·51, Dielectric polari-
·c acid: J. Am. Chem.

·perties of rocks and
·cal constants, Clark,
·m.
·H., 1959, Dielectric
·ity of natural-state
l.
·solid state physics:
& Sons, Inc.
·sion of resistivity and
·iconductors at audio
p. 121.
·erfrequenzdispersion
und der elektrischen
·errite: Phys. Status

and magnetism: v. I,

·l properties of rocks:

·mena in rocks: New

Cunningham, D. R.,
·lectrical conductivity
A new laboratory
p. 5101.
·tivity (ρ) and dielec-
·nating electric fields:

I., 1965, Electrical
·d alternating electric
(English Trans.), p.

·ics and waves: Cam-

der dielectrischen:
·wellscher Vorstellun-
371.
·al communication.
·rch, MIT.
·rystalline dielectrics:

Area MT L&L Marysville Ht. Flow

GEOPHYSICS, VOL. 38, NO. 5 (OCTOBER 1973), P. 941–956, 11 FIGS., 3 TABLES

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

DAVID D. BLACKWELL* AND CZANG-GO BAAG‡

A unique geothermal area has been discovered during the course of a regional heat-flow study using holes drilled for mineral exploration. There are no surface manifestations of abnormal subsurface temperature in spite of the fact that at one locality a temperature of 58°C was measured at a depth of only 220 m. The area of anomalous heat flow straddles the Continental Divide near the old gold mining camp of Marysville, Mont. about 30 km northwest of Helena. Measured values of conducted heat flow range from 3.2 to 19.5 μcal/cm² sec. The immediate source of the high heat flow is either an unexposed reservoir of thermal fluids or a very shallow still-cooling magma chamber. At the present time the magma chamber model is preferred. The presence of additional similar areas in the western U. S. is suggested by the data from regional heat-flow studies. However, in most of the other areas only single anomalous heat-flow value is available, whereas at Marysville a region of several tens of km² is known to have abnormal heat-flow values. It is suggested that temperature measurements should be made in available drill holes deeper than 30 m in the high heat-flow regions of the western U. S. as an inexpensive way to explore for other "blind" geothermal reservoirs.

INTRODUCTION

During the course of an investigation of the regional heat-flow distribution in the northwestern U. S., Blackwell (1969) found unusually high values of conducted heat flow (averaging 6.5 μcal/cm² sec) at a locality about 30 km northwest of Helena, Mont., and 4.5 km west of the old gold mining camp of Marysville. Since that work, data have been obtained for an additional eleven holes in four other areas as much as 4 km from the original locality. In all the drill holes a conducted heat flow well in excess of the regional background is indicated. The highest value is 19.5 μcal/cm² sec and is the highest reported continental value of conducted heat flow measured outside a known geothermal area. The average gradient at that locality is 240°C/km in rock with a thermal conductivity of about 8 mcal/°C sec cm. In spite of extremely high gradients and resulting high temperatures at shallow depths, there are no surface manifestations of anomalous subsurface temperatures. The area appears to be unique in this respect and the object of this paper is to present the data and suggest some possible explanations for the high heat flow. The data have been mentioned briefly before (Blackwell, 1970), and the results reported here are preliminary in that additional work is in progress in the area. A gravity survey has been carried out, data are being reduced, and shallow drilling (<150 m) is in progress. However, the presently available data are believed to be of sufficient interest to justify publication at this time.

GEOLOGY

The geology of the Marysville stock, which outcrops over an area of about 5 km² around the town of Marysville, was the subject of a classic paper by Barrell (1907). From mine workings he

† Manuscript received by the Editor March 16, 1973; revised manuscript received April 17, 1973.
* Southern Methodist University, Dallas, Tex. 75222
‡ University of Texas at Dallas, Tex. 75230

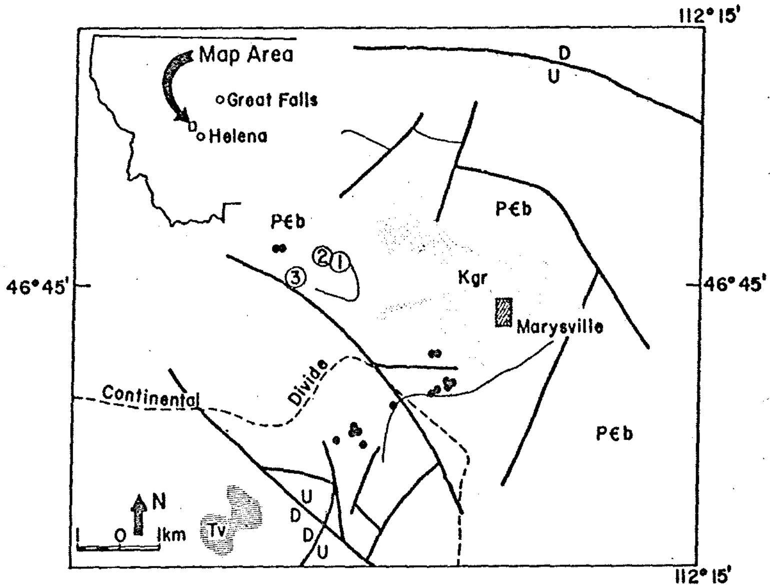


FIG. 1. Location map and generalized geologic map of the Marysville area (after Barrell, 1907; Ratcliffe, personal comm.). The heavy lines are the trace of faults. The symbols Kgr, *P€b*, and Tv stand for Cretaceous granodiorite (Marysville stock), Precambrian Belt Series, and Tertiary volcanics, respectively. Dikes and sills and a few small outcrops of Tv are not shown. Also not shown are Paleozoic sedimentary rocks lying unconformably above the Belt Series in the southwest corner of the map, and Quaternary alluvium in Little Prickly Pear Creek at the northwest edge of the map. The light line outside the Kgr indicates the limit of contact metamorphosed Belt rock surrounding the Marysville stock (Barrell, 1907). Locations of the drill holes are shown as solid dots. The location of the centers of spherical magma chambers are shown as circled numbers. The numbers correspond to the models shown in Figure 10.

developed detailed evidence supporting the stoping theory of magma emplacement. One of his figures is included in a widely used textbook on structural geology (Billings, 1954). More recently, aspects of the geology have been discussed by Knopf (1950), Mantei and Brownlow (1967), and Rostad (1969). M. Ratcliff (personal communication, 1971) has mapped parts of the Ellison 15 minutes, Canyon 7½ minutes and Granite Butte 7½ minutes quadrangles, including part of the area mapped by Barrell (1907). The mapping of Ratcliff covers the area of anomalous heat flow values discussed here.

The area location, generalized geologic information, and heat flow values are shown in Figure 1. Locations of the drill sites are shown on a generalized topographic map of the area in Figure 2. The bedrock in the area consists of Precambrian sedimentary rocks of the Belt Series (see Ross, 1963). The two formations outcropping most extensively in the area are Empire Shale and Helena Limestone. The shale is in most places a dense, blocky fracturing argillite. The limestone is actually a very impure limestone or dolomite with a silica content of about 33 percent (Knopf, 1950, p. 837). In much of the area the limestone has been transformed into a dense low porosity calc-silicate hornfels. To the southwest Paleozoic and Mesozoic sedimentary rocks onlap the Belt rocks.

The sedimentary rocks are cut by several ages of intrusive rocks, but the only exposed body of any size is the Marysville stock which, because of its proximity and similarity in composition to rocks of the Boulder batholith, was presumed to be of late Cretaceous age (Barrell, 1907; Knopf, 1950). According to a potassium-argon determination the age is 79 my (Baadsgaard et al, 1961) or about the age of older phases of the Boulder batholith and of the Elkhorn Mountains volcanics (Tilling et al, 1968). There are several suites of dikes and sills both pre- and post-emplacement of the Marysville stock. Several small outcrops of rhyolitic and dacitic volcanics occur in the area and more extensive outcrops occur to the north and south. These rocks may be correlatives of the Lowland Creek volcanics of

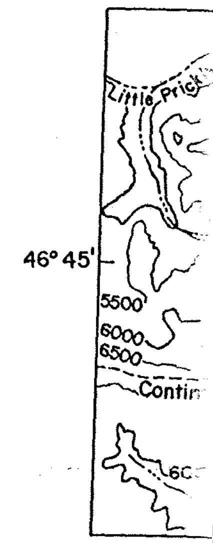


FIG. 2. Generalized topographic
of measured drill holes are shown a
are μcal/cm² sec.

the Boulder batholith region
(49 my) in age (Smedes and
However, Melson (1971) repor
flora of probable Oligocene a
beds in lavas near Little Prick
north of the Marysville distric
holes at Empire Creek and Ba
quartz porphyry stocks which
little or no surface expression
intrusive rocks is Tertiary.
intrusive has been dated by
techniques at 48 my (Rostad,
communication).

The Marysville stock is surr
belt of contact metamorphosed
(see Figure 1), and thus the
much greater subsurface exten
exposure would indicate, p
west where the contact belt is
and where dikes and sills are m
Belt rocks. The stock occup
structural and topographic h
by doming associated with e
stock. Most faults in the a
faults, and some can be traced
ters. Maximum displacement
the order of a few hundred feet

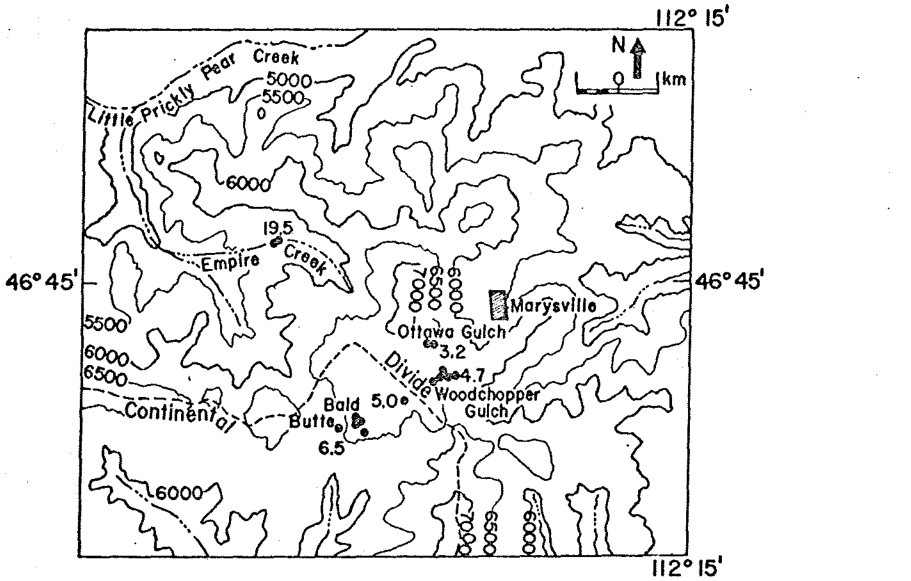


FIG. 2. Generalized topographic map of the Marysville area. The contour interval is 500 ft (152 m). Locations of measured drill holes are shown as solid dots. Heat flow value for each locality is also shown. Units of heat flow are $\mu cal/cm^2$ sec.

the Boulder batholith region which are Eocene (49 my) in age (Smedes and Thomas, 1965). However, Melson (1971) reported collection of a flora of probable Oligocene age from silt-stone beds in lavas near Little Prickly Pear Creek, just north of the Marysville district. In addition, drill holes at Empire Creek and Bald Butte cut small quartz porphyry stocks which have, respectively, little or no surface expression. The age of these intrusive rocks is Tertiary. The Bald Butte intrusive has been dated by potassium-argon techniques at 48 my (Rostad, 1969, and personal communication).

The Marysville stock is surrounded by a broad belt of contact metamorphosed sedimentary rocks (see Figure 1), and thus the stock may have a much greater subsurface extent than its present exposure would indicate, particularly to the west where the contact belt is 2 km or more wide, and where dikes and sills are most abundant in the Belt rocks. The stock occupies the center of a structural and topographic high perhaps caused by doming associated with emplacement of the stock. Most faults in the area are high angle faults, and some can be traced for several kilometers. Maximum displacements appear to be on the order of a few hundred feet.

HEAT FLOW

Temperature measurements are presented for 15 drill holes (Figures 1 and 2) forming a rough triangle with sides of 5.3, 4.7, and 2.5 km (enclosing an area of about 30 km^2). The holes were all drilled for mineral exploration; access to the holes and core for thermal conductivity measurements was kindly granted by the companies and individuals involved in the exploration. The two drill holes with the highest values of heat flow are in a valley occupied by Empire Creek. Five with intermediate heat-flow values are on a topographic feature called Bald Butte, and five with low (relative) heat-flow values are near a small valley called Woodchopper Gulch.

Data are also presented for two holes north of Ottawa Gulch and for a single hole on the Continental Divide between Woodchopper Gulch and Bald Butte. Heat-flow values calculated at these last two points are considered to be of low reliability, however. Several holes are quite shallow (<100 m), but because of high gradients, surface effects are quickly overcome and similar gradients are observed in adjacent drill holes (Table 1).

The largest uncertainty in the heat-flow determinations stems from the fact that many of the holes are inclined. Depths shown for all the in-

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/cm²sec	Heat Flow Corr. µcal/cm²sec
Ottawa Gulch	46°44′	112°19′									
DDH — 1			1964	45	70-135	7.50	12	37.1	42.3	2.78	3.18
						0.25		0.3	0.4	0.11	
DDH — 2			1964	45	31-92	(7.50)		35.3	43.1	(2.7)	(3.2)
								0.4	0.5		
Mean Value											3.2
Woodchopper G.	46°44′	112°19′									
DDH — 3			1974	45	18-64	(7.48)		46.0	61.7	(3.4)	(4.6)
								1.1			
DDH — 4			1958	68	29-97	7.48	6	52.4	59.9	3.89	4.48
						0.45		1.1	1.8	0.31	
DDH — 5			1946	45	21-130			> 50.9	—	—	—
DDH — 6			1979	67	28-106	6.89	12	72.2	72.3	4.98	4.98
						0.26		0.3	0.3	0.21	
DDH — 7			1993	90	30-50	(7.06)[2]		49.4	49.7	(3.4)	(3.5)
								0.5	0.5		
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	70.5	(4.45)	(5.0)
								0.9	1.0		
Bald Butte	46°43′	112°21′									
DDH — 9			2043	90	100-210	11.7	13	70.4	78.6	8.0	8.9
						0.8		2.1	2.3	0.2	
DDH — 10			2092	90	60-80			(65.5)			
DDH — 11			2001	70	52-281	8.42	13	72.5	80.5	6.38	7.10
						0.36		0.5	0.9	.07	
DDH — 12			2043	90	100-280	9.02	13	72.5	79.9	6.68	7.35
						0.58		1.6	1.5	0.15	
DDH — 13			1921	55	140-250	7.28	8	83.9	81.9	6.27	6.12
						0.62		1.2	1.1	0.16	
Mean Value						8.08[3]	27		80.2		6.5
						0.28			0.7		
Empire Creek	46°45′	112°22′									
DDH — 14			1654	45	88-164	16.4	7	83.7	74.8	13.7	12.3
						0.2		1.2	1.5	0.2	
					164-193	7.69	5	177.2	166.1	13.2	12.3
						0.12		2.5	2.4	0.4	
DDH — 15			1654	90	160-220	8.12	7	267.3	240.4	21.7	19.5
						0.15		1.5	0.9	0.5	
Best Value											19.5

[1] Number of conductivity samples.
[2] Harmonic average of conductivity measurements for DDH-4 and DDH-6
[3] Average 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 procedure 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

"ought" to be. Because de
seldom available to proper
the dip of isothermal surfa
holes, such heat flow dete
sidered of lower precision
holes.

The mechanical details
and reduction are summar
(1968b) and are listed in Ta
are least-squares straight
temperature-depth data in
The conductivity values lis
monic averages. Standard e
neath the appropriate data
shown for heat-flow values
relate only to the interna
data. The water table varies
holes from about 20 to 50 m
be no systematic difference
or below water, gradients a
water table are not disting
heat-flow values, except th
and 15 were calculated as
least-squares gradient and
thermal conductivity. Heat
three holes were calculate
integral method.

Topographic corrections h
all the drill holes for which h
calculated. The correction w
conventional way (Birch, 19
only to a distance of 2 km
variation of the geotherma
possible recent nature of th
make the assumptions nece
a terrain correction, tenuo
tainly the close-in topogra
hence the correction was a
2 km.

Ottawa Gulch

The lowest value of heat
Marysville area is in DDH-
(see Figure 1). The hole
morphosed Empire Shale. Th
curve is shown in Figure 3.
value of heat flow is 3.2 µcal
isolated about 0.5 km north
on Woodchopper Gulch and
side so the vertical gradie
determined. DDH-2 is abou
hillside west of DDH-1, with

(K), gradient and heat flow. for the inclined holes. andard error

No[1]	Gradient Unc. °C/km	Gradient Corr. °C/km	Heat Flow Unc. μcal/cm²sec	Heat Flow Corr.
12	37.1	42.3	2.78	3.18
	0.3	0.4	0.11	
	35.3	43.1	(2.7)	(3.2)
	0.4	0.5		
				3.2
	46.0	61.7	(3.4)	(4.6)
	1.1			
6	52.4	59.9	3.89	4.48
	1.1	1.8	0.31	
	>50.9	—	—	—
12	72.2	72.3	4.98	4.98
	0.3	0.3	0.21	
	49.4	49.7	(3.4)	(3.5)
	0.5	0.5		
				4.7
	63.0	70.5	(4.45)	(5.0)
	0.9	1.0		
13	70.4	78.6	8.0	8.9
	2.1	2.3	0.2	
	(65.5)			
13	72.5	80.5	6.38	7.10
	0.5	0.9	.07	
13	72.5	79.9	6.68	7.35
	1.6	1.5	0.15	
8	83.9	81.9	6.27	6.12
	1.2	1.1	0.16	
27		80.2		6.5
		0.7		
7	83.7	74.8	13.7	12.3
	1.2	1.5	0.2	
5	177.2	166.1	13.2	12.3
	2.5	2.4	0.4	
7	267.3	240.4	21.7	19.5
	1.5	0.9	0.5	
				19.5

vertical depth from lateral le is successful only if the l. Experience shows that rizontal, even when they

"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 μcal/cm² 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 μcal/cm² 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

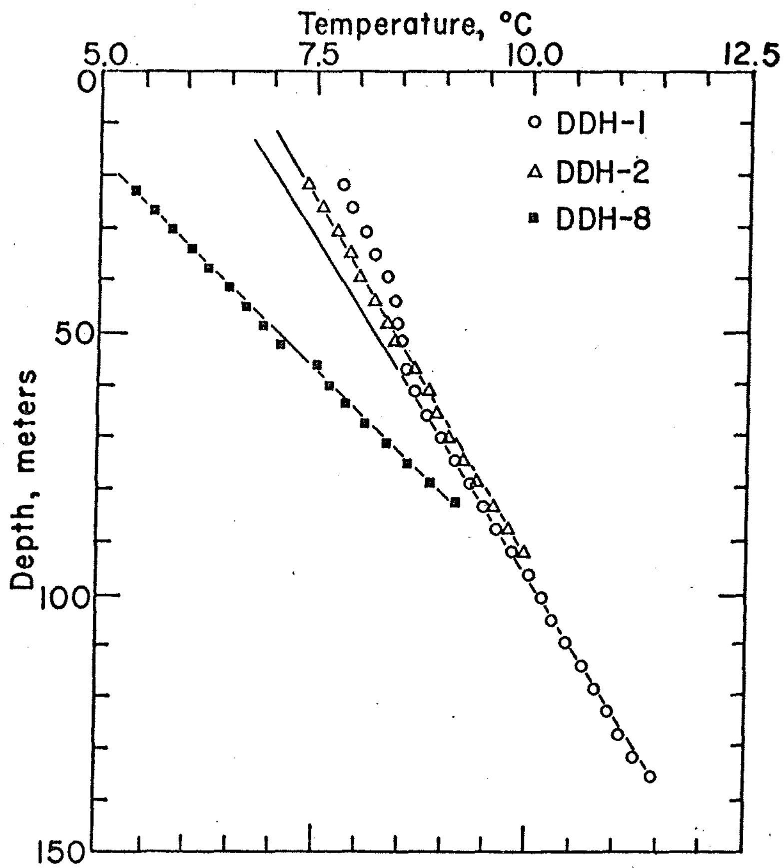


FIG. 3. Temperature-depth curves for the Ottawa Gulch (DDH-1, and DDH-2) and Continental Divide (DDH-8) localities.

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 1 σ 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 $\mu cal/cm^2$ sec.

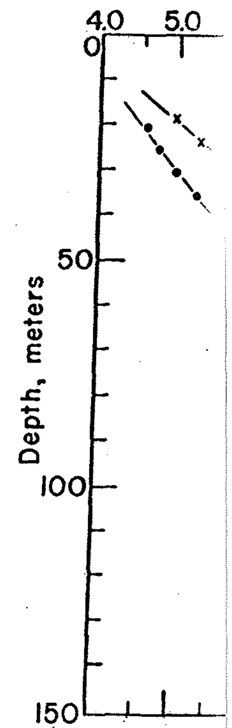


FIG. 4. Temperature-depth

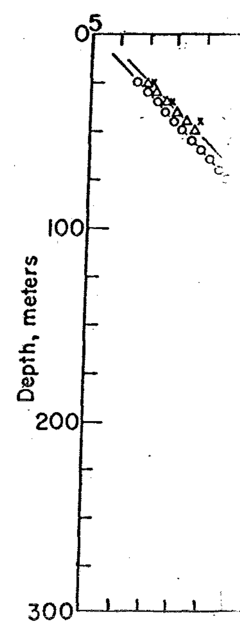
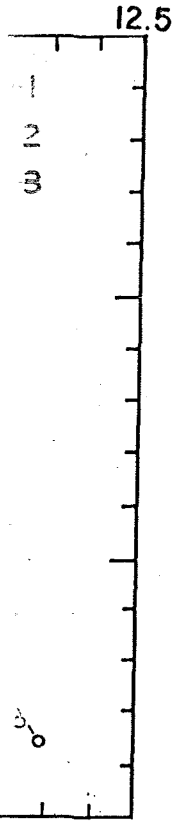


FIG. 5. Temperature-depth cu
depth curves for D



…and DDH-2)

…at flow around the stock will …rably by its presence. Thus, …flow in DDH-9 is given by …vity and the observed gradi-

…cted heat-flow values have …han the uncorrected data. …n-corrected gradients, unlike …ients, do not differ at a 1 σ …heat-flow differences are due …e. Therefore, the best value …e locality is taken as the … the Helena Limestone con- …-11, 12, and 13, and the …he geothermal gradients in …13. The best value of heat …nearby topography is 6.5

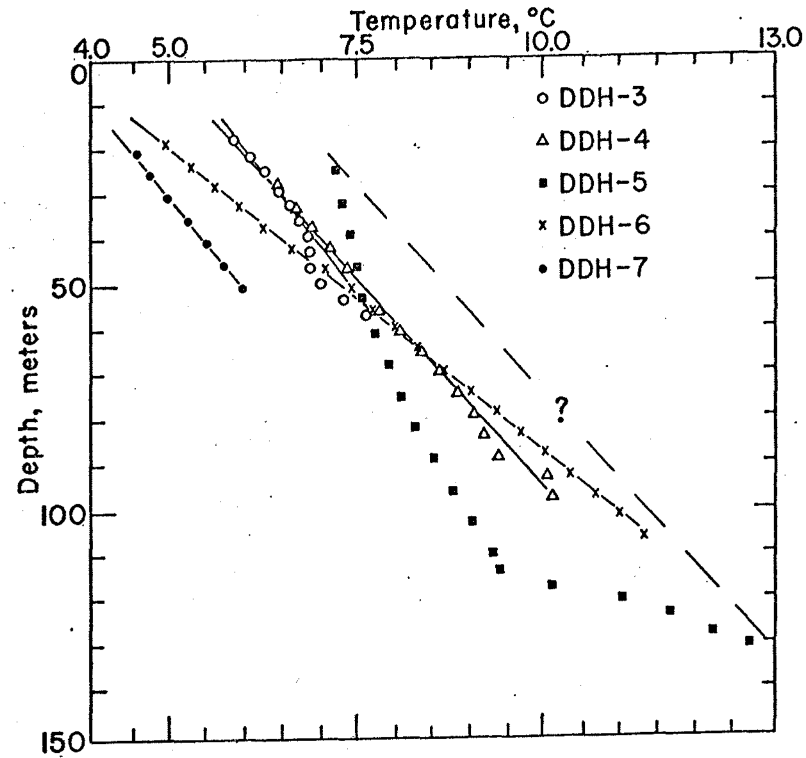


Fig. 4. Temperature-depth curves for the Woodchopper Gulch locality (DDH-3, 4, 5, 6, and 7).

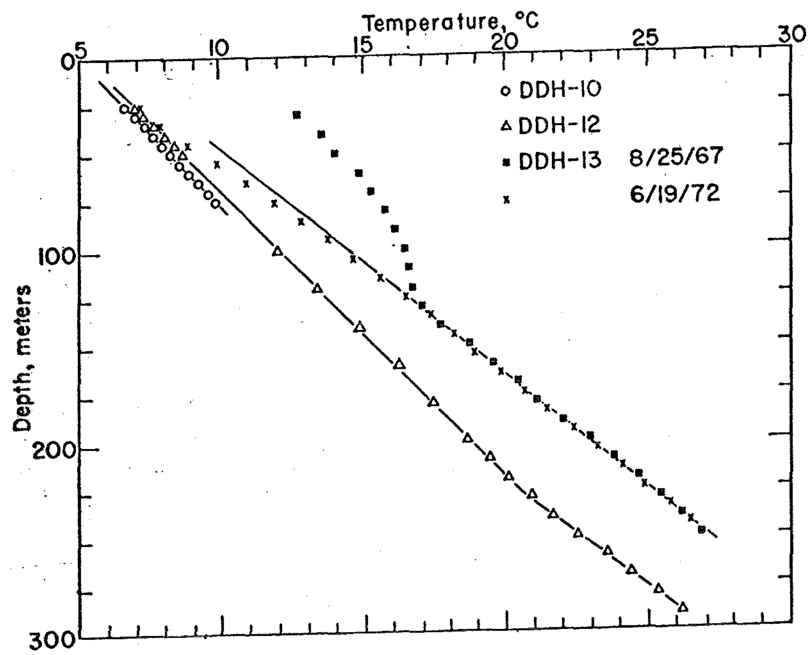


Fig. 5. Temperature-depth curves for DDH-10, 12, and 13 at the Bald Butte locality. Temperature-depth curves for DDH-9, 11, and 12 are shown in Blackwell (1969, Figure 5).

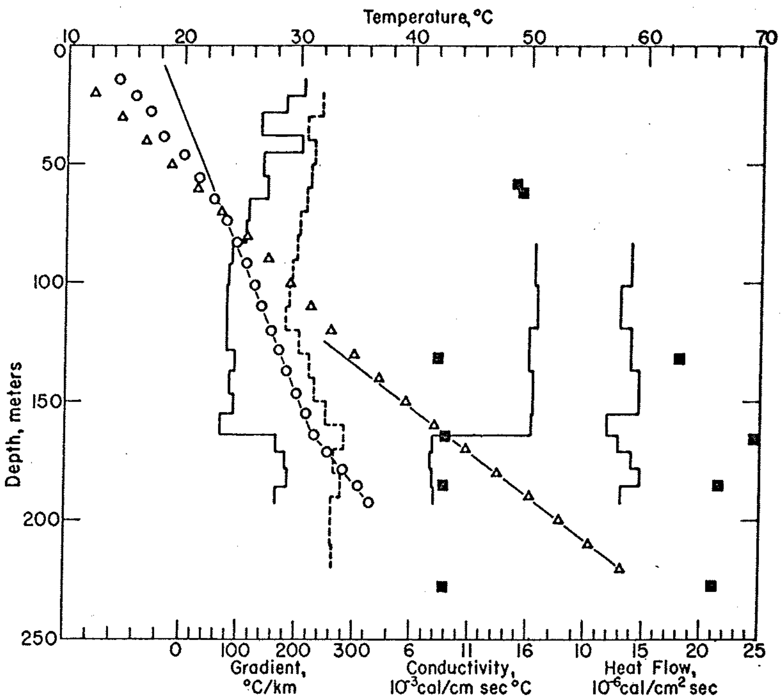


FIG. 6. Temperature-depth curves for DDH-14 (circles) and DDH-15 (triangles) at the Empire Creek locality. Bar graphs of gradient, thermal conductivity, and heat flow are shown for DDH-14. A bar graph of gradient for DDH-15 (dashed curve) is also included. The solid squares represent depths of thermal 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 vertical 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 μcal/cm² 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 μcal/cm² 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

Table 2. Heat

Locality
Ottawa Gulch
Woodchopper Gulch
Continental Divide
Bald Butte
Empire Creek

the gradient corresponding
flow of 1.9 μcal/cm² sec and
conductivity, from the obs
results are shown in Table 2.
should be associated with the
ent is difficult to estimate. A
is probably reasonable for
Bald Butte, and Woodchop
For the Ottawa Gulch and
localities the band might be
cent. Hence, in subsequent
are constrained primarily by
Bald Butte, and Woodchopp
The observed heat-flow pat
tion of the Ottawa Gulch lo
with sources of simple shape
the Ottawa Gulch locality
source cannot have a sim
Ottawa Gulch is closer to E
Woodchopper Gulch. Howe
lack of data available to
shape and because the heat-
Gulch is not well determined
be neglected in the following
less, the value in Ottawa G
complicated source shape.
For purposes of the disc
need to be put on the min
source of the anomaly. Infor
mum depth comes from the
DDH-15 was drilled to a de
and remained in quartz por
depth. The hole was suppose
with iron pipe to 440 m, but
the temperature probes will
Extrapolation of the observe
bottom-hole temperature of
water reservoir at such temp

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

Locality	No. of Holes	Heat Flow μcal/cm²sec	K μcal/cmsec°C	Gradient °C/km	Anomalous Gradient °C/km (± 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 μcal/cm² 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 140–150°C. Had a water reservoir at such temperatures been penetrated, 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 μcal/cm² 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, $T_0 = T_m + 250$°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 $T = 0$°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 $T = 0$°C. It is merely

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

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

approximately one-half th
divided by the depth to th
The timing of the appeara
gradient at the surface (ar
time of the gradient) is a fu
ity of the material. The ti
with various capping layer
temperatures would satisfy
at the Empire Creek localit
7. The diffusivity assumed
the one-dimensional instan
maximum possible depth to
ber is only 2.4 km if T_0 is
3.0 km if $T_0 = 1300$°C (Figu
of the anomalous gradient a
locality represents a sever
depth to the source of the
the intrusion could range fro
150,000 years based on this

The maximum depth to
chamber, if it has existed lo
steady state, is just over tw
instantaneous model with t
the gradient in the steady-sta

$$(dT/dz)_{z=0} = ($$

where the symbols are the sam

The data from Woodchop
Butte indicates that one bo
must be between those two lo
pire Creek site, however. A
mizes the size of the body is
the body to be infinite in e
south, and west and to have
northwest–southeast or north–
pire Creek and Bald Butte.
body will be assumed to ha
boundary between Empire Cre
The geometry of the model for
are made is shown in Figure 8.
ure 8 are the gradients from
with highest-quality data pro
west–southeast and north–so
For a few classes of instanta
those that can be made up o
dimensional solutions, the sha
gradient curve uniquely gives
sion as well as information wh
put limits on the depth to the t
its thickness. The geometry s
has been analyzed by Simmon

resent whose heat is not tapped
cause of lack of water or im-
vall rocks. The Marysville
sent one such area.
models will be discussed: in-
and spherical *instantaneous*
, 1959, p. 255) heat sources.
del represents the maximum
nrealistic) size for the causa-
spherical model represents
ize. The models assume uni-
erties for magma and wall
re of intrusion of 1000 or
uctive cooling and a *single*
rusion. The ground surface
ar surface is assumed in the
onstant for all time by use of
. Details of the solidification
(such as a convection in a
nored, as is detailed consid-
the latent heat of solidifica-
otes that for instantaneous
nperature used can account
ects of latent heat if, instead
re T_m, the initial tempera-
$-L/c$, where L is the latent
ic heat of the magma. So for
/gm, and a specific heat of
$_m$+250°C. Thus, the as-
ures correspond roughly to
of granites and gabbros.
e justified only by the lack
ssible composition of the
nitial temperature), phys-
magma chamber, and lack
a to limit possible model

onship can be derived for
at the surface of a plane
C everywhere, overlying a
itial temperature of T_0
), followed by subsequent
ng with the upper surface
aining at T=0°C. It is

$$= 0.48(T_0/H), \qquad (1)$$

surface gradient, and H
capping layer. Thus, the
e surface is independent
and is never more than

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 cm²/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°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

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

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

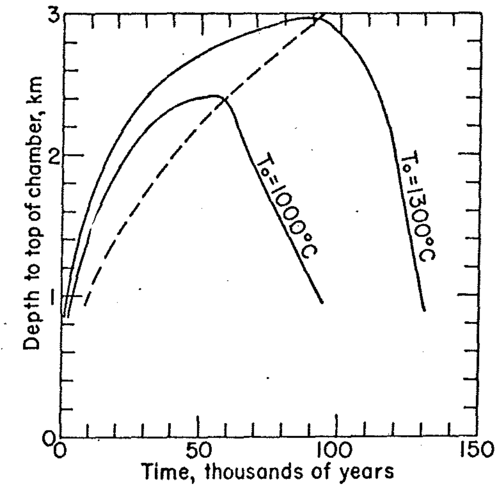


FIG. 7. Plot showing locus of time when an infinite instantaneous (see text) magma chamber with a roof of thickness given by the ordinate value and with the specified initial temperature would have a surface gradient of 220°C/km. The dotted line is the locus of the time of maximum gradient for a given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

class of models shown, the surface gradient is given by

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

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 midpoint of the anomaly (x=0 in Figure 8) required for the anomaly to drop to 52 percent of the midpoint value, then the time since intrusion is

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

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

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

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-

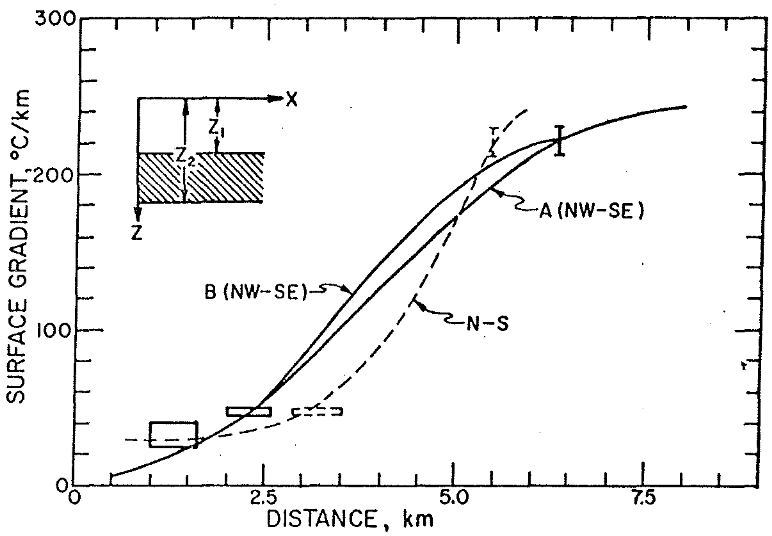


FIG. 8. Anomalous gradient data from Empire Creek, Bald Butte, and Woodchopper Gulch projected onto north-south (dashed) and northwest-southeast (solid) cross-sections. The size of the symbol is proportional to the uncertainty of measurement. The interpretational model is shown in the left corner. Models 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 $[(z_1-z_2)/x]$. 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, $25{,}200\pm7000$ years, and 225°C/km, respectively, while curve B has values of 1.35 ± 0.15 km, $38{,}000\pm10{,}000$ years and 250°C/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

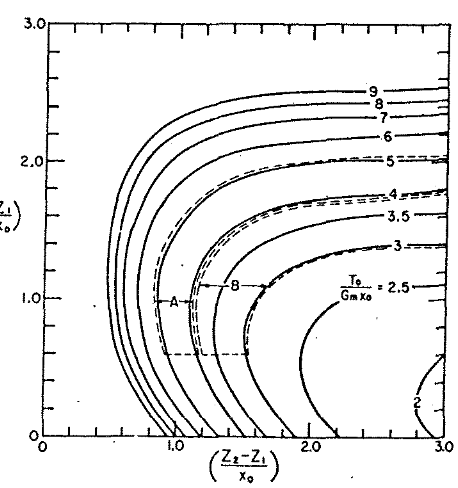


FIG. 9. Contour plot of the dimensionless parameter $T_0/G_m x_0$ as a function of scaled depth to top of the body (z_1/x_0) and thickness of the body $[(z_2-z_1)/x_0]$ for the model shown in Figure 8. The dashed curves correspond to the range of parameters which would generate anomaly curves A and B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

of the body is a square or greater than 6–10 km, then would still be valid. There obviously needed to the nor to furnish constraints upon

A final model to be con that probably comes closest reasonable model, is a spher the calculation is for instan subsequent conductive coo describing the surface gradi temperature of such a sourc by Rikitake (1959). The i assumed to be 1300°C and other assumed quantities are model, and the above condi with center to the northwest determination will satisfy th data; if the source is spher sphere must lie between Ba Creek. The results of the c models, for three cases that

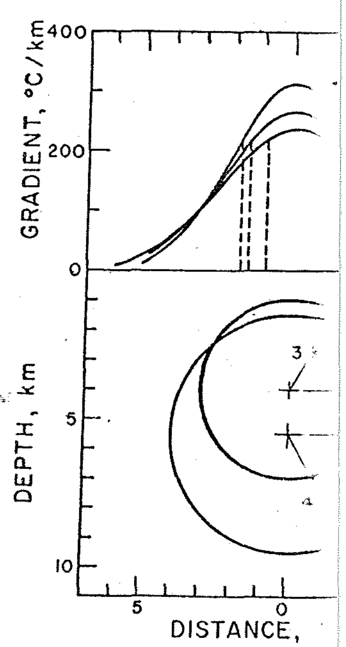
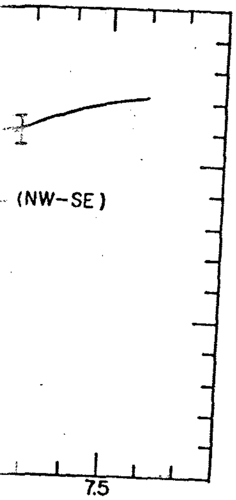
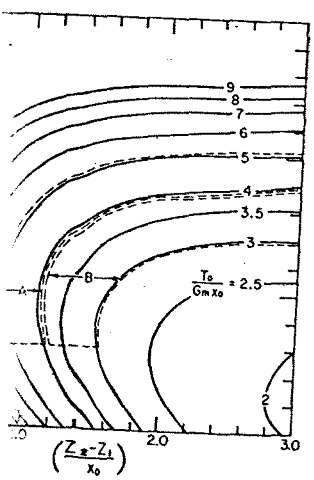


FIG. 10. Spherical magma cham face gradients, and observed data lines). Assumed diffusivity is 0.0 has a magma chamber 3 km in 4.0 km, and 40,000 years old. M Model 1, but with an age of 60 has a magma chamber 4 km in 5.5 km and age of 40,000 years.



…chopper Gulch projected onto north-
…ne symbol is proportional to the un-
…orner. Models A and B are discussed

…insensitive to the thickness of
… to be applicable, the extent of
…have to be infinite to the north-
…nd southwest. If the plan section



… of the dimensionless parameter
… of scaled depth to top of the
…kness of the body $[(z_2-z_1)/x_0]$
…n Figure 8. The dashed curves
…ge of parameters which would
…rves A and B in Figure 8,
… C and 1300°C.

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 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 subsurface conditions.

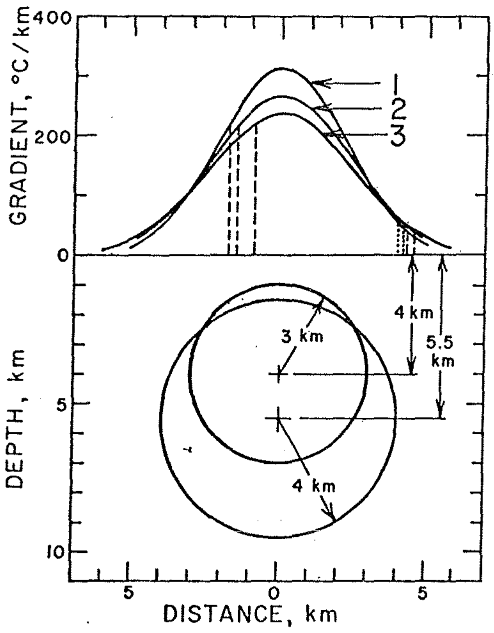


FIG. 10. Spherical magma chambers, calculated surface gradients, and observed data (dotted and dashed lines). Assumed diffusivity is 0.015 cm²/sec. Model 1 has a magma chamber 3 km in radius, center buried 4.0 km, and 40,000 years old. Model 3 is the same as Model 1, but with an age of 60,000 years. Model 2 has a magma chamber 4 km in radius; center buried 5.5 km and age of 40,000 years.

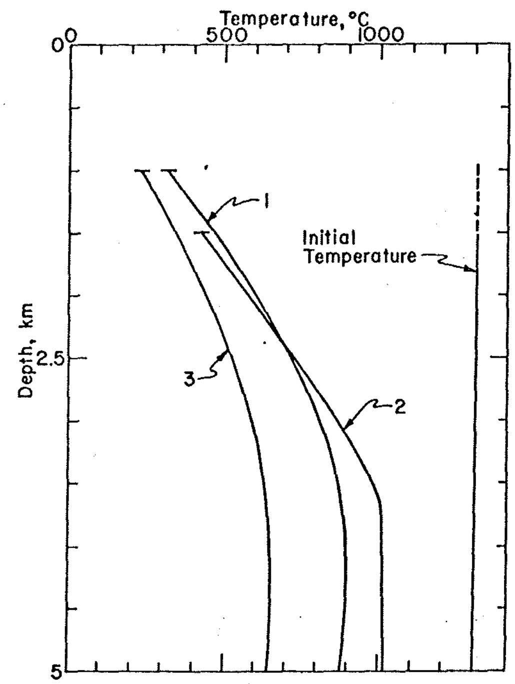


FIG. 11. Current and initial temperatures in the magma chamber for the three spherical models (Figure 10).

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 ± 20°C/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

[1]Values apply to the uncorrected least-squares gradients.

pairs of holes DDH-6 and DD trees) and DDH-3 and DDH- clearing) even though the drill ho one hundred meters apart. Th rected for the vegetation contra phy differ by much less than the

Thus it seems that, given ap tions not as restrictive as prev geothermal gradients can be mea drill holes which will be in reaso with those measured at greater de tions are that the hole not be in relief, that no obvious shallow moving groundwater be present tions in surface temperature du contrasts or other effects (lakes cities, etc.) are not present. To the gradient anomalies caused perature variations can be rem the chances for making a suc measurement are improved if higher than normal and if mor in a given area is available. Thes supported by data from a study gradient and heat flow in sou where elevation, vegetation, an are in general not present (see B well, 1973). The rocks are mos consolidated lake bed deposits canics with low thermal conduct gradient, even for a background 1.5 μcal/cm^2 sec, is 40–50°C/km almost without exception, the ent is sensibly constant from ap to (in the absence of conduc the total depth of the drill hole.

DISCUSSION

The unique feature of the M is that there are no surface anomalous subsurface tempera heat flow 10 times the regional area of high heat flow is of inte contribution to the understand structure of the crust and from a source of thermal energy.

Many other "blind" geother the one described here undoub western U.S. Regional heat flo area have delineated three broa heat flow (Roy et al, 1968b, 1971). The average regional

...al areas the enhancement of heat flo... gradient) may be 2–10 times norma... gradient error from such effects wi... than in the eastern U.S., for exampl... ...ents were made in most of the dri... ...ysville beginning at 10 m. Compari... ...ncorrected interval average gradien... ...oximately 20 and 40 m and the un... ...st-squares gradient in the segmen... ...ue used for the heat-flow calculatior... shown in Table 3 for the drill hole... ...a are available. The results are en... the possibilities of making gradient... in shallow holes. The difference... two gradients for each drill hole... ...udes the effects of possible conduc... ...ns (in general, no thermal conduc... were collected from as shallow as... ...able effects (the water tables in the... ...n a few meters to 50 m or so), dif... ...eight of topographic effects, and... ...ation as well. Clearly it should be... ...e heat flow measurements in shal... gradients are high and rocks are...

...radients are high, vegetation con... still be significant. Some of the... ...rrected gradients at the Wood... locality is due to such effects. ... are indicated by the difference in... ...face temperatures between the...

...een approximately 20 and 40 m) ...eat flow values (Table 1)

...ected ...ent ...m	Difference Percent
...1	−17.5
...3	+1.4
...0	+6.3
	−6.7
	−1.8
	−7.9
	−9.2
	−1.5
	+17.2
	−4.0
	−8.8
	+1.7
	−13.4

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 μcal/cm² 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 μcal/cm² sec. In the areas of high regional heat flow, except in extremely unusual situations, heat flow values in excess of 3 μcal/cm² 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 μcal/cm² 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.

ACKNOWLEDGMENTS

William R. Wade and AMAX Exploration, Inc. made available drill holes, core samples, and geologic information essential to the study. Ora H. Rostad, Giles Walker, and Eugene C. Robertson provided assistance, information, and discussion during the course of the study. M. Ratcliffe provided unpublished geologic information on the Marysville district. Dr. Francis Birch pointed out the relationship of the surface heat flow to the capping thickness for the semiinfinite instantaneous model discussed in the text. The field and laboratory measurements were made by R. Spafford and R. A. Arnett. The work was supported by National Science Foundation Grant GA 11351 to Southern Methodist University.

REFERENCES

Baadsgaard, H., Folinsbee, R. E., and Lipson, J., 1961, Potassium-argon dates of biotites from Cordilleran granites: Bull. Geol. Soc. Amer., v. 72, p. 689–702.

Barrell, J., 1907, Geology of the Marysville Mining District, Montana (A study of igneous intrusion and contact metamorphism): USGS Prof. Pap. 57, 182 p.

Billings, M. P., 1954, Structural geology: 2nd edition, Englewood Cliffs, N. J., Prentice-Hall, 514 p.

Birch, F., 1950, Flow of heat in the Front Range, Colorado: Bull. Geol. Soc. Amer., v. 61, p. 567–630.

——— 1966, Earth heat flow measurements in the last decade, *in* Advances in earth science: edited by P. M. Hurley, Cambridge, MIT Press, p. 403–430.

Blackwell, D. D., 1969, Heat flow determinations in the northwestern United States: J. Geophys. Res., v. 74, p. 992–1007.

——— 1970, Heat flow near Marysville, Montana (abstract): EOS, v. 51, p. 824.

Bodvarsson, G., 1970, Evaluation of geothermal prospects and the objectives of geothermal exploration: Geoexpl., v. 8, p. 7–17.

Bowen, R. G., and Blackwell, D. D., 1973, Progress report on geothermal measurements in Oregon: The Ore Bin, v. 35, p. 6–7.

Carslaw, H. S., and Jaeger, J. C., 1959, Conduction of heat in solids: 2nd edition, Oxford, Clarendon Press, 510 p.

Diment, W. H., 1964, Comments on paper by E. A. Lubimova "Heat flow in the Ukrainian shield in relation to recent tectonic movement": J. Geophys. Res., v. 70, p. 2466–2467.

Fox, F. G., 1959, Structure and accumulation of hydrocarbons in southern foothills, Alberta, Canada: Bull. Amer. Assoc. Petrol. Geol., v. 43, p. 992–1025.

Helgeson, H. C., 1968, Geologic and thermodynamic characteristics of the Salton Sea geothermal system: Amer. J. Sci., v. 266, p. 129–166.

Hyndman, R. D., and Everett, J. E., 1968, Heat flow measurements in a low radioactivity area of the western Australian Precambrian shield: Geophys. J. Roy. Astron. Soc., v. 14, p. 479–486.

Jaeger, J. C., 1965, Applications of the theory of heat conduction to geothermal measurements, *in* Terrestrial heat flow: Geophys. Monograph 8, edited by W. H. K. Lee, Washington, D. C., American Geophysical Union, p. 7–23.

Knopf, A., 1950, The Marysville granodiorite stock, Montana: Amer. Mineralogist, v. 35, p. 834–844.

Lovering, T. S., and Goode, H. D., 1963, Measuring geothermal gradients in drill holes less than 60 feet deep, east Tintic district, Utah: USGS Bull., no. 1172, 48 p.

Mantei, E. J., and Brownlow, A. H., 1967, Variation in gold content of minerals of the Marysville quartz diorite stock, Montana: Geochimica et Cosmochim. Acta, v. 31, p. 225–235.

Melson, W. G., 1971, Geology of the Lincoln Area, Lewis and Clark County, Montana: Smithsonian Contr. Earth Sci., no. 7, 29 p.

Poley, J. Ph., and Van Stevenick, J., 1970, Delineation of shallow salt domes and surface faults by temperature measurements at a depth of approximately 2 metres: Geophys. Prospect., v. 18, p. 666–700.

Rikitake, T., 1959, Studies of the thermal state of the earth. The second paper: Heat flow associated with magma intrusion: Bull. Earthquake Res. Inst., Tokyo Univ., v. 37, p. 233–243.

Robinson, G. D., Klepper, M. R., and Obradovich, J. D., 1968, Overlapping plutonism, volcanism, and tectonism in the Boulder Batholith region, Western Montana, *in* Studies in volcanology: edited by R. R. Coats, R. L. Hay, and C. A. Anderson: Geol. Soc. Amer. Mem. 116, p. 557–576.

Ross, C. P., 1963, The Belt series in Montana: USGS Prof. Paper 346, 122 p.

Rostad, O. H., 1969, The use of geochemistry at the Bald Butte molybdenite prospect, Lewis and Clark County, Montana: Quart. Colo. School Mines, v. 64 (1), p. 437–449.

Roy, R. F., Blackwell, D. D., and Birch, F., 1968a, Heat generation of plutonic rocks and continental heat flow provinces: Earth Planet. Sci. Let., v. 5, p. 1–12.

Roy, R. F., Decker, E. R., Blackwell, D. D., and Birch, F., 1968b, Heat flow in the United States: J. Geophys. Res., v. 73, p. 5207–5221.

Roy, R. F., Blackwell, D. D., and Decker, E. R., 1972, Continental heat flow, *in* Nature of the solid earth: edited by E. C. Robertson, McGraw-Hill Book Co., Inc. p. 506–543.

Sass, J. H., Lachenbruch, A. H., Monroe, R. J., Greene, G. W., and Moses, T. H., Jr., 1971, Heat flow in the western United States: J. Geophys. Res., v. 76, p. 6376–6413.

Schmidt, R. G., 1963, Preliminary geologic map and sections of the Hogan 4 Southeast quadrangle, Lewis and Clark County, Montana: USGS Misc. Geol. Inv. Map I-379.

Simmons, G., 1967, Interpretation of heat flow anomalies 2. Flux due to initial temperature of intrusives: Rev. Geophys., v. 5, p. 109–120.

Smedes, H. W., and Thomas, H. H., 1965, Reassignment of the Lowland Creek volcanics to Eocene age: J. Geol., v. 73, p. 508–510.

Tilling, R. I., Klepper, M. R., and Obradovich, J. D., 1968, K-Ar ages and time span of emplacement of the Boulder Batholith, Montana: Amer. J. Sci., v. 266, p. 671–689.

Warren, R. E., Sclater, J. G., Vacquier, V., and Roy, R. F., 1969, A comparison of terrestrial heat flow and transient geomagnetic fluctuations in the southwestern United States: Geophysics, v. 34, p. 463–478.

White, D. E., Muffler, L. P. J., and Truesdell, A. H., 1971, Vapor-dominated hydrothermal systems compared with hot-water system: Econ. Geol., v. 66, p. 75–97.

SHORT NOTES

THE COVARIANCE C

T. S. EDRINGTON*

Noise (of seismic and ot modeled as a shot process, i.e bination of wavelets. Speci random noise process and g waveform of the wavelet, the

$$X(t) = \sum_i g(t$$

where the T_i are Poisson poi ful result (derived by Backu this model is that if the wave across a sensor array, and i are uniformly distributed i cross-power spectrum for a product of the power spectru and a zero-order Bessel func of Backus et al,

$$\Phi_{01}(f) = \Phi_{00}(f)J_0$$

In view of the widespread seems appropriate to offer a valid derivation. The gene arbitrary distribution of wave problem with the derivation the upper limit of the sum i In general, N is infinite, bu with N finite and let it go to i in the development. If N is it is a random variable tha which case the interchange [Backus et al, equation (3)]

The present note will deri result

† Manuscript received by the Ed

* Sandia Laboratories, Albuquer