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Both

**THE MARYSVILLE, MONTANA, GEOTHERMAL PROJECT
ENVIRONMENTAL ANALYSIS
OF THE
DEEP GEOTHERMAL RESEARCH WELL**

to
**BUREAU OF LAND MANAGEMENT
DISTRICT OFFICE
P.O. BOX 1227
MISSOULA, MONTANA 59801**

from
**BATTELLE-NORTHWEST
ROGERS ENGINEERING CO., INC.**

February 15, 1973

**Donated By:
Herbert Rogers Jr.
Rogers Engineering Co.**

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ENVIRONMENTAL ANALYSIS
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I. DESCRIPTION OF PROPOSED ACTION AND ALTERNATIVES

The objective of this research project is to investigate a geothermal anomaly of high heat flow discovered in 1969 in central Montana, and to determine how this natural resource might be developed as a source of useful energy. Under Phase I, the natural resource will be explored, drilled, and modeled at an estimated cost of \$2,588,935 over a 3-year period. Phase II, depending upon the nature of the heat source, will be developing the resource under a cooperative effort of government and private industry. This environmental analysis is intended to cover the drilling and logging operations noted under Phase I, the only work being undertaken at this time. As can be seen from Figure 1, further tests may be run at this site in later phases of the study. But since the nature of these tests are highly dependent on the results of Phase I, it is not considered productive to speculate on their environmental impact. As shown in Figure 1, however, any later experiments would cover a range of underground experiments, some of which consume water and others which would produce water. Before a meaningful analysis of such work can be written, it will be necessary to analyze the results of Phase I findings.

A. Location

The well will be located in a geothermal anomaly near Marysville, Montana, an old gold mining town located about 20 miles northwest of Helena (see Figure 2). Measured heat flows in a local region near Marysville have been found to range from 3.1 to as high as $19.5 \mu\text{cal}/\text{cm}^2\text{-sec}$,⁽¹⁾ compared with a western Montana

(1) Blackwell, D. D., "Heat Flow Near Marysville, Montana," (abs.), Eos. Trans., American Geophysical Union, vol. 51, p. 824, 1970.

regional average of 1.9, and a world-wide average of 1.5. Although there is an obvious thermal anomaly, the nature of the source (dry and conductive or wet and convective) and its geophysical properties are unknown. Evidence that the anomaly consists of a dry granitic pluton 10,000 to 80,000 years old will require verification.

Details of the site geographic location and site layout are shown in Figure 3. The work site can be reached via two routes: through the old mining town of Marysville, or through Canyon Creek (a country store and gas station, only). The Marysville route is a difficult drive, with sharp turns and a climb to near the Continental Divide. The Canyon Creek route is 4 miles longer, but follows the valleys and is therefore the preferred access. It is a good gravel road, maintained by the County, and capable of handling the project's traffic. The road is not graded too well, but is adequate from the Helena National Forest boundary on Lost Horse Creek to the drill site. The typical surface structure throughout the area consists of topsoil and fractured shales and gravels near the surface, which simplifies road construction.

B. Site Preparation

Site preparation will consist of moving about 5,000 yards of earth for the purpose of leveling. The total site area is less than one acre. Large unsightly mounds from old placer mining operations exist on the north end of the site. Where practical these mounds will be leveled and the material used for roads and parking. As shown in Figure 3, a small number of trees will have to be removed from a scattered growth along the south edge of the site. An estimate of the number and size of trees which must be removed is: 6 to 8 trees, 10-14 in. diameter; and 50 to 60 trees, 2-10 in. diameter.

Water for the drilling operation will be obtained from one or more (if required) water wells at the site. Mr. Wesley Lindsay, President of the

FIGURE 1. Planned Geothermal Resource Development Program

FIGURE 2. Location of Marysville, Montana

FIGURE 3. Maps and Plot Plan of the Drillsite

Montana Water Well Drillers Association, visited the site and believes that the required 50 gpm of water could probably be obtained from one to three wells at a depth of about 100 ft.

Service Road - As seen in Figure 3, a crossing of Empire Creek both in and out of the work area will be necessary. The size of galvanized steel culvert pipe needed will be selected after the drainage area and run-off are calculated. Fill for the entrance and exit roads will be taken from the gravel mounds nearby. Gravel and rock will be used where the fill is exposed to the creek's flow. The elevation over the culvert pipes will be held low in order to pass water over the road in the event of abnormally high run-off; and rock on downstream slopes will prevent erosion and wash-out.

Drill Pad - The maximum area to be concreted for the drilling operation will be a ⁸ 5 ft-by-¹² 8 ft drilling cellar, ⁶ 6 ft deep. Tentative plans are to leave this in place and fill it up level with the graded surrounding area, if abandoned.

Water Storage - The contract specifications will require the drilling contractor to furnish a minimum of 1,000 barrels of reserve water storage for drilling operations (and to furnish piping from well's pressure tank to this storage).

Diesel Fuel Storage on Site - The contract specifications will require the drilling contractor to provide a minimum of 2,500 gallons of secure diesel fuel storage on site. An adequate berm area will be provided surrounding this tank to contain the entire volume if accidentally spilled.

Settling Pond - The settling pond shown will be 8 ft deep, and will serve as a deposit for the solid cuttings from the drilling and as a reserve mud pit. This pit will provide ample volume to prevent any return of fluids to the Empire Creek. It will be bermed to exclude entry of any surface run-off.

Parking Area - Figure 3 shows an area allotted for parking. This is at the upstream or high end of the site and was selected to avoid felling any more trees than necessary. Additional parking is available in various parts of the area assigned to cementing and logging trucks.

C. Disposal Plans

The disposal of spoil from the drilling operation has been planned to minimize any possible environmental effects. The size of the planned settling pond is such that it will receive the total volume of spoil and still provide ample reserve mud-pit volume. It is expected that the spoil will accumulate as gravelly chunks and thickened slurry to a depth of about 2 ft over the area of the sump. With the expected high drilling temperatures, flashing of the water portion of the drilling fluid during cooling will tend to minimize the volumes of waste fluids.

The recommended final disposition of the spoil (solid, viscous slurry and liquids, if any) is to bury them in the settling pond. This has been the drilling industry practice for many years, and no deleterious environmental effects are known by expert practitioners of the drilling industry. The mud ingredients are designed fundamentally to seal off porous formations, so it is felt that no lining of the settling pond is indicated. Therefore, leaching of fluids back to Empire Creek is not expected. The mud ingredients, basically bentonites, lignites, barites, and non-ionic surfactants, are natural materials, and are not expected to degrade under the temperature predicted. Thus, even if leaching were possible, no deleterious effects on the stream would result.

Sanitary waste disposal will be handled by chemical facilities using trailer-mounted holding tanks and septic service pickup.

Details of the proposed well are shown in Figure 4. Plans are to drill to about 6,000 ft or to a limiting temperature (approximately 800 °F). The volume of cutting spoil will be about 500 cubic yards and will be disposed of as described above.

D. Alternatives

The alternatives to the planned well are limited. The alternative of not drilling the well has little merit since the potential of the geothermal energy resource will never be realized if basic research such as that described here is not accomplished. And because geothermal energy may be of considerably less impact on the environment than other common sources, it is self-defeating not to accept the minor perturbations of such research efforts.

Location of the hole is limited by the location of the underlying anomaly. From surface and near-surface measurements made by Dr. David Blackwell of Southern Methodist University during the summer of 1973, it is apparent that the selected site is near the center of the anomaly. Some of Dr. Blackwell's work is included in Appendix A for reference.

While there are other possible drilling sites, they all have serious drawbacks. They either involve more timber cutting or more earth moving than the present site. In addition, most sites would require relocation of Empire Creek; but by a careful layout of the site (see Figure 3) it has been possible to avoid this relocation at the present drilling site. Any site not located on the Empire Creek bottom would require severe cutting and filling of the steep mountain sides, causing much greater impact than could be expected at the planned site.

E. Contractors

The prime contractor for this project is Battelle-Northwest (BNW) with a parallel contract to Southern Methodist University (SMU) and subcontracts to Rogers Engineering Company, Inc. (REC) and Systems Science and Software (SSS).

FIGURE 4. Deep Well Profile

The principal investigators are:

Battelle-Northwest, Richland, Washington

Donald H. Stewart, Director, Geothermal Programs

William R. McSpadden, Project Manager

Southern Methodist University Dallas, Texas

David D. Blackwell, Associate Professor of Geophysics

Rogers Engineering, San Francisco, California

James D. Kuwada, Vice President, Engineering

Systems Science & Software, LaJolla, California

Russell E. Duff, Manager, Radiation and Fluid Physics Division

The project is sponsored by the RANN Division of the National Science Foundation (NSF). The NSF Program Manager is Ritchie B. Coryell.

II. DESCRIPTION OF THE ENVIRONMENT

A. Location

The proposed drilling site is located about 3 miles west of Marysville, Montana. More specifically, it is located in Section 32, Township 12 N, Range 6 W. (see Figure 3). The well site is approximately one-half mile west of the Empire Mine.

B. Climate

Climate in this area is relatively dry, with precipitation averaging 19.4 in. as shown in Table 1. The mean annual temperature of Marysville is 40.7 °F, with temperatures ranging from -22 °F to 91 °F. The climate summary of nearby Helena is shown in Table 2.

C. Topography

The drill site is situated in the ⁷~~bottom~~ of Empire Creek, ^{VALLEY} and the topography is generally steep with an average elevation of 5,750 ft above mean sea level.

D. Vegetation

Natural vegetation is limited for the most part to forested areas of Douglas fir and Ponderosa pine. There is little understory, the open areas being covered with grasses (Stipa comata and bluegrasses predominating). Certain annual plants are found after the snow has melted.

E. Fish and Wildlife

Several species of migratory birds may frequent the area at various times of the year. Small mammal life is limited to small rodents, bobcats, fox, and rabbits. Large mammals such as deer and bear are present in the area, however there are no indications that the Empire Creek area offers substantial winter and summer grazing for deer, nor exists near to established migration routes.

TABLE 1

Average Precipitation at Marysville, Montana

<u>Month</u>	<u>Precipitation</u>
January	2.35
February	.76
March	1.27
April	1.47
May	1.92
June	4.29
July	1.01
August	.62
September	1.95
October	1.18
November	1.26
December	1.32
Annual	19.40

The average was computed from U. S. Weather Bureau measurements made at Marysville No. 3 for years 1968, 1969 and 1970.

TABLE 2

Helena Climate Summary

<u>TEMPERATURE (°F)</u>	<u>Apr.</u>	<u>May</u>	<u>June</u>	<u>July</u>	<u>Summer Climate</u>	
					<u>Aug.</u>	<u>Sept.</u>
Warmest Observed	85	90	98	102	102	96
Average Maximum	56	65	72	84	82	69
Average Minimum	31	40	47	52	50	41

RELATIVE HUMIDITY

Average % at 5 P.M.	43	43	46	32	32	39
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PRECIPITATION

Average Total (in.)	0.9	1.6	2.2	1.0	0.9	1.2
No. Days .01 or more	8	11	13	8	8	6

SNOWFALL

Average Total (in.)	4	*	0	0	0	2
No. Day 1.0 or more	1	0	0	0	0	*

*Less than 1/2

<u>TEMPERATURE (F°)</u>	<u>Oct.</u>	<u>Nov.</u>	<u>Dec.</u>	<u>Jan.</u>	<u>Winter Climate</u>	
					<u>Feb.</u>	<u>March</u>
Warmest Observed	84	70	60	62	68	73
Average Maximum	58	42	22	28	34	43
Average Minimum	32	21	13	8	12	21

RELATIVE HUMIDITY

Average % at 5 P.M.	48	63	69	66	62	55
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PRECIPITATION

Average Total (in.)	0.7	0.6	0.6	0.5	0.4	0.7
No. Days .01 or more	6	7	8	7	7	9

SNOWFALL

Average Total (in.)	2	9	8	8	7	8
No. Days 1.0 or more	1	2	3	2	2	3

There may be certain species of wildlife that frequent the area which are listed as endangered species. The site is situated in State Hunting District No. 443, which in 1973 was open for hunting for antlered bull elk and mule and white tail deer from October 21 through November 25. There is no available data on the number of hunting days for the Empire Creek area. The drilling site is situated along the side of Empire Creek (with a flow of a few cubic feet/second) which is a tributary of Lost Horse Creek. In the immediate area of the site the creek flows through abandoned tailing ponds where the banks and stream bed are compacted tailings. No spawning or forage habitats for fish appear to exist in this area. However, such areas do exist in Lost Horse and Little Prickly Pear Creek, but no definitive areas have been identified.

F. Recreation

The drilling site is located in a remote area not readily accessible to the general public. It supports some use by hunters. There is no available estimate of the number of user days of recreation occurring in the area.

G. Special Aesthetic Values, Historical, or Archeological Sites

There are no archeological sites of importance in the well site area. It is recognized, though, that the Marysville area is steeped in mining tradition. Hence, coordination with the local historical societies will be effected to insure that there is no interferences with any of their planned activities.

H. Land Use

The drilling site is located on lands withdrawn for reclamation purposes. The area is forested and supports no agricultural or industrial enterprises. Limited grazing by cattle is permitted by the Bureau of Land Management (BLM).

In all likelihood the area would remain undisturbed except for timber cutting if the geothermal project is not developed. Since it is not suitable

for other development. However, if mining operations were restored, the tailing ponds would be renovated for operation.

I. Geology of the Area

The geology of the area is described in some detail in Blackwell's work in Appendix A.

J. Water Quality

Water in the area occurs in Empire Creek and as groundwater, generally at a depth of 100 ft.

III. ENVIRONMENTAL IMPACT OF THE PROPOSED ACTION

A. Anticipated Impacts

As shown in the following environmental analysis worksheets the most significant impact is expected from the noise and dust of traffic into the area. During the drilling period a certain amount of noise and diesel fumes can be expected from the drilling rig. This will be localized, though, in the immediate unpopulated area.

The impact on the environment from drilling this proposed test well should be minimal. About one acre of land will be stripped and leveled for an access road and work area during drilling. The nature of the construction lends itself to restoration of natural conditions at the completion of the drilling program.

The behavioral patterns of a few animals might possibly be altered with the introduction of men and machinery in the immediate vicinity, but this effect is expected to be minimal. Drilling of this well will have no effect on fish life in the lower parts of the creek if construction plans to prevent run-off are followed. Endangered species of wildlife will not be affected by the project.

The drilling operation will be easily visible from the Empire Creek road. Since this is a remote dirt mountain road, the normal traffic on it is very low, from 0-10 vehicles per day. Thus, the aesthetic impact of the drilling operation will be very low and will, in any event, be limited to the expected 90-day drilling period.

There is a potential for silting of Empire Creek and the downstream waters it feeds. However, all of the site preparation, drilling, and restoration operations have been designed to minimize or eliminate any possibility of this silting.

ENVIRONMENTAL ANALYSIS WORKSHEET

Remarks: Checklist pertains to immediate site where drilling site will be located.

STAGES OF IMPLEMENTATION		Geothermal Test Hole - drilling, testing, restoration				REMARKS
DISCRETE OPERATIONS	Site Preparation	Drilling	Restoration			
I. NON LIVING COMPONENTS						
A. AIR						
Dust from earth movement	-L		-L			
Diesel Fumes		-L				
Traffic Dust	-L	-L	-L			
B. LAND						
Soil Erosion						Will not occur if stipulations are followed.
Regrade	-L		+L			
Sump Construction	-L		+L			
Operation		0				
Relocation Section of Creek	-L	0	0			
C. WATER						
Siting <i>SILTING(?)</i>	0		0			
Surface Run-off	0	0	0			
Oil Pollution		0	0			
Sewage		0		0		
Drilling Cuttings & Mud		0	0			
Thermal Degradation		0				
Ground Water	0					
II. LIVING COMPONENTS						
A. PLANTS (AQUATIC)						
Timber	-L	0	0			
Surface Cover	-L	0	+L			Reseeding of disturbed area planned.
B. PLANTS (TERRESTRIAL)						

Encl. 1-51

STAGES OF IMPLEMENTATION						
DISCRETE OPERATIONS		Site Pre- ration	Drilling	Restoration	REMARKS	
C.	ANIMALS (AQUATIC)					
	Downstream Biota	0	0	0		Will not occur if stipulations are followed.
D.	ANIMALS (TERRESTRIAL)					
	Non-game Mammals	0	0	0		No significant impact can be anticipated.
	Game Mammals	0	0	0		
	Birds	0	0	0		
III. ECOLOGICAL INTERRELATIONSHIPS						
A.	ECOLOGICAL PROCESSES	0	0	0		
IV. HUMAN VALUES						
A.	LANDSCAPE CHARACTER					
	Inharmonious (sound)	-L	-L	-L	-L	Traffic & Drilling Noise
	Aesthetics		-L	-L	+L	
B.	SOCIOCULTURAL INTERESTS	0				
	Long-Term Social Values		0	+M	0	

Encl. 1-52

The possibility of an oil spill in the work area is recognized. A berm will be provided around the diesel storage area to insure that any spillage is contained and does not reach Empire Creek. As was pointed out by the Region 8 EPA personnel,⁽¹⁾ a greater hazard probably exists from a potential trucking accident on the road to the site. While it is impossible to prevent such an accident, provisions will be made by the fuel supplier for the services of an emergency cleanup service in case of such an unforeseen accident.

Although it is considered highly improbable from the present geologic data, steam could be encountered in the drilling operation. The drilling rig will be equipped with a blowout preventer to ensure that any such steam would be kept under control. In the event that steam should be encountered, analysis of the steam will be made for chemical and gaseous content and it will then be capped off. Before any flow testing would be performed, this statement would be amended to cover the potential noise, chemical, and gas problems involved in such tests.

The dust caused by traffic into the area during the drilling operation will cause some impact. Although graded areas in the drilling area will be covered with gravel, unusually dry and windy weather could cause some dust problems. If these potential problems should arise, they will be handled by water sprinkling.

(1) John E. Hardaway, personal communication, December 6, 1973.

B. Possible Mitigating or Enhancing Measures

The Empire Creek area presently includes a number of gravel mounds from old placer mining which are rather unsightly. In leveling the drilling area several of these mounds will be moved. The entire area will be reseeded after the research is completed. Thus, the net effect may be an actual enhancement, of the area in the long-term. Wherever Empire Creek crosses through the operating area it will be riprapped or culverted. After analyzing the water, removal of the culverts after completion of the research may be indicated to prevent eventual collapse and stream blockage. If this is done, the affected area will be riprapped. In these areas the stream will no longer be contacting tailings material as it is presently doing. This may have a favorable effect on water quality since trace impurities such as mercury or cyanides are often leached from such tailings.

C. Recommendations for Mitigation or Enhancement

In summary, the recommendations are:

1. Dust - cover bladed area with rock and gravel; sprinkle work area and roads with water if unexpected weather conditions arise.
2. Vegetation - cut minimum number of trees necessary to prepare drilling area; reseed with native grass after completion.
3. Siltation - riprap or culvert Empire Creek wherever it is affected.
Drain work areas toward sump provided for drill cuttings. Remove culverts during restoration if acidity of water is high.
4. Oil Spill - provide berm around oil storage area. Provide for emergency cleanup in case of road accident.
5. Sanitary Waste - provide for chemical toilets, holding tanks, and septic service pickup.

6. Drill Spoil - provide silting pond for drill spoil. Bury this spoil and drill mud during restoration.

7. Steam Escape - provide blowout prevention on drilling rig.

D. Residual Impacts

The residual impacts should be minimal. The drilling area will be reseeded after filling the settling pond and the drill pit. The cut trees and any change in the topography caused by the leveling will be the only residual impacts.

IV. RELATIONSHIP BETWEEN SHORT-TERM USE AND LONG-TERM PRODUCTIVITY

The shortage of power and oil in the country requires that every effort be made to find new energy sources. The fundamental research being proposed here has a small effect on the short-term use of the land. The results of the research could provide data which lead to the availability of a major new energy source in all the western states. While such long-term productivity is still in the future and of necessity speculative, the minor short-term impacts are easily justified.

V. IRREVERSIBLE AND IRRETRIEVABLE COMMITMENTS OF RESOURCES

In the course of this research the only irreversible commitment of resources is the cutting of a very small amount of timber.

VI. PERSONS, GROUPS, GOVERNMENT AGENCIES CONTACTED

A. NSF Advisory Board

The Board provides advice peer review, and comment to the National Science Foundation Geothermal Program Manager on progress and direction of the project, and meets once or twice per year, or as requested by the NSF Program Manager. Following project reviews, Board Members respond individually with letters to the NSF Program Manager who factors their advice into his decisions. Board Members will be appointed for each review and composition of The Board will vary to match the peer review needs of the project as it progresses. The Board for the review of Oct. 26, 1973 was:

Dr. Jesse Denton, Director
National Center for Energy
& Power Management
260 Towne Building
University of Pennsylvania
Philadelphia, PA 19174

Charles R. Draper
Montana Department of
Intergovernmental Relations
Capital Station
Helena, MT 59601

Dr. Gerald W. Johnson, Director
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Los Alamos, NM 87544

Lillian K. Stone
Environmental Review Officer
Office of Environmental Projects Review
Department of Interior
Room 5325
18th & C Streets
Washington, DC 20240

B. Congressional Testimony

Committee on Science and Astronautics
Subcommittee on Energy
Chairman: Mike McCormack
Geothermal Energy Hearing, Sept. 11
Testimony by W. R. McSpadden

Geothermal Energy R&D Act, Feb. 11, 1974
Testimony by D. D. Blackwell and W. R. McSpadden

C. Federal Agencies

Atomic Energy Commission
Washington DC

Contact

Gerald W. Johnson
Anthony Ewing
Lewis Werner

Bureau of Land Management
District Office, Missoula MT

John Fields
Robert Newman
Carl Lind

Environmental Protection Agency
Region 8, Denver, Colo.
San Francisco

John Hardaway
James W. Shaw
Robert C. Scott

U. S. Forest Service
Helena Forest, Helena MT

Wm. Taliaferro
James Whipple

U. S. Geological Survey
Menlo Park, CA

L.J.P. Muffler

D. Montana State Agencies

Office of Lt. Governor

Contact

Wm. Christiansen

Dept. of State Lands

Robert Rudio
Robert Duncan

Dept. of Natural Resources &
Conservation

Gary Wicks	Lynn A. Brant
Ron Guse	Albert Tsao
John Hug	Don Chisholm
Judson Sweet	Frank Culver
Larry Jakub	Jim Holloran

Dept. of Fish & Game

James Posewitz
Alan Wipperman

Dept. of Intergovernmental
Relations

Frank McChesney
Raymond Dominick
C.R. Draper

Environmental Quality Council

Fletcher Newby
Walter Enderlin
Richard Klingler
Thomas Gill

Bureau of Mines & Geology

S. L. Groff
Miller Hansen

Air Quality Bureau

Fred O. Gray

Montana Historical Society

Sam Gilluly

E. Universities and Research Laboratories

University of Montana	Gary Crosby
Montana State University	Robert Chadwick
Montana College of Mineral Science and Technology	Koehler Stout Frank Diebold Charles Wickman
Oregon State University	Lorin Davis James Welte
Yakima Valley College	Harold Jones
University of Pennsylvania	Jesse C. Denton
Stanford University	Henry J. Ramey
Los Alamos Scientific Laboratory	Morton Smith

F. Professional Societies Presentations

Montana Professional Planners Association	Oct. 12, 1973
Society of Industrial and Applied Mathematics	Nov. 9, 1973
Professional Engineers of Oregon	Dec. 11, 1973
American Society of Mechanical Engineers	Feb. 6, 1974
Professional Engineers of Montana	Feb. 22, 1974
Institute of Electrical and Electronic Engineers	Feb. 13, 1974

G. Presentations to Civic and Community Organizations

Date	Organization	Place
July 24, 1973	Lions Club	Helena, MT
July 25	KFBB-TV	Great Falls, MT
Aug. 8	Rotary Club	Helena, MT
Aug. 9	Helena JC's	Helena, MT
Aug. 20	Kiwanis Club	Helena, MT
Sept. 11	Exchange Club	Butte, MT
Jan. 26, 1974	Lions Club	Moses Lake, WN

VII. INTENSITY OF PUBLIC INTEREST

Because public interest is high, extensive news coverage of The Marysville Geothermal Project is being obtained. Approximately 100 releases have appeared in the Northwest newspapers although many are duplicates. In addition TV interviews with the project scientists have occurred in Helena and Great Falls. In July, the NSF prepared a film on their geothermal projects, including The Marysville Project, which has been used over the national TV networks. All of the presentations listed in the above paragraphs were followed by question-and-answer sessions and in most cases there was extensive public participation. The public reaction to the project has been highly favorable.

APPENDIX A

HEAT FLOW IN A "BLIND" GEOTHERMAL
AREA NEAR MARYSVILLE, MONTANA

Blackwell and Baag

Table 1. Location, elevation, inclination, depth, thermal conductivity (K), gradient and heat flow.
The depth range listed is the vertical depth below the surface for the inclined holes.
The values shown immediately below averages are standard error

Locality	N. Lat.	W. Long.	Elev. meters	Inclination degrees	Depth range, meters	K mcal/cmsec°C	No ¹	Gradient Unc. °C/km	Gradient Corr. °C/km	Heat Flow Unc. μcal/cm ² sec	Heat Flow Corr.
Ottawa Gulch	46°44'	112°19'									
DDH — 1			1964	45	70-135	7.50 0.25	12	37.1 0.3	42.3 0.4	2.78 0.11	3.18
DDH — 2			1964	45	31-92	(7.50)		35.3 0.4	43.1 0.5	(2.7)	(3.2)
Mean Value											3.2
Woodchopper G.	46°44'	112°19'									
DDH — 3			1974	45	18-64	(7.48)		46.0 1.1	61.7	(3.4)	(4.6)
DDH — 4			1958	68	29-97	7.48 0.45	6	52.4 1.1	59.9 1.8	3.89 0.31	4.48
DDH — 5			1946	45	21-130			> 50.9	—	—	—
DDH — 6			1979	67	28-106	6.89 0.26	12	72.2 0.3	72.3 0.3	4.98 0.21	4.98
DDH — 7			1993	90	30-50	(7.06) ²		49.4 0.5	49.7 0.5	(3.4)	(3.5)
Mean Value (DDH-4 and DDH-6)											4.7
Continental Div.	46°43'	112°19'									
DDH — 8			2076	48	30-82	(7.06) ²		63.0 0.9	70.5 1.0	(4.45)	(5.0)
Bald Butte	46°43'	112°21'									
DDH — 9			2043	90	100-210	11.7 0.8	13	70.4 2.1	78.6 2.3	8.0 0.2	8.9
DDH — 10			2092	90	60-80			(65.5)			
DDH — 11			2001	70	52-281	8.42 0.36	13	72.5 0.5	80.5 0.9	6.38 0.07	7.10
DDH — 12			2043	90	100-280	9.02 0.58	13	72.5 1.6	79.9 1.5	6.68 0.15	7.35
DDH — 13			1921	55	140-250	7.28 0.62	8	83.9 1.2	81.9 1.1	6.27 0.16	6.12
Mean Value						8.08 ³ 0.28	27		80.2 0.7		6.5
Empire Creek	46°45'	112°22'									
DDH — 14			1654	45	88-164	16.4 0.2	7	83.7 1.2	74.8 1.5	13.7 0.2	12.3
					164-193	7.69 0.12	5	177.2 2.5	166.1 2.4	13.2 0.4	12.3
DDH — 15			1654	90	160-220	8.12 0.15	7	267.3 1.5	240.4 0.9	21.7 0.5	19.5
Best Value											19.5

¹Number of conductivity samples.

²Harmonic average of conductivity measurements for DDH-4 and DDH-6

³Average of Helena "limestone" conductivities only.

clined drill holes are vertical depths from the surface above the point of temperature measurement. The quantity desired for the heat flow is the vertical geothermal gradient, but the pro-

cedure used to obtain vertical depth from lateral depth along the drill hole is successful only if the isotherms are horizontal. Experience shows that isotherms are seldom horizontal, even when they

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"ought" to be. Because detailed information is seldom available to properly take into account the dip of isothermal surfaces in inclined drill holes, such heat flow determinations are considered of lower precision than in vertical drill holes.

The mechanical details of data acquisition and reduction are summarized by Roy et al (1968b) and are listed in Table 1. The gradients are least-squares straight lines fitted to the temperature-depth data in the given interval. The conductivity values listed are mean harmonic averages. Standard errors are shown beneath the appropriate data entry. The errors shown for heat-flow values are statistical and relate only to the internal consistency of the data. The water table varies in depth in the drill holes from about 20 to 50 m. As there seems to be no systematic difference in gradients above or below water, gradients above and below the water table are not distinguished in Table 1. All heat-flow values, except those for DDH-12, 14, and 15 were calculated as the product of the least-squares gradient and average harmonic thermal conductivity. Heat-flow values in these three holes were calculated by the resistance-integral method.

Topographic corrections have been applied to all the drill holes for which heat-flow values were calculated. The correction was calculated in the conventional way (Birch, 1950), but was carried only to a distance of 2 km. The rapid lateral variation of the geothermal gradient and the possible recent nature of the heat flow anomaly make the assumptions necessary for calculating a terrain correction, tenuous at best. But certainly the close-in topography has an effect; hence the correction was arbitrarily carried to 2 km.

Ottawa Gulch

The lowest value of heat flow available in the Marysville area is in DDH-1 on Ottawa Gulch (see Figure 1). The hole cuts contact metamorphosed Empire Shale. The temperature-depth curve is shown in Figure 3. The terrain corrected value of heat flow is $3.2 \mu\text{cal}/\text{cm}^2 \text{ sec}$. The hole is isolated about 0.5 km north of the group of holes on Woodchopper Gulch and inclined into a hillside so the vertical gradient is rather poorly determined. DDH-2 is about 100 m along the hillside west of DDH-1, with the same inclination

and bearing and thus furnishes redundant gradient data. The conductivity for DDH-2 is assumed to be the same as in DDH-1 because no samples were available from DDH-2.

Woodchopper Gulch

Five drill holes were measured in a relatively small cluster. The temperature-depth curves are shown in Figure 4. All the drill holes are in Helena Limestone which is less metamorphosed and impure than at the Bald Butte locality. All the drill holes are relatively shallow and all (excepting DDH-7) are inclined. The temperatures in the deepest hole (DDH-5) are disturbed by water entering the drill hole at the water table, about 50 m, and exiting at 113 m (vertical depths). The effect of the water circulation reaches all the way to the bottom of the drill hole, however, so only a lower limit for the gradient can be established. Drill holes 3 and 7 are extremely shallow and 3 is disturbed by water flow, so the heat-flow values are not included in the average.

The heat-flow values for the two drill holes (DDH-4 and DDH-6) which are thought to be the most reliable because of their depth, gradient linearity and sample availability, differ by about 10 percent. The holes are less than 200 m apart and have the same bearing and inclination so neither value is favored over the other. The best value for Woodchopper Gulch is the mean of DDH-4 and DDH-6: $4.7 \mu\text{cal}/\text{cm}^2 \text{ sec}$.

Continental Divide

Temperatures were measured in a single drill hole (DDH-8) on the Continental Divide between Woodchopper Gulch and Bald Butte. The hole is inclined at a rather shallow angle, thus the uncertainty in the vertical gradient is large. Because no thermal conductivity samples were collected, the average conductivity for DDH-4 and DDH-6 is used to calculate a heat-flow value. The uncertainty of the determination is quite high and the value is an estimate at best.

Bald Butte

Temperatures were measured in five drill holes. Heat-flow values, uncorrected for topography, have already been published (Blackwell, 1969, p. 995, and Figure 5) for three of the drill holes (DDH-9, 11, 12). Temperatures were also measured in DDH-10 and DDH-13 (Figure 5). DDH-10 is very shallow and a heat-flow value is not calculated; however, the heat flow in DDH-13

FIG. 3. Temperature-depth curves for the Ottawa Gulch (DDH-1, and DDH-2) and Continental Divide (DDH-8) localities.

is calculated and included in the average. Two series of temperature-depth measurements are plotted for DDH-13. During the first logging, a small water flow was issuing from the collar. Before the second logging, the water flow had stopped. The logs clearly indicate the entry of water into the drill hole at 130 m. The drill holes cut hornfelsed Helena Limestone, which in this locality was quite silty and has been transformed into a dark rock composed of calc-silicate minerals cut by numerous quartz veins.

DDH-9 cuts the small porphyry stock intruding the Helena (Rostad, 1969) and has a similar gradient to the remainder of the drill holes, but a higher conductivity and thus a higher heat flow. This heat flow has not been included in the average as it is assumed to be a refractive effect. The shape of the stock is similar to a

needle and so the heat flow around the stock will not be affected measurably by its presence. Thus, the true regional heat flow in DDH-9 is given by the Helena conductivity and the observed gradient.

The terrain-corrected heat-flow values have a greater scatter than the uncorrected data. However, the terrain-corrected gradients, unlike the uncorrected gradients, do not differ at a 1σ confidence limit and heat-flow differences are due to conductivity alone. Therefore, the best value of heat flow for the locality is taken as the harmonic mean of all the Helena Limestone conductivities in DDH-11, 12, and 13, and the arithmetic mean of the geothermal gradients in DDH-9, 11, 12, and 13. The best value of heat flow corrected for nearby topography is $6.5 \mu\text{cal}/\text{cm}^2 \text{ sec}$.

FIG. 4. Temperature-depth curves for the Woodchopper Gulch locality (DDH-3, 4, 5, 6, and 7).

FIG. 5. Temperature-depth curves for DDH-10, 12, and 13 at the Bald Butte locality. Temperature-depth curves for DDH-9, 11, and 12 are shown in Blackwell (1969, Figure 5).

FIG. 6. Temperature-depth curves for DDH-14 (circles) and DDH-15 (triangles) at the Empire Creek locality. Bar graphs of gradient, thermal conductivity, and heat flow are shown for DDH-14. A bar graph of gradient for DDH-15 (dashed curve) is also included. The solid squares represent depths of thermal conductivity measurement and spot heat flow values for DDH-15. Not all available conductivity measurements for the hole are shown, however, as some are below the interval plotted.

Empire Gulch

The two drill holes (DDH-14 and DDH-15) cut a small quartz porphyry stock below a quartz cap. The two units are clearly shown in the bar graphs of gradient and thermal conductivity (Figure 6). The lower part of the quartz cap is horizontal because, although the thermal conductivity is twice as high in the quartz cap as in the porphyry (determined as the harmonic mean of the samples from DDH-14 and DDH-15), the heat flow is exactly the same (Table 1)! The rock cut by the intrusive is Empire Shale dipping less than 30 degrees. Similar rocks (Belt Series argillites) elsewhere for which data are available have conductivities in the range of 7-8 mcal/cm sec °C (Blackwell, 1969, unpublished), as does the Empire Shale in DDH-1 in Ottawa Gulch. Thus, thermal conductivity of the quartz porphyry and shale are similar and the heat flow, although measured in the porphyry, cannot have a significant refraction component.

Possible errors introduced by calculating ver-

tical gradients from inclined drill holes are clear at this locality. The isothermal surfaces are dipping in the direction of the inclination of DDH-14 so the calculated "vertical" gradient differs from the true vertical gradient by 35 percent. The inclination of the isothermal surfaces is into a hillside, contrary to the expected behavior. Thus, the best value of heat flow is the one measured in the vertical drill hole (DDH-15). That value is $19.5 \mu\text{cal/cm}^2 \text{ sec}$.

ORIGIN OF ANOMALOUS HEAT-FLOW VALUES

A summary of heat flow, gradient, and conductivity information for each of the five localities is shown in Table 2. The regional heat flow in western Montana is "high" and is about $1.9 \mu\text{cal/cm}^2 \text{ sec}$ (Blackwell, 1969 and unpublished data); thus the lowest value of heat flow measured in the Marysville area is almost twice the background. The "anomalous" gradient at each locality (which is the number to be used in the interpretation section) is obtained by subtracting

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Table 2. Heat flow, thermal conductivity, gradient, and anomalous gradient

Locality	No. of Holes	Heat Flow $\mu\text{cal}/\text{cm}^2\text{sec}$	K $\mu\text{cal}/\text{cmsec}^\circ\text{C}$	Gradient $^\circ\text{C}/\text{km}$	Anomalous Gradient $^\circ\text{C}/\text{km}$ ($\pm$ percent)
Ottawa Gulch	2	3.2	7.50	42.7	17.4 ± 25
Woodchopper Gulch	2	4.7	7.06	66.6	39.7 ± 5
Continental Divide	1	(5.0)	(7.06)	70.5	43.6 ± 25
Bald Butte	4	6.5	8.08	80.2	56.7 ± 5
Empire Creek	1	19.5	8.12	240.4	217.0 ± 5

the gradient corresponding to a background heat flow of $1.9 \mu\text{cal}/\text{cm}^2 \text{ sec}$ and the in-situ thermal conductivity, from the observed gradient. The results are shown in Table 2. The error band which should be associated with the "anomalous" gradient is difficult to estimate. A figure of ± 5 percent is probably reasonable for the Empire Creek, Bald Butte, and Woodchopper Gulch localities. For the Ottawa Gulch and Continental Divide localities the band might be as large as ± 25 percent. Hence, in subsequent sections, the models are constrained primarily by the Empire Creek, Bald Butte, and Woodchopper Gulch data.

The observed heat-flow pattern, with the exception of the Ottawa Gulch locality, is compatible with sources of simple shape. If the heat flow at the Ottawa Gulch locality is valid, then the source cannot have a simple shape because Ottawa Gulch is closer to Empire Creek than is Woodchopper Gulch. However, because of the lack of data available to fully define a source shape and because the heat-flow value at Ottawa Gulch is not well determined, the value there will be neglected in the following sections. Nonetheless, the value in Ottawa Gulch may indicate a complicated source shape.

For purposes of the discussion, some limits need to be put on the minimum depth to the source of the anomaly. Information on the maximum depth comes from the succeeding analysis. DDH-15 was drilled to a depth of almost 550 m and remained in quartz porphyry to the total depth. The hole was supposed to have been cased with iron pipe to 440 m, but for unknown reasons the temperature probes will not go below 220 m. Extrapolation of the observed gradient implies a bottom-hole temperature of $140\text{--}150^\circ\text{C}$. Had a water reservoir at such temperatures been pene-

trated, there would have been no doubt about it. This evidence, plus the fact that local relief over the anomaly exceeds 500 m, suggests that the minimum depth to the top of the source must be in excess of 550 m in Empire Creek.

Because of the size and strength of the anomaly, explanations such as refraction, radioactive sources, or oxidization of sulfides can be ruled out. The only reasonable explanations are a buried reservoir of thermal fluid or a buried, still cooling magma chamber! On the basis of presently available data, either hypothesis could explain the data so both will be discussed.

Hot water reservoir

In other areas where high values of conducted heat flow similar to the value in Empire Creek have been measured, their origin has been attributed or proved to be convection at depth of heated groundwater (see for example, Helgeson, 1968; White et al, 1971). In fact, Rikitake (1959) developed a model (to be used in the following section) for a spherical magma chamber, in order to explain a heat-flow value of $12 \mu\text{cal}/\text{cm}^2 \text{ sec}$. However, from the results of the model he concluded that the chamber would have to be at an unreasonably shallow depth (in his case) for heat-flow value to be explained by such a model. Thus, he concluded that the value was due to convecting groundwater.

In the Marysville area there is no obvious reservoir in the area where high values are observed, and there are no surface manifestations of high-temperature fluid at depth (such as hot or warm springs or recent volcanics). In fact, there are few large springs at all in the district. The country rocks (Precambrian sediments of the Belt Series) are extremely impermeable except

for permeability due to interconnected fractures. The anomalous heat-flow values are separated by a distance of over 5 km and do not appear to have any systematic structural relationships with mapped geology or faults. In order to explain the spread of heat-flow data, any reservoir must have a lateral extent of several kilometers, but no obvious possibilities appear in the geology; lack of thermal springs argues against the presence of a high degree of fracture porosity in the rocks of the area.

In the rank of pure speculation, it might be possible that regional low-angle thrust faults of large displacement, mapped to the east, extend beneath the Marysville district and that a suitable reservoir might be fractured rock along, or permeable Paleozoic carbonates below, the thrust fault. The zone of thrust faulting is continuous with that to the north (Robinson et al, 1968) which includes the Lewis Overthrust of the Glacier Park area and the McConnell Overthrust in Canada. Demonstrated net slips of 45 km or more are available for these faults (see Fox, 1959). The nearest mapped, large displacement thrust fault to the Marysville district is the Eldorado thrust fault just west of Wolf Creek, Montana (Schmidt, 1963) approximately 40 km to the northeast. The Eldorado thrust has a stratigraphic throw of several kilometers, but the net slip is unknown.

Assuming a suitable reservoir is present, little can be said about its temperature, size, and depth because of lack of data. If the observed gradients in Empire Creek extend only 500 m below the maximum depth of DDH-15 and the reservoir is present at that depth, the temperature would be on the order of 250°C, or about as high as observed in other presently known geothermal areas. If the reservoir is beneath a regional thrust fault, then measurements presented here would reflect conducted heat flow in the impermeable cap over the reservoir and indicate the pattern of convection in the reservoir.

Buried magma chamber

In view of the lack of evidence for a hot water reservoir, other possibilities ought to be considered. Recent studies of geothermal systems suggest that the source of heat for such systems must be magma chambers at depths of several kilometers (Bodvarsson, 1970, for example). Therefore, it seems reasonable that other magma

chambers may be present whose heat is not tapped by groundwater because of lack of water or impermeability of wall rocks. The Marysville anomaly may represent one such area.

Three very simple models will be discussed: infinite, semiinfinite, and spherical *instantaneous* (Carslaw and Jaeger, 1959, p. 255) heat sources. The semiinfinite model represents the maximum (and undoubtedly unrealistic) size for the causative body while the spherical model represents much smaller body size. The models assume uniform thermal properties for magma and wall rocks, a temperature of intrusion of 1000 or 1300°C, simple conductive cooling and a *single* pulse of magma intrusion. The ground surface temperature (a planar surface is assumed in the calculation) is kept constant for all time by use of the method of images. Details of the solidification of a magma chamber (such as a convection in a cooling magma) are ignored, as is detailed consideration of the effect of the latent heat of solidification. Jaeger (1965) notes that for instantaneous models the initial temperature used can account approximately for effects of latent heat if, instead of melting temperature T_m , the initial temperature used is $T_0 = T_m + L/c$, where L is the latent heat and c is the specific heat of the magma. So for a latent heat of 50 cal/gm, and a specific heat of 0.2 cal/gm°C, $T_0 = T_m + 250^\circ\text{C}$. Thus, the assumed initial temperatures correspond roughly to melting temperatures of granites and gabbros. Such simple models are justified only by the lack of information on possible composition of the magma (and thus the initial temperature), physics of solidification in a magma chamber, and lack of detailed surface data to limit possible model shapes or histories.

An interesting relationship can be derived for the maximum gradient at the surface of a plane layer, initially at $T = 0^\circ\text{C}$ everywhere, overlying a half-space with an initial temperature of T_0 (temperature at time = 0), followed by subsequent simple conductive cooling with the upper surface of the plane layer remaining at $T = 0^\circ\text{C}$. It is merely

$$(dT/dz)_{z=0} = 0.48(T_0/H), \quad (1)$$

where $(dT/dz)_{z=0}$ is the surface gradient, and H is the thickness of the capping layer. Thus, the maximum gradient at the surface is independent of the thermal properties and is never more than

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approximately one-half the initial temperature divided by the depth to the top of the chamber. The timing of the appearance of the maximum gradient at the surface (and the variation with time of the gradient) is a function of the diffusivity of the material. The times at which models with various capping layer thicknesses and initial temperatures would satisfy the observed gradient at the Empire Creek locality are shown in Figure 7. The diffusivity assumed is $0.015 \text{ cm}^2/\text{sec}$. For the one-dimensional instantaneous model, the maximum possible depth to the top of the chamber is only 2.4 km if T_0 is 1000°C , and less than 3.0 km if $T_0 = 1300^\circ\text{C}$ (Figure 7). The magnitude of the anomalous gradient at the Empire Creek locality represents a severe constraint on the depth to the source of the anomaly. The age of the intrusion could range from a few thousand to 150,000 years based on this model.

The maximum depth to the corresponding chamber, if it has existed long enough to reach steady state, is just over twice the depth for the instantaneous model with the same T_0 because the gradient in the steady-state case will be

$$(dT/dz)_{z=0} = (T_0/H), \quad (2)$$

where the symbols are the same as in equation (1).

The data from Woodchopper Gulch and Bald Butte indicates that one boundary of the body must be between those two localities and the Empire Creek site, however. A model which maximizes the size of the body is one which assumes the body to be infinite in extent to the north, south, and west and to have a boundary striking northwest-southeast or north-south between Empire Creek and Bald Butte. For simplicity the body will be assumed to have a vertical plane boundary between Empire Creek and Bald Butte. The geometry of the model for which calculations are made is shown in Figure 8. Also shown in Figure 8 are the gradients from the three localities with highest-quality data projected onto northwest-southeast and north-south cross-sections. For a few classes of instantaneous models, i.e., those that can be made up of a product of one-dimensional solutions, the shape of the surface gradient curve uniquely gives the time of intrusion as well as information which can be used to put limits on the depth to the top of the body and its thickness. The geometry shown in Figure 8 has been analyzed by Simmons (1967). For the

FIG. 7. Plot showing locus of time when an infinite instantaneous (see text) magma chamber with a roof of thickness given by the ordinate value and with the specified initial temperature would have a surface gradient of $220^\circ\text{C}/\text{km}$. The dotted line is the locus of the time of maximum gradient for a given roof thickness.

class of models shown, the surface gradient is given by

$$(dT/dz)_{z=0} = \frac{T_0}{2\sqrt{\pi kt}} (e^{-z_2^2/4kt} - e^{-z_1^2/4kt}) \cdot \{1 + \text{erf}[x/(4kt)^{1/2}]\}, \quad (3)$$

where z_2 and z_1 are the depths to the bottom and top of the body, respectively, and k is thermal diffusivity. If x_0 is the distance from the mid-point of the anomaly ($x=0$ in Figure 8) required for the anomaly to drop to 52 percent of the mid-point value, then the time since intrusion is

$$t_0 = x_0^2/k. \quad (4)$$

With $t=t_0$, equation (3) for the maximum amplitude at any time becomes

$$G_m = (dT/dz)_{\max} = \frac{T_0}{x_0\sqrt{\pi}} (e^{-z_2^2/4x_0^2} - e^{-z_1^2/4x_0^2}). \quad (5)$$

So from the anomaly shape and magnitude, a unique time (assuming the shape is exactly known and the assumed model is identical to the causative body) and an infinite set of (z_1, z_2) can be found which will satisfy the anomaly. The am-

FIG. 8. Anomalous gradient data from Empire Creek, Bald Butte, and Woodchopper Gulch projected onto north-south (dashed) and northwest-southeast (solid) cross-sections. The size of the symbol is proportional to the uncertainty of measurement. The interpretational model is shown in the left corner. Models A and B are discussed in the text (see also Figure 9).

biguity is illustrated in Figure 9 which is a contour plot of $T_0/G_m x_0$ as a function of scaled depth to the top of the body (z_1/x_0) and scaled body thickness $[(z_2 - z_1)/x_0]$. As the figure illustrates, for a given anomaly and values for x_0 , G_m , and T_0 , there are many pairs of z_1 and z_2 which will satisfy the observations.

In order to apply the model, the data shown in Figure 8 were used to define an anomaly curve. The shape of the anomaly implied by the north-south projection (dashed line) is not similar to those generated by the model considered here because of the tail of the anomaly, whereas the data projected onto the northwest-southeast profile are consistent with such a model. Two interpretations of the possible anomaly shape are shown in Figure 8 (indicated by A and B). Curve A has values of x_0 , t_0 , and G_m equal to 1.1 ± 0.1 km, $25,200 \pm 7000$ years, and $225^\circ\text{C}/\text{km}$, respectively, while curve B has values of 1.35 ± 0.15 km, $38,000 \pm 10,000$ years and $250^\circ\text{C}/\text{km}$. The range of values of the quantity $T_0/G_m x_0$ are shown in Figure 9 for those two models assuming values of T_0 to be between 1000 and 1300°C . Values of the parameter z_1/x_0 less than 0.6 can be ruled out by the drill hole in Empire Creek. Models with z_1/x_0 greater than 1.5–2.0 (the exact value depends on the value of $T_0/G_m x_0$) where the contours become

horizontal, are insensitive to the thickness of the body.

For this model to be applicable, the extent of the body does not have to be infinite to the northwest, northeast, and southwest. If the plan section

FIG. 9. Contour plot of the dimensionless parameter $T_0/G_m x_0$ as a function of scaled depth to top of the body (z_1/x_0) and thickness of the body $[(z_2 - z_1)/x_0]$ for the model shown in Figure 8. The dashed curves correspond to the range of parameters which would generate anomaly curves A and B in Figure 8, assuming T_0 's of 1000°C and 1300°C .

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of the body is a square or rectangle with sides greater than 6–10 km, then the model used here would still be valid. Therefore, more data are obviously needed to the northwest and southwest to furnish constraints upon this sort of model.

A final model to be considered, and the one that probably comes closest to being a physically reasonable model, is a spherical source. As before, the calculation is for instantaneous intrusion and subsequent conductive cooling. The equations describing the surface gradient and the internal temperature of such a source have been derived by Rikitake (1959). The initial temperature is assumed to be 1300°C and the diffusivity and other assumed quantities are as before. With this model, and the above conditions, no single source with center to the northwest of the Empire Creek determination will satisfy the observed gradient data; if the source is spherical, the axis of the sphere must lie between Bald Butte and Empire Creek. The results of the calculations, and the models, for three cases that satisfy the gradient

FIG. 10. Spherical magma chambers, calculated surface gradients, and observed data (dotted and dashed lines). Assumed diffusivity is $0.015 \text{ cm}^2/\text{sec}$. Model 1 has a magma chamber 3 km in radius, center buried 4.0 km, and 40,000 years old. Model 3 is the same as Model 1, but with an age of 60,000 years. Model 2 has a magma chamber 4 km in radius; center buried 5.5 km and age of 40,000 years.

FIG. 11. Current and initial temperatures in the magma chamber for the three spherical models (Figure 10).

data, are shown in Figure 10. In cases 1 and 3 the chambers are 3 km in diameter, buried 1 km beneath the surface, and have ages of 40,000 and 60,000 years, respectively. In case 2, the chamber is 4 km in radius, buried 1.5 km and has an age of 40,000 years. The surface projections of the centers of these chambers are shown as circled numbers in Figure 1. Figure 11 shows calculated temperatures in the chamber for the three spherical models. It must be reemphasized that the initial assumptions and model upon which these examples are based are tenuous at best and give only order of magnitude estimates of possible sub-surface conditions.

HEAT-FLOW DETERMINATIONS IN SHALLOW BOREHOLES

Theoretically, it should be possible to make heat-flow measurements with only a single logging in boreholes deeper than 20 m, the depth at which the temperature variation due to the seasonal air temperature variation becomes negligible for typical values of thermal properties (see Lovering and Goode, 1963, for a detailed discussion). In practice, heat-flow measurements may not be

considered reliable unless the holes are 200-300 m deep (see Birch, 1966). The gradients measured in the shallow parts of drill holes (even in regions of gentle topography) often depart remarkably from those measured deeper in the drill holes, particularly in regions of low to normal heat flow. These "anomalous" shallow gradients have been attributed to conductive effects such as recent climatic changes or to nonconductive effects such as "water circulation" (Diment, 1964; detailed discussion by Birch, 1966). Water circulation between fracture zones or aquifers cut by a drill hole is readily identifiable by the stair step nature of the temperature depth curves (Birch 1966, Figure 8; DDH-5 at Woodchopper Gulch, etc.). It is now clear that most other effects not directly attributable to obvious water circulation in the drill hole are related to steady state or transient variations in ground surface temperature due to vegetation contrasts (Hyndman and Everett, 1968; Roy et al, 1972). In the conterminous U.S., at least, general climatic effects do not seem to be present. Vegetation contrasts can cause ground surface temperature variations of up to 2°C over a lateral distance of a few tens of meters (see Poley and Van Stevenick, 1970). The resulting effect on geothermal gradients can be as much as $\pm 20^\circ\text{C}/\text{km}$ at shallow depths, but the most drastic cases can be easily recognized (as when the hole is drilled in a small clearing, for example) and a correction applied. Furthermore,

in geothermal areas the enhancement of heat flow (and thus of gradient) may be 2-10 times normal, and thus the gradient error from such effects will be much less than in the eastern U.S., for example.

Measurements were made in most of the drill holes at Marysville beginning at 10 m. Comparisons of the uncorrected interval average gradient between approximately 20 and 40 m and the uncorrected least-squares gradient in the segment of the drill hole used for the heat-flow calculation (Table 1) are shown in Table 3 for the drill holes for which data are available. The results are encouraging for the possibilities of making gradient measurements in shallow holes. The difference between the two gradients for each drill hole (column 5) includes the effects of possible conductivity variations (in general, no thermal conductivity samples were collected from as shallow as 40 m), water table effects (the water tables in the holes range from a few meters to 50 m or so), different depth weight of topographic effects, and errors of calculation as well. Clearly it should be possible to make heat flow measurements in shallow holes when gradients are high and rocks are impermeable.

Even where gradients are high, vegetation contrast effects can still be significant. Some of the scatter of uncorrected gradients at the Woodchopper Gulch locality is due to such effects. These contrasts are indicated by the difference in extrapolated surface temperatures between the

Table 3. Comparison between uncorrected shallow gradients (between approximately 20 and 40 m) and the uncorrected least-squares gradients used to calculate heat flow values (Table 1)

DDH No.	Shallow Gradient °C/km	Depth Interval ¹ meters	Uncorrected Gradient °C/km	Difference Percent
1	30.6	70-135	37.1	-17.5
2	35.8	31-92	35.3	+1.4
3	48.9	18-64	46.0	+6.3
4	49.4	29-97	52.4	-6.7
6	70.9	28-106	72.2	-1.8
7	45.5	30-50	49.4	-7.9
8	57.2	30-82	63.0	-9.2
10	64.5	60-80	65.5	-1.5
11	85.0	52-281	72.5	+17.2
12	67.5	100-280	70.3	-4.0
13	76.5	140-250	83.9	-8.8
14	180.3	164-193	177.2	+1.7
15	231.5	160-220	267.3	-13.4

¹Values apply to the uncorrected least-squares gradients.

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pairs of holes DDH-6 and DDH-7 (3.5°C, in trees) and DDH-3 and DDH-4 (5.0°C, in a clearing) even though the drill holes are less than one hundred meters apart. The gradients corrected for the vegetation contrasts and topography differ by much less than the raw data.

Thus it seems that, given appropriate conditions not as restrictive as previously assumed, geothermal gradients can be measured in shallow drill holes which will be in reasonable agreement with those measured at greater depths. The conditions are that the hole not be in an area of high relief, that no obvious shallow aquifers with moving groundwater be present, and that variations in surface temperature due to vegetation contrasts or other effects (lakes, recent logging, cities, etc.) are not present. To a certain extent the gradient anomalies caused by surface temperature variations can be removed. Certainly, the chances for making a successful gradient measurement are improved if the gradient is higher than normal and if more than one hole in a given area is available. These conclusions are supported by data from a study of the geothermal gradient and heat flow in southeastern Oregon where elevation, vegetation, and aquifer effects are in general not present (see Bowen and Blackwell, 1973). The rocks are mostly relatively unconsolidated lake bed deposits, tuffs, and volcanics with low thermal conductivities so that the gradient, even for a background heat flow of about $1.5 \mu\text{cal}/\text{cm}^2 \text{ sec}$, is 40–50°C/km. In those holes, almost without exception, the geothermal gradient is sensibly constant from approximately 20 m to (in the absence of conductivity variations) the total depth of the drill hole.

DISCUSSION

The unique feature of the Marysville anomaly is that there are no surface manifestations of anomalous subsurface temperatures in spite of a heat flow 10 times the regional average. Such an area of high heat flow is of interest both from its contribution to the understanding of the thermal structure of the crust and from its possible use as a source of thermal energy.

Many other "blind" geothermal areas such as the one described here undoubtedly exist in the western U.S. Regional heat flow studies in that area have delineated three broad regions of high heat flow (Roy et al, 1968b, 1972; Sass et al, 1971). The average regional heat flow in these

zones of high heat flow is about $2.2 \mu\text{cal}/\text{cm}^2 \text{ sec}$. In the areas of high regional heat flow, except in extremely unusual situations, heat flow values in excess of $3 \mu\text{cal}/\text{cm}^2 \text{ sec}$ cannot be explained unless some extra component of heat flow is present, in addition to the mantle component and the component due to radioactive decay in the crust (see Roy et al, 1968a). Yet of the approximately 200 measurements (if anything, biased against sites near geothermal areas as most are in holes drilled for mineral exploration) so far published in the high heat-flow zones (Roy et al, 1968b; Warren et al, 1969; Sass et al, 1971; etc.), approximately 10 percent of the measurements have values in excess of $3 \mu\text{cal}/\text{cm}^2 \text{ sec}$. Thus, there are many other areas similar to Marysville in the western U.S. However, most of the other areas of extra high heat flow are represented by a single measurement, whereas at Marysville there are enough closely spaced measurements to give some idea of the size and intensity of the anomaly.

Additional geophysical studies are in progress in the Marysville area in order to delineate further the geographic limits of the anomaly and identify the nature of the source. These studies include further drilling and a gravity survey. Seismic surveys are also planned. Electrical studies of the area are in progress by the USGS. The models presented above are only considered for order of magnitude ideas as to the implications of the heat flow data. Further studies should give much more definitive information on the source size, shape, and intensity.

At present it is not clear that the area would have been recognized by other geophysical investigation. Thus, in high heat flow regions of the western U.S., regional heat-flow studies alone may discover many of these "blind" anomalies. Such surveys might be sponsored by state or federal agencies in order to delineate anomalous areas for further study by government or industry. If drill holes 30 m (100 ft) deep can be utilized, then many previously drilled shallow holes should be available that have been ignored in previous regional surveys. The desirable spacing of these types of measurements would be less than 5 km.

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