RESULTS OF THE 1988 GEOTHERMAL GRADIENT TEST DRILLING PROJECT FOR THE STATE OF WASHINGTON

by

DOUGLAS B. BARNETT

and

MICHAEL A. KOROSEC

WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES

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Division of Geology and Earth Resources standards and nomenclature

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CONTENTS

	Page
Introduction	1
Geologic settings of drill sites	2
Procedures	6
Results	8
Carlton Creek (DNR 88-1)	8
Snyder Mountain (DNR 88-2)	9
Chambers Creek (DNR 88-3)	9
Table Mountain (DNR 88-4)	10
Babyshoe Ridge (DNR 88-5)	11
Pin Creek (DNR 88-6)	12
Quartz Creek (DNR 88-7)	12
Shingle Mountain (DNR 88-8)	13
Discussion	31
Heat flow estimates	31
Geothermal potential of the southern Washington Cascade Range	32
Conclusions	34
References cited	35
Appendix A - Lithologic logs for the 1988 drill holes	38

ILLUSTRATIONS

Figure 1	Locations of the 1988 geothermal gradient test holes	3
Figure 2	Schematic representation of construction details for the 1988 geothermal gradient test wells	7
Figure 3	Carlton Creek gradient profile	15
Figure 4	Snyder Mountain gradient profile	17
Figure 5	Chambers Creek gradient profile	19
Figure 6	Table Mountain gradient profile	21
Figure 7	Babyshoe Ridge gradient profile	23
Figure 8	Pin Creek gradient profile	25
Figure 9	Quartz Creek gradient profile	27
Figure 10	Shingle Mountain gradient profile	29
Figure 11	Zone of high temperature gradients in the southern Washington Cascade Range	33

TABLES

		Page
Table 1	Geothermal drilling projects of the Washington Division of Geology and Earth Resources.....	1
Table 2	Data summary for 1988 drill holes.....	4
Table 3	Carlton Creek temperature-vs.-depth data.....	16
Table 4	Snyder Mountain temperature-vs.-depth data.....	18
Table 5	Chambers Creek temperature-vs.-depth data.....	20
Table 6	Table Mountain temperature-vs.-depth data.....	22
Table 7	Babyshoe Ridge temperature-vs.-depth data.....	24
Table 8	Pin Creek temperature-vs.-depth data.....	26
Table 9	Quartz Creek temperature-vs.-depth data.....	28
Table 10	Shingle Mountain temperature-vs.-depth data.....	30
Table 11	Estimated heat flow values.....	31

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INTRODUCTION

During late summer and early fall of 1988, the Washington Department of Natural Resources, Division of Geology and Earth Resources (DGER) completed drilling eight shallow geothermal gradient test wells in the southern Washington Cascade Range. This report describes the preliminary results of the 1988 drilling and gradient measuring, and summarizes our current perspectives on distribution and magnitude of the geothermal resource potential in the southern Washington Cascades.

The 1988 project was the sixth of its kind undertaken by DGER since 1975 (Table 1). The major funding for the 1988 and 4 of the earlier projects was provided by the U.S. Department of Energy (Grant No. DE-FG07-88ID12740 for 1988), with subordinate cost sharing by the State of Washington. The results of the past projects, along with other geothermal exploration projects, are described in Schuster and others (1978), Schuster and Korosec (1981), Korosec and Schuster (1981) Korosec and others (1983), Korosec (1983, 1984), and Barnett (1986).

Table 1

Geothermal Drilling Projects of the Washington Division of Geology and Earth Resources

Year	Number of holes drilled	Reference
1975	5	Schuster and others, 1978
1979	11	Korosec and Schuster, 1981

Table 1. (continued)

Year	Number of holes drilled	Reference
1981	11	Schuster and Korosec, 1981
1983	3	Korosec, 1983
1985	7	Barnett, 1986
1988	8	This report

Additional temperature gradient information for the state is provided by Blackwell (1980), Korosec and Schuster (1981), Korosec and others (1982, 1983), Stoffel and Widness (1983), and Blackwell and others (1985).

GEOLOGIC SETTING OF DRILL SITES

All eight holes of the 1988 project were drilled in the Gifford Pinchot National Forest in Lewis and Skamania Counties (Fig. 1). The holes were sited to test areas of the range where heat flow data were still lacking, and to further investigate structural trends or heat-flow anomalies that were partially tested in earlier drilling projects. Regional geology for the areas surrounding the drill sites is presented in Korosec (1987a, 1987b) and Schasse (1987). Specific locations of the sites are given in Table 2.

The Carlton Creek hole (DNR 88-1) is located near Quaternary basalt and basaltic andesite vents on the western edge of the Pliocene and Pleistocene volcanic field of White Pass and Tumac Mountain. This is also near a fault defined by the trend of Carlton Creek. The predominant country rock is lower Oligocene volcaniclastic rocks of the Ohanapecosh Formation. Two probable Quaternary vents, previously unrecognized, were mapped in the area in 1988 during field work leading to the selection of the drill site.

The Snyder Mountain hole (DNR 88-2) is located in a previously untested area adjacent to the Pliocene and Pleistocene volcanic field of the Goat Rocks. The site is 13 km south of the

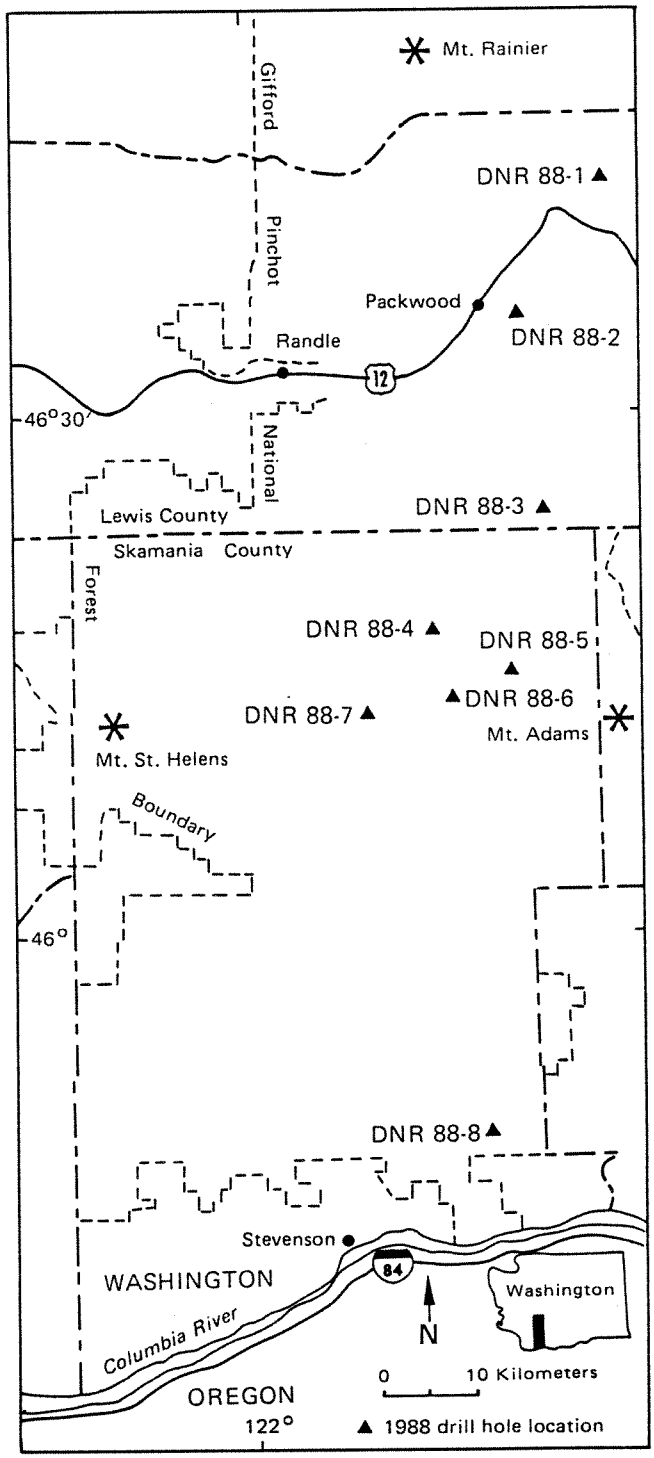


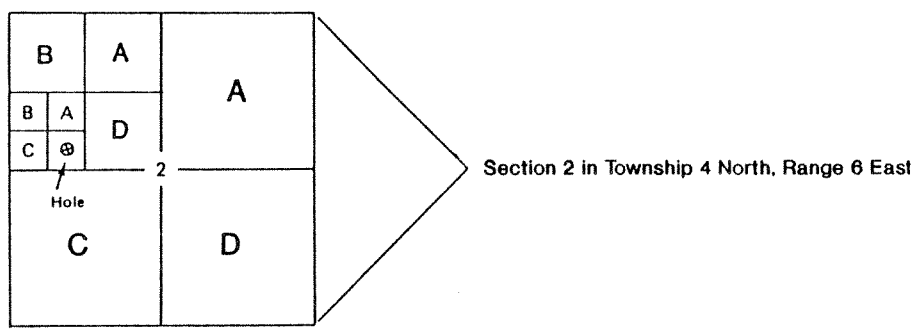
Figure 1. Locations of the geothermal gradient test holes drilled in 1988. Refer to Table 2 for more specific locations.

Table 2. Data summary for 1988 drill holes.

Hole name	Location T., R., sec.	Date completed	Date of last temperature logging	Total depth (meters)	Gradient (°C/km)* / Interval of measurement (meters)	Bottom-hole temperature (°C)
Carlton Creek (DNR 88-1)	T.14N.,R.10E. sec. 11, AAC	9-16-88	11-9-88	152.2	51.7 / 25.0-152.2	13.4
Snyder Mountain (DNR 88-2)	T.13N.,R.9E. sec. 24, ADD	9-27-88	9-30-88	152.4	**	4.5
Chambers Creek (DNR 88-3)	T.11N.,R.10E. sec. 35, BCD	10-4-88	11-9-88	152.3	58.9 / 45.0-152.3	13.3
Table Mountain (DNR 88-4)	T.9N.,R.9E. sec. 5, ADC	10-11-88	11-9-88	152.3	56.9 / 35.0-152.3	12.8
Babyshoe Ridge (DNR 88-5)	T.9N.,R.10E. sec. 18, BCD	10-18-88	10-24-88	152.6	**	5.1
Pin Creek (DNR 88-6)	T.9N.,R.9E. sec. 34, ADD	10-25-88	11-9-88	152.5	49.7 / 35.0-152.5	11.8
Quartz Creek (DNR 88-7)	T.8N.,R.8E. sec. 8, BBC	10-31-88	11-9-88	152.5	31.2 / 30.0-152.5; 35.1 / 100.00-152.5	10.1
Shingle Mountain (DNR 88-8)	T.4N.,R.9E. sec. 27, CBB	11-8-88	11-17-88	152.6	35.3 / 55.0-152.6	12.9

*Derived from best-fit line of linear regression analysis
**Disturbed gradient or isothermal

Example description for hole locations given in Table 2



Correct location description for the hole shown in the above example is: 4N., 6E., Sec. 2, BCD

Ohanapecosh drill hole of 1979, which yielded a geothermal gradient of 46°C/km. The deeply eroded vent area and most of the flows of the Goat Rocks are located in the Goat Rocks Wilderness Area. This required that test drilling be located outside the restricted area, where Miocene hypabyssal andesites have extensively intruded the Oligocene Ohanapecosh Formation.

The Chambers Creek hole (DNR 88-3) lies just west of a region of Quaternary andesite and basalt vents and flows at the interpreted northern extent of the Mount Adams volcanic trend (Hammond and Korosec, 1983). Most of these eruptive centers are known to be monogenetic, but they otherwise lack detailed descriptions. The nearest large Quaternary volcanic edifice is the Walupt Lake volcano about 4 km to the east. At the drill site, Eocene continental sedimentary rock is exposed along an anticlinal axis. The regional geology of the Chambers Creek area is presented in more detail by Korosec (1987a).

The Table Mountain hole (DNR 88-4) is located near the projection of a north-trending fault that is coincident with the Indian Heaven fissure zone to the south. The country rock is primarily upper Oligocene Ohanapecosh Formation, lower Miocene tuffaceous rocks, and andesite flows of the Council Bluff formation (Korosec, 1987a). The hole is also 5 km south of the Spud Hill hole (DNR 85-2) drilled in 1985 (Barnett, 1986). The Spud Hill hole, which is also along the Indian Heaven structural trend, is 152 m deep and produced a gradient of 72°C/km.

The Babyshoe Ridge hole (DNR 88-5) was drilled in an intensely silicified shear zone that parallels and may be homothetic to the Table Mountain-Spud Hill fault system. The shear zone cuts andesite flows and pyroclastic rocks of the Council Bluff formation. The hole is about 1 km WNW of flows from the Mount Adams volcano and 10 km from the summit crater.

The Pin Creek hole (DNR 88-6) is situated amid minor fault zones that are associated with the Spud Hill-Table Mountain trend. The faults cut andesitic flows and volcaniclastic rocks of the Council Bluff formation and are inferred to extend south into the main body of the Indian Heaven volcanic field. Exposures of rock near the drill site display a moderate degree of disruption and brecciation. Interstices between clasts and other voids are typically filled with zeolites and clay. The Pin Creek hole is within 2 km of areas that had pending geothermal lease applications by private industry at the time of the drilling project.

The Quartz Creek hole (DNR 88-7) is in an area of isolated Quaternary basalt vents north of the Indian Heaven volcanoes and within a NNW-trending mineralized fissure system of Miocene or younger age. The fissure system has not been mapped as a fault by previous workers in this area, but field work during 1988

indicates that a broad area of hydrothermal alteration is present and is possibly related to a major shear zone or fault intersection. Unaltered country rock away from the fissure system consists of lower Miocene tuffaceous volcaniclastic rocks, and may be correlative to the Stevens Ridge Formation.

The Shingle Mountain hole (DNR 88-8) lies about 2 km north of the trace of the Little Wind River fault (site of several thermal springs) near the Columbia River Gorge in a broad area that had remained untested until 1988. Access to the fault by drilling equipment is limited because most of the area south of the drill site lies within the Columbia Gorge National Scenic Area. The country rock consists of layered volcaniclastic and epiclastic rocks of Oligocene or Miocene age, and contains minor coal-bearing horizons.

PROCEDURES

Seven holes of the 1988 project were drilled to the target depth of 152 m. Babyshoe Ridge (DNR 88-5) was drilled to 158 m to create a sump for caving borehole materials originating from near the 100-m level of this hole. A Chicago Pneumatic 7000 rotary drill was used with an air and mist drilling fluid. In each hole, poorly consolidated surficial materials and regolith were penetrated using an 6-in.-diameter roller bit. Six-in. steel surface casing was driven through the unconsolidated surface layers by a pneumatic hammer and an impact plate placed on top of the section of casing being driven. The remainder of the hole was then drilled with a down-hole pneumatic hammer and a 6-in.-diameter button bit combination. Biodegradable surfactants such as "Orvus K" were added to drilling water as a deflocculant in clay-rich portions of the holes. Lithologic samples were collected at 5-ft (1.5 m) intervals.

Figure 2 is a schematic diagram of the typical geothermal gradient test well construction for the 1988 project. Following the completion of drilling, the drill rods were extracted and 1-1/2-in. steel pipe was installed from the surface to total depth. After insertion, the pipe was filled with water and welded to the surface casing, suspending it within the hole. The water-filled pipe serves as a stable observation conduit for temperature gradient measurements. These readings were taken after the hole had been completed and the system allowed to equilibrate with the local thermal regime. Particular care was necessary during sealing procedures to ensure that any intrabore flow of water was effectively stemmed. To accomplish this, a 1-in. tremie was inserted into the annulus to total depth, the upper end of the tremie connected to a mud pump, and the sealing mixture (either cement or bentonite) pumped in from the bottom of the hole. As the hole filled with sealant, the tremie was withdrawn in stages,

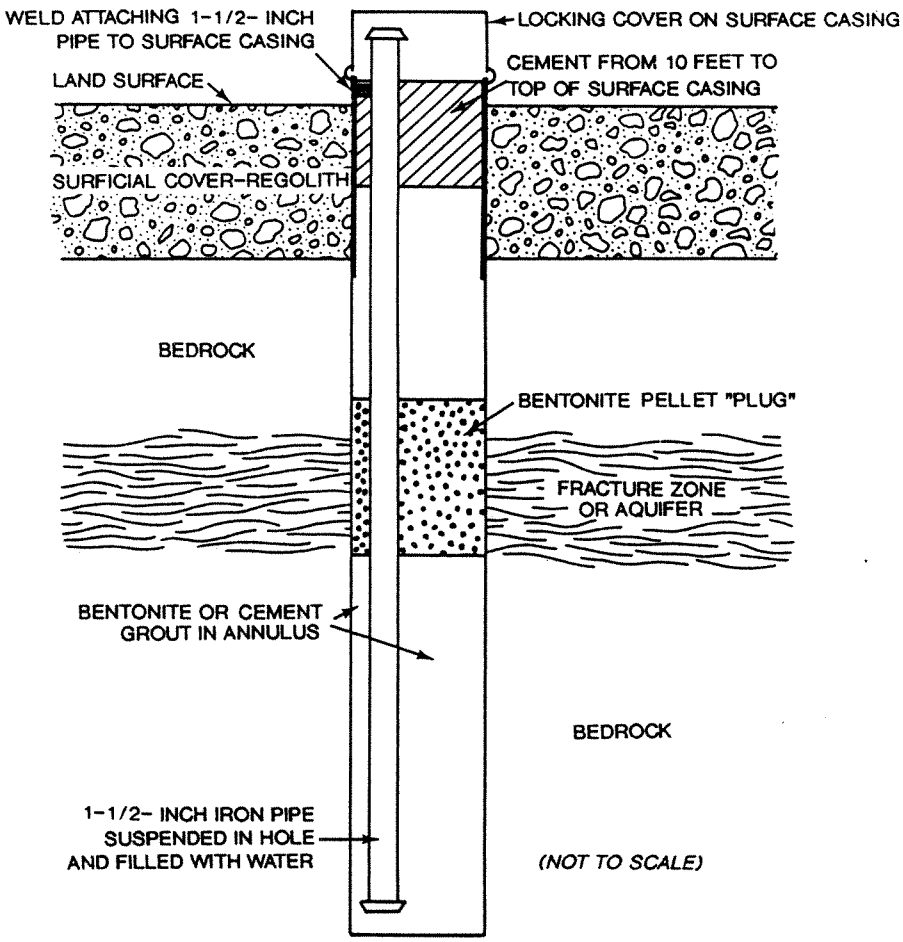


Figure 2. Schematic representation of construction details for the geothermal gradient test wells drilled in 1988. The 1-1/2-in. pipe is suspended from the surface casing to eliminate bends in the pipe that could hinder probe passage.

so that the lower orifice of the tremie was near the portion of the hole being filled, yet still below the surface of the rising fluid column. Occasionally, a severely fractured stratum or an aquifer having a high hydraulic head was encountered in the hole. To counter these conditions, bentonite pellet "plugs" were emplaced at the level of the problem, or cement was pumped into the hole and allowed to cure overnight before resumption of sealing procedures. When sealing was complete, a locking surface security cap was attached to the 6-in. surface casing for the protection of the 1-1/2-in. pipe. Time required for the drilling and construction of a test well averaged approximately 5 days.

Following sealing, the borehole-pipe system was given 2 to 3 weeks to assimilate the natural thermal character of the area. A down-hole temperature probe was then lowered into the water-filled 1-1/2-in. pipe. Readings were taken from the top to bottom of the hole at 5-m intervals in each hole. Repeated loggings with the temperature probe at about 1-week intervals usually revealed the thermal equilibrium status of the hole through the comparison of temperature-vs.-depth graphs from the separate logging sessions. A hole was assumed to be near equilibrium when no perceptible change was observed in the graphs from two successive loggings. Temperature gradients were calculated using the direct measurements and linear regression analysis for the relatively undisturbed values below the zone of seasonal influence. This zone of fluctuating temperatures usually occurs at depths of 0-50 m, but this varies with location.

RESULTS

Details of the lithologies encountered during the drilling of the 1988 test holes are given in Appendix A.

The temperature-vs.-depth profiles in Figures 3 through 10 display the actual temperature values ("Temp. (^{o}C)") that were measured, and the best-fit, linear regression estimates in the column labeled "Predicted (^{o}C)." A summary of parameters for the 1988 temperature gradient test holes is presented in Table 2. Temperature observations for individual holes are listed in Tables 3 through 10.

The following descriptions summarize the geologic, hydrogeologic, and thermal conditions encountered during drilling and subsequent temperature measurements for each hole.

Carlton Creek (DNR 88-1)

Although sited within 100 m of a probable Quaternary basalt plug, the rock materials penetrated by this hole consist mostly of felsite or felsic tuffs. Thin volcaniclastic and epiclastic

layers are intercalated with the flows and tuffs down to the 110-m level. Below this point, the rock type is predominantly felsite, but is more andesitic near the bottom of the hole. The felsite and andesite invariably show weak to strong hydrothermal phyllic, to advanced argillic alteration. Disseminated pyrite is also common in the altered horizons.

A significant aquifer was encountered at approximately 80 m producing about 20 gpm during the drilling. When drilling had been completed and drill rods removed, water was flowing at the surface at the rate of about 0.5 gpm. This flow was effectively shut off by cementing most of the hole after the 1-1/2-in. pipe was installed.

The temperature-vs.-depth profile for this hole is presented in Figure 3. The straight-line gradient from the linear regression analysis over the interval 25 m to 152 m (T.D.) is 51.7°C/km. The aquifer intercepted at about 80 m apparently imparts a slightly higher gradient to the interval of 25 m to 70 m. The gradient over this interval, calculated from direct measurements, is 51.8°C/km.

Snyder Mountain (DNR 88-2)

This hole was drilled entirely within a Miocene porphyritic andesite flow or hypabyssal intrusion. The section may be a series of flows, as suggested by the presence of saprolitic, Fe oxide-rich horizons that resemble weathered surfaces of flow tops. No water table or confined aquifers were encountered in this hole, but severe fracturing is ubiquitous. Considerable difficulty was experienced in trying to seal the hole because of the numerous large voids. Several hole-volumes of cement and bentonite along with bentonite pellet "plugs" were required to fill and effectively seal the hole.

The temperature-vs.-depth profile (Fig. 4) indicates the geothermal gradient is isothermal to at least 152 m at this location. Cold air and downward-percolating meteoric water in fractures have served to uncouple this area from the true crustal conductive heat flow. It may be part of a large, ancient block slide. Investigations of the area prior to drilling did not indicate such conditions would be encountered.

Chambers Creek (DNR 88-3)

After being cased through 5 m of glacial drift, the Chambers Creek hole was drilled in a section of epiclastic sedimentary rock characterized by arkosic to subarkosic sandstone with

intercalated carbonaceous claystone and siltstone horizons. Some of the finer grained horizons contain thin coal layers and abundant carbonaceous debris. Andesite and basalt sills and a felsic dike were also encountered and, in places, have imparted a baked contact to the enclosing sediments. Slickensides were noted at the 100-m level, possibly indicating some minor faulting in the area. This section of rock has been mapped as Eocene continental sediments by Korosec (1987a).

Two substantial aquifers, producing a combined discharge of approximately 200 gpm during drilling, were encountered at depths of 55 m and 72 m. The interception of these two zones resulted in a static water level of 15 m. Despite the fairly voluminous water production during drilling, no extraordinary difficulty was experienced during the sealing of the hole.

The temperature-vs.-depth profile for the Chambers Creek hole is presented in Figure 5. From 45 m to the total depth of 152 m, the best-fit, straight-line gradient, derived through linear regression, is 58.9°C/km. This gradient was the highest observed during the 1988 project. From inspection of the profile, it appears that there may be an additional aquifer at 120 m that separates a segment of higher gradient (between about 45 m and 115 m) from a segment of lower gradient (below the 120 m level). Three or four short, individual segments within the 45-to-115-m interval may reflect either isolated sandstone aquifers, each having unique temperature character, or differences in thermal conductivity of the lithologic units.

Table Mountain (DNR 88-4)

The blue-green pyroclastic and volcaniclastic rocks typical of the Oligocene Ohanapecosh Formation were the exclusive lithologies encountered in this hole. Volcanic agglomerate and volcanic wacke are the most abundant lithologic types, but they are separated by minor horizons of claystone, tuff, and tuff breccia.

Minor aquifers at 18 m and 87 m produced a discharge of about 30-35 gpm during drilling, and a static water level of 53 m upon cessation of drilling. Several hole volumes of grout and four bentonite pellet plugs were required to seal the severely fractured rock believed to be associated with the aquifers.

The best-fit, straight-line gradient for the Table Mountain data, shown in Figure 6, is 56.9°C/km over the interval between 35 m and 152.3 m (T.D.). Presumably, because of relative uniformity in the rock (and therefore, thermal conductivity), and lack of disturbances from aquifers, there is a conspicuous absence of perturbations in the temperature-vs.-depth profile.

This is reflected in the high correlation coefficient in the linear regression analysis.

Babyshoe Ridge (DNR 88-5)

This hole is located in a U.S. Forest Service borrow pit that exposes a large, silicified fault zone. The fault was first mapped by Harle (1974), who placed it about 0.5 km west of the drill site. It is likely that there are numerous fault planes or homothetic fault segments in the immediate area of the drill hole. Fracture foliation and mullion surfaces indicate that the fault strikes NNE and dips steeply SE to nearly vertical at this location. In places along the borrow pit exposure is a replacement banding texture that is mostly coplanar with the general orientation of the fault. The banding suggests an outward pervasion of reactive fluids from the fractures into the wall rock. Most of the exposure is strongly silicified, and Fe oxides are abundant as open-space fillings. Some parts of the pit expose a breccia consisting of Fe oxide-cemented clasts as much as several centimeters across. In other areas of the exposure, the rock is less silicified, but displays strong argillic alteration. Although the original texture of the host rock is not discernable in any part of the pit exposure, geologic mapping in the surrounding area indicates that the unaltered, original rock type is probably andesite flows of the early Miocene Council Bluff formation (Korosec, 1987a).

The original lithologies of many of the rock samples logged for the first 60 m of the hole are largely unrecognizable because of ubiquitous silicification and argillic alteration. Below 60 m, some of the material is identifiable as mostly andesite or basalt with somewhat less alteration. Hematite and goethite are common as replacement minerals and open-space fillings throughout the extent of the hole. Nowhere were fresh sulfides observed.

Significant aquifers were intercepted at 30.5 m, 61.0 m, and 140.2 m. Because of numerous fractures and probable thief zones in the hole, it is difficult to estimate the combined water production from these zones. Discharge rates would fall off as drilling progressed past water-producing zones, until the next aquifer was encountered. Water production, while drilling, was down to 75 to 80 gpm after the lowest aquifer was reached at 140.2 m. The static water level was 32 m the day after the drilling stopped.

At the time of the last logging (October 24, 1988), the Babyshoe Ridge hole had not reached equilibrium. This is evident by the two conspicuously high temperature readings at the 100 m and 120 m levels on the temperature-vs.-depth curve (Fig. 7). The two anomalies are the result of cement pumped into the hole

which is filling substantial cavities at these levels. The cement was still curing at the time of the logging, and the elevated temperature was a result of the thermochemical reactions. Fracturing and consequent void space allowed the pooling of greater amounts of cement in the 100 m and 120 m horizons. Beginning at the base of the zone of seasonal influence, at about 35 m, the best-fit, straight-line gradient from 35 m to 152.6 m (T.D.) is 2.8°C/km. Because there was still heat generation from the exothermic reaction of cement at the time of the last logging, and many of the temperature readings may be artificially high, it is likely that the equilibrated gradient will be nearly isothermal. The hole did not reach below the zone of infiltrating, cold meteoric water.

Pin Creek (DNR 88-6)

The 152-m section penetrated by this hole consists mostly of layers of andesitic-to-basaltic pyroclastic rock with interlayered sills or flows. Some fractured horizons were encountered, and most of these contained abundant zeolites as cavity fillings. Because of the lack of severe fracturing and the abundance of clay, no problems with water incursion were encountered.

The static water level stabilized at 55 m the day after drilling had ceased, even though the only measurable amount of water production (about 1 gpm during drilling) was detected near the bottom of the hole. These conditions indicate an aquifer of low transmissivity but relatively high hydraulic head. However, no difficulty was experienced in sealing the hole.

The temperature-vs.-depth profile for this hole is presented in Figure 8. The best-fit, straight-line gradient for the interval 35 m to 152.5 m (T.D.) is 49.7°C/km. The gradient slightly, but abruptly, increases near the 100 m level, then decreases slightly at 145 m to the bottom of the hole. This probably reflects differences in thermal conductivity of the rocks at these levels.

Quartz Creek (DNR 88-7)

Felsite and felsic tuff constitute the dominant rock types penetrated by this hole to the total depth of 152.5 m. The hole was spudded in a zone known to contain hydrothermal alteration and sulfide replacement mineralization. Outcrops several meters northwest and northeast of the drill site consist of argillically-altered felsic tuff that contains pyrite and quartz veins, and locally appears brecciated. Slickensides and mullion

were observed in a road exposure about 0.5 km northwest of the drill site.

Weak to intense hydrothermal alteration obscures most original rock textures throughout the hole. Argillic and phyllic alteration is observed in most of the rock cuttings, and disseminated pyrite occurs in varied concentrations in all but a few thin horizons. Judging from the orientations of quartz veins (fissures?) and fractures in nearby outcrops, the drill-hole probably intercepts the plane of the mineralized, altered zone at a small angle.

No significant aquifers were encountered during the drilling, but the static water level had reached 5 m by the morning after drilling was complete. As in the Pin Creek hole, the transmissivity is interpreted to be low because of the lithologies encountered (clays), and because little water was produced during drilling. The hydraulic head was sufficient to produce a high static water level in the hole when no pumping (drilling) was occurring.

The calculated gradient for DNR 88-7 from 30 m to 152.5 m (T.D.) as derived from direct measurements is 31.3^{o}C/km. The gradient over the same interval using the best-fit, linear regression calculation is 31.2^{o}C/km. Evidence of a higher gradient is seen over the last 52.5 m of the hole, where calculations from the direct measurements yield 35.1^{o}C/km.

Shingle Mountain (DNR 88-8)

This hole was drilled in a section of upper Oligocene strata dominated by andesitic, tuffaceous volcaniclastic and epiclastic rocks. The unit is widespread throughout the southern Washington Cascade Range, and it may be partially correlative to the upper parts of the more silicic Ohanapecosh Formation (Korosec, 1987b). The lithologies encountered during drilling are mostly tuff, tuffaceous sandstone, or volcanic wacke. One very thin coal horizon was intercepted near the 60-m level.

No significant water production was observed during drilling. However, the day following the cessation of drilling, water was flowing from the hole at a rate of 1 to 2 gpm. This strongly indicates low transmissivity (or low permeability) and high head conditions. Because of the possibility of a high-pressure head, several bentonite pellet plugs were emplaced, and one cemented section was allowed to cure overnight before continuing the sealing.

The temperature-vs.-depth graph for the Shingle Mountain hole is presented in Figure 10. From what appears to be the base

of the layer of surface convective influence (at approximately 55 m) to the total depth of 152.6 m, the geothermal gradient calculated from direct measurements is 35.0°C/km. Over the same interval, the linear regression estimate yields a gradient of 35.3°C/km. However, at the time of the last logging, only a few days had elapsed since drilling. For this reason, and because of the numerous irregularities that are visible in the temperature-vs.-depth profile, it is suspected that the hole probably had not reached a state of thermal equilibrium. These early measurements may represent minimum gradient values for the area.

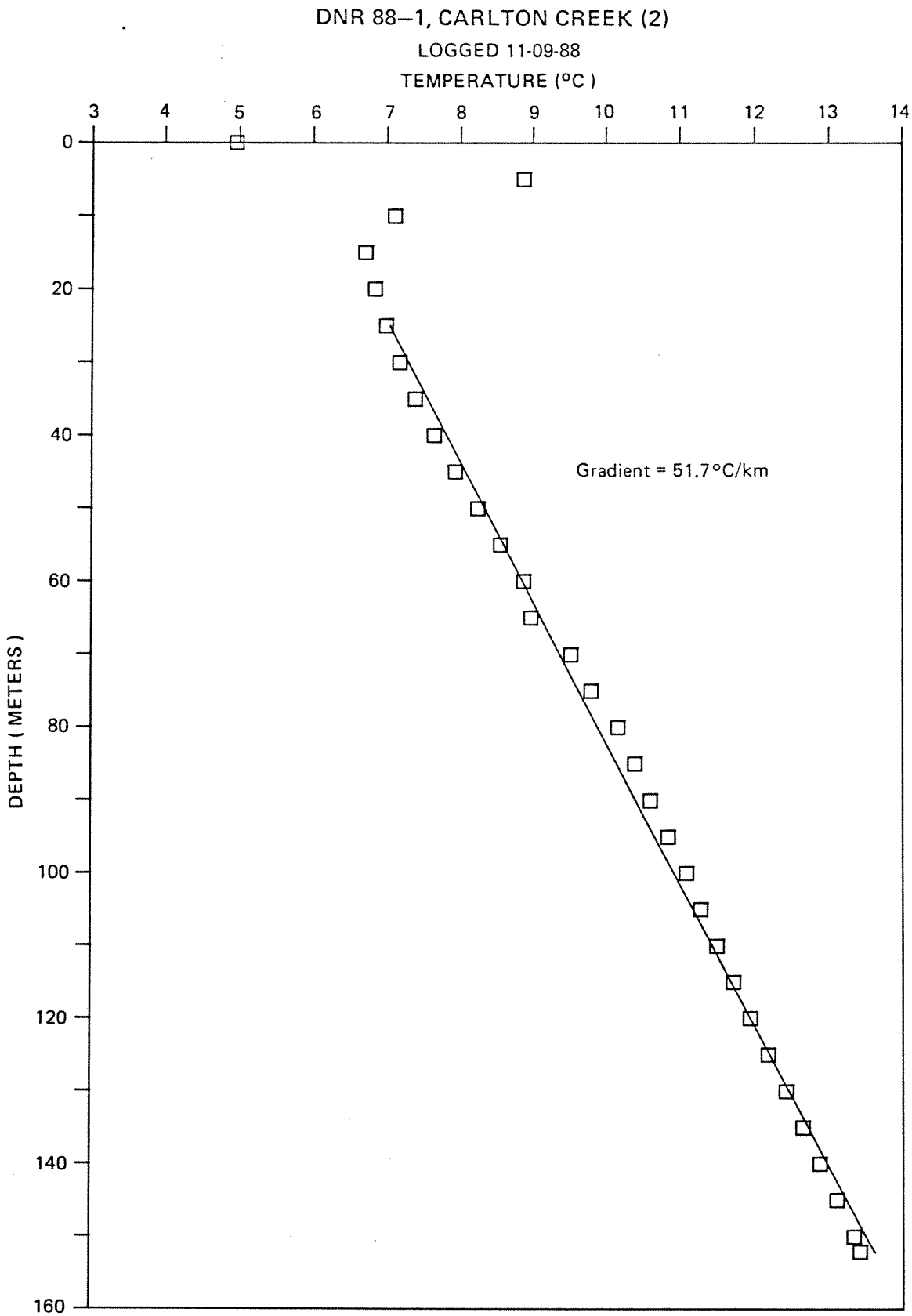


Figure 3. Carlton Creek geothermal gradient profile.

Table 3. Carlton Creek temperature-vs.-depth data.

DNR 88-1, CARLTON CREEK.
LOGGED 11-09-88
LOCATION = 14N, 10E, SEC. 11, AAC

Depth (meters)	Temp. (°C)	Estimated (°C)	Gradient (°C/km)
0.00	4.96		
5.00	8.87		782.00
10.00	7.11		-352.00
15.00	6.71		-80.00
20.00	6.84		26.00
25.00	6.99	7.04	30.00
30.00	7.18	7.30	38.00
35.00	7.39	7.56	42.00
40.00	7.65	7.82	52.00
45.00	7.93	8.07	56.00
50.00	8.24	8.33	62.00
55.00	8.55	8.59	62.00
60.00	8.87	8.85	64.00
65.00	8.97	9.11	20.00
70.00	9.52	9.37	110.00
75.00	9.80	9.62	56.00
80.00	10.16	9.88	72.00
85.00	10.39	10.14	46.00
90.00	10.60	10.40	42.00
95.00	10.84	10.66	48.00
100.00	11.09	10.92	50.00
105.00	11.28	11.17	38.00
110.00	11.50	11.43	44.00
115.00	11.72	11.69	44.00
120.00	11.95	11.95	46.00
125.00	12.19	12.21	48.00
130.00	12.43	12.47	48.00
135.00	12.65	12.72	44.00
140.00	12.88	12.98	46.00
145.00	13.11	13.24	46.00
150.00	13.34	13.50	46.00
152.15	13.42	13.61	37.21

Regression Output:

Constant	5.749717
Std Err of Y Est	0.146053
R Squared	0.995101
No. of Observations	27
Degrees of Freedom	25
X Coefficient(s)	0.051664
Std Err of Coef.	0.000724

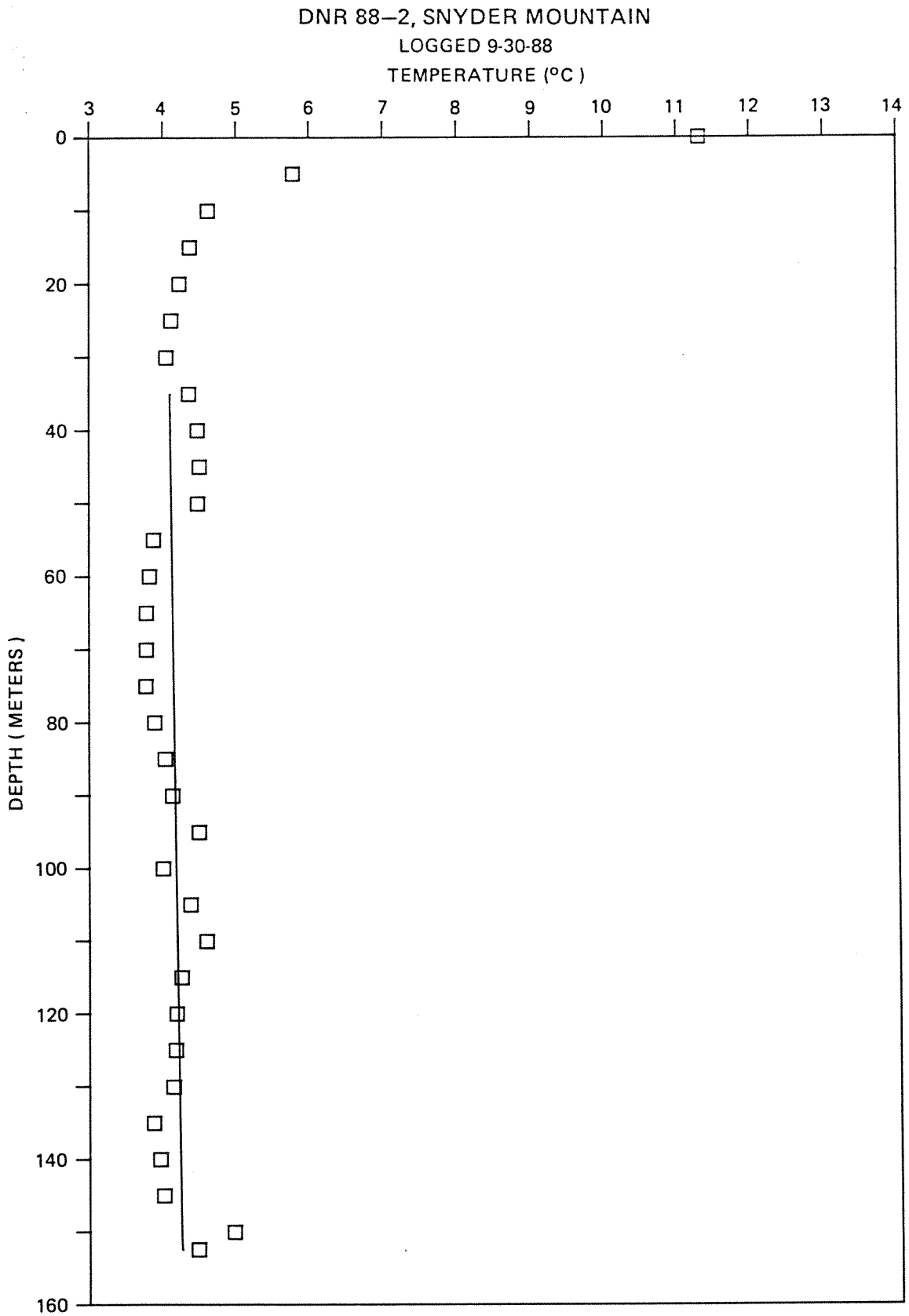


Figure 4. Snyder Mountain geothermal gradient profile.

Table 4. Snyder Mountain temperature-vs.-depth data.

DNR 88-2, SNYDER MOUNTAIN.
LOGGED 09-30-88
LOCATION = 13N, 09E, SEC. 24, ADD

Depth (meters)	Temp. (°C)	Estimated (°C)	Gradient (°C/km)
0.00	11.32		
5.00	5.79		-1106.00
10.00	4.62		-234.00
15.00	4.37		-50.00
20.00	4.23		-28.00
25.00	4.12		-22.00
30.00	4.05		-14.00
35.00	4.36	4.10	62.00
40.00	4.48	4.11	24.00
45.00	4.50	4.11	4.00
50.00	4.48	4.12	-4.00
55.00	3.88	4.13	-120.00
60.00	3.82	4.13	-12.00
65.00	3.78	4.14	-8.00
70.00	3.78	4.14	0.00
75.00	3.77	4.15	-2.00
80.00	3.89	4.16	24.00
85.00	4.03	4.16	28.00
90.00	4.13	4.17	20.00
95.00	4.49	4.17	72.00
100.00	4.00	4.18	-98.00
105.00	4.37	4.19	74.00
110.00	4.59	4.19	44.00
115.00	4.25	4.20	-68.00
120.00	4.18	4.21	-14.00
125.00	4.17	4.21	-2.00
130.00	4.14	4.22	-6.00
135.00	3.87	4.22	-54.00
140.00	3.96	4.23	18.00
145.00	4.01	4.24	10.00
150.00	4.96	4.24	190.00
152.40	4.47	4.25	-204.17

Regression Output:

Constant	4.057435
Std Err of Y Est	0.315340
R Squared	0.020937
No. of Observations	25
Degrees of Freedom	23
X Coefficient(s)	0.001232
Std Err of Coef.	0.001757

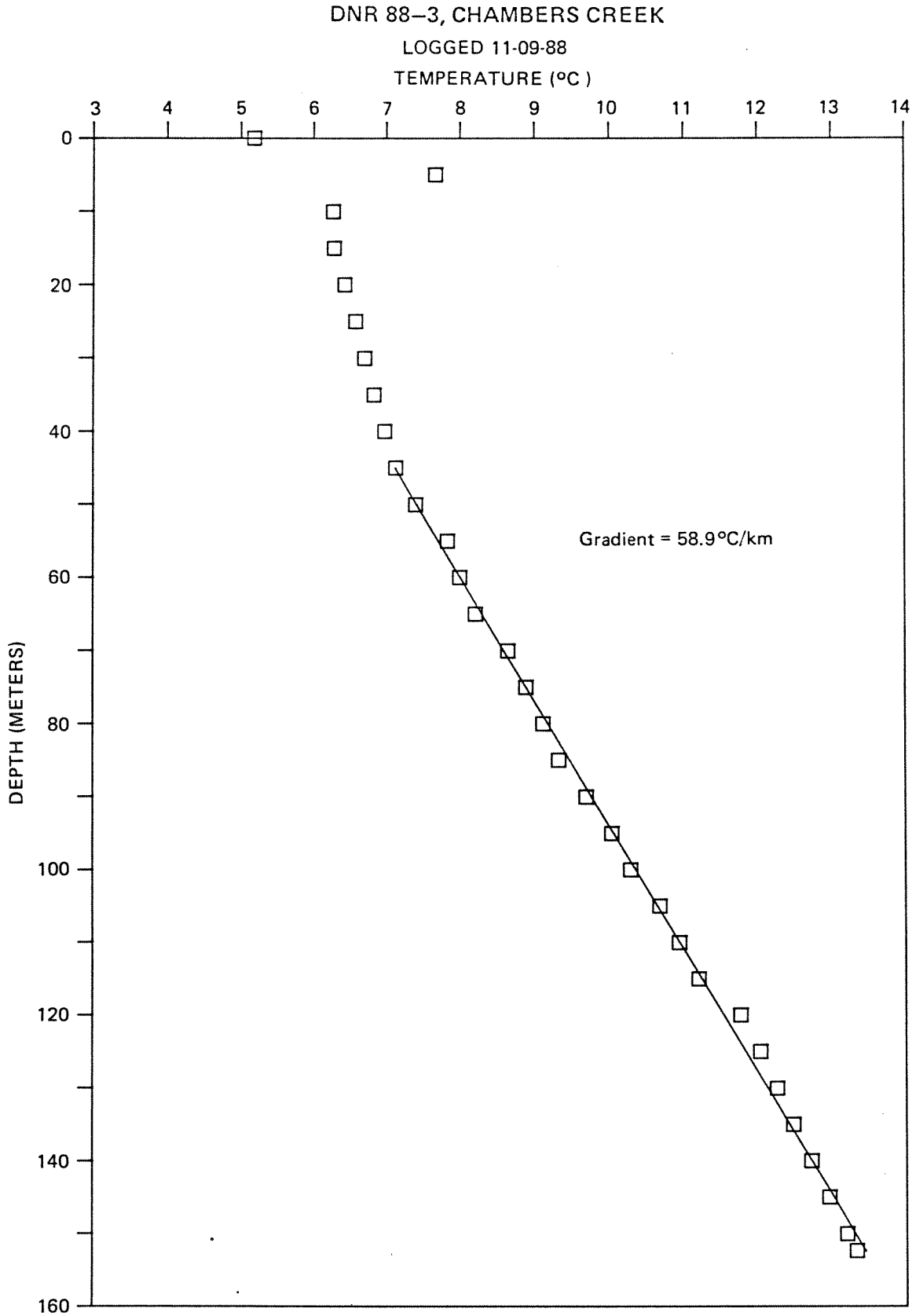


Figure 5. Chambers Creek geothermal gradient profile.

Table 5. Chambers Creek temperature-vs.-depth data.

DNR 88-3, CHAMBERS CREEK.
LOGGED 11-09-88
LOCATION = 11N, 10E, SEC. 35, BCD

Depth (meters)	Temp. (°C)	Estimated (°C)	Gradient (°C/km)
0.00	5.18		
5.00	7.67		498.00
10.00	6.27		-280.00
15.00	6.28		2.00
20.00	6.43		30.00
25.00	6.58		30.00
30.00	6.70		24.00
35.00	6.83		26.00
40.00	6.98		30.00
45.00	7.13	7.12	30.00
50.00	7.40	7.41	54.00
55.00	7.83	7.71	86.00
60.00	8.00	8.00	34.00
65.00	8.21	8.30	42.00
70.00	8.65	8.59	88.00
75.00	8.89	8.89	48.00
80.00	9.12	9.18	46.00
85.00	9.33	9.48	42.00
90.00	9.70	9.77	74.00
95.00	10.04	10.06	68.00
100.00	10.29	10.36	50.00
105.00	10.68	10.65	78.00
110.00	10.94	10.95	52.00
115.00	11.20	11.24	52.00
120.00	11.76	11.54	112.00
125.00	12.03	11.83	54.00
130.00	12.25	12.13	44.00
135.00	12.47	12.42	44.00
140.00	12.71	12.71	48.00
145.00	12.95	13.01	48.00
150.00	13.19	13.30	48.00
152.34	13.32	13.44	55.56

Regression Output:

Constant	4.470268
Std Err of Y Est	0.098121
R Squared	0.997674
No. of Observations	23
Degrees of Freedom	21
X Coefficient(s)	0.058882
Std Err of Coef.	0.000620

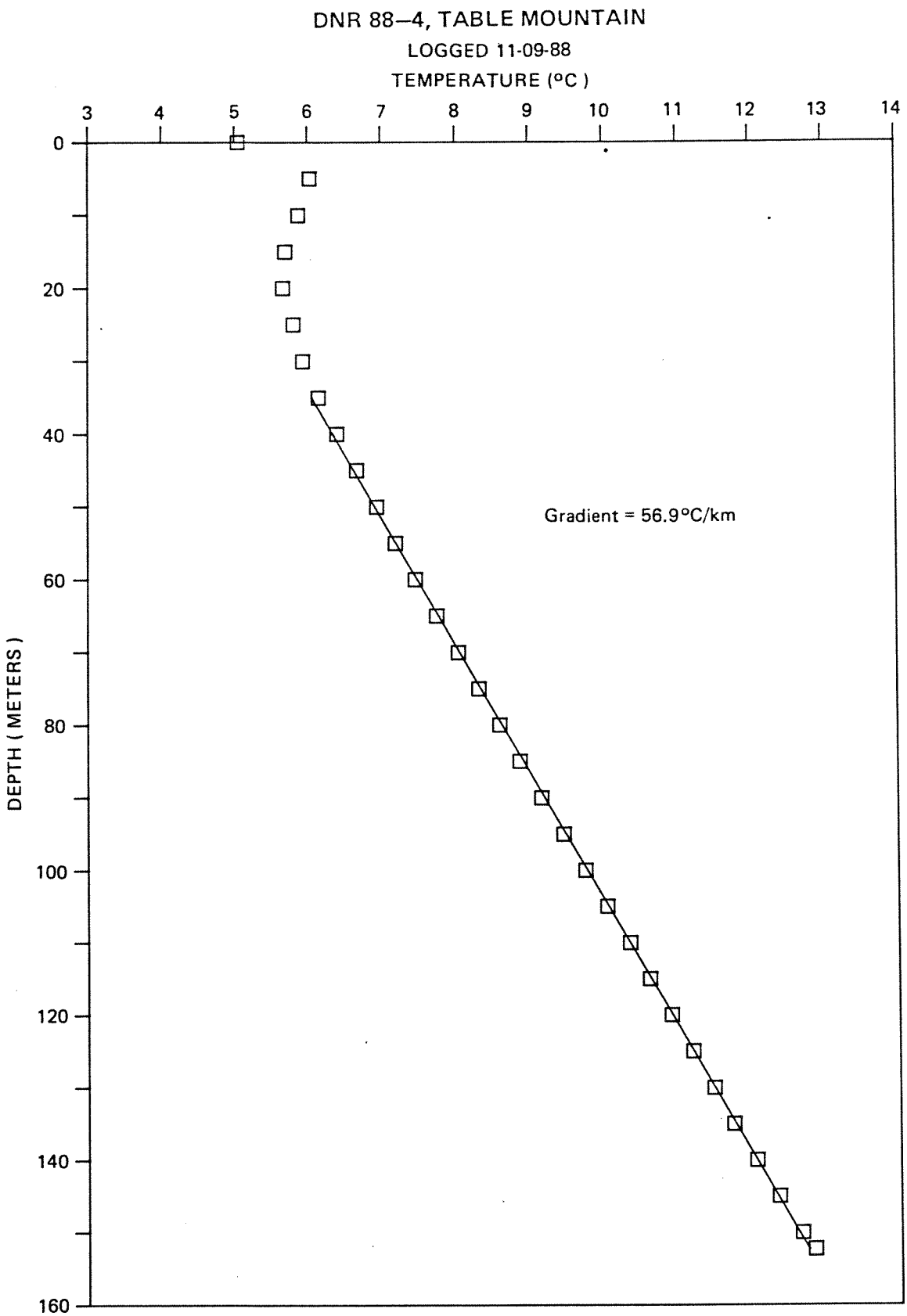


Figure 6. Table Mountain geothermal gradient profile.

Table 6. Table Mountain temperature-vs.-depth data.

DNR 88-4, TABLE MOUNTAIN.
LOGGED 11-09-88
LOCATION = 09N, 09E, SEC. 05, ADC

Depth (meters)	Temp. (°C)	Estimated (°C)	Gradient (°C/km)
0.00	5.05		
5.00	6.04		198.00
10.00	5.88		-32.00
15.00	5.70		-36.00
20.00	5.67		-6.00
25.00	5.81		28.00
30.00	5.94		26.00
35.00	6.16	6.07	44.00
40.00	6.41	6.36	50.00
45.00	6.68	6.64	54.00
50.00	6.95	6.93	54.00
55.00	7.20	7.21	50.00
60.00	7.47	7.50	54.00
65.00	7.75	7.78	56.00
70.00	8.04	8.06	58.00
75.00	8.32	8.35	56.00
80.00	8.60	8.63	56.00
85.00	8.87	8.92	54.00
90.00	9.16	9.20	58.00
95.00	9.46	9.49	60.00
100.00	9.75	9.77	58.00
105.00	10.04	10.05	58.00
110.00	10.34	10.34	60.00
115.00	10.61	10.62	54.00
120.00	10.90	10.91	58.00
125.00	11.19	11.19	58.00
130.00	11.47	11.48	56.00
135.00	11.74	11.76	54.00
140.00	12.05	12.05	62.00
145.00	12.35	12.33	60.00
150.00	12.66	12.61	62.00
152.32	12.83	12.75	73.28

Regression Output:

Constant	4.082136
Std Err of Y Est	0.037230
R Squared	0.999693
No. of Observations	25
Degrees of Freedom	23
X Coefficient(s)	0.056883
Std Err of Coef.	0.000207

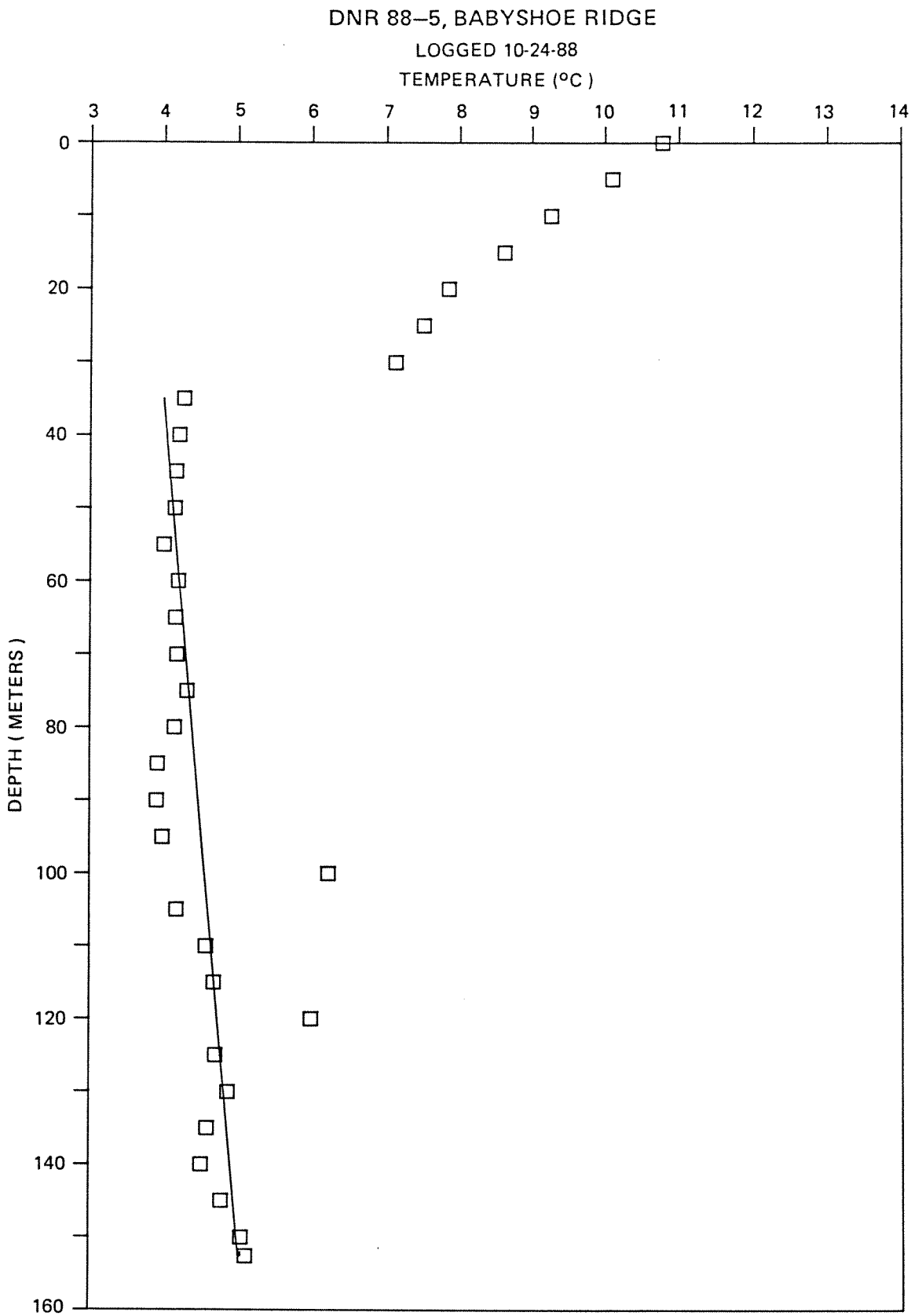


Figure 7. Babyshoe Ridge geothermal gradient profile.

Table 7. Babyshoe Ridge temperature-vs.-depth data.

DNR 88-5, BABYSHOE RIDGE.
LOGGED 10-24-88
LOCATION = 09N, 10E, SEC. 18, BCD

DEPTH (METERS)	TEMP. (DEG. C)	ESTIMATED (DEG. C)	GRADIENT (DEG. C/km)
0.00	10.78		
5.00	10.10		-136.00
10.00	9.26		-168.00
15.00	8.62		-128.00
20.00	7.85		-154.00
25.00	7.51		-68.00
30.00	7.13		-76.00
35.00	4.27	4.00	-572.00
40.00	4.21	4.04	-12.00
45.00	4.17	4.08	-8.00
50.00	4.15	4.13	-4.00
55.00	4.00	4.17	-30.00
60.00	4.20	4.21	40.00
65.00	4.16	4.26	-8.00
70.00	4.18	4.30	4.00
75.00	4.32	4.35	28.00
80.00	4.15	4.39	-34.00
85.00	3.92	4.43	-46.00
90.00	3.91	4.48	-2.00
95.00	3.99	4.52	16.00
100.00	6.23	4.56	448.00
105.00	4.18	4.61	-410.00
110.00	4.58	4.65	80.00
115.00	4.69	4.70	22.00
120.00	6.00	4.74	262.00
125.00	4.71	4.78	-258.00
130.00	4.88	4.83	34.00
135.00	4.60	4.87	-56.00
140.00	4.52	4.91	-16.00
145.00	4.79	4.96	54.00
150.00	5.06	5.00	54.00
152.60	5.12	5.02	23.08

Regression Output:

Constant	3.689467
Std Err of Y Est	0.507341
R Squared	0.293974
No. of Observations	25
Degrees of Freedom	23
X Coefficient(s)	0.008747
Std Err of Coef.	0.002826

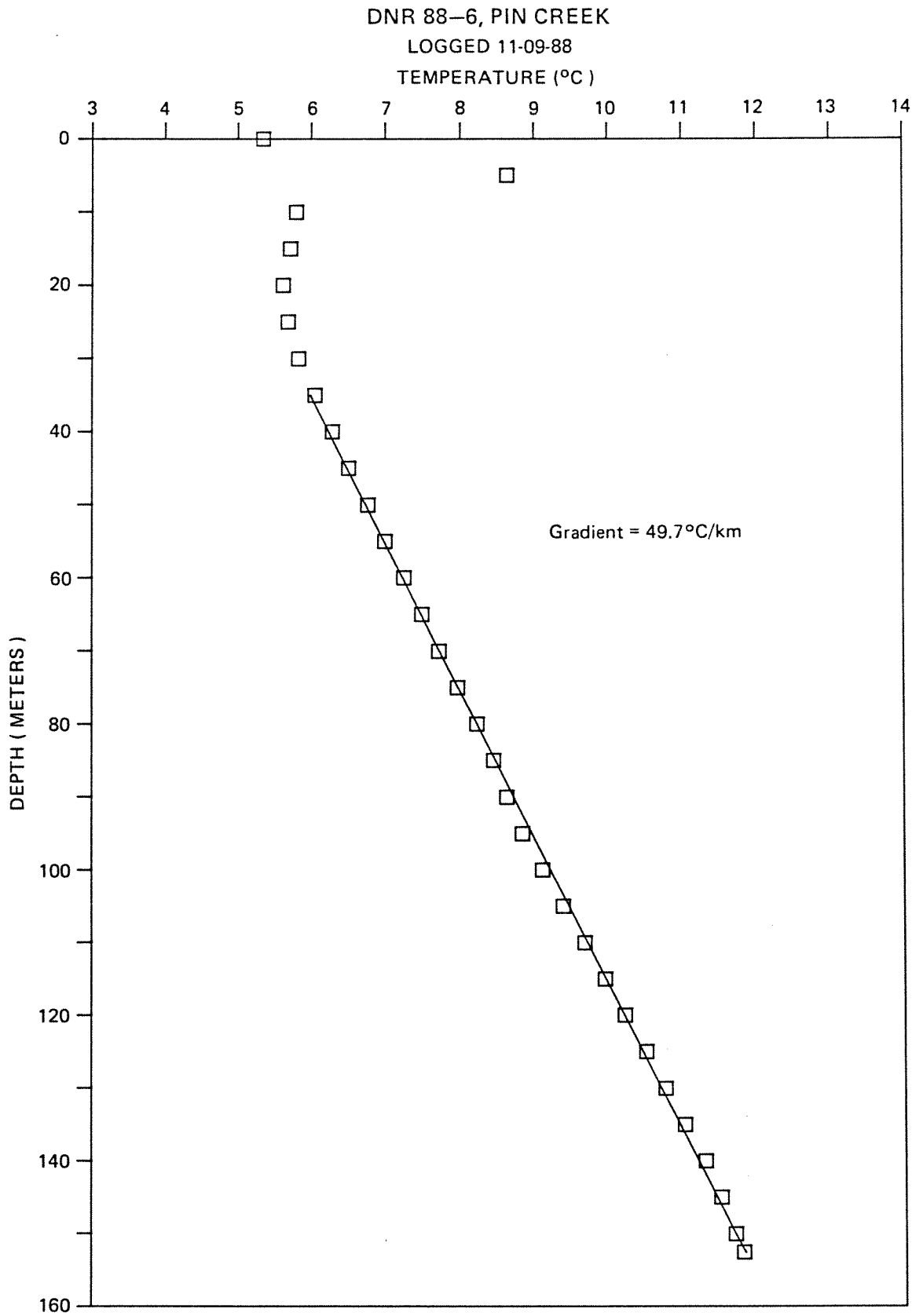


Figure 8. Pin Creek geothermal gradient profile.

Table 8. Pin Creek temperature-vs.-depth data.

DNR 88-6, PIN CREEK.
LOGGED 11-09-88
LOCATION = 09N, 09E, SEC. 34, ADD

Depth (meters)	Temp. (°C)	Estimated (°C)	Gradient (°C/km)
0.00	5.35		
5.00	8.64		658.00
10.00	5.80		-568.00
15.00	5.72		-16.00
20.00	5.62		-20.00
25.00	5.69		14.00
30.00	5.83		28.00
35.00	6.05	5.99	44.00
40.00	6.29	6.24	48.00
45.00	6.51	6.49	44.00
50.00	6.77	6.74	52.00
55.00	7.00	6.98	46.00
60.00	7.25	7.23	50.00
65.00	7.49	7.48	48.00
70.00	7.72	7.73	46.00
75.00	7.97	7.98	50.00
80.00	8.23	8.23	52.00
85.00	8.45	8.47	44.00
90.00	8.63	8.72	36.00
95.00	8.84	8.97	42.00
100.00	9.11	9.22	54.00
105.00	9.39	9.47	56.00
110.00	9.68	9.72	58.00
115.00	9.95	9.96	54.00
120.00	10.22	10.21	54.00
125.00	10.50	10.46	56.00
130.00	10.76	10.71	52.00
135.00	11.02	10.96	52.00
140.00	11.30	11.21	56.00
145.00	11.51	11.45	42.00
150.00	11.70	11.70	38.00
152.53	11.81	11.83	43.48

Regression Output:

Constant	4.253048
Std Err of Y Est	0.056960
R Squared	0.999061
No. of Observations	25
Degrees of Freedom	23
X Coefficient(s)	0.049661
Std Err of Coef.	0.000317

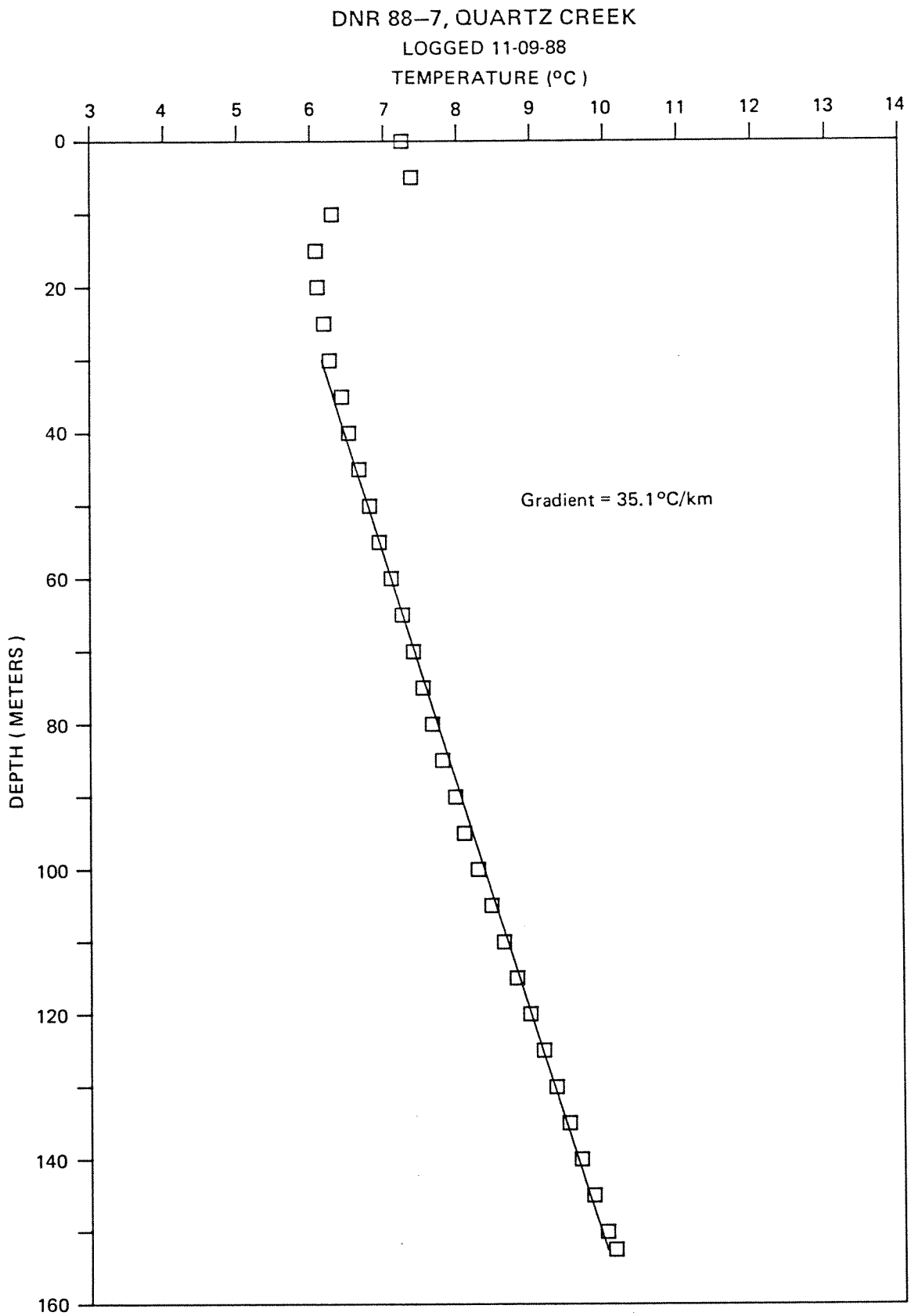


Figure 9. Quartz Creek geothermal gradient profile.

Table 9. Quartz Creek temperature-vs.-depth data.

DNR 88-7, QUARTZ CREEK.
LOGGED 11-09-88
LOCATION = 08N, 08E, SEC. 08, BBC

Depth (meters)	Temp. (°C)	Estimated (°C)	Gradient (°C/km)
0.00	7.26		
5.00	7.39		26.00
10.00	6.30		-218.00
15.00	6.08		-44.00
20.00	6.10		4.00
25.00	6.19		18.00
30.00	6.26	6.16	14.00
35.00	6.43	6.31	34.00
40.00	6.52	6.47	18.00
45.00	6.66	6.62	28.00
50.00	6.80	6.78	28.00
55.00	6.93	6.94	26.00
60.00	7.09	7.09	32.00
65.00	7.24	7.25	30.00
70.00	7.39	7.40	30.00
75.00	7.52	7.56	26.00
80.00	7.64	7.72	24.00
85.00	7.78	7.87	28.00
90.00	7.95	8.03	34.00
95.00	8.07	8.18	24.00
100.00	8.25	8.34	36.00
105.00	8.43	8.50	36.00
110.00	8.60	8.65	34.00
115.00	8.77	8.81	34.00
120.00	8.95	8.96	36.00
125.00	9.13	9.12	36.00
130.00	9.30	9.28	34.00
135.00	9.47	9.43	34.00
140.00	9.63	9.59	32.00
145.00	9.80	9.74	34.00
150.00	9.98	9.90	36.00
152.48	10.09	9.98	44.35

Regression Output:

Constant	5.220150
Std Err of Y Es	0.066853
R Squared	0.996969
No. of Observations	26
Degrees of Freedom	24
X Coefficient(s)	0.03119
Std Err of Coef.	0.00035

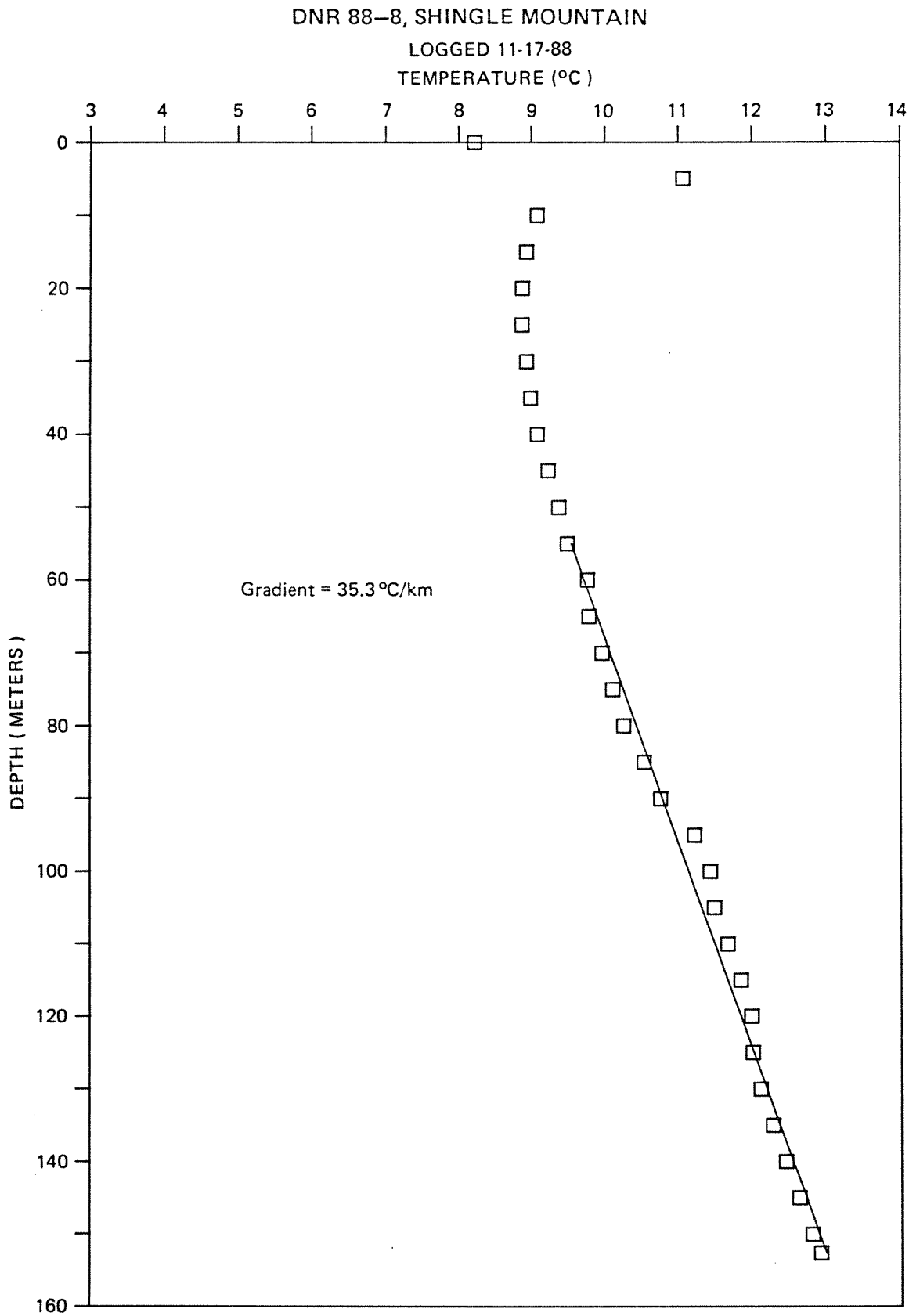


Figure 10. Shingle Mountain geothermal gradient profile.

Table 10. Shingle Mountain temperature-vs.-depth data.

DNR 88-8, SHINGLE MOUNTAIN
LOGGED 11-17-88
LOCATION = 04N, 09E, SEC. 27, CBB

Depth (meters)	Temp. (°C)	Estimated (°C)	Gradient (°C/km)
0.00	8.22		
5.00	11.07		570.00
10.00	9.08		-398.00
15.00	8.93		-30.00
20.00	8.88		-10.00
25.00	8.87		-2.00
30.00	8.93		12.00
35.00	8.99		12.00
40.00	9.08		18.00
45.00	9.23		30.00
50.00	9.37		28.00
55.00	9.49	9.54	24.00
60.00	9.76	9.72	54.00
65.00	9.78	9.89	4.00
70.00	9.96	10.07	36.00
75.00	10.10	10.25	28.00
80.00	10.25	10.42	30.00
85.00	10.53	10.60	56.00
90.00	10.75	10.78	44.00
95.00	11.21	10.95	92.00
100.00	11.42	11.13	42.00
105.00	11.48	11.31	12.00
110.00	11.66	11.48	36.00
115.00	11.84	11.66	36.00
120.00	11.98	11.84	28.00
125.00	12.00	12.01	4.00
130.00	12.10	12.19	20.00
135.00	12.27	12.36	34.00
140.00	12.44	12.54	34.00
145.00	12.62	12.72	36.00
150.00	12.80	12.89	36.00
152.64	12.91	12.99	41.67

Regression Output:

Constant	7.601366
Std Err of Y Est	0.145937
R Squared	0.983198
No. of Observations	21
Degrees of Freedom	19
X Coefficient(s)	0.035285
Std Err of Coef.	0.001058

DISCUSSION

Heat Flow Estimates

Thermal conductivity values for the lithologies drilled during the 1988 project were measured by Kelley and Blackwell at the Southern Methodist University, and are presented in Table 11. The harmonic mean was calculated using 6 to 7 rock thermal conductivity measurements from each hole. Corrections for porosity were estimated, based on porosity measurements made for similar material during past projects. This produces a range of probable thermal conductivities, and consequently, a range of calculated heat flow values. Gradients used are those derived from the best-fit, linear regression analysis and are not corrected for terrain effects.

Table 11. Calculated Heat Flow Values

Hole	Gradient ($^oC/km$)	Thermal conductivity harmonic mean (W/m^oc)	Porosity-corrected thermal conductivity (W/m^oC)	Calculated heat flow (mW/m^2)
Carlton Creek (DNR 88-1)	52	3.08	2.8 to 3.0	146 to 156
Chambers Creek (DNR 88-3)	58	2.60	2.2 to 2.5	127 to 145
Table Mountain (DNR 88-4)	57	1.46	1.3 to 1.4	74 to 80
Pin Creek (DNR 88-6)	50	1.70	1.5 to 1.7	75 to 85
Quartz Creek (DNR 88-7)	31	2.25	1.9 to 2.2	59 to 68
Shingle Mountain (DNR 88-8)	35	1.60	1.4 to 1.5	49 to 52

The holes at Table Mountain, Pin Creek, Quartz Creek, and Shingle Mountain were drilled in clay-rich volcaniclastic rock types similar to those that have been tested for thermal conductivity in past projects. The range of thermal conductivity values for these rocks is 1.3 to 2.2 W/m^oC. Porosities typically range from 1 to 10 percent.

Shingle Mountain has the lowest estimated heat flow, 49 to 52 mW/m^2, typical of values determined for the western and southwestern portions of the Columbia Basin and western Cascade Range foothills. The heat flow for Quartz Creek (59 to 68 mW/m^2) may represent a transition between the lower gradients of the western Cascade Range foothills and the higher gradients of the central range (Blackwell and others, 1985). Heat flow for the central range is typified by the modestly high values of Pin Creek (75 to 85 mW/m^2) and Table Mountain (74 to 80 mW/m^2) and the very high values for Chambers Creek and Carlton Creek.

The Chambers Creek (DNR 88-3) lithologies are dominated by arkosic sandstone, siltstone and intercalated claystone sequences. Thin basalt or andesite sills occur at two levels. A wide range of thermal conductivities and porosities exists for these rocks. Using the mean thermal conductivity and a range of porosities of 5 to 12 percent, the heat flow is estimated to be very high; between 127 and 145 mW/m^2.

A thermal conductivity of 2.8 to 3.0 W/m^oC was determined for the fine-grained silicic igneous rocks of the Carlton Creek hole. With a temperature gradient of $52^oC/Km$, the heat flow is estimated to be from 146 to 156 mW/m^2, the highest heat flow determined by the 1988 project.

Geothermal Potential of the Southern Washington Cascade Range

The Cascade Range of southern Washington, with its numerous Quaternary volcanic centers, tectonic setting, complex structure, easy access, and relatively favorable land ownership (outside of the parks and wilderness areas) represents Washington's best province for the exploration of high-temperature geothermal resources. Through the U.S. Department of Energy's State-coupled assessment program, the DGER has conducted preliminary surveys of the Cascade province. The preliminary work has crudely delineated a zone of temperature gradients greater than $50^oC/km$, with projected heat flow greater than 80 mW/m^2. This zone is shown in Figure 11. The 1988 work has further supported the validity of this feature.

Many of the known hydrothermal systems occur within this zone as indicated by the occurrence of thermal and mineral springs. These hydrothermal systems are, in part, responsible for several of the high gradients. However, many of the highest gradients, ranging from 70 to $90^oC/km$, have been measured in areas with no surface hydrothermal manifestations. The nature and extent of these blind geothermal systems are not known, but

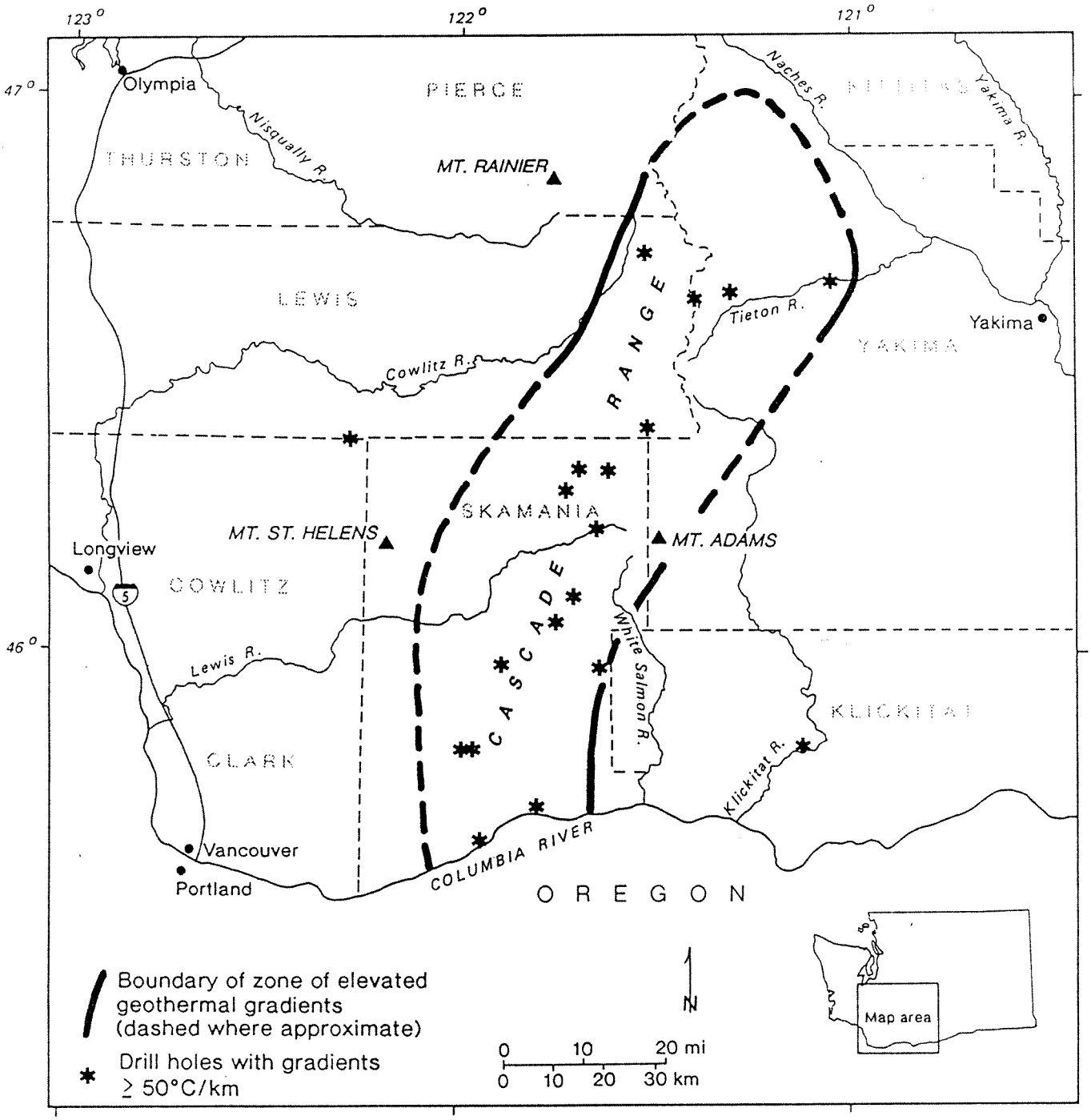


Figure 11. Zone of high temperature gradients in the southern Washington Cascade Range. Also shown are the locations of drill holes with gradients of 50°C/Km or greater.

are strongly suspected to be related to (a) the active volcanic arc, (b) plutonism associated with the volcanic arc, and (c) hydrothermal systems controlled by the plutonism and regional structure.

Beginning to emerge from our studies is the potential importance of regional fault zones in producing locally elevated gradients. Deep-seated faults or zones of crustal weakness which have surface expressions as faults, lineaments, and/or alignment of young intrusions and volcanic centers, are attractive targets for deep geothermal test holes. Possible examples of this kind of control are the Indian Heaven-Table Mountain-Spud Hill trend, an area northwest of Mount Adams, and the Mount St. Helens-Wind River lineament(s) (Berri and Korosec, 1983).

Because of the typically low inherent permeability of the undisturbed Oligocene to Miocene volcanic rocks, structures that have induced secondary permeability, such as fault zones, should be sought as exploration targets. Carefully located shallow holes, or deeper holes, will have the best chance of penetrating the zone of downward-moving, cold meteoric water associated with the upper levels of these structures.

CONCLUSIONS

Results of the 1988 geothermal project helped to confirm the existence of a large region in the southern Washington Cascade Range characterized by temperature gradients in excess of 50°C/Km. During the 1988 project the gradients in four of the holes (Carlton Creek, Chambers Creek, Table Mountain, and Pin Creek) equalled or exceeded this value.

From the disappointing results of two of the 1988 drill holes (Snyder Mountain and Babyshoe Ridge), and other holes from previous projects, it is clear that a heat flow anomaly cannot always be identified through shallow drilling. Local, significant differences in observed gradients in the southern Washington Cascades are partially the result of varied subsurface lithologies, which have peculiar thermal conductivities, and the distribution of cold versus warm aquifers. When drilling shallow holes, it is important to avoid highly permeable recharge areas that impart cold, "rain curtain" effects on the borehole.

There still exist large areas of the Cascade Range that have not been tested by shallow drilling, both within and outside of the projected high-gradient zone. Future test drilling of these areas will be necessary to refine the areal bounds of this zone, but significant understanding of the nature and potential of this geothermal resource will only come about with deeper drilling.

REFERENCES CITED

Barnett, D. B., 1986, The 1985 geothermal gradient drilling project for the State of Washington: Washington Division of Geology and Earth Resources Open File Report 86-2, 36 p.

Beach, R. D. W.; Jones, F. W.; Majorowicz, J. A., 1987, Heat flow and heat generation estimates for the Churchill Basement of the Western Canadian Basin in Alberta, Canada: Geothermics, v. 16, p. 1-16.

Berri, D. A.; Korosec, M. A., 1983, Geological and geothermal investigation of the lower Wind River valley, southwestern Washington, Cascade Range: Washington Division of Geology and Earth Resources Open File Report 83-5, 46 p., 2 pl., scale 1:24,000.

Blackwell, D. D., 1980, Heat flow and geothermal gradient measurements in Washington to 1979 and temperature-depth data collected during 1979: Washington Division of Geology and Earth Resources Open File Report 80-9, 524 p.

Blackwell, D. D.; Steele, J. L.; Kelley, S. A., 1985, Heat flow and geothermal studies in the State of Washington: Washington Division of Geology and Earth Resources Open File Report 85-6, 77 p.

Galson, D. A.; Wilson, N. P.; Scharli, U.; Rybach, L., 1987, A comparison of the divided-bar and QTM methods of measuring thermal conductivity: Geothermics, v. 16, p. 215-226.

Hammond, P. E.; Korosec, M. A., 1983, Geochemical analyses, age dates, and flow-volume estimates for Quaternary volcanic rocks, southern Cascade Mountains, Washington: Washington Division of Geology and Earth Resources Open-File Report 83-13, 36 p., 1 pl.

Harle, D. S., 1974, Geology of Babyshoe Ridge area, southern Cascades Washington: Oregon State University of Master of Science thesis, 71 p., 1 pl., scale 1:24,000.

Korosec, M. A., 1983, The 1983 temperature gradient and heat flow drilling project for the State of Washington: Washington Division of Geology and Earth Resources Open File Report 83-12, 13 p.

Korosec, M. A., 1984, Summary of geothermal exploration activity in the State of Washington from 1978 to 1983: Final program report to the U.S. Department of Energy: Washington Division of Geology and Earth Resources Open File Report 84-2, 42 p.

Korosec, M. A., 1987a, Geologic map of the Mount Adams quadrangle, Washington: Division of Geology and Earth Resources Open File Report 87-5, 39 p., 1 pl., scale 1:100,000.

Korosec, M. A., 1987b, Geologic map of the Hood River quadrangle, Washington and Oregon: Washington Division of Geology and Earth Resources Open File Report 87-6, 42 p., 1 pl., scale 1:100,000.

Korosec, M. A.; Schuster, J. E.; 1981, The 1979-1980 geothermal resource assessment program in Washington: Washington Division of Geology and Earth Resources Open File Report 81-3, 270 p., 1 pl., scale 1:24,000.

Korosec, M. A.; Phillips, W. M.; and Schuster, J. E., 1982, The low temperature geothermal resources of eastern Washington: Washington Division of Geology and Earth Resources Open File Report 82-1, 20 p.

Korosec, M. A.; Phillips, W. M.; Schuster, J. E.; Danes, Z. F.; Biggane, J. H.; Hammond, P. E.; Clayton, G. A., 1983, The 1980-1982 geothermal resource assessment program in Washington; with chapters on thermal springs, gravity investigations, heat-flow drilling, low-temperature resources in eastern Washington, geology of the south Cascades and White Pass areas, and targets for geothermal resource exploration: Washington Division of Geology and Earth Resources Open File Report 83-7, 299 p.

Martinez-Baez, L. F., 1980, Thermal conductivity of core samples from the Cerro Prieto geothermal field--Experimental results and an improved prediction method: Geothermics, v. 9, p. 169-178.

Schasse, H. W., 1987, Geologic map of the Mount Rainier quadrangle, Washington: Washington Division of Geology and Earth Resources Open File Report 87-16, 143 p., 1 pl., scale 1:100,000.

Schuster, J. E.; Blackwell, D. D.; Hammond, P. E.; Huntting, M. T.; 1978, Heat flow studies in the Steamboat Mountain-Lemei Rock Area, Skamania County, Washington: Washington Division of Geology and Earth Resources Information Circular 62, 56 p.

Schuster, J. E.; Korosec M. A., 1981, Preliminary report on heat-flow drilling in Washington during 1981: Washington Division of Geology and Earth Resources Open File Report 81-8, 36 p.

Stoffel, K. L.; Widness, Scott, 1983, Fluid-temperature logs for selected wells in eastern Washington: Washington Division of Geology and Earth Resource Open File Report 83-15, 354 p.

Weast, R. C.; Astle, M. J., 1978, CRC Handbook of Chemistry and Physics: CRC Press, Inc., p. E-16.

APPENDIX A: Lithologic logs for the 1988 drill holes

CARLTON CREEK (DNR 88-1)

Depth (Meters) From	To	Description
0.0	2.5	Colluvium and glacial drift; rounded clasts of various lithologies in clay and sand matrix; andesite and basalt clasts predominate.
2.5	17.0	Rhyolite; white to light gray-green; locally silicified with chalcedonic horizons; argillic alteration and pyritization 10.0-13.0 m.
17.0	29.2	Claystone and sandstone in alternating layers; medium gray-green to black.
29.2	64.6	Dacitic lava or tuff; medium to light gray-green; plagioclase phyric in some parts; calcite amygdules in harder layers; weak to strong propyllitic alteration throughout.
64.6	78.5	Volcanic sandstone; red-brown to gray-green; fine- to coarse-grained; andesitic rock fragments predominate.
78.5	80.0	Claystone, calcareous; light gray-green to white; water encountered at 79.3 m, approximately 20 gpm.
80.0	81.5	Volcanic agglomerate; blue-green and dark gray; saprolitic in part; contains intermediate to felsic tuff and/or lava fragments, detrital quartz grains, and claystone fragments.
81.5	83.1	Sandstone; dark gray-brown; medium-grained.
83.1	92.3	Felsic welded tuff or lava; light brown to greenish-white; some large fragments show eutaxitic textures and fiamme; contains disseminated pyrite; goethite along fracture surfaces; pervasively silicified at some horizons.

CARLTON CREEK (DNR 88-1) - cont'd

Depth (Meters) From	To	Description
92.3	95.4	Sandstone; medium gray-green-brown; medium- to coarse-grained; minor coal and carbonaceous shale layers.
95.4	107.7	Rhyolite; white, pink, and light gray-brown; K-feldspar and quartz phyric.
107.7	110.8	Sand and/or weathered and fractured rhyolitic to rhyodacitc volcanic fragments; medium gray-brown.
110.8	152.4 (T.D.)	Rhyolite or rhyodacite; white to gray-brown; some intervals display phyllic alteration and contain disseminated pyrite; more melanocratic in some intervals; plagioclase phenocrysts visible in some fragments. Water was flowing from the hole at approximately 0.5 gpm the day after the drilling was completed.

SNYDER MOUNTAIN (DNR 88-2)

Depth (Meters) From	To	Description
0.0	15.2	Andesite porphyry; light to medium gray-brown to red-brown; saprolitic in upper part of interval; some limonite blebs visible in larger cuttings.
15.2	68.6	Andesite porphyry; color varies from medium gray-green, gray-brown, gray-blue to red-brown (red-brown probably represents weathered horizons between flows); plagioclase phyric; groundmass weakly altered in most of interval.
68.6	153.0 (T.D.)	Andesite porphyry; medium gray-brown to bluish-green with local red-brown layers at probable weathered flow boundaries; minor amounts of epiclastic detritus commonly present, especially at 73.2-86.9 m, 105.2-106.7 m, 132.6-134.1 m, and 149.4-153.0 m; abundant zeolites in groundmass 79.3-80.8 m.

CHAMBERS CREEK (DNR 88-3)

Depth (Meters) From	To	Description
0.0	4.6	Colluvium and glacial drift; contains large boulders of dark blue-green to black basalt and hydrothermally altered andesite.
4.6	6.1	Claystone, dark gray-green to black; carbonaceous; cuttings are fine and spongy.
6.1	10.7	Sandstone, silty; medium to dark gray-green; fine-grained; carbonaceous and micaceous.
10.7	38.1	Sandstone; light gray-green; fine- to medium-grained; micaceous; soft; platy carbonaceous debris or coal fragments at 24.4-25.9 m.
38.1	46.6	Sandstone; light to medium gray-green to brown; medium- to coarse-grained; arkosic or subarkosic.
46.6	52.7	Claystone; black to dark gray; carbonaceous.
52.7	59.5	Andesite; medium gray to gray-green; plagioclase phyric; phyllic alteration with minor disseminated pyrite; calcite and quartz vein with fine-grained minor sulfides (pyrite?) 54.8-57.0 m; water encountered at 54.9 m, approximately 100 gpm.
59.5	64.0	Sandstone; medium to dark gray; medium- to fine-grained.
64.0	65.5	Siltstone; dark gray to black; carbonaceous.
65.5	67.1	Claystone; dark gray to black; carbonaceous.

CHAMBERS CREEK (DNR 88-3) - cont'd

Depth (Meters) From	To	Description
67.1	68.6	Sandstone, silty; medium to dark gray; fine-grained; black laminae (carbonaceous debris?) visible in larger cuttings; micaceous.
68.6	71.6	Sandstone; light to medium gray; fine- to medium-grained; slight salt and pepper coloration; micaceous; water encountered at 71.6 m, approximately 200 gpm.
71.6	73.2	Sandstone; medium gray to white; fine-grained; calcite replacement of matrix.
73.2	80.8	Andesite; dark gray; plagioclase as groundmass and phenocrysts; disseminated pyrite, abundant calcite veinlets, and fracturing 77.7-80.8 m.
80.8	82.3	Sandstone; light gray to white; fine- to medium-grained.
82.3	83.8	Siltstone, with subordinate fine-grained sandstone; dark gray to black.
83.8	89.3	Claystone; black; carbonaceous.
89.3	106.7	Basalt; medium gray; plagioclase and pyroxene phyric; calcite veinlets; slickensides with chlorite and/or serpentine(?) on fracture surfaces; locally silicified 103.6-105.2 m.
106.7	112.8	Sandstone, with subordinate siltstone; medium to dark gray; fine-grained.
112.8	115.9	Claystone; black; carbonaceous; with felsic dike or sill which displays argillic alteration and is plagioclase and K-feldspar phyric and slightly carbonatized and silicified; claystone is hard, as though baked at intrusive contact.

CHAMBERS CREEK (DNR 88-3) - cont'd

Depth (Meters) From	To	Description
115.9	117.4	Claystone; black; carbonaceous, with boney coal and some vitrain bands; much softer than superjacent interval.
117.4	123.2	Siltstone, with subordinate fine-grained sandstone; medium gray; slightly micaceous; disseminated carbonaceous debris.
123.2	134.1	Sandstone; light gray; medium-grained; soft; micaceous; arkosic to subarkosic.
134.1	135.7	Sandstone; medium gray; fine- to medium-grained; harder than superjacent sandstone.
135.7	140.2	Sandstone; medium gray; fine-grained; soft; micaceous; arkosic to subarkosic.
140.2	141.8	Sandstone, with subordinate siltstone; fine-grained; variegated black and light gray; contains laminae of carbonaceous debris.
141.8	143.3	Sandstone; medium gray; fine-grained; micaceous.
143.3	144.8	Sandstone; medium gray; medium-grained; micaceous; harder than superjacent interval; arkosic.
144.8	146.3	Sandstone; light to medium gray; fine- to medium-grained; micaceous; arkosic(?).
146.3	147.9	Siltstone, with subordinate claystone; dark gray to black; fine-grained, carbonaceous.
147.9	150.9	Sandstone; light gray; fine- to medium-grained; soft; micaceous; arkosic(?).
150.9	152.4 (T.D.)	Siltstone; black; fine-grained; carbonaceous.

TABLE MOUNTAIN (DNR 88-4)

Depth (Meters) From	To	Description
0.0	1.5	Soil and colluvium; medium red-brown; slightly clayey sand texture.
1.5	42.7	Volcanic agglomerate or volcanic wacke; medium to dark gray-brown; larger clasts are of aphyric basalt or andesite; alternating clay- and sand-rich layers; appears tuffaceous locally and has plagioclase crystals and lithic fragments in fine-grained matrix.
42.7	45.7	Volcanic sandstone; medium- to fine-grained; medium to dark gray; less clay than in superjacent interval.
45.7	47.3	Claystone; medium to dark gray.
47.3	128.0	Volcanic wacke; medium to dark gray-brown, locally dark purplish gray to black; minor zeolites in fractures 51.8-53.4 m; water production at 86.9 m, 30-35 gpm.
128.0	152.4 (T.D.)	Tuff and tuff breccia; dark gray-green to blue-gray; larger clasts are aphyric to porphyritic basalt or andesite; matrix also contains euhedral magnetite and plagioclase; entire interval contains fine, black, glassy rock fragments in tuffaceous matrix, locally imparting a speckled appearance.

BABYSHOE RIDGE (DNR 88-5)

Depth (Meters) From	To	Description
0.0	2.1	Ballast, borrow material, crushed rock intermingled with clay and plant debris.
2.1	6.1	Clay; yellow-brown; mixed with gray-green intrusive or volcanic rock (propyllitic alteration ?).
6.1	12.2	Silicified volcanic or intrusive rock of unrecognizable type; medium gray-blue-green; abundant chalcedony and veinlets of zeolites and quartz; probable brecciation.
12.2	13.7	Clay (argillic alteration in volcanic or intrusive rock); light gray-blue-green to light brown.
13.7	18.3	Silicified volcanic or intrusive rock; medium gray-brown; Fe oxide-stained (most Fe oxide is along fractures and veinlets).
18.3	45.7	Silicified and brecciated volcanic or intrusive rock; very light brown and medium gray-green to locally red-brown; argillic alteration; feldspar laths and tablets visible in some parts (adularia?); locally contains veinlets of hematite and/or goethite and disseminated grains of sericite and/or other secondary micas; water encountered at 30.5 m, 100 gpm.
45.7	53.4	Silicified volcanic or intrusive rock; light to medium gray-brown to gray-red; jasperoidal, chalcedonic and mixed with red-brown clayey fault gouge(?); most cuttings coated with Fe and Mn oxides.
53.4	59.5	Silicified, jasperoidal rock of uncertain parentage; light gray-red to light brown; contains disseminated hematite or goethite.

BABYSHOE RIDGE (DNR 88-5) - cont'd

Depth (Meters) From	To	Description
59.5	64.0	Basalt; medium gray-red; pyroxene phyric; Fe oxides in veinlets; water encountered at 61.0 m, 150-200 gpm.
64.0	71.6	Basalt or basaltic andesite; yellowish red-brown to green; silicified and locally brecciated; goethite and limonite in fractures and vugs; probable secondary feldspars.
71.6	73.2	Silicified volcanic rock (probably basaltic andesite); medium to dark red-gray; jasperoidal; conchoidal fracture; mixed with white clay of an argillic alteration component; limonite and goethite in fractures and veinlets.
73.2	76.2	Silicified volcanic rock (probably basaltic andesite); black; glassy; light red-brown bands in some cuttings (jasperoidal ?).
76.2	99.1	Clayey sandstone, and volcanic wacke with local conglomeratic sandstone and claystone; medium to dark gray-red to gray-green; abundant clay-chlorite fracture fillings.
99.1	125.0	Andesite (or basalt); black to dark green, some reddish cast; plagioclase phyric; chlorite on fracture surfaces; slickensides on some larger cuttings; glassy groundmass.
125.0	129.6	Andesite; light to medium gray-green with some red-brown component; feldspar and quartz phyric; magnetite; some tuffaceous parts show possible propyllitic alteration.

BABYSHOE RIDGE (DNR 88-5) - cont'd

Depth (Meters) From	To	Description
129.6	137.2	Tuff or tuffaceous volcanic sandstone; medium dark gray with red cast; contains black, selvage-like (fracture filling?) material; halloysite or similar mineral coating some surfaces.
137.2	154.0	Andesite (or basalt); dark blue-gray with purplish cast; hard; appears tuffaceous in part; mostly featureless, but some cuttings contain lithic clasts; water encountered at 140.2 m, approximately 75-80 gpm.
154.0	158.5 (T.D.)	Tuff; crystal/lithic; dark to medium gray-green with slight red cast; featureless groundmass; K-feldspar phenocrysts; chloritized; soft.

PIN CREEK (DNR 88-6)

Depth (Meters) From	To	Description
0.0	6.1	Fill and colluvium; light to medium brown; mixed with organic debris.
6.1	9.1	Clay, weathered bedrock, regolith; medium brown to blue-gray.
9.1	10.7	Volcanic agglomerate or flow breccia(?); medium brown; abundant calcite, zeolites and chalcedony in vugs and fractures.
10.7	12.2	Basalt; dark brown to black.
12.2	42.7	Volcanic agglomerate; gray and blue-green, red-gray at 21.0 m; clay matrix; andesitic or basaltic clasts; abundant zeolites 28.0-33.0 m.
42.7	47.3	Volcanic sandstone and wacke; dark gray-red; much less clay than in superjacent interval.
47.3	50.3	Volcanic agglomerate and wacke; gray-red; basaltic or andesitc clasts.
50.3	56.4	Basalt; black; plagioclase and pyroxene phyric; zeolites in fractures.
56.4	61.0	Volcanic wacke and claystone; medium to dark purplish-gray; wacke is clay matrix-supported.
61.0	74.7	Volcanic sandstone and wacke; dark gray to red-brown; possible tuffaceous component; less clay than in superjacent interval; slickensides on some larger fragments at 61.0-62.5 m.
74.7	77.7	Claystone, with volcanic wacke; medium gray.
77.7	82.3	Tuff, and tuff breccia; medium gray-red; clay and zeolite matrix; andesitic(?) lithic fragments.

PIN CREEK (DNR 88-6) - cont'd

Depth (Meters) From	To	Description
82.3	96.0	Andesite; dark red-gray; aphyric to glassy, but locally plagioclase phyric; severe fracturing reported by drillers 82.3-85.4 m.
96.0	99.1	Volcanic sandstone and wacke; medium dark red-brown.
99.1	100.6	Claystone; medium to dark red-brown; soft.
100.6	134.1	Volcanic wacke; red-brown, but medium gray 109.8-112.8 m, and especially red 114.3-128.0 m; locally high silt and clay content.
134.1	141.8	Volcanic siltstone and wacke; medium gray-green-brown with some red components in possible fractured areas; zeolites, quartz, and, in places, calcite in amygdules or vugs and as intergranular replacement; locally clay-rich.
141.8	152.4 (T.D.)	Basalt; medium to dark gray-brown; plagioclase phyric; water encountered near bottom of hole, approximately 1 gpm.

QUARTZ CREEK (DNR 88-7)

Depth (Meters) From	To	Description
0.0	1.5	Road ballast, colluvium, and modern plant debris; dark brown to black.
1.5	7.6	Regolith, highly weathered bedrock, and Fe oxide-stained volcanic rock(?); medium red-brown.
7.6	9.1	Tuff or tuff breccia(?); light gray; phyllic and argillic alteration; disseminated pyrite; clay-rich.
9.1	10.7	Felsite or felsic tuff(?); light gray-brown; phyllic and argillic alteration; small vugs with limonitic quartz.
10.7	15.2	Felsite or felsic tuff(?); yellow ochre to red; argillic alteration; Fe oxide-enriched.
15.2	19.8	Felsite or felsic tuff(?); light gray-red-brown to green; argillic alteration; abundant disseminated pyrite.
19.8	22.9	Felsite or felsic tuff(?); light brown; argillic (phyllic?) alteration; extremely clay-rich; disseminated pyrite.
22.9	24.4	Felsite or felsic tuff(?); same as above except less pyrite than superjacent interval.
24.4	35.1	Felsite or felsic tuff(?); light to medium gray-brown; argillic alteration; Fe oxides and local quartz and pyrite in veinlets; little or no disseminated pyrite.
35.1	39.6	Dacite or rhyodacite; medium to light gray-green; K-feldspar phenocrysts partially altered to clay; minor disseminated pyrite and limonite after pyrite; moderately hard;

QUARTZ CREEK (DNR 88-7) - cont'd

Depth (Meters) From	To	Description
39.6	42.7	Felsite or felsic tuff(?); medium to light gray-brown; strong argillic alteration; minor disseminated pyrite.
42.7	74.7	Felsic tuff; light to medium blue-gray; phyllic and argillic alteration; some horizons relatively unaltered, but contains disseminated pyrite throughout interval.
74.7	76.2	Felsite; white to light tan; less alteration than in superjacent interval; contains very fine grained disseminated pyrite.
76.2	114.3	Felsite and/or felsic tuff; light to medium gray; argillic and phyllic(?) alteration; disseminated pyrite throughout interval, locally very dense; local minor silicification.
114.3	117.4	Felsic tuff and tuffaceous sandstone(?); medium to light gray-brown; minor phyllic(?) and argillic alteration; disseminated pyrite but less than in superjacent interval.
117.4	128.0	Andesite; light to dark gray-brown; aphyric to glassy; locally plagioclase phyric.
128.0	147.9	Felsic tuff; light to medium gray; potassic alteration(?); secondary feldspars(?) as long as 2 mm cross primary textural features; locally strong argillic alteration, pyritization; arsenopyrite(?); local quartz-filled amygdules and minute reticulate quartz veinlets.
147.9	152.4 (T.D.)	Felsic tuff; light to medium gray; contains quartz-filled amygdules and vugs; much less altered than in superjacent interval.

SHINGLE MOUNTAIN (DNR 88-8)

Depth (Meters) From	To	Description
0.0	0.3	Talus and colluvium; multicolored; clay-rich; friable.
0.3	7.6	Tuff breccia or volcanic wacke; brown to gray-green; intercalated with siltstone and clay.
7.6	19.8	Tuff or tuff breccia, andesitic(?); black to medium gray and gray-green; black lithic fragments supported in very fine-grained matrix; local lamination noted with possible carbonaceous material along laminae; fractures with Fe oxides 18.3-19.8 m.
19.8	24.4	Tuffaceous agglomerate with volcanic wacke; dark gray to black; small (1-2 mm) lithic fragments disseminated throughout fine-grained, tuffaceous portions; also contains larger fragments of aphyric basalt.
24.4	33.5	Tuff, ashflow(?), with volcanic wacke layers; contains aphyric basalt lithic fragments with serpentine(?) and/or chlorite on fracture surfaces.
33.5	56.4	Sandy tuff, or volcanic wacke; medium gray; contains some darker, larger cuttings comprised of aphyric basalt and claystone(?) with black, carbonaceous laminae; small, black lithics disseminated in tuffaceous portions.
56.4	57.9	Tuff; medium dark gray-green; clay-rich; harder than superjacent interval.
57.9	61.0	Tuff, sandy, or clay-rich, tuffaceous sand; medium to dark gray; contains coal (as much as 50% of sample volume) especially from 57.9 to 59.5 m, mostly durain-like and boney; some coal fragments display slickensides.

Depth (Meters) From	To	Description
61.0	65.5	Tuffaceous sand or volcanic wacke; dark gray to black.
65.5	70.1	Tuff (ashflow or tephra?); medium gray; contains minor amount of coal 65.5-67.1 m.
70.1	76.2	Tuff; medium to dark gray.
76.2	80.8	Tuffaceous sand or sandy, silty tuff; light to medium gray.
80.8	82.3	Tuff; light to medium gray-green; more homogeneous in texture and harder than superjacent intervals.
82.3	91.5	Volcanic wacke or sandy, silty tuff; medium to dark gray.
91.5	93.0	Claystone or tuff; dark gray to black; minor Fe oxides on fracture surfaces.
93.0	100.6	Tuff or volcanic wacke; red-brown; strong Fe oxide replacement; less altered in the lower 3.0 m of interval.
100.6	111.3	Tuff; medium to dark brown, lighter brown near bottom of interval; small black lithic fragments disseminated throughout fine-grained matrix.
111.3	152.4 (T.D.)	Volcanic sandstone, siltstone, or sandy-silty tuff; dark gray to black; zeolites and minor chalcedony throughout most of the interval, especially 118.9-120.4 m, 125.0-126.5 m, 135.7-138.7 m, and 146.3-152.4 m; particularly sandy 117.4-118.9 m, and 129.6-134.1 m; though no water production was reported during drilling, two days after drilling was completed water was flowing at the surface at 1-2 gpm.