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GEOTHERMAL GRADIENTS IN THE MISSOULA AND BITTERROOT VALLEYS, WEST-CENTRAL MONTANA

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations 80-89

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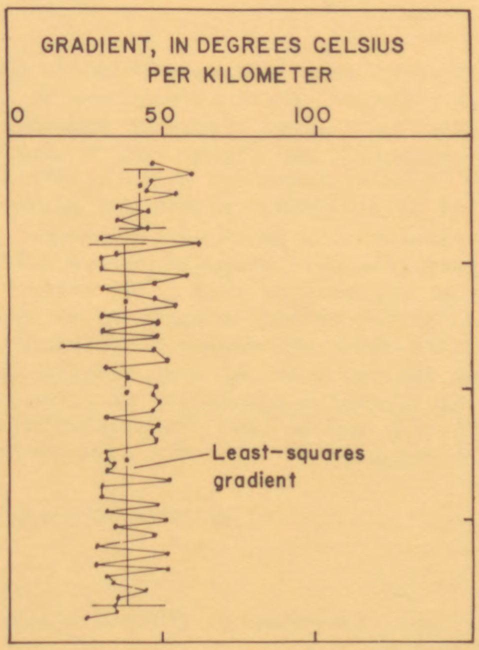

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A maximum temperature of 31.7 degrees Celsius was measured at a depth of 869 meters. Estimated temperatures at a depth of 1 kilometer at the drill sites ranged from about 34 to 63 degrees Celsius. Temperatures exceeding 90 degrees Celsius probably would not occur at depths less than 1,500 meters.

Values of thermal conductivity needed to maintain an assumed regional heat flow of about 2.1 heat flow units along the measured geothermal gradients generally exceeded published values for the rock and soil penetrated by the wells. Laboratory determinations of the thermal conductivity of cores and cuttings would be useful to refine the estimates and to test the conclusion that the measured temperatures are not hotter than normal.

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CONTENTS

ILLUSTRATIONS

TABLE

METRIC CONVERSION TABLE

The following factors can be used to convert the International System (SI) of metric units in this report to the equivalent inch-pound units.

Multiply metric unit	By	To obtain inch-pound unit
degree Celsius per kilometer (°C/km)	0.05486	degree Fahrenheit per 100 feet (°F/100 ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	3.281	foot (ft)
meter per kilometer (m/km)	5.280	foot per mile (ft/mi)
millimeter (mm)	0.03937	inch (in.)

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by the formula:

$$°F = 1.8°C + 32$$

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ABSTRACT

Temperature-depth profiles of six cased test holes in the Missoula and Bitterroot Valleys consist of linear segments, the intersections of which commonly correspond with lithologic boundaries. Geothermal gradients commonly decreased with depth, probably as a result of compaction and higher quartz content of the deeper sedimentary deposits. There is no evidence for hydrothermal discharge.

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INTRODUCTION

Most of the hot (more than 38°C) springs in Montana occur in the western part, within or marginal to block-fault valleys in which valley fill is a potential, but virtually unexplored, geothermal reservoir (Chadwick and Leonard, 1979). Because adequate supplies of water for domestic or agricultural use are normally available at depths of less than 100 m, geothermal and ground-water conditions at greater depths are largely unknown.

During 1978-79, seven test holes were drilled by Bendix Field Engineering Service under contract to the U.S. Department of Energy for the purpose of assessing the uranium content of lower Tertiary sedimentary rocks in the Missoula and Bitterroot valleys of west-central Montana. Six of the holes were cased by the U.S. Geological Survey and Montana Bureau of Mines and Geology for hydraulic testing and measurement of geothermal gradients in the valley fill (fig. 1) and one was abandoned. Hotter than normal temperatures or higher geothermal gradients in the test holes could reveal extensive reservoirs for hot water in the deep aquifers. The purpose of this report is to present and to analyze briefly the results of thermal logging of the holes.

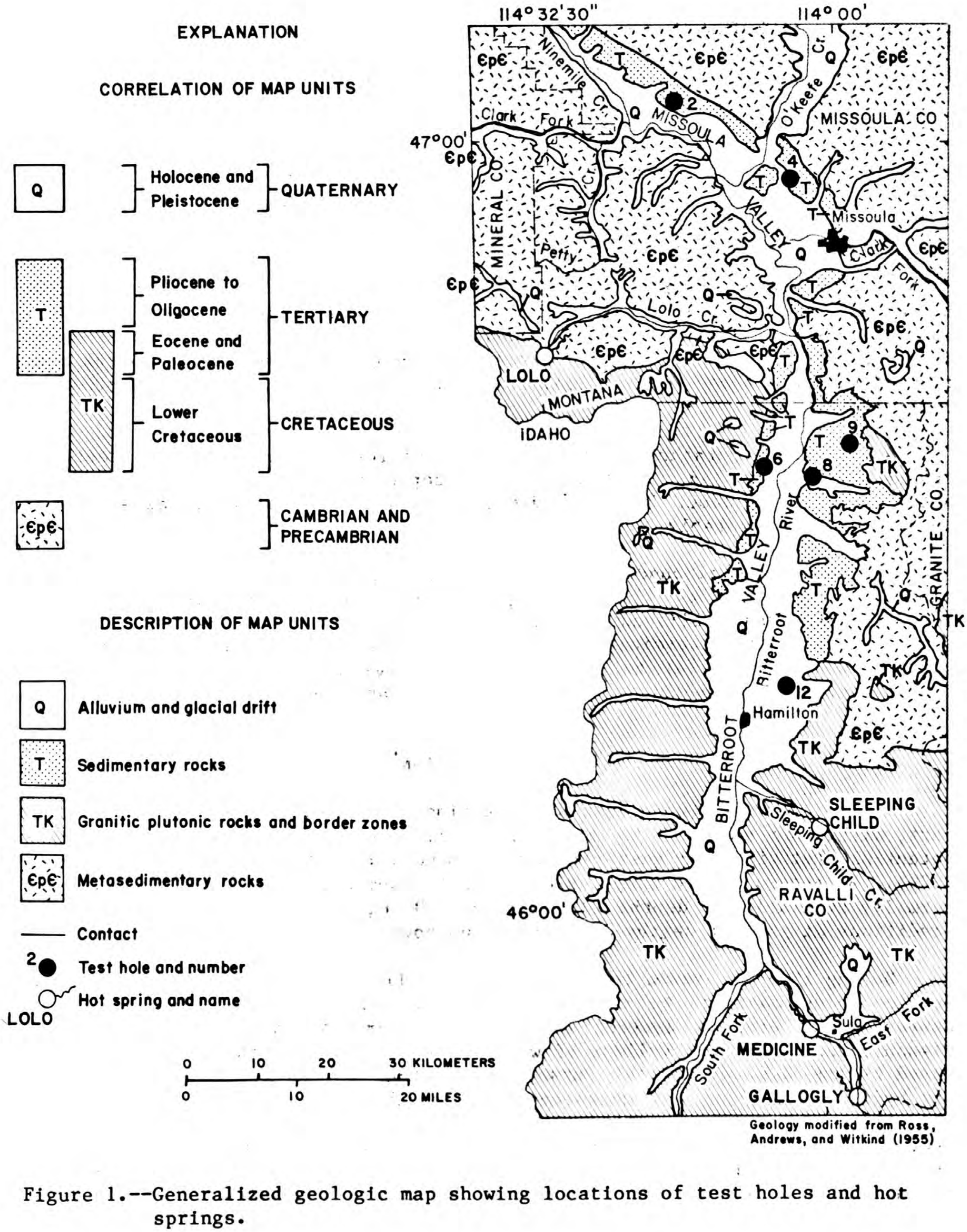

Figure 1.--Generalized geologic map showing locations of test holes and hot springs.

The Missoula and Bitterroot Valleys occur along and south of the western extension of the Montana lineament. This structural feature, oriented nearly west-northwest, forms the approximate northern boundary of the Boulder and Idaho batholiths and separates the predominantly metamorphic-granitic crystalline province to the south from the folded Precambrian metasedimentary province to the north (Weidman, 1965). The lineament may represent the junction of crustal plates along which recent tectonic movement favors ascent of thermal waters. Several hot springs and the well known Marysville thermal anomaly occur along or near the lineament.

Many of the hot springs in southwestern Montana issue from crystalline rock along the boundaries of block-fault valleys that were formed during Late Cretaceous and early Tertiary time. Lolo, Sleeping Child, Medicine, and Gallogly Hot Springs (fig. 1) issue from crystalline rock that forms the boundaries of the Bitterroot Valley. The Missoula Valley was formed by faulting, but the Bitterroot Valley may have been formed by synclinal warping and gravity sliding, later modified by faulting (Curry, 1977; also see Pardee, 1950, p. 389-392).

The valleys subsequently filled with alluvial and colluvial sediments containing layers of volcanic ash. Results of geologic mapping and geophysical studies described by McMurtrey and others (1965, 1972) indicate that the thickness of Tertiary and Quaternary valley fill ranges from about 900 to 4,000 m in the Missoula Valley and from about 600 to 1,200 m in the Bitterroot Valley (Curry, 1977). Test hole 4 in the Missoula Valley penetrated bedrock at a depth of 853 m and test hole 8 in the Bitterroot Valley (fig. 1) penetrated bedrock at a depth of 725 m (P. M. Norbeck, Montana Bureau of Mines and Geology, written commun., 1979).

METHOD OF INVESTIGATION

Subsurface temperatures were measured in test holes at intervals of 6.1 to 15.2 m using a manually operated thermistor-Wheatstone bridge combination capable of measuring temperatures with a precision of $\pm 0.1^{\circ}C$ to a depth of 914 m, the extent of the cable. The objective was to obtain temperature logs of each of the test holes after sufficient time had elapsed after drilling to establish thermal equilibrium, but before the drilling mud that inhibited lateral and vertical circulation in the well bore was removed by bailing.

Four test holes were completed with 102-mm (4-inch nominal) diameter steel casing, perforated at depths where borehole geophysical and lithologic logs indicated permeable sediments suitable for hydraulic testing. Unfortunately, consolidation of drilling mud in the lower part of three of the test holes (2, 8, 12) soon after termination of drilling, or inflow of sediment through perforations, precluded measurement of temperature to total casing depth (table 1).

Two test holes were completed with 51-mm (2-inch nominal) diameter steel casing, plugged at the base and filled with clear water. Presumably, the drilling fluid inhibited circulation of water in the annulus between the casing and the wall of the hole. Temperature logging of these smaller diameter holes was delayed to permit equilibration of water temperatures. An unexplained blockage in test hole 6 precluded logging the lower 153 m of the cased hole.

RESULTS

Geothermal gradients

Measured temperatures generally increased with depth, reaching a maximum of 31.7°C in test hole 4 at a depth of 869 m, but the rate of change (geothermal gradient) varied from test hole to test hole and with depth in each hole (table 1). Below a depth of about 100 m, and at shallower depths in some holes, the temperature-depth profile of each hole consists of rectilinear segments corresponding to major depth intervals (figs. 2-7). The intersections of the segments commonly correspond to lithologic boundaries reported by Montana Bureau of Mines and Geology (P. M. Norbeck, written commun., 1979).

The linearity of the segments indicates that a single (mean) value for the temperature gradient represents each of the major intervals. Gradients representing intervals between individual measurements vary widely (figs. 2-7), probably as a result of localized lateral movement of water through permeable strata, as well as vertical variations in lithology. However, the linear coefficients of correlation between temperature and depth within each major interval exceed 0.99.

Least-squares geothermal gradients calculated for major depth intervals range from about 19 to 77°C/km (table 1). The geothermal gradients of most major intervals, and the depth-weighted mean gradient for each test hole (25.1 to 58.2°C/km, table 1), are less than the 60°C/km commonly used for estimation of subsurface temperatures in valley fill.

At depths greater than 100 m, the geothermal gradients for each of the major intervals normally decreased with depth. Therefore, deep subsurface temperatures estimated from gradients in shallow wells at the same sites normally would be hotter than the actual values. For example, the temperature at a depth of 200 m in test hole 2 is 16.7°C (fig. 2). By extrapolating the thermal gradient of 33.6°C/km, representing the interval 18.3-227.1 m, the estimated temperature at a depth of 692 m would be 33.2°C [16.7°C + (492 m x 33.6°C/km ÷ 1000 m/km)]. The measured temperature at the depth of 692 m was 27.4°C.

With due recognition of the hazards of extrapolation, estimated temperatures at a depth of 1 km were calculated from the temperatures and gradients in the lower intervals of the test holes. The estimated temperatures ranged from about 34°C for deep test holes 2 and 4 in the Missoula Valley to about 63°C for shallow test holes 9 and 12 in the Bitterroot Valley (table 1). Actual temperatures at the sites of the shallower holes probably are cooler. Temperatures exceeding 90°C probably would not occur at any of the test sites at depths less than about 1,500 m.

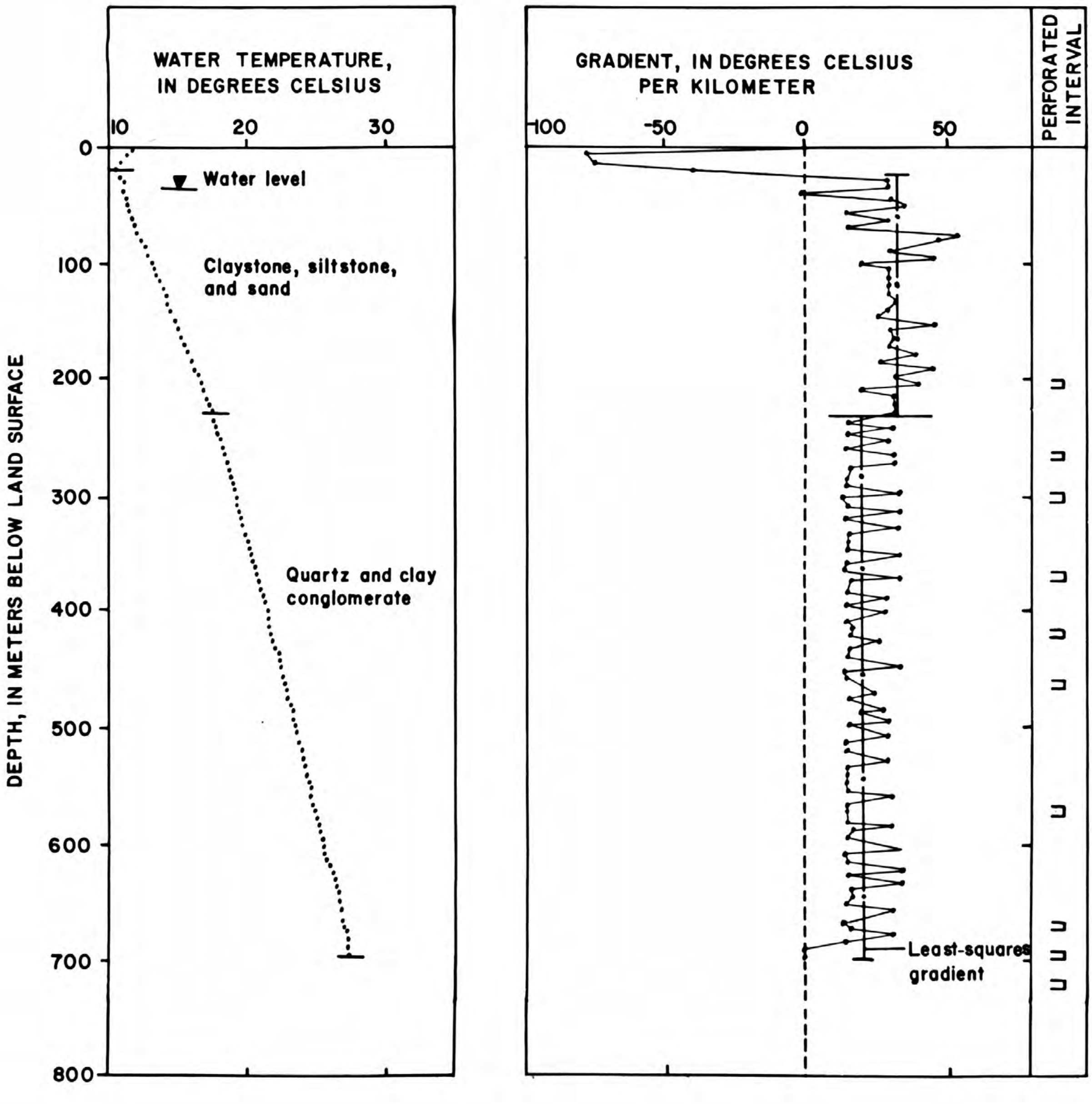

Figure 2.--Temperature profile, geothermal gradients, and lithologic summary for test hole 2. Lithology reported by Montana Bureau of Mines and Geology.

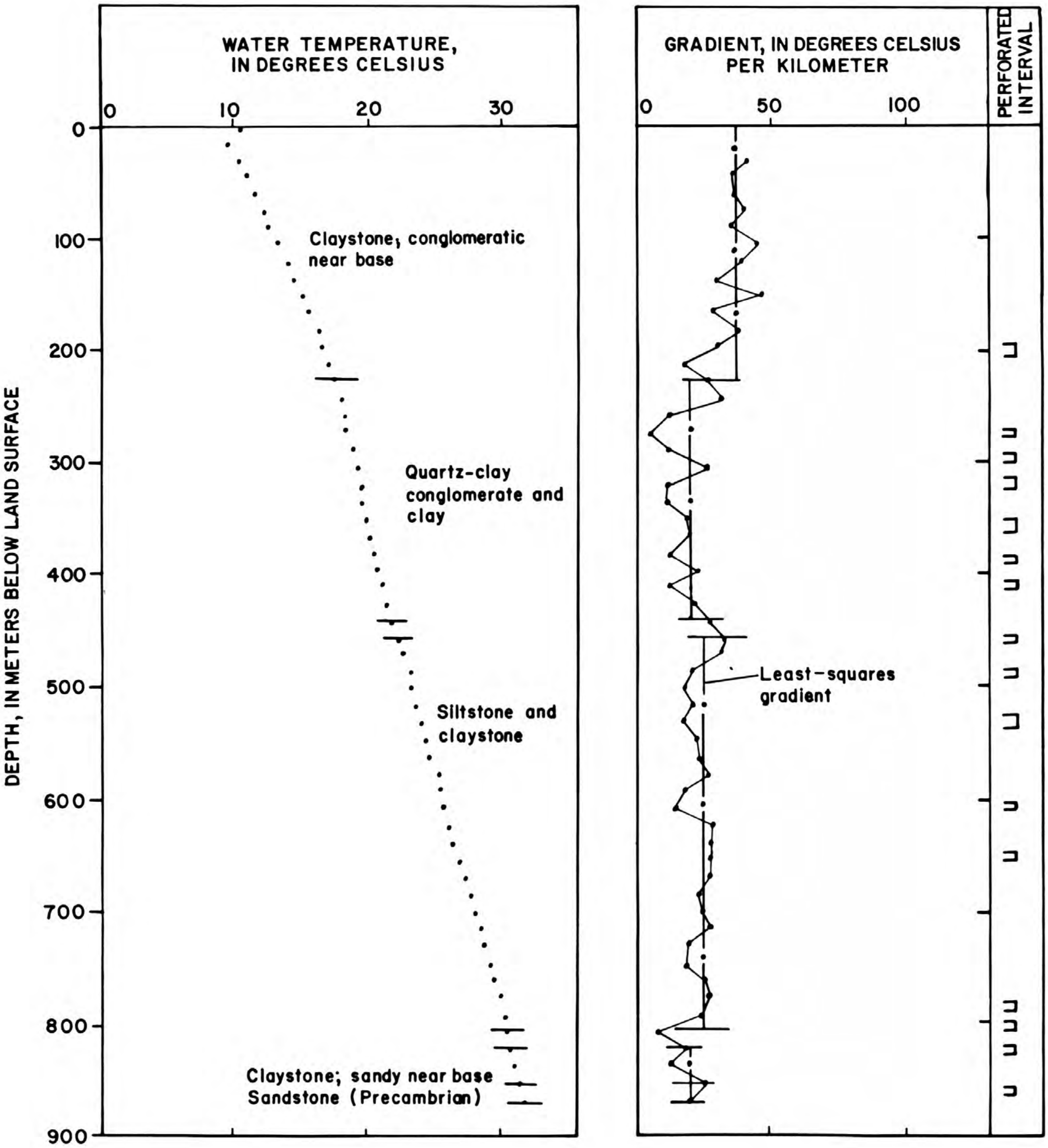

Figure 3.--Temperature profile, geothermal gradients, and lithologic summary for test hole 4. Lithology reported by Montana Bureau of Mines and Geology.

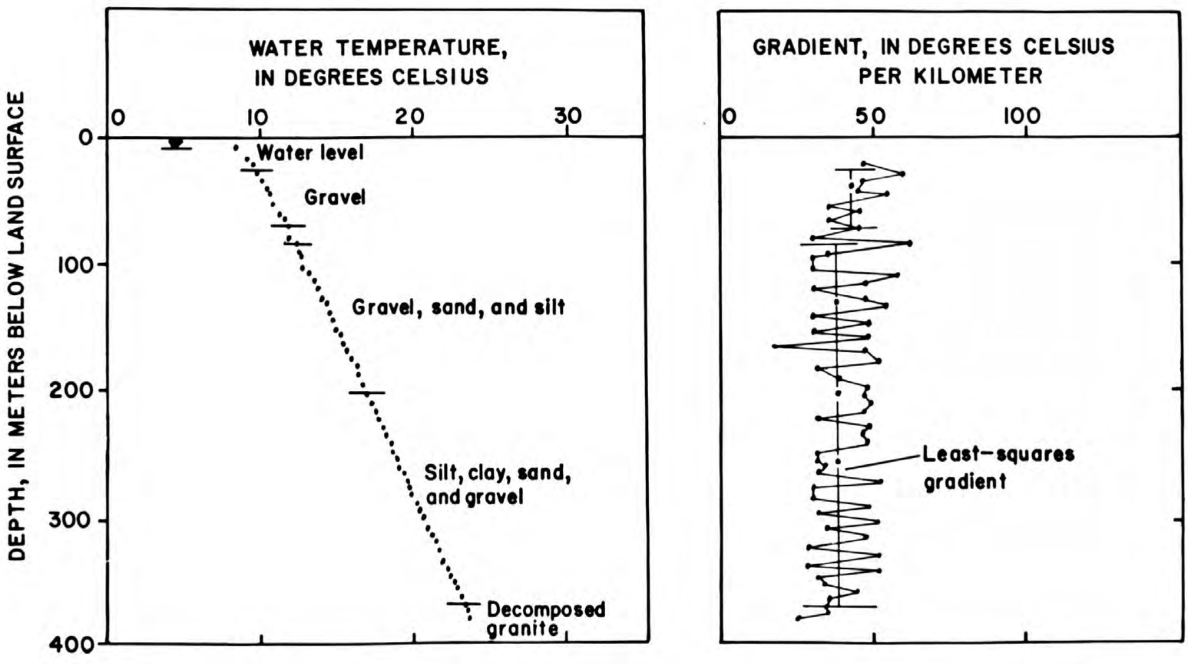

Figure 4.--Temperature profile, geothermal gradients, and lithologic summary for test hole 6. Lithology reported by Montana Bureau of Mines and Geology.

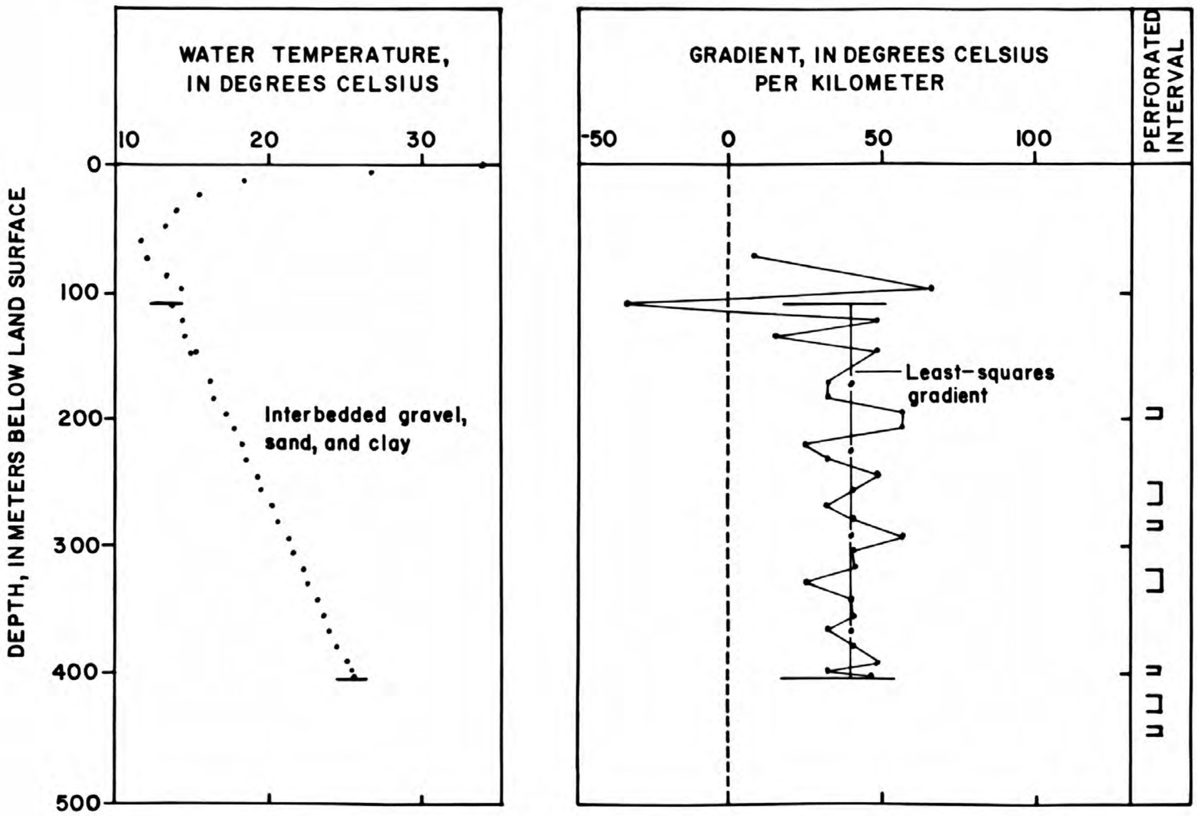

Figure 5.--Temperature profile, geothermal gradient, and lithologic summary for test hole 8. Lithology reported by Montana Bureau of Mines and Geology.

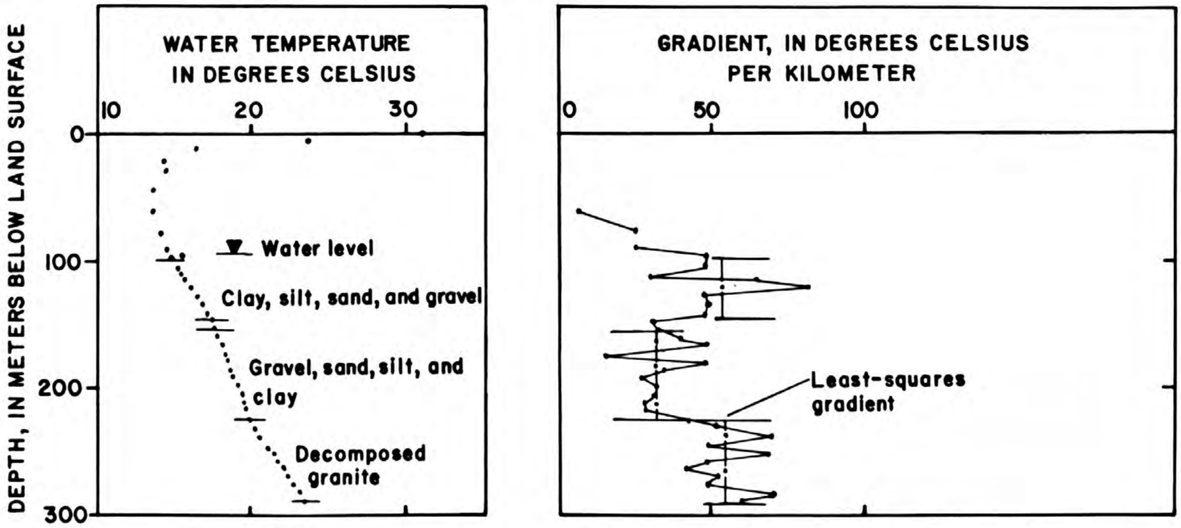

Figure 6.--Temperature profile, geothermal gradients, and lithologic summary for test hole 9. Lithology reported by Montana Bureau of Mines and Geology.

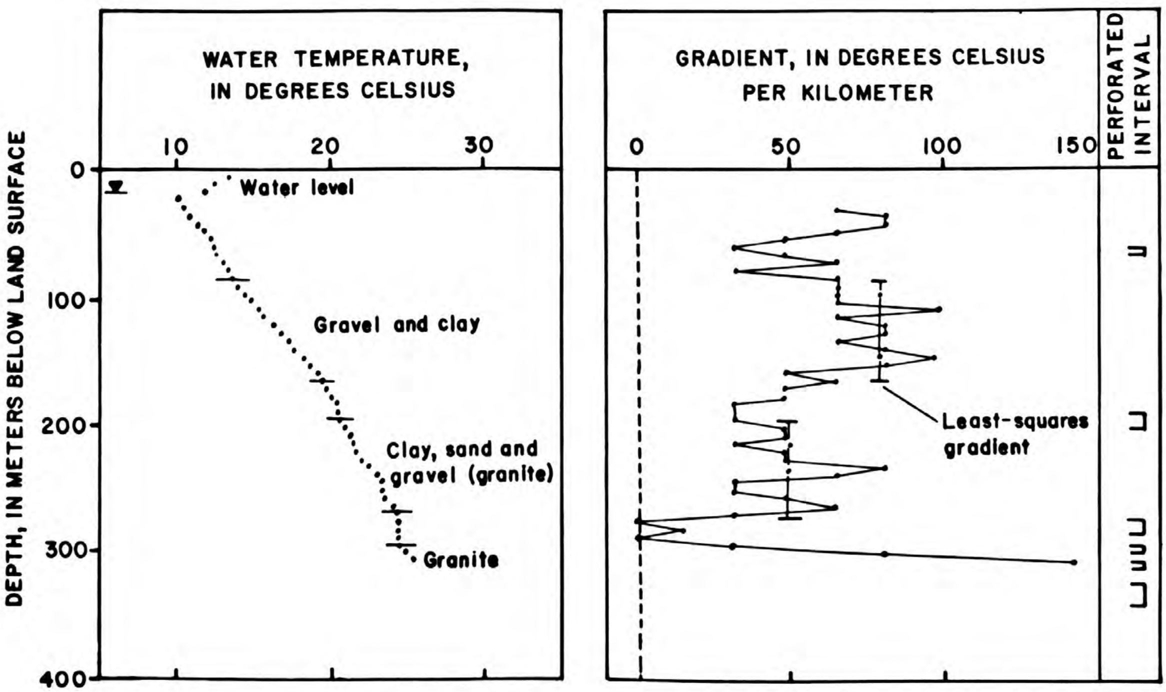

Figure 7.--Temperature profile, geothermal gradients, and lithologic summary for test hole 12. Lithology reported by Montana Bureau of Mines and Geology.

Heat flow

Regional heat flow in the area ranges from 1.5 to 2.5 HFU (heat flow units) (Sass and others, 1976); larger or smaller values can be considered anomalous. The rectilinearity of the temperature-depth profiles indicates vertical conductive heat flow through each of the major depth intervals. Vertical conductive heat flow can be calculated from the equation:

$$q = K \times G \times 10^{-2}, \tag{1}$$

where q is the heat flow, in heat flow units (1 HFU=1×10^{6} calories per square centimeter per second);

K is the thermal conductivity, in heat conductance units (1 HCU=1×10^{-3} calories per centimeter per second per degree Celsius); and

G is the geothermal gradient, in degrees Celsius per kilometer.

Rearranging:

$$K = \frac{q \times 10^{2}}{G}. \tag{2}$$

Blackwell and Chapman (1977) cite a K of about 3.5 HCU as representative of valley fill in the Basin and Range Province to the south, where the geothermal gradient is about 60°C/km and the normal regional heat flow is about 2 HFU. Although those values are not necessarily applicable to the study area, they are useful bases for comparison.

Most of the thermal gradients given in table 1 are less than 60°C; therefore, unless the thermal conductivity of the valley fill were larger than 3.5 HCU, heat flow would be less than 2.1 HFU, which is about the median reported regional heat flow for the study area.

Determinations of K from cuttings and cores, which are necessary for rigorous calculations of heat flow, have not been made as part of this study. Unless the wide variations in the geothermal gradients in the intervals between successive temperature measurements (shown in figs. 2-7) were caused by lateral movement of ground water, the thermal conductivity of individual layers of the stratified sediment also varies widely. Measurements of K for a large number of samples probably would be needed to obtain representative values of thermal conductivity for extended depth intervals. However, published values of K for the rock or soil penetrated in each of the test holes can be compared with K calculated from the measured gradients and the reported regional heat flow to approximately assess the probability of larger (or smaller) than normal heat flow. Indications of larger than normal heat flow might justify the additional effort required to obtain precise determinations of K.

Values of K calculated from equation 2 for q=2.0 and 2.5 HFU and generalized lithologic descriptions for major intervals are listed in table 1. Calculated values of K less than published values for similar lithologic types would suggest larger than normal heat flow that, in turn, might provide justification for more detailed study.

For example, the least-squares thermal gradient for the interval 227-692 m in test hole 2 in the Missoula Valley is 21.4°C/km. For regional heat flows of 2.0 and 2.5 HFU, the calculated K's are 9.4 and 11.7. According to Robertson (1979, fig. 9) values of K exceeding 9 are rare and applicable mainly to relatively impermeable saturated quartzose sandstones. Instead, the interval in test hole 2 is described as quartz and clay conglomerate. Even if K were 9 HCU, heat flow corresponding to the measured gradient would be less than 2 HFU. For a more reasonable K of 6 HCU (Robertson, 1979, fig. 2), the calculated heat flow would be less than 1.3 HFU.

For the interval 18.3-227.1 m in the same test hole, the calculated values of K are 6.0 and 7.4 for 2.0 and 2.5 HFU. The interval is described as predominantly claystone and siltstone for which a value of 5 HCU may be a generous estimate (Robertson, 1979, fig. 10). As part of a related study, values of K less than 4 were recently determined for apparently similar sediment at shallower depth from test holes in the Madison River valley. If K were 5 HCU, the heat flow represented by G=33.6°C/km would be 1.7 HFU.

The larger and generally increasing calculated values of K with depth probably reflect increasing compaction (solidity) and quartz content. Although the evidence does not support anomalously large heat flow in the vicinity of test holes 2 and 4 in the Missoula Valley, laboratory determinations of K for selected cores would be useful for comparison with the apparently excessive calculated values.

Calculated values of K (table 1) for test holes in the Bitterroot Valley generally are less than for the test holes in the Missoula Valley, but occur within the range of published estimates. Therefore, they do not indicate abnormal heat flow through the relatively unconsolidated sediment. The greatest weighted-mean gradient (58.2°C/km) for any of the holes was measured in test hole 12, located about 19.3 km northwest of Sleeping Child Hot Springs. The granitic bedrock, reportedly penetrated at a depth of about 292 m, might be continuous with the crystalline rock from which the springs issue. However, there is no evidence of hydrothermal discharge. Unless K for the overlying sediments exceeds typical values, no significant thermal anomaly is apparent.

SUMMARY

Temperatures measured in six cased test holes in the Missoula and Bitterroot Valleys generally increased with depth, reaching a maximum of 31.7°C at a depth of 869 m. Temperature-depth profiles of each test hole consist of straight-line segments, the intersections of which commonly correspond approximately with lithologic boundaries. The linearity of the segments indicates that a single (mean) value for the temperature gradient is representative of each major interval. Gradients for intervals between individual measurements vary widely, probably as a result of local lateral movement of ground water as well as vertical variations in lithology. However, linear coefficients of correlation between temperature and depth within each major interval exceed 0.99.

Least-squares gradients calculated for major depth intervals range from about 19 to 77°C/km. The geothermal gradients for most major intervals and the depth-weighted mean gradient for each test hole are less than 60°C/km. Geothermal gradients normally decreased with depth. Estimated temperatures at a depth of 1 km ranged from about 34°C in the Missoula Valley to about 63°C in the Bitterroot Valley. Temperatures exceeding 90°C probably would not occur at depths less than about 1,500 m beneath the test sites.

The linearity of the temperature-depth profiles indicates vertical heat flow through each of the major depth intervals. Apparent thermal conductivities (*K*) of the sediment calculated from the geothermal gradients for regional heat flow between 2.0 and 2.5 HFU are generally much larger at test sites in the Missoula Valley, and slightly larger in the Bitterroot Valley, than published values for similar soil and rock. Therefore, heat flow apparently is not greater than the assumed regional values and there in evidence of hydrothermal discharge. Increased apparent values of *K* with depth probably reflect increased compaction (solidity) and quartz content of the valley fill.

Laboratory determinations of the thermal conductivity of cores and cuttings from the test holes would be useful to refine estimates of temperature and heat flow and to test the conclusion that measured subsurface temperatures are not hotter than normal for the region. However, wide variations within small intervals of depth indicate that a large number of determinations would be required to obtain values representative of the penetrated sections.

REFERENCES

Blackwell, D. D., and Chapman, D. S., 1977, Interpretation of geothermal gradient and heat flow data for basin and range geothermal systems: Geothermal Resources Council Transactions, v. 1., p. 19-20.

Chadwick, R. A., and Leonard, R. B., 1979, Structural controls of hot-spring systems in southwestern Montana: U.S. Geological Survey Open-File Report 79-1333, 25 p.

Curry, W. E., 1977, Drilling plan for Missoula and Bitterroot Valleys, Montana: Bendix Field Engineering Corporation report, 20 p.

McMurtrey, R. G., Konizeski, R. L., and Brietkrietz, Alex, 1965, Geology and ground-water resources of the Missoula Basin, Montana: Montana Bureau of Mines and Geology Bulletin 47, 35 p.

McMurtrey, R. G., Konizeski, R. L., Johnson, M. V., and Bartells, J. V., 1972, Geology and water resources of the Bitterroot Valley, southwestern Montana, *with a section on* Chemical quality of water, by H. A. Swenson: U.S. Geological Survey Water-Supply Paper 1889, 80 p.

Pardee, J. T., 1950, Late Cenozoic block faulting in western Montana: Geological Society of America Bulletin, v. 61, p. 359-406.

Robertson, E. C., 1979, Thermal conductivities of rocks: U.S. Geological Survey Open-File Report 79-356, 31 p.

Ross, C. P., Andrews, D. A., and Witkind, I. J., 1955, Geologic map of Montana: Scale 1:500,000 (reprinted 1958).

Sass, J. H., Diment, W. H., Lachenbruch, A. H., Marshall, B. V., Munroe, R. J., Moses, T. H., Jr., and Urban, T. C., 1976, A new heat-flow contour map of the conterminous United States, 1976: U.S. Geological Survey Open-File Report 76-756, 24 p.

Weidman, R. W., 1965, The Montana Lineament: Billings Geological Society Guidebook, 16th Annual Field Conference, p. 137-143.

Table 1.--*Depths, geothermal gradients, estimated temperatures, and calculated*

[m = meter; mm = millimeter; °C = degrees Celsius; °C/km = degree Celsius per kilometer;

Test-hole number	Location	Total depth (m)	Casing depth (m)	Casing diameter (mm)	Date cased	Date bailed or filled	Date temperature logged	Depth interval logged top (m)	Depth interval logged base (m)
2	15N21W17CCC (lat 470310, long 1141725)	766.9	731.5	102	10/27/78	2/20/79	11/08/78	18.3	227.1
								227.1	691.9
								18.3	691.9
4	14N20W24ABDC (lat 465737, long 1140347)	886.1	872.6	102	8/29/78	2/05/79	11/08/78	14.9	228.6
								243.8	442.3
								457.2	807.4
								823.0	868.7
								14.9	868.7
6	10N20W32DDBA (lat 463435, long 1140757)	529.1	529.1	51	12/04/78	4/07/79	5/21/79	29.0	71.3
								84.1	375.8
								29.0	375.8
8	09N19W06BAAC (lat 463434, long 1140213)	830.0	800.7	102	--	1/20/79	7/23/78	109.7	401.4
9	10N19W26BBB (lat 463605, long 1135734)	313.9	313.9	51	12/13/78	4/08/79	5/22/79	97.8	147.5
								153.6	225.6
								225.6	285.6
								97.8	285.6
12	06N20W14BBBB (lat 461659, long 1140409)	338.3	338.3	102	04/06/79	6/30/79	7/12/79	85.3	164.6
								195.1	268.2
								85.3	268.2

thermal conductivities for test holes

HCU = heat conductance units; HFU = heat flow units]

Temperature at base (°C)	Least-squares thermal gradient (G) (°C/km)	Coefficient of correlation (r)	Y intercept (°C)	Weighted mean thermal gradient (°C/km)	Estimated temperature @ depth of 1 km (°C)	Estimated depth for temperature of 90°C (m)	Calculated thermal conductivity, K, in HCU for heat flow of: 2.0 HFU	2.5 HFU
--	33.6	0.999	9.9	--	--	--	6.0	7.4
27.4	21.4	.999	12.9	--	34.0	3,620	9.4	11.7
--	--	--	--	25.1	--	--	8.0	9.9
--	36.7	.998	9.5	--	--	--	5.4	6.8
--	19.0	.997	13.4	--	--	--	10.5	13.2
--	23.7	.999	11.5	--	--	--	8.4	10.6
31.7	20.3	.994	14.0	--	34.4	3,740	9.8	12.3
--	--	--	--	25.8	--	--	7.8	9.7
--	44.6	.999	8.5	--	--	--	4.5	5.6
23.7	39.3	.999	9.0	--	48.2	2,060	5.1	6.4
--	--	--	--	40.0	--	--	5.0	6.2
25.5	40.4	.999	9.3	40.4	49.7	2,000	5.0	6.2
--	53.2	.996	9.6	--	--	--	3.8	4.7
--	33.6	.998	12.4	--	--	--	6.0	7.4
23.4	55.4	.999	7.5	--	63.0	1,490	3.6	4.5
--	--	--	--	46.1	--	--	4.3	5.4
--	76.8	.999	6.9	--	--	--	2.6	3.2
24.3	51.0	.998	10.8	--	61.3	1,570	4.0	4.9
--	--	--	--	58.2	--	--	3.4	4.3