry and Geothermometry of Water From Mixed Sources

The basic tools for estimation of subsurface temperature in geothermal areas have been provided in a series of papers by Fournier and co-workers (Fournier, et al, 1974a, 1974b; Fournier and Rowe, 1966, Fournier and Truesdell (1973). Application of the Na-K-Ca geothermometer of Fournier and Truesdell (1973) by Swanberg (1974) to published analysis of thermal spring waters in Utah (Mundorff, 1970) has indicated several anomalously high temperatures; the highest of these is the Roosevelt KGRA. Our own analyses of water from cool seeps in the Roosevelt KGRA also indicates the anomalously high temperature. These methods of temperature estimation must be applied with caution; they are invalid in vapor-dominated systems, in systems where the assumed reaction mineral assemblages are not present, and in systems where the chemical composition of cool mixing water is not known. An additional complication is contamination of the warm spring water with Jurassic salt and gypsum or Holocene playa evaporites.

Much chemical and geological data in the region required for construction of an appropriate geological model and estimation of sub-surface water-rock interaction temperatures is available in the open literature, unpublished reports, files of government agencies, and computer data banks. Analyses of waters from many of the major nonthermal springs of Utah are available in Mundorff (1971). Analyses of many of the thermal springs are available in Mundorff (1970). Analyses of well waters in the region are available from Lee (1908), Meinzer (1911), Fix Nelson, and Butler (1950), Sandberg (1963), Sandberg (1966), Hood and Rush (1966), and Mower and Cordova (1974). Temperature data are frequently included. Many analyses, particularly the older ones, are incomplete or unrealiable.

We propose to assemble all available spring and well chemistry together with geological information to provide a basis for estimation of subsurface temperatures, sources of dissolved constituents, possible cool mixing water compositions, and extent of warm water reservoirs. Flowing wells and springs in key locations for which incomplete or unreliable data are available will be resampled and their waters analyzed. Any flowing wells or springs for which data are not available will be sampled and the waters analyzed for trace and major elements and ions. If flowing waters are encountered in heat flow holes, they will be sampled and analyzed. A thorough search of available computer data storage banks such as GRID of Lawrence Berkeley Laboratory and the Desert Research Institute, of government agency files such as UGMS and USG, and of published reports containing water analyses will be conducted. All such data retrieved will be assembled into a computer compatible data bank.

2.3 Recent and Proposed Work of USGS in S.W. Utah

Lippman et al (1975) have reported on K/Ar dates for silicic volcanic rocks in S.W. Utah. Roberts (1975) has conducted a preliminary study of mercury in soils near faults at Roosevelt Hot Springs KGRA. Frischknecht (1975) is conducting a reconnaissance magnetic variation/MT survey of S.W. Utah. Rowley and Gayland (1975) are planning to map the geology of two or more quadrangles near the Roosevelt Hot Springs KGRA. Pearson and Fournier (1975) are planning to measure tritium and radiocarbon in a well currently being drilled by Phillips Petroleum Co. at Roosevelt Hot Springs KGRA. Arnow and Rush (1975) are proposing to drill, for heat flow and water chemistry, a number of holes in S.W. Utah.

Our recent discussion with all of these people have led us to conclude that our proposed research is strictly complementary to theirs and by careful continuing coordination no redundancy will result.

2.4 Proposed Work of the UGMS in Utah

Director D. H. McMillan of the Utah Geological and Mineral Survey has indicated a desire to measure heat flow in holes that the UGMS may be drilling for other purposes, primarily in the Colorado Plateau. We shall coordinate our activities with any of those of the UGMS.

2.5 Coordination with E. Decker, University of Wyoming

Edward Decker is involved in measurements both in holes drilled specifically by him and also by others, of heat flow values in northeastern

Utah. We will coordinate our activities with his in order to insure that there is no overlap of effort.

2.6 Coordination with W. P. Nash and F. H. Brown, University of Utah

Nash and Brown are proposing a chemistry/petrology/geochronology/paleomagnetism study of young silicic rocks (and one basalt flow) in southwestern Utah. We shall stay abreast of any results of their proposed studies which would have a bearing on our studies.

2.7 Recent Work of the University of Utah Geothermal Team

See attachment.

3.0 Some Special Crustal Problems in S.W. Utah

Much of the thrust of U.S.G.S. activities in southwest Utah is to provide an understanding of the transition zone between the Basin and Range to the west and the Colorado Plateau to the east. Our research objectives are complementary to this, for example, an additional problem requiring understanding is the origin and evolution of the several east-west crustal lineaments in Utah. Figure 1 shows these lineaments in relation to the KGRA's in Utah. The Pioche-Beaver-Tushar trend, for example, is marked by (a) a 40 km right-lateral offset of gravity features on its northern boundary, (b) generally high magnetic intensity, (c) an abundance of young acidic to basic extrusives and intrusives, (d) base metal and iron mineralization, (e) an abundance of thermal springs, and (f) most of the KGRA's in Utah.

Figure 3 shows that a 100 km wide east-west band of Tertiary volcanics lies immediately south of the northern border of the Pioche-Beaver-Tushar trend. These volcanics are largely intermediate in composition and may make contributions to the aeromagnetic highs of the Pioche-Beaver-Tushar trend and the Iron Springs trend. Also contributing to the magnetic highs of these latter two trends are basalt flows immediately to the north and to the south of the intermediate volcanic rocks, and intrusive igneous rocks, labeled as Precambrian, Jurassic, and Tertiary in Figure 3, but known to be dominantly in the 20 to 40 my age range. The Deep Creek-Tintic and the Oquirrh-Uinta trends are intruded by igneous rocks of similar age. The former trend contains the Burgin mine at East Tintic. The Bingham and Park City mining camps lie within the Oquirrh-Uinta trend.

The thermal springs of Utah (Mundorff, 1970) lie largely within the Intermountain Seismic Belt as shown in Figure 4. The boundaries of the Basin and Range, the Colorado Plateau, and the Rocky Mountains are also shown in this figure. Key questions to which the proposed research shall be addressed are:

1) Is the physiographic boundary between the Basin and Range also a heat flow boundary?
2) Do the Deep Creek-Tintic, Pioche-Beaver-Tushar, and Iron Springs trends cut across the physiographic boundary between the Basin and Range and the Colorado Plateau as the Oquirrh-Uinta trend appears to do?
3) Where is the western termination of the Oquirrh-Uinta trend?
4) Which is most important in controlling the location of geothermal resources in Utah, the east-west trends or the Intermountain Seismic Belt?
5) Do the east-west trends exhibit anomalously high heat flow, relative to adjacent Basin and Range terrain?
6) Are the very young silicic rocks or the Quaternary basalts in Utah related to high heat flow?

Bearing on the above key questions are several important observations as follows:

1) Seismic data (e.g., Smith and Sbar, 1974, and Smith et al, 1975), aeromagnetic data (Shuey et al, 1975), and gravity data (Cook, 1975) all indicate that the *geologic* boundary between Basin and Range and the Colorado Plateau lies an average of 50 km, and as much as 100 km, to the east of the physiographic boundary.
2) Cook (1975) interprets the gravity map of Utah to infer that the Pioche-Beaver-Tushar trend continues well into the Colorado Plateau.
3) On a local scale, both east-west and north-south faulting is

important in delineating the geothermal reservoir at Roosevelt Hot Springs KGRA.

4) Figure 2 illustrates the gross inadequacy of heat flow measurements in Utah in general and in the Basin and Range/Colorado Plateau transition in particular.

5) Smith et al (1975) note that "A pronounced north-trending physiographic break known as the Wasatch Front, marks the boundary between the northern Basin-Range Province to the west with a thin crust (∿ 30km), low Pn velocity (∿ 7.6-7.8 km/sec), and high heat flow (> 1.5 hfu): and Colorado Plateau to the east with a thicker crust (∿ 43 km), higher Pn velocity (∿ 7.8 km/sec), and normal heat flow (< 1.5 hfu). The physiographic boundary also coincides with an area of Cenozoic faulting as well as with a zone of pronounced seismicity along the Intermountain Seismic Belt that is characterized by focal mechanisms representative of high-angle normal faulting with east-west extension."

6) Eaton (1975) notes that "A fundamental, west-trending, transverse, crustal boundary crosses the Basin and Range province between St. George, Utah, and northern Death Valley." This trend is most readily depicted in the seismicity map of Smith and Sbar (1974) reproduced here as Figure 5. Eaton continues, "The boundary is characterized by a steep, north-facing gravity gradient of 70-100 mgls, a coherent zone of moderate seismicity, which continues northeast as the Intermountain Seismic Belt, a west-trending trough in the M-discontinuity, with relatively low crustal P velocities on the south, and a suggestive variation in Pn. There may be a local heat flow gradient at this latitude, but the data are admittedly open to other

interpretations."

7) Figure 6 (after Mount, 1964) shows five sulfur occurrences deep in the Colorado Plateau (Emery County). At least one of these sulfur deposits is associated with a hot spring.

4.0 Work Plan

4.1 Heat Flow

Several mining companies have advised us of the availability of drill holes and cores retrieved from them. Currently, these holes extend from the Tintic Mining District in the north to the Wah-Wah and the Tushar Mountains in the south. So far, we have about 30 holes available to us. We expect to expand this number to 50-75 holes during the project by contact with mining and petroleum companies, municipalities and individuals. As many as 8 additional holes will be drilled and cored in areas where data is sparce yet critical.

Thermal gradients will be measured in all available holes whether or not they are suitable for heat flow determinations. When possible thermal conductivities will be measured on available cores, cuttings or surface samples. Heat flow values will be calculated from these data and terrain corrections made for terrain effects if applicable. We will also measure radioactivity values of granitic rocks in the areas in order to obtain information on basement radioactivity so that reduced heat flow values can be calculated and included in the interpretation.

4.2 Water Chemistry

The water data which we obtain directly or retrieve will be combined with all available geological and geophysical data to evaluate a) local potential for convective hydrothermal systems and b) the effect of ground water on thermal gradient measurements in the area.

The sodium-calcium-potassium thermometer of Fournier and Truesdell (1973) and the silica thermometer of Fournier and Rowe (1966) will be applied to all water analyses to estimate temperatures and possible mixing models and to evaluate possible geothermal areas.

4.3 Drilling

We plan to drill up to 8 holes between 200 and 300 feet deep in bedrock using a combined rotary-percussion rig. Cores will be retrieved every 50 feet (nominal). These holes will be carefully located to insure insofar as possible that heat flow values will be obtained in these shallow holes. Careful placement of holes will avoid surface temperature effects, should enable adequate heat flow measurements to be made in these shallow holes, and the amount of money that can be saved by shallow drilling for heat flow justifies the effort in this respect.

4.4 Petrology/Lithology/ and Alteration

All cuttings and cores will be logged as to lithology. Where these subsurface data can contribute to new interpretations of local geology, such interpretations will be made. This may involve occasional local mapping in the immediate vicinity of the hole.

Thin sections will be made of significant facies of igneous rocks, and petrographic descriptions prepared. If previously unknown fine-grained silicic igneous rocks are encountered in drilling, study of them will be coordinated with Nash and Brown.

Altered zones or mineralization encountered during drilling will be cored. Alteration will be studied by standard x-ray diffraction and analytical methods. Type of alteration, in relation to known assemblages of geothermal areas, will be used to assist in evaluating the geothermal potential in the immediate vicinity of the hole.

Splits of cores and cuttings, not used for our heat flow, alteration, or petrographic studies will be made available to other researchers on their request.

4.5 Geothermal Resource Potential

The geothermal gradients, heat flow and water chemistry data will be reduced and prepared in a suitable form for comparison with other geological and geophysical data. In particular we will compare the results with the location of silicic and basaltic intrusives and extrusives, active tectonism, zones of young alteration, hot or warm spring occurrences, and young spring deposits. The object of these correlations will be to determine the possible locations of undefined convective hydrothermal systems, limits on known hydrothermal convective systems, estimates of the maximum temperatures in hydrothermal systems, and information on the regional controls of the systems of geothermal importance. Southeastern Utah is a very large area and it is unrealistic to expect to be able to more than scratch the surface for adequate regional geothermal assessment, particularly since up until the present time this area of Utah has been particularly lacking in heat flow studies. However, we feel this study will be very important in overcoming this lack of basic information

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6.0 Facilities

6.1 Heat Flow

The University of Utah has thermistor probes, cable, reels, and a precision digital voltmeter available for thermal gradient measurements. We expect some attrition of cables and reels and we will need an alternate measurement system for backup. Accordingly, we have budgeted for reels, cables, and an inexpensive impedance bridge.

Thermal conductivity apparatus for measurements of waters is nearing completion at the University of Utah. Apparatus suitable for thermal conductivity measurements on chips is available at Southern Methodist University.

7.0 Management

Responsibility for the Management of research grants and contracts falls under the activities of the office of the Vice President for Research at the University of Utah. Some $38 million in research grants and contracts are administered annually by this office.

Delegation of authority for day to day management of grants and contracts is made to the departments of the University. In the Department of Geology and Geophysics, Dr. S. H. Ward, Principal Investigator of the proposed research, will provide the necessary technical and overall management during the period of the award. Mr. W. L. Forsberg, Business Manager, will administer the administrative requirements and activities of the grant. Approximately $2.8 million in research grants and contracts are being administered by Mr. Forsberg and his staff.

Department of Geology and Geophysics

University of Utah

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Business Management Proposal

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TABLE OF CONTENTS

1.0 Introduction

A June 1, 1976 project start date is requested so the summer effort can be initiated as early as possible. Our field experience on the NSF Grant No. GI-43741, "Geothermal Exploration Systems and Their Applications in Utah" required a considerable amount of time to make the contract arrangements for the drilling and to complete the drilling project prior to the arrival of adverse weather conditions.

Experience of cost requirements of other research projects was used to develop the cost elements of this project where applicable. Other proposed cost elements are based on our best engineering judgements.

The proposed budget is required to provide the necessary manpower and support items to complete the research outlined in the Statement of Work.

2.0 Statement of Work

We propose to complete the following tasks in that portion of Utah within the hachured outline shown in Figure 1. Our emphasis will be the Basin and Range Province but we will attempt to obtain data on areas east of the Basin-Range/Colorado Plateau physiographic boundary in order to locate the possible heat flow boundary. However, it must be pointed out at this time, that it is not clear, that there is a heat flow boundary and that high heat flow values may actually occur in the Colorado Plateau. If this high heat flow exists we certainly want to determine this fact as it will be very important in terms of the regional geothermal evaluation.

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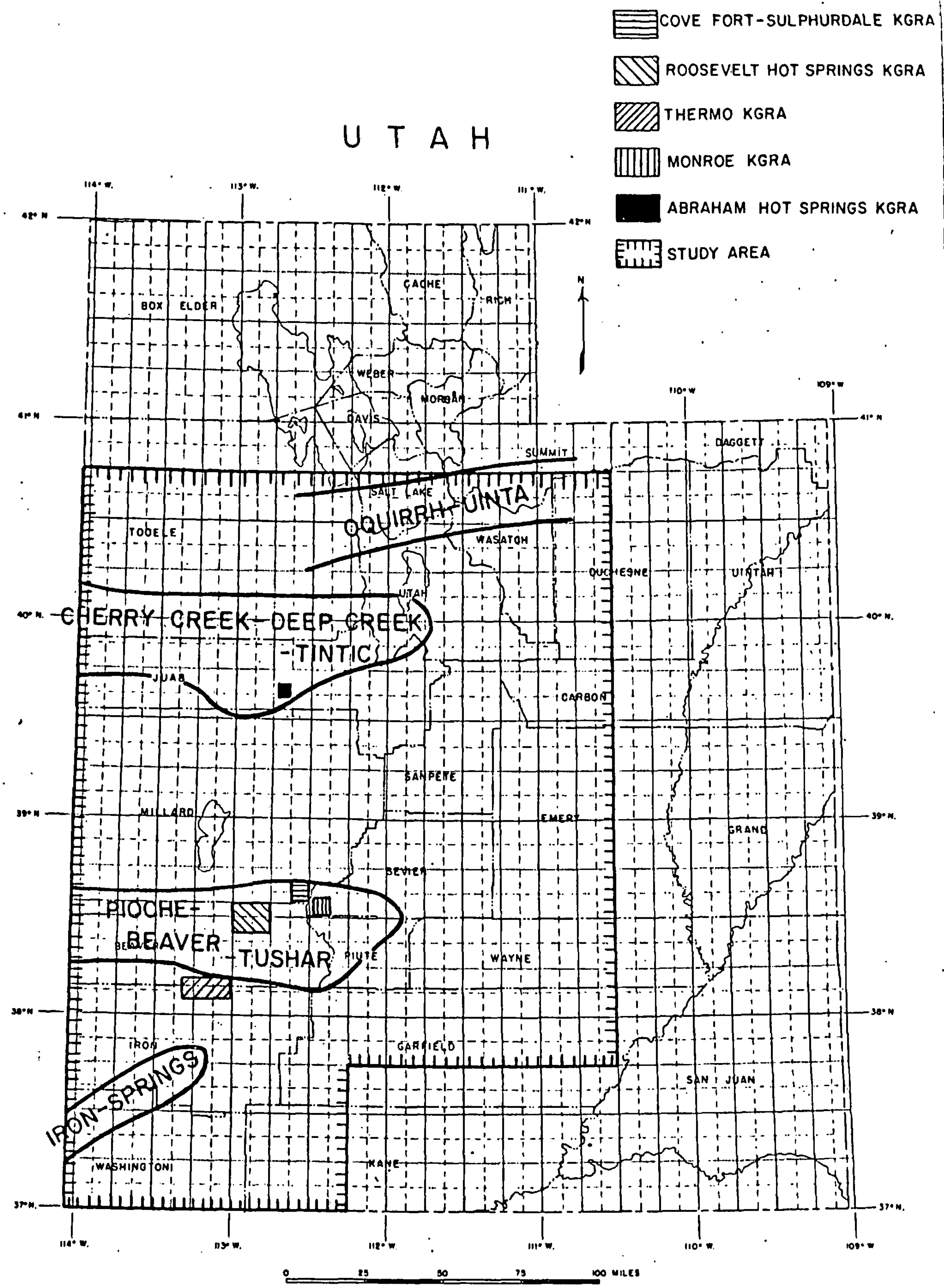


LOCATION OF STUDY AREA, MINERAL BELTS, AND KNOWN GEOTHERMAL RESOURCE AREAS.

Figure 1

3.0

CONTRACT PRICING PROPOSAL

(RESEARCH AND DEVELOPMENT)

Office of Management and Budget Approval No. 29-RO184

This form is for use when *(i)* submission of cost or pricing data (see FPR 1-3.807-3) is required and *(ii)* substitution for the Optional Form 59 is authorized by the contracting officer.

PAGE NO. 1

NO. OF PAGES 2

NAME OF OFFEROR: University of Utah

HOME OFFICE ADDRESS:
Office of Research Administration
University of Utah, S.L.C., UT 84112

SUPPLIES AND/OR SERVICES TO BE FURNISHED: Regional Heat Flow and Geochemical Studies in S. W. Utah

DIVISION(S) AND LOCATION(S) WHERE WORK IS TO BE PERFORMED: Dept. of Geology and Geophysics

TOTAL AMOUNT OF PROPOSAL: $ 99,400.00

GOV'T SOLICITATION NO.:

DETAIL DESCRIPTION OF COST ELEMENTS

1. DIRECT MATERIAL *(Itemize on Exhibit A)*			EST COST ($)	TOTAL EST COST[1]	REFERENCE[2]
a. PURCHASED PARTS			$ 2,340		Exhibit A
b. SUBCONTRACTED ITEMS					
c. OTHER—*(1)* RAW MATERIAL					
(2) YOUR STANDARD COMMERCIAL ITEMS					
(3) INTERDIVISIONAL TRANSFERS *(At other than cost)*					
TOTAL DIRECT MATERIAL				$ 2,340	
2. MATERIAL OVERHEAD[3] *(Rate %X$ base =)*				-0-	
3. DIRECT LABOR *(Specify)* *	ESTIMATED HOURS	RATE/ HOUR	EST COST ($)		
Senior Personnel a. P.I.-S.H.Ward 87 hrs.	780	$18.56	$14,480		
b. Co.I.-1)W.T.Parry 87 hrs. 2)J.A.Whelan					
173 hrs. 3)W.R.Sill 260 hrs. 4)D.D.Blackwell 173 hrs.					
Graduate Research Assistant	1,298	4.24	5,500		
Undergraduate Research Assistant	1,298	2.70	3,500		
Electronics Technician	173	5.92	1,025		
Secretarial *TOTAL DIRECT LABOR*	519	3.82	1,980	$26,485	
4. LABOR OVERHEAD *(Specify Department or Cost Center)*[3]	O.H. RATE	X BASE =	EST COST ($)		
61% of Salaries Wages and Employee					
Benefits	61%	$30,347	$18,513		
TOTAL LABOR OVERHEAD				$18,513	
5. SPECIAL TESTING *(Including field work at Government installations)*			EST COST ($)		
TOTAL SPECIAL TESTING				-0-	
6. SPECIAL EQUIPMENT *(If direct charge) (Itemize on Exhibit A)*				600	Exhibit A
7. TRAVEL *(If direct charge) (Give details on attached Schedule)*			EST COST ($)		
a. TRANSPORTATION			$ 6,105		
b. PER DIEM OR SUBSISTENCE			7,295		
TOTAL TRAVEL				$13,400	Schedule No. 1
8. CONSULTANTS *(Identify—purpose—rate)*			EST COST ($)		
TOTAL CONSULTANTS				-0-	
9. OTHER DIRECT COSTS *(Itemize on Exhibit A)*				$38,062	Exhibit A
10. *TOTAL DIRECT COST AND OVERHEAD*				99,400	
11. GENERAL AND ADMINISTRATIVE EXPENSE *(Rate % of cost element Nos.)*[3]				-0-	
12. ROYALTIES[3]				-0-	
13. *TOTAL ESTIMATED COST*				99,400	
14. FEE OR PROFIT				-0-	
15. *TOTAL ESTIMATED COST AND FEE OR PROFIT*				99,400	

*No new hires required

OPTIONAL FORM 60
October 1971
General Services Administration
FPR 1-16.806
5060-101

This proposal is submitted for use in connection with and in response to *(Describe RFP, etc.)*

Regional Heat Flow and Geochemical Studies in S. W. Utah

and reflects our best estimates as of this date, in accordance with the Instructions to Offerors and the Footnotes which follow.

TYPED NAME AND TITLE	SIGNATURE
NAME OF FIRM	DATE OF SUBMISSION

EXHIBIT A—SUPPORTING SCHEDULE *(Specify. If more space is needed, use reverse)*

COST EL NO.	ITEM DESCRIPTION *(See footnote 5)*		EST COST ($)
1 a.	Expendable Supplies and Equipment		$ 2,340.00
	1. Replacement Parts		
	a. Reels	$ 200.00	
	b. Cables	400.00	
	2. Laboratory Chemicals & Glassware	500.00	
	3. Electronic Parts	500.00	
	4. Wire	200.00	
	5. Office Supplies	240.00	
	6. Misc. Supplies	300.00	
6	Permanent Equipment		
	1. Impedance Bridge		600.00
9	Employee Benefits		3,862.00
	1. 19% of $17,485.00	$3,322.00	
	2. 6% of $9,000.00	540.00	
9	Publication Cost		1,200.00
	1. Drafting and Reproduction	$ 500.00	
	2. Report Preparation	700.00	
9	Computer Costs - 5 hours @ $600/hr.		3,000.00
9	Drilling Costs - (8) 200' holes @ $15/ft.		24,000.00
9	Equipment Use Charges		6,000.00
	1. Thermal Conductivity	$3,000.00	
	2. X-Ray and Geochemical Analysis of 100 Samples	3,000.00	

I. HAS ANY EXECUTIVE AGENCY OF THE UNITED STATES GOVERNMENT PERFORMED ANY REVIEW OF YOUR ACCOUNTS OR RECORDS IN CONNECTION WITH ANY OTHER GOVERNMENT PRIME CONTRACT OR SUBCONTRACT WITHIN THE PAST TWELVE MONTHS?

☒ YES ☐ NO *(If yes, identify below.)*

NAME AND ADDRESS OF REVIEWING OFFICE AND INDIVIDUAL	TELEPHONE NUMBER/EXTENSION
DHEW Audit Agency 225 So. 2nd East S.L.C. UT 84111	(801)524-4111

II. WILL YOU REQUIRE THE USE OF ANY GOVERNMENT PROPERTY IN THE PERFORMANCE OF THIS PROPOSED CONTRACT?

☐ YES ☒ NO *(If yes, identify on reverse or separate page)*

III. DO YOU REQUIRE GOVERNMENT CONTRACT FINANCING TO PERFORM THIS PROPOSED CONTRACT?

☒ YES ☐ NO *(If yes, identify.):* ☐ ADVANCE PAYMENTS ☒ PROGRESS PAYMENTS OR ☐ GUARANTEED LOANS

IV. DO YOU NOW HOLD ANY CONTRACT *(Or, do you have any independently financed (IR&D) projects)* FOR THE SAME OR SIMILAR WORK CALLED FOR BY THIS PROPOSED CONTRACT?

☐ YES ☒ NO *(If yes, identify.):*

V DOES THIS COST SUMMARY CONFORM WITH THE COST PRINCIPLES SET FORTH IN AGENCY REGULATIONS?

☒ YES ☐ NO *(If no, explain on reverse or separate page)*

See Reverse for Instructions and Footnotes

4.0 Research Contract Proposal Budget

Year Beginning June 1, 1976

	USGS Funded Man-Months				USGS Proposed Amount	U of U Cost Share
	Cal	Acad	Sum			
A. Salaries and Wages:						
1. Senior Personnel				$14,480.00		$ 2,766.00 (.60 MM)
a. P.I. S. H. Ward			.5			
b. Co.I. D. D. Blackwell			1.0			
c. Co.I. W. T. Parry			.5			
d. Co.I. W. R. Sill		1.5	1.0			
e. Co.I. J. A. Whelan			1.0			
2. Other Personnel						
a. Graduate Research Assistant				5,500.00		
100% 3 Summer Months			3.0			
50% 9 Academic Months		4.5				
b. Undergraduate Assistant				3,500.00		
100% 3 Summer Months			3.0			
50% 9 Academic Months		4.5				
c. Electronics Technician			1.0	1,025.00		
d. Secretarial		2.0	1.0	1,980.00		
Total Salaries and Wages		12.5	12.0		$ 26,485.00	
B. Employee Benefits:						
19% of Salaries and Wages less Research Assistants				$ 3,322.00		$ 526.00
6% Salaries and Wages Research Assistants				540.00		
Total Employee Benefits					$ 3,862.00	$ 526.00

			USGS Proposed Amount	U of U Cost Share
C.	Total Salaries and Wages and Employee Benefits:		$ 30,347.00	$ 3,292.00
D.	Permanent Equipment:			
	1. Impedance Bridge		$ 600.00	
E.	Expendable Supplies and Equipment			
	1. Replacement Parts			
	a. Reels	$ 200.00		
	b. Cables	400.00		
	2. Laboratory Chemicals & Glassware	500.00		
	3. Electronic Parts	500.00		
	4. Wire	200.00		
	5. Office Supplies	240.00		
	6. Misc. Supplies	300.00		
	Total Expendable Supplies and Equipment		$ 2,340.00	
F.	Travel			
	1. Vehicle Rental (3) 15,000 @ $.25/mile	$ 3,750.00		
	2. Vehicle Insurance	150.00		
	3. Vehicle Damage Repairs	500.00		
	4. Gasoline & Oil	250.00		
	5. Per Diem			
	a. 3 Persons for 60 Days Each @ $25/day	4,500.00		
	6. Supervisory Trips to Research Areas			
	a. 6 Trips @ $300/each	1,800.00		
	7. Research Area Local Labor (3 People for 20 Days)	1,650.00		
	8. Scientific Meetings (2)	800.00		
	Total Travel		$ 13,400.00	

		USGS Proposed Amount	U of U Cost Share
G. Publication Costs:			
1. Drafting and Reproduction	$ 500.00		
2. Report Preparation	700.00		
Total Publication Costs		$ 1,200.00	
H. Computer Costs:			
1. UNIVAC - 1108, 5 Hours @ $600/hour		$ 3,000.00	
I. Other Costs:			
1. Drilling Costs			
a. 8 Holes @ 200 feet deep @ $15/foot	$ 24,000.00		
2. Equipment Use Charges			
a. Thermal Conductivity	3,000.00		
b. X-ray and Geochemical analysis (100 samples @ $30/sample)	3,000.00		
Total Other Costs		$ 30,000.00	
J. Total Direct Costs:		$ 80,887.00	$ 3,292.00
K. Indirect Costs			
61% of Salaries and Wages and Employee Benefits		$ 18,513.00	$ 2,008.00
L. Total Costs:			
M. Total Estimated Project Cost:		$ 99,400.00	$ 5,300.00

5.0 Schedule No. 1 - Travel

Item No.	Destination or Purpose	No. of Trips	No. of Days	No. of People	Air Fare	Per Diem	Auto & Misc.	Total
1.	Vehicle Rental				$	$	$3,750.00	$3,750.00
2.	Vehicle Insurance						150.00	150.00
3.	Vehicle Damage Repairs						500.00	500.00
4.	Gasoline and Oil						250.00	250.00
5.	Field Research Area	1	60	3		4,500.00		4,500.00
6.	Field Research Area	6	7	1		1,050.00	750.00	1,800.00
7.	Field Research Area	3	20	1		1,500.00	150.00	1,650.00
8.	Scientific Meetings							
	a. West Coast	1	3	1	130.00	105.00	50.00	285.00
	b. East Coast	1	4	1	300.00	140.00	75.00	515.00
	Total				$430.00	$7,295.00	$5,675.00	$13,400.00

6.0 Current Federal Funded Research

	Project Title	Agency	Duration	Funding	P.I. and Co.I. Effort
1.	Workshop on Geophysics Applied to Detection, Delineation and Evaluation of Geothermal Resources (14-08-001-G-191)	USGS	5-22-75 to 5-21-76	$18,455.00	P.I. S.H. Ward 2%*
2.	Lunar Data Synthesis (NSG-7090)	NASA	7-1-74 to 6-30-76	102,400.00	P.I. S.H. Ward 2½%* 1 month summer Co.I.-W. R. Sill 40%
3.	Multifrequency Electromagnetic Exploration (GA 31021)	NSF	9-1-71 to 8-31-76	77,800.00	P.I. S.H. Ward 2%* .5 month summer Co.I-G. W. Hohmann 15% (no cost)
4.	Geothermal Exploration Systems and their Applications in Utah. (AER 74-01043 A01)	NSF	5-01-74 to 10-31-76	558,800.00	P.I. S.H. Ward 7%* .5 month summer Co.I.-W. T. Parry 3%* 1 month summer W.R. Sill 45% J.A. Whelan 3%* 1.5 months summer
5.	An Inductive Method of Electromagnetic Sounding of Water Bearing Strata (GA-24421)	NSF	10-1-70 to 7-31-76	102,500.00	P.I. S.H. Ward 2%* .5 month summer
6.	Operations of Telemetered Seismograph stations for Data Collection and Epicenter Determinations along the Wasatch Front, Utah (14-08-001-14107)	USGS	11-1-73 to 9-30-76	179,802.00	P.I. S.H. Ward 2½%*
7.	Regional Seismicity and Tectonics of the Southern Intermountain Seismic Belt, including the Wasatch Front (EAR 73-0055-02)	NSF	10-15-73 to 3-31-78	160,000.00	P.I. S.H. Ward 2%*

	Project Title	Agency	Duration	Funding	P.I. and Co.I. Effort
8.	Geophysical Studies of the Afro-Arabian Plate Foundry and Tectonics of Egypt (DES 75-21851)	NSF	9-1-75 to 8-31-77	74,800.00	P.I. D.D. Blackwell 11%
9.	Heat Flow Studies in Southern Mexico (GA-30590)	NSF	1-1-71 to 8-31-76	93,300.00	P.I. D.D. Blackwell 5%
10.	The Numerical Solution of Singular Integral Equations (DAHC-04-G-0175)	U.S. Army	7-1-74 to 6-30-77	30,757.00	P.I. F. Stenger 2 months summer
				$1,398,700	

* Academic Year - no cost

7.0 Proposals Submitted

	Project Title	Agency	Duration	Funding	P.I. and Co.I. Effort
1.	Deep Probing Electromagnetic System	NSF	1-1-76 to 12-31-76	$ 234,300	P.I.-S. H. Ward 1 Month Summer Co.I.-W. R. Sill 4 Months Summer
2.	Regional Heat Flow and Geochemical Studies in S.W. Utah	USGS	6-1-76 to 5-31-77	99,400	P.I.-S. H. Ward .5 Month Summer Co.I.'s- D. D. Blackwell 1 Month Summer W. T. Parry .5 Month Summer W. R. Sill 2.5 Months Summer J. A. Whelan 1 Month Summer
3.	Proposal for Workshop on Geothermal Case Histories	USGS	8-1-76 to 7-31-77	34,000	P.I.-S. H. Ward 2%*
4.	Forward and Inverse Interpretation of Multiple Electrical Data Sets Over Two-Dimensional Structures - Theoretical Development and Field Example	NSF	4-1-76 to 3-31-77	278,000	P.I.-S. H. Ward 1 Month Summer/yr. Co.I.'s - W. R. Sill 25% F. Stenger 1 Month Summer/yr. W. E. Mason, Jr. 2 Months Summer/yr. G. W. Hohmann 15% No Cost C. M. Swift, Jr. 15% No Cost

*Academic Year - No Cost

	Project Title	Agency	Duration	Funding	P.I. and Co.I. Effort
5.	Proposal for the Design of Continuously Monitoring Resistivity System	USGS	10-1-75 to 9-30-76	$ 29,900	P.I.-W. R. Sill 16% Co.I.-S. H. Ward .5 Month Summer
6.	The Numerical Solution of Singular Integral Equations	U.S. Army	7-1-76 to 6-30-77	16,000	P.I.-F. Stenger 2 Months Summer
				$671,600	

8.0 Attachments - Forms

a. Representations, Certifications, and Acknowledgements

b. Affirmative Action Program

c. Patent Information Checklist

REPRESENTATIONS, CERTIFICATIONS, AND ACKNOWLEDGMENTS

The Offeror represents and certifies as part of his offer that: *(Check or complete all applicable boxes or blocks.)*

1 SMALL BUSINESS *(See par. 14 on SF 33-A.)*

He ☐ is, ☒ is not, a small business concern. If offeror is a small business concern and is not the manufacturer of the supplies offered, he also represents that ll supplies to be furnished hereunder ☐ will, ☒ will not, be manufactured or produced by a small business concern in the United States, its possessions, or Puerto Rico.

2. REGULAR DEALER—MANUFACTURER *(Applicable only to supply contracts exceeding $10,000.)*

He is a ☐ regular dealer in, ☐ manufacturer of, the supplies offered.

3. CONTINGENT FEE *(See par. 15 on SF-33-A.)*

(a) He ☐ has, ☒ has not, employed or retained any company or person *(other than a full-time, bona fide employee working solely for the offeror)* to solicit or secure this contract, and (b) he ☐ has, ☒ has not, paid or agreed to pay any company or person *(other than a full-time bona fide employee working solely for the offeror)* any fee, commission, percentage, or brokerage fee contingent upon or resulting from the award of this contract; and agrees to furnish information relating to (a) and (b) above, as requested by the Contracting Officer. *(For interpretation of the representation, including the term "bona fide employee," see Code of Federal Regulations, Title 41, Subpart 1-1.5.)*

4. TYPE OF BUSINESS ORGANIZATION

He operates as ☐ an individual, ☐ a partnership, ☒ a nonprofit organization, ☒ a corporation, incorporated under the laws of the State of ______________________________

5. AFFILIATION AND IDENTIFYING DATA *(Applicable only to advertised solicitations.)*

Each offeror shall complete (a) and (b) if applicable, and (c) below:

(a) He ☐ is, ☒ is not, owned or controlled by a parent company. *(See par. 16 on SF 33-A.)*

(b) If the offeror is owned or controlled by a parent company, he shall enter in the blocks below the name and main office address of the parent company.

Name of Parent company and main office address ______________________________

(include ZIP Code) ______________________________

(c) Employer's identification number *(See par. 17 on SF 33-A.)* ____________________ *(Offeror's E.I. No.)* ____________________ *(Parent Company's E.I. No.)*

6. EQUAL OPPORTUNITY

He ☒ has, ☐ has not, participated in a previous contract or subcontract subject either to the Equal Opportunity clause herein or the clause originally contained in section 301 of Executive Order No. 10925, or the clause contained in section 201 of Executive Order No. 11114, that he ☒ has, ☐ has not, filed all required compliance reports, and that representations indicating submission of required compliance reports, signed by proposed subcontractors, will be obtained prior to subcontract awards. *(The above representation need not be submitted in connection with contracts or subcontracts which are exempt from the clause.)*

7 BUY AMERICAN CERTIFICATE

The offeror hereby certifies that each end product, except the end products listed below, is a domestic source end product (as defined in the clause entitled "Buy American Act"), and that components of unknown origin have been considered to have been mined, produced, or manufactured outside the United States.

XCLUDED END PRODUCTS	COUNTRY OF ORIGIN

CERTIFICATION OF INDEPENDENT PRICE DETERMINATION *(See par. 18 on SF 33-A.)*

(a) By submission of this offer, the offeror certifies, and in the case of a joint offer, each party thereto certifies as to its own organization, that in connection with this procurement:

(1) The prices in this offer have been arrived at independently, without consultation, communication, or agreement, for the purpose of restricting competition, as to any matter relating to such prices with any other offeror or with any competitor;

(2) Unless otherwise required by law, the prices which have been quoted in this offer have not been knowingly disclosed by the offeror and will not knowingly be disclosed by the offeror prior to opening in the case of an advertised procurement or prior to award in the case of a negotiated procurement, directly or indirectly to any other offeror or to any competitor; and

(3) No attempt has been made or will be made by the offeror to induce any other person or firm to submit or not to submit an offer for the purpose of restricting competition.

(b) Each person signing this offer certifies that:

(1) He is the person in the offeror's organization responsible within that organization for the decision as to the prices being offered herein and that he has not participated, and will not participate, in any action contrary to (a) (1) through (a) (3) above, or

(2) (i) He is not the person in the offeror's organization responsible within that organization for the decision as to the prices being offered herein but that he has been authorized in writing to act as agent for the persons responsible for such decision in certifying that such persons have not participated, and will not participate, in any action contrary to (a) (1) through (a) (3) above, and as their agent does hereby so certify; and (ii) he has not participated, and will not participate, in any action contrary to (a) (1) through (a) (3) above.

CERTIFICATION OF NONSEGREGATED FACILITIES

(Applicable to (1) contracts, (2) subcontracts, and (3) agreements with applicants who are themselves performing federally assisted construction contracts, exceeding $10,000 which are not exempt from the provisions of the Equal Opportunity clause.)

By the submission of this bid, the bidder, offeror, applicant, or subcontractor certifies that he does not maintain or provide for his employees any segregated facilities at any of his establishments, and that he does not permit his employees to perform their services at any location, under his control, where segregated facilities are maintained. He certifies further that he will not maintain or provide for his employees any segregated facilities at any of his establishments, and that he will not permit his employees to perform their services at any location, under his control, where segregated facilities are maintained. The bidder, offeror, applicant, or subcontractor agrees that a breach of this certification is a violation of the Equal Opportunity clause in this contract. As used in this certification, the term "segregated facilities" means any waiting rooms, work areas, rest rooms and wash rooms, restaurants and other eating areas, time clocks, locker rooms and other storage or dressing areas, parking lots, drinking fountains, recreation or entertainment areas, transportation, and housing facilities provided for employees which are segregated by explicit directive or are in fact segregated on the basis of race, color, religion or national origin, because of habit, local custom, or otherwise. He further agrees that (except where he has obtained identical certifications from proposed subcontractors for specific time periods) he will obtain identical certifications from proposed subcontractors prior to the award of subcontracts exceeding $10,000 which are not exempt from the provisions of the Equal Opportunity clause; that he will retain such certifications in his files; and that he will forward the following notice to such proposed subcontractors (except where the proposed subcontractors have submitted identical certifications for specific time-periods):

Notice to prospective subcontractors of requirement for certifications of nonsegregated facilities.

A Certification of Nonsegregated Facilities must be submitted prior to the award of a subcontract exceeding $10,000 which is not exempt from the provisions of the Equal Opportunity clause. The certification may be submitted either for each subcontract or for all subcontracts during a period (e.g., quarterly, semiannually, or annually). *NOTE: The penalty for making false statements in offers is prescribed in 18 U.S.C. 1001.*

ACKNOWLEDGMENT OF AMENDMENTS	AMENDMENT NO.	DATE	AMENDMENT NO.	DATE
The offeror acknowledges receipt of amendments to the Solicitation for Offers and related documents numbered and dated as follows				

NOTE —*Offers must set forth full, accurate, and complete information as required by this Solicitation (including attachments). The penalty for making false st*

Standard Form 33, continued:

10. AFFIRMATIVE ACTION PROGRAM: The offeror represents that (check one):

(1) he (x) has developed and has on file, or (2) he ( ) has not developed and does not have on file at each establishment affirmative action programs as required by the rules and regulations of the Secretary of Labor, or (3) he ( ) has not previously had contracts subject to the written affirmative action program requirement of the rules and regulations of the Secretary of Labor.

The following certification is required to be included with all offers:

(a) Have you participated in any contractual agreement which contained the Equal Employment Opportunity Clause prescribed in Section 202 of Executive Order 11246? Yes X No ____ If answer to (a) is yes, answer question (b).

(b) Were you required pursuant to the Rules and Regulations on Equal Employment Opportunity (41 CFR 60-1) to file a compliance report as the result of such contractual agreement? Yes X No ____ If answer to (b) is yes, answer question (c).

(c) Did you file the necessary compliance report in accordance with the instructions contained on the appropriate report form? Yes X No ____
If answer to (c) is yes, answer question (d). Date filed: ____

(d) Name of agency requiring report Regional Office of HEW.

(e) Has any action been required of you to improve your compliance posture?
Yes ____ No X

(f) How many persons are currently employed by you and your affiliates?
Number of Persons: 9627.

PATENT INFORMATION CHECKLIST

To be completed by Prospective Contractor and returned with your proposal.

1. Is your organization known as manufacturer or source of products or services in the area involved? Yes ______ No X ______

2. Is your organization regularly engaged in the sale, whether domestic or foreign, of such products or services to the general public and the Government? Yes ______ No X ______

3. Does your organization have a record of developing non-Government commercial markets for inventions in the area involved?

Yes ______ No X ______

4. Does your organization have an "established non-Government commercial position" in the area involved? Yes ______ No X ______

5. Is your organization an educational or nonprofit institution having an established patent policy approved by DOD? Yes X ______ No ______

6. Is your organization a research and development corporation formed within the last five years for establishing a non-Governmental commercial position directly related to this field of technology?

Yes ______ No X ______

7. Is your organization an independent research and development division of and created by a parent corporation within the last five years as a non-Governmental commercial antity in the field of technology directly related to this Procurement? Yes ______ No X ______

Signed ____________________

RECEIVED
Geophysics Division Operations
JUL 13 1976

THE UNIVERSITY OF UTAH

COLLEGE OF MINES
AND MINERAL INDUSTRIES

DEPARTMENT OF GEOLOGY
AND GEOPHYSICS
717 MINERAL SCIENCE BUILDING

July 8, 1976

H. L. Bauer, Jr.
Bear Creek Mining Company
1826 Kennecott Building
10 East South Temple
Salt Lake City, Utah 84133

Dear Herm:

Thank you very much for your letter of July 1, 1976. I shall contact Paul L. Hunter to seek access to drill holes which might *not* involve Steam Corporation of America or Phillips Petroleum Company permission. Mr. Arentz has expressed a desire that we *defer* our work on KCC/SCA/Phillips properties; we shall abide by that desire (cc. letter attached).

Our research depends entirely upon cooperation of members of the resource industry. Accordingly, we shall always appreciate their help while acknowledging their restrictions.

Your help is most sincerely appreciated.

Yours sincerely

Stan

Stanley H. Ward
Chairman

SJW:mkd

cc: Samuel S. Arentz
Paul L. Hunter
P.M. Wright
J.C. Wilson

SALT LAKE CITY 84112

RECEIVED
Geophysics Division Operations
JUL 13 1976

THE UNIVERSITY OF UTAH

COLLEGE OF MINES
AND MINERAL INDUSTRIES

DEPARTMENT OF GEOLOGY
AND GEOPHYSICS
717 Mineral Science Building

July 8, 1976

Mr. Paul L. Hunter
General Manager
Tintic Division
Kennecott Copper Corporation
2300 West 1700 South
Salt Lake City, Utah

Dear Mr. Hunter:

You have received a copy of Herm Bauer's letter of July 1, 1976. I understand from W.R. Sill that you have also spoken with Sill and Arentz's in Eureka. Hence you know that we seek drill holes in which we might measure thermal gradients in available drill holes. Mr. Arentz has expressed a desire that we defer our activities (see copy of letter attached) in which both Steam Corporation of America and Phillips Petroleum Corporation have a joint interest. It is our intent to recognize this desire. Hence, we wish to express our interest in access to any drill holes in your Division which are not covered under the KCC/SCA/Phillips agreements. Your early advice on this matter would be sincerely appreciated.

Yours sincerely,

Stan Ward

Stanley H. Ward
Chairman

SHW:mkd

cc: H.L. Bauer, Jr.
S.S. Arentz, Jr.
P.M. Wright ✓
J.C. Wilson

SALT LAKE CITY 84112

STEAM CORPORATION OF AMERICA
1720 BENEFICIAL LIFE TOWER
SALT LAKE CITY, UTAH 84111
(801) 533-8333

July 2, 1976

D. Stanley Ward, Chairman
Department of Geology and Geophysics
College of Mines and Mineral Industries
University of Utah
Salt Lake City, Utah 84112

Dear Stan:

Confirming our telephone conversation this morning, I will appreciate your deferring work on the area covered by our geothermal leases in the Tintic area for the time being.

We have entered into a joint venture agreement with Phillips Petroleum Company covering our leases in the area, and that company presently has several crews working in the area.

We have greatly appreciated your cooperation and the work your department is doing in this important field, and I will make the area accessible to your personnel at the earliest possible date.

With kindest regards,

Sincerely yours,

Samuel S. Arentz

SSA:cl

RECEIVED
Geophysics Division Operations
JUL 13 1976

THE UNIVERSITY OF UTAH

COLLEGE OF MINES
AND MINERAL INDUSTRIES

DEPARTMENT OF GEOLOGY
AND GEOPHYSICS
717 Mineral Science Building

July 8, 1976

Mr. Paul Mogensen, Manager
Southwest Tintic Division
Bear Creek Mining Company
1826 Kennecott Building
10 East South Temple
Salt Lake City, Utah 84133

Dear Mr. Mogensen:

Herm Bauer has suggested that I contact you concerning the availability of drill holes, in the Southwest Tintic District, for thermal gradient measurements. We would like to put a thermal probe into any hole in which a reliable thermal gradient can be otained and for which representative drill core or outcrop samples can be made available. Mike Wright, who completed his Ph.D. dissertation in terrestrial heat flow, has offered to provide the background information on our studies.

Your early cooperation would be appreciated.

Yours sincerely,

Stan Ward

Stanley H. Ward
Chairman

SHW:mkd

cc: H.L. Bauer, Jr.
P.M. Wright. ✓
J.C. Wilson

SALT LAKE CITY 84112

→ PMW for your info

Bear Creek Mining Company

Head Office

H. L. BAUER, JR.
PRESIDENT

July 1, 1976

Mr. S. H. Ward, Chairman
College of Mines & Mineral Industries
Department of Geology & Geophysics
University of Utah
717 Mineral Science Building
Salt Lake City, Utah 84112

Dear Stan:

Utah: Tintic - Geothermal

With reference to your letter of June 22, Kennecott and Bear Creek would like to enhance your Department's study of heat flow in the state by making available accessible drill holes in the Tintic District. We will require certain restraints on publication of data pertaining to mineralization, but this should not interfere with your study. John Costain made heat flow measurements at Bingham under the same conditions.

With regard to available holes at Kennecott's Tintic Division, contact should be made directly with the General Manager, Mr. Paul L. Hunter. Tintic Division has leased out its geothermal rights and Phillips Petroleum is now operator of the lease. It may be necessary for you to get concurrence from Phillips to conduct the heat flow measurements, but I suggest you take this matter up with Mr. Hunter.

With regard to Bear Creek's Southwest Tintic Project, Paul Mogensen, Tintic Division, is willing to handle this for us and direct you to holes that may be open. The people who will be running the survey must make certain not to drop anything in the holes as we wish to maintain them for deeper drill testing. Furthermore, all holes should be securely capped when not running instruments down them.

Our Geophysics people at Kennecott Exploration Services will be interested in learning of your results.

Sincerely,

ORIGINAL SIGNED BY
H. L. BAUER, JR.

H. L. Bauer, Jr.

HLB:ps

cc: R. C. Babcock
P. L. Hunter
A. P. Mogensen
J. C. Wilson

COLLEGE OF ARTS AND SCIENCES

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Blacksburg, Virginia 24061

DEPARTMENT OF GEOLOGICAL SCIENCES

June 26, 1971

Dr. P. M. Wright
Kennecott Copper Corporation
2300 West 1700 South
Salt Lake City, Utah 84104

Dear Mike:

At long last here is the paper including the Bingham hole. This is a preliminary copy only. I will be in Utah in a few weeks and would like to discuss some points with you including a) how much I can say about the lithology and stratigraphy, b) exact location, c) cause of the distinct change in the gradient at about 1,000 meters.

There is some additional work to be done on the thermal conductivity measurements since I was not able to get most of the samples prepared before I left. I have them all now, however, and will finish the conductivity measurements when I get back. Also, the topographic correction needs more work. I would like to submit the paper to the JGR at the end of August, and thought we could save some time by getting a preliminary copy to you now. You will probably prefer to wait until the final draft is ready before submitting it to Kennecott management for approval.

See you in a few weeks.

Sincerely yours,

John

John K. Costain
Professor of Geophysics

JKC:cc

HEAT FLOW AT SPOR MOUNTAIN, JORDAN VALLEY, BINGHAM, AND LA SAL, UTAH

by

John K. Costain and P. M. Wright

ABSTRACT

Geothermal gradients were determined in 20 holes in Utah at Spor Mountain, Enterprise, La Sal, Monticello, Bingham, and Jordan Valley. Temperatures were measured using platinum and thermistor probes. The resistance of the probe was compared with primary resistance standards accurate to ±0.001%. Thirteen of the 20 holes are believed to be disturbed by shallow ground water effects. Thermal conductivity was measured on rock discs using a divided-bar apparatus. The discs were machined from drill core and from bulk rock specimens. A heat flow value of 2.8 μcal/cm^2-sec was found at Spor Mountain (39°43' N. Lat., 113°13' W. Long.). This value may be subject to revision because of possible circulation of warm ground water in the area. A heat flow value of 1.8 μcal/cm^2-sec was estimated at Jordan Valley (40°47.0' N. Lat., 112°04.3' W. Long.). The heat flow at La Sal (38°14.3' N. Lat., 109°16.3' W. Long.) was found to be 1.2 ±0.2 μcal/cm^2-sec, and is believed to be representative for that area. Terrain corrections calculated for La Sal were approximately 3% of the gradient. The heat flow at Bingham (40°32' N. Lat., 112°09' W. Long.) is 2.5* ±0.21 μcal/cm^2-sec.

estimate - see inside

INTRODUCTION

Temperatures were measured in 20 holes at Spor Mountain, Enterprise, La Sal, Monticello, Bingham, and Jordan Valley, Utah. Figure shows the published heat flow determinations made to date in Utah, including the new values in this paper. With these determinations, several values are now available for the Colorado Plateau province and for the Basin and Range province in Utah. In Figure , solid circles denote areas where a heat flow value has been determined, and open circles mark areas where only the geothermal gradient was measured. Temperatures were measured in five holes in the Enterprise area, and in one hole near Monticello, San Juan County. In the Enterprise and Monticello areas, the temperature gradients were disturbed by shallow ground water circulation, and no further interpretion of these holes was justified. Details of these measurements can be found in Wright (1966).

TEMPERATURE MEASUREMENTS

For the holes at Spor Mountain, Jordan Valley, and La Sal, we used a platinum resistance thermometer, Model 134HH, made by Rosemount Engineering Company, with a nominal ice-point resistance of 1,000 ohms. Initial calibration of this probe by Rosemount Engineering Company at temperatures of 0° C ±0.015° C, 50° C ±0.02° C, and 100° C ±0.02° C gave probe resistances of 999.99 ohms, 1197.38 ohms, and 1391.89 ohms, respectively. The International Practical Temperature Scale of 1948 for platinum resistance thermometers used in the range 0° C to 630.5° C (Berry, 1962; Robertson and Walch, 1962) is based on the Callendar equation

$$T = \frac{(R_T - R_0)}{\alpha R_0} + \delta \frac{(T-1)}{100} \cdot \frac{(\ T\ )}{100}$$

General Location Map goes here.

where

R_T = resistance at temperature T (°C)

R_0 = resistance at 0° C, i.e., the ice-point resistance

α = the "fundamental" coefficient of a platinum thermometer obtained by calibration of the probe

δ = the Callendar coefficient, obtained by calibration o the probe

Typical values of α and δ are 0.0039261 and 1.495, respectively.

A change in temperature of 0.01° C corresponds, for the 1,000-ohm element, to a change in resistance of approximately 0.036 ohm. Any system used to measure resistance must therefore be able to detect a change in resistance of this magnitude in order to resolve temperature changes as small and smaller than 0.01° C. In order to measure temperature to an accuracy of ±0.01° C at, say, 50° C using a conventional Wheatstone bridge this means measuring the resistance of a probe whose nominal ice-point resistance is 1,000 ohms to an accuracy of 1197.38 ±0.036 ohms, or to about 0.003%. The individual bridge decades can be calibrated to this accuracy. However, because of the limited resistance range that will be encountered in the field using a 1,000-ohm platinum probe, about 390 ohms for the temperature range from 0° C-100° C, it is possible to compare the resistance of the probe with the constant resistance of an accurate primary standard for which the resistance is known to ±0.001%. For all of the holes except the one at Bingham, we used a comparison bridge, Model DBR-1, manufactured by the RdF Corporation, Hudson, New Hampshire. This bridge balances out most of the probe resistance with a primary standard resistance accurate to ±0.001%. That is, if the nominal resistance of the probe is 1,000, 2,000, or 5,000, ohms, then the resistance of the primary standard is 1,000.00, 2,000.00, or 5,000.00 ohms, respectively. The standards were calibrated by the manufacturer, by a secondary standards laboratory, and by the National Bureau of Standards. The final balance is achieved using the Rubicon decade resistances in the bridge. These resistances are variable from 0 to 99.99 ohms in steps of 0.01 ohm, and can be switched into either of the lower two arms of the bridge so that the decade resistance can be either added to or subtracted from the primary standard. The resistance of the decade is varied until the bridge is balanced. A null detector with a sensitivity of 0.01 microamp per scale division will detect a bridge unbalance of 0.01 ohm. For a temperature of 50° C, and taking into account the accuracy of the decade (±0.05%) this gives a probe resistance, R_p of

$$\begin{aligned} R_p &= (1000.00 \pm 0.010) + (50.23 \pm 0.025) \\ &= 1050.23 \pm 0.035 \text{ ohms} \end{aligned}$$

or an accuracy of about 0.003%. This is the optimum accuracy that could be hoped for in measuring absolute values of temperatures. It is unlikely that temperatures measured in drill holes using this system will be more accurate than several hundredths of a Centigrade degree for other reasons discussed below. However, relative values, or precision, will be more accurate. We believe the accuracy of our temperature measurements with the 1,000-ohm probe to be ±0.05° C, and the precision to be 0.003° C. The hole at Bingham was logged using a 5,000-ohm platinum resistance probe with a precision of about 0.001° C.

Terminals on the DBR-1 resistance comparison bridge for connection to three lead wires effectively place the battery of the bridge in the circuit at the sensor elements, and a lead-wire resistance appears in each lower arm of the bridge. If the resistances of the lead wires in the 4-conductor cable were equal then automatic compensation for lead-wire resistance would be obtained. However, measurement showed that none of the resistances of the four cable conductors was the same, and a switching scheme was devised so that lead-wire resistance could be eliminated. Switching was provided by a Leeds and Northrup rotary switch with very low contact resistance so that any two of the four lead wires could be used for these averages. Thus, four probe resistance readings resulted from using all possible combinations of lead wires. During field measurements these four resistance determinations always agreed to within 0.01 ohm.

Different apparatus was used at the Bingham, Utah hole, and we are now using a Honeywell 1551-E Mueller bridge in conjunction with Electroscientific Industries SR-1 standard resistors, which are accurate to 0.001%. A Honeywell 3972 DC microvolt null detector is used to balance the bridge. The Mueller bridge also allows balancing out most of the resistance of the probe with an external primary standard resistance. The final balance is then achieved using decades built into the bridge.

Most workers in heat flow use thermistors for temperature measurement, and it will be in order here to discuss the suitability of platinum for temperature measurements in deep holes. We have consistently obtained excellent results using platinum. For example, periodic relogging of hole (B-1-2) 28dcc-1 near Salt Lake City over a period of two years showed differences in absolute temperature at any given depth of no more than ±0.03° C, using probes of different ice-point resistances made by different manufacturers. This accuracy has always prevailed for repeat measurements in every hole measured, regardless of depth, and using probes of nominal ice-point resistances of 1,000, 2,000, and 5,000 ohms made by different manufacturers. Gradients have always repeated to within 2% or better. There are disadvantages in using platinum; bridge calibration and galvanometer sensitivity become more critical because of the lower resolution of platinum as compared with thermistors, and, for the probes we have been using, the time constants are longer. Many repeat measurements in several holes confirm that the calibration curve for platinum does shift slightly, but that it shifts parallel to itself, and the constant shift can be determined by noting the change in the ice-point resistance. The shift is apparently related to the amount and type of mechanical shock received by the probe over the years. For short intervals in a drill hole, the resolution afforded by thermistors is a definite advantage, and we have now essentially shifted to thermistors because of the better resolution and faster time constants. We have compared some of our gradients measured at Bingham, Utah, using platinum with those obtained using a Fenwal K-1868 thermistor with an ice-point resistance of about 11,000 ohms and resistance of about 4,800 ohms at 20° C. The differences are negligible.

For the holes at Spor Mountain, Jordan Valley, and La Sal, we used U.S. Steel 4-H-1 double-armored Amergraph cable. This is a heavy cable with a resistance of about 15 ohms per thousand feet and a breaking strength of 7,200 pounds. The leakage resistance of our 1,000-foot Amergraph cable was always greater than 50 megohms and usually greater than 100 megohms. The cable was marked at 5-meter intervals. Tests made by the Mechanical Engineering Department at the University of Utah established that the cable stretch was about 0.03 percent when the 1,000-foot cable hung fully extended under its own weight of 142 pounds per

1,000 feet. Depths at which temperatures are reported in this paper using the armored cable should therefore be accurate to better than 0.1 meter, the maximum expected stretch for the cable. We have since changed to lighter, more portable cables, and are now using Vector 4-conductor types A342198 and B128465.

A capstan hoist was used to bring the armored cable out of the hole. The diameter of the capstan is 16 inches and the capstan is powered by a 2-hp, 110-volt electric motor with a speed variable from zero to 90 feet per minute. The maximum direct-lift capability of the hoist is about 1,800 pounds. Power is supplied by a 3,000-watt, 110-volt gasoline-driven alternator. The use of a capstan hoist permits storing the cable on the take-up reel under very little tension since most of the tensional stress that is present in the cable while it is being raised is relieved in the several wraps of cable around the capstan. Relieving the stress is not as important when using the lighter Vector cables.

The vehicle used for the field work, a 1965 Chevrolet panel truck, is air-conditioned and thermally insulated with polyurethane. The back end is fitted with a removeable polyurethane insulated door which is generally in place during logging operations. This makes it possible to control the inside temperature to within about 3° C during field measurements. Temperature control minimizes changes in the resistance of the primary standards and the bridge due to temperature variations. The temperature coefficient of resistance of the Julie primary standard resistances was less than 0.0007 ohm/°C. over the range 20° C to 30° C

MEASUREMENT OF THERMAL CONDUCTIVITY

Of the several methods that have been used to measure the thermal conductivity of rocks (Beck, 1965) the most common method is the stacked, divided-bar apparatus described by Birch (1950). The apparatus constructed by us for our work is designed after that used in the Hoffman Laboratory at Harvard University.

Rock discs 0.875, 1.180, 1.305, and 1.425 inches in diameter were commercially prepared from rock samples. The surfaces of the discs were machined flat and parallel to ±0.0003 inch with diameters uniform and accurate to ±one percent. Copper-constantan thermocouples were inserted into copper discs to measure the temperature differences across the quartz and across the rock specimen. Thermal resistance at the contacts between the discs was reduced by applying a thin layer of Vaseline to the disc faces. Thermal resistance was further reduced by applying an axial pressure of 200 bars to the stack. In order to ensure axial heat flow and minimize radial heat loss the stack was insulated with a tight-fitting block of high-density Polystyrene. A temperature differential of about 15° C was applied across the stack. Measurements of the emf drop across each quartz disc and across the rock specimen were made with a Leeds and Northrup K-3 potentiometer. The temperature difference across the stack was held constant by Lauda K-2/R and Colora NB thermostatically controlled temperature baths. All of our conductivity measurements are relative to the value for fused quartz, although the thermal conductivities of several specimens were also measured using crystalline quartz and found to agree with the values obtained from fused quartz to within two percent or less.

Each time the stack is assembled to measure a new sample or to repeat a measurement, there is no assurance that exactly the same conditions of thermal resistance, thermocouple seating, or radial heat loss can be duplicated. However, repeat measurements on the same rock disc were almost always reproducible to within two percent.

For some of the more porous rock discs, it was found that the Vaseline would soak into the rock during measurement, leaving only a small area of good contact. After the disc had been measured a few times, less Vaseline would be absorbed, and a progressively better contact would result. This had the effect of causing the apparent rock conductivity to increase with successive measurements until the faces of the discs no longer absorbed Vaseline. When this "equilibrium" state was reached, reproducibility of measurement was almost always within two percent.

In order to obtain a more uniform contact, and to prevent Vaseline from being absorbed by the specimen, a thin foil of aluminum 0.001" thick was bonded to the flat faces of some of the discs with epoxy cement. Curing of the epoxy was completed at room temperature under about 5,000 psi for at least 12 hours. This resulted in a good bond and a smooth, mirror-like disc face. Vaseline was used as a contact substance between these aluminum-surfaced discs and the copper discs of the stack. Measurements made in this manner were reproducible to about 0.5 percent. Several discs which had been measured without the aluminum foil coating were later surfaced as described above. The thermal conductivity results were the same, within about two percent, as those which had been obtained after the disc had stopped absorbing Vaseline. Repeatibility was also improved by epoxying the copper discs to the quartz reference discs using silver epoxy cement.

Reproducibility of measurement is not necessarily an indication that the measured value is correct. It is difficult to assign an absolute accuracy to the measurements. Roy (1963, p. 7) states that "systematic and random errors in the measurement of a single disc amount to ±5 percent." It seems likely that this figure would also apply to our conductivity apparatus.

RESULTS

Geothermal gradients measured in a borehole are not always suitable for heat flow determinations. A negative gradient or a near-zero gradient is often the result of shallow ground water disturbances, i.e., the holes were not deep enough to obtain a regionally representative geothermal gradient. Indeed, it is not always possible to be certain when the gradient is representative. Ideally, for laterally isotropic layered rock sequences, if the vertical heat flow remains constant along the length of the borehole, then the product of the geothermal gradient and the thermal conductivity should be the same anywhere in the hole. Roy, Decker, Blackwell and Birch (1968, p. 5213) give an excellent correlation between lithology, gradient and conductivity over a thickness of 120 meters of layered argillites and quartzites. Their work also points out the potential usefulness of precision temperature measurements as an aid in stratigraphic correlation.

Detailed sampling of the rocks for thermal conductivity measurements is not always possible, and if only a limited number of heat flow determinations can be made from a borehole, then the samples for thermal conductivity measurements should be selected from those intervals in the hole where the gradient is uniform. Furthermore, thermal conductivity should be measured in the laboratory under conditions of temperature and water saturation similar to the environment from which the rock was taken (Birch and Clark, 1940; Walsh and Decker, 1966).

The overall accuracy of the heat flow measurements reported herein is probably 10-15%. If the rock discs on which the thermal conductivity measurements are made are known to be representative of the rock as a whole, if the geothermal gradients are stable and are not disturbed by ground water movement, if isotherms are not refracted by local geology, and if geological corrections for uplift, erosion and topography can be properly made, then a higher accuracy could be realized, probably to within five percent.

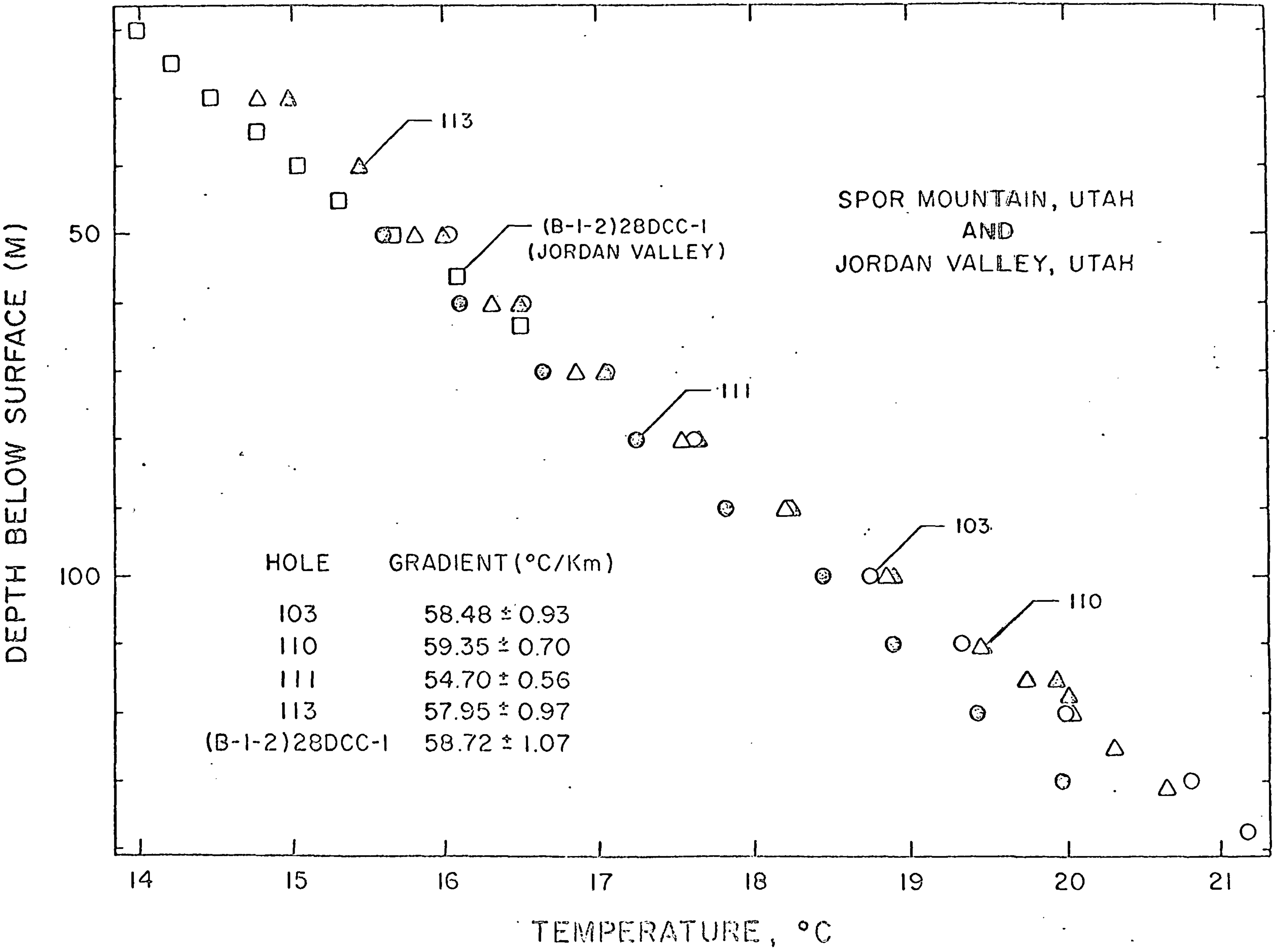
The heat flow determinations at Spor Mountain, Jordan Valley and La Sal point out some problems encountered in obtaining a heat flow determination. No core was available for thermal conductivity measurements for the holes at La Sal, Utah, and conductivity was measured from bulk rock specimens that were representative of the rock penetrated in the boreholes. The holes at Spor Mountain, Utah, were dry when drilled and when measured, and thermal conductivity measurements on rock discs from these areas were made on specimens that were in a shelf-dried condition. The hole at Jordan Valley, Utah, was drilled into unconsolidated sediments for which the thermal conductivity had to be estimated. Shallow ground water disturbances might be affecting the heat flow determination at Spor Mountain. The results of all of the measurements are shown on Figure . Geothermal gradients for all holes were computed by fitting a least squares straight line to points on the temperature vs. depth curve.

Spor Mountain. Spor Mountain is in the central part of Juab County, Utah, in the Basin and Range province. Temperatures were measured in five holes drilled by the Brush Beryllium Company in the Topaz Mountain Tuff. (Lat. 39°43' N., Long. 113°13' W.).

Four of these holes were within 1,500 feet of each other and had an average gradient of 58° C /km. The fifth hole (Hole 106) located 2,000 feet to the north was found to have a lower gradient of 47° C /km. Figure shows the temperature profiles obtained for all holes except Hole 106. The reason for the difference between this hole and the holes to the south is not clear. Wright (1966) discusses in detail possible reasons for the difference.

Thermal conductivity values were determined for 20 rock discs from the Spor Mountain area. These discs were cut from nine rock specimens. Specimens 10SM66 through 14SM66 (Table 1) were pieces of core from Hole 110, taken over the depth interval from 120 meters to 127 meters. Temperatures were measured over this interval in Hole 110. Specimens 15SM66 through 17SM66 were core specimens from Hole 111, but they were from a depth interval deeper than the deepest temperatures measurement in that hole. Specimens 18SM66 were blocks taken from outcrops near Holes 110, 113, 103. All of the rock specimens are representative of the volcanic Topaz Mountain Rhyolite. Table 1 also lists results of the thermal conductivity measurements on rocks from the Spor Mountain area. The average value is 5.4 mcal/cm-sec-°C

A geothermal gradient of 58° C /km and a rock conductivity of 5.4 mcal/cm-sec-°C give a heat flow of 3.1 μcal/cm^2-sec. It is difficult to place error limits on this value because it is not known how closely the 58° C./km gradient represents the actual regional,



HOLE	GRADIENT (°C/Km)
103	58.48 ± 0.93
110	59.35 ± 0.70
111	54.70 ± 0.56
113	57.95 ± 0.97
(B-1-2)28DCC-1	58.72 ± 1.07

Disc Number	Thickness (inches)	Conductivity (mcal/cm-sec-°C)	Location	Remarks
10SM66	1/2	5.51	Hole 110 (123m)	no prominent banding
11SM66-1	1/2	5.36		
11SM66-2	3/4	5.50	Hole 110 (123m)	contorted banding
11SM66-3	1	5.52		
13SM66	3/4	3.78	Hole 110 (125m)	volcanic breccia, fragments to 1 cm.
14SM66-1	1/2	5.49		
14SM66-2	3/4	5.46	Hole 110 (127m)	no prominent banding
14SM66-3	1	5.43		
15SM66-1	1/2	6.21	Hole 111	3 bonds, 1/4" wide
15SM66-2	3/4	6.25	below 130 m	45° to disc
16SM66-1	1/2	6.43	Hole 111	1 band, 1/2" wide
16SM66-2	1	6.63	below 130 m	70° to disc axis
17SM66-1	1/2	5.46	Hole 111	
17SM66-2	3/4	5.66	below 130 m	
18SM66-1	1/2	4.63		
18SM66-2	1	4.64	surface	no banding
18SM66-3	1-1/2	4.73		
19SM66-1	1/2	5.47		
19SM66-2	1	5.63	surface	no banding
19SM66-3	1-1/2	5.63		

Table 1. Conductivity measurements from Spor Mountain area.

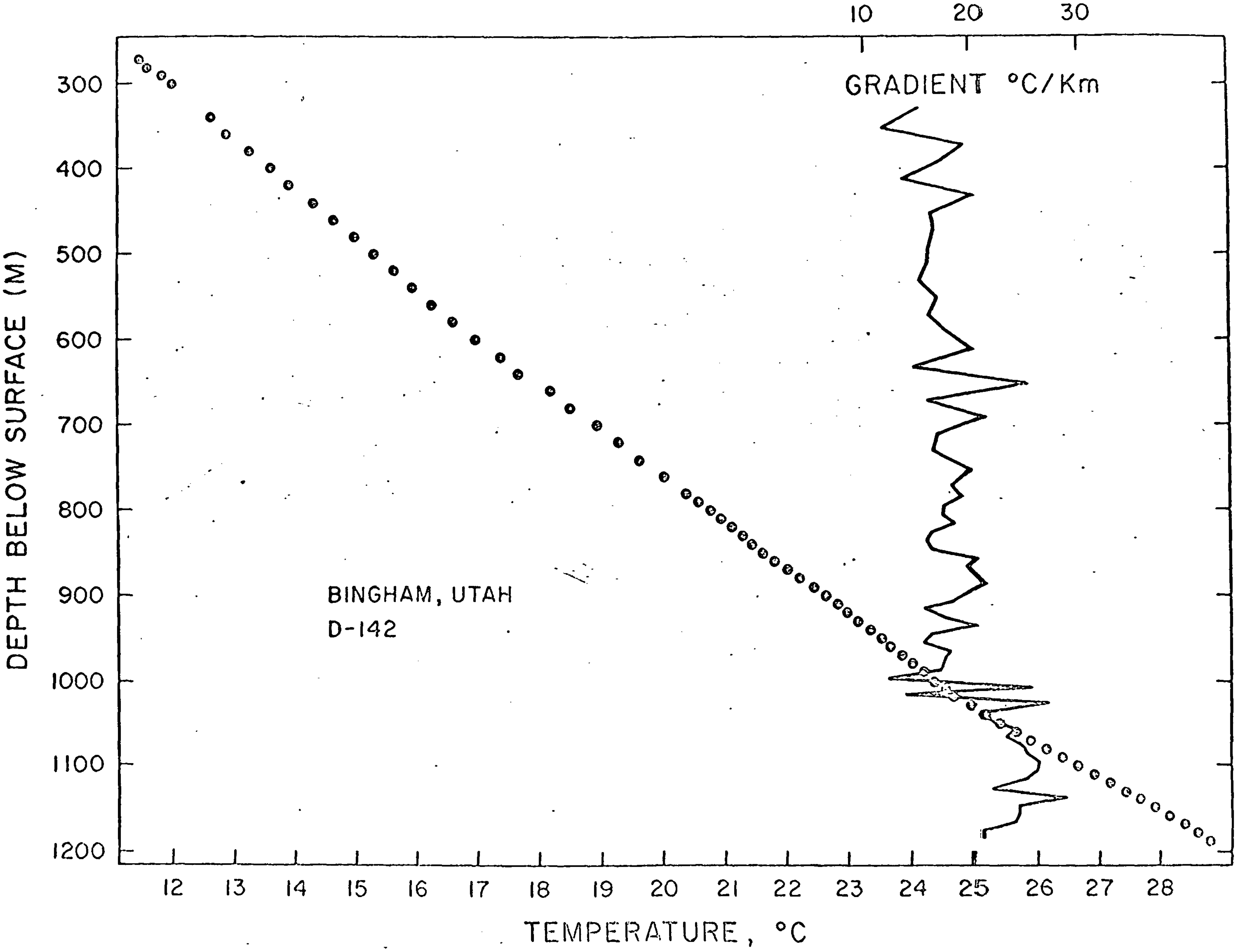
undisturbed gradient. Variations in the geothermal gradient were found between Hole 106 and the four holes to the south in the Spor Mountain area and this variation might possibly be attributed to near-surface ground water disturbances.

Jordan Valley. The geothermal gradient determined in borehole (B-1-2) 28dcc-1 in Jordan Valley (Lat. 40°47.0' N., Long. 112°04.3' W.) near Salt Lake City was 58.9° C /km. The temperature profile is shown in Figure . This hole was drilled into the interbedded sandy and muddy layers of the relatively unconsolidated Lake Bonneville deposits. Although a core drill was used, core recovery was very poor because of the unconsolidated nature of the deposits, and no core was available for laboratory measurements of thermal conductivity.

The high gradient of 58.9° C /km is believed to be due to the low thermal conductivity of the unconsolidated Lake Bonneville deposits. According to Langseth (1965, p. 70), published conductivity values for oceanic sediments are generally within 25 percent of 2.0 mcal/cm-sec-°C. This value could presumably be used as an indication of the thermal conductivity of the material in the hole in Jordan Valley. The conductivity of the Bonneville sediments is probably larger than 2.0 mcal/cm-sec-°C for two reasons: (1) the Bonneville sediments contain more quartz (in the sandy layers) than deep oceanic sediments contain, and (2) because the porosity of a sand is generally less than the porosity of a typical oceanic lutite, which may contain 75 percent water, a sand contains more solid material per unit volume than a lutite. Many well-consolidated shales and sandy shales have thermal conductivities about 4.0 mcal/cm-sec-°C and lower (Birch, 1954; Joyner, 1960). We may use this value as an upper limit. The sediments penetrated by the hole, then, probably have a thermal conductivity greater than 2.0 mcal/cm-sec/°C and less than 4.0 mcal/cm-sec-°C. If a thermal conductivity of 3.0 mcal/cm-sec-°C is used, the heat flow value would be about 1.8 μcal/cm^2-sec.

This value of heat flow is the approximate value of the regional heat flow in Jordan Valley. According to Marine and Price (1964, p.47), Jordan Valley contains two areas of thermal springs. The hole under discussion was drilled in an area which is characterized by warm water above 15° C Temperatures in this hole were found to be about 16° C at depths below 50 meters.

Bingham, Utah. The hole at Bingham, Utah, drilled by Kennecott Copper Corporation is located in R. 3 W., T. 3 S. on the side of the Bingham copper pit at an elevation of 1,951 meters above sea level. Temperatures were measured to a depth of 1,200 m. The temperature profile and gradient are shown in Figure . Of particular concern is the magnitude of the topographic correction to the gradient. The level of the bottom of the pit is approximately 1,676 meters above sea level and the horizontal distance from the hole to the bottom of the pit is one kilometer. Most of the peaks within ten kilometers of the hole have elevations between 2,650 and 2,710 meters above sea level. Nelson Peak, with an elevation of 2,853 meters above sea level, about 9 km to the north, is the highest peak within a radius of 10 km of the hole. The steady-state topographic correction considered relief within a 20-km radius of the hole and corrections to the measured temperatures were computed for depths from 776 meters to 1,186 meters. Details of the procedure used for making the correction after Birch (1950) can be found in Wright (1966). Topographic relief was estimated using the method of Kane (1962). The geothermal gradient and standard deviation of the

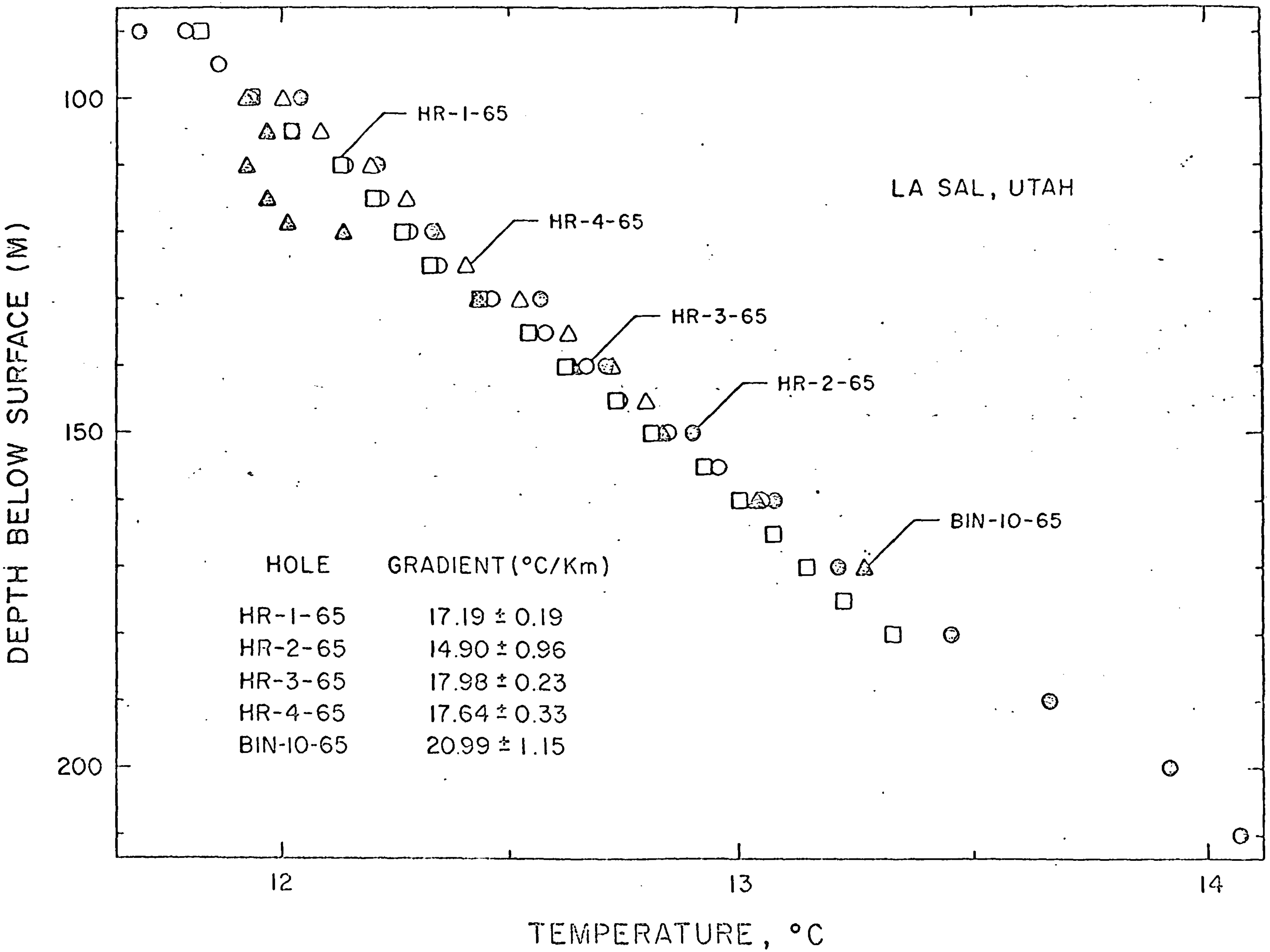

10
20
30
GRADIENT °C/Km
300
400
500
600
700
800
900
1000
1100
1200
DEPTH BELOW SURFACE (M)
BINGHAM, UTAH
D-142
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
TEMPERATURE, °C

gradient from 776 meters to 1,016 meters depth in the hole is 18.14 ±0.10° C /km. From 1,026 meters to 1,186 meters in the hole the gradient is 24.24 ±0.13° C./km. The temperature profile and gradient for D-142 are shown in Figure . The topographic correction was found to be 4%* of the gradient for the interval 776-1016 meters and 2%* for the interval 1026-1186 meters. The temperature profile and gradient are shown in Figure .

Conductivity was measured on 30 discs made from core taken from the hole. The discs were 0.875 inch in diameter and 0.5 and 1.0 inch in thickness. The average conductivity for the interval 776-1,015 meters based on 20 samples was found to be 13.7* mcal/cm-sec-°C. The average conductivity for the interval 1,026-1,186 meters, based on 10 samples, was 10.2* mcal/cm-sec-°C. The product of average thermal conductivity and the least squares gradient for the two intervals yields a heat flow value of 2.5 µcal/cm^2-sec. This value is probably good to at least 10% and the topographically corrected heat flow value is therefore 2.5* ±0.25 µcal/cm^2-sec.

La Sal, Utah. Most of the holes logged were in the Chinle Formation which is composed of fluvial mudstones and sandstones with irregular conglomeratic beds which probably represent ancient stream channels. Temperatures were measured in four holes close together belonging to the Atlas Minerals Corporation in the Big Indian mining district. Detailed information can be found in Wright (1966). The measured temperatures give a straight-line least squares gradient of about 17.7° C./km. High coefficients of correlation indicate a nearly linear relation between temperature and depth. The gradient typically passes several times through maximum and minimum values of about 22 and 14° C /km. The plots of temperature gradient versus depth are similar for all of these holes

* rough estimate


LA SAL, UTAH
HR-1-65
HR-4-65
HR-3-65
HR-2-65
BIN-10-65
HOLE GRADIENT (°C/Km)
HR-1-65 17.19 ± 0.19
HR-2-65 14.90 ± 0.96
HR-3-65 17.98 ± 0.23
HR-4-65 17.64 ± 0.33
BIN-10-65 20.99 ± 1.15
DEPTH BELOW SURFACE (M)
100
150
200
12
13
14
TEMPERATURE, °C

and are shown in Figure . The 14° C /km-gradient is measured in the more sandy layers, whereas the 22° C /km-gradient is representative of the shaly beds.

Since no core was available for these holes, thermal conductivity was measured from bulk rock specimens. Table 2 gives the measured thermal conductivity values along with disc thickness and a brief rock description. The four specimens labelled H66 were taken from the lower 75 feet of the Chinle Formation. Specimens 1L66 through 11L66 were taken from surface exposures on the Wingate-Chinle cliff and talus slope immediately east of the La Sal triangulation station (Lat. 38°14' 16.9" N., Long. 109°16'20.7" W.). Specimens 1SJ66 and 11L66 are both representative of the Wingate Sandstone. The remainder of the L66 specimens were collected within 3.5 miles of the holes. Table 2 also gives an estimate based on hand specimen examination of the amount of quartz sand in the rock. In general, it can be seen that the more sandy portions of the Chinle Formation have a higher thermal conductivity than the more muddy portions. Specimen 8H66, with an approximate sand content of 80 percent, was found to have a thermal conductivity of 8.37 mcal/cm-sec-°C. Specimen 9H66, with an approximate sand content of 10 percent, had a thermal conductivity of 5.45 mcal/cm-sec-°C. The other Chinle specimens had conductivities and sand contents between these extremes.

The average value of thermal conductivity for the 10 specimens from the Chinle Formation was 6.9 mcal/cm-sec-°C. It is unlikely, however, that this value represents the average Chinle conductivity. The L66 specimens in the Chinle were collected from a slope on which outcrops projected through the talus. The beds which had survived

Disc Number	Thickness (inches)	Conductivity (mcal/cm-sec-°C)	Location	Remarks
4H66-1	1/2	6.88	Alice incline	Chinle, 20% quartz; sandy mudstone
4H66-2	1	7.16		
6H66-1	1/2	7.40		
6H66-2	1	7.68		
6H66-3	1/2	7.28	Alice incline	Chinle, 50% quartz; muddy sandstone
6H66-4	1	7.08		
8H66	1	8.37	Alice incline	Chinle, 80% quartz; sandstone
9H66	1	5.45	Alice incline	Chinle, 10% quartz; mudstone
1L66-1	1/2	7.05	Surface	Chinle, 70% quartz; muddy sandstone
1L66-2	1	7.50		
2L66	1	7.98	Surface	Chinle, 80% quartz; sandstone
5L66	1	6.09	Surface	Chinle, 75% quartz; muddy sandstone
6L66	1	7.98	Surface	Chinle, 70% quartz; muddy sandstone
7L66	1	6.42	Surface	Chinle, 70% quartz; muddy sandstone
9L66-1	1/2	5.42	Surface	Chinle, 40% quartz: sandy mudstone
9L66-2	1	6.00		
11L66-1	1/2	11.50	Surface	Wingate, 95% quartz; sandstone
11L66-2	1	12.19		
15J66-1	1/2	11.67	Surface	Wingate, 95% quartz; sandstone
15J66-2	1	12.10		

Table 2. Thermal conductivity measurements from La Sal area.

surface weathering enough to form a resistant outcrop were the more sandy layers. Also, the more shaly layers of the Chinle were highly weathered, and were too incompetent to make discs. Therefore, specimen collecting was biased toward the sandstones, and the average thermal conductivity of the Chinle Formation is probably less than 6.9 mcal/cm-sec-°C. The Chinle has been described in many areas near the Big Indian mining district (Dane, 1935; Barber, 1933; Rodgers, 1954). These descriptions, taken as a whole, indicate that the typical Chinle is about 50 percent sandstone, and about 50 percent shale or mudstone. The average conductivity of the three mudstones (less than 50 percent quartz) in the La Sal specimens listed in Table 2 is 5.9 mcal/cm-sec-°C; the average conductivity of the sandstones (50 percent or more quartz) in these specimens is 7.3 mcal/cm-sec-°C. The mean of these values is 6.6 mcal/cm-sec-°C, the value accepted as the average thermal conductivity of the Chinle Formation.

The measured temperature gradient and thermal conductivity can be combined in several ways to obtain a heat flow value. The average geothermal gradient in the Chinle Formation was observed to be 17.7° C/km. The average thermal conductivity for the Chinle was 6.6 mcal/cm-sec-°C. The product of these two quantities indicates a heat flow value of 1.2 μcal/cm^2-sec. Also, the temperature gradient in the Wingate Sandstone was 12° C /km, and the measured thermal conductivity of the Wingate was about 12 μcal/cm-sec/°C. The product of these two quantities gives a heat flow of 1.4 μcal/cm^2-sec.

Temperature measurements taken in the Chinle Formation in the HR-65 holes indicated the existence of beds of varying thermal conductivity. A gradient of about 14° C /km was typical in the most sandy layers. Chinle sandstone beds had an average conductivity of about 8 mcal/cm-sec-°C. A heat flow of 1.1 μcal/cm^2-sec is believed to be representative for the La Sal, Utah, region.

A topographic evolution correction to correct for effects of topography, uplift and erosion (Birch, 1950) was calculated for the La Sal holes. The uncertainty place on the uncorrected heat flow value for La Sal was 20 percent. The computed topographic evolution corrections were only a few percent. The value of 1.2 ±0.2 mcal/cm^2-sec is therefore the corrected heat flow value at La Sal, Utah.

ACKNOWLEDGEMENTS

This work was supported by National Science Foundation Grants GP-2625, Ga-608 and GA-1384. The University of Utah Research Committee sponsored some of the preliminary work in temperature measurement when the authors were at the University of Utah.

Dr. Robert F. Roy made many helpful suggestions in regard to temperature measurement and the design of the thermal conductivity apparatus.

Walter Rohloff did the machine work at the University of Utah and made many original and significant contributions to the design of the hoisting equipment.

The Atlas Minerals Corporation, Brush Beryllium Company, Hogle Investment Company, and Kennecott Copper Corporation gave permission to log boreholes on their property and their cooperation is gratefully acknowledged.

COLLEGE OF ARTS AND SCIENCES

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DEPARTMENT OF GEOLOGICAL SCIENCES (703) 951-6521

July 25, 1973

RECEIVED
Geophysics Division Operations
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Dr. Orson L. Anderson, Editor
Journal of Geophysical Research
Institute of Geophysics and Planetary Physics
University of California
Los Angeles, California 90024

Dear Dr. Anderson:

Re: JGR MS#2893-2

Enclosed are two (2) copies of the revised paper "Heat Flow at Spor Mountain, Jordan Valley, Bingham, and La Sal, Utah" by J. K. Costain and P. M. Wright. The Checklist for Authors is also enclosed. With reference to the comments included in your letter of December 8, 1972,

(1) The discussion of the instrumentation and corrections has been considerably shortened.

(2) Location, gradient, conductivity, and heat flow for all areas have been incorporated in a summary table as recommended (Table 1).

(3) The vaseline problem was avoided by bonding aluminum foil to each face of the disc. The discussion in the manuscript has been amplified and clarified.

With reference to the comments of Reviewer A:

(1) The suggested table has been included (Table 1).

(2) The discussion of the temperature measuring apparatus has been considerably shortened, and some sections deleted. The discussion of the platinum probes has been retained.

(3) The vaseline problem was avoided by bonding aluminum foil to the rock discs. The discussion has been clarified in the manuscript.

(4) Brand names of circulating baths and vacuum pumps have been deleted. Brand names of some of the temperature-measuring instrumentation have been retained since I think this is of some interest.

(5) The procedure on calibration has been clarified.

(6) First paragraph under Results has been deleted.

(7) A comparison of our results with values obtained at Bingham by Roy et al. (1968, p. 5219) has been included. Differences in gradients and conductivities have been pointed out. More detailed comparisons are not possible since rock types are not included in Roy et al. (1968). The reason for our preferred value of 2.3 μcal/cm^2-sec has been discussed in detail.

(8) Hole 106 has been added to Figure 2, and the discussion of the gradients has been amplified.

(9) Lithology has been included in Table 5.

(10) The units of heat flow are now consistent throughout the paper (μsec/cm^2-sec).

With reference to the general comments of Reviewer B:

(1) The text has been shortened and many details omitted.

(2) Table 1 now contains all portions of holes used for gradient calculations. Table 1 is a summary table for all localities.

(3) Text clarified where noted by Reviewer B in manuscript.

With reference to the specific comments of Reviewer B:

(1) Abstract and Introduction revised.

(2) Temperature and thermal conductivity measuring systems have been deleted from abstract. Also statement about rock discs.

(3) Page 9 revised. Shorter statement of comparison with crystalline quartz included just before RESULTS section.

(4) Walsh and Decker reference included as suggested.

(5) Redundancy removed. Section has been revised.

(6) Mining company names deleted from text.

D-142, Bingham, Utah

(1) Intervals used for gradients and core recovery have been better defined.

(2) A (shortened) discussion of topography has been retained since D-142 is not included in Wright (1966).

(3) Discussion of theory of topographic evolution correction has been deleted. Wright (1966) referred to for details of topographic correction, including discussion of square grid.

Spor Mountain, Utah

(1) Statement that holes were dry when drilled and measured included in text.

(2) Hole 106 has been added to Figure 2.

(3) Statement that samples were dry when thermal conductivity was determined has been included.

(4) The discussion has been shortened by including material in Table 3.

La Sal, Utah

(1) Hole BIN-8-64 was inadvertently omitted. This was in Wingate, not Chinle. BIN-8-64 now included in text and Figure 3. Comments a) and b) incorporated in text.

(2) The steady-state terrain correction was noted in the text.

(3) This section completely revised and shortened.

(4) Errors have been included on gradients.

Figure 4

Physiographic provinces have been added.

All comments of the reviewers made in the manuscripts have been incorporated in the revised manuscript. The pages have been re-ordered and Checklist comments noted. A short form of the title is "Heat Flow in Utah".

Sincerely,

John Costain

John K. Costain
Professor of Geophysics

JKC/js

cc: P. M. Wright

MS # 2893-2

Date 12/6/72

Author(s) Costain + Wright

JOURNAL OF GEOPHYSICAL RESEARCH
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HEAT FLOW AT SPOR MOUNTAIN, JORDAN VALLEY, BINGHAM, AND LA SAL, UTAH

by

John K. Costain

Virginia Polytechnic Institute and State University

Blacksburg, Virginia 24061

and

P. M. Wright

Kennecott Exploration Inc.

Salt Lake City, Utah 84104

ABSTRACT

Geothermal gradients were obtained in drill holes in Utah at Spor Mountain, Enterprise, La Sal, Monticello, Bingham, and Jordan Valley. A heat flow of 3.0 ± 0.3 μcal/cm^2-sec was found at Spor Mountain (39°43' N. Lat., 113°13' W. Long.). The flux at Jordan Valley (40°47.0' N. Lat., 112°04.3' W. Long.) is estimated to be 1.8 ± 0.6 μcal/cm^2-sec. The revised heat flow at La Sal (38°14.3' N. Lat., 109°16.3' W. Long.) on the Colorado Plateau is 1.5 ± 0.2 μcal/cm^2-sec. The heat flow at Bingham (40°32' N. Lat., 112°09' W. Long.) is 2.3 ± 0.3 μcal/cm^2-sec. On the basis of much of the heat flow data now available for the Colorado Plateau, including our revised values at La Sal, there appears to be less justification for defining the Colorado Plateau as a separate heat flow province with abnormally low heat flow.

INTRODUCTION

Temperatures were measured in drill holes at Spor Mountain, La Sal, Bingham, and Jordan Valley, Utah. Five drill holes were logged for temperature in the Enterprise area and one hole near Monticello, San Juan County. In the Enterprise and Monticello areas, the temperature gradients were disturbed by shallow ground-water circulation, and no further interpretation of the data from these holes was justified (Wright, 1966).

TEMPERATURE MEASUREMENTS

For the holes at Spor Mountain, Jordan Valley and La Sal, we used a platinum resistance thermometer, Model 134HH, manufactured by Rosemount Engineering Company, with a nominal ice-point resistance of 1000 ohms. A change in temperature of 0.01°C corresponds, for a 1000-ohm element, to a change in resistance of approximately 0.036 ohm. Any system used to measure resistance must be able to detect a change in resistance of this magnitude in order to resolve temperature changes as small and smaller than 0.01°C. To measure temperature to an accuracy of ±0.01°C at, say, 50°C would require measuring the resistance of a probe whose nominal ice-point resistance is 1000 ohms to an accuracy of 1197.38 ± 0.036 ohms, or to about 0.003%. The individual resistance bridge decades can be calibrated to this accuracy; however, because of the limited resistance range that will be encountered in the field using a 1000-ohm platinum probe, about 390 ohms for the temperature range from 0-100°C, it is possible to compare the resistance of the probe with the constant resistance of an accurate primary standard for which the resistance is known to ±0.001%. For all of the holes except the one at Bingham, we used a comparison bridge, Model DBR-1, manufactured by the RdF Corporation, Hudson, New Hampshire. This bridge balances out most of the probe resistance with a primary standard resistance accurate to within ±0.001%. If the nominal resistance of the probe used was 1000, 2000, or 5000 ohms, then the resistance of the primary standard used was 1000.00 ± 0.01, 2000.00 ± 0.02, or 5000.00 ± 0.05 ohms, respectively. The standards were calibrated by the manufacturer, by a secondary standards laboratory, and by the National Bureau of Standards. The final bridge balance was achieved using the Rubicon decade resistances in the bridge. We believe the accuracy of our temperature measurements with the 1000-ohm probe to be ±0.05°C, and the precision to be ±0.01 °C. The hole at Bingham was logged using a 5000-ohm platinum resistance probe with a precision of about ±0.002°C.

Different apparatus was used at the Bingham hole, and we are now using a Honeywell 1551-E Mueller bridge in conjunction with Julie Research Laboratories and Electroscientific Industries SR-1 standard resistors, which are accurate to ±0.001%. A Honeywell 3972 DC microvolt null detector is used to balance the bridge. The Mueller bridge also provides for balancing out most of the resistance of the probe with an external primary standard resistance. As with the comparison bridge, final balance is achieved using decades built into the bridge.

Most temperature measurements for terrestrial heat flow determinations are made using thermistors, and it will be in order here to discuss the suitability of platinum for temperature measurements in deep holes. We have consistently obtained excellent results using platinum. For example, periodic relogging of hole (B-1-2)28dcc-1 in Jordan Valley near Salt Lake City over a period of two years showed differences in absolute temperature at any given depth of no more than ±0.03°C, using probes of different nominal resistances made by different manufacturers. We obtained this accuracy for repeated measurements in every hole not disturbed by ground water movement, regardless of depth, and using probes of nominal ice-point resistances of 1000, 2000, and 5000 ohms. There are disadvantages to using platinum; bridge calibration and galvanometer sensitivity are more critical because of the lower resolution of platinum as compared with thermistors, and, for the probes we have been using, the time constants are longer. Repeated measurements in several holes confirm that the calibration curve for platinum may shift slightly, but that it shifts parallel to itself, and the shift can be determined by noting the change in the ice-point resistance. The shift is apparently related to the amount and type of mechanical shock received by the probe over the years. Over a period of five months the resistance of the 1000-phm probe was found to increase by about 0.7 ohm, corresponding to an apparent temperature increase of about 0.2°C. This increase was generally small for any given field trip, and no change in ice-point resistance was noted between field trips (Wright, 1966, p. 130-131). For short intervals in a drill hole, the better resolution of thermistors is a definite advantage. Our original reason for using platinum was the better stability of platinum over thermistors; however, thermistor probes with excellent stability such as the Fenwal oceanographic type probes are now available and we have essentially shifted to thermistors for field measurements with occasional checks using a platinum probe. We have compared gradients obtained with a 5000-ohm platinum element with those obtained using a Fenwal oceanographic probe of about 11,000 ohms ice-point resistance and about 4800 ohms at 20°C. The difference in the gradients over intervals of about 100 m was less than two per cent.

For the holes at Spor Mountain, Jordan Valley, and La Sal, we used U. S. Steel 4-H-1 4-conductor double-armored Amergraph cable. This is a heavy cable with a resistance of about 15 ohms per thousand feet and a breaking strength of 7200 pounds. The leakage resistance of the Amergraph cable was always greater than 50 megohms and usually greater than 100 megohms. We have since changed to lighter, more portable cables, and are now using Mark Products WF-TQ-190 W/4 Penalastic-filled polyurethane cables. Four-conductor cables were used for all temperature measurements to minimize effects of lead resistance.

DETERMINATION OF THERMAL CONDUCTIVITY

Of the several methods used to determine the thermal conductivity of rocks (Beck, 1965) the most common is the divided bar apparatus described by Birch (1950). The apparatus constructed by us was designed after that used in the Hoffman Laboratory at Harvard University.

Rock disks 2.22, 3.0, 3.31, and 3.62 cm in diameter were commercially prepared from rock samples. The surfaces of the disks were machined flat and parallel to ±0.0008 cm with diameters uniform and accurate to ± one per cent. Copper-constantan thermocouples were inserted into copper discs to measure the temperature differences across fused quartz reference disks and across the rock specimen. Thermal resistance at the contacts between the disks was reduced by applying a thin layer of vaseline to the disk faces, and by applying an axial pressure of at least 100 bars to the stack. In order to ensure axial heat flow and minimize radial heat loss the stack was insulated with a tight-fitting machined block of high-density polystyrene. A temperature differential of about 10°C was applied across the stack. Measurements of the emf across each quartz disk and across the rock specimen were made with a Leeds and Northoup K-3 potentiometer. The temperature difference across the stack was held constant by thermostatically controlled temperature baths.

Repeated measurements on the same low-porosity rock disk were almost always reproducible to within two percent. For some of the more porous disks, it was found that a small amount of vaseline would soak into the rock during measurement. After the disk had been measured a few times, less vaseline would be absorbed. This had the effect of causing the apparent rock conductivity to increase with successive measurements until the faces of the disks no longer absorbed vaseline. When this "equilibrium" state was reached the thermal conductivity rarely increased by more than five percent, and repeated measurements reproduced to within two percent. In order to prevent vaseline from being absorbed by the specimen, a thin foil of aluminum 0.00254 cm thick was bonded to the flat faces of some of the disks with epoxy cement. Curing of the epoxy was completed at room temperature under about 350 bars for at least 12 hours. This resulted in a good bond and a smooth, mirror-like disk face. Vaseline was used as a contact substance between these aluminum-surfaced disks and the copper disks of the stack. Measurements made in this manner were reproducible to about 0.5 percent. Several disks which had been measured without the aluminum foil coating were later surfaced as described above. The thermal conductivity results were the same, within about two percent. Reproduction of measurements was also improved by cementing the copper disks to the quartz reference disks using silver epoxy cement.

Reproducibility of measurement is not necessarily an indication that the measured value is correct. It is difficult to assign an absolute accuracy to the measurements. Roy (1963, p. 7) states that "systematic and random errors in the measurement of a single disk amount to 5 percent." It seems likely that this figure would also apply to our conductivity apparatus.

If temperatures are measured in a water-filled drill hole, it is important to saturate the rock samples thoroughly before thermal conductivity determinations are made (Birch and Clark, 1940; Walsh and Decker, 1966). This was not done for the thermal conductivity measurements previously reported for La Sal, Utah (Costain and Wright, 1968). Except for hole BIN-8-65, however, the temperature measurements were made in water-filled holes (Wright, 1966, p. 76). The heat flow values for La Sal were therefore too low, and revised values are given herein. All rock samples, except as noted, were saturated with water while exposed to a vacuum of 5 microns. The samples were measured after soaking for several days.

Thermal conductivities reported herein were measured while the temperature of the sample was within 5°C of its _in situ_ temperature. The stacks of the divided-bar apparatus were calibrated at the _in situ_ temperature by replacing the rock samples with GE-101 fused quartz disks of the same size. The calibration thus included a correction for radial heat loss and contact resistance; i.e., the "stack correction factor" required to make the measured conductivity equal to the known conductivity of fused quartz never exceeded seven percent, and was usually about three percent. The known thermal conductivity, K, of the fused quartz at a temperature of T°C was based on the equation (Ratcliffe, 1959)

$$K = (3160 + 4.6T - 0.016T^2) \times 10^{-3} \text{ mcal/cm-sec-°C}$$

The thermal conductivities of several specimens were also measured using crystalline quartz cut perpendicular to the optic axis. The results agreed with the conductivity values obtained using fused quartz to within less than three percent.

RESULTS

Bingham, Utah. Hole D-142 at Bingham is located on the side of the Bingham Canyon copper mine (40° 31' N. Lat., 112° 09' W. Long.) at an elevation of 1963 meters above sea level. Temperatures were measured to depth of 1200 m. The temperature profile and gradient are shown in Figure 1. Table 1 summarizes straight-line least-squares gradients in this hole for several intervals.

Since the Bingham hole is not included in Wright (1966), a few details concerning the terrain correction will be given here. The level of the bottom of the open-pit mine is approximately 1810 m above sea level. The horizontal distance from the hole to the bottom of the mine is one kilometer. Most of the peaks within 20 km of the hole have elevations between 2200 and 2700 m above sea level. Nelson Peak, 2853 m above sea level and about 9 km to the north, is the highest peak within a distance of 20 km from the hole. Terrain corrections to the geothermal gradient were calculated using the method described by Birch (1950, p. 582-600) and Wright (1966, p. 149-178). In order to examine the changes in the "corrected" gradient for different assumptions about the physiographic history, corrections were calculated assuming uplifts of from 0 to 4572 m, evolution times of from 10 m.y. to infinity, and atmospheric temperature gradients of from -3 °C/km to -6 °C/km. Table 2 summarizes the results of the effects of different physiographic histories. The observed gradient for the depth interval 656-936 m is 18.45 ± 0.25 °C/km. The largest correction to the observed gradient is for short evolution times.

For an evolution time of 10 m. y. the correction to the observed gradient, assuming no uplift and 4572 m uplift, is -9 % and -15 %, respectively, for an atmospheric gradient of -6 °C/km. For an atmospheric gradient of -3 °C/km, the results are the same within about 3 %. For longer evolution times the corrections are much smaller. Although the physiographic history of the region is not completely known, the effects of uplift and erosion for assumptions which probably bracket the correct physiographic history are shown in Table 2. Assuming extreme conditions of 4572 m uplift and 10 m. y. evolution time, the corrected gradient is only about 15 % less than the observed gradient. For an infinite evolution time, the corrected steady-state gradient is 18.03 ± 0.074 °C/km, or about -2 % of the observed gradient. This value has been used for the corrected heat flow determinations given in Table 1.

The Bingham mine is centered on a small composite granite and granite porphyry stock which intrudes quartzites of lower Pennsylvanian age. Hole D-142 is drilled in quartzite until a depth of about 1036 m where it enters the stock. Associated dikes of quartz latite porphyry and latite porphyry were emplaced last, cross-cutting all other rocks (James, Smith and Bray, 1961). The granite has few feldspar phenocrysts and no quartz phenocrysts. Phenocrysts of feldspar make up about 50 per cent of the granite porphyry and average 3.5 mm in length. Quartz phenocrysts are rare. The dikes of quartz latite porphyry contain feldspar phenocrysts which make up about 35 percent of the rock and average 2.5 mm in length. Quartz phenocrysts, averaging 2 mm in diameter, make up 3 per cent of the rock. The groundmass of the dikes is aphanitic. The latite porphyry contains no quartz phenocrysts and, except for color, is similar to the quartz latite porphyry in appearance. Since no samples of the stock below

1036 m were available for thermal conductivity determinations, the thermal conductivity of the rock for the depth interval 1046-1156 m was assumed to be approximately equal to that of the dikes cut by the hole above 1036 m. The locations of the dikes in the hole were well defined by a gamma-ray log run in hole D-142 to a depth of 841 m using a Well Reconnaissance Geo-Logger Model 8036. The hole was blocked to this logging tool at 841 m. The log was essentially featureless throughout the quartzites, but excellent response was obtained for dikes at depth intervals 671-686 m and 747-754 m. At about 1036 m the hole penetrated the main Bingham porphyry stock within which the gradient is 24.77 ± 0.36 °C/km. Samples of dike rock for thermal conductivity determinations were prepared from core taken from depths of 676, 681, 752, and 854 m. The mean thermal conductivity and standard error as determined from four saturated cylinders under a pressure of 100 bars was 9.08 ± 0.95 mcal/cm-sec-°C. The resulting heat flow within the stock is 2.25 μcal/cm^2-sec with a probably error of about 15% because of the assumption that the dike rock has approximately the same thermal conductivity as the main Bingham prophyry stock. In the depth interval 656-936 m, the mean of 7 thermal conductivity determinations of the quartzite and four samples of dike rock, is 12.73 ± 0.98 mcal/cm-sec -°C. Combined with an observed gradient of 18.45 ± 0.25 °C/km in the quartzites, this gives a heat flow of 2.35 μcal/cm^2-sec., in good agreement with the deeper interval. The mean thermal conductivity of the quartzites only was 14.77 ± 0.32 mcal/cm-sec -°C. Table 3 lists thermal conductivity determinations from hole D-142.

Our heat flow values at Bingham are somewhat higher than those determined by Roy et. al. (1968, p. 5219) who reported two values at Bingham of 1.5 and 1.9 μcal/cm^2-sec. The lower value of 1.5 μcal/cm^2-sec was apparently determined in the main Bingham stock since the average thermal conductivity reported was 7.19 ± 0.28 mcal/cm-sec-°C. The value of 1.9 μcal/cm^2-sec was apparently determined in the quartzites since the mean conductivity was 11.5 mcal/cm -sec-°C. Our mean conductivities are about 29% and 26% higher for rocks which presumably would correspond to the quartzites and stock, respectively; our gradients are about 9% and 27% higher in the quartzites and stock, respectively. Undoubtedly, with the large differences in thermal conductivity between the porphyry and quartzites, refraction is probably an important factor in the differences observed.

We feel the best heat flow value from hole D-142 is 2.3 ± 0.3 μcal/cm^2-sec. If only our three lowest conductivity values for the dike rock cut by hole D-142 are considered, the assumed conductivity of the stock would be 8.18 ± 0.87 mcal/cm-sec-°C and the flux in the stock would be 2.0 μcal/cm^2-sec, still within our assumed uncertainty, and the lower conductivity value is in better agreement with that of Roy et. al. (1968, p. 5219). We prefer the higher value of 2.3 ± 0.3 μcal/cm^2-sec since it is compatible with flux values obtained above and below the boundary of the main Bingham stock as penetrated by hole D-142.

Jordan Valley. The temperature profile in drill hole (B-1-2)28dcc-1 in Jordan Valley (40° 47.0' N. Lat., 112° 04.3' W. Long.) near Salt Lake City, Utah is shown in Figure 2. This hole was drilled into interbedded sandy and muddy layers of the relatively unconsolidated Lake Bonneville deposits. Because of poor recovery of the unconsolidated deposits no material was available for laboratory measurements of thermal conductivity. No topographic correction to the gradient was necessary.

The high gradient of 58.7 °C/km (Figure 2) is believed to be due to the low thermal conductivity of the unconsolidated Lake Bonneville deposits. According to Langseth (1965, p. 70), published conductivity values for oceanic sediments are generally within 25 percent of 2.0 mcal/cm-sec-°C. This value could presumably be used as a lower bound for the thermal conductivity of the material in Jordan Valley. The conductivity of the Bonneville sediments is probably higher than 2.0 mcal/cm-sec-°C for two reasons: (1) the Bonneville sediments contain more quartz (in the sandy layers) than deep oceanic sediments, and (2) the porosity of a sand is generally less than the porosity of a typical oceanic lutite, which may contain 75 percent water; therefore a sand contains more solid material per unit volume than a lutite. Many well-consolidated shales and sandy shales have thermal conductivities about 4.0 mcal/cm-sec-°C and lower (Birch, 1954; Joyner, 1960). We may use this value as an upper limit. The sediments penetrated by the hole, then probably have a thermal conductivity greater than 2.0 mcal/cm-sec-°C and less than 4.0 mcal/cm-sec-°C. If a thermal conductivity of 3.0 mcal/cm-sec-°C is used, the regional heat flow in Jordan Valley would be about 1.8 ± 0.6 μcal/cm^2-sec.

Spor Mountain. Spor Mountain is in the central part of Juab County, Utah, in the Basin and Range province. Temperatures were measured in five drill holes in the Topaz Mountain tuff. Four of these holes were within 460 m of each other and had an average gradient of 58 °C/km. The fifth hole (hole 106), located 600 m to the north, was found to have a lower gradient of 46.9 °C/km. Figure 2 shows the temperature profiles for all holes.

Table 4 lists the results of thermal conductivity determinations from the Spor Mountain area. Disks were cut from nine specimens. All of the rock specimens are representative of the Topaz Mountain rhyolite. The mean thermal conductivity and standard error of 20 rhyolite specimens was 5.47 ± 0.14 mcal/cm-sec-°C. The mean geothermal gradient of all five holes is 55.5 ± 3.7 °C/km. This gives an average heat flow of 3.0 ± 0.3 μcal/cm^2-sec. The gradient over the depth interval 120 to 127 m in hole 110 is 55.0 ± 1.0 °C/km. The mean conductivity and standard error of 8 samples over this interval in hole 110 is 5.26 ± 0.2 mcal/cm-sec-°C. The product indicates a flux of 2.9 ± 0.2 μcal/cm^2-sec. No terrain corrections were necessary. The variation in the geothermal gradient between hole 106 (46.9 °C/km) and the four holes to the south (average value 57.6 °C/km) might be due to near-surface ground-water circulation, or more probably is the result of lateral variation in the thermal conductivity of the rhyolite. No core was available from hole 106. All thermal conductivity values were determined on unsaturated specimens in a shelf-dried state, since the holes were all dry when logged.

The heat flow in the Spor Mountain area is taken to be 3.0 ± 0.3 μcal/cm^2-sec. The uncertainty of 10% is assigned primarily because not all of the conductivity determinations were made on core from the holes.

La Sal. Most of the gradients were determined in holes drilled into the Chinle Formation which is composed of fluvial mudstones and sandstones with irregular conglomeratic beds which probably represent ancient stream channels. One hole (BIN-8-64) was drilled entirely in the Wingate Sandstone, which overlies the Chinle. Temperatures were measured in four holes (HR series) within 150 m of each other, and in two holes (BIN series) about three km northwest of the HR group in the Big Indian mining district (Wright, 1966). The temperature profiles are shown in Figure 3. The average straight-line least-squares gradient in the HR holes is 17.7 ± 0.26 °C/km. The gradient typically passes several times through maximum and minimum values of about 22 and 14 °C/km (Wright, 1966, p. 79-86). The 14 °C/km gradient is measured in the more sandy layers of the Chinle, whereas the 22 °C/km is representative of the shaly beds. Using data from below 120 meters in hole BIN-10-65, the straight-line least-squares gradient is 21.9 ± 0.32 °C/km.

The holes at La Sal were surrounded by rather rugged topography, and a correction for topographic evolution was determined. The atmospheric temperature gradient assumed for the correction was -5.7 °C/km. According to Eardley (1962, p. 424) the central part of the Colorado Plateau was uplifted 1829 to 2438 m, probably beginning in Pliocene time. For an uplift of 1829 m, 335 m of erosion, and an evolution time of 15 m. y., the conditions which Eardley considers most representative, the corrected gradient in HR-1-65 is 17.79 ± 0.20 °C/km, or 3.5 % greater than the observed gradient. For an infinite evolution time the corrected gradient is 18.38 ± 0.20

°C/km, or about 7 per cent greater than the observed gradient in HR-1-65. For Eardley's assumptions about the physiographic history, the correction to the gradient is small.

No core was available for the La Sal holes, and thermal conductivity was determined from samples prepared from bulk rock specimens. All specimens were collected within 2 km of the HR holes, and within less than 6 km of the BIN holes. The lithology typical of the Chinle Formation is about 50 per cent sandstone and about 50 per cent mudstone (Wright, 1966, p. 92-94). We previously reported heat flow values at La Sal based on measurements of samples in a shelf-dried condition. Nine of the Chinle samples have since been remeasured after being vacuum-saturated with distilled water. The difference between the dry and saturated conductivities is shown in Table 5.

The mean value and standard error of the thermal conductivity of 8 saturated specimens of the Chinle Formation is 8.61 ± 0.26 mcal/cm-sec-°C. This represents an increase of about 20 per cent over the corresponding unsaturated mean value of 7.15 ± 0.29. One sample of the Wingate was remeasured after saturation; unsaturated conductivity values were used for the Wingate since hole BIN-8-64, which was entirely in the Wingate, was logged dry (Wright, 1966, p.77).

The average geothermal gradient in the Chinle Formation in the HR-65 holes was 17.7 ± 0.2 °C/km. The mean thermal conductivity of the saturated samples of Chinle was 8.61 mcal/cm-sec-°C. The product indicates a flux of 1.5 μcal/cm^2-sec. Hole BIN-8-64 was dry when logged. The temperature gradient in the Wingate sandstone in this hole was 12.1 ± 0.8 °C/km, and the mean unsaturated Wingate conductivity of 4 samples was 11.9 ± 0.14 mcal/cm-sec-°C, giving a heat flow of 1.44 ± 0.11 μcal/cm^2-sec.

Previously reported (Costain and Wright, 1968) values for La Sal were given as 1.2 ± 0.2 $\mu cal/cm^2$-sec based entirely on thermal conductivity measurements of unsaturated rocks. The revised value for La Sal, based on conductivity measurements on saturated Chinle rocks as well as unsaturated Wingate sandstone is 1.5 ± 0.2 $\mu cal/cm^2$-sec. The uncertainty placed on the revised value is primarily a result of the uncertainty of the conductivity of the Wingate and Chinle rocks, since measurements were not made on core samples from holes in which the gradients were determined.

DISCUSSION

Decker (1969) presented nine new heat flow values in Colorado and New Mexico. Only one of these values, 1.22 $\mu cal/cm^2$-sec at Cerrillos, New Mexico near the southern border of the Southern Rocky Mountains, fell below 1.6 $\mu cal/cm^2$-sec. Sass, et al. (1971) presented a large number of additional values for the Rocky Mountain and Colorado Plateau provinces. All of their "Category 1" values for the Colorado Plateau were 1.5 $\mu cal/cm^2$-sec or above. North of the Colorado Plateau province, at Green River, they obtained a value of 1.6 $\mu cal/cm^2$-sec. In the Basin and Range province, Sass et al. (1971) gave a number of new values south and west of the Colorado Plateau. Only five values are less than 1.5 $\mu cal/cm^2$-sec and these are close to other sites (< 20 km) where the heat flow is greater than 1.5 $\mu cal/cm^2$-sec. It would appear that the low heat flow values in Arizona, southwest and south of the Colorado Plateau, 5 out of 25 determinations, may not be representative of the regional heat flux, and could be either the result of refraction, or shallow ground water circulation.

The revised value given in this paper for La Sal, Utah, on the Colorado Plateau, is 1.5 $\mu cal/cm^2$-sec. This is in close agreement with values found for the northern part of the Colorado Plateau by Sass et al. (1971), although it is considerably higher than Spicer's (1964) value of 1.2 $\mu cal/cm^2$-sec. On the basis of much of the heat flow now available there appears to be less evidence to delineate the Colorado Plateau as a separate heat flow province with abnormally low heat flow.

The extensive recent tectonic activity in the Basin and Range province is reflected by the high surface heat flow. Depending on the upward penetration of fault zones, heat flow anomalies might be expected to (1) follow superimposed trends associated with block faulting, and (2) fall off rapidly away from the fault zone if the source is shallow. No linear trends in heat flow are apparent from the data available to date; however, the density of heat flow determinations is not sufficient to rule out the possibility of linear heat flow patterns associated with major trends in block faulting. Figure 4 shows all of the published heat flow values in Utah to date. A higher density of heat flow determinations might show the anomalies to be closely associated with linear seismic zones such as the Wasatch line in Utah. The heat flow at Bingham, Utah, very close to the Wasatch line, is about 2.3 $\mu cal/cm^2$-sec. Heat flow profiles and microseismicity studies near active fault zones could establish such a correlation.

The Cordilleran Thermal Anomaly Zone (CTAZ) of Blackwell (1969) may include the Colorado Plateau province. Decker (1969) and Sass et al. (1971) obtained high heat flow values (> 2.0 $\mu cal/cm^2$-sec) near the eastern boundary of the Plateau. The apparent overall higher heat flow in the Basin and Range province, about 2.0 $\mu cal/cm^2$-sec, suggests a higher density of fracture zones with deeper penetration into the mantle than to the east in the Colorado Plateau province.

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of gradients, conductivities, and heat flow.

Depth Range, meters	K, mcal/cm sec °C*	Gradient °C/Km*	q(unc) µcal/cm^2-sec	q(corr) µcal/cm^2-sec
576-886	13.25 ± 0.76 (15)[§]	18.64 ± 0.3(22)[§]	2.47 ± 0.18	
656-936	12.73 ± 0.98 (11)	18.45 ± 0.25(23)	2.35 ± 0.21	2.30 ± 0.18
1046-1156	9.08 ± 1.09 (4)[†]	24.77 ± 0.36 (12)	2.25 ± 0.31	
1046-1156	8.18 ± 0.87 (3)[‡]	24.77 ± 0.36 (12)	2.03 ± 0.24	
				2.3 ± 0.3
20-63	3.0± 1.0	58.72± 1.07 (9)	1.8 ± 0.6	1.8 ± 0.6
50-138	5.47 ± 0.14(20)	58.48 ± 0.93(10)	3.20 ± 0.13	
30-152	5.47 ± 0.14(20)	46.94 ± 0.51(4)	2.57 ± 0.09	
30-131	5.26 ± 0.2(8)	59.35 ± 0.70(12)	3.12 ± 0.16	
120-127	5.26 ± 0.2(8)	55.0 ± 1.1(3)	2.89 ± 0.17	
50-130	5.47 ± 0.14(20)	54.70 ± 0.56(9)	2.99 ± 0.11	
30-118	5.47 ± 0.14(20)	57.95 ± 0.97(10)	3.17 ± 0.3	
	5.47 ± 0.14(20)	55.48 ± 0.73	3.0 ± 0.3	3.0 ±0.3

of gradients, conductivities, and heat flow.

(Continued)

Depth Range, meters	K mcal/cm sec °C*	Gradient °C/Km*	q(unc) µcal/cm²-sec	q(corr) µcal/cm²-sec
90-180	Mean Chinle	17.19 ± 0.19(18)	1.48 ± 0.06	1.53 ± 0.07
50-210	conductivity	14.90 ± 0.96(17)	1.28 ± 0.13	
90-160	= 8.61 ± 0.26(8)	17.98 ± 0.23(15)	1.55 ± 0.07	
100-145		17.64 ± 0.33(10)	1.52 ± 0.07	
130-170		21.90 ± 0.32 (5)	1.89 ± 0.15	
	11.9 ± 0.14(4) (Wingate)	12.13± 0.79	1.44 ± 0.12	
				1.5 ± 0.2

are straight-line least-squares gradients.

76, 681, 752, and 853 m.

76, 752, and 853 m.

thermal conductivity determinations.

Evolution Time, my	Elevation of Uplifted Surface, m	Corrected Gradient, °C/km	Evolution Time, my	Elevation of Uplifted Surface, m	Corrected Gradient, °C/km
10	4,572	15.73 ± 0.066	100	4,572	17.25 ± 0.072
	3,048	16.09 ± 0.066		3,048	17.37 ± 0.071
	0	16.80 ± 0.066		0	17.61 ± 0.071
10	3,048	16.73 ± 0.070	100	3,048	17.60 ± 0.073
	1,524	17.10 ± 0.070		1,524	17.73 ± 0.073
	0	17.48 ± 0.070		0	17.85 ± 0.073

Table 2. Summary of corrected geothermal gradients for hole D-142, Bingham, for the depth interval 656-936 m, α = 6 °C/km, collar elevation of hole = 1963 m, diffusivity = 0.02 cm^2/sec, observed gradient = 18.45 °C/km. Steady-state gradient (infinite evolution time) is 18.03 ± 0.074 °C/km.

Table 3. Thermal conductivity from core samples, hole D-142, Bingham, Utah.

Depth (meters)	Thermal Conductivity* ($mcal/cm^2$-sec-°C)
587.7	12.99
629.7	14.96
630.6	15.29
646.2	15.52
675.8	8.30*
680.6	11.79*
696.2	15.39
752.0	6.61*
767.8	15.31
790.7	14.62
799.2	15.60
825.7	14.99
844.9	12.46
853.2	9.62*
884.8	15.35

*Porphyry dike.

*All disks 2.22 cm diameter and 2.54 cm thickness.

Disc Number	Thickness (cm)	Conductivity (mcal/cm-sec-°C)	Location
10SM66	1.27	5.51	Hole 110 (123m)
11SM66-1	1.27	5.36	Hole 110 (123m)
11SM66-2	1.91	5.50	
11SM66-3	2.54	5.52	
13SM66	1.91	3.78	Hole 110 (125m)
14SM66-1	1.27	5.49	Hole 110 (127m)
14SM66-2	1.91	5.46	
14SM66-3	2.54	5.43	
15SM66-1	1.27	6.21	Hole 111 (below 130m)
15SM66-2	1.91	6.25	
16SM66-1	1.27	6.43	Hole 111 (below 130m)
16SM66-2	2.54	6.63	
17SM66-1	1.27	5.46	Hole 111 (below 130m)
17SM66-2	1.91	5.66	
18SM66-1	1.27	4.63	surface
18SM66-2	2.54	4.64	
18SM66-3	3.81	4.73	
19SM66-1	1.27	5.47	surface
19SM66-2	2.54	5.63	
19SM66-3	3.81	5.63	

Table 4. Thermal Conductivity measurements from Spor Mountain area. All values determined from shelf-dried specimens.

Table 5

Thermal Conductivity Measurements From La Sal, Utah

Sample No.	Thickness, cm	Thermal Conductivity mcal/cm-sec-°C		Remarks, Location
		dry	saturated	
4H66-1	1.27	6.88	--	From lower 75 feet of Chinle Formation, Alice inclined shaft. Sandy mudstone, ± 20% quartz
4H66-2	2.54	7.16	8.75	
6H66-1	1.27	7.40	--	From lower 75 feet of Chinle Formation, Alice inclined shaft. Muddy sandstone, ± 50% quartz
6H66-2	2.54	7.68	9.14	
6H66-3	1.27	7.28	--	
6H66-4	2.54	7.08	--	
8H66	2.54	8.37	9.24	From lower 75 feet of Chinle Formation, Alice inclined shaft. Sandstone, ± 80% quartz
9H66	2.54	5.45	--	From lower 75 feet of Chinle Formation, Alice inclined shaft. Mudstone, 10% quartz
1L66-1	1.27	7.05	--	Sample 1L66 through 9L66 are Chinle from surface exposures on the Wingate-Chinle cliff and talus slope just east of La Sal triangulation station (38° 14' 16.9" N. Lat., 109° 16' 20.7" W. Long.) Muddy sandstone, ± 80% quartz.
1L66-2	2.54	7.50	9.32	
2L66	2.54	7.98	--	Sandstone, ± 80% quartz Chinle.

Table 5
con't.

Sample No.	Thickness, cm	Thermal Conductivity mcal/cm-sec-°C		Remarks, Location
		dry	saturated	
5L66	2.54	6.09	7.08	Chinle. Muddy sandstone, ± 70% quartz.
6L66	2.54	7.98	9.08	Chinle. Muddy sandstone, ± 70% quartz.
7L66	2.54	6.42	7.86	Chinle. Muddy sandstone, ± 70% quartz.
9L66-1	1.27	5.42	--	Chinle. Sandy mudstone. ± 40% quartz.
9L66-2	2.54	6.00	8.38	
11L66-1	1.27	11.50	--	Wingate. From Wingate-Chinle cliff. See 1L66. ± 95% quartz.
11L66-2	2.54	12.19	13.94	
1SJ66-1	1.27	11.67	--	Wingate. From Wingate-Chinle cliff. See 1L66. ± 95% quartz.
1SJ66-2	2.54	12.10	--	

Figure Captions

Figure 1. Temperature profile in hole D-142, Bingham, Utah.

Figure 2. Temperature profiles in drill holes at Spor Mountain and Jordan Valley, Utah

Figure 3. Temperature profiles in drill holes at La Sal, Utah

Figure 4. Heat flow measurements to date in Utah.

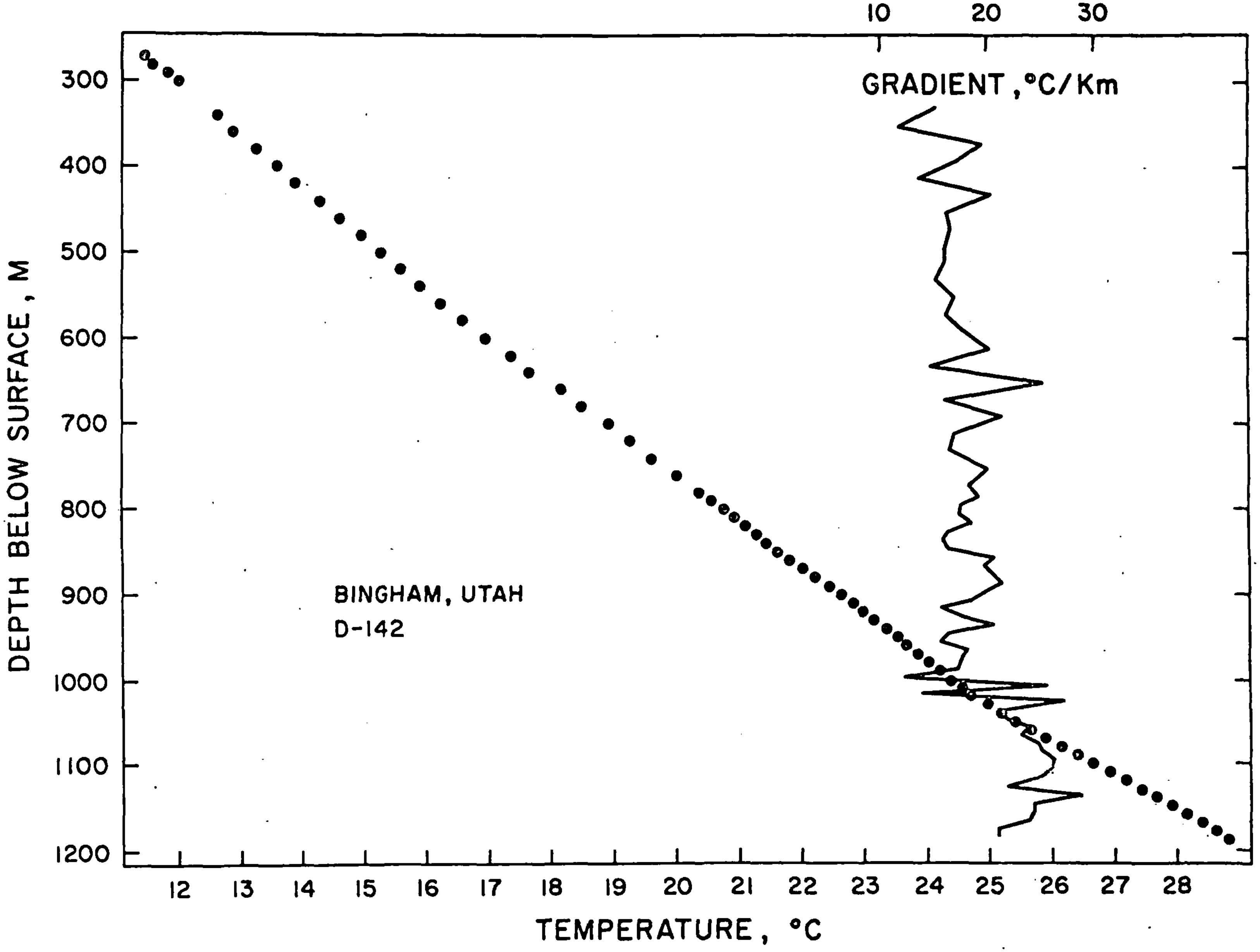
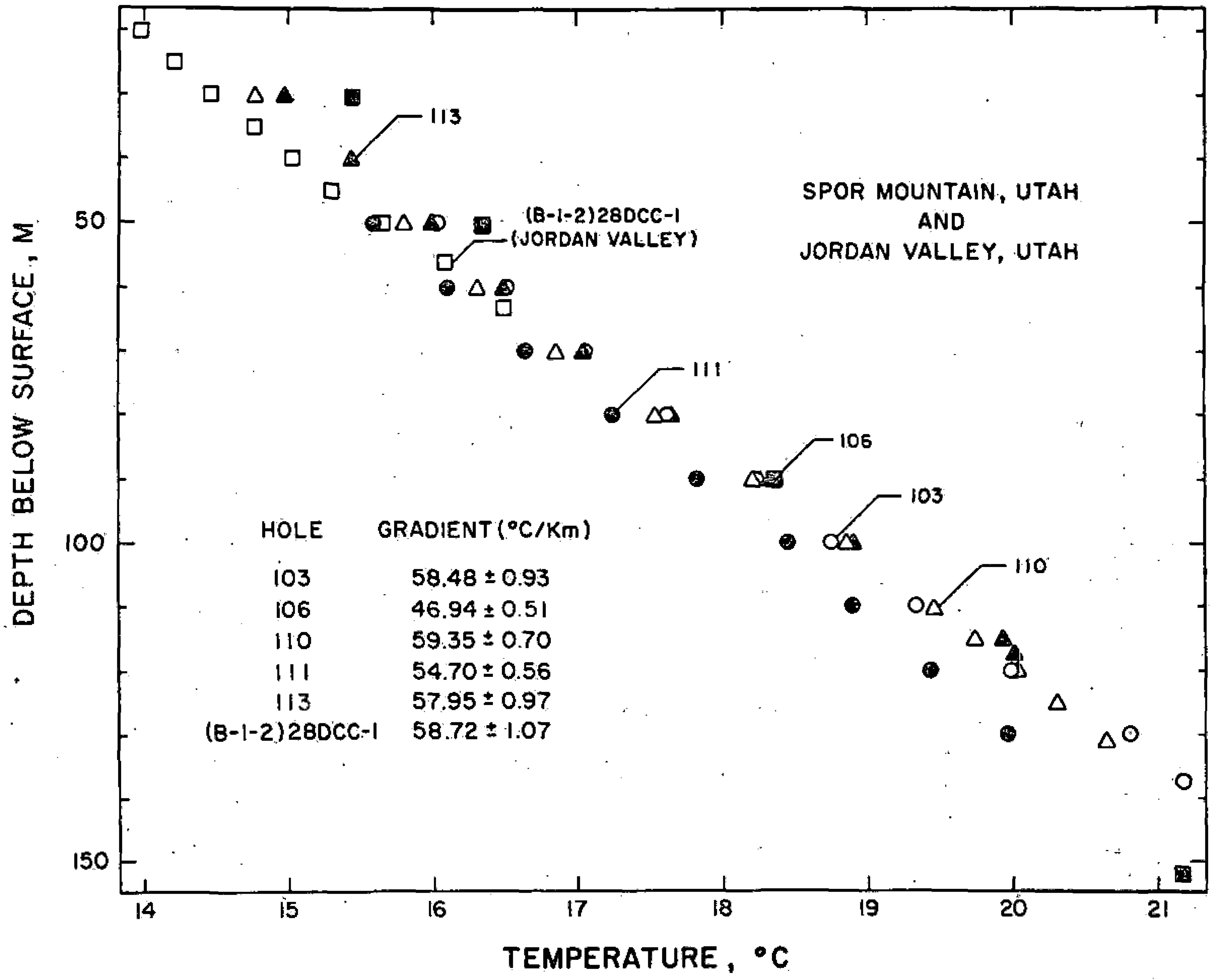

10
20
30
GRADIENT, °C/Km
300
400
500
600
700
800
900
1000
1100
1200
DEPTH BELOW SURFACE, M
BINGHAM, UTAH
D-142
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
TEMPERATURE, °C

FIG 1



HOLE	GRADIENT (°C/Km)
103	58.48 ± 0.93
106	46.94 ± 0.51
110	59.35 ± 0.70
111	54.70 ± 0.56
113	57.95 ± 0.97
(B-1-2)28DCC-1	58.72 ± 1.07

FIG 2

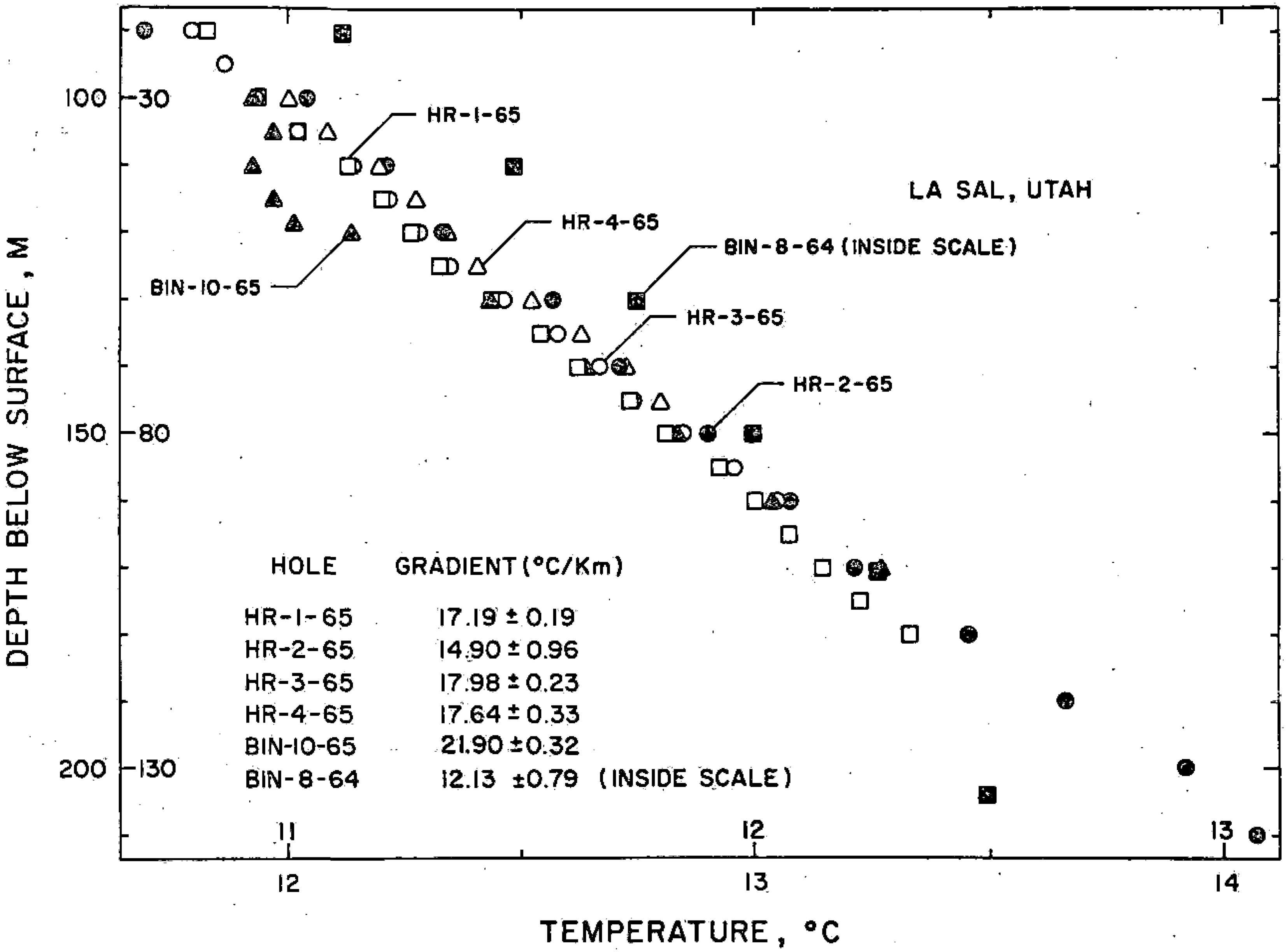
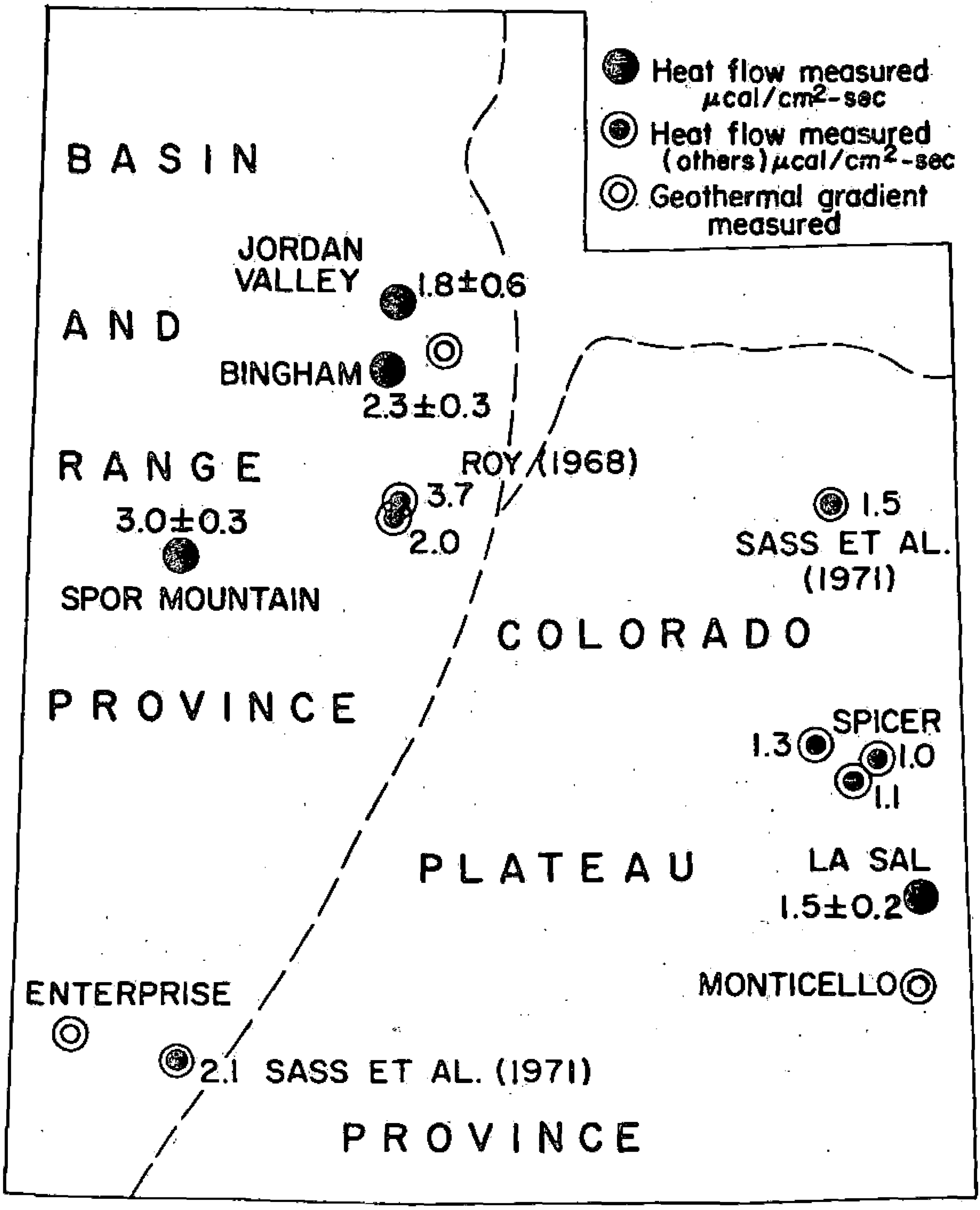

LA SAL, UTAH
HR-1-65
HR-4-65
BIN-8-64 (INSIDE SCALE)
HR-3-65
HR-2-65
BIN-10-65
HOLE
GRADIENT (°C/Km)
HR-1-65 17.19 ± 0.19
HR-2-65 14.90 ± 0.96
HR-3-65 17.98 ± 0.23
HR-4-65 17.64 ± 0.33
BIN-10-65 21.90 ± 0.32
BIN-8-64 12.13 ±0.79 (INSIDE SCALE)
DEPTH BELOW SURFACE, M
100
150
200
30
80
130
11
12
13
12
13
14
TEMPERATURE, °C

FIG. 3

FIG. 4


● Heat flow measured μcal/cm²-sec
◉ Heat flow measured (others) μcal/cm²-sec
◎ Geothermal gradient measured
BASIN AND RANGE PROVINCE
COLORADO PLATEAU PROVINCE
JORDAN VALLEY 1.8±0.6
BINGHAM 2.3±0.3
ROY (1968)
3.7
2.0
3.0±0.3
SPOR MOUNTAIN
1.5
SASS ET AL. (1971)
SPICER
1.3
1.0
1.1
LA SAL 1.5±0.2
MONTICELLO
ENTERPRISE
2.1 SASS ET AL. (1971)

Part of yearly report by Dept of Geophysics, Univ. of W. Ontario
London, Canada.

Heat Flow Measurements ((Beck), Sass, Judge, Mustonen)

All available data on underground temperatures in Southwestern Ontario are being obtained. A preliminary study based on over 100 conductivity determinations indicates that the mean thermal conductivities of individual sedimentary sections can be correlated over large distances within Southwestern Ontario. A study of the five major formations involving about 1000 conductivity determinations is now in progress.

Over one hundred and fifty determinations of thermal conductivity for the U.W.O. hole have been made. When combined with temperature data, these result in a mean heat flow of 0.82 ± 0.05. Work is continuing on the preparation of a heat flow contour map of Southwestern Ontario

Temperature measurements have been obtained from over 80 boreholes within an area of 5 km^2 around Lake Dufault Mines, Quebec. Isotherm maps have been contoured for -500, 0, and + 500 ft. above mean sea level. There is little evidence that temperatures have been disturbed by water flow or oxidation of sulphides. It is difficult to correlate the minor temperature perturbations that occur with topography, structure, or geological history, as they have almost certainly been caused by a complicated combination of all of these factors. About 200 thermal conductivities have been measured and a conductivity contrast between the two main rock-types (Andesite and Rhyolite) has been noted. The ore has a thermal conductivity about twice that of the country rock but this has not been reflected in the thermal gradients near ore bodies, possibly because of the relatively small volume occupied by high grade ore. The low heat flow (about 0.7) at the Dufault site confirms the values measured by Misener and others within the Grenville Province.

Over 100 conductivities have been measured on rocks from two holes (Muskox South and Muskox North) at the Muskox site near Coppermine N.W.T. Temperatures measured in Muskox South during the summer of 1965 have been corrected for the warming effect of a nearby lake and have been combined with conductivity data to give a heat flow of 1.3 ± 0.1 μcals/cm^2 sec (Beck & Sass, 1966). Preliminary studies indicate a high degree of correlation between thermal conductivity and mineralogy for rocks from the Muskox holes.

[illegible] station, using [illegible] recordings and [illegible] was set up at Eskimo Point N.W.T. The [illegible] to be relatively flat with a thickness of [illegible] and [illegible] the coast, and then [illegible]

35 Km on the eastern side. Further studies are being made on the detection and application of converted waves using a three component array to crustal interpretation.

During October 1965, the department cooperated with the Americans in successfully recording the operation Longshot nuclear shot. A three component station was set up near Wawa, Ontario.

Preparations are now under way for participation in the "Early Rise" Lake Superior seismic experiment. Recordings here will be done on a new Sanborne hot wire recorder. This station will be used to fill in a grid on time-term study of the crust.

C. GEOMAGNETISM

Paleomagnetism (Palmer, Carmichael)

A major portion of the academic year was devoted to an intensive study of the remanent magnetization of some 230 samples of volcanic rock collected from 5 areas around the perimeter of Lake Superior. Stability of the remanent magnetization of these Keweenawan lavas is indicated by AC demagnetization experiments, by conglomerate tests and fold tests. Statistical examination of the results of these tests are now examined on a routine basis by the use of the IBM 7040 computer on campus. In addition to providing pole positions for North America in Keweenawan time (1.05 b.y.), the presence of reversals of magnetic polarity in these sequences, will be an aid in correlating these units from one area to another. This will be an aid in reconstructing the development of this major volcanic pile of the Canadian Shield.

The above Keweenawan data, together with other results obtained, or in progress in our laboratory, will enable us to calculate paleomagnetic pole positions for North America for the ages 1.05 b.y., 1.47 b.y. and 2.1 b.y.

In addition to providing a pole position, the measurement of the remanent magnetization of a group of samples from a rock unit can be used to calculate paleolatitudes for the continental mass of which the rock unit is a part at the time the rock unit in question was deposited. The most recent glaciation, the Pleistocene, was confined to regions of the earth in high or intermediate latitudes. Paleomagnetic data has indicated that the glacial deposits of Permian age found on the major continents of the Southern hemisphere were deposited in high latitudes in Permian time. There is evidence however, that glacial deposits of the Late Precambrian may have had a world-wide distribution. It is therefore of scientific interest to test whether earlier Precambrian glaciations were world-wide or confined to polar or near-polar regions. With this idea in mind, a suite of varvites from the Huronian sequence near Iron Bridge, Ontario have been collected and initial measurements of their natural remanent magnetization have been completed in our own laboratory and at the magnetic laboratory of the Dominion Observatory, Ottawa.

A manuscript reporting our investigation of the paleomagnetism of the Late Triassic North Mountain Basalt of Nova Scotia is in preparation and will be submitted for publication this coming year.

Six weeks in March and April of this past year were spent on a research trip to Chile and Peru. A collection of Jurassic, Cretaceous, and Tertiary rocks was obtained. It is hoped that these suites of samples will provide paleomagnetic poles for South America that can be compared with paleomagnetic data from other continents of the southern hemisphere

Attenuation of Elastic Waves by Magnetic Fields (Lilley, Carmichael)

Elastic waves in conducting materials have been shown to be attenuated by magnetic field gradients. Both experimental and theoretical studies have been conducted on the problem. The conducting media used were bars of aluminum copper and brass in various thicknesses from one eighth to three eighths inches and lengths from one to twelve feet. Standing elastic waves were generated by a piezoelectric crystal and the displacement was measured using strain gauges. The attenuation has been shown to be due to the field gradient.

D..OTHER

Hydrodynamics of the earth's Core (Smylie, Beck)

An experimental set-up in cylindrical geometry has been constructed to investigate the feasibility of using high electric field gradients in a dielectric fluid to produce thermal convection under a central force. Work is continuing on the development of the apparatus.

6. ABSTRACTS OF THESES

M.Sc.

LAW, L. K. "Anistropic Susceptibility of Rock Samples"

It would be useful in rock magnetism studies to have a versatile apparatus capable of routinely determining the remanent magnetic vector, the anisotropic susceptibility and the variation of these parameters with temperature. A vibrational magnetometer with the coil configuration of Krause (1963) measures three orthogonal components of the magnetic vector without changing the orientation of the sample and has provisions for a furnace. This type of system was constructed and an orthogonal set of Helmholtz coils added to obtain sufficient measurements for the determination of the anisotropic susceptibility. The computer program for the computation of the susceptibility ellipsoid is presented. Examples of the method are given, using core samples from the Nakina area. The problems of the vibrational system are discussed and recommendations made to improve the present minimum detectable signal level of approximately 2 x 10^{-4} emu/c.c.

M.Sc.

NEOPHYTOU, J.P. "Tritium Dating Theory And Applications"

The variation of ^{3}H and ^{90}Sr inventories, the factors influencing global fallout in general and of ^{3}H in particular, with special emphasis on Canadian fallout, and ^{3}H content of Saskatchewan waters are investigated. On the basis of these findings, a broader theory for interpreting ^{3}H "age" in hydrological studies is developed and applied to determine the transit times and velocity of water circulating in the Coronation Mine near Flin Flon, Manitoba.

The present ^{3}H and ^{90}Sr inventories are 235 ± 25 kg and 37 ± 4 Mc respectively. The distribution of tritium depends on the same meteorological factors influencing the fallout of other radio-active nuclides namely jet streams, global winds, humidity, precipitation and their variability. In addition ^{3}H fallout is complicated by the additional factors of evaporation and molecular exchange between the atmosphere and the ocean surfaces. The annual pattern of ^{3}H in precipitation exhibits maxima in spring and minima in late autumn, a point on which other investigators agree. The fallout over Canada follows the increased inventory of radio-active nuclides. The ^{3}H content of Saskatoon precipitation can be taken as a guide for the total average fallout in precipitation for the whole of Canada. Assuming that the moratorium of nuclear testing will last the future peaks of ^{3}H in the precipitation at Saskatoon are predicted on the basis of ^{3}H inventory. The small lakes of Saskatchewan are effective in retaining de-

Best Regards
Marshall

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A New Steady-State Method for Determining Thermal Conductivity

MARSHALL REITER AND HAROLD HARTMAN

New Mexico Institute of Mining and Technology, Socorro 87801

A new steady-state absolute method for determining the thermal conductivity of rock specimens is presented. The technique involves putting a known quantity of heat into a specimen with an ohmic heater and determining the thermal gradient across the specimen with thermocouples. It follows from the steady-state conduction equation that the thermal conductivity can be calculated from the expression $K = q/(\Delta T/\Delta z)$. The heating element and the sample are insulated with polyurethane to reduce thermal losses. The bottom of the specimen is placed in contact with a massive aluminum block that serves as a thermal sink and remains essentially an isotherm for the duration of an experiment. Thermal-conductivity values for fused and crystalline quartz determined by the new apparatus agree with Ratcliffe's data to within 1.5% for fused quartz and to within 2% for crystalline quartz. Thermal-conductivity values of rock specimens measured on our apparatus agree to within 3.5% with the thermal-conductivity values of the same specimens determined on a divided-bar apparatus. It is estimated that the system has an absolute accuracy of ±4%. The apparatus is easier and less expensive to construct than many other thermal-conductivity systems. The apparatus should also be applicable to measuring thermal diffusivity by a variation on Ångström's method.

Theory. A general discussion of the various methods employed to measure the thermal conductivity of rock specimens is given by *Beck* [1960, 1965] and *Jaeger* [1965]. The present method of determining thermal conductivity is an absolute technique differing from that described by *Ratcliffe* [1959, 1960] in essentially one way: the constant-temperature baths used by Ratcliffe are replaced in our system by a massive aluminum heat sink. Absolute methods typically involve putting a known quantity of heat into a specimen and measuring the resulting equilibirum gradient across the specimen. In the steady state one can apply the conduction equation

$$q = K(\Delta T/\Delta z) \tag{1}$$

where q is the flux of heat (heat flow per unit area per unit time) into the specimen, K is the thermal conductivity of the specimen, and $(\Delta T/\Delta z)$ is the thermal gradient across the specimen. From equation 1 the thermal conductivity follows as

$$K = q/(\Delta T/\Delta z) \tag{2}$$

To measure K, one must therefore determine q and $(\Delta T/\Delta z)$.

Description of apparatus. Figure 1 illustrates the new apparatus. The heating element, screwed to the upper copper disk, is molded in polyurethane so that almost all the heat output is directed into the rock specimen. (Heat losses through the insulation will be discussed later.) Because the sample is radially insulated, the heat flow will be essentially axial into the massive aluminum block. (Radial heat losses will also be discussed later.) The temperature of the aluminum block changes very little over the duration of an experiment. Therefore the lower surface of the rock is almost an isotherm during an experiment. By extending the duration of an experiment from 20 min to several hours we could not detect experimentally a measurable change in the thermal conductivity of the specimen (the average time required to measure the thermal conductivity of a sample 1.27 cm thick is approximately 20 min). We may therefore conclude that, mainly owing to temperature fluctuation in the room, the heat input of the aluminum block is experimentally insignificant. The aluminum block used in this apparatus weighed 31.8 kg. Of course, any large piece of metal can be used for the thermal sink.

Examining equation (2), one can see that the parameters necessary to determine K are q and $(\Delta T/\Delta z)$. The value of q is calculated by determining the power output of the heater and dividing by the surface area of the specimen. Knowing the energy dissipation of the heater involves measuring the current through and the voltage across the heater. Power to the heater is supplied by a constant-current–constant-voltage power supply. Copper-constantan thermocouples are used to determine the temperature difference ΔT across the specimen. A micrometer is used to determine specimen dimensions, the diameter and the thickness (Δz) of the specimen.

Our K-2 potentiometer demonstrates a reproducibility of approximately $\pm 1 \times 10^{-6}$ volt. To keep the potentiometer reproducibility at better than 1%, we maintain $150\text{–}200 \times 10^{-6}$ volt between thermocouples. This necessitates putting a 4°–5°C temperature difference across the specimen. For the samples in this study, which are 3.683 cm in diameter and 1.27 cm thick, this temperature difference requires a power dissipation of about 0.5 watt for fused quartz and 2.5 watts for crystalline quartz. Power dissipation for the rock samples lies between these limits.

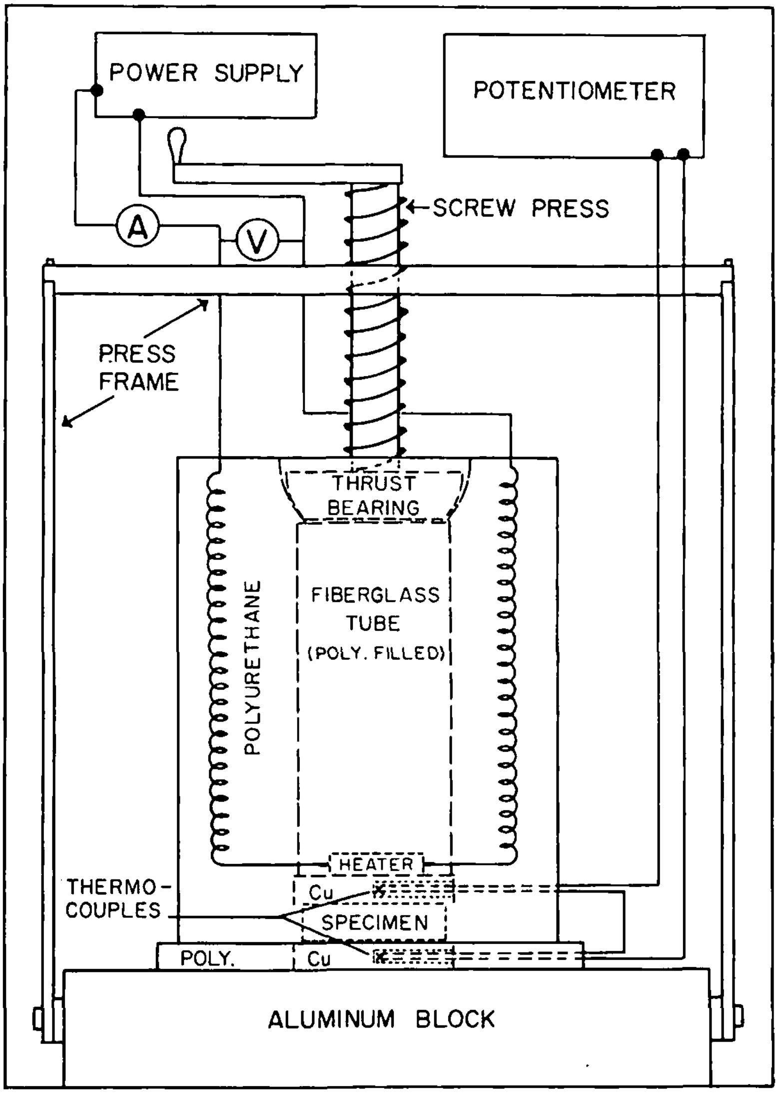

Fig. 1. Schematic diagram illustrating the new apparatus.

In our study the diameter of the specimens matched the diameter of the upper copper heating disk. Smaller-diameter specimens can be used if an appropriate insulating bushing is placed around the specimen, but the amount of heat axially dissipated through the insulating bushing must be considered. Of course, one can also construct different-sized heating elements that match the diameter of the specimens to be measured.

A thrust bearing mounted to a screw press pushes against the fiber glass tube and puts axial pressure on the specimen. This pressure reduces the contact resistance at the specimen surfaces. With the screw-press arrangement we did not measure the axial pressure. (We believe it to be more than several bars.) The apparatus can easily be modified to incorporate a hydraulic system for axial pressure, and in such an arrangement the axial pressure can readily be measured. Wakefield thermal compound is applied to the flat surfaces of the specimen to give better thermal contact. (Calculations of the errors introduced in the thermal-conductivity measurements by the film at the contact surfaces of the specimen are presented later.)

The new system could be used to determine thermal conductivities at different temperatures by varying the temperature of the aluminum block.

The present technique for measuring thermal conductivity should also lend itself to measuring thermal diffusivity. This measurement might be accomplished by connecting the heater to a timing device that would create a square-wave heating current and then monitoring the thermocouple output at each end of the specimen with a strip-chart recorder. This technique would require a slight change in the thermocouple setup because in the present system we are interested only in determining ΔT. The theory for such a technique is essentially an extension of Ångström's method and is presented for an experimental system by *Kanamori et. al.* [1968].

Data and errors. Table 1 presents a comparison of the data taken in this study with data taken by other techniques. The standards of fused and crystalline quartz, whose thermal conductivities have been measured by many scientists, and rock samples previously measured on a divided-bar apparatus have been used to evaluate the relative accuracy of our apparatus. Mean thermal-conductivity values for fused and crystalline quartz measured on our apparatus agree with other accepted measurements to within 2%. All the data taken on the divided-bar apparatus agree with our data to within 3.5%. *Roy* [1963] states that the absolute accuracy of the divided-bar apparatus is ±5%. *Ratcliffe* [1959] estimates the accuracy of his thermal-conductivity measurements to be ±1.5%. We therefore conclude that there is good agreement between the data taken on our system and the data taken by other investigators on other systems.

The most probable sources of error in our measurements are meter inaccuracy, heat losses through the polyurethane insulation (both from the heater and radially from the rock), and thermal-contact resistance. The meters used have an accuracy of ±1%.

We have calculated that a maximum of 2.5% of the energy produced by the heater can be lost through the insulation if the specimen is fused quartz and 1.5% if the specimen is crystalline quartz. These calculations employ the ratios of the thermal conductivities, lengths of thermal paths, and surface areas of the insulation and of the rock. A similar calculation for the radial heat losses in the specimen indicates that a maximum of 1.5% of the heat introduced into the top surface of the fused quartz specimen and less than 1% of that introduced into the crystalline quartz sample can be radially lost. For fused quartz the heat losses could therefore introduce a maximum error of 4% in the thermal-conductivity measurements. This error would tend to increase the measured thermal conductivity; i.e. the measured q would appear greater than the actual q through the specimen. Ratcliffe used a guard heater to eliminate heat losses in his measurements. If heat loss is the only reason for the difference between our data and Ratcliffe's data for fused quartz, the difference (3.33–3.28 mcal/cm sec °C) suggests that our total heat losses would be less than 4%. This value would be proportionally less for crystalline quartz.

Calculation of the errors introduced into thermal-conductivity measurements by the contact films at the surface of the specimen, based on *Ratcliffe*'s [1959, p. 23] formula, indicates that for a fused or a crystalline quartz specimen 1 cm thick the errors will be 1.5% and 7.5%,

TABLE 1. Comparison of Data Obtained by the Present Method with Data Obtained by Other Techniques

Sample	No. of Measurements	Values for Present Method,* Mean Value ± S. D., mcal/cm sec °C			Values Determined by Other Techniques, mcal/cm sec °C
Fused quartz	9	3.33	±	0.02	3.28†
Crystalline quartz (normal to the optic axis)	9	14.8	±	0.1	15.1‡
CC-4-400 (carbonate)	6	13.5(5)	±	0.0(2)	14.0§
CC-4-1124 (carbonate)	6	9.66	±	0.08	10.0§
CC-4-1325 (carbonate)	6	12.4	±	0.1	12.5§
CC-2-2424 (carbonate)	6	8.49	±	0.10	8.22§

* Measurements taken at mean sample temperature of 26°C ± 1.5°C.

† *Ratcliffe* [1959].

‡ Preferred value, *Ratcliffe* [1959].

§ Value measured on the divided-bar apparatus at Virginia Polytechnic Institute.

respectively, if a 0.00254-cm gyclerial film is used and 0.3 and 1.5% if a 0.00254-cm Wakefield thermal-compound film is used. (Ratcliffe calculated these errors in his conductivity measurements to be 1–5% for fused quartz and 2.5–13% for crystalline quartz, depending on the thickness of the specimen.) For the applied axial pressure in our apparatus the thickness of the contact films can be reduced. Consequently, we expect an insignificant error to result from contact resistance for fused quartz. Discrepancies between the values in Table 1 for fused quartz are probably due to a combination of additional thermal losses and better contact resistance with our system and possible specimen differences.

Ratcliffe prefers a value of 15.1 mcal/cm sec °C for the thermal conductivity of crystalline quartz normal to the optic axis. However, other data cited by Ratcliffe suggest that crystalline quartz may possess a lower thermal conductivity, (e.g., the Griffiths and Kaye value of 14.7 mcal/cm sec °C). Values of the thermal conductivity of crystalline quartz normal to the optic axis at 25°C between 14.7 and 15.1 mcal/cm sec °C now appear to be within acceptable limits. Again, slight specimen differences might contribute to the differences in the data. (Note that increased thermal losses and better thermal contact with our system would tend to produce differences in the data opposite from those observed.)

If all possible errors are taken into account, the writers believe the above analysis allows the present technique an absolute accuracy of ±4%.

Comparison with other techniques. Figure 1 illustrates the relative simplicity of our apparatus. Instead of a metal block, most other techniques employ thermal sinks whose temperatures are regulated by expensive water baths. These thermal sinks involve machining and necessitate the construction of a rather sophisticated frame. Our experience has shown that our apparatus is considerably easier and less expensive to construct than a typical divided-bar apparatus.

Requirements for specimen preparation are the same with our technique as with other techniques such as the divided bar. However, changing specimen size with the divided bar involves a repertory of quartz reference disks and stack members. These extra stacks involve extra expense. As previously pointed out, we may interchange specimen sizes up to the diameter of the heating plate by employing an appropriate insulating bushing.

The time per measurement with our system is approximately 20 min. This is comparable to, or slightly faster than, the time per measurement with the divided-bar apparatus. Because it is an absolute technique, the new system takes slightly longer to achieve equilibrium; however, specimen changing is less time consuming.

Acknowledgments. We thank Chester McKee and John Colburn for many helpful suggestions about the design of the apparatus. Dr. John K. Costain, professor of geophysics, Virginia Polytechnic Institute, supplied the specimens and critically read the manuscript.

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(Received December 28, 1970;
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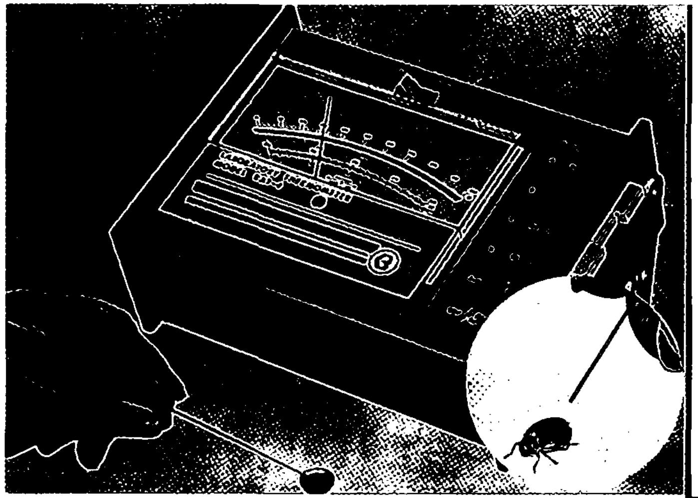

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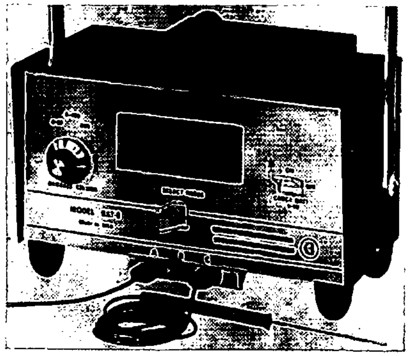

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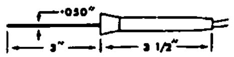
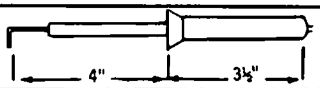
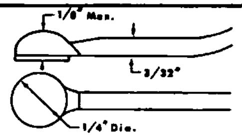
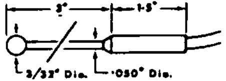
HT 1	Lab 'workhorse' probe for gases, liquids, solids.	Welded stainless steel shaft, plastic handle, immersible.	2 Sec.		$25
HT 2	As HT 1 but with 9" shaft.		2 Sec.		$35
NEW BT 1	'Workhorse' like HT 1 (above) but also good for surface temps.	Rugged, welded stainless steel, immersible	0.9 Sec.		$35
SST 1	Skin *surface (tape on)* and axillary.	*Gold alloy,* fast response.	0.9 Sec.		$35
OT 1	Oral and lab. use	Stainless steel 30 ga. with handle. Fast response, immersible.	1.0 Sec.		$30
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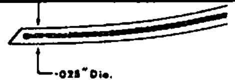
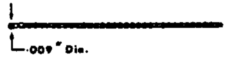
IT 1	Rectal, etc. in small animals. Also tissue implantable with 18 ga. needle.	Flexible, Teflon-sheathed, immersible.	0.1 Sec.		$35
IT 2	Tissue implantable, with 24 ga. needle. Also microbiology.	Sensor bead only .009" dia. Teflon leads. Fast response.	0.05 Sec.		$25
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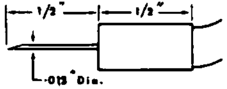
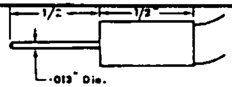
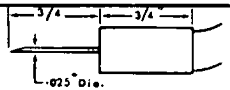
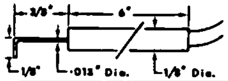
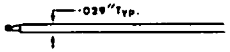
MT 3 & MT 3/S	Subcutaneous temperatures; also semi-solids. Acupuncture etc.	Microprobe needle .013" dia. (29 ga.) Very fast response. Needle lengths up to 2". Can be re-sharpened.	0.25 Sec. 0.25 Sec.		$50
MT 4	Microbiology; instant skin and surface temperatures. Locate "hotspots" in electrical circuits.	Microprobe, blunt .013" dia. (29 ga.) Very fast response.	0.1 Sec.		$50
MT 5	Industrial & Lab use. Surface temps and small specimen measurements.	Rugged Microprobe .025" dia. (23 ga.) Fast response	0.25 Sec		$30
MT D	Dental and skin (hand held).	Microprobe, blunt. Very fast response. Stainless steel, immersible.	0.1 Sec.		$60
PT 6	Inexpensive, flexible probes for multi-point measurements.	Welded beads, tough Kapton insulation, 5 ft. leads. Usable to 400°C.	.01 Sec.		$48 per pack of 6
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Heat Flow at Spor Mountain, Jordan Valley, Bingham, and La Sal, Utah

JOHN K. COSTAIN

Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061

P. M. WRIGHT

Kennecott Exploration Inc., Salt Lake City, Utah 84104

Geothermal gradients were obtained in drill holes in Utah at Spor Mountain, Enterprise, La Sal, Monticello, Bingham, and Jordan Valley. A heat flow of 3.0 ± 0.3 μcal/cm^2 sec was found at Spor Mountain (39°43′N, 113°13′W). The flux at Jordan Valley (40°47.0′N, 112°04.3′W) is estimated to be 1.8 ± 0.6 μcal/cm^2 sec. The revised heat flow at La Sal (38°14.3′N, 109°16.3′W) on the Colorado Plateau is 1.5 ± 0.2 μcal/cm^2 sec. The heat flow at Bingham (40°32′N, 112°09′W) is 2.3 ± 0.3 μcal/cm^2 sec. On the basis of much of the heat flow data now available for the Colorado Plateau, including our revised values at La Sal, there appears to be less justification for defining the Colorado Plateau as a separate heat flow province with abnormally low heat flow.

Temperatures were measured in drill holes at Spor Mountain, La Sal, Bingham, and Jordan Valley, Utah. Five drill holes were logged for temperature in the Enterprise area, and one hole near Monticello, San Juan County. In the Enterprise and Monticello areas the temperature gradients were disturbed by shallow groundwater circulation, and no further interpretation of the data from these holes was justified [*Wright*, 1966].

TEMPERATURE MEASUREMENTS

For the holes at Spor Mountain, Jordan Valley, and La Sal we used a platinum resistance thermometer, model 134HH, manufactured by Rosemount Engineering Company, with a nominal ice point resistance of 1000 ohms. A change in temperature of 0.01°C corresponds, for a 1000-ohm element, to a change in resistance of approximately 0.036 ohm. Any system used to measure resistance must be able to detect a change in resistance of this magnitude in order to resolve temperature changes as small as and smaller than 0.01°C. To measure temperature to an accuracy of ±0.01°C at, say, 50°C would require measuring the resistance of a probe whose nominal ice point resistance is 1000 ohms to an accuracy of 1197.38 ± 0.036 ohms, or to about 0.003%. The individual resistance bridge decades can be calibrated to this accuracy; however, because of the limited resistance range that will be encountered in the field by using a 1000-ohm platinum probe, about 390 ohms for the temperature range 0°–100°C, it is possible to compare the resistance of the probe with the constant resistance of an accurate primary standard for which the resistance is known to ±0.001%. For all of the holes except the one at Bingham we used a comparison bridge, model DBR-1, manufactured by the RdF Corporation, Hudson, New Hampshire. This bridge balances out most of the probe resistance with a primary standard resistance accurate to within ±0.001%. If the nominal resistance of the probe used was 1000, 2000, or 5000 ohms, then the resistance of the primary standard used was 1000.00 ± 0.01, 2000.00 ± 0.02, or 5000.00 ± 0.05 ohms, respectively. The standards were calibrated by the manufacturer, by a secondary standards laboratory, and by the National Bureau of Standards. The final bridge balance was achieved by using the Rubicon decade resistances in the bridge. We believe the accuracy of our temperature measurements with the 1000-ohm probe to be ±0.05°C and the precision to be ±0.01°C. The hole at Bingham was logged by using a 5000-ohm platinum resistance probe with a precision of about ±0.002°C.

A different apparatus was used at the Bingham hole, and we are now using a Honeywell 1551-E Mueller bridge in conjunction with Julie Research Laboratories and Electroscientific Industries SR-1 standard resistors, which are accurate to ±0.001%. A Honeywell 3972 dc microvolt null detector is used to balance the bridge. The Mueller bridge also provides for balancing out most of the resistance of the probe with an external primary standard resistance. As is true with the comparison bridge, final balance is achieved by using decades built into the bridge.

Most temperature measurements for terrestrial heat flow determinations are made by using thermistors, and here the suitability of platinum for temperature measurements in deep holes is discussed. We have consistently obtained excellent results using platinum. For example, periodic relogging of hole (B-1-2)28dcc-1 in Jordan Valley near Salt Lake City over a period of 2 years showed differences in absolute temperature at any given depth of no more than ±0.03°C, when probes of different nominal resistances made by different manufacturers were used. We obtained this accuracy for repeated measurements in every hole not disturbed by groundwater movement regardless of depth, using probes of nominal ice point resistances of 1000, 2000, and 5000 ohms. There are disadvantages to using platinum; bridge calibration and galvanometer sensitivity are more critical because of the lower resolution of platinum compared with that of thermistors, and, for the probes that we have been using, the time constants are longer. Repeated measurements in several holes confirm that the calibration curve for platinum may shift slightly but that it shifts parallel to itself and the shift can be determined by noting the change in the ice point resistance. The shift is apparently related to the amount and the type of mechanical shock received by the probe over the years. Over a period of 5 months the resistance of the 1000-ohm probe was found to increase by about 0.7 ohm, corresponding to an apparent temperature increase of about 0.2°C. This increase was generally small for any given field trip, and no change in ice point resistance was noted between field trips [*Wright*, 1966, pp. 130–131]. For short intervals in a drill hole the better resolution of thermistors is a definite advantage. Our original reason for using platinum was the better stability of platinum over thermistors; however, thermistor probes with excellent stability, such as the Fenwal oceanographic-type probes, are now available, and we have essentially shifted to thermistors for field measurements, making occasional checks by using a platinum probe. We have compared gradients obtained with a 5000-ohm platinum element with those obtained with a Fenwal oceanographic probe of about 11,000-ohm ice point resistance and about 4800 ohms at 20°C. The difference in the gradients over intervals of about 100 meters was less than 2%.

For the holes at Spor Mountain, Jordan Valley, and La Sal we used U.S. Steel Corporation 4-H-1 four-conductor double-armored Amergraph cable, which is a heavy cable with a resistance of about 15 ohms/1000 feet and a breaking strength of 7200 pounds. The leakage resistance of the Amergraph cable was always greater than 50 MΩ and usually greater than 100 MΩ. We have since changed to lighter more portable cables and are now using Mark Products WF-TQ-190 W/4 Penalastic-filled polyurethane cables. Four-conductor cables were used for all temperature measurements to minimize the effects of lead resistance.

DETERMINATION OF THERMAL CONDUCTIVITY

Of the several methods used to determine the thermal conductivity of rocks [*Beck*, 1965] the most common is the divided-bar apparatus described by *Birch* [1950]. The apparatus constructed by us was designed after that used in the Hoffman Laboratory at Harvard University.

Rock disks 2.22, 3.0, 3.31, and 3.62 cm in diameter were commercially prepared from rock samples. The surfaces of the disks were machined flat and parallel to ±0.0008 cm, diameters being uniform and accurate to ±1%. Copper-constantan thermocouples were inserted into copper disks to measure the temperature differences across fused quartz reference disks and across the rock specimen. Thermal resistance at the contacts between the disks was reduced by applying a thin layer of vaseline to the disk faces and by applying an axial pressure of at least 100 bars to the stack. In order to ensure axial heat flow and to minimize radial heat loss, the stack was insulated with a tight-fitting machined block of high-density polystyrene. A temperature differential of about 10°C was applied across the stack. Measurements of the emf across each quartz disk and across the rock specimen were made with a Leeds and Northrup K-3 potentiometer. The temperature difference across the stack was held constant by thermostatically controlled temperature baths.

Repeated measurements on the same low-porosity rock disk were almost always reproducible to within 2%. For some of the more porous disks it was found that a small amount of vaseline would soak into the rock during measurement. After the disk had been measured a few times, less vaseline would be absorbed. This caused the apparent rock conductivity to increase with successive measurements until the faces of the disks no longer absorbed vaseline. When this 'equilibrium' state was reached, the thermal conductivity rarely increased by more than 5%, and repeated measurements reproduced to within 2%. In order to prevent vaseline from being absorbed by the specimen, a thin foil of aluminum 0.00254 cm thick was bonded to the flat faces of some of the disks with epoxy cement. Curing of the epoxy was completed at room temperature under about 350 bars for at least 12 hours. This curing resulted in a good bond and a smooth mirrorlike disk face. Vaseline was used as a contact substance between these aluminum-surfaced disks and the copper disks of the stack. Measurements made in this manner were reproducible to about 0.5%. Several disks that had been measured without the aluminum foil coating were later surfaced as was described above. The thermal conductivity results were the same, within about 2%. Reproduction of measurements was also improved by cementing the copper disks to the quartz reference disks by using silver epoxy cement.

Reproducibility of measurement is not necessarily an indication that the measured value is correct. It is difficult to assign an absolute accuracy to the measurements. *Roy* [1963, p. 7] states that 'systematic and random errors in the measurement of a single disk amount to 5 percent.' It seems likely that this value would also apply to our conductivity apparatus.

If temperatures are measured in a water-filled drill hole, it is important to saturate the rock samples thoroughly before thermal conductivity determinations are made [*Birch and Clark*, 1940; *Walsh and Decker*, 1966]. This saturation was not done for the thermal conductivity measurements previously reported for La Sal, Utah [*Costain and Wright*, 1968]. Except for hole Bin-8-65, however, the temperature measurements were made in water-filled holes [*Wright*, 1966, p. 76]. The heat flow values for La Sal were therefore too low, and revised values are given herein. All rock samples, except as noted, were saturated with water while they were exposed to a vacuum of 5 μm. The samples were measured after soaking for several days.

Thermal conductivities reported herein were measured while the temperature of the sample was within 5°C of its in situ temperature. The stacks of the divided-bar apparatus were calibrated at the in situ temperature by replacing the rock samples with GE-101 fused quartz disks of the same size. The calibration thus included a correction for radial heat loss and contact resistance; i.e., the 'stack correction factor' required to make the measured conductivity equal to the known conductivity of fused quartz never exceeded 7% and was usually about 3%. The known thermal conductivity K of the fused quartz at a temperature of T°C was based on [*Ratcliffe*, 1959]

$$K = (3160 + 4.6T - 0.016T^2) \times 10^{-3} \text{ mcal/cm sec °C}$$

The thermal conductivities of several specimens were also measured by using crystalline quartz cut perpendicular to the optic axis. The results agreed with the conductivity values obtained by using fused quartz to within less than 3%.

RESULTS

Bingham, Utah. Hole D-142 at Bingham is located on the side of the Bingham Canyon copper mine (40°31′N, 112°09′W) at an elevation of 1963 meters above sea level. Temperatures were measured to a depth of 1200 meters. The temperature profile and gradient are shown in Figure 1. Table 1 summarizes straight-line least squares gradients in this hole for several intervals.

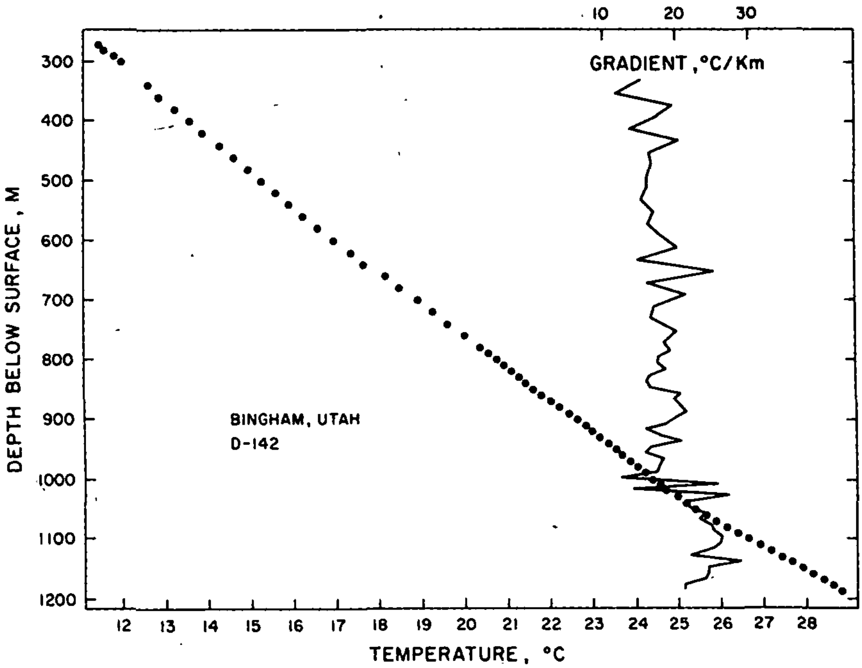

Fig. 1. Temperature profile in hole D-142, Bingham, Utah.

Since the Bingham hole is not included in *Wright* [1966], a few details concerning the terrain correction will be given here. The level of the bottom of the open-pit mine is approximately 1810 meters above sea level. The horizontal distance from the hole to the bottom of the mine is 1 km. Most of the peaks within 20 km of the hole have elevations between 2200 and 2700 meters above sea level. Nelson Peak, 2853 meters above sea level and about 9 km to the north, is the highest peak within a distance of 20 km from the hole. Terrain corrections to the geothermal gradient were calculated by using the method described by *Birch* [1950, pp. 582-600] and *Wright* [1966, pp. 149-178]. In order to examine the changes in the 'corrected' gradient for different assumptions about the physiographic history, corrections were calculated by assuming uplifts of from 0 to 4572 meters, evolution times of from 10 m.y. to infinity, and atmospheric temperature gradients of from −3°C/km to −6°C/km. Table 2 summarizes the results of the effects of different physiographic histories. The observed gradient for the depth interval 656–936 meters is 18.45° ± 0.25°C/km. The largest correction to the observed gradient is for short evolution times. For an evolution time of 10 m.y. the correction to the observed gradient, when no uplift and 4572 meters of uplift are assumed, is −9 and −15%, respectively, for an atmospheric gradient of −6°C/km. For an atmospheric gradient of −3°C/km the results are the same within about 3%. For longer evolution times the corrections are much smaller. Although the physiographic history of the region is not completely known, the effects of uplift and erosion for assumptions that probably bracket the correct physiographic history are shown in Table 2. When extreme conditions of 4572 meters of uplift and 10 m.y. of evolution time are assumed, the corrected gradient is only about 15% less than the observed gradient. For an infinite evolution time the corrected steady state gradient is 18.03° ± 0.074°C/km, or about −2% of the observed gradient. This value has been used for the corrected heat flow determinations given in Table 1.

The Bingham mine is centered on a small composite granite and granite porphyry stock that intrudes quartzites of lower Pennsylvanian age. Hole D-142 is drilled in quartzite to a depth of about 1036 meters, where it enters the stock. Associated dikes of quartz latite

TABLE 1. Summary of Gradients, Conductivities, and Heat Flow

Locality	Geographic Position	Elevation, meters	Depth Range, meters	*K*, mcal/cm sec °C[*]	Gradient, °C/km[*]	Uncorrected *q*, µcal/cm^2 sec	Corrected *q*, µcal/cm^2 sec
Bingham, D-142	40°32'N, 112°09'W	1963	576 to 886	13.25 ± 0.76 (15)[¶]	18.64 ± 0.3 (22)[¶]	2.47 ± 0.18	
			656 to 936	12.73 ± 0.98 (11)	18.45 ± 0.25 (23)	2.35 ± 0.21	2.30 ± 0.18
			1046 to 1156	9.08 ± 1.09 (4)[†]	24.77 ± 0.36 (12)	2.25 ± 0.31	
			1046 to 1156	8.18 ± 0.87 (3)[§]	24.77 ± 0.36 (12)	2.03 ± 0.24	
Best value							2.3 ± 0.3
Jordan Valley, (B-1-2)28dcc-1	40°47'N, 112°04.3'W	1285	20 to 63	3.0 ± 1.0	58.72 ± 1.07 (9)	1.8 ± 0.6	1.8 ± 0.6
Spor Mountain							
103		1451	50 to 138	5.47 ± 0.14 (20)	58.48 ± 0.93 (10)	3.20 ± 0.13	
106		1451	30 to 152	5.47 ± 0.14 (20)	46.94 ± 0.51 (4)	2.57 ± 0.09	
110	39°43'N, 113°13'W	1462	30 to 131	5.26 ± 0.2 (8)	59.35 ± 0.70 (12)	3.12 ± 0.16	
110		1462	120 to 127	5.26 ± 0.2 (8)	55.0 ± 1.1 (3)	2.89 ± 0.17	
111		1448	50 to 130	5.47 ± 0.14 (20)	54.70 ± 0.56 (9)	2.99 ± 0.11	
113		1457	30 to 118	5.47 ± 0.14 (20)	57.95 ± 0.97 (10)	3.17 ± 0.3	
Best value (average of five holes)				5.47 ± 0.14 (20)	55.48 ± 0.73	3.0 ± 0.3	3.0 ± 0.3
La Sal							
HR-1-65	38°14.8'N, 109°17.4'W	2104	90 to 180	Mean Chinle conductivity = 8.61 ± 0.26 (8)	17.19 ± 0.19 (18)	1.48 ± 0.06	1.53 ± 0.07
HR-2-65	38°14.8'N, 109°17.4'W	2099	50 to 210		14.90 ± 0.96 (17)	1.28 ± 0.13	
HR-3-65	38°14.8'N, 109°17.4'W	2102	90 to 160		17.98 ± 0.23 (15)	1.55 ± 0.07	
HR-4-65	38°14.8'N, 109°17.4'W	2099	100 to 145		17.64 ± 0.33 (10)	1.52 ± 0.07	
Bin-10-65	38°16.3'N, 109°18.4'W	1981	130 to 170		21.90 ± 0.32 (5)	1.89 ± 0.15	
Bin-8-64	38°16.3'N, 109°18.4'W			11.9 ± 0.14 (4) (Wingate)	12.13 ± 0.79	1.44 ± 0.12	
Best value							1.5 ± 0.2

[*] Errors are standard errors. Gradients are straight-line least squares gradients.
[†] Samples of dike rock from depths of 676, 681, 752, and 853 meters.
[§] Samples of dike rock from depths of 676, 752, and 853 meters.
[¶] Number of temperature measurements or thermal conductivity determinations.

TABLE 2. Summary of Corrected Geothermal Gradients for Hole D-142, Bingham, for the Depth Interval 656 to 936 Meters

Evolution Time, m.y.	Amount of Uplift Assumed, meters	Corrected Gradient, °C/km
10	4572 (4572)	15.73 ± 0.066
	3048 (4572)	16.09 ± 0.066
	0 (4572)	16.80 ± 0.066
	3048 (3048)	16.73 ± 0.070
	1524 (3048)	17.10 ± 0.070
	0 (3048)	17.48 ± 0.070
100	4572 (4572)	17.25 ± 0.072
	3048 (4572)	17.37 ± 0.071
	0 (4572)	17.61 ± 0.071
	3048 (3048)	17.60 ± 0.073
	1524 (3048)	17.73 ± 0.073
	0 (3048)	17.85 ± 0.073

The collar elevation of the hole is 1963 meters, α = 6°C/km, the diffusivity is 0.02 cm^2/sec, the observed gradient is 18.45°C/km, and the steady state gradient (infinite evolution time) is 18.03 ± 0.074°C/km. Numbers in parentheses denote original elevation of uplifted surface.

porphyry and latite porphyry were emplaced last, crosscutting all other rocks [*James et al.*, 1961]. The granite has few feldspar phenocrysts and no quartz phenocrysts. Phenocrysts of feldspar make up about 50% of the granite porphyry and average 3.5 mm in length. Quartz phenocrysts are rare. The dikes of quartz latite porphyry contain feldspar phenocrysts, which make up about 35% of the rock and average 2.5 mm in length. Quartz phenocrysts, averaging 2 mm in diameter, make up 3% of the rock. The groundmass of the dikes is aphanitic. The latite porphyry contains no quartz phenocrysts and except for color is similar to the quartz latite porphyry in appearance. Since no samples of the stock below 1036 meters were available for thermal conductivity determinations, the thermal conductivity of the rock for the depth interval 1046–1156 meters was assumed to be approximately equal to that of the dikes cut by the hole above 1036 meters. The locations of the dikes in the hole were well defined by a gamma ray log run in hole D-142 to a depth of 841 meters by using a Well Reconnaissance Geo-Logger model 8036. The hole was blocked to this logging tool at 841 meters. The log was essentially featureless throughout the quartzites, but excellent response was obtained for dikes at depth intervals of 671–686 and 747–754 meters. At about 1036 meters the hole penetrated the main Bingham porphyry stock, within which the gradient is 24.77° ± 0.36°C/km. Samples of dike rock for thermal conductivity determinations were prepared from core taken from depths of 676, 681, 752, and 854 meters. The mean thermal conductivity and the standard error as determined from four saturated cylinders under a pressure of 100 bars were 9.08 ± 0.95 mcal/cm sec °C. The resulting heat flow within the stock is 2.25 μcal/cm^2 sec, there being a probable error of about 15% because of the assumption that the dike rock has approximately the same thermal conductivity as the main Bingham porphyry stock. In the depth interval 656–936 meters the mean of seven thermal conductivity determinations of the quartzite and four samples of dike rock is 12.73 ± 0.98 mcal/cm sec °C. Combined with an observed gradient of 18.45° ± 0.25°C/km in the quartzites, this value gives a heat flow of 2.35 μcal/cm^2 sec, in good agreement with the deeper interval. The mean thermal conductivity of the quartzites only was 14.77 ± 0.32 mcal/cm sec °C. The thermal conductivity determinations from hole D-142 are as follows (depths are in meters, and thermal conductivities are in millicalories per square centimeter second degree Celsius):

Depth	Thermal Conductivity
587.7	12.99
629.7	14.96
630.6	15.29
646.2	15.52
675.8	8.30*
680.6	11.79*
696.2	15.39
752.0	6.61*
767.8	15.31
790.7	14.62
799.2	15.60
825.7	14.99
844.9	12.46
853.2	9.62*
884.8	15.35

(The values with asterisks are for a porphyry dike. All disks are 2.22 cm in diameter and 2.54 cm thick.)

Our heat flow values at Bingham are somewhat higher than those determined by *Roy* *et al.* [1968, p. 5219], who reported two values at Bingham of 1.5 and 1.9 μcal/cm^2 sec. The lower value of 1.5 μcal/cm^2 sec was apparently determined in the main Bingham stock, since the average thermal conductivity reported was 7.19 ± 0.28 mcal/cm sec °C. The value of 1.9 μcal/cm^2 sec was apparently determined in the quartzites, since the mean conductivity was 11.5 mcal/cm sec °C. Our mean conductivities are about 29 and 26% higher for rocks, which presumably would correspond to the quartzites and the stock, respectively; our gradients are about 9 and 27% higher in the quartzites and the stock, respectively. Undoubtedly, with the large differences in thermal conductivity between the porphyry and the quartzites, refraction is probably an important factor in the differences observed.

We feel the best heat flow value from hole D-142 is 2.3 ± 0.3 μcal/cm^2 sec. If only our three lowest conductivity values for the dike rock cut by hole D-142 are considered, the assumed conductivity of the stock would be 8.18 ± 0.87 mcal/cm sec °C, and the flux in the stock would be 2.0 μcal/cm^2 sec, still within our assumed uncertainty, and the lower conductivity value is in better agreement with that of *Roy et al.* [1968, p. 5219]. We prefer the higher value of 2.3 ± 0.3 μcal/cm^2 sec, since it is compatible with flux values obtained above and below the boundary of the main Bingham stock as penetrated by hole D-142.

Jordan Valley. The temperature profile in drill hole (B-1-2)28dcc-1 in Jordan Valley (40°47.0'N, 112°04.3'W) near Salt Lake City, Utah, is shown in Figure 2. This hole was drilled into interbedded sandy and muddy layers of the relatively unconsolidated Lake Bonneville deposits. Because of poor recovery of the unconsolidated deposits, no material was available for laboratory measurements of thermal conductivity. No topographic correction to the gradient was necessary.

The high gradient of 58.7°C/km (Figure 2) is believed to be due to the low thermal conductivity of the unconsolidated Lake Bonneville deposits. According to *Langseth* [1965, p. 70], published conductivity values for oceanic sediments are generally within 25% of 2.0 mcal/cm sec °C. This value could presumably be used

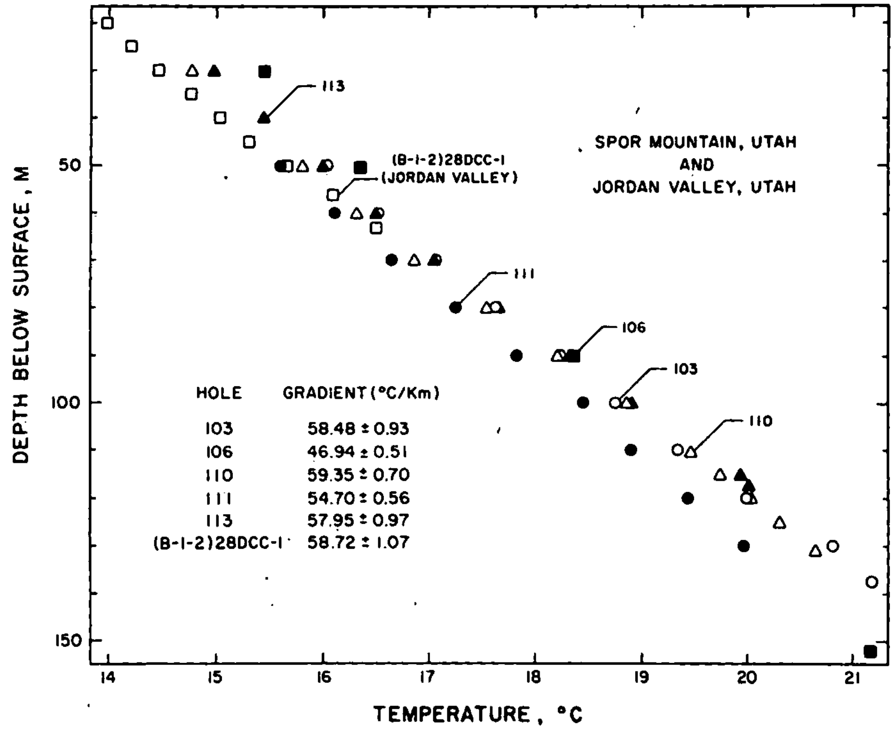

Fig. 2. Temperature profiles in drill holes at Spor Mountain and Jordan Valley, Utah.

as a lower bound for the thermal conductivity of the material in Jordan Valley. The conductivity of the Bonneville sediments is probably higher than 2.0 mcal/cm sec °C because (1) the Bonneville sediments contain more quartz (in the sandy layers) than deep oceanic sediments and (2) the porosity of a sand is generally less than the porosity of a typical oceanic lutite, which may contain 75% water; therefore a sand contains more solid material per unit volume than a lutite. Many well-consolidated shales and sandy shales have thermal conductivities of about 4.0 mcal/cm sec °C and lower [*Birch*, 1954; *Joyner*, 1960]. We may use this value as an upper limit. The sediments penetrated by the hole then probably have a thermal conductivity greater than 2.0 mcal/cm sec °C and less than 4.0 mcal/cm sec °C. If a thermal conductivity of 3.0 mcal/cm sec °C is used, the regional heat flow in Jordan Valley would be about 1.8 ± 0.6 μcal/cm^2 sec.

Spor Mountain. Spor Mountain is in the central part of Juab County, Utah, in the Basin and Range province. Temperatures were measured in five drill holes in the Topaz Mountain tuff. Four of these holes were within 460 meters of each other and had an average gradient of 58°C/km. The fifth hole (hole 106), located 600 meters to the north, was found to have a lower gradient of 46.9°C/km. Figure 2 shows the temperature profiles for all holes.

Table 3 lists the results of thermal conductivity determinations from the Spor Mountain area. Disks were cut from nine specimens. All of the rock specimens are representative of the Topaz Mountain rhyolite. The mean thermal conductivity and the standard error of 20 rhyolite specimens were 5.47 ± 0.14 mcal/cm sec °C. The mean geothermal gradient of all five holes was 55.5° ± 3.7°C/km. This value gives an average heat flow of 3.0 ± 0.3 μcal/cm^2 sec. The gradient over the depth interval 120–127 meters in hole 110 was 55.0° ± 1.0°C/km. The mean conductivity and the standard error of eight samples over this interval in hole 110 were 5.26 ± 0.2 mcal/cm sec °C. The product indi-

TABLE 3. Thermal Conductivity Measurements from the Spor Mountain Area

Disk No.	Thickness, cm	Conductivity, mcal/cm sec °C	Location
10SM66	1.27	5.51	hole 110 (123 meters)
11SM66-1	1.27	5.36	
11SM66-2	1.91	5.50	hole 110 (123 meters)
11SM66-3	2.54	5.52	
13SM66	1.91	3.78	hole 110 (125 meters)
14SM66-1	1.27	5.49	
14SM66-2	1.91	5.46	hole 110 (127 meters)
14SM66-3	2.54	5.43	
15SM66-1	1.27	6.21	hole 111 (below 130 meters)
15SM66-2	1.91	6.25	
16SM66-1	1.27	6.43	hole 111 (below 130 meters)
16SM66-2	2.54	6.63	
17SM66-1	1.27	5.46	hole 111 (below 130 meters)
17SM66-2	1.91	5.66	
18SM66-1	1.27	4.63	
18SM66-2	2.54	4.64	surface
18SM66-3	3.81	4.73	
19SM66-1	1.27	5.47	
19SM66-2	2.54	5.63	surface
19SM66-3	3.81	5.63	

All values were determined from shelf-dried specimens.

cates a flux of 2.9 ± 0.2 μcal/cm² sec. No terrain corrections were necessary. The variation in the geothermal gradient between hole 106 (46.9°C/km) and the four holes to the south (average value, 57.6°C/km) might be due to near-surface groundwater circulation or more probably to lateral variation in the thermal conductivity of the rhyolite. No core was available from hole 106. All thermal conductivity values were determined on unsaturated specimens in a shelf-dried state, since the holes were all dry when they were logged.

The heat flow in the Spor Mountain area is taken to be 3.0 ± 0.3 μcal/cm² sec. The uncertainty of 10% is assigned primarily because not all of the conductivity determinations were made on core from the holes.

La Sal. Most of the gradients were determined in holes drilled into the Chinle formation, which is composed of fluvial mudstones and sandstones with irregular conglomeratic beds that probably represent ancient stream channels. One hole (Bin-8-64) was drilled entirely in the Wingate sandstone, which overlies the Chinle. Temperatures were measured in four holes (HR series) within 150 meters of each other and in two holes (Bin series) about 3 km northwest of the HR group in the Big Indian mining district [*Wright*, 1966]. The temperature profiles are shown in Figure 3. The average straight-line least squares gradient in the HR holes is 17.7° ± 0.26°C/km. The gradient typically passes several times through maximum and minimum values of about 22° and 14°C/km [*Wright*, 1966, pp. 79–86]. The 14°C/km gradient is measured in the more sandy layers of the Chinle, whereas the 22°C/km is representative of the shaly beds. By means of data from below 120 meters in hole Bin-10-65, the straight-line least squares gradient is 21.9° ± 0.32°C/km.

The holes at La Sal were surrounded by rather rugged topography, and a correction for topographic evolution was determined. The atmospheric temperature gradient assumed for the correction was −5.7°C/km. According to *Eardley* [1962, p. 424] the central part of the Colorado Plateau was uplifted 1829–2438 meters, probably beginning in Pliocene time. For an uplift of 1829 meters, 335 meters of erosion, and an evolution time of 15 m.y. (conditions that Eardley considers most representative) the corrected gradient in HR-1-65 is 17.79° ± 0.20°C/km, or 3.5% greater than the observed

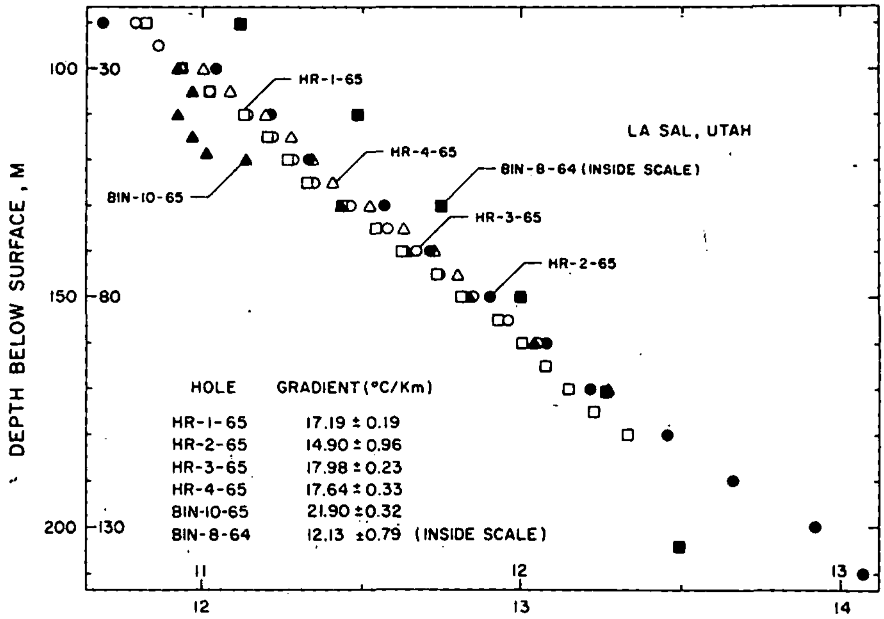

Fig. 3. Temperature profiles in drill holes at La Sal, Utah.

gradient. For an infinite evolution time the corrected gradient is 18.38° ± 0.20°C/km, or about 7% greater than the observed gradient in HR-1-65. For Eardley's assumptions about the physiographic history the correction to the gradient is small.

No core was available for the La Sal holes, and thermal conductivity was determined from samples prepared from bulk rock specimens. All specimens were collected within 2 km of the HR holes and within less than 6 km of the Bin holes. The lithology typical of the Chinle formation is about 50% sandstone and about 50% mudstone [*Wright*, 1966, pp. 92–94]. We previously reported heat flow values at La Sal based on measurements of samples in a shelf-dried condition. Nine of the Chinle samples have since been remeasured after being vacuum-saturated with distilled water. The difference between the dry and the saturated conductivities is shown in Table 4.

The mean value and the standard error of the thermal conductivity of eight saturated specimens of the Chinle formation are 8.61 ±

TABLE 4. Thermal Conductivity Measurements from La Sal, Utah

Sample No.	Thickness, cm	Thermal Conductivity, mcal/cm sec °C Dry	Thermal Conductivity, mcal/cm sec °C Saturated	Remarks, Location
4H66-1	1.27	6.88		From lower 75 feet of Chinle formation, Alice-inclined shaft; sandy mudstone, ±20% quartz.
4H66-2	2.54	7.16	8.75	
6H66-1	1.27	7.40		From lower 75 feet of Chinle formation, Alice-inclined shaft; muddy sandstone, ±50% quartz.
6H66-2	2.54	7.68	9.14	
6H66-3	1.27	7.28		
6H66-4	2.54	7.08		
8H66	2.54	8.37	9.24	From lower 75 feet of Chinle formation, Alice-inclined shaft; sandstone, ±80% quartz.
9H66	2.54	5.45		From lower 75 feet of Chinle formation, Alice-inclined shaft; mudstone, 10% quartz.
1L66-1	1.27	7.05		Samples 1L66 to 9L66 are Chinle from surface exposures on the Wingate-Chinle cliff and talus slope just east of La Sal triangulation station (38°14'16.9"N, 109°16'20.7"W); muddy sandstone, ±80% quartz.
1L66-2	2.54	7.50	9.32	
2L66	2.54	7.98		Chinle; sandstone, ±80% quartz.
5L66	2.54	6.09	7.08	Chinle; muddy sandstone, ±70% quartz.
6L66	2.54	7.98	9.08	Chinle; muddy sandstone, ±70% quartz.
7L66	2.54	6.42	7.86	Chinle; muddy sandstone, ±70% quartz.
9L66-1	1.27	5.42		Chinle; sandy mudstone, ±40% quartz.
9L66-2	2.54	6.00	8.38	
11L66-1	1.27	11.50		Wingate; from Wingate-Chinle cliff; see 1L66; ±95% quartz.
11L66-2	2.54	12.19	13.94	
1SJ66-1	1.27	11.67		Wingate; from Wingate-Chinle cliff; see 1L66; ±95% quartz.
1SJ66-2	2.54	12.10		

0.26 mcal/cm sec °C. This value represents an increase of about 20% over the corresponding unsaturated mean value of 7.15 ± 0.29. One sample of the Wingate was remeasured after saturation; unsaturated conductivity values were used for the Wingate, since hole Bin-S-64, which was entirely in the Wingate, was logged dry [*Wright*, 1966, p. 77].

The average geothermal gradient in the Chinle formation in the HR-65 holes was 17.7° ± 0.2°C/km. The mean thermal conductivity of the saturated samples of Chinle was 8.61 mcal/cm sec °C. The product indicates a flux of 1.5 μcal/cm^2 sec. Hole Bin-S-64 was dry when it was logged. The temperature gradient in the Wingate sandstone in this hole was 12.1° ± 0.8°C/km, and the mean unsaturated Wingate conductivity of four samples was 11.9 ± 0.14 mcal/cm sec °C, giving a heat flow of 1.44 ± 0.11 μcal/cm^2 sec.

Previously reported [*Costain and Wright*, 1968] values for La Sal were given as 1.2 ± 0.2 μcal/cm^2 sec, based entirely on thermal conductivity measurements of unsaturated rocks. The revised value for La Sal, based on conductivity measurements on saturated Chinle rocks as well as on unsaturated Wingate sandstone, is 1.5 ± 0.2 μcal/cm^2 sec. The uncertainty placed on the revised value is primarily a result of the uncertainty of the conductivity of the Wingate and Chinle rocks, since measurements were not made on core samples from holes in which the gradients were determined.

DISCUSSION

Decker [1969] presented nine new heat flow values in Colorado and New Mexico. Only one of these values, 1.22 μcal/cm^2 sec at Cerrillos, New Mexico, near the southern border of the southern Rocky Mountains, fell below 1.6 μcal/cm^2 sec. *Sass et al.* [1971] presented a large number of additional values for the Rocky Mountain and Colorado Plateau provinces. All of their 'category 1' values for the Colorado Plateau were 1.5 μcal/cm^2 sec or above. North of the Colorado Plateau province, at Green River, they obtained a value of 1.6 μcal/cm^2 sec. In the Basin and Range province, *Sass et al.* [1971] gave a number of new values south and west of the Colorado Plateau. Only five values are less than 1.5 μcal/cm^2 sec, and these sites are close to other sites (<20 km) where the heat flow is greater than 1.5 μcal/cm^2 sec. It would appear that the low heat flow values in Arizona southwest and south of the Colorado Plateau (5 out of 25 determinations) may not be representative of the regional heat flux and could be the result of either refraction or shallow groundwater circulation.

The revised value given in this paper for La Sal, Utah, on the Colorado Plateau is 1.5 μcal/cm^2 sec. This value is in close agreement with values found for the northern part of the Colorado Plateau by *Sass et al.* [1971], although it is considerably higher than *Spicer*'s [1964] value of 1.2 μcal/cm^2 sec. On the basis of much of the heat flow now available, there appears to be less evidence to delineate the Colorado Plateau as a separate heat flow province with abnormally low heat flow.

The extensive recent tectonic activity in the Basin and Range province is reflected by the high surface heat flow. Depending on the upward penetration of fault zones, heat flow anomalies might be expected to (1) follow superimposed trends associated with block faulting and (2) fall off rapidly away from the fault zone if the source is shallow. No linear trends in heat flow are apparent from the data available to date; however, the density of heat flow determinations is not sufficient to rule out the possibility of linear heat flow patterns associated with major trends in block faulting. Figure 4 shows all of the published heat flow values in Utah to date. A higher density of heat flow determinations might show the anomalies to be closely associated with linear seismic zones, such as the Wasatch line in Utah. The heat flow at Bingham, Utah, very close to the Wasatch line, is about 2.3 μcal/cm^2 sec. Heat flow profiles and microseismicity studies near active fault zones could establish such a correlation.

The Cordilleran thermal anomaly zone (CTAZ) of *Blackwell* [1969] may include the Colorado Plateau province. *Decker* [1969] and *Sass et al.* [1971] obtained high heat flow values (>2.0 μcal/cm^2 sec) near the eastern boundary of the plateau. The apparent overall higher heat flow in the Basin and Range province, about 2.0 μcal/cm^2 sec, suggests a higher density of fracture zones with deeper penetration into the mantle than that to the east in the Colorado Plateau province.

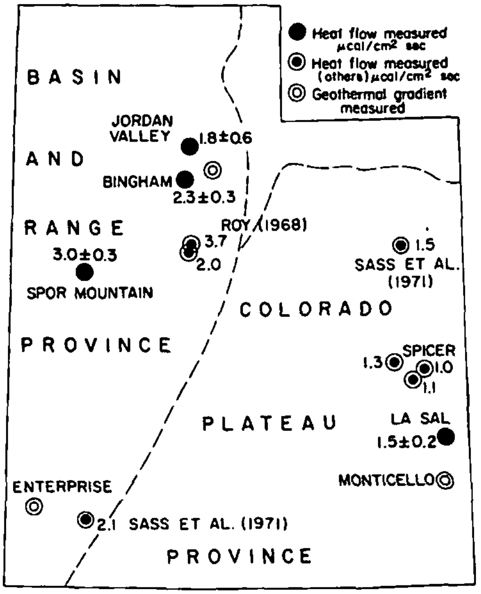

Fig. 4. Heat flow measurements to date in Utah.

Acknowledgments. This work was supported by National Science Foundation grants GP-2625, GA-608, and GA-1384. The University of Utah Research Committee sponsored some of the preliminary work in temperature measurement when the authors were at the University of Utah.

Dr. Robert F. Roy made many helpful suggestions in regard to temperature measurement and the design of the thermal conductivity apparatus. Walter Rohloff did the machine work for the thermal conductivity apparatus at the University of Utah and made many original and significant contributions to the design of the hoisting equipment.

The Atlas Minerals Corporation, the Brush Beryllium Company, the Hogle Investment Company, and the Kennecott Copper Corporation gave permission to log boreholes on their property, and their cooperation is gratefully acknowledged.

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December 8, 1972

Professor John K. Costain
Department of Geological Sciences
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061

Dear Professor Costain:

RE: HEAT FLOW AT SPOR MOUNTAIN, JORDAN VALLEY, AND LA SAL

JGR MS #2893-2 (Costain and Wright)

Your paper represents a lot of work, and it contains new information. However, there are a few comments I have which I suggest you consider:

(1) The instrumentation and corrections are discussed in more detail than is appropriate for the JOURNAL OF GEOPHYSICAL RESEARCH.

(2) Location, gradient, conductivity, and heat flow should be presented in a summary table as in Roy et al. (1968 - JOURNAL OF GEOPHYSICAL RESEARCH) or Sass et al. (1971 - JOURNAL OF GEOPHYSICAL RESEARCH).

(3) The vaseline problem and other specific points raised by the reviewers should be accommodated or refuted.

Please indicate in your cover letter the revisions you have made, or explain why you do not agree with the reviewers' suggestions. Please include two (2) copies of the revised paper, being certain to incorporate instructions from the enclosed "Checklist for Authors."

Sincerely yours,

Orson L. Anderson (ck)

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OLA/ck

MS # 2893-2

Date 12/6/72

Author(s) Costain + Wright

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Review of Heat Flow at Spor Mountain, Jordan Valley, Bingham and LaSal, Utah

by J. K. Costain and P. M. Wright

A

General Comments

I think that this paper should be published because of the new information it contains. I believe there are several ways in which the paper could be improved for publication however.

Specific Comments

1. Include a table listing the important information for each drill hole such as latitude, longitude, collar elevation, etc. al la Roy et al., 1968 or Sass et al., 1971. This procedure should simplify the abstracting of such material for summary publications and also avoid errors and misquotations in such uses.

2. I believe the discussion on the temperature measuring apparatus (pages 2 - 7) could be removed from the paper without loss of interest or content. The general techniques are enough used that such material seems redundant. A very short paragraph on the platinum probes might, however, be useful.

3. The experience with vaseline noted on page 9 was also found in the laboratory at Harvard. The explanation for this phenomenon seems to be that the dry rocks absorb the vaseline which then acts as a fluid to fill the pores of the rock and decrease the thermal resistance caused by air filled pores. When the rock is essentially saturated with vaseline or the vaseline has been pushed as far into the rock as it can go then, the rock no longer takes up vaseline and the conductivity no longer increases. Such a behavior is usually not observed when measurements are made on saturated rocks. The appropriate numbers to use are the initial numbers made on dry rocks if that is the quantity required or the conductivity measured in saturated rocks. The significance of the conductivity of a rock "saturated" the vaseline is questionable at best.

4. I don't see that it is necessary for you to list the brand of vacuum pumps used in your saturation experiments. I think we can assume that whatever vacuum pump was used was satisfactory for the required results. Similar comment is true for the circulating baths.

5. I don't understand the significance of the sentence "The calibration thus incorporated to correct for radial heat loss and contact resistence never exceeds 7%". What do you mean by the statement the calibration never exceeds 7%?

6. I believe the first paragraph under the title <u>Results</u> could be deleted with no significant modification in the results of the paper.

7. Roy et al. (1968, p. 5219) published two values of heat flow at Bingham, Utah, yet these numbers are not referred to in the discussion by the authors on the heat flow at Bingham. Roy et al published measurements on 22 samples of the Bingham porphyry with an average thermal conductivity of 7.2. Twenty-two measurements (probably of the quartzites) had an average conductivity of 11.5. They determined heat flow values of 1.5 and 1.9. It appears that combining the two sets of results would suggest that the gradient in the Bingham granitic rock would be on the order of 25°C/km while the gradient and the quartzites would be between 17 and 20°C/km. The appropriate conductivity for the higher gradient would appear to be between 7.2 and 8.9. In the quartzites the heat flow value probably involves a certain amount of refraction because of the extremely high thermal conductivity. The best heat flow is probably that in the granitic rocks. With the range of conductivities from 7.2 to 8.9 and a gradient of 25, the heat flow would be between 1.8 and 2.2. Thus it seems to me that the best value of heat flow at Bingham would probably be 2.0 ± 10% rather than the value of 2.5 ± 10% resulting from the analysis on page 18.

8. In the analysis of the heat flow at Spor Mountain the hole 106 is not plotted while all the others are. I think it would be helpful if this hole was plotted as well. Also it seems that there might be lateral variations of thermal conductivity large enough to explain the differences in gradient. Thus there may be other explanations for the variation in gradient besides such nonconductive explanations as near-surface ground water.

9. I think it would be helpful if the lithology was included in Table 5 as well as the conductivity measurement.

10. The units of heat flow are inconsistent on page 29. The author should either stick to HFU or 10^{-6}cal/cm^{2}sec.

(signed) David D. Blackwell

Q B

Costain and Wright -- Heat Flow at Spor Mountain, Jordan Valley, Bingham, and La Sal, Utah

Although much effort has gone into this research, I can not recommend publication of this manuscript in J.G.R. The paper should be shortened and re-submitted for later review and publication in the Journal.

My general comments are:

1. Too many details, interesting only to a very few specialists. If possible, make more references to Wright (1966), for details.

2. With the exception of hole D-142 at Bingham, Utah, it is not clear which portions of holes were used for gradient calculations. A short summary table for all basic heat flow data might be appropriate for each locality.

3. There is much confusion, redundancy and some possible inconsistencies at places in the text.

Some of my specific comments are summarized below (see text also).

1. Confusion between first 3 lines of abstract and introduction. For example, 20 and 13 holes (abstract) vs 20 and 5 holes at Enterprise and Monticello (Introduction).

2. Delete temperature and thermal conductivity measuring systems from abstract. Delete statement about rock discs also.

3. Delete last 5 lines of paragraph at top of page 9. Put shorter version of comparison with crystalline quartz on page 11, just before RESULTS section.

4. Refer to Walsh and Decker (1964) and others at beginning of last paragraph on page 10. Delete from first paragraph on page 11.

5. First paragraphs under RESULTS, pages 11-12. When compared with subsequent discussions of localities these seem redundant. Would suggest replacing by short statement that gradients are least-squares gradients, that

standard errors are used, and that values of flux are probably good to within ± 10-15%. Also might mention something about intervals used for gradient calculations and why.

6. Delete mining company names from text -- just mention in acknowledgements.

D-142, Bingham, Utah

1. Possible confusion between 656-936 meter depths mentioned on p. 12, and "no core below depth 885 meters . . . " on page 17.

2. Delete lengthy discussion of topo-sheets, etc. If possible, refer readers to Wright (1966) for details. The writers mention that magnitude of terrain correction is of concern but don't say why.

3. Delete most of paragraph on bottom of p. 14. Simply refer to Birch (1950). Then incorporate next paragraph. Why were these physiographic histories used? Might include highlights of preceding paragraph here (sq. grid, out to 16 km.).

Spor Mountain, Utah

1. Mention holes dry when drilled and measured.

2. Plot hole #106 in Figure 2! If not plotted, Why?

3. In K section mention that samples were dry!

4. Shorten.

La Sal, Utah

1. First paragraph, p. 23. Not clear. Why were "most" of holes in Chinle? Was BIN-10-65 not in Chinle?

Would suggest:

a) One paragraph locating holes and describing general geology. Use Wright (1966) for additional details.

b) One paragraph on T-D plots; indicating general (depth-ranges) and fine-structure.

2. Paragraphs on Terrain. Why no steady-state terrain correction- more justification. It should be noted that lapse rate of ground-surface temperature possibly not the same as that for air. Fortunately not much difference when using drill holes.

3. Paragraphs on K. Separate "dry" Ks from "wet" Ks. Use eleven wet as correction? Shorten sections and clearly separate Costain & Wright (1968) from new results.

4. Why no errors on gradients?

Figure 4. Needs physiographic provinces. Slightly more complete caption or explanations.