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THE 1979-1980 GEOTHERMAL RESOURCE ASSESSMENT PROGRAM IN WASHINGTON

by

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with contributions from
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Note: Appendix D is part of special edition reports only. This section is available from the Division of Geology and Earth Resources as Open File Report 80-9.

I. INTRODUCTION

Geothermal resource assessment activities during 1979 have included temperature-gradient and heat-flow investigations, geochemical investigation of mineral and thermal springs, geologic mapping, a resistivity survey, regional gravity measurements, and preparation of geothermal resource maps for Washington.

The State of Washington thus far has received very little attention from prospective geothermal developers. Consequently, the geologic, geochemical, and geophysical data base with respect to geothermal has been either scattered or nonexistent. Our assessment efforts have, therefore, been primarily directed toward synthesizing and interpreting existing data, and providing regional geophysical and geochemical data bases where none have previously existed. Attention was focused on the southwestern Cascades of Washington during 1979.

The work was carried out by both subcontractors and in-house geologists. The findings of each of the project investigators working on the geothermal assessment program are presented as separate chapters in this report. Some of the individual projects are more complete than others and therefore appear as more detailed presentations.

At the end of each chapter report, the principle investigators, J. Eric Schuster and Michael A. Korosec, have added further information, including comments on project status, how it relates to other projects, usefulness, work yet to be completed, future directions, and interpretations of the data. The interpretations are occasionally made with little data or background information and may not represent the beliefs of the project investigator, but are presented anyway so as to help shape future investigations in the areas affected.

Temperature-Gradient and Heat-Flow Investigations

Shallow drilling and measurements of temperature gradients in existing wells were accomplished in the following areas: (1) the Cowlitz River valley between Interstate 5 on the west and White Pass on the east, (2) the Mount St. Helens area, and (3) the Camas area, located in Clark County east of Vancouver, Washington.

In the Cowlitz River valley, usable temperature gradients were measured in about 22 water wells located in the western portion of the valley, generally between Interstate 5 on the west and the City of Morton on the east. Temperature gradients in these wells are generally 30°C/km or less.

Two gradients measured in existing wells located to the east of the City of Morton and gradients measured in five of the six 500-foot-deep gradient wells drilled during 1979 between the town of Randle and White Pass (both to the east from Morton) are 46°C/km and higher. This suggests that the transition between "Puget Lowland type" temperature gradients of about 30-40°C/km or less (with associated heat flow values of less than 40 mWatts/m^2) and "High Cascade type" gradients of about 45°C/km or more (with associated heat flow values of 60 to 80 mWatts/m^2 or higher) occurs between the City of Morton and the town of Randle. The transition appears to be fairly sharp (perhaps 8 kilometers or less in width) and seems to occur closer to Morton than to Randle.

In the Mount St. Helens area, there are no existing wells except for three holes drilled during 1979 by the Division. The temperature gradient from St. Helens No. 1 drill hole, to the north-northwest of Mount St. Helens, is very low at 19°C/km, and appears to be affected by local hydrologic conditions. In St. Helens No. 2 drill hole, to the west of Mount St. Helens, the gradient is 38°C/km. The third drill hole, to the east-southeast of Mount St. Helens, is isothermal.

In the Camas area, several gradients measured in existing water wells located to the west of 122°20'W. (about the longitude of the City of Camas) yielded temperature gradients of less than 40°C/km, but two water wells located to the east of 122°10'W. produced gradients of about 53° and 69°C/km. Two gradient wells drilled by the Division near Camas produced gradients of 31.5°C/km and 37°C/km. The former well was drilled in Tertiary volcanics and sediments and the latter entirely in late(?) Tertiary sediments. All heat flow values calculated for the Camas area fall in the range of 40 to 60 $mWatts/m^2$.

Geochemistry of Thermal and Mineral Springs

During the 1979 field season, 46 springs, representing 15 different spring systems located in the Cascade and Olympic Mountains, were surveyed for temperature, flow, conductivity, and pH. Of these springs, 38 were sampled and analyzed by the Division of Geology and Earth Resources. Chemical species measured include specific conductivity, pH, Na, K, Ca, Mg, Li, SiO_2, alkalinity, Cl, CO_2, Br, and I.

Tables 4.1 through 4.5 present a listing of the springs, their temperatures, specific conductivities, and reservoir temperatures as predicted by the SiO_2-Quartz and Na-K-Ca geothermometers. Detailed descriptions, analyses, and discussions of observed chemistry for these springs are presented in Chapter IV.

Geologic Mapping

Geoff Clayton, from the University of Washington, mapped the volcanic geology of the Tumac Mountain-White Pass area, located to the south and east of Mount Rainier National Park. Field studies have been completed and a geologic map has been prepared.

Resistivity

A resistivity study was conducted in the Camas area by F. A. Rigby of Science Applications, Inc., and R. B. McEuen of Exploration Geothermics. Two regions of relatively low resistivity were found, and drill sites were recommended to test these two areas. The two Camas drill holes were located at or within a short distance of the drill sites recommended by Rigby and McEuen.

Gravity

During 1979, Z. F. Danes of the University of Puget Sound measured gravity at

743 stations in the south Cascades. The area covered extends from 121°W. on the east to 122°30'W. on the west, and from the Columbia River on the south to the Cowlitz River valley on the north. Computations have continued well into 1980. It is expected that a south Cascades gravity map and report will be ready for distribution by early 1981. Dr. Danes has also produced relatively detailed gravity maps for the Camas and North Bonneville areas, located near the Columbia River in southwestern Washington.

Geothermal Resource Maps

Data acquisition, reduction, and plotting for public and scientific geothermal resource maps of Washington were a large part of the 1979-1980 program. This work was carried out with the assistance and cooperation of personnel from Oregon Institute of Technology, National Oceanic and Atmospheric Administration, and University of Utah Research Institute. Information compiled for the two maps includes well water temperatures, temperature gradients, heat flow, thermal and mineral springs, water geochemistry, faults, Quaternary volcanic rocks and volcanic centers, National Parks, wilderness areas, federal reservations, Indian reservations, lease status, and current and potential geothermal uses.

II. GEOTHERMAL PROGRAM PUBLICATIONS

The 1979 Geothermal Assessment Program led to the release of the following publications by the Division of Geology and Earth Resources. Portions of this report are taken directly from these publications.

References Cited

Danes, Z. F., 1979, Bouguer gravity map of the Camas area, Washington and Oregon: Washington Division of Geology and Earth Resources Open-File Report 79-6, scale 1:62,500.

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.

Bloomquist, R. G., 1980, Geothermal leasing status, January 1980, Washington: Division of Geology and Earth Resources Open-File Report 80-10, scale 1:126,730, (in preparation).

Clayton, G. A., 1980, Geology of White Pass-Tumac Mountain area, Washington: Washington Division of Geology and Earth Resources Open-File Report 80-8, 1 map, scale 1:24,000.

Korosec, M. A., 1980, Bibliography of geothermal resource information for the State of Washington: Washington Division of Geology and Earth Resources Open-File Report 80-4, 16 p.

Korosec, M. A.; Kaler, Keith, 1980, Well temperature information for the State of Washington: Washington Division of Geology and Earth Resources Open-File Report 80-7, 87 p.

Korosec, M. A.; Kaler, Keith; Schuster, J. E.; Bloomquist, R. G.; Simpson, S., 1980, Geothermal resource map of Washington State, Nontechnical edition: Washington Division of Geology and Earth Resources, Geologic Map 25, 1 sheet, scale 1:500,000.

Korosec, M. A.; McLucas, G. B., 1980, Quaternary volcanics in the State of Washington: Washington Division of Geology and Earth Resources Open-File Report 80-6, scale 1:500,000.

McLucas, G. B., 1980, Fault map of Washington, with references: Washington Division of Geology and Earth Resources Open-File Report 80-2, scale 1:100,000.

Schuster, J. E.; Korosec, M. A., 1980, Geothermal resource assessment in Washington. In Resource Assessment/Commercialization Planning Meeting, Salt Lake City, Utah, January 21-24, 1980: U.S. Department of Energy, p. 146-152.

III. HEAT FLOW AND GEOTHERMAL GRADIENT MEASUREMENTS IN WASHINGTON THROUGH 1979

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III. HEAT FLOW AND GEOTHERMAL GRADIENT MEASUREMENTS IN WASHINGTON THROUGH 1979

Introduction

This chapter presents a summary of all published and unpublished heat flow and geothermal gradient measurements made in the State of Washington prior to 1979, and held in the files of the Geothermal Laboratory at Southern Methodist University, and a preliminary list of temperature gradient information collected in 1979. The data in the files include published heat flow values and temperature-depth data with accompanying pertinent information from the publications of Roy (1963), Roy and others (1968), Blackwell (1969, 1974), Sass and others (1971), Steele (1975) and Schuster and others (1978). Also included are temperature data from Spicer (1964) and Sass and Monroe (1974). A few unpublished temperature logs made by the U.S. Geological Survey Water Resources Division in Tacoma, Washington, and by the U.S. Geological Survey Geothermal Group in Menlo Park, California, are also included.

This chapter is divided into two sections: in the first section, a summary of the geothermal gradient data and well locations is presented in tabular form and plotted on a map. In the second section of the report (Appendix D), listings for individual drill holes of temperature versus depth for all wells available in Washington are included. In some cases, more than one temperature logging is available. Each temperature-depth log has been plotted on a graph accompanying the temperature listings.

The history of geothermal measurements in Washington began in the 1930's when U.S. Geological Survey personnel directed by VanOstrand made temperature measurements in several oil wells in the State of Washington. These data became available on open file in 1964 (Spicer, 1964). Temperature data from two of these wells (20N/12W-8 and 11N/26E-20CC) are included in the data set in this report and estimated heat flow values have been calculated for these two holes based upon thermal conductivity values estimated from the lithologic units encountered in the holes. Following these studies there was a long hiatus until the early 1960's, when R. F. Roy made heat flow measurements in the Metaline mining district in northeastern Washington and measured temperatures in a deep oil well drilled in the Columbia Plateau (Development Associates Basalt Explorer No. 1, 21N/31E-10CB). The heat flow values in the Metaline district were published in 1963 (Roy, 1963; Roy and others, 1968). In the mid-1960's investigations were started by the author of this chapter. The first results of these studies were published in 1969 (Blackwell, 1969). Continued investigations were supported by NSF Grant No. GA11351. The preliminary results were published in 1974 (Blackwell, 1974). The most up-to-date summary of heat flow and geothermal gradient from a state-wide point of view is the 1974 report. In that paper several preliminary heat flow values were discussed. The final heat flow values for those sites are included in this report. In the 1960's, measurements were made at several localities in the state by the U.S. Geological Survey Geothermal Group in Menlo Park, California. These results were published by Sass and others (1971).

All pertinent facts dealing with the measurements made in the 1960's (Roy and others, 1968; Blackwell, 1969; and Sass and others, 1971) are listed in Sass and Monroe (1974). Temperature-depth data, individual thermal conductivity measurements, and terrain correction information for each hole are included here. The temperature data have been abstracted from Sass and Monroe for inclusion in this report.

Subsequent to these studies, detailed studies of more localized areas were made in the Turtle Lake quadrangle of northeastern Washington (Steele, 1975) and in the Indian Heaven area in the southern Washington Cascade Range (Schuster and others, 1978). In 1978 a reconnaissance study of the southern Columbia Plateau was carried out to investigate the regional heat flow. Preliminary water chemistry studies indicated the possibility of anomalous heat flow values in the area, (C. A. Swanberg, personal communication, 1977). The studies were part of a regional geothermal analysis of the Pacific Northwest supported by NSF Grant No. AER-76-00108 (see Blackwell, 1978). In the 1970's, a few temperature logs were made by the U.S. Geological Survey Geothermal

Group at Menlo Park (holes 3N/5E-4CAB and 3N/5E-4BDC1, John Sass, personal communication, 1977). These data are included in this report. In addition miscellaneous data, mostly temperature data from holes for which no heat flow determinations were made, either because of lack of thermal conductivity information or poor quality gradients are included for completeness.

In addition to the data included in this report, there are two extensive sets of temperature logs available for the Columbia Plateau region. One set was obtained by investigators from the U.S. Geological Survey Water Resources Division in Tacoma, Washington and one set by the Washington State University Hydrologic Program at Pullman, Washington. These data are now on file at the Washington Department of Natural Resources and are in the process of being prepared for release.

Data Format

Geothermal gradient information from the State of Washington is summarized in tables 3.1, 3.2, and 3.3. Included in table 3.1 are location, hole name, elevation, geothermal gradient, depth interval, thermal conductivity (where available), heat flow (where available), a summary of the rocks encountered in the drill hole, and a quality indicator for all holes. These data have been taken from the publications discussed above, and from the files of the Geothermal Laboratory at Southern Methodist University. More recent studies (1979) by Southern Methodist University and the State of Washington supported by the U.S. Department of Energy, are reported in preliminary form in table 3.3. The individual holes are located by latitude and longitude to the nearest 0.1' if possible. The holes are also located by township and range. Location within the section is by a letter code where A = NE, B = NW, C = SW, D = SE. The first letter represents the quarter-section, the second the quarter-quarter-section, and the third (if listed) represents the quarter-quarter-quarter-section. The designation 16 N 22 E 13 ABD, for example, represents a well in the southeast quarter of the northwest quarter of the northeast quarter of

Table 3.1 Pre-1979 Geothermal Gradients and Heat Flow in Washington State.

Geothermal data for the State of Washington available up to 1979. T C is thermal conductivity in watts per meter per °K ($Wm^{-1}K^{-1}$). Uncorrected and (terrain) corrected gradient and terrain corrected heat flow are shown. Significance of heat flow quality number is explained in text. Locations of data taken from the literature are listed at the end of the table.

TOWNSHIP RANGE	SECTION	N.LAT. (Deg.-Min)	W.LONG. (Deg.-Min)	HOLE NO.	MEASURED DATE	BOTTOM TEMP. (°C)	DEPTH INTERVAL (meters)	AVG. T.C. ($Wm^{-1}K^{-1}$)	NO. T C	UNCORR. GRAD. (°C/Km)	CORR. GRAD. (°C/Km)	CORR. H.F. (mWm^{-2})	H.F. QUALITY	
40N/27E-	6B1	48-59.8	119-29.4	DDH-A	7/17/71	14.62	50.0 140.0			30.2 .7			5	
40N/27E-	6B2	48-59.9	119-29.3	DDH-C	7/17/71	13.91	45.0 210.0			21.3 .1			5	
40N/27E-	6B3	48-59.9	119-29.6	DDH-E	7/17/71	15.41	155.0 225.0			23.6 .2			5	Best Value 70
40N/27E-	6B4	48-59.8	119-29.5	DDH	7/17/71	14.96	60.0 200.0			25.5 .1			5	
40N/27E-	6BDC	48-59.7	119-29.2	DDH-K-5	7/17/71	15.31	60.0 180.0	3.16 .08	19	25.2 .1	22.3	70.	1	
40N/33E-	2ACD	48-59.7	118-35.9	DDH-702	7/15/71	10.82	75.0 205.0	3.17 .13	22	25.2 .6	22.7	72.	1	
40N/33E-	2DBB1	48-59.6	118-36.1	DDH-7012	7/15/71	9.39	100.0 150.0			26.5 .3			10	
40N/33E-	2DBB2	48-59.6	118.36.0	DDH-7013	7/22/71	9.38	130.0 155.0			25.8 .3			5	Best Value 72
40N/33E-	2DBB3	48-59.7	118.36.0	DDH-7011	7/22/71	10.78	80.0 215.0	3.15 .13	20	25.0 .3			1	
40N/43E-	35D	48-55.0	117-20.0	METL-CS2	8/24/61	17.91	350.0 396.0	5.15	14	25.9	22.4	115.	6	Best Value 106
40N/43E-	35D	48-55.0	117-20.0	METL-CS9	8/29/61	16.82	320.0 366.0	4.81	5	22.0	20.0	96.	6	
39N/41E-	2BDB	48-55.0	117-35.7	DDH-3	6/16/65	12.37	100.0 240.0	5.98 .04	16	23.9 .1	21.0	126.	6	
39N/41E-	2CAB	48-54.9	117-35.8	DDH-2	6/17/65	13.34	290.0 340.0	6.02 .04	16	22.0 .1	20.4	123.	6	
39N/41E-	2CBA	48-54.9	117-36.0	DDH-4	6/16/65	9.56	120.0 200.0			14.1 .8			20	Best Region Value 84
39N/41E-	2CBB	48-54.9	117-36.1	DDH-5	6/16/65	9.92	120.0 180.0			17.2 .6			20	
39N/41E-	2CBD	48-54.8	117-36.0	DDH-1	6/15/65	10.81	130.0 220.0			18.3 .7			20	
37N/26E-	8DBC	48-43.0	119-35.5	DDH-1	7/24/71	16.48	165.0 435.0	3.50 .13	26	19.4 .2	21.5	75.	1	
37N/32E-	33AAC	48-40.0	118-46.4	DDH-3	7/21/70	14.39	150.0 260.0	2.41 .04	17	30.9 .2	31.1	76.	1	
37N/32E-	34B1	48-39.8	118-45.7	DDH-A	7/21/70	11.44	100.0 195.0			21.8 .2			10	
37N/32E-	34B2	48-39.8	118-45.7	DDH-B	7/31/70	9.13	50.0 95.0			24.5 .8			20	
37N/32E-	34B3	48-39.8	118-45.7	DDH-C	7/31/70	9.46							30	
36N/20E-	19ABB	48-36.8	120-23.3	DDH-LD13	8/ 8/71	11.68	75.0 170.0			23.7	23.2		5	
36N/20E-	19ADC	48-36.5	120-23.1	DDH-LD10	8/ 8/71	14.41	140.0 275.0	2.88 .08	15	28.3 .2	26.7	77.	1	Best Value 75
36N/20E-	19DAB	48-36.3	120-23.1	DDH-LD7	8/ 8/71	14.94	240.0 360.0	3.19 .29	4	24.0 .1	23.0	73.	1	
34N/ 1E-	1CBB	48-27.5	122-38.0	DDH-1	8/ 2/71	11.61	80.0 220.0	2.96 .04	25	12.7 .1	12.6	37.	1	

TOWNSHIP RANGE	SECTION	N.LAT. (Deg.-Min)	W.LONG. (Deg.-Min)	HOLE NO.	MEASURED DATE	BOTTOM TEMP. (°C)	DEPTH INTERVAL (meters)	AVG. T.C. ($Wm^{-1}K^{-1}$)	NO. T C	UNCORR. GRAD. (°C/Km)	CORR. GRAD. (°C/Km)	CORR. H.F. (mWm^{-2})	H.F. QUALITY	
33N/31E-	14ACB	48-21.8	118-52.3	DDH-3	8/ 7/70	11.44	205.0 270.0	3.11 .08	9	20.4 .3	22.4	69.	1	Best Value 68
33N/31E-	14BDA	48-21.8	118-52.6	DDH-1	6/20/70	9.86	130.0 230.0	3.36 .13	17	16.6 1.0	20.4	69.	6	
33N/31E-	14BDC	48-21.6	118-52.8	DDH-2	6/20/70	9.35	120.0 200.0	3.36 .13	18	16.8 .3	19.5	66.	1	
31N/15E-		48-11.9	120-58.6	DDH-141	9/ 2/70	4.81							30	
31N/15E-		48-11.9	120-58.6	DDH-2	9/ 2/70	4.06	70.0 75.0			21.6 .3			30	
30N/16E-		48- 6.1	120-49.8	DDH-1	8/ 5/70	14.04	20.0 175.0			49.0 5.5			20	
30N/33E-	31BDD	48- 3.5	118-42.4	DDH-A	8/11/66	9.49	115.0 195.0	3.81	2	14.6 .2	19.7	75.	1	Best Value 71
30N/33E-	31CAB	48- 3.3	119-42.4	DDH-B	8/23/66	9.82	120.0 255.0	4.15 .21	11	11.6 .1	17.9	74.	1	
30N/33E-	31CAC	48- 3.2	118-42.4	DDH-C	8/16/67	14.79	90.0 420.0	3.76 .17	28	13.5 3.5	18.6	68.	1	
							420.0 470.0	2.98 .21	8	17.4 1.4	23.2	69.	1	
29N/37E-	36DDD	47-58.5	118- 4.0	DDH-2	10/15/72	16.87	60.0 380.0	3.13	25	28.4 .3	27.0	85.	1	
28N/37E-	9DBD	47-56.6	118- 9.2	S-9	8/11/70	13.80	100.0 133.0	3.00 .04	6	26.0 .1	25.1	76.	6	
27N/37E-	2BBB	47-52.4	118- 7.4	WW-EAST	8/10/72	14.89	90.0 150.0	3.31 .04	6	24.8	26.7	87.	6	Best Value 89
27N/37E-	3AAA	47-52.4	118- 7.4	WW-WEST	8/10/72	12.22	60.0 100.0	3.26	6	26.5	27.8	91.	6	
27N/38E-	28BBB	47-49.0	118- 1.5	S-28	8/10/72	13.58	100.0 145.0	2.54	2	33.8	33.0	84.	6	
25N/ 9E-	4AAD	47-41.1	121-38.9	DDH-11	11/ 1/72	2.98							30	
25N/ 9E-	4ADA	47-41.0	121-38.9	DDH-12	11/ 1/72	3.36	120.0 145.0	3.03	2	10.5 .1	20.0	61.	16	
23N/11E-	1C	47-30.5	121-21.2	DDH-1	6/25/65	6.79	80.0 130.0	3.93 .21	9	16.2 .3	14.7	58.	16	Best Value 57
23N/11E-	10DCA	47-29.5	121-24.1	DDH-2	7/24/65	18.88	86.6 251.0	3.03 .08	24	25.2 1.0	18.6	56.	16	
22N/20E-	26CBB	47-22.1	120-18.0	NORCO-1	8/ 4/70	35.68	310.0 900.0	2.18 .21	18	26.8 .2	28.4	62.	1	
21N/31E-	10CB	47-20.0	118-55.0	DABE-1	8/31/61	57.54	61.0 1250.0	1.67 .21		42.0 2.0	42.0	70.	6	
20N/12W-	8	47-14.3	124-11.5	VO-MO 1	0/ 0/30	35.56	304.8 1066.8	1.30		27.4 1.7	27.4	36.	6	
20N/15E-	18DDD	47-13.2	121- .5	DDH-E	7/14/72	11.61	5.0 200.0			20.8 3.5			20	
16N/12W-	24DAD	46-51.0	124- 6.0	TW-1	8/ 4/71	14.29	60.0 155.0	1.48 .04	22	26.5 2.2	26.5	38.	1	
16N/ 4E-	14CD	46-51.9	122-16.3	WW-14P1	12/ 8/71	10.23	40.0 75.0			12.4 .8			30	
16N/35E-	22CDA	46-51.4	118-24.5	BAUMN1WW	2/ 9/78	15.33	.0 315.0	1.59		23.0	23.0	36.	26	
13N/19E-	24AA	46-36.3	120-23.1	GJR-WW	3/13/72	19.95	120.0 225.0	1.59		26.4 .6			30	
13N/26E-	25	46-35.0	119-31.0	DH-1	1/13/70	21.89	53.0 183.0	1.71 .03	19	37.2 .3	37.2	64.	1	

TOWNSHIP RANGE	SECTION	N.LAT. (Deg.-Min)	W.LONG. (Deg.-Min)	HOLE NO.	MEASURED DATE	BOTTOM TEMP. (°C)	DEPTH INTERVAL (meters)	AVG. T.C. ($Wm^{-1}K^{-1}$)	NO. T C	UNCORR. GRAD. (°C/Km)	CORR. GRAD. (°C/Km)	CORR. H.F. (mWm^{-2})	H.F. QUALITY	
12N/ 1W-	7AAB	46-32.7	122-50.8	RDH-SU8	1/ 7/72	25.21	50.0 565.0			29.0 .2			5	
							90.0 360.0			33.2 .2			5	
							375.0 565.0			25.2 .1			5	
12N/ 1W-	8CAB	46-32.3	122-50.2	SU-14	6/13/67	25.55	100.0 400.0	1.09 .04	59	33.8 .1	33.8	36.	1	
12N/ 1W-	8CCC	46-31.9	122-50.5	RDH-SU37	1/12/72	24.66	45.0 150.0			27.7 .4			5	
							150.0 395.0			33.5 .1			5	
							395.0 540.0			24.6 .1			5	
12N/ 1W-	8DAA	46-32.3	122-49.5	SU-12	1/12/72	25.72	110.0 365.0			27.3 .3			5	Best Value 36
							260.0 578.0			21.5 .3			5	
12N/ 1W-	8DAD	46-32.2	122-49.5	SU-11	6/12/67	21.31	100.0 340.0	1.09 .04	59	34.6 .2	34.6	37.	1	
12N/ 1W-	9CCC	46-32.0	122-48.7	SU-4	6/12/67	28.78	100.0 380.0	1.09 .04	59	32.8 .3	32.8	36.	1	
							710.0 760.0	1.77 .01	5	19.4 .6	19.4	34.	1	
12N/ 1W-	17ADA	46-31.6	122-50.1	SU-902	3/19/73	31.21	90.0 340.0			32.7 1.0			5	
							340.0 690.0			24.8 .5			5	
							690.0 847.0			22.2 .3			5	
12N/ 1W-	17BAD	46-31.8	122-49.5	SU-10	3/19/73	19.83	90.0 348.0			34.8 .9			5	
12N/40E-	14DAD	46-31.2	117-45.6	SCOTT-WW	7/29/78	13.54	15.0 62.5	1.59		33.9 .4	40.0	64.	16	
12N/40E-	17ADA	46-31.6	117-49.3	DODGEJCT	2/27/78	14.71	.0 90.0	1.59		42.0	41.7	66.	26	
11N/24E-	15 1	46-26.0	119-47.0	RS-1	6/ 7/67	96.29	900.0 2500.0	1.59 .13	6	34.8	37.1	58.	6	Best Value 58
11N/24E-	15 2	46-26.0	119-47.0	RS-2	1/14/69	13.72	58.0 119.0	1.72 .04	14	28.0 .2	33.2	57.	6	
11N/26E-	20CC	46-25.2	119-35.4	VO-SOC 1	0/ 0/30	13.72	30.5 670.6	1.59		37.4 4.4	35.6	56.	6	
11N/45E-	32DAB	46-23.3	117-11.5	SILCOTWW	2/19/78	17.50	10.0 192.0	1.59		31.3 .5	32.0	51.	6	
11N/46E-	19BB	46-25.4	117- 5.9	PTWLMAWW	1/17/78	12.63							30	
11N/46E-	32BCA	46-23.5	117- 4.5	WWPC7-1W	2/15/78	26.17	15.0 405.0	1.59		35.6	35.6	56.	6	
10N/ 6E-	8DDA	46-21.6	122- 4.5	DDH-9	10/25/72	6.51	80.0 135.0			14.4 .5			20	
							80.0 270.0			9.9 1.1			20	
							120.0 270.0	3.68 .17	6	12.5	18.5	68.	16	Best Value 69
10N/ 6E-	18BDB	46-21.1	122- 6.4	DDH-1	10/31/71	10.56	205.0 210.0	3.85 .13	6	22.0	18.0	69.	16	

TOWNSHIP RANGE	SECTION	N.LAT. (Deg.-Min)	W.LONG. (Deg.-Min)	HOLE NO.	MEASURED DATE	BOTTOM TEMP. (°C)	DEPTH INTERVAL (meters)	AVG. T.C. ($Wm^{-1}K^{-1}$)	NO. T C	UNCORR. GRAD. (°C/Km)	CORR. GRAD. (°C/Km)	CORR. H.F. (mWm^{-2})	H.F. QUALITY
10N/28E-	14ACC	46-21.1	119-16.2	DH-3-WW	8/12/70	47.78	174.0 608.0	1.65 .07	16	25.1 .3			1
							608.0 1079.0	1.52 .03	15	34.6 .3			1
							174.0 1079.0	1.59		30.0	30.0	47.	1
10N/39E-	30AA	46-19.4	117-58.6	WARNERWW	2/10/78	11.86							30
10N/41E-	30BD	46-22.4	117-39.5	NEIBLEWW	8/ 3/78	11.35	10.0 90.0	1.59		22.1 .6	27.2	43.	16
9N/32E-	13BA	46-16.0	118-45.2	POWER-WW	2/10/78	22.20	135.0 210.0	1.59		34.8 .6	34.8	55.	6
8N/33E-	21D	46- 9.3	118-41.0	GLUCK-WW	2/ 3/78	24.05	15.0 50.0			58.6 1.6	58.6		6
							50.0 200.0	1.59		37.7 1.0	37.7	60.	6
8N/36E-	30BA	46- 9.0	118-21.4	VANAUSWW	1/13/78	10.98							30
8N/44E-	2AAD	46-12.3	117-15.0	REEVESWW	7/28/78	10.93	10.0 50.0			19.4 .8			20
7N/ 8E-	2BCD	46- 7.5	121-46.2	DGER-4	9/14/76	9.10	85.0 150.0	1.25 .03	5	48.5 .5	44.5	56.	1
7N/ 8E-	36C	46- 2.9	121-45.0	DGER-7	9/14/76	3.55	15.0 25.0	1.17		70.0	58.0	67.	16
7N/ 9E-	17AA	46- 5.9	121-42.0	DGER-3	9/13/76	12.98	115.0 150.0	1.24 .11	4	58.5 2.5	53.4	66.	1
7N/33E-	24DC	46- 4.0	118-37.4	MT-WW	3/16/72	17.01	200.0 235.0	1.59		17.0 .5	17.0	27.	26
7N/34E-	36CAD	46- 2.3	118-30.3	STILERWW	2/ 8/78	13.39	10.0 32.5	1.00		55.4 3.2	55.4	56.	16
7N/35E-	25AAC	46- 3.7	118-22.2	ARTID8WW	1/30/78	19.70	85.0 260.0	1.59		34.0	34.0	54.	16
7N/35E-	25ABA	46- 3.8	118-22.3	GUG-WW	1/30/78	12.72	45.0 70.0			33.7 9.8			30
7N/35E-	35AA	46- 2.9	118-22.3	WWCOLLWW	1/30/78	20.54	100.0 165.0			27.4 .4			30
7N/36E-	17CAD	46- 5.4	118-20.3	WWGC-WW	8/ 8/78	20.94	100.0 225.0	1.59		35.4 .5	35.4	56.	6
7N/36E-	19BD	46- 4.4	118-21.5	DKFF-WW	3/15/72	20.58	110.0 250.0			23.1 3.1			30
7N/36E	33BB	46- 2.9	118-19.3	WW-7	3/14/72	28.64	.0 425.0	1.59		33.3	33.3	53.	16
7N/46E-	2AA	46- 8.0	116-55.1	DODD-WW	2/18/78	15.31	160.0 275.0	1.59		27.6 .7	36.1	57.	16
7N/46E-	13BA	46- 9.7	116-53.5	HELBAR	3/ 4/78	13.01	15.0 85.0	1.59		53.0 1.0	40.8	65.	16
6N/ 7E-	23BAC	45-59.9	121-53.6	DGER-5	9/14/76	11.50	100.0 150.0	1.23 .06	6	51.0 .4	49.8	61.	1
6N/ 9E-	25ACC	45-58.6	121-37.4	DGER-2	9/13/76	12.19	100.0 150.0	1.42 .03	8	53.8 .8	52.7	75.	1
6N/33E-	10BD	46- 1.5	118-37.3	BRNAMWW	2/ 2/78	31.78	10.0 60.0			78.9 4.8	78.9		10
							60.0 305.0	1.05		69.0 8.0	69.7	73.	6
6N/33E-	10AD	46- 1.0	118-40.6	GARDNAWW	2/ 2/78	16.39	20.0 85.0	1.05		104.1 5.0	106.8	112.	16
6N/36E-	4CA	46- 1.5	118-20.7	HILLRDWW	3/31/78	13.88	35.0 57.5	1.13		81.8 3.6	81.8	93.	16
6N/43E-	12CCC	46- .3	118-30.6	FROG-WW	2/ 8/78	11.01							30

TOWNSHIP RANGE	SECTION	N.LAT. (Deg.-Min)	W.LONG. (Deg.-Min)	HOLE NO.	MEASURED DATE	BOTTOM TEMP. (°C)	DEPTH INTERVAL (meters)	AVG. T.C. ($Wm^{-1}K^{-1}$)	NO. T C	UNCORR. GRAD. (°C/Km)	CORR. GRAD. (°C/Km)	CORR. H.F. (mWm^{-2})	H.F. QUALITY	
5N/ 8E-	22ABC	45-54.8	121-46.8	DGER-6	9/14/76	2.71	15.0 55.0	1.26 .21		2.0			30	
3N/ 5E-	4ACA	45-46.4	122-11.6	SS-21	9/15/76	13.66	25.0 305.0			23.5	20.0	56.	5	
3N/ 5E-	4ACB	45-46.5	122-11.8	SS-23	9/15/76	11.35	15.0 150.0			16.7 .2			10	
							150.0 245.0			24.6 .2			10	
3N/ 5E-	4BCA	45-46.5	122-12.1	SS-18	9/15/76	13.19	30.0 140.0			20.3 .2			10	
3N/ 5E-	4BDA	45-46.5	122-11.9	SS-8	10/ 9/75	9.42	20.0 70.0				20.0	56.	5	
3N/ 5E-	4BDB	45-46.5	122-12.1	SS-20	9/15/76	13.52	35.0 300.0				20.0	56.	5	
3N/ 5E-	4BDC1	45-46.5	122-12.0	SS-4	7/14/75	9.26	30.5 152.4			15.5 .2			5	Best Value 56
3N/ 5E-	4BDC2	45-46.4	122-13.0	SS-22	9/16/76	11.51	30.0 220.0			23.2 .3			5	
3N/ 5E-	4CAB	45-46.3	122-12.0	SS-3	9/16/76	14.20	205.0 390.0			24.4 .2			10	
3N/ 5E-	4CAC	45-46.2	122-12.0	SS-6	9/16/76	11.52	15.0 120.0				20.0	56.	5	
							120.0 215.0						5	
3N/21E-	19BAB	45-44.1	120-13.6	RB-1	10/30/74	19.03	30.0 70.0	1.59		54.3 2.0	53.8	85.	6	
2N/ 7E-	22ABC	45-38.8	121-55.7	DH-1083	10/28/75	11.35							30	
2N/ 7E-	22BBA1	45-38.9	121-56.1	DH-1201	10/28/75	12.45	40.0 82.0			40.5 1.2			10	
2N/ 7E-	22BBA2	45-38.9	121-56.1	DH-1203	10/28/75	12.29	45.0 80.0			34.8 2.1			20	
2N/ 7E-	22BBA3	45-38.9	121-56.1	DH-1204	10/28/75	11.72	40.0 60.0			24.6 1.3			30	
2N/ 7E-	22BBA4	45-38.9	121-56.1	DH-1209	10/28/75	11.98	50.0 60.0			19.0 2.9			30	
2N/ 7E-	22BBA5	45-38.9	121-56.0	DH-1210	10/28/75	12.77							30	
2N/ 7E-	22BBA6	45-38.9	121-56.1	DH-1029	10/28/75	13.05							30	
2N/ 7E-	22BBA7	45-38.9	121-56.1	USCE1440	4/12/77	12.62	20.0 85.0			30.4 6.1			20	
							50.0 84.5			42.4 2.8			20	
2N/ 7E-	22BBA8	45-38.9	121-56.1	USCE1329	4/12/77	12.47	25.0 75.0			29.3 2.7			10	
2N/ 7E-	22BBC1	45-38.8	121-56.3	USCE1462	4/12/77	11.43							30	
2N/ 7E-	22BBC2	45-38.8	121-56.3	USCE1465	4/12/77	11.99							30	
2N/ 7E-	22BBC3	45-38.8	121-56.3	USCE1378	4/12/77	12.11	45.0 75.0			36.7 1.1			20	
2N/ 7E-	22BBC4	45-38.8	121-56.3	USCE1455	4/12/77	12.29							30	
2N/ 7E-	22BBC5	45-38.8	121-56.2	USCE1371	4/12/77	12.11							30	
2N/ 7E-	22BBD1	45-38.8	121-56.2	USCE1385	4/12/77	13.02	25.0 75.0			34.2 2.7			10	
2N/ 7E-	22BBD2	45-38.8	121-56.1	USCE1475	4/12/77	12.40	40.0 58.0			36.8 .8			20	

TABLE 3.1 cont.

Sources of published temperature-depth and heat flow data

Hole Location	Reference
40N/43E-35D1	Roy, 1963; Roy et al, 1968; Sass and Munroe, 1974
40N/43E-35D2	" " " "
39N/41E-2BDB	Blackwell, 1969
39N/41E-2CAB	"
39N/41E-2CBA	"
39N/41E-2CBB	"
39N/41E-2CBD	"
30N/33E-31BDD	Blackwell, 1969 - Recorrected for this report
30N/33E-31CAB	" "
30N/33E-31CAC	" "
29N/37E-36DDD	Steele, 1975
28N/37E-9DBD	"
27N/37E-2BBB	"
27N/37E-3AAA	"
27N/38E-28BBB	"
23N/11E-1C	Blackwell, 1969 - Recorrected for this report
23N/11E-10DCA	" "
21N/31E-10CB	R. F. Roy, personal communication, 1964
20N/12W-8	Spicer, 1964
16N/12W-24DAD	Also logged by U.S.G.S. W.R.D., Tacoma
13N/26E-25	Sass et al., 1971; Sass and Munroe, 1974
12N/1W-8CAB	" " "
12N/1W-3DAD	" " "
12N/1W-9CCC	" " "
11N/24E-15 1	" " "
11N/24E-15 2	" " "
11N/26E-20CC	Spicer, 1964
10N/28E-14ACC	Sass et al, 1971

TABLE 3.2 Washington Heat Flow (Pre-1979)

Township, Range Section	W. Latitude	W. Longitude	No. of Holes	Best Heat Flow Value mWm-2
40N/27E 6B	48°59.8'	119°29.4'	5	70
40N/33E 2D	48°59.6'	118°36.0'	4	72
40N/43E 35D	48°55.0'	117°20.0'	2	106
39N/41E 2C	48°54.9'	117°35.9'	5	84
37N/26E 8D	48°43.0'	119°35.5'	1	75
37N/32E 33A	48°40.0'	118°46.4'	1	76
36N/20E 19A	48°36.5'	120°23.1'	3	75
34N/01E 1C	48°27.5'	122°38.0'	1	37
33N/31E 14A	48°21.8'	118°52.6'	3	68
30N/33E 31C	48°03.3'	118°42.4'	4	71
29N/37E 36D	47°58.5'	118°04.0'	1	85
28N/37E 9D	47°56.6'	118°09.2'	1	76
27N/37E 3A	47°52.4'	118°07.4'	2	89
27N/38E 28B	47°49.0'	118°01.5'	1	84
25N/09E 4A	47°41.0'	121°38.9'	1	61
23N/11E 1C	47°30.5'	121°21.2'	2	57
22N/20E 26C	47°22.1'	120°18.0'	1	62
21N/31E 10C	47°20.0'	118°55.0'	1	70
20N/12W 8	47°14.3'	124°11.5'	1	36
16N/12W 24D	46°51.0'	124°06.0'	1	39
13N/26E 25	46°35.0'	119°31.0'	1	64
12N/01W 09C	46°32.0'	122°48.7'	8	36
12N/40E 14D	46°31.2'	117°45.6'	1	64

TABLE 3.2 cont. Washington Heat Flow (Pre-1979)

Township, Range Section	W. Latitude	W. Longitude	No. of Holes	Best Heat Flow Value mWm-2
12N/40E 17A	46°31.6'	117°49.3'	1	66
11N/24E 15	46°26.0'	119°47.0'	2	58
11N/26E 20C	46°25.2'	119°35.4'	1	56
11N/45E 32D	46°23.3'	117°11.5'	1	51
11N/46E 32B	46°23.5'	117°04.5'	1	56
10N/06E 18B	46°21.1'	122°06.4'	2	69
10N/28E 14A	46°21.1'	119°16.2'	1	47
10N/41E 3D	46°22.4'	117°39.5'	1	43
09N/32E 13B	46°16.0'	118°45.2'	1	55
08N/33E 21D	46°09.3'	118°41.0'	1	60
07N/08E 2B	46°07.5'	121°46.2'	1	56
07N/08E 36C	46°02.9'	121°45.0'	1	67
07N/09E 17A	46°05.9'	121°42.0'	1	66
07N/33E 24D	46°04.0'	118°37.4'	1	27
07N/34E 36C	46°02.3'	118°30.3'	1	56
07N/35E 25A	46°03.7'	118°22.2'	1	54
07N/36E 17C	46°05.4'	118°20.3'	1	56
07N/36E 33B	46°02.9'	118°19.3'	1	53
07N/46E 2A	46°08.0'	116°55.1'	1	57
07N/46E 13B	46°09.7'	116°55.5'	1	65
06N/07E 23B	45°59.9'	121°53.6'	1	61
06N/09E 25A	45°58.6'	121°37.4'	1	75
06N/33E 1D	46°01.5'	118°37.3'	1	73
06N/33E 10A	46°01.0'	118°40.6'	1	112
06N/36E 4C	46°01.5'	118°20.7'	1	93
03N/05E 4A	45°46.5'	122°11.8'	8	56
03N/21E 19B	45°44.1'	120°13.6'	1	85

Table 3.3 1979 Geothermal Gradients and Heat Flow in Washington State.

TOWNSHIP/RANGE SECTION	NORTH LATITUDE (Deg.-Min)	WEST LONGITUDE (Deg.-Min)	HOLE NUMBER & DATE	COLLAR ELEVATION (Meters)	DEPTH INTERVALS (Meters)	UNCORRECTED GRADIENT (°C/Km)	CORRECTED GRADIENT (°C/Km)	CORRECTED HEAT FLOW mW/m^2
18N/ 3E- 12DBD	47- 3.5	122-21.8	BETHL HS 8/21/79	140				
18N/ 5E- 6CDA	47- 4.2	122-13.2	BENJAMIN 8/22/79	167	30.0 68.0	10.9 .6	21.4	
17N/ 2E- 2DAA	46-59.2	122-22.8	MILLER 8/20/79	144	62.5 97.5	21.4 .4	21.4	
					140.0 177.0	25.4 .3	25.4	
16N/ 4E- 22BAB	46-51.8	122-17.4	DN SMITH 8/19/79	262				
16N/ 4E- 23DDD	46-51.0	122-15.4	ANDERSON 8/19/79	432	25.0 86.5	9.0 .5		
15N/ 1W- 21BBB			RDH-1 8/ 9/79	75				
15N/ 4E- 14DDA	46-46.8	122-15.3	B LINDSEY 8/19/79	566	100.0 122.0	14.6 .4		
15N/ 6E- 22ABD	46-46.5	122- 1.8	ASHFRD-1 7/17/79	965	30.0 68.0	137.0 5.0		
14N/ 2W- 4ABD	46-44.0	122-56.2	THOMAS 6/15/79	85	90.0 150.5	20.8 .4		
14N/ 1W- 23DDA	46-40.8	122-45.6	AGNEW 6/14/79	135				
14N/ 1W- 26CAA	46-40.2	122-46.3	REYNOLDS 6/15/79	125	75.0 92.3	199.0 8.0		
14N/ 5E- 4CAD1	46-43.4	122-11.0	MOUNCE 6/ 6/79	451				

14N/ 5E- 4CAD2	46-43.4	122-10.8	PENNGTON 6/12/79	449			
14N/ 8E 6BCC	46-43.8	121-51.1	RDH-LONG 8/14/79	720	10.0 99.5	28.0	
14N/10E- 8DCB	46-42.9	121-34.7	RDH-OHNP 8/27/79	490	75.0 115.0	46.1 1.8	
					103.0 116.0	49.8 .2	
13N/ 4W- 7ABA	46-38.0	123-13.6	ARNOLD 9/ 1/79	85	110.0 128.5	20.6 .5	20.6
13N/ 3W- 35BAB	46-34.5	123- 1.5	MOHORIC 8/31/79	170	120.0 135.0	29.4 .2	
13N/ 2W- 25AAA	46-35.3	122-52.0	DRUCKMAN 7/ 5/79	91	16.0 30.0	182.0 4.0	182.0
13N/ 1W- 17ADA	46-36.9	122-49.4	ANDERSON 5/25/79	92			
13N/ 1W- 18CBB	46-36.7	122-51.8	OLSON 5/26/79	85	65.0 91.0	11.5 .7	11.5
13N/ 1W- 19DCD	46-35.4	122-51.1	SUNDWN 1 6/ 7/79	93	40.0 225.0	21.3 .7	
13N/ 1W- 29DCC	46-34.6	122-50.0	WULZ 6/ 8/79	102			
13N/ 2E- 17BBA	46-36.9	122-35.5	STANSELL 5/26/79	232			
13N/ 5E- 18ABD	46-37.0	122-13.6	ROM 1 6/15/79	358	10.0 55.0	27.0 1.1	
					18.0 57.0	26.9 1.3	23.0
13N/ 9E- 16BCA	46-37.2	121-41.6	RDH-PKWD 9/ 4/79	359	20.0 52.0	46.5 .8	
					10.0 152.0	45.2 1.5	43.5

13N/11E- 2DC	46-38.3	121-23.5	RDH-WTPS 8/27/79	1365	10.0 148.5	52.4 1.1	
12N/ 1E- 12DCB	46-32.1	122-37.4	TALBOTT 6/ 4/79	171	30.0 125.0	21.0	21.0
12N/ 2E- 5DCD	46-32.9	122-34.7	PLANT 6/16/79	284	125.0 155.0	22.7	25.4
12N/ 2E- 9DAD	46-32.1	122-33.2	LCMPK 3 6/23/79	146	60.0 205.0	23.0 .8	
12N/ 2E- 11AAD	46-32.7	122-30.8	HADDALER 5/24/79	184			
12N/ 2E- 16ADC	46-31.5	122-33.4	LCMPK 2 6/ 1/79	149			
12N/ 2E- 16AAA	46-31.9	122-33.3	LKSDCM 1 6/23/79	136	70.0 106.0	18.2 1.7	
12N/ 2E- 20CCC	46-30.2	122-35.6	MFPKFS 1 5/22/79	85	20.0 57.0	25.6 1.3	
12N/ 3E- 7CDB	46-32.1	122-29.0	GOODWIN 5/24/79	210	40.0 86.0	19.1 2.0	19.1
12N/ 3E- 17DCB	46-31.3	122-27.5	AUST 7/ 4/79	226	30.0 50.0	18.7 .4	
					30.0 137.5	15.3 .8	
					90.0 138.5	20.5 .8	
12N/ 3E- 19BC			MOSSRK-3 8/ 3/79				
12N/ 3E- 19CBD	46-30.4	122-29.2	MOSSRK-1 8/ 1/79	348	65.0 232.5	27.0 1.3	27.0
12N/ 3E- 19CCA	46-30.3	122-29.2	MOSSRK-2 8/ 1/79	390	40.0 135.0	26.0	
					135.0 156.5	28.1 .5	

12N/ 3E-	46-30.3	122-23.8	MARCHANT	253		
23DCC			6/ 9/79			
12N/ 3E-	46-29.9	122-22.9	CHURCH-2	420		
25CAB			8/29/79			
12N/ 4E-	46-33.3	122-18.0	WARK	316		
3BCD			6/ 8/79			
12N/ 4E-	46-33.2	122-18.4	BISHOP	287	19.0	17.4
4DAB			6/ 8/79		42.5	1.1
12N/ 7E-	46-31.4	121-56.4	RDH-RAND	274	35.0	41.6
16CC			11/13/79		129.0	1.5
					35.0	44.7
					90.0	.8
					90.0	34.3
					129.0	.6
12N/ 7E-	46-30.0	121-55.1	POL-RAN1	281	15.0	38.5
27CAB			9/ 7/79		34.3	.8
12N/ 8E-	46-33.2	121-47.1	RDH-DVSM		50.0	5.4
3DCD			9/ 6/79		146.0	.5
					40.0	-.3
					147.0	
11N/ 2W-	46-24.7	122-54.0	WALLACE	24	15.0	13.6
26BDC			8/14/79		190.0	.5
					190.0	8.6
					261.5	.5
9N/ 2W-	46-17.7	122-52.1	MOCK	196	20.0	13.5
1ADB			8/ 3/79		135.0	.6
9N/ 5E-	46-16.0	122-14.2	RDH-STH1	78	30.0	17.8
18BB			11/14/79		80.0	.5
					30.0	20.2
					122.5	1.3

8N/ 4E- 14DD	46-10.4	122-16.1	RDH-STH2 11/14/79	1066	50.0 150.0	24.2 1.9	
					112.0 150.0	34.4 1.0	
5N/ 1E- 5CDC	45-56.4	122-42.9	EPPERSON 8/16/79	94	100.0 177.5	19.6 .2	21.5
5N/ 1E- 23CBA	45-54.1	122-39.3	GRIMM 8/ 1/79	158	120.0 246.0	32.1 .5	
5N/ 2E- 24DDA	45-53.9	122-29.5	WALLAM 8/ 1/79	243	35.0 104.0	14.0 3.3	
5N/ 2E- 25DBC	45-53.2	122-30.1	HAGEDORN 7/31/79	201	70.0 158.0	33.1 .6	
5N/ 3E- 28CCC	45-53.0	122-34.5	DREW 8/ 1/79	603	70.0 97.5	20.4 .3	20.4
5N/14E- 22BCB	45-54.5	121- 2.9	URBAN 9/12/79	585	40.0 137.5	29.7 .8	31.2
4N/ 1E- 21ACD	45-49.0	122-41.2	KING 8/ 2/79	79	155.0 236.0	24.7 .3	24.7
4N/ 3E- 18CCB	45-49.6	122-29.5	HOARSH 6/24/79	131	50.0 109.0	31.1 10.0	
					37.5 107.5	28.6 1.2	
					85.0 107.5	29.7 .5	
4N/ 3E- 20ADD	45-49.1	122-28.7	WINSTON 7/28/79	210	135.0 220.0	38.3 .2	
3N/ 3E- 21DAB	45-43.8	122-26.2	ZINTZ 7/ 9/79	250	30.0 103.0	26.7 .5	
3N/ 3E- 21DBD	45-34.6	122-26.4	BOTTMLLR 7/ 5/79	219	30.0 188.0	28.7 1.0	

3N/ 3E-	42-31.5	122-24.4	PLEW	442	30.0	22.3	
23BDB			7/31/79		183.5	3.1	
3N/ 7E-	45-42.3	121-52.0	NIX	146	15.0	36.6	
36BDD			9/ 8/79		150.0	.6	
					200.0	24.0	24.4
					290.0	.2	
3N/ 8E-	45-43.2	121-46.8	CALLAHAN	115	60.0	28.6	
27ACD			9/14/79		84.0	1.8	
3N/12E-	45-42.6	121-18.4	BRADLEY	161	35.0	33.0	33.9
28DCD			9/13/79		185.0	7.5	
3N/15E-	45-41.8	120-55.5	JAEKEL	594	40.0	26.8	27.4
34CCB			9/13/79		149.0	4.0	
2N/ 3E-	45-40.0	122-22.6	VALDESE	365	25.0	23.0	
12CAD			1/ 2/80		127.0	.7	
					100.0	27.5	
					127.0	.3	
2N/ 3E-	45-38.3	122-26.4	RDH-CAM2	79	25.0	43.8	
21DC			12/12/79		70.0	1.7	
2N/ 3E-	45-38.3	122-24.0	FRENCH	134			
26AAC			6/10/79				
2N/ 4E-	45-38.1	122-15.5	WITTERS	207			
29ABB			6/30/79				
2N/ 4E-	45-37.9	122-15.4	WILLIAMS	201			
29ACB			6/27/79				
2N/ 5E-	45-37.1	122- 9.8	RICHARDS	414			
35BBC			9/ 7/79				
2N/ 5E-	45-36.8	122- 7.5	GROSS	268	10.0	51.5	
36DDA			7/10/79		92.0	3.1	
2N/ 5E-	45-36.7	122- 7.7	PATTEN	274	10.0	52.7	
36DDB			7/25/79		129.0	3.0	

1N/ 3E- 2DB	45-35.9	122-23.9	RDH-CAM1 12/19/79	67	60.0 150.0	29.9 1.2
1N/ 3E- 6CCD1	45-38.5	122-29.4	NIELSN 1 6/26/79	62		
1N/ 3E- 6CCD2	45-38.5	122-29.4	NIELSN 2 6/26/79	62		
1N/ 3E- 11CDC	45-34.9	122-24.4	CRWN ZLL 9/ 6/79	7		
1N/ 4E- 5DAD	45-35.9	122-24.9	HATTON 6/19/79	135		
1N/ 4E- 6BCC	45-36.1	122-22.3	ZIMMER 7/ 9/79	164		
1N/ 5E- 1CDD	45-35.6	122- 8.1	SKM CS 1 9/ 6/79	36		

section 13, township 16 N. and range 22 E., Willamette Meridian. Thermal conductivity values are from measurements on core or cuttings samples or estimated based on lithology (values in parentheses). The heat flow values are generally given to two decimal places. Note, however, that the errors of the values are discussed below. The quality indicators are as follows: a quality number of 1, 6, or 16 implies a heat flow value with an estimated error of approximately ±5 percent, ±10 percent and ±25 percent, respectively. A quality value of 30 indicates that no reliable heat flow or geothermal gradient can be calculated from the data because of some problem in the measurements. Usually the poor quality is due to intradrill-hole water flow in holes which were used as water wells and thus are uncased and ungrouted. A quality indicator of 5, 10, or 20 indicates a hole for which the geothermal gradient shown has an estimated error of ±5 percent, ±10 percent, or ±25 percent, respectively. Heat flow values have not been calculated for these holes, either because they are in an area where heat flow data are already available, or because there is no thermal conductivity information available.

The data are summarized in figure 3.1. Shown on this map are locations of holes for which data are available, as listed in table 3.1. In some cases, several holes in very close proximity to one another have been included as a single symbol on a map. Also shown on the map are heat flow values for holes of 1, 6, or 16 quality. Again multiple holes may have been included on this map as a single locality.

The equipment which has been used for almost all of these measurements is described by Roy and others (1968) and by Sass and others (1971). The only exception is the measurements obtained by VanOstrand. These were measurements made with maximum reading thermometers. In general, the precision of the instruments is approximately ± .02°C and the accuracy is approximately ± 0.2°C.

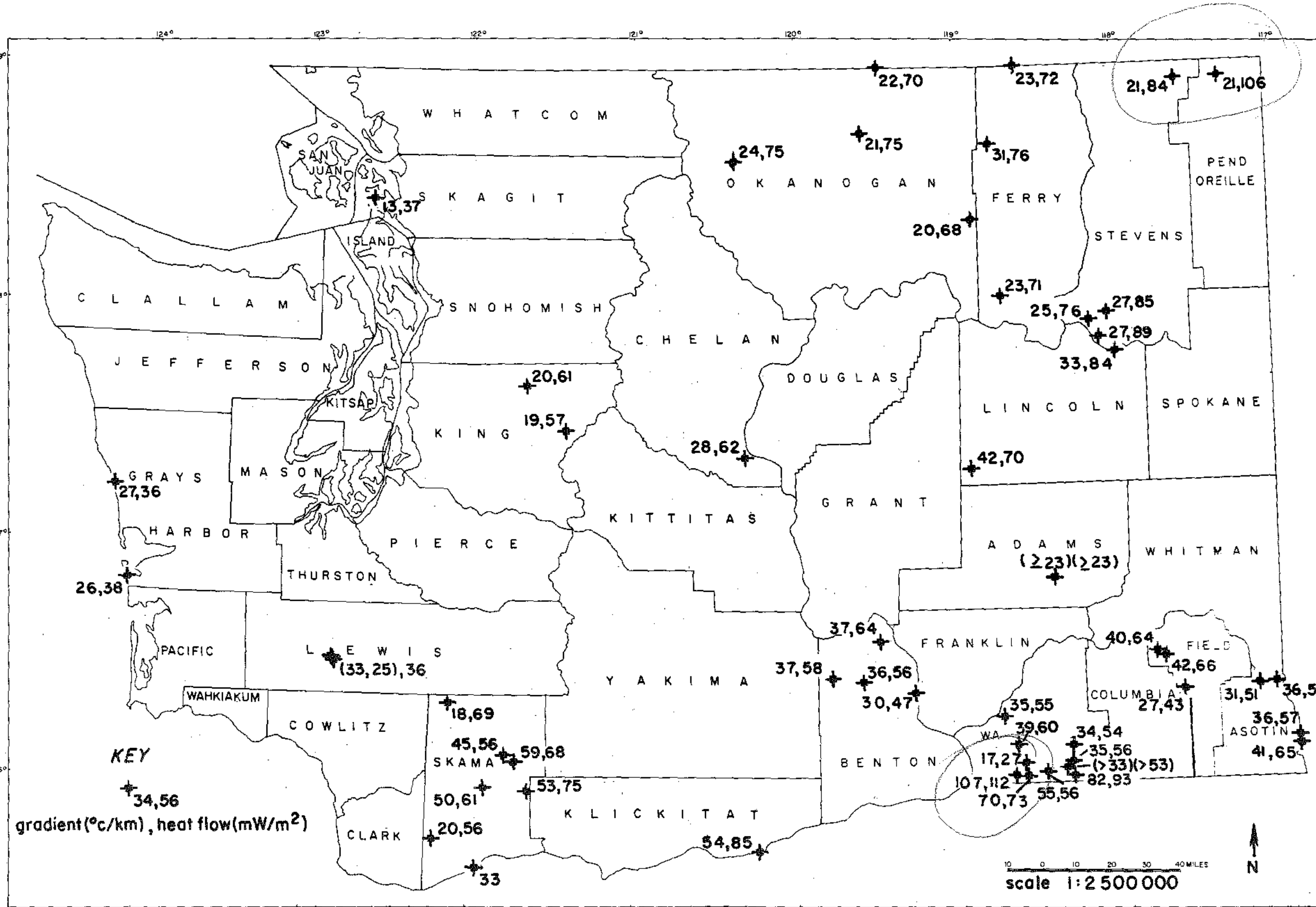


FIGURE 3.1.—Heat-flow and temperature gradient map of Washington (pre 1979 data)

Discussion

The results of these studies have been discussed in preliminary form by Blackwell (1974) from a state-wide point of view. These early data have been supplemented beginning in 1978 and 1979 by extensive new information, with the 1979 data shown on the included map (figure 3.1), in table 3.3, and listed in Appendix D. Brief descriptions of the data and results will be found in Blackwell (1978) and Sass and others (1980). The 1979 data together with the earlier data, will be discussed by Blackwell and others in technical reports to be issued in the near future.

References Cited

Blackwell, D. D., 1969, Heat flow determinations in the northwestern United States: Journal of Geophysical Research, v. 74, p. 992-1007.

Blackwell, D. D., 1974, Terrestrial heat flow and its implications on the location of geothermal reservoirs in Washington: Washington Division of Geology and Earth Resources Information Circular 50, p. 21-33.

Blackwell, D. D., 1978, Heat flow and energy loss in the western United States. In Smith, R. B.; Eaton, G. P., editors, Cenozoic Tectonics and Regional Geophysics of the Western Cordillera: Geological Society of America Memoir 152, p. 175-208.

Roy, R. F., 1963, Heat flow measurements in the United States: Harvard University Ph. D. thesis, 76 p.

Roy, R. F., Decker, E. R.; Blackwell, D. D.; Birch, F., 1968, Heat flow determinations in the United States: Journal of Geophysical Research, v. 73, No. 16, p. 5207-5221.

Sass, J. H.; Lachenbruch, A. H.; Munroe, R. J.; Greene, G. W.; Moses, T. H., 1971, Heat flow in the western United States: Journal of Geophysical Research, v. 76, p. 6379-6413.

Sass, J. H.; Munroe, R. J., 1974, Basic heat-flow data from the United States; U.S. Geological Open-File Report 74-9, 456 p.

Sass, J. H.; Blackwell, D. D.; Chapman, D. S.; Costain, J. K.; Decker, E. R.; Lawver, L. A.; Swanberg, C. A., 1980, Heat flow from the crust of the United States. In Touloukina, Y. W.; Judd, W. R.; Roy R. F., editors, Physical Properties of Rocks and Minerals (Chapter 13): McGraw-Hill (in press).

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.

Spicer, H. C., 1964, A compilation of deep earth temperature data, U.S.A., 1910-1945: U.S. Geological Survey Open-File Report 147, 74 p.

Steele, J. L., 1975, A heat flow study in the Turtle Lake quadrangle, Washington: Southern Methodist University M. S. thesis, 60 p.

Additions and Comments

By Michael A. Korosec

Statewide Regional Heat Flow

Informaton gathered during the 1979 geothermal project (table 3.2 and Appendix A), together with pre-1979 data (table 3.1), have begun to delineate wide regions within the state which demonstrate similar temperature gradient and heat flow characteristics. Since these areas roughly correspond to the physiographic provinces, a variation of these standard provinces will be used here to discuss the density of coverage and our present state of knowledge for regional heat flow. Figure 3.2 is a preliminary statewide heat flow map, based on only scattered data. On this map, the state has been divided into five "heat flow regions"; 1) the Western Washington region, which includes the physiographic provinces of the Puget Lowland, Willapa Hills, and Olympic Peninsula, 2) the North Central region which includes the north and central Cascades, 3) the Northeast region, which includes Okanogan, Ferry, Stevens, and Pend Oreille Counties in the Okanogan Highlands, 4) the Southeast region, which extends from the southern Cascades, through the Columbia Basin, to the Idaho border, and 5) the South Central region, which includes the south Cascades (from roughly Snoqualmie Pass south to the Columbia River) and the Simcoe Mountains.

For the most part, the boundaries between these heat flow regions are only poorly defined. For lack of better evidence, many of these boundaries have been sketched in to correspond to the physiographic province boundary. This is not to imply that heat flow transitions occur at these boundaries. In fact, a few heat flow transition zones have been shown to occur many 10's of miles offset from physiographic province boundaries, as discussed later.

1) Western Washington: The highest number of temperature gradients and heat flow values have been obtained from within this heat flow region, but vast areas are still poorly defined, especially the Willapa Hills and central Olympic Peninsula, where virtually no data exist. Because there are only a few pre-existing wells in

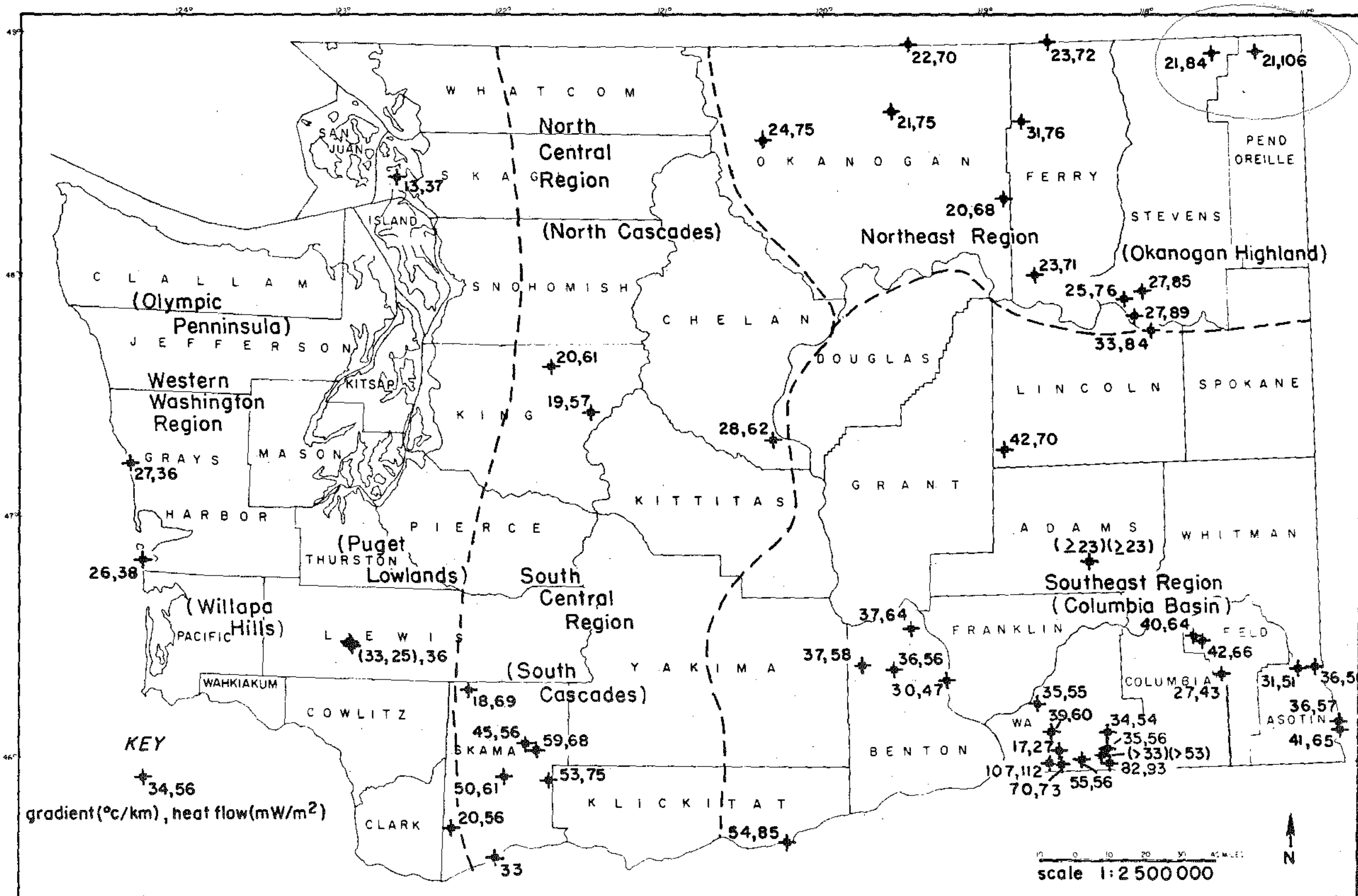


FIGURE 3.2.—Preliminary heat-flow region map of Washington.

these areas, it is not likely that data will be available in the near future. (It is suspected that temperature gradients and heat flows are low in these areas, and thus the state geothermal program includes no plans to drill heat flow holes in these provinces. In addition, most of the Olympic Peninsula is part of the Olympic National Park and therefore closed to exploration.) Within the Western Washington region, heat flow values range from 20 to 45 mWatts/m^2, and temperature gradients are usually 15 to 35° C/km.

2) North Central: There are only two data points within this region, and both are located in King County, at the far southern end of the region. It is suspected that the increased heat flow associated with the Cascade mountains of Oregon and southern Washington also exists within the central and northern Cascades. The existence of the Quaternary volcanic centers Mount Baker and Glacier Peak further suggests that this province should have at least moderate heat flow, with values higher than those of western Washington. Values are suspected to range from 50 to 80 mWatts/m^2, with possibly higher anomalous values associated with the two volcanoes.

3) Northeast Washington: This region corresponds to the Okanogan Highland and has a good scattering of well locations which provide consistent data. While temperature gradients are low or normal, from 20 to 30° C/km, the heat flow has been determined to be a moderately high 70 to 105 mWatts/m^2 because of the high conductivity of the rocks in the region.

4) Southeast region: This relatively large section of the state may actually contain many smaller "sub-regions", each with its own characteristic heat flow values. A tremendous number of well logs are available for the Columbia Basin, because of the large number of moderately deep irrigation wells drilled since the early 1900's, but only a few of these have calculated heat flows. Many wells are poorly cased, partially cased, or completely uncased, and water flow up and down the drill holes produces stair-step temperature vs. depth plots. The straight-line segments of these gradients are most likely meaningless. For these holes, only the

bottom hole temperature can be reliably reported. The heat flow values that have been reported for "well behaved" holes fall mostly in the range of 55 to 70 mWatts/m^2, but some values range as high as 93 and 112 mWatts/m^2, especially around the Walla Walla area. Gradients from these wells range from 35 to 45° C/km, with values of 70, 82, and 107° C/km for the anomalous holes near Walla Walla.

If the data sets reported in Appendix A are used, especially the well log information from Washington State University, a number of wells are found to have relatively high bottom hole temperatures. Roughly 300 wells have bottom hole temperatures greater than 20° C, but water flow within these wells prevents the direct measurement of temperature gradients. However, assuming a value for the mean annual surface temperature, a temperature gradient can be calculated using the two temperature end points and the known depth of the well. Throughout the Columbia Basin, the mean annual surface temperature is known to range primarily between 10° and 14° C; controlled by elevation, slope angle, slope orientation, and vegetative cover. For simplicity, the average value of 12° C was chosen as a standard for gradient calculations. (This might have introduced a large error for many wells, especially the shallow or low bottom-hole-temperature wells. This was kept in mind when examining specific wells.) Most calculated gradients fell in the range of 35° to 45° C/km, with many as high as 65° C/km or higher. Some of the "anomalous wells" are scattered throughout the Columbia Basin, but most are clustered in specific areas. Using the calculated gradients from all wells, including cold deep wells, two types of anomalous areas (moderate potential and high potential) have been identified on the map of figure 3.3. These areas correspond to the anomalies identified on the Washington State Geothermal Resource Map (Korosec and others, 1981). (The light gray areas of the resource map are the moderate potential anomalies of figure 3.3, and the dark gray resource map areas correspond to the high potential areas of figure 3.3.) Moderate potential areas are defined as regions where several wells have calculated temperature gradients higher than 45° C/km,

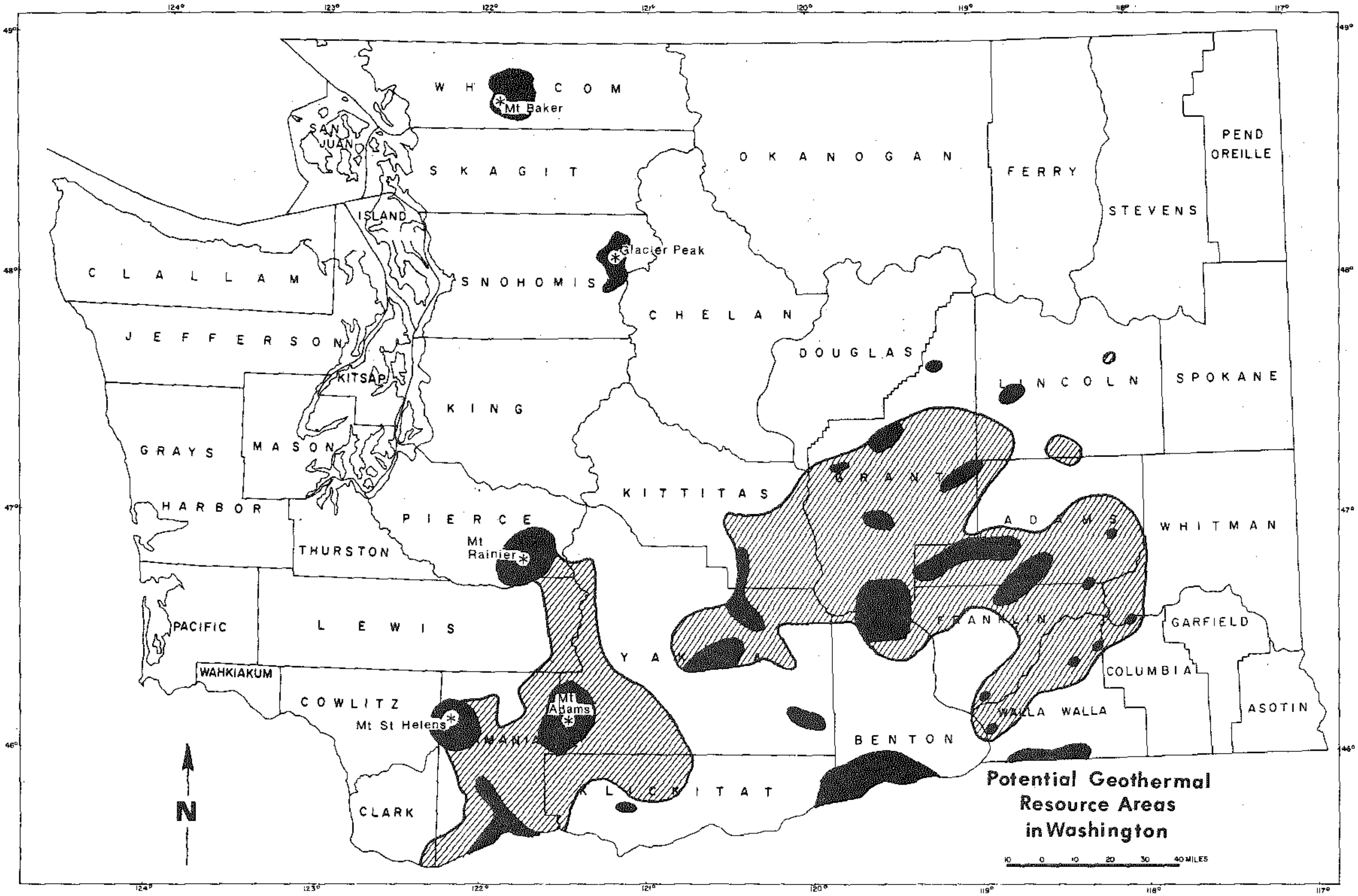
FIGURE 3.3.—Anomalous temperature gradient areas of Washington.

Dark Gray Areas. In the Cascade Range, the dark gray shaded areas at the five major Quaternary stratovolcanoes indicate high potential for low- to high-temperature geothermal resources. Favorable indicators are young igneous rocks, hot springs, and fumaroles.

In southeastern Washington, dark gray shaded areas depict regions which have a significant number of wells with calculated temperature gradients greater than 50°C/km. Warm water is likely to be encountered at relatively shallow depths, although there are cold wells within the dark gray areas.

Hachured Areas. In the Cascade Range province, the areas depict regions of volcanic activity during the past 1 million years. Low- to moderate- and perhaps even high-temperature resources may underlie these areas. Typical temperature gradients are in the range of 45° to 55°C/km.

In southeastern Washington, hachured areas indicate regions where several wells have calculated temperature gradients higher than 45°C/km, although there are also colder wells within these areas. Low- to moderate-temperature resources may underlie large portions of these regions. Further exploration is needed to delineate the resources.



although colder wells are often found within these regions. The high potential areas are defined as regions which have a significant number of wells with calculated temperature gradients greater than 50° C/km, with relatively fewer or no colder wells in the surrounding area. The boundaries of these different anomalous areas are indefinite, especially where the density of wells is low.

It is suspected that the heat flow within these areas is also relatively higher than the regional heat flow for the Columbia Basin (greater than 50 to 70 $mWatts/m^2$), but not enough information is available to determine qualitative heat flow values.

5) South Central Washington: The Geothermal Drilling Projects of 1975 (Indian Heaven area, Schuster and others, 1978) and 1979, by the Division of Geology and Earth Resources (see table 3.4), have begun to characterize the regional heat flow regime of the South Cascades (see figure 3.4). Heat flow values range from 60 to 90 $mWatts/m^2$, with temperature gradients of 45° to 55° C/km. Large regions within this province have no wells or drill holes, such as the Central Cascades extending from the Cowlitz River north to the North Central region (Snoqualmie Pass, Snoqualmie Batholith area), including the Mount Rainier region. The Tumac Plateau to Bumping Lake area, the Mount Adams area, and the Cascade Mountains south of the basalt fields of Indian Heaven are also without heat flow or temperature gradient determinations.

The western boundary of the South Central region is defined by a relatively sharp heat flow transition (closely spaced contours on the map in figure 3.4). Heat flow increases from less than 40 $mWatts/m^2$ to greater than 60 $mWatts/m^2$ from west to east over a distance of less than 12 km, roughly along a north-south line between Washougal and Skamania on the south, through Mount St. Helens, continuing north between the towns of Morton and Randle, and extending further north somewhere between the Eatonville and Mount Rainier-Longmire area.

The eastern boundary of the South Central heat flow region is very poorly known, but may correspond to the topographic change moving from the Quaternary volcanics of the south Cascades to the Miocene Yakima Basalt plains further east (Columbia River

Table 3.4 RESULTS OF HEAT-FLOW DRILLING, 1979, SOUTHWEST CASCADES, WASHINGTON

Well Name	Location		USGS Quadrangle	Spud Date	Completion Date	Elevation M	Depth M	Bottom-hole Temp., °C	Gradient, °C/Km
	N. Latitude	W. Longitude							
Longmire	46° 43' 46"	121° 51' 05"	Randle 15'	7/25/79	7/31/79	710	100	8.5	69??
Ohanapecosh	46° 42' 54"	121° 34' 39"	Packwood 15'	8/2/79	8/31/79	488	115	11.1	46.5
White Pass	46° 38' 17"	121° 23' 27"	White Pass 15'	8/16/79	8/22/79	1365	150	11.5	49
Packwood	46° 38' 15"	121° 41' 35"	Packwood 15'	8/23/79	8/25/79	366	152	14.0	46
Davis Mtn.	46° 33' 10"	121° 47' 07"	Randle 15'	8/29/79	8/31/79	610	147	7.9	4
Randle	46° 31' 22"	121° 56' 22"	Randle 15'	9/5/79	9/10/79	274	129	14.1	46
Mt. St. Helens #1	46° 15' 57"	122° 14' 13"	Spirit Lk. 15'	9/13/79	9/20/79	780	125	9.9	19
Mt. St. Helens #2	46° 10' 22"	122° 16' 06"	Cougar 15'	11/1/79	11/7/79	1067	154	8.2	38
Mt. St. Helens #3	46° 07' 37"	122° 09' 09"	Mt. St. Helens 15'	11/8/79	11/15/79	805	131	4.2	2
Camas No. 1	45° 35' 55"	122° 23' 53"	Camas 7½'	12/11/79	12/14/79	67	152	14.4	31.5
Camas No. 2	45° 38' 20"	122° 26' 25"	Lacamas Creek 7½'	11/28/79	12/7/79	79	72	11.7	37

Basalts). To the south, the preliminary heat flow contours indicated in figure 3.4 line up with contours drawn for the Oregon Cascades by D.D. Blackwell and others in earlier reports.

Because of the existence of a large number of Quaternary volcanic centers in the south Cascades, including the three large stratovolcanoes Mt. Rainier, Mount Adams, and Mount St. Helens, it is not unreasonable to suspect that heat flow anomalies may be associated with a few of these volcanic systems. Unfortunately, no anomalies have thus far been detected, but nor have these specific areas been adequately examined.

Assessment of Heat Flow Projects

The heat flow drilling which will be carried out under the 1980-1981 geothermal assessment project will provide two new heat flow values for the North Central region (Scenic, near Stevens Pass, and Snoqualmie Summit on Snoqualmie Pass). The project will also add one drill hole north of Mount Rainier, two to four drill holes along the Wind River near the Columbia Gorge, and three holes between White Pass and the Naches area, all of which are part of the South Central heat flow region. The three holes east of White Pass will better define the transition zone between the South Central and the Southeast regions. The drill holes along the Wind River, together with holes planned near North Bonneville, by the U.S. Department of Energy Region X Commercialization Program, may identify heat flow anomalies, (a suspicion based on the existence of a relatively large number of warm and hot springs in the area). At the very least the project will provide regional information for a previously unexamined portion of the south Cascades. In addition, temperature measurements in wells throughout the Columbia Basin during the 1980-81 assessment project will help further delineate the anomalous areas in the southeast section of the state, and may lead to the establishment of new anomalous areas.

Beyond the 1980-81 geothermal assessment effort, a lot of work will be needed in the North Central, Southeastern, and South Central regions. Future work will better define the transition boundaries and the potential for anomalies within the regions.

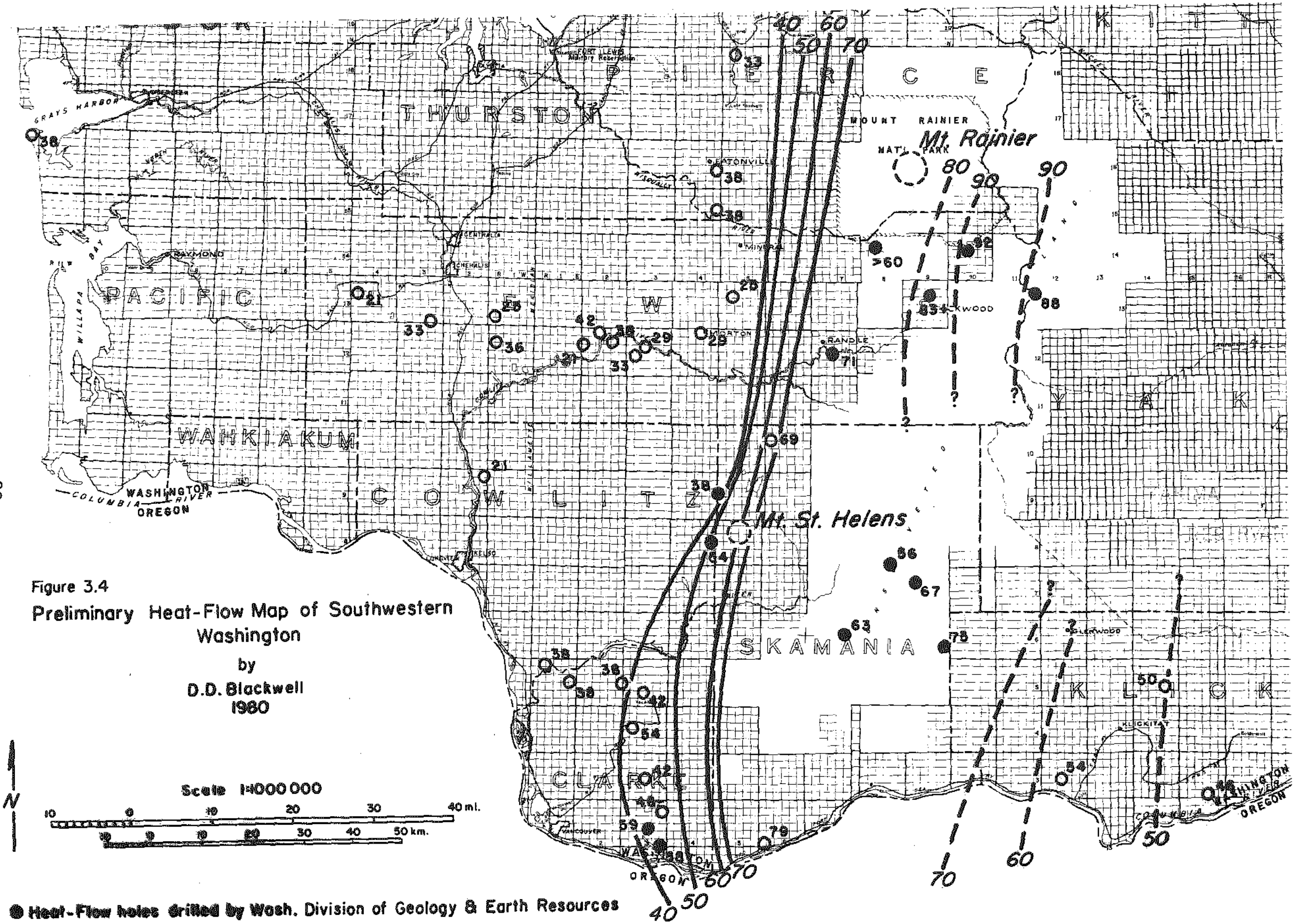


Figure 3.4

Preliminary Heat-Flow Map of Southwestern Washington

by

D.D. Blackwell

1980

● Heat-Flow holes drilled by Wash. Division of Geology & Earth Resources

○ Water wells

Heat-flow units are milliwatts per square meter (mW/m²)

For the North Central region, where no deep wells exist, except for a few mineral exploration holes, any heat flow drill holes will greatly add to the present poor understanding we now have for this area. Large portions of this area cannot be studied in the near future, due to exploration closures because of land status or lack of road access. These areas include the North Cascades National Park, the Pasayten Wilderness Area, Mount Shuksan area, Glacier Peak Wilderness Area, and the Alpine Lakes Wilderness Area. Areas needing heat flow exploration which are accessible and are of geothermal interest include the Mount Baker area, the region west of Glacier Peak Wilderness Area, and the Skykomish and Snoqualmie River valleys, especially near the Garland Warm Springs on the North Fork of the Skykomish River, and the Skykomish River valley between Index and Scenic where a few mineral springs have been reported.

In the Southeast region, there should be a continuing effort to measure temperature gradients in all available wells, but especially within or around the anomalous areas which have already been preliminarily identified. Actual heat flow calculations for these anomalies will not be possible, unless the wells are cased, geophysically logged, and/or materials have been collected from depth for thermal conductivity measurements. Until such a hole is drilled, we will be forced to rely on calculated temperature gradients from the deep irrigation wells.

A more concerted effort to accurately determine the actual mean annual surface temperature for each of these holes will lead to more accurate temperature gradient calculations, and will give more credence to the temperature gradient anomalies.

In the South Central region (the south Cascades), large areas will remain unexamined after the 1980-81 project. One such area is the Goat Rocks Wilderness Area south through the Mount Adams Wilderness Area, and continuing southeast through the Simcoe Mountains. The land status of the Goat Rocks and Mount Adams Wilderness Areas will prevent heat flow drilling in the future. The far eastern portion of this region is part of the Yakima Indian Reservation. Any drilling in this region would have to be done in cooperation with the Yakima Indian Nation, and it is doubtful that the Division of Geology and Earth Resources will conduct such a venture in the near future.

The region between Goat Rocks and Mount Adams is part of the Gifford Pinchot National Forest and is easily accessible by logging roads. A large number of very young Quaternary volcanic centers occur in this area, and because of the relatively close proximity to the Quaternary stratovolcano Mount Adams and the Goat Rocks Miocene to Quaternary volcanic complex, this region should be a prime target for heat flow drilling in the near future.

Another large unexamined area extends to the south from the Cowlitz River Valley between the longitudes of Mount St. Helens and Mount Adams to the existing heat flow drill holes in the Steamboat Mountain-Lemei Rock area. Nearly all of this land is part of the Gifford Pinchot National Forest. Heat flow anomalies may lie within this area, but except for a few scattered Quaternary volcanic centers, there is presently little evidence available to suggest that heat flow exceeds 80 to 90 $mWatt/m^2$.

Other blanks within the South Central heat flow region include the area between Bumping Lake and White Pass, the western side of the Cascades between the Snoqualmie River and Greenwater Rivers (which includes the Lester Hot Springs area in the Green River Valley), the Big Lava Bed area between Wind River and White Salmon River, and the Simcoe Mountains south of the Yakima Indian Reservation and north of the Klickitat and Little Klickitat Rivers. In the foreseeable future, the Division will most likely consider drilling heat flow holes in a number of these areas (including the Klickitat, Trout Lake, Walupt Lake, the Bumping Lake-Tumac Plateau areas), but no definite plans have been made to date.

Additional specific heat flow drilling targets of interest which should be considered by others engaging in heat flow studies for geothermal exploration include Government Mineral Springs on the Wind River (where the Division of Geology hopes to drill a hole in Spring, 1981), Ahtanum Creek west of Tampico (including the Ahtanum Soda Springs area), the Klickitat River valley east of Mount Adams (part of the Yakima Indian Reservation), and the Lookout Mountain area south of the East Fork of the Lewis River and north of the Bonneville-Stevenson area.

IV. THERMAL AND MINERAL SPRING INVESTIGATIONS

(Surveys and Analyses, 1978-1979)

by

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Division of Geology and Earth Resources
Olympia, Washington

IV. THERMAL AND MINERAL SPRING INVESTIGATIONS

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Division of Geology and Earth Resources

The locations, temperatures, and conductivities of all known thermal and mineral springs in the State of Washington are found in table 4.1. The information comes from a variety of sources, including Washington Division of Geology and Earth Resources files, Washington Division of Water Resources Water Supply Bulletins, U.S. Geological Survey Open-File Reports, and U.S. Geological Survey Topographic Maps.

During the 1978 and 1979 field seasons, 20 spring systems were visited and sampled for chemical analysis. Many of these springs have never been analyzed before, and the existence of a few are reported here for the first time.

Of these spring systems, 13 have been surveyed in greater detail, including examinations of several individual springs within each system. Separate reports on each of these systems are found in the section following Results.

Methods

At most springs, a set of three water samples were collected: unfiltered, filtered, and filtered acidified. Filtered samples were collected by taking up spring water in a 50 ml plastic syringe and passing it through a 0.4 micron Nuclepore filter, held in a 47 mm Swin-Lok membrane holder, into a 1 liter collapsible plastic container (Cubi-tainer). The acidified samples were treated by adding about 3 ml of concentrated nitric acid to about 1 liter of filtered water.

Temperature, conductivity, chloride, and pH were measured in the field. Temperatures were measured with a portable digital Markson 701, which was found to be accurate to 0.05°C over the range of 5° to 90°C. Conductivity was measured with a Hach Mini Conductivity Meter model 17250, with built-in temperature compensator. Chloride concentrations were estimated using the Hach Chloride Test Kit 7-P which employs a drop-titration method. The pH was detected with ColorpHast Indicator Sticks. In many cases, the chloride and pH were not measured in the field.

Battelle Northwest Laboratories analyzed all samples collected during the 1978 field season. The following methods were used:

Cl^- $AgNO_3$	Titration
HCO_3^-, CO_3^{-2}	Alkalinity Titration
F^-	Ion Chromatography
SiO_2	Molybdosilicate Colorimetric
SO_4^{-2}	Turbidimetric
All other cations	Inductively Coupled Argon Plasma Emission Spectroscopy

Samples collected during the 1979 field season were analyzed at the Division's water chemistry laboratory. The following methods were used:

Cl^-, Br^-, I^-	Specific Ion Electrodes and Orion Specific Ion Meter 901
Alk	Hach Model AL-DT Digital Titration
SO_4^{-2}	Hach Model SF-1 Tubimetric Test Kit
SiO_2	Molybdosilicate Colorimetric with Sulfite Reduction; Bausch and Lomb Spectronic 710
All other cations	Varian AA575 ABQ Atomic Absorption Spectrophotometer

Results

Spring chemistry data have been divided into two tables, reflecting the two different laboratories which analyzed the waters. Table 4.2 contains analyses for springs collected by the author during the 1979 field season, and analyzed by the author at the Division of Geology and Earth Resources lab facilities. Table 4.3 contains analyses for springs collected during the 1978 field season by Division personnel and analyzed by Battelle Northwest Laboratories. Table 4.5 summarizes the location, temperature, conductivity, and geothermometric information on many of the springs.

Table 4.1 - Thermal and Mineral Springs of Washington State

COUNTY		SPRING NAME	T	R	Location 1/4	1/4	Sec	Temperature °C (- = less than) (+ = greater than)	Estimated Flow 1/min	Conductivity umhos/cm
Chelan										
	1.	Little Wenatchee Soda Spring	27N	15E		NW	10	- 20°		
	2.	Medicine Spring	26N	18E		SE	13	- 20°		
Clallam										
	3.	Olympic Hot Springs	29N	8W		NW	28	48°	500	320
	4.	Piedmont Sulfur Spring	30N	9W			11	- 20°		
	5.	Sol Duc Hot Springs	29N	9W		NW	32	50°	560	350
Cowlitz										
	56.	Green River Soda Springs	10N	4E		NE	2	25-30°		
	57.	Pigeon Springs	7N	1E	NE	NW	36	- 20°		
Grays Harbor										
	6.	Newskah Mineral Springs	16N	9W			9	19°	400	400
King										
	7.	Diamond Mineral Spring	21N	6E		SW	21	11°		
	8.	Flaming Geyser Springs	21N	6E		SE	27	13°		

COUNTY		SPRING NAME	T	R	Location 1/4	1/4	Sec	Temperature °C	Estimated Flow l/min	Conductivity umhos/cm
	9.	Goldmeyer Hot Springs	23N	11E		NW	14	53°		
	10.	Lester Hot Springs	20N	10E			21	49°	200	520
	11.	Money Creek Soda Springs	26N	11E		SE	30	- 20°		
	12.	Ravenna Park Sulfur Spring	25N	4E			9	~ 20°		
	13.	Scenic Hot Springs	26N	13E		NE	32	50°	110	2350
	14.	Skykomish Soda Springs	26N	11E		NW	27	- 20°		
Kitsap										
	15.	Bremerton Sulphur Spring	24N	1E	SE	NE	3	- 20°		
Kittitas										
	16.	Medicine Creek Mineral Spring	21N	17E	SE	SW	22	9°	6	300
Klickitat										
	17.	Blockhouse Mineral Springs	4N	15E		SW	9	- 20°		
	18.	Fish Hatch Warm Spring	6N	13E	SE	NE	4	24°	15	1660
	19.	Klickitat Mineral Springs	4N	13E			23, 24	27°		
	64.	Klickitat Soda Springs	5N	13E	SE	NE	25	15-17°		

SPRING NAME	T	R	Location 1/4	1/4	Sec	Temperature °C	Estimated Flow l/min	Conductivity umhos/cm
COUNTY								
Lewis								
20. Alpha Mineral Spring	13N	2E			5	- 20°		
21. Ohanapecosh Hot Springs	14N	10E		NW	4	50°	110	4650
22. Packwood Hot Spring	13N	9E			32	38°		
23. Packwood Mineral Well(Spring)	13N	10E		NW	6	- 20°		
24. Summit Creek Soda Springs	14N	11E	NE	SW	18	12°	100	8500
25. Vance Mineral Spring	12N	7E	NW	SW	22	- 20°		
Okanogan								
26. Hot Lake	40N	27E		NE	18	40-50°		
27. Poison Lake	39N	27E		SE	5	40-50°		
Pierce								
28. Longmire Mineral Springs	15N	8E		SE	29	25°	250	6500
59. Mt. Rainier Fumaroles	16N	8E			23	52-72°		
29. St. Andrews Soda Spring	15N	7E			1	- 20°		
Skamania								
35. Bonneville Hot Springs	2N	7E		SW	16	36°	80	800
31. Collins Hot Springs	3N	9E		SW	31	40-50°		

COUNTY	SPRING NAME	T	R	Location 1/4	1/4	Sec	Temperature °C	Estimated Flow l/min	Conductivity umhos/cm
Skamania									
	32. Government Mineral Springs	5N	7E			31	10°		
	33. Little Soda Spring	4N	7E		SE	5	8°		
	34. Little Wind River Mineral Seep	3N	8E		SW	2	- 20°		
	61. Mt. St. Helens Fumaroles	8N	5E			4	88°		
	36. Orr Creek Warm Springs	10N	10E		NE	19	22°	100	180
	37. Rock Creek Hot Springs	3N	7E		NE	27	+ 20°		
	38. Shiperds Hot Springs	3N	8E		SE	21	45-50°		
	39. St. Martin Hot Springs	3N	8E		SE	21	49°		
Snohomish									
	40. Gamma Hot Springs	31N	13E		SE	24	60°	15	2800
	41. Garland Mineral Springs	28N	11E		NW	25	29°	100	
	42. Kennedy Hot Springs	30N	12E		NE	1	38°	60	3400
	58. Suiattle River Mineral Seep	31N	15E		NE	18	10°	8	2350
	43. Sulphur Creek Hot Springs	32N	13E		NE	19	37°	10	500
Walla Walla									
	45. Warm Springs Canyon Warm Spring	6N	32E		SE	2	22°		

SPRING NAME	T	R	Location 1/4	Location 1/4	Sec	Temperature °C	Estimated Flow l/min	Conductivity umhos/cm
COUNTY								
Whatcom								
44. Baker Hot Springs	38N	9E		SW	20	42°		820
63. Dorr Fumarole Field	38N	8E	NW	NW	17	90°		
62. Sherman Crater Fumaroles	38N	8E	SW	NE	19	90-130°		
Yakima								
49. Ahtanum Soda Springs	12N	15E		SW	8	- 20°		
51. Bumping River Soda Springs	17N	13E		NW	34	- 20°		
52. Goose Egg Soda Spring	14N	14E		SW	33	10°	80	2700
53. Indian Mineral Springs	15N	12E	NE	NE	10	- 20°		
54. Klickitat Meadow Soda Springs	11N	13E	NW	SE	4	14°	25	440
55. Little Rattlesnake Soda Springs	15N	14E		W	34	- 20°		
46. McCormick Meadow Soda Springs	11N	12E	NE	SW	24	10°	8	1500
60. Mt. Adams Fumaroles	8N	10E			1	+ 50°		
47. Simcoe Soda Springs	11N	15E		SW	9	+ 20°		
48. Soda Spring Creek Soda Spring	9N	12E	NW	NE	35	- 20°		

Table 4.2 - THERMAL AND MINERAL SPRING CHEMISTRY (Analyses by Division of Geology and Earth Resources lab)

I.D.	T	Cond	pH	Cl	SO_4	SiO_2	Na	K	Ca	Mg	Li	Br	I
BVA-2	36.2	805	8.2	196	8	50	160	1	31	0.5	0.1	1.2	0.01
BVB-2	29.2	790	-	-	78	50	146		28	0.5	0.1	-	-
GEA-1	9.5	2700	6.0	192	4	100	269	10	171	92	0.06	2.4	0.04
LSA-1	48.4	520	-	215	30	67	104	3	7	0.1	0.35	-	-
LSE-1	45	-	-	200		67	98	2	12	0.1	0.33	-	-
LSF-1	45	-	-	200		66	112	3	8	0.2	0.33	-	-
LMA-1	22.0	5400	6.0	876	40	112	508	43	460	150	1.9	5.3	0.05
LMB-1	13.3	600	5.2	63	5	31	50	4	43	15.3	0.1	0.4	0.01
LMC-1	25.1	6550	6.2	1204	-	141	645	51	582	-	2.4	6.2	0.04
LMD-1	11.2	1920	5.8	112	-	82	72	10	210	42	0.3	0.7	0.01
LME-1	11	-	-	324	-	98	184	19	262	63	0.8	1.8	0.02
LMF-1	19.1	6000	6.6	915	-	128	568	44	520	153	2.1	5.4	0.04
LMG-1	22	-		946	-	102	555	43	500	-	2.1	5.4	0.03
MCA-1	8.7	300	7.4			37	70		3	0.3	0.3	-	-
NSA-1	17.5	380	-			51	76		4	0.6	0.01	-	-
NSB-1	19	390	-			52	82		5	1.7	0.01	-	-
OHA-1	39.5	4400	-	1010	175	106	895	47	68	5.1	2.81	-	-
OHB-1	45.0	4500	-	1000	-	107	889	47	65	4.9	2.83	-	-
OHC-1	43.6	-	-	987	-	108	825	44	64	4.9	2.82	-	-
OHD-1	50.1	4650	-	1030	165	107	895	50	64	4.9	2.82	-	-
OHG-1	47.8	-	-	1050	175	106	895	48	58	4.7	2.80	-	-
OHH-1	30.6	-	-	978	-	98	870	46	69	5.5	2.75	-	-
OCA-1	21.7	175	-	28	1	29	29	9	3	0.1	0.01	-	-
SMA-1	32	2350	-	756		57	360	6	73	0.5	0.3	4.5	0.02

Table 4.2 - THERMAL AND MINERAL SPRING CHEMISTRY (Analyses by Division of Geology and Earth Resources lab) (Cont.)

I.D.	T	Cond	pH	Cl	SO_4	SiO_2	Na	K	Ca	Mg	Li	Br	I
SDA-1	34	355	9.2	20		64		1	3	0.1	0.1	0.2	0.01
SDB-1	50	342	9.2	18		65		1	1	0.1	0.1	0.2	0.01
SDC-1	40	345	9.2	19		64		1	1	0.1	0.1	0.2	0.01
SDD-1	46	305	9.2	18		58		1	2	0.1	0.1	0.2	0.01
SBA-1	5.3	110	-			47	17		8	2.8	-	-	-
SBB-1	8.1	120	-			28	9		5	2.4	-	-	-
SCA-1	11.6	8500	-	1620	2	104	1684	73	240	100	5.52	-	-
SCB-1	9.7	2000	-	253	1	30	235	12	14	13	0.80	-	-
CSA-1	18.3	-	-	88	5	56	88	9	9	0.9	0.03	0.5	0.01
YMA-1	22.2	-	-	87	-	66	101	9	6	0.3	0.01	0.6	0.01

Table 4.3 - THERMAL AND MINERAL SPRING CHEMISTRY (by Battelle Northwest Lab)

I.D.	T	Cond	pH	Cl	HCO_3	CO_3	SO_4	SiO_2	Na	K	Ca	Mg	Li	F	B
BKA-1	42	820	7.93	109	157	0	95	125	179	11.8	5.8	0.2	0.4	3.0	3.1
BKB-1		780	7.96	99	124	0	90	90	154	10.5	5.9	0.3	0.3	3.0	2.7
KNB-1		-	-	622	-	-	-	180	728	128	184	60	4.4	-	9.5
KNC-1		700	8.30	-	291	0	2	-	-	-	-	-	-	1.0	
KND-1		3200	8.17	626	1143	0	2	180	741	132	187	62	4.8	1.0	9.7
LMB	13	600	6.89	69	247	0	5	-	47	15.5	58	18	0.1	3.0	0.2
OLM-1		320	8.95	10	85	19	37	80	60	-	1.2	0.01	0.03	1.0	0.8
OLB-1		-	-	10	-	-	-	-	62	2.4	1.0	0.01	0.03	-	0.8
SD 1		380	7.93	20	137	3	34	80	75	2.2	1.3	0.01	0.1	1.0	1.3
SD 2		360	8.43	18	129	-	35	-	74	2.6	1.1	0.01	0.1	1.0	1.3
SFA-1		480	7.62	54	102	0	60	100	102	2.8	1.6	0.01	0.1	3.0	0.6
SRA-1		2350	6.93	709	63	0	30	23	292	79	222	3.2	1.2	1.0	3.0

Table 4.4 - Water Identifier Codes

OH	Ohanapecosh Hot Springs
GE	Goose Egg Soda Springs
OC	Orr Creek Warm Springs
SC	Summit Creek Soda Springs
LS	Lester Hot Springs
CS	Corbett Station Warm Springs
YM	YMCA Warm Well
NS	Newskah Warm Springs
MC	Medicine Creek Mineral Springs
LM	Longmire Mineral Springs
BV	Bonneville Hot Springs
SB	Studebaker Mineral Springs
SD	Sol Duc Hot Springs
SM	St. Martin Hot Springs
BK	Baker Hot Springs
KN	Kennedy Hot Springs
OL	Olympic Hot Springs
SF	Sulfur Hot Springs
SR	Suiattle River Mineral Seeps

TABLE 4.5 - THERMAL AND MINERAL SPRING DATA

Name		County	Location (T/R-1/4 sec)	T (°C)	Specific Conductivity	Geothermometers	
						Si-Quartz	Na-K-Ca
Baker Hot Springs	A	Whatcom	38/9E-SW 20	42	820	150	170
" "	B	"	"	--	780	132	169
Bonneville Hot Sprs.	A	Skamania	2/7E-SW 16	36.2	805	102	65
" "	B	"	"	29.2	790	102	---
Goose Egg Soda Sp.	A	Yakima	14/14E-SW 33	9.5	2700	137	124
Kennedy Hot Sprs.	B	Snohomish	30/12E-NE 1	35	---	173	220
" "	D	"	"	38	3200	173	222
Lester Hot Sprs.	A	King	20/10E-21	48.4	520	116	123
" "	B	"	"	44.5	---	---	---
" "	C	"	"	48.4	---	---	---
" "	D	"	"	45	---	---	---
" "	E	"	"	45	500	116	104
" "	F	"	"	45	500	116	119
Longmire Mineral Sprs.	A	Pierce	15/8E-SE 29	22	5400	144	164
" "	B	"	"	13.3	600	81	144
" "	C	"	"	25.1	6550	157	170
" "	D	"	"	11.2	1920	127	162
" "	E	"	"	11	---	136	161
" "	F	"	"	19.1	6000	152	160
" "	G	"	"	24	---	138	161
Medicine Cr. Min. Spr.	A	Kittitas	21/17E-SW 22	8.7	300	87	---
Newskah Warm Sprs.	A	Grays Hbr.	16/9W-NW 9	17.5	380	103	---
" "	B	"	"	19	390	104	---
" "	C	"	"	18.5	600	---	---
" "	D	"	"	18.8	---	---	---

Name		County	Location (T/R-1/4 sec)	T (°C)	Specific Conductivity	Geothermometers Si-Quartz	Na-K-Ca
Ohanapecosh Hot Sprs.	A	Lewis	14/10-NW 4	39.5	4400	141	165
" "	B	"	"	45	4500	141	166
" "	C	"	"	43.6	---	142	165
" "	D	"	"	50.1	4650	141	169
" "	E	"	"	37.1	---	---	---
" "	F	"	"	44.3	---	---	---
" "	G	"	"	47.8	---	141	168
" "	H	"	"	30.6	---	136	165
Olympic Hot Sprs.	A	Clallam	29/8W-NW 28	48	320	125	---
" "	B	"	"	48	---	---	142
Orr Cr. Warm Sprs.	A	Skamania	10/10E-NE 19	21.7	175	78	231
Sol Duc Hot Sprs.	A	Clallam	29/9W-NW 32	34	355	114	93
" "	B	"	"	50	342	114	99
" "	C	"	"	40	345	114	98
" "	D	"	"	46	305	109	97
St. Martin Hot Sprs.	A	Skamania	3/8E-SE 21	32	2350	108	102
Suiattle R. Min. Seep	A	Snohomish	31/15E-NE 18	10	2350	69	227
Sulphur Cr. Hot Sprs.	A	Snohomish	32/13E-SE 18	37	480	137	131
Summit Cr. Soda Spr.	A	Lewis	14/11E-SW 18	11.6	8500	140	155
" "	B	"	"	9.7	2000	80	155

Individual Spring System Investigations

This section contains 12 reports on individual spring systems. Each report has been divided into four sections: an Introduction, which describes directions to reach the area; Geothermal Features, where spring statistics, chemistry and geothermometers are discussed; Geology, where available geologic information such as mapped bedrock units, proximity of Quaternary volcanic and Tertiary intrusive rocks, and heat-flow information are presented; and Comments, in which the author examines the available information and presents conjectures and interpretations.

A three letter and one number identification system has been contrived and is used in the tables. The first two letters are an abbreviation of the spring name. The third letter refers to a specific spring within a family of springs (A, B, C, ... etc.), and the number keys to the time during which the sample was collected (see Table 4.4).

Several springs are described in greater detail than others. This is a result of the availability of published information and the relative time spent in the vicinity of the spring systems.

A few springs were visited just long enough to collect water samples. Individual reports have not been written for these springs, but the results of chemical analyses are presented in the tables. They include Kennedy Hot Springs (KN), Suiattle River Mineral Seep (SR), Saint Martin Hot Springs (SM), Newskah Warm Springs (NS) and Olympic Hot Springs (OL).

Baker Hot Springs

Whatcom County
T. 38 N., R. 9 E., SW1/4 Sec. 20
Mt. Shuksan 1953, 15' USGS Quad.

Baker Hot Springs, also known as Morovitz Hot Springs, are located on a hillside in the Swift Creek Valley, near Morovitz Creek, within the Mount Baker Recreation area They are found by following a trail 1/2 mile from a parking area on Forest Road 3816, which is reached by following State Route 20 east from Sedro Woolley to Forest Road 385 (Baker Lake Road). Use of a Mount Baker-Snoqualmie National Forest Map is recommended.

Geothermal Features

One main spring and several smaller seeps issue from a heavily vegetated hillside with a total flow of 8 to 10 gpm. The immediate area has been cleared and picnic facilities have been constructed. A wooden tub which once collected waters from the main spring was removed by the National Forest Service in September 1978.

Waters collected from the main pool (BAK-1) and from a smaller spring (BKB-1) in August 1978 were analyzed by Battelle Northwest Laboratory. Results of the analyses are presented in table 4.3.

Both waters had high SiO_2, Li, F, and B concentrations, low Ca and Mg concentrations, and a relatively high K/Na ratio. Chloride and bicarbonate are the dominant anions, but a significant amount of $SO_4^{=}$ is present. The main spring has about 10 percent to 20 percent higher concentrations for most species measured, except for Ca and Mg, which are slightly higher for the smaller spring.

When geothermometers are applied, predicted reservoir temperatures are about 150°C for the Si-Quartz geothermometer and 171°C with the Na-K-Ca geothermometer. The difference may be due to mixing with ground water near the surface, or loss of SiO_2 due to precipitation and re-equilibration within the system, as suggested by the slow flow of water observed at the surface.

Geology

Baker Hot Springs is located just east of the flanks of Mount Baker, 7 miles from the summit. Mount Baker is a Quaternary andesitic stratovolcano which continues to show signs of activity in the form of extensive steaming fumaroles in Sherman Crater and within the Dorr Fumarole Field on the northeast slope.

Geologic reports on Mount Baker include Coombs (1939), and Stavert (1971), and a summary is provided by Bloomquist (1979). Hazards have been studied by Crandell and others (1973), Hyde and Crandell (1975, 1978), and eruptive sequences are reported by Easterbrook (1975, 1976), and Swan (1978). Thermal activity has been examined by McLane and others (1976), Sato and others (1976), Frank and others (1975, 1977), Malone (1976), and Kiver (1978).

There is very little published geologic mapping that covers the far east flanks of Mount Baker and the Swift Creek valley between Mount Shuksan and Mount Baker. From unpublished sketch maps, it appears the hot springs flow from glacial drift. Somewhere below the unconsolidated material, a Quaternary volcanic flow from the west terminates against Carboniferous-Permian volcanics and sediments. The older unit, which is extensively exposed east of Swift Creek, is thought to underlie a significant portion of the stratovolcano.

No heat-flow data or temperature gradient information is available for the immediate area or for this region of the North Cascades.

Comments

Because of the proximity of Baker Hot Springs to the stratovolcano and the chemical composition of its waters, there is little doubt that this spring is directly related to the volcanic system. The predicted reservoir temperature is high, at least 150° to 170°C, and may be higher if mixing is occurring. A mixing model has been constructed which assumes the chemical concentrations and temperature of the ground water (10 to 20 ppm SiO_2, 2 to 20 ppm Na, 0 to 3 ppm K, and 5 to 8 ppm

Ca, at 10° to 12°C). This model predicts mixing of about 2/3 thermal and 1/3 ground water. The reservoir temperature is predicted to have been about 170° to 175°C, but cools through conductive or convective heat loss to about 60°C before it mixes with the ground water.

Another hot spring is reported to flow from the creek bed of Swift Creek, 3 to 4 miles north of Baker Hot Springs, between the elevations of 1,800 to 2,200 feet. The spring may be partially within the creek, completely covered during times of high water.

Bonneville Hot Springs-Moffett's Hot Springs

Skamania County
T. 2 N., R. 7 E., Sec. 16, SW1/4
Bonneville Dam 1957, 15' USGS Quad.

This privately owned resort, formerly known as Moffett's Hot Springs, is located northeast of the town of North Bonneville, along Greenleaf Creek. Two drilled wells supply water for a swimming pool and tubs within the main recreation building. Other facilities include an office, rental cabins, and camper-trailer parking areas.

Geothermal Features

In 1971, both wells were in use. The main well, reportedly 25 feet deep, flowing 90°F (32°C), was used to supply the swimming pool. The well was pumped for greater yield, but the owners reported it would flow artesian. The second well was used to supply mineral baths and drinking water for the cabins. Its reported temperature was 82°F (28°C) and was definitely not artesian.

In 1979, only the main well was being used. Artesian flow was producing about 20 gpm of 36°C water. Waters were sampled from a spigot near the well head (sample BVA-). Results of the analyses are presented in table 4.2. The waters are very basic, have high Cl^- relative to alkalinity, low K/Na, and low Li/Na. The various geothermometers produce the following reservoir temperature estimates:

NA-K-Ca	B = 1/3	T = 62.6°C
Na-K-Ca	B = 4/3	T = 27.9
SiO_2	Quartz	T = 102.1
SiO_2	Alpha Cristobalite	T = 51.7
SiO_2	Amorphous	T = -13.9

Results suggest the reservoir temperatures may not be too much higher than the observed well head temperature, unless chemical re-equilibration is taking place. The spring waters are flowing through unconsolidated landslide debris at a relatively slow rate. Several fresh-water cold springs are found throughout the area, and near surface mixing may consequently be occurring.

About 50 meters north of the well heads at Bonneville Hot Springs, a gas line runs underground, roughly NE-SW through a cleared corridor. By following this line up the hill (SW), a warm spring is found, forming a warm water drainage flowing across the clearing. The spring comes out along the hillside on the north side of the clearing, just 10 to 15 meters from the old resort road which leads to a cold spring cistern (11.5°C). The warm spring, referred to as Pipeline Warm Spring or BVB, varies flow from 0 to 10 gpm. It appears to be associated with a cold water spring, where it breaks through alluvium. The spring temperature ranges from 17°C to 31.6°C over a 5-minute time interval. By digging around and diverting the cold water flow from the warm water flow, the cold spring was found to be 12.0°C at its coldest, but it fluctuated by about 4°C, suggesting separation was not complete. Warm water flow was accompanied by periodic bubbling, possibly CO_2 gas. The total conductivity and chemical composition of this water is very similar to that of the main hot well and probably represents a similar source which has been diluted slightly more than the hot well water.

Several other warm to hot springs have been reported in the area, including Hamilton Creek Warm Spring and Bass Lake Hot Springs. The building of the new State Hwy. 14 bridge over Hamilton Creek covered up a spring reported to flow 25° to 30°C water at 10 to 20 gpm on the east bank of the creek. No trace of this spring was found in August 1979. At that time, the creek waters and air temperature were warm at 20°C and would have masked any thermal waters coming up within the creek bed.

Bass Lake Hot Springs, (SE1/4SE1/4 sec. 16, T. 2 N., R. 7 E.) may still exist, but the entire area around its reported site has been disturbed by the construction of the second powerhouse at Bonneville Dam, and the subsequent rerouting of the railroad. The springs, which are reportedly as warm as the springs at the Bonneville resort, form pools on the north side of Bass Lake on property once owned by Mr. Ziegler of North Bonneville. The springs may occur on the north end of a small clearing, reached by following the railroad tracks east to the point where the clearing and slough meet and the old lake basin ends.

Warm springs are also reported to occur throughout the area within a mile, north and east of Bonneville resort.

Geology

The entire area is covered by a large recent landslide. The material is primarily Yakima Basalt and Eagle Creek Formation (Miocene volcanics, conglomerates, and sediments) which overlie heavily zeolitized Ohanapecosh Formation (Eocene volcanics). Waters (1973) provides a geologic map of the slide and surrounding area, and presents a simple mechanism to explain the slide, involving failure along the Ohanapecosh-Eagle Creek contact due to saprolite clay.

Within a mile due north of the hot wells at Bonneville, Waters (1973) has mapped two Quaternary intrusions of olivine basalt into the Yakima Basalt very near the head of the slide (NE1/4 sec. 17 and SE1/4 sec. 8, T. 2 N., R. 7 E.). Two other Quaternary intrusions are mapped 3 miles due north of the resort above the Red Bluffs scarp (SE1/4 sec. 32, T. 3 N., R. 7 E.). These features are not discussed within the text.

Heat-flow studies in the area include the temperature logging of test holes drilled as part of the Bonneville Dam powerhouse project. Temperature gradients range from 25° to 70°C/km for holes 50 to 85 meters deep which have been drilled primarily through sedimentary units (unconsolidated landslide debris and slide blocks), but bottom in bedrock. Most gradients are 40° to 50°C/km.

Comments:

Thermal waters throughout the area may represent a single thermal source flowing below the slide and mixing with ground water within the slide. The mixed waters are surfacing along contacts or weaknesses within the slide block. The ultimate thermal sources may be related to the source for Rock Creek Hot Spring to the north and the various hot springs along the Wind River to the northeast, but this cannot be stated with any degree of certainty due to the lack of chemical information on many of the springs. Bass Lake, Rock Creek, and Shiperds Hot Springs will be examined in 1980.

Collins Hot Springs

Skamania County
T. 3 N., R. 9 E., Sec. 31
Hood River 1957, 15' USGS Quad.

Located near the junction of Collins Creek with the Columbia River along State Hwy. 14, about 8 miles east of Stevenson.

A natural hot spring was cased off for a resort hotel in 1860. The two-story building and a single story bathhouse were torn down in 1916. The site has since been flooded by waters of the Columbia River behind Bonneville Dam. The spring is reportedly capped and valved in a square steel housing which is 3 feet by 3 feet at the top and 5 feet by 5 feet at the base. The structure stands in about 12 feet of water, about 30 feet from the shore.

The acreage along this portion of the Columbia River and Collins Creek was privately owned, as of 1971 (Merle Burgess Family, Tacoma, WA), but the Gifford Pinchot National Forest Map of 1975 shows this area as National Forest.

Geothermal Features

No specific temperature or chemical data are available on the hot spring. Earlier reports seem to indicate that the artesian pressure was sufficient to create spouting to 6 meters through a restricted valve. The temperature is thought to have been between 40°C and 50°C.

Geology

The area is located on the lower portion of the Wind River Landslide. The debris is probably Yakima Basalt (Miocene). There are several Tertiary intrusives in the immediate vicinity, and the Trout Creek Hill Quaternary basalt flow extends down the Wind River valley 2 miles to the east (Wise, 1970). Several Quaternary Volcanic Centers are mapped 5 to 8 miles northeast of the area (Hammond, P. E., unpublished map).

No heat-flow data are available for the area.

Comments:

This thermal feature is very likely related to the thermal systems working to produce hot springs along the Wind River, including St. Martin and Shiperds Hot Springs. Since this spring is in or near a slide, the thermal waters may be issuing from some source beneath the slide, as was suggested for Bonneville Hot Springs.

Goose Egg Soda Spring

Yakima County
T. 14 N., R. 14 E., SW1/4, SW1/4 Sec. 33
Tieton Basin, 1967, 7 1/2' USGS Quad.

The spring is located along Forest Road 1430 in the Tieton Ranger District of the Wenatchee National Forest. It is reached by taking the White Pass Highway (State Route 12) to Tieton River Road, about 1 1/2 miles east of Rimrock Village. The road is followed south, along Milk Creek for 1 1/2 miles, where a gravel road takes off to the southeast. The left fork of the gravel road turns northeast and passes east of the spring shelter, 1/4 mile up the road. The area is used as a cow pasture, and is either a private in-holding or is leased from the National Forest.

Geothermal Features

Under the shelter, a single spring flows 15 to 20 gpm cold CO_2 charged water from an iron-stained concrete cistern. During a survey and sampling trip in June 1979, the water had a temperature of 9.5°C, 2,700 umhos/cm conductivity, and a pH of 6.0. Results of chemical analyses are presented in table 4.2 (see GEA-1).

The spring water has a high alkalinity and Cl^- content, with very little $SO_4^=$, and shows a significant Br^- concentration. Cations are dominated by Na and Ca, with a high Ca/Na ratio and only a moderate K/Na ratio. Both the SiO_2 and Mg concentrations are relatively high, but only a trace of Li was detected.

The Quartz-Silica geothermometer predicts a reservoir temperature of 137°C, while the Na-K-Ca geothermometer gives 124°C. The Mg correction to the Na-K-Ca temperature is dT_{Mg} = 75°C, producing a predicted reservoir temperature of 49°C.

Geology

The regional geology around Goose Egg Soda Spring has been mapped by Becraft (1950) and Swanson (1964, 1966, 1978). The Tieton basin is covered by a large recent landslide, still active in some areas. Blocks of upper Miocene Yakima Basalt are gliding northwest from Divide Ridge over clayey till and bentonites of the Spencer

Creek and Wildcat Creek Formations (Oligocene-Miocene) (Swanson, 1964). It is believed that the slide has changed the course of the Tieton River, which may have once flowed between Goose Egg Mountain and Kloochman Rock, along what is now Milk Creek.

Several andesite intrusives protrude above the landslide debris, including Goose Egg Mountain, Chimney Peaks, and Kloochman Rock. They are middle Miocene in age, and of augite-hypersthene composition (Swanson, 1978).

About 1/2 mile due north of the spring, a Pleistocene olivine basalt has been mapped by Swanson. Several others are found throughout the area, including two areas north of the Tieton River. These rocks are most likely remnants of flows originating on the Cascade Ridge to the west (Swanson, 1964).

No heat flow or temperature gradient information is available for the immediate area. The Washington Division of Geology and Earth Resources Geothermal Assessment Project will drill several heat-flow holes along the White Pass highway between the Cascade Crest and Yakima Valley during fall 1980. This will probably include a site within a few miles of Goose Egg Soda Spring, near Goose Egg Mountain.

Comments:

A very old report by F. G. Plummer, 1900, (USGS 21st Annual Report, pt. 5) mentions a hot spring in this region. The spring, whose temperature was reported to be about 100°F, was located south of the Tieton River, in sec. 34, T. 14 N., R. 14 E. Forest Rangers familiar with the region report they have never found any thermal springs in the vicinity.

There are several cold-water soda springs throughout the southeast and central Cascades, many in close proximity to areas of Quaternary volcanics. Interpretation of these spring systems will be difficult until further information is gathered on each of them. Their origin may or may not be tied to thermal systems at depth, and the springs could have a greater potential than their discouraging surface temperatures suggest.

Lester Hot Springs

King County
T. 20 N., R. 10 E., Sec. 21
Greenwater 1956, 15' USGS Quad.

The springs are located along Green River Road (Road Number 212) about 25 miles east of Palmer Junction, 2 miles west of Lester, and about 13 miles west of Stampede Pass. The springs flow from the hillside above the river (north side), just below the road. In 1900, the Green River Hot Springs Hotel and sanitarium were built on the flat field which lies between the railroad tracks and the river bank, opposite the hot springs. This grew into a prominent resort, but was abandoned and destroyed sometime before 1935. The land is presently part of the City of Tacoma Watershed.

Geothermal Features

A survey and sampling trip to Lester Hot Springs was conducted in August 1979. Results of analyses are presented in table 4.2. The main spring (LSA) flows at about 20 gpm, 48.4°C, from a cave which runs back 3 to 4 meters into the hillside. The cave is about 1½ meters high and contains water about 3/4 meters deep, dammed by a pile of rocks and a sheet of plastic just beyond the mouth of the cave. The water flows from a hole roughly 8 cm in diameter near the back corner of the cave's roof, forming a small waterfall. The roof of the cave is covered by white crystalline salts and several 2 to 5 cm stalactites. The water was very clear, with a conductivity of 520 umhos/cm and pH of 7.6 (see analysis for sample LSA-1).

About 6 meters along the trail immediately west of the cave, a smaller spring (LSB) flows at about 4 to 5 gpm. Its temperature was measured at 44.5°C in August 1979.

Spring LSC is located immediately east of the cave, about 3 meters off the trail and slightly downslope. A moderate sized orifice with several smaller seeps produce a flow of about 5 to 10 gpm of 48.4°C water. The water flows directly downslope to the river, about 10 vertical meters below.

LSD encompasses many small areas of seeps with temperatures ranging up to 45°C with a combined flow of about 5 gpm. The area is located at about the same level on the hillside as the cave, and extends for about 6 meters east of the cave.

LSE has several hot springs flowing directly out of the bedrock fractures on a steep slope about 3 meters above the river. These springs lie west of the main area, on the far side of a creek drainage, and are easily found by walking along the river at low water. The total flow was estimated to be about 10 gpm, with the highest temperature reaching 45°C (see analysis for LSE-1).

Following the creek drainage upslope from area E, another spring is found about 2/3 of the way to the road. The path from the road passes very close to this location, and game trails lead directly to the spring. Water flows at about 5 gpm from under a large boulder in the drainage at 45°C (see analysis for LSF-1).

Residents from the town of Lester have indicated that several areas in the meadow across the river from the main springs (at the site of the old resort) remain snow free in the winter. These areas are rumored to be buried hot springs. The most prominent area is located on the extreme east end of the meadow.

Lester Hot Springs waters are relatively low in total dissolved solids (as determined by conductivity), with Cl^- dominating the anions, and relatively low alkalinity and $SO_4^{(-2)}$. The K/Na ratio is fairly low, as are the concentrations of Ca and Mg. A significant Li concentration was detected, resulting in a relatively high Li/Na ratio.

The Si-Quartz and Na-K-Ca geothermometers predict only moderate reservoir temperatures, but do demonstrate fairly good agreement.

Sample	SiO_2-Quartz Temperature(°C)	Na-K-Ca Temperature(°C)
LSA-1	116	123
LSE-1	116	104
LSF-1	116	119

Geology

P. E. Hammond (1963) provides a geologic map for this region in the west-central Cascades. The alluvial-filled valley cuts the Huckleberry Mountain Formation of the Keechelus Volcanic Group (Ohanapecosh Formation) (Oligocene). The hot springs are located on the contact of a Tertiary intrusive which forms the mountain to the north. The material is hornblende dacite porphyry of late Miocene or Pliocene age. About 1/4 mile west, on the north side of the river, a smaller intrusive has been mapped by Hammond, consisting of pyroxene-hornblende andesite believed to be early Miocene. The closest exposed Quaternary volcanics are found about 10 miles south of the area, on Dalle Ridge. No heat flow or measured temperature gradients are available for the area or the region.

Comments:

The good agreement between Si-Quartz and Na-K-Ca geothermometers suggests these values represent the actual reservoir temperature, with heat loss due to conduction and minimal mixing with ground water. However, it has also been suggested by other geologists working in the area that the spring waters are re-equilibrating with the bedrock and/or surficial debris and observed chemistry may not represent actual reservoir equilibrium chemistry (Dan Vice, Burlington Northern, personal communication, 1979).

Longmire Mineral Springs

Pierce County
T. 15 N., R. 8 E., SE1/4 Sec. 29
Mt. Rainier West, 1971, 7.5' USGS Quad.

Longmire Mineral Springs are scattered throughout a meadow southwest of Mount Rainier within the National Park. The area is reached by following State Highway 706 from Elbe, 6 miles beyond the Longmire. The meadow is north of the road, across from the National Park Headquarters, a hotel, store, and gas station. Park service personnel conduct guided walks through the meadow, with an emphasis on biological aspects of the area.

The springs were discovered in 1883 by James Longmire. By the 1890's, a hotel and several bathhouses were a popular attraction, owing to the proclaimed medicinal value of the mineral waters. The Park Service has restored the area to a natural state, and very few signs of this development can be detected today.

Geothermal Features

On a surveying and sampling trip in July 1979, the numerous thermal and mineral springs at Longmire were observed using Harry M. Majors' "Springs of Lassen and Mt. Rainier National Parks" (1964, unpublished) as a guide. Using a numbering system set up in 1919, an attempt was made to locate each of the 50 listed springs. This goal was soon abandoned because much of the marsh has been inundated over the last two decades by increased beaver activity. The entire upper marsh is now covered by ponds. Gas bubbling and iron staining continues in these areas but water sampling is extremely difficult.

Many of the springs in the southeast corner of the meadow are small pools which bubble, but do not seem to be flowing. Some are completely dried up, but commence to flow again in the late fall, according to park rangers.

Springs 1, 1a, and 2 are filled in. The area around springs 3 through 11 has several small bubbling springs with temperatures ranging from 21.5°C to 25°C. (The air temperature was 27°C, on a partly cloudy day).

Springs 13, 14, and 15 form small pools with temperatures around 25.1°C, pH of 6.2, and conductivity of 6550 umhos/cm. A sample was collected at spring 15, called Marsh Spring or Rim Spring (see analysis for LMC in table 4.2).

Springs 16 through 18 had temperatures from 22°C to 26°C, with a conductivity of 5070 umhos/cm to 5400 umhos/cm. Spring 16, called Post Spring, was sampled at 22.0°C with a conductivity of 5,400 umhos/cm (see analysis for LMA in table 4.2).

Spring 19, called Soda Spring, bubbles and flows from a stone basin at the edge of the meadow. Its temperature and conductivity are significantly lower than other springs, at 13.3°C and 600 umhos/cm, and the pH was measured to be 5.2 (see analysis for LUM in tables 4.2 and 4.3).

Spring 46 flows from a stone cistern near an old log cabin (homestead cabin). The spring known as Iron Mike, flows iron-stained water a few gallons per minute at 11.2°C with a pH of 5.8 and conductivity of 1,920 umhos/cm. (see analysis for sample LMD in table 4.2).

A smaller iron-soda spring was found below the path across from the cabin flowing from near the base of a large fir tree. Spring 47, known as Little Iron Mike, flows at a rate of 1 or 2 gpm. Temperature and conductivity information for this spring were lost, but the values were very similar to those of Iron Mike spring. A partial analysis is found in table 4.2 under LME.

Several small warm springs with moderate flows are found around the Iron Terrace, a tufa platform in the northwest corner of the meadow. They flow from algae filled pools which form holes in the terrace. Various temperatures measured in these pools were 24.1°, 26.7°, 28.3°, and 29.2°C. Ledge Spring, No. 26, on the eastern edge of the terrace, flowed at 23.1° to 26.2°C. Sample LMG was collected in the area, and a partial analysis is presented in table 4.2.

Sand Spring, the spring which previously had been measured to be the warmest at Longmire, reportedly 4° to 5°C warmer than springs in the southeast corner of the marsh, was located on the northeast side of the Iron Terrace in the 1960's. On this latest trip, the spring could not be discerned, probably because of flooding due to beaver activity.

At trail marker No. 16, springs 29 and 30 were found along with several newer springs flowing 5 to 8 gpm at 19.1°C, and building up a new iron-stained tufa terrace. Pronounced bubbling occurs in the main pool next to the boardwalk. This spring, called Medicine Spring, had a conductivity of 6,000 umhos/cm and a pH of 6.6. An analysis of these waters is found in table 4.2 as LMF.

Analyses of waters collected at Longmire show large variations between the various springs in the area. Part of the variation can be explained by the degree of mixing with colder ground water.

The following table summarizes some of the geochemical information on the springs sampled in 1979. A more complete analysis of these waters is presented in table 4.2.

			Geothermometers	
	T(°C)	Specific Conductivity	Si-Quartz	Na-K-Ca
LMA-1	22	5400	144	164
LMB-1	13.3	600	81	144
LMC-1	25.1	6500	157	170
LMD-1	11.2	1920	127	162
LME-1	11	-	136	161
LMF-1	19.1	6000	152	160
LMG-1	24	-	138	161

Geology

The springs at Longmire are located only 8 miles from the crest of the stratovolcano Mount Rainier, and about 2 miles from the base. A detailed study of the geology of the park area is provided by Fiske and others (1963).

Longmire Meadow is a large alluvial flat situated in a slightly elevated portion of the glaciated valley of the Nisqually River. The bedrock is Eocene volcanics of the Ohanapecosh Formation. Rampart Ridge immediately north and west of the meadow represents a Quaternary hypersthene-augite andesite flow from Mount Rainier (Fiske and others, 1963).

Several intrusives invade the rocks of the Ohanapecosh and Stevens Ridge Formations in this area of the park. Three sills of diabase and basalt outcrop immediately north of the meadow. Several larger sills are found about 1 mile east to southeast of the area. These sills are considered to be pre-Tatoosh intrusive rocks, Oligocene to Miocene in age. (Fiske and others, 1963).

In the same area north of these sills, several diorite and quartz diorite intrusives associated with the Tatoosh Pluton are mapped by Fiske and others, 1963. These rocks are of Miocene to Pliocene age.

The closest Quaternary volcanic centers are the craters and plugs atop Mount Rainier.

During the summer of 1979, a heat flow hole was drilled south of the Nisqually River, about 2¼ miles southwest of Longmire. The 100-meter-deep hole had a bottom hole temperature of only 8.5°C, but the temperature change measured over the bottom 20 meters indicated a temperature gradient of 69°C/km, well above the regional gradients which range from 45° to 55°C/km, but this might not be a true equilibrium gradient.

Comments:

The springs at Longmire probably represent hot, high salinity waters leaking from a hydrothermal system associated with Mount Rainier's volcanic system, which are mixing with cold ground water near the surface. The reservoir temperatures might be quite high. The relatively high concentrations of calcium and magnesium complicate this interpretation.

Because Longmire is (within) a National Park, any further investigations will have to be considered as academic studies rather than direct commercial exploration.

Reference

Tabor, R. W.; Waite, R. B., Jr.; Frizzell, V. A., Jr.; Swanson, D. A.; Byerly, G. R., 1977, Preliminary map of Wenatchee 1:100,000 quadrangle, Washington: U.S. Geological Survey Open-File Report 77-531.

Medicine Creek Mineral Spring

Kittitas County
T. 21 N., R. 17 E., SE1/4SW1/4 Sec. 22
Liberty 1961, 15' USGS Quad.

This cold mineral spring is reached by taking State Route 97 from Cle Elum north to Mineral Springs Resort, located along Swauk Creek, a few miles south of Blewett and Swauk Passes. The spring is found along a short dirt path which follows Mineral Creek west from the campground. The area is part of the Ellensburg Ranger District of the Wenatchee National Forest.

Geothermal Features

This spring has a very cold, feeble flow of mineral water, emitting about 1 to 2 gpm from a packed dirt bank on the north side of the creek. There is a slight H_2S odor present, and white filamentous bacteria grow alongside the small pool formed by the spring. A small concrete cistern was dug out from around the spring in 1979. During a sampling trip in September 1979, the water was measured at 8.7°C with a conductivity of 300 umhos/cm and pH of 7.4. A partial analysis of these waters is found in table 4.2, under MCA.

Geology

The spring is located in an area underlain by the Swauk Formation, a lower Eocene continental unit comprising thin to thickly bedded zeolitic, micaceous, lithofeldspathic sandstone (Tabor and other, 1977). The closest volcanics are the lower to middle Eocene Teanaway Basalt, found in a broad band 3 miles west of the spring. The basalts are cut by rhyolitic dikes of middle to upper Eocene age. The entire area is underlain by the Jurassic Ingalls complex, which includes ultramafics, foliated massive serpentinites, and serpentinized peridotite, and silica carbonates and magnesium carbonates derived from alteration of serpentinites (Tabor and others, 1977).

Comments:

Not enough information is available to apply geothermometers. Further chemical analysis is needed to better understand this system, but the very low flow, cold temperatures, low conductivity (consequent low total dissolved solids) and the local and regional geology virtually remove this area from geothermal consideration.

Reference

Tabor, R. W.; Waite, R. B., Jr.; Frizzell, V. A., Jr.; Swanson, D. A.; Byerly, G. R., 1977, Preliminary map of Wenatchee 1:100,000 quadrangle, Washington: U.S. Geological Survey Open-File Report 77-531.

Ohanapecosh Hot Springs

Lewis County
T. 14 N., R. 10 E., NW1/4 Sec. 4
Packwood 1962, 15' USGS Quad.

Ohanapecosh Hot Springs are located within the southeast section of Mount Rainier National Park along the Ohanapecosh River. The campground is located about 12 miles north of Packwood, 4 miles north of U.S. Route 12 on State Route 123, and about 1.5 miles beyond the park boundary. A small health resort was operating in this area in the 1920's. By the 1940's it had grown to include a lodge, bathhouse, and 30 cabins, but the resort closed down in 1961. The National Park Service has restored the area to a natural state, except for a self-guided nature trail which circles the hot springs area.

Geothermal Features

Ohanapecosh is a complex system of warm to hot springs, with a total flow estimated to be 100 to 120 liters per minute. The springs are scattered over an area of about 40 acres between the Ohanapecosh River on the west and a ridge to the east. The vegetative cover throughout the region is very thick and may conceal additional springs.

During two trips in July and August 1979, the following information and water samples were collected. By following the established nature trail loop counterclockwise (opposite of the recommended route in the trail pamphlet), the first group of springs was found just east of the path, part way up a slope, (Area A). Several small orifices, producing a total flow of 5 to 10 gpm of 39.5°C water, have built up a terrace of iron-stained tufa. A moderate H_2S odor was detected, and the water was measured to have a conductivity of 4,400 umhos/cm. Sample OHA was collected at this point.

Immediately north along the path, a second group of springs was flowing with a total production of about 566 gpm with an average conductivity of 4,500 umhos/cm, (area B). Within the pool formed by the springs, measuring roughly 2 to 3 meters across, three separate springs were bubbling away, about 3/4 meters apart, with temperatures of 45.6° and 45.2°C (from west to east). Sample OHB was collected from above the warmest spring.

Next to area B, to the north, a pool with a diameter of about 1 meter was filled with algae and surrounded by tree roots (area C). No bubbling was observed but a flow of 3 gpm was draining the pool. Sample OHC was collected directly from the pool, where a temperature of 43.6°C was measured.

About 8 meters farther north, the main springs form a series of pools, producing a total flow of 15 to 20 gpm. Bubbling occurred at several points along the sandy bottom of the pool, and a moderately strong H_2S odor was detected. The maximum temperature recorded was 50.1°C, but a reliable conductivity could not be measured because of the temperature limitations of the portable conductivity meter.

Area E was found several meters farther up the trail just east of the path. Warm iron-stained water was slowly seeping out from two small seeps in a shallow erosion channel, draining into a small creek formed by a nearby cold spring. The two warm seeps had temperatures of 36.2°C and 37.1°C. The flow in July 1979 was about 1/2 gpm, but had been reduced to a trickle by August.

Area F is west of the main spring area, where the trail loops around back towards the camping area. A large tufa terrace has been built up, over which flows hot water from the main springs of areas A, B, C and D. The cascading waters fall a vertical distance of about 4 to 5 meters, then spread out into a marshy area below. In addition, several small springs flow directly out of the tufa terrace, the warmest measuring 44.3°C.

Near the top of the large tufa terrace, 47.8°C water was flowing out of a crusted over pipe at about 5 to 8 gpm. Sample OHG was collected directly from the pipe.

On the far northwest corner of the campground, about 1/4 km from the other springs, a small warm spring was found, which measured about 1/2 meter in diameter. The pool had a maximum temperature of 30.6°C near its northern side, where bubbles were periodically produced. Sample OHH was collected from the pool. Several old tufas surround the area, suggesting that spring activity in the area was at one time much greater.

The table below summarizes some of the data collected for the Ohanapecosh Hot Springs and the results of geothermometers applied.

			Geothermometers	
	T°C	Cond.	SiO_2 Quartz	Na-K-Ca
OHA	39.5	4400	141	165
OHB	45	4500	141	166
OHC	43.6	-	142	165
OHD	50.1	4650	141	169
OHE	37.1	-	-	-
OHF	44.3	-	-	-
OHG	44.8	-	141	168
OHH	30.6	-	136	165

Besides the relatively high silica and potassium content, the waters were rich in lithium, producing a high lithium/sodium ratio.

Geology

A detailed study of the geology of Mount Rainier National Park is provided by Fiske and others (1963). The springs flow from Oligocene-Eocene volcanics of the Ohanapecosh formation. Several diorite sills and dikes of the Miocene-Pliocene Tatoosh pluton outcrop within a few miles surrounding the springs. The Quaternary vents at the crest of Mount Rainier are about 12 miles away, but andesite flows from these vents extend to within 5 miles of the area. No significant structural features have been mapped in the immediate vicinity of the springs, but this may be due to the heavy vegetative cover.

A heat flow hole was drilled in 1979 within the Ohanapecosh River valley, just south of the park boundary and about 1.5 miles south-southwest from the springs. The hole, completed to a depth of 115 meters, had a bottom hole temperature of 11.1°C and a gradient of 46.5°C/km. This is thought to represent the regional temperature gradient and therefore showed no anomalous conditions.

Comments:

Because of its proximity to Mount Rainier, high lithium content, and high geothermometer results, it is suspected that Ohanapecosh Hot Springs are directly related to the thermal system of the stratovolcano. The wide range in temperatures and salinities observed from spring to spring within the spring system suggests that mixing with cold water is taking place, probably very close to the surface. The values do not fall along a simple mixing line when temperature is plotted against the various chemical species, suggesting that there may be significant conductive heat loss and/or the mixing is very complex.

Orr Creek Warm Springs

Skamania County
T. 10 N., R. 10 E., NE1/4 Sec. 19
Green Mountain 1970, 71/2' USGS Quad.

About 11 miles northwest of the summit of Mount Adams, small warm springs flow down to Orr Creek from a creek drainage in a logging clear cut. This area is located about 20 miles southeast of Randle, about 28 miles by road. It is found by following Forest Road 123 south from Randle to Road 101, which crosses the Cispus River and Orr Creek. About 2.5 miles east and north on this road, Road 101 turns off to the southeast and crosses Orr Creek again. Several hundred yards beyond the creek, a timber sale access road takes off to the southwest. This road is followed for about 1/3 mile through a first cut (which has been growing back for several years) and into a second newer clear cut. The spring is found on the far west side of the cut, about 1/2 of the way down the cleared slope. Several game trails lead across field cut to the spring.

Geothermal Features

The main spring flows from under some large overturned stumps in a shallow depression which forms a drainage for the upper slope. The area was obviously disturbed during logging operations. During an August 1979 sampling trip, the spring was producing 21.8°C water at 20 to 30 gpm with a conductivity of 175 umhos/cm (see OCA-1 in table 4.2 for a complete analysis of the water). A slight H_2S odor was detected, and white filamentous bacteria (probably Sphaerotilus sp.), was observed growing near the orifice.

Trees replanted in the clear cut seem to be growing much faster around the spring and its drainage, in a band roughly 7 meters wide. The forester who provided the initial information on thermal waters in the area had confirmed that the spring remains warm year round, producing snow-free ground during the winter.

A quick survey of the immediate area showed a number of small warm seeps throughout the area, including a couple in the woods immediately west of the area.

Considering the relatively warm temperature of this spring, the total dissolved solids, as estimated by conductivity measurements, is quite low. Sulfate is extremely low, while carbonate and Cl^- dominate the anions. The K/Na ratio is high, while Ca and Mg concentrations are very low. Li could not be detected.

The low concentration of SiO_2 results in a relatively low temperature predicted for the reservoir, as determined by the Si-Quartz geothermometer (78° C). This is in sharp contrast to the very high predicted reservoir temperature of 231° C as determined by the Na-K-Ca geothermometer.

Geology

The Orr Creek Warm Springs area is included in preliminary geologic maps of the south Cascades by P. E. Hammond (1973, 1975). The springs flow from the lower slopes of Green Mountain, which is mapped as part of the Eocene Ohanapecosh Formation. Green Mountain may be related to the East Canyon Ridge Unit which has been described by D. S. Harle (1974). The closest Quaternary volcanics are Mount Adams lava flows which cover the valley floors of the Cispus River and Orr Creek. About 5 to 6 miles west of the springs, Quaternary volcanic centers are mapped on Spud Hill and at the junction of East Canyon Creek with the Cispus River. From 4 to 6 miles east of the springs, several very young volcanic centers are mapped, including Two Lakes Volcano (30,000 years), Walupt Lake Volcano (15,000 years), and the closest center, about 4 miles east, the Potato Hill Volcano (10,000 years old).

No heat flow or temperature gradient information is available for this area or region.

Comments:

The proximity of this spring system to the late Quaternary volcanic centers in the region suggests the thermal waters may be deriving their heat from magmatic sources. The low total salts and large discrepancy between the geothermometers suggest a high degree of mixing with ground waters is occurring or the aquifer is being heated by conductive heat transfer. This would explain the low SiO_2 and Li values. A more detailed survey of the area is recommended.

Sol Duc Hot Springs

Clallam County
T. 29 N., R 9 W., NW1/4 Sec. 32
Bogachiel Peak 1950, 71/2' USGS Quad.

This spring is within the Olympic National Park, and is located southwest of Port Angeles on the northern margin of the Olympic Mountains, along the Sol Duc River.

A large resort was built in 1912, consisting of a 4-story hotel, 3-story 40 feet by 100 feet sanatorium, 40 feet by 200 feet bath house, gymnasium, and several smaller buildings. A fire destroyed the entire resort in 1916. During the late 1920's and 1930's, a lodge, two pools, and about 40 cabins were constructed. The present-day facilities include the newer motel, hotel, pools, several of the cabins, and facilities for camping and recreational vehicle parking. Plans to upgrade and modernize the facilities are now being considered by the National Park Service. Bloomquist (1979) provides a baseline study of this resort and its resource from the standpoint of geothermal development. The study includes land classification; geochemical, geological, and geophysical data summaries; and details on development status.

Geothermal Features

The major springs at Sol Duc have been cased off into concrete collecting cisterns. Three cisterns are located along the west side of the hot swimming pool and a fourth collects waters under the lodge basement. By convention (from earlier reports), the southernmost cistern is identified as number 1, the center cistern is number 2, the northernmost is number 3, and the basement cistern is number 4. Chemical analyses determined for waters collected from these cisterns in April, 1979, are reported in table 4.2.

Cistern 1 consists of a pit excavated to the eastward sloping surface of the bedrock that underlies the alluvial gravel (K. L. Walters, 1967, unpublished report).

An estimated 20 gpm of 48°C waters enters from the southeast corner, about 20 gpm of 41°C enters from the southeast corner, and about 5 gpm of 31.5°C water discharges from a 4-inch concrete pipe near the center base of the south wall. An iron pipe connects cistern 1 and 2, producing a flow of 2 gpm into cistern 1 (Walters, 1969, unpublished report). During an April sampling trip, the cisterns were not being pumped, but were flowing artesian and emptying into a storm drain north of the area. The combined waters within cistern 1 had a temperature of 40°C and conductivity of 345 umhos/cm (see analyses for sample SDC-1). No overflow discharge exists for this cistern when not being pumped, suggesting hydrologic equilibrium between spring inflow and leakage through the walls and along the bottom contact of the cistern.

Cistern 2 is similar in construction to number 1. About 15 gpm of 48°C water enters the cistern from the northeast corner, and an additional 15 gpm of 48°C water flows from the rock near the center of the floor (Walters, 1969, unpublished report). This cistern is free of a pump, but has an overflow port at the high water line which leads to cistern 3. In April 1979 these waters were the coldest, at 34°C, but had the highest conductivity at 355 umhos/cm (see analyses for sample SDA-1).

Cistern 3, similar to number 2, can be pumped at a sustained pumping rate of 40 gpm at 50°C without a drawdown. The temperature in April 1979 was also 50°C, with a conductivity of 342 umhos/cm (see analyses for SDB-1).

Cistern 4 is located below the basement floor of the lodge. Waters ranging in temperature between 42°C and 44°C are reported to flow into this cistern from a pipe in the south wall. This may represent a combination of waters seeping from under the pool and from the other cisterns (Walters, 1967, unpublished report). A submersible pump produces 20 gpm for use in the pool and supplies hot water for the lodge and its tubs. In April 1979, the temperature was 46°C, with a conductivity of 305 umhos/cm (see analysis for SDD-1).

A fluorescent dye experiment by N. P. Dion (unpublished report, USGS, 1978) suggests cisterns 2 and 3 are hydraulically connected and seep into cistern 1, cistern 1 seeps into cistern 4, and cisterns 2 and 4 flow into the storm drain. Total discharge from the system is estimated to be 150 to 170 gpm.

Further hydrologic information is reported by Walters and Dion, including hydrostatic level comparisons and recommendations for increasing temperature and flow.

During the April 1979 sampling trip, a survey of the banks along the Sol Duc River in the vicinity of the resort located several areas where thermal waters were seeping out of the alluvium and into the river. They range in temperature from 11°C to 45°C, with flows up to 3 or 4 gpm but typically less than 1 gpm. A detailed description of these seeps including their location, temperatures, and conductivity was made, and will be presented in other reports. Waters were not collected for detailed chemical analysis, however.

Results of geothermometers applied to waters collected from the cisterns are higher than observed temperatures, but represent a relatively low temperature reservoir with respect to other geothermal systems.

	Measured T	SiO_2-Quartz T	Na-K-Ca T
SDC-1 Cistern 1	40° C	114	98
SDA-1 Cistern 2	34° C	114	93
SDB-1 Cistern 4	50° C	114	99
SDD-1 Cistern 4	46° C	109	97

The waters have relatively high alkalinity, moderate sulfate, and low chloride, with a relatively low total salinity, considering its temperature. The K/Na ratio is low, as is the Li concentration. Campbell and others (1970) classify the waters as thermal meteoric undergoing deep circulation.

Geology

Regional geology of the area is best presented by Tabor and Cady (1978). The Sol Duc River valley is filled with Olympic alpine glacial debris. The bedrock below the valley fill at the resort is projected to be a contact between two different sandstone units of the Western Olympic Lithic assemblage, upper Eocene to Oligocene. The sandstones are thick bedded to the southwest, but more brecciated and granular conglomeratic to the northeast. The closest volcanics are Eocene basalts of the Crescent Formation, found 4 to 10 miles to the north.

Comments:

Thermal waters are easily spotted in the vicinity. Because of the H_2S content of the water, white filamentous bacteria (probably Sphaerotilus) proliferates where the temperature is 13° to 40°C.

Because of the lack of Pleistocene to Recent volcanics in the area, the thermal waters are most likely the result of deep circulation of ground waters which are convecting up along a major structural feature, such as a fault plane. This is further suggested by the low Cl and Li concentrations, low K/Na ratio, and relatively low reservoir temperatures suggested by geothermometers.

No information is available on the thermal gradient in this area, making calculations of depth of circulation purely speculative. However, if an average gradient of 20° to 30°/km is used, 2½ to 3 km deep circulation could produce temperatures predicted by the geothermometers.

The chemistries, surface temperatures, and predicted reservoir temperatures are very similar for Sol Duc and Olympic Hot Springs. These waters may share a common origin, or genetic conditions of formation.

Sulphur Creek Hot Springs

Snohomish County
T. 32 N., R. 13 E., NE1/4, Sec. 19
Downey Mtn. 1963, 71/2' USGS Quad.

These springs are located within the Glacier Peak Wilderness Area. The Sauk River Road is followed north from Darrington or south from Rockport to Forest Road 345, which is followed east along the Suiattle River for 20 to 25 miles to Sulphur Creek Campground. A dirt trail leaves the area from the northeast side of the road, running along the north side of Sulphur Creek. About 1.5 km up the trail, a sign marks the Wilderness boundary. A short distance beyond this, a log bridge crosses the creek and joins a dirt path which continues northeast along the creek. The hot springs are found about 100 meters up the trail.

Geothermal Features

Several warm and hot springs are found along a drainage which steeply slopes down to the creek from the south. The area is heavily vegetated and conceals most of the springs. The main spring flows from a fracture in the bedrock exposed just above the bank of the creek. The temperature was about 37°C during a sampling trip in August, 1978. The hot water was flowing through a sinter-lined channel into a pool dug into the creek bank. White filamentous bacteria formed along stringy masses within the channel. The springs farther up the drainage were a few degrees cooler. Their small pools were filled with dark green algae, but no inorganic deposits were detected. The drainages leading from these springs contain white filamentous bacteria. An analysis of water collected in August 1978 is presented in table 4.3, as sample SFA.

The specific conductivity is quite low, at about 480 umhos/cm, and the relative concentration of M, K, Li, and B are also very low. When geothermometers are applied, the springs are predicted to have reservoir temperatures of 137°C by the Si-Quartz method and 131°C by the Na-K-Ca method.

Geology

Very little detailed geologic mapping is available for the area around Sulphur Creek. In a large areal study by Grant (1966), the bedrock was mapped as pre-Jurassic Cascade metamorphics. The spring is located along an inferred fault which runs through the creek N. 55° E. and cuts the Green Mountain Unit, a biotite-biote hornblende schist. The fault is thought to be a high angle, dipping 25° to the northwest. Sulphur Mountain, south and east of the springs, was mapped as a gneissose, pyroxene-bearing trondhjemite.

No heat flow or temperature gradient information is available for the area or the region.

Comments:

Sulphur Creek Hot Springs may be the result of deep circulation through a fault or fracture system. Despite its close proximity to the Quaternary Cascade strato-volcano Glacier Peak, the chemistry of waters from the springs do not suggest a volcanic origin (relatively low Li and B). It is likely, however, that the spring waters have been diluted by shallow ground water. Some degree of mixing can be seen taking place at the surface, creating different conditions from spring to spring. A more complete survey is recommended, with complete analyses for each of the springs in the system.

Reference

Grant, A. R., 1966, Bedrock geology of the Dome Peak area, Chelan, Skagit, and Snohomish Counties, northern Cascades, Washington: University of Washington Ph.D. thesis.

Summit Creek Soda Spring

Lewis County
T. 14 N., R. 11 E., NE1/4SW1/4, Sec. 18
White Pass 1962, 15' USGS Quad.

The area is reached by taking the White Pass Highway, State Route 12, to Forest Road 1400, and following this dirt and gravel road to its eastern terminus, at Summit Creek Soda Springs Campground.

Geothermal Features

Along the northeast side of Summit Creek a cold, CO_2 charged spring has built up a large iron-stained tufa terrace, about 7 meters above the river bed. The main soda spring flows from a manmade rock and cement cistern which stands about 3/4 meters above ground level.

On a July 1979 survey and collecting trip, the spring was flowing about 40 to 50 gpm at 11.6°C. Water samples were collected from the cistern (SCA) and from a smaller spring which flows from the lower north side of the large tufa mounts (SCB). This second spring had a temperature of 9.7°C and a conductivity of 2000 umhos/cm. The chemical analyses are presented in table 4.2. When geothermometers are applied, reservoir temperatures are calculated as follows:

	T Si-Quartz	T Na-K-Ca
SCA	140	155
SCB	80	155

The Li concentration is quite high, as is the resulting Li/Na ratio. The water is charged with dissolved CO_2 which vigorously bubbles out at the surface, but also has a very high Cl^- content. SCB water appears to be diluted SCA water.

Geology

Summit Creek valley has been cut into the Pliocene Ridge Top andesite. The Pleistocene Valley flow basalt, which originated from vents near the Cascade Divide to the east of Cowlitz Pass, covers the valley floor from the crest to a few miles west of the springs. In the area around the springs, the basalt flow has been eroded by the creek (Ellingson, 1959). The immediate area surrounding the springs has been covered by Recent alluvium. About 1.5 km northeast and 2.5 km south of the area, the Miocene Jug Lake diorite intrusive is exposed. (Ellingson, 1959.)

Comments:

Several other cold soda springs with tufa mounds are reported to exist along Summit Creek farther up the valley to the east, within a mile of the main spring. Despite their very cold temperatures, these Soda Springs may be related to the volcanic systems which exist in the region. The ratios of various chemical species for waters from Summit Creek Soda Spring, especially Na/Li, look very similar to values calculated for Ohanapecosh Hot Springs which is southeast of Mount Rainier and only about 7 km northwest of Summit Creek Soda Spring.

V. REGIONAL GRAVITY SURVEY OF THE SOUTHERN CASCADES, WASHINGTON

by

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V. REGIONAL GRAVITY SURVEY OF THE SOUTHERN CASCADES, WASHINGTON

by

Z. F. Danes

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Introduction

In numerous areas of recent volcanism throughout the world, geothermal systems have been discovered, developed, and are now making significant contributions to the energy needs of the respective areas. The State of Washington, having five strato-volcanoes and numerous smaller volcanic centers, all of Quaternary age, must contain abundant, but as yet undiscovered, commercially developable geothermal systems.

Discovery and development of geothermal systems in other areas of the world have occurred because those areas exhibit abundant surficial manifestations (hot springs, geysers sulfataras) of the geothermal systems. In the State of Washington, these surficial manifestations are largely lacking. Thermal springs, with the exception of those near Mount Rainier and Mount Baker, have chemical compositions indicative of low temperature geothermal systems (Schuster and others, 1978 p. 20-21). The lack of thermal springs in the Mount St. Helens/Mount Adams area may indicate that if high temperature geothermal systems exist in the area, they are buried by young volcanics (Schuster and others, 1978, p. 44). The few heat flow measurements made in the southern Cascades do not reveal areas having requisite high geothermal gradients.

The available data indicate that the search for geothermal power in the State of Washington will be difficult, and will have to rely upon exploration techniques capable of detecting possible buried geothermal systems which have no surficial manifestation.

Gravity surveys give useful data which can be interpreted to reveal regional and local structures and subsurface lithologies. Gravity surveys in the Geysers area (1966, California Division of Mines and Geology), in the Broadlands area of New Zealand

(1970, Hochstein and Hunt), in the Raft River area of Idaho (1978, Maybe and others), and in the Roosevelt Hot Springs area of Utah reveal that gravity anomalies are associated with geothermal systems. We make and emphasize the point that gravity data alone cannot reveal geothermal systems. Gravity anomalies can be produced by an infinite combination of variables. However, gravity surveys coupled with bedrock geology and water geochemistry can reveal target areas which can be explored with other more site specific and expensive techniques.

Research

We have completed a regional gravity survey of the southern Cascades of Washington, with the purpose of delineating regional geological structures and target areas which can be explored with more site specific techniques. The initial study area comprised approximately twenty-two 15' quadrangles, bounded by the Columbia River on the south, by 46°30' on the north, by 122°30' on the west, and by 121° on the east. This area, having the most intensive and extensive recent volcanism of any area of comparable size in the state (Hammond, 1975; and Crandell and Mullineaux), must be considered as the state's prime target area for geothermal power.

The project objectives were as follows:

1. Compile existing gravity data for the map area.
2. Obtain sufficient new gravity data to complete uniform regional coverage of the area with a station density of 1 per 5 square miles.
3. Reduce existing and new gravity data using the standardized reductions applied to gravity data by the U.S. Geological Survey in Denver.
4. Compile the reduced data into free-air and Bouguer gravity maps at a scale of 1:100,000.
5. Establish a computerized file of all raw and reduced gravity data for the map area to facilitate data exchange and interpretation.

During the period of July 1979 through June 1980, gravity observations were carried out in the area from 45°30'N to 46°30'N and from 121°45'E to 122°30'W. Also surveyed was a small area from 46°30'N and 121°30'E.

Altogether, 877 gravity readings have been taken; of those, about 250 are base readings, repeats, calibrations and ties; the rest are new values.

All stations were incorporated into our existing network and both new and old values have been submitted to the Denver Office of the U.S. Geological Survey for terrain corrections. These comprise:

A. 15' Quadrangles

Bonneville Dam	118 Stations	Mount St. Helens	169 Stations
Bridal Veil	43 "	Spirit Lake	65 "
Camas	117 "	White Pass	20 "
Cougar	71 "	Willard	46 "
Elk Rock	53 "	Wind River	61 "
Husum	82 "	Yacolt	62 "
Lookout Mtn.	58 "		
		TOTAL	965 Stations

B. 7½' Quadrangles

Blue Lake	12 Stations	Lost Horse Plateau	2 Stations
Burnt Peak	11 "	McCoy Peak	7 "
East Canyon Butte	14 "	Piscoe Meadows	2 "
French Butte	10 "	Quartz Creek Butte	5 "
Glenwood	51 "	Sleeping Beauty	49 "
Greenhorn Buttes	12 "	Spencer Butte	5 "
Jennies Butte	11 "	Twin Buttes	2 "
Lone Butte	45 "	Wallupt Lake	16 "
		TOTAL	254 Stations
		GRAND TOTAL	1219 Stations

Base maps on a scale 1:62,500 have been prepared.

While it is always dangerous to interpret preliminary data, a few conclusions may be warranted, but should still be taken with caution.

1. The dominating feature in the area is the regional westerly gravity gradient of about one mgal/km.

2. Superposed over this gradient are numerous local anomalies that seem to cluster along "trends", marked red (positive) and yellow (negative) on the preliminary map. Surprisingly, those "trends" seem to strike at right angles to the known tectonic trends in the south Cascades.

3. Areas of known recent volcanic activity (that is, Mount St. Helens, 46°10'N, 122°10'W; and Goat Rocks, 46°25'N, 121°20'W) are accompanied by well established gravity minima, possibly due to large quantities of low density intrusive rocks at shallow crustal depths.

4. Areas of similar negative anomalies, and, therefore, prospective geothermal energy resources, are found in southern Elk Rock district; east of Spirit Lake; in southern Cougar district; and northern Lookout Mountain district.

Again, those conclusions are based on preliminary data, and may be modified when all the corrections have been applied. Nevertheless, gravity anomalies probably can delineate geothermal prospects in this area, and the present survey should continue.

Additions and Comments

by Michael A. Korosec

The 1979 gravity data provide a tremendous number of stations with sufficient station density to enable the construction of a reliable regional gravity map for the southern Cascades. Work being carried out in 1980 will allow for the construction of a similar map for the central Cascades and portions of the northern Cascades, especially around the Mount Baker area. The only "holes" which will remain on the maps will exist in the central interior and the central and eastern portions of the north Cascades. Since these unmeasured regions are a) remote, with difficult access, b) within National Parks and Wilderness Areas, and c) not suspected to be significant geothermal provinces by the known geology (except for the Glacier Peak area) or open to development even if they are, the regional portion of the gravity survey program can be considered nearly complete. The only exception is the area south and southeast to Mr. Baker (down to the South Fork Stillaguamish and east to the Glacier Peak Wilderness Area). This region will likely be surveyed in 1981.

Future work should focus on specific areas of interest, either coinciding with geothermal provinces being examined by other projects of the Division's geothermal program, or on areas which suggest the existence of significant gravity anomalies from the regional map. For example, the regional gravity survey around the Mount St. Helens area showed a pronounced gravity low in the Coldwater Creek area 10 to 15 kilometers north-northwest of the volcano. The extent and significance of this low can only be guessed, because of the relatively low station density in the area (the low is defined by only a few gravity values). Since a fault zone extends north-northwest from the volcano through this area, and since the shallow (or intermediate) magma chamber is suspected to be offset northwest of the central crater, it is possible that a significant geothermal reservoir may underlie the area. Tighter gravity station density may provide useful information which will begin to answer some of the questions which this anomaly generates.

In the near future, a thorough examination of the regional gravity maps should be carried out in an effort to identify all of the significant anomalies within the south and central Cascades, and the areas around Mount Baker. Where the anomalies cannot be readily explained by known geology, and where they are questionable or poorly defined, a program should be developed to systematically survey these areas, possibly leading to the production of detailed gravity maps which can be used to site future heat flow drilling, geochemical soil surveys, or other geophysical surveys.

VI. GEOLOGY OF THE WHITE PASS - TUMAC MOUNTAIN AREA, WASHINGTON

by

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VI. GEOLOGY OF THE WHITE PASS-TUMAC MOUNTAIN AREA, WASHINGTON

by Geoffrey A. Clayton

Abstract

The Tumac Plateau-White Pass-Rimrock Lake-northern Goat Rocks region in the southern Cascade Range Washington lies at the crest and on the eastern slope of the Cascades 35 to 45 km southeast of Mount Rainier. When viewed on topographic maps, or on the 1:250,000 Yakima raised relief map, the Tumac Plateau appears as an anomalous bulging area, relatively undissected by rivers, and dotted with lakes. This bulging morphology is due to the eruption of lava from at least 10 late Quaternary vents distributed on and around the Tumac Plateau. To the south, Hogback Mountain and the Goat Rocks are more erosionally dissected centers of Quaternary volcanism. Lavas range in composition from olivine basalt and high-alumina basalt to rhyolite. Structurally the area may be a dome. The Russell Ranch formation and Indian Creek amphibolite, the only exposure of pre-Tertiary rocks in the southern Cascades of Washington, crop out at altitudes as high as 6,000 ft. Tertiary formations tend to dip away from the Tumac Plateau. The Ohanapecosh Formation, several kilometers thick to the west of the Cascade crest, is absent at the crest and is not yet definitely correlated with Tertiary rocks on the east side of the crest. The age and throw of faults paralleling the Carlton Creek, Clear Fork, Cowlitz River, and Indian Creek valleys are unknown. Detailed field mapping, petrologic and geochemical studies, and radiometric dating of rock units in the area, was designed to clarify the record of Quaternary volcanism, define the major structures which control the location of a high-level silicic magma chamber inferred to exist beneath the northwestern portion of the area, and permit a better understanding of smaller scale structures which might control hydrothermal systems and localization of heat.

Introduction: The Structure and Stratigraphy of the Tertiary Rocks in the Carlton Pass-White Pass-Rimrock Lake-Goat Rocks Region

The 1979 geologic mapping was part of a larger study by Joseph Vance and Geoffrey Clayton. This study of the structure and stratigraphy of the Tertiary rocks of the Carlton Pass-White Pass-Rimrock Lake-Goat Rocks region focuses on a detailed subdivision and chronology of the stratigraphic section, identifying zones of crustal weakness, and estimating displacement along Tertiary and Quaternary faults. Findings will allow correlation and comparison of the volcanic history of the study region with volcanic episodes elsewhere in the Cascade Range and will help clarify relationships between deformation, volcanism, and subduction, and regional tectonics in the Northwest.

Previous Work

Abbott (1953) studied the rocks in the northeastern portion of Carlton Pass. He mapped volcanic rocks now assigned to the Ohanapecosh Formation (Fiske, Hopson, and Waters, 1964) as overlying Puget Group sandstones along the northwest side of the Bumping River valley. Abbott also mapped a fault zone in the upper Carlton Creek - upper Bumping River valley separating uplifted lower Tertiary rocks to the northwest from down-dropped middle Tertiary Ohanapecosh Formation to the southeast. Thus he inferred faulting was younger than middle Tertiary. The Tertiary rocks of the White Pass - Tieton Pass - Goat Rocks area were studied in reconnaissance by Ellingson (1968). Ellingson (1968) also described fault zones at Clear Lake, along the south side of Rimrock Lake, across Cartright Creek, and paralleling Indian Creek, but the age and displacement of these faults is uncertain. Swanson (1964) mapped and described Tertiary rocks around the eastern end of Rimrock Lake, but was unable to definitively correlate these rocks with units west of the Cascade crest. Swanson's 1964 mapping and rock descriptions were field checked and found to be quite accurate, so it was decided not to undertake further mapping in this area. Radiometric dates on these rocks of the eastern slope of the Cascades are needed, however, to test lithologic correlations with units on the western slope of the Cascades.

Objectives and Problems

The objectives of this study have been as follows:

(1) Tertiary volcanic and plutonic rocks are being mapped and sampled in the field; they specifically included: welded tuffs at Spencer Creek, crystal tuffs south of Kloochman Rock, Wildcat Creek Formation and overlying ash flows and tuffs, pyroclastic flows in the Fifes Peak of Tieton Volcano, andesite at Shellrock Peak, breccia at Bootjack rock, the microdiorite of Kloochman Rock, Goose Egg Mountain, Westfall Rocks and unnamed hills in this northwest-trending zone of intrusions (Swanson, 1964), rhyolitic ash in Indian Creek, intrusive rocks at Jug Lake and Twin Peaks, silicified basalts at Tieton Pass, olivine basalt near Conrad Meadows, basal Ohanapecosh Formation in Summit Creek (Ellingson, 1959, 1968, 1972), and in Carlton Pass (Abbott, 1953), Ohanapecosh Formation cropping out on the north side of Johnson Peak, quartz tuff in the northern Tumac Plateau, intrusive rocks at Pear Butte and Carlton Ridge, hornblende porphyry at McNiel Peak, and pyroclastic breccia at the Devils Horns.

(2) Detailed mapping projects have been planned for the Clear Lake fault zone, the Indian Creek fault zone and the fault in Cartwright Creek (Ellingson, 1972), the Carlton Creek fault (Abbott, 1953), and faults in late Pleistocene lake sediments west of Penoyer Lake (observed by Clayton and Porter of University of Washington).

(3) Rocks are being correlated on the basis of lithology, stratigraphic position, petrographic similarity, and by ages obtained by the fission-track and K-Ar radiometric dating techniques.

(4) A map of the Tertiary rocks has been drafted.

The problems this study seeks to solve include: identifying and mapping Tertiary and younger fracture zones and faults which may localize the circulation of geothermal fluids; determining the age and displacement of faults which may have controlled the ascent of magma; evaluating the Tertiary section as a cap rock which may focus the geothermal resource at the crest of anticlinal and domal structures, and the definition of the age of Tertiary volcanic episodes in this portion of the Cascades, and their interrelations with movement of the Pacific and Juan de Fuca Plates and with regional tectonics.

Ellingson (1972) concludes that the White Pass region has been positive relief since the Eocene, and that Quaternary faulting has lowered the southeastern Tumac Plateau 2,300 feet relative to Russell Ridge to the east. If the doming and uplift of this region are independent of the general pattern of the Cascade Orogeny, then a hot-spot model (Suppe and others 1975) may be applicable to the region. As part of the study, field work and radiometric dating have been designed to provide data to determine if late Tertiary precursors to the unusually time continuous and compositionally diverse Quaternary volcanic rocks exist. Although the present subcrustal structure and rate of possible subduction beneath western Washington are uncertain, the Cenozoic dynamics of oceanic plates in the Pacific Northwest are well known (Atwater 1970; Silver 1971; Riddihough 1978). By comparing these plate motions, spreading at the Juan de Fuca Rise (Vine and Mathews, 1963; Kennet and others, 1977), and the record of volcanism in the study region, there has been an attempt to determine the relationships between rate of subduction, volcanic activity, and tectonics. The Cenozoic record of volcanism and tectonics of this region have been compared with data from studies by Armstrong (1978), Christiansen and Lipman (1972), Hamilton and Myers (1966), Vance and Naeser (1977), Vance (1977 and 1979), Vogt and others (1976), to see if patterns inferred by the above authors are similar to those of the study area.

Another important and unique aspect of the Tertiary record in the study region is that six important Tertiary rock units of western Washington crop out within it. Eocene volcanic rocks similar to those mapped in westernmost Washington by Snavely and Wagner (1963) crop out at Tieton Pass (Ellingson 1968, p. 28) and the Puget Group, Ohanapecosh Formation, Fifes Peak Formation, Stevens Ridge Formation and, Columbia River Basalt crop out elsewhere in the region. Stratigraphic relationships between these rocks are being carefully studied. Radiometric dating of these volcanic units along with paleomagnetic studies allow evaluation of the suggestion by Vance (1979) that the Cascade Range underwent a major clockwise rotation during the early Tertiary in sympathy with the rotation of the Oregon coastal block recognized by (Simpson and Cox, 1977).

Quaternary Volcanic Rocks in the Tumac Plateau - White Pass - Goat Rocks Area

The Tumac Plateau-White Pass-Goat Rocks area contains a record of Quaternary volcanic rocks unique in the State of Washington. Hundreds of eruptions have occurred in the region at varying intervals during Quaternary time. Fifteen vents have been located and the existence of others are inferred because many lavas cannot be correlated with the known vents. The volcanic rocks range widely in composition and include high-alumina basalt, olivine basalt, basaltic andesite, andesite, dacite, and rhyolite.

Quaternary volcanism in Washington State north of the Tumac Plateau-White Pass-Goat Rocks study area has been largely restricted to andesitic stratovolcanoes. The dominant type of Quaternary volcanism in Washington State south of the study area has been the eruption of basalt in fissure zones and the formation of two large andesitic stratovolcanoes. The Tumac Plateau may be the northern terminus of a fissure zone, possibly the Indian Heaven fissure zone described by Hammond and others (1976). The Indian Heaven fissure zone is oriented north-south and passes through the western flank of Mount Adams. The Tumac Plateau, Hogback Mountain, the Goat Rocks, and Lake View Mountain define a linear north-south zone of Quaternary volcanism that also intersects Mount Adams.

Two major sets of lineaments visible on Landsat photographs converge at the northern boundary of the Tumac Plateau. The St. Helens lineament, oriented northeast-southwest, is traceable through Carlton Pass, defining the northwest boundary of the Tumac Plateau. An en-echelon set of lineaments oriented northwest-southeast, sub-parallel to the Olympic-Wallowa lineament, are traceable along the Indian Creek valley, through Pear Butte, and through the Rattlesnake Peaks (Lepley, personal communication 1978). These lineaments may correspond to major crustal structures which extend to sufficient depth to have controlled the ascent of magma.

Previous field mapping had indicated that Quaternary volcanism in the Tumac Plateau area was restricted to an area between the St. Helens and Indian Creek lineaments. Kincaid Mountain 1 km northwest of Jug Lake, Sugarloaf Mountain 2 km south of Bumping Lake, and an eroded volcanic cone and flow that dams upper Indian Creek forming Pear Lake are Quaternary vents at the northern perimeter of the study area. Lines drawn on a map to connect Kincaid Mountain and Sugarloaf Mountain, and the Pear Lake vent and Sugarloaf Mountain, closely parallel the St. Helens and Indian Creek lineaments, respectively. The Tumac Plateau, with at least 5 additional vents, the Summit Creek soda springs, with an inferred high temperature source, the Clear Fork Cowlitz River dacite vent, the Hogback Mountain vent, and the Round Mountain vent area (Ellingson 1968), all lie between the traces of the two sets of lineaments.

The northern portion of the study area contains the Tumac Plateau, a 40 km^2 olivine basalt shield volcano. Tumac Mountain, a Holocene cinder cone (Abott 1953), is the centrally located vent of the shield volcano. Around the Tumac Plateau are outcrops of leucocratic lava. Abbott (1953) mapped the northwest portion of the Tumac Plateau and grouped all the leucocratic lavas he inferred to be Pliocene or younger into a single unit named Deep Creek andesite. Ellingson (1959) mapped a leucocratic lava in the Cowlitz Pass area and named it Ridge Top andesite. After further field work, Ellingson (1968) grouped all leucocratic lavas of the southern and eastern Tumac Plateau area, renamed them Spiral Butte andesite, and inferred they are Pliocene in age.

Field mapping, geochemical, and petrographic studies by the author indicate that the "Ridge Top-Spiral Butte" andesite is a sequence of basalt flows, probably mid-Pleistocene in age. The basalts were erupted into a paleo-valley system oriented north-south across the present valley system. The ridge top position is due to erosional inversion of topography, a process that has also perched the Tieton Andesite (to be discussed later) high above present valley bottoms. Furthermore, other leucocratic lavas grouped in the Spiral Butte andesite are now known to be siliceous andesites erupted from at least 8 vents inferred to mid-late Pleistocene in age. The vents are identifiable by their high topographic relief, their primary volcanic morphology, and/or the presence of welded, scoria breccia, with mottled primary oxidation patterns, and other vent agglomerates. Lava erupted from vents at Deer Lake Mountain, Sugarloaf Mountain, and 500 m south of Pear Lake forms distinct valley-filling flows in the presently existing drainage system. The smooth U-shaped morphology usually observed in the glacially scoured valleys in this area is modified by bulging lava flow morphology. Because these lava flows have not been profoundly scoured by glaciers and are contained in the bottoms of presently existing valleys, they are inferred to be late Pleistocene in age. Spiral Butte, with well-preserved paired lava levees defining a tight spiral around the vent, may have been formed subglacially. Its anomalous shape has been only slightly affected by the ice cap that covered the Tumac Plateau during the Evans Creek (or Fraser) Glaciation. The Clear Fork Cowlitz River dacite flow has been glaciated on its lower portion but glacial ice has destroyed the vent area and scoured the upper portion of the flow (Ellingson 1968). Since the Clear Fork Cowlitz River valley contained an active tributary glacier to the Cowlitz glacier during the Evans Creek Glaciation, the dacite flow must be post Evans Creek in age, and thus less than 14,000 years old.

Hogback Mountain and Round Mountain are in the middle of the study area. Ellingson (1968) inferred that Round Mountain is a Quaternary vent which erupted basaltic lava. At Hogback Mountain, a sequence of more than 125, 1-2 m thick, scoriaceous, blocky lava flows of high alumina basalt crop out. Ellingson inferred that lava ponded in a crater about 1 to 2 km in diameter at the summit of Hogback Mountain and flowed down a paleo-valley to the northwest, obliquely across the present drainage system. Erosion by cirque glaciers has also destroyed the summit crater. The Hogback Mountain basalts are probably middle Pleistocene in age.

In the southern portion of the study area are the Goat Rocks, a deeply dissected volcanic complex which began its eruptive history in late Miocene or early Pliocene time, and continued to be active until the late Pleistocene. The Goat Rocks volcano of middle Pleistocene age may have reached an altitude of 15,000 feet (Ellingson 1968). The Tieton Andesite (Becraft 1950) is perhaps the worlds longest known andesite flow, extending 80 km from its source in the Goat Rocks to its terminus in Yakima. This lava flow has a K-Ar age of 690,000 years b.p. (Bentley, personal communication, 1977). Near its source, this lava flow is a ridge-top cap rock which has resisted erosion, causing inversion of the topography. In the canyon of the Tieton River, remnants of the lava are found clinging to valley walls more than 100 m above the present valley bottom. The Tieton Andesite followed a paleo-valley system around the northwest side of Westfall Rocks, but has since been breached by the present east-west Tieton River, which now flows to the south of Westfall Rocks. The degree of erosion is of similar magnitude to that observed at Hogback Mountain. Late Pleistocene andesites have also been erupted from the Goat Rocks. The Old Snowy andesite flowed south down Goat Creek, and occupies the bottom of the present valley.

Further work in the area was designed to clarify the early and middle Pleistocene record. Detailed field mapping, petrographic, and geochemical studies have allowed accurate interpretation of the stratigraphy, and radiometric dating should establish an absolute time framework for the eruptive history of the area. With geochemical differentiation trends, Sr^{87}/Sr^{86} ratios, and trace element concentrations, constraints on the genesis of the magma and its ascent to the surface are being examined. The probability of the existence of high-level silicic magma chambers or other heat sources potentially important as a geothermal resource is still being evaluated.

Results

Results of the 1979 field study are presented on a map of scale 1:24,000, found within the pocket on the back cover of this report. The map was first released as Open-File Report 80-8 of the Washington Division of Geology and Earth Resources.

References Cited

Abbott, A. T., 1953, The geology of the northwest portion of the Mt. Aix quadrangle, Washington: University of Washington Ph. D. thesis, 256 p.

Armstrong, R. L., 1978, Cenozoic igneous history of the U.S. Cordillera from 42° to 49° N. latitude: Geological Society of America Memoir (in press).

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, p. 3513-3536.

Becraft, G. E., 1950, Definition of the Tieton Andesite on lithology and structure Washington State University Ph. D. thesis, 26 p.

Campbell, K. V.; Miers, J. G.; Nichols, B. M.; Oliphant, J.; Pytlak, S.; Race, R. W.; Shaw, G. H.; Gresens, R. W., 1970, A survey of thermal springs in Washington State: Northwest Science, v. 44, no. 1, p. 1-11.

Christiansen, R. W.; Lipman, P. W., 1972, Cenozoic volcanism and plate tectonic evolution of the western United States II; Late Cenozoic: Philosophical Transactions of the Royal Society, London, A. v. 271, p. 249-284.

Dungan, M. A.; Vance, J. A.; Blanchard, D., 1979, Tectonic setting and trace element geochemistry of Mesozoic ophiolitic rocks in western Washington: American Journal of Science (in press).

Ellingson, J. A., 1959, General geology of the Cowlitz Pass area, central Cascade Mountains, Washington: University of Washington M. S. thesis, 60 p.

Ellingson, J. A., 1968, Late Cenozoic volcanic geology of the White Pass-Goat Rocks area, Cascade Mountains, Washington: Washington State University Ph. D. thesis, 112 p.

Ellingson, J. A., 1969, Paleozoic sedimentary and metamorphic rocks in the southern Cascade Mountains, Washington: Geological Society of America Abstracts with Programs for 1969, Part 3, p. 15-16.

Ellingson, J. A., 1972, The rocks and structure of the White Pass area, Washington: Northwest Science, v. 46, no. 1, p. 9-24.

Fiske, R. S.; Hopson, C. A.; and Waters, A. C., 1963, Geology of Mount Rainier National Park, Washington: U.S. Geological Survey Professional Paper 444, 93 p.

Fox, P. J.; Schreiber, E.; Rowlett, H.; McCamy, K., 1976, The geology of the oceanographer fracture zone-A model for fracture zones: Journal of Geophysical, Research, v. 81, p. 4117-4128.

Goetsch, S. A., 1978, The metamorphic and structural history of the Quartz Mountain-Lookout Mountain area, Kittitas County, central Cascades, Washington: University of Washington M. S. thesis, 86 p.

Hamilton, W.; Myers, W. B., 1966, Cenozoic tectonics of the western United States: Review of Geophysics, v. 4, p. 509-549.

Hammond, P. E.; Pederson, F. A.; Hopkins, K. D.; Aikens, D.; and others, 1976, Geology and gravimetry of the Quaternary basaltic volcanic field, south Cascade Range, Washington: Proceedings of the 2nd United Nations Symposium on the Development and use of Geothermal Resources, v. 1, p. 397-405.

Karson, J.; Dewey, J. F., 1978, Coastal complex, western Newfoundland-An early Ordovician oceanic fracture zone: Geological Society of America Bulletin, v. 89, p. 1037-1049.

Kennet, J. P.; McBirney, A. R.; Thunell, R. C., 1977, Episodes of Cenozoic volcanism in the circum-Pacific region: Journal of Volcanology and Geothermal Research, v. 2, p. 145-163.

Mattinson, J. M., 1972, Jurassic metamorphism of basement gneisses near Mount Rainier, Washington: Carnegie Institute Year Book, no. 71, p. 576-578.

Riddihough, R. P., 1978, The Juan de Fuca Plate: EOS, v. 59, no. 9, p. 836-842.

Saleeby, J., 1977, Fracture zone tectonics, continental margin fragmentation, and emplacement of the Kings-Kaweah ophiolite belt, southwest Sierra Nevada, California. In Coleman, R. D.; Irwin, W. P., editors, North American ophiolites: Oregon Department of Geology and Mineral Industries Bulletin 95, p. 141-159.

Silver, E. A., 1971, Small plate tectonics in the northeastern Pacific: Geological Society of America Bulletin, v. 82, p. 3491-3496.

Simmons, G. C., 1950, The Russell Ranch Formation: Washington State University M. S. thesis, 26 p.

Simmons, G. C.; Van Noy, R. M.; Zilka, N. T., 1974, Mineral resources of the Cougar Lakes-Mount Aix study area, Yakima and Lewis Counties, Washington: U.S. Geological Survey Open-file Report 74-243, 22 p.

Simpson, R. W.; Cox, A., 1977, Paleomagnetic evidence for tectonic rotation of the Oregon Coast Range: Geology, v. 5, no. 10, p. 585-589.

Snavely, P. D., Jr.; Wagner, H. C., 1963, Tertiary geologic history of western Oregon and Washington: Washington Division of Mines and Geology Report of Investigations 22, 25 p.

Stout, M. W., 1964, Geology of a part of the south-central Cascade Mountains, Washington: Geological Society of America Bulletin, v. 75, p. 317-337.

Suppe, J.; Powell, C.; Berry, R., 1975, Regional topography, seismicity, Quaternary volcanism, and the present-day tectonics of the western United States: American Journal of Science, v. 275 A, p. 397-436.

Swanson, D. A., 1964, The middle and late Cenozoic volcanic rocks of the Tieton River area, south-central Washington: Johns Hopkins University Ph. D. thesis, 334 p.

Vance, J. A., 1977, Early and middle Cenozoic magmatism and tectonics, Cascade Mountains, Washington: EOS (Abs.), v. 58, p. 1247.

Vance, J. A., 1979, Early and middle Cenozoic arc magmatism and tectonics in Washington State: Geological Society of America Abstracts with Programs (in press).

Vance, J. A.; Naeser, C. W., 1977, Fission track geochronology of the Tertiary volcanic rocks of the central Cascade Mountains, Washington: Geological Society of America Abstracts with Programs, v. 9, no. 4, p. 520.

Vance, J. A.; Miller, R. B., 1979, The Straight Creek fault-A major Cenozoic structure in the Washington Cascades: Submitted to S.E.P.M. volume, Cenozoic Paleogeography.

Vine, F. J.; Mathews, D. H., 1963, Magnetic anomalies over ocean ridges: Nature, v. 199, p. 947-949.

Vogt, P. R.; Lowrie, A.; Bracey, D. R.; Hey, R. N., 1976, Subduction of seismic oceanic ridges-Effects on shape, seismicity, and other characteristics of consuming plate boundaries: Geological Society of America Special Paper 172, 59 p.

Additions and Comments

by Michael A. Korosec

In 1979 geologic mapping in the White Pass-Tumac Mountain area of the Washington central Cascades, and additional mapping carried out in 1980 for the area to the north (up to Bumping Lake), has given us a better idea of the type and extent of volcanism experienced by this region. Geoff Clayton has been able to demonstrate that this section of the Cascades is possibly a huge dome-like structure, which has experienced nearly continuous volcanism from the Miocene, through the Pliocene and Pleistocene, activity which has continued into the Holocene. Through this period of time, there are indications that the "center" of the bulk volcanic activity may be moving slowly to the north.

Further studies by Clayton will begin shedding light on the complex nature of the rocks and magmas beneath the structural dome, and may lead to the development of general magma mixing models and determinations of what types of magma chambers exist today.

Beyond the 1980 field mapping, additional work could be carried out in the region to the south, including the Goat Rocks volcanics. Working with geologists who are studying volcanic fields of the south Cascades, (Dr. Paul Hammond, Portland State University in particular), time-space-composition models for most of Washington's Quaternary to recent volcanism might be worked out. This should lead to a better understanding of this complex geologic province and to new methods which will allow for specific targeting of potential volcanic-related geothermal resources.

VII. GEOTHERMAL INVESTIGATIONS IN THE CAMAS AREA, WASHINGTON, 1979

by

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VII. GEOTHERMAL INVESTIGATIONS IN THE CAMAS AREA, WASHINGTON, 1979

by

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Introduction

The town of Camas, Washington, is located along the Columbia River west of the Cascade Mountains. Crown Zellerbach Corporation operates a large pulp and paper mill within the town. This mill is the largest single industrial energy consumer in the State of Washington. As such, the Camas area became a very desirable place to look for geothermal energy.

There were a few geologic indicators which suggest the possible existence of geothermal resources. The Lacamas Fault extends northwest from the Columbia River near Camas, and can be traced along Lacamas Lake to a point about 8 miles northwest of town. Throughout the region, several small cinder cones dot the landscape. These basaltic volcanics, part of the Boring Lava, are thought to be early to middle Pleistocene in age.

The best indicators of possible geothermal resources, however, were the existence of a warm spring and warm well across the Columbia River in Oregon. Corbett warm spring, flowing about 10 gpm at 18°C, lies on an extension of the strike of the Lacamas Fault, about 6 miles southeast of the town. The Y.M.C.A. well, located 3 miles farther south, is 313 feet deep, and produces water with a temperature of 22°C. When Na-K-Ca geothermometers are applied to these waters (using beta=1/3), Corbett Warm springs and the Y.M.C.A. well are both predicted to have equilibrium reservoir temperatures of 177°C. The Quartz-Silica geothermometer predicts equilibrium reservoir temperatures of 107° and 115°C for the spring and well.

The 1979 Project

To better delineate the geothermal potential of the Camas area, the Division subcontracted a gravity survey of the region (conducted by Dr. Z. F. Danes, University of Puget Sound) and a DC Resistivity Survey of the fault zone (conducted by R. B. McEuen of Exploration Geothermics, and F. A. Rigby of Science Applications, Inc.). The final report from the resistivity survey is presented in Appendix C. In addition, the Division measured temperature gradients in existing wells, drilled two heat flow holes based on the results of the resistivity and gravity surveys, and resampled and analyzed the waters from the spring and well across the Columbia River in Oregon.

Results

Measurements conducted for existing wells in the Camas area yielded temperature gradients of less than 40°C/km, typically falling between 25° and 35°C/km. Two water wells located to the east of 122°10'W, about 15 to 18 miles east of Camas, produced gradients of about 53 and 69°C/km.

The two gradient-heat flow wells drilled by the Division, Camas No. 1 and Camas No. 2, gave temperature gradients of 31.5 and 37°C/km. The former well was drilled 152 meters into Tertiary volcanics and sediments and the latter, 72 meters deep, was entirely in late(?) Tertiary sediments.

The results of the water analyses for the Corbette Spring and the Y.M.C.A. well were virtually the same as previous analyses (see table 4.2).

Discussion

Despite the existence of Quaternary volcanic rocks in the area, Camas seems to lie within the low heat flow province of the Puget Lowland, just west of the transition zone which leads to the higher heat flow province of the south Cascades. The Boring Basalts, which crop out near the town (Green Mountain, Brunner Hill, and west of Prune Hill), are very small centers, too old to have retained any heat. They are thought to be anywhere from 100,000 to 1 million years old, as reported by various geologists. Some of the material exposed in the road cuts near Prune Hill looks fresh enough to be younger than 100,000 years old, but no work has been done to qualify the actual age. (Although originally proposed as part of the geothermal investigation at Camas, geologic mapping and age dating of the material in the vicinity of Camas was dropped in favor of the resistivity survey, a recommendation handed down by an ad hoc committee of U.S. Department of Energy, U.S. Geological Survey, Department of Natural Resources, and consulting geologists interested in the Camas project.) No matter what the age, it appears that the sources of magma for these volcanics were either very small or very deep, and have since cooled and discontinued supplying heat to the surface.

From previous mapping, the only other significant volcanic center is the Boring Basalt field at Battleground, about 12 to 14 miles (20 to 23 km) north of the town. There have been a few rumors of the existence of warm water wells in the Battleground area, but none have been found. The two wells that were deep enough to measure in that area, only 1 and 2 miles from the volcanics, produced temperature gradients of 25° and 40° C/km, similar to the low gradients found throughout the region.

Temperature gradients do not start to increase significantly until one moves about 15 to 18 miles east to about Skamania. Figure 3.4 shows the contoured heat flow picture for southwestern Washington. Camas falls between the 40 and 50 mWatts/m^2 contours.

Despite lying within a low heat flow province, with little chance of tapping heat from a volcanic system, it was still possible that deep seated structures, like faults or fracture zones, might have been allowing relatively moderate to high temperature fluids to migrate from deeper depths into shallower aquifers.

The Lacamas Fault was a likely candidate for this, being the most extensive and well recognized fault in the area. Though many geologists caution against extending structural features across the Columbia River between Washington and Oregon, it was curious that Corbett Station warm spring should fall on an extension of the strike of the Lacamas Fault. But even if this warm spring is controlled by part of the fault, it does not necessarily mean that warm waters are rising along the entire length of the fault, expecially 6 to 10 miles to the northwest in the Camas area. The two areas are separated by the Columbia River, a major structure which is very poorly understood. Most geologists hesitate projecting anything across this structure.

None of the temperature gradients measured near the town were at all anomalous, suggesting that if warm water was flowing upward at only isolated points along the fault, the effects were not significant enough to appreciably increase the local gradients. In an effort to pinpoint possible zones of warm water upwelling along the fault, a D.C. resistivity survey was designed and carried out by a subcontractor (see Appendix C). Two-dimensional earth modeling of the results identified two areas with resistivity anomalies. These anomalies, resistivity lows with values of about 10 ohm-meters, consisted of a relatively small area towards the south end on the study area (just north of the town), and a broader area located north of Lacamas Lake. The southern anomaly was modeled as alternating layers of resistive and conductive material, and the northern lows were modeled as a less complex, homogeneous section of fairly conductive ground.

Drill holes located in close proximity to the centers of these anomalies produced only average gradients and heat flow, similar to values measured in existing wells throughout the region.

From available geologic mapping in the area, and as suggested by materials collected during the drilling operation, it is likely that the resistivity lows are being produced (at least in part) by "clay" zones within the Tertiary sands, gravels, and breccias of the Troutdale Formation. The northern hole was drilled entirely within the Troutdale, but the southern hole bottomed in basalt (which was either Miocene Columbia River complex or early Pleistocene "Skamania Volcanics"). If the basalt was part of the Skamania Volcanics, it is possible that Troutdale clays and gravels underlie the formation, fitting the two-dimensional resistivity model of alternating conductive and resistive strata.

Conclusions

The 1979 geothermal assessment program in the Camas area did not find any indication that significant geothermal resources underlie the Camas area at shallow depths. The results also suggest that there are no large anomalous geothermal resources at intermediate to deeper depths. The area is characterized by average temperature gradients and low heat flow.

If economics dictated that production wells be 8,000 feet (2.4 km) deep for the Crown Zellerbach Paper Mill Project, temperatures encountered at the bottoms of such holes may be in the range of 95 to 115°C (using temperature gradients of 35 to 40°C/km). In order to reach the targeted temperature used in early project feasibility studies, 180°C, production holes would need to be drilled to depths of 14,000 to 16,000 feet (4.2 to 4.8 km). In addition, there is no guarantee that flowing aquifers exist at any of these depths. Original studies assumed there would be fracture zones, associated with the Lacamas Fault which would serve as aquifers. There is presently no information on the nature of the Lacamas Fault or its fracture zones at depth.

With what we know at this point in time, it is unlikely that geothermal resources can be economically utilized at Camas. With so little encouraging information and so much discouraging data, the Division has no intention of further pursuing any geothermal projects in the Camas area.

VIII. GEOTHERMAL ASSESSMENT OF MOUNT ST. HELENS, WASHINGTON, 1979

by

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VIII. GEOTHERMAL ASSESSMENT OF MOUNT ST. HELENS, WASHINGTON, 1979

by

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Introduction

The reawakened Cascade stratovolcano Mount St. Helens was a prime geothermal target of the Division of Geology and Earth Resources in 1979, prior to the mountain's eruption. Mount St. Helens was known to be a young volcano, having been observed to erupt in historical time. The previous volcanic episode began about 1842 and ended in 1857. While other Cascade stratovolcanoes exhibited more surface manifestations of existing thermal activity, such as Mount Baker with its large steaming fumaroles in Sherman Crater, Mount St. Helens became the most attractive target in part because of its land status and proximity to population centers. The land ownership in the region, (roughly 1/3 US Forest Service, 1/3 State lands, and 1/3 private), and its proximity to the cities of Vancouver, Portland, Longview, Kelso, and Castle Rock, placed Mount St. Helens at the top of the list, ahead of the more remote stratovolcanoes, most of which are locked up in National Parks or Wilderness Areas.

During 1979, the Division initiated a geothermal assessment of Mount St. Helens with an examination of available literature. A gravity survey was carried out by Dr. Z. F. Danes, as part of a broader survey of the entire south Cascades, of springs on and around the flanks, and drilling three 125 to 155 meter cased drill holes for the purposes of measuring temperature gradients and calculating heat flow.

From the literature, and from discussions with local residents familiar with the mountain, the only existing thermal surface features included warm ground at the site of a reported fumarole near the Boot on the upper north flank at an elevation of 2740 meters (9040 feet) (Phillips, 1942; Friedman and Frank, 1977), warm ground on the upper southwest flank at an elevation between 2650 and 2750 m (about 8800 feet) along a contact of the dacite summit dome (Friedman and Frank, 1977), warm ground along the southern base of Pumice Butte on the Plains of Abraham, warm ground near the upper reaches (northern section) of the Ape Caves area, and warm ground near the terminous of the Floating Island Lava Flow.

The warm ground areas near the summit were detectable by aerial thermal infrared surveys in 1966 (Moxham, 1970) and confirmed by aerial photography and ground verification in early 1972 (Friedman and Frank, 1977). The other warm ground areas have only been confirmed by observations of local residents in the area. They have reported deep holes through the snow cover, over relatively extensive areas in some cases, at the bottoms of which green grass and plants grew year around. There is no reason to question these observations, especially the occurrence at the terminus of the Floating Island Lava Flow, where there was also reported to be sulfur fumes and elk licks.

Results

Several springs were sampled during the late summer and fall around Mount St. Helens. All were cold, with very low dissolved salts. A partial analysis of these waters was carried out by the author, and only very low levels of normal ground water ions (Na, K, Ca, SiO_2, HCO_3, and Cl) with no lithium were detected. Most springs on Mount St. Helens flowed out from lava flows, such as Kalama Springs on the southwest side and Moss Springs on the southeast side. The waters probably originate as meteroic water from snow and glacial ice melts, which flow through the lava flows to the lower slopes. The waters probably never penetrate deep enough to be heated by possible heat sources. This idealized sheet flow of water down the flanks may prevent the detection of thermal features at the surface by dissipating the heat and diluting any hot waters that are convected upward.

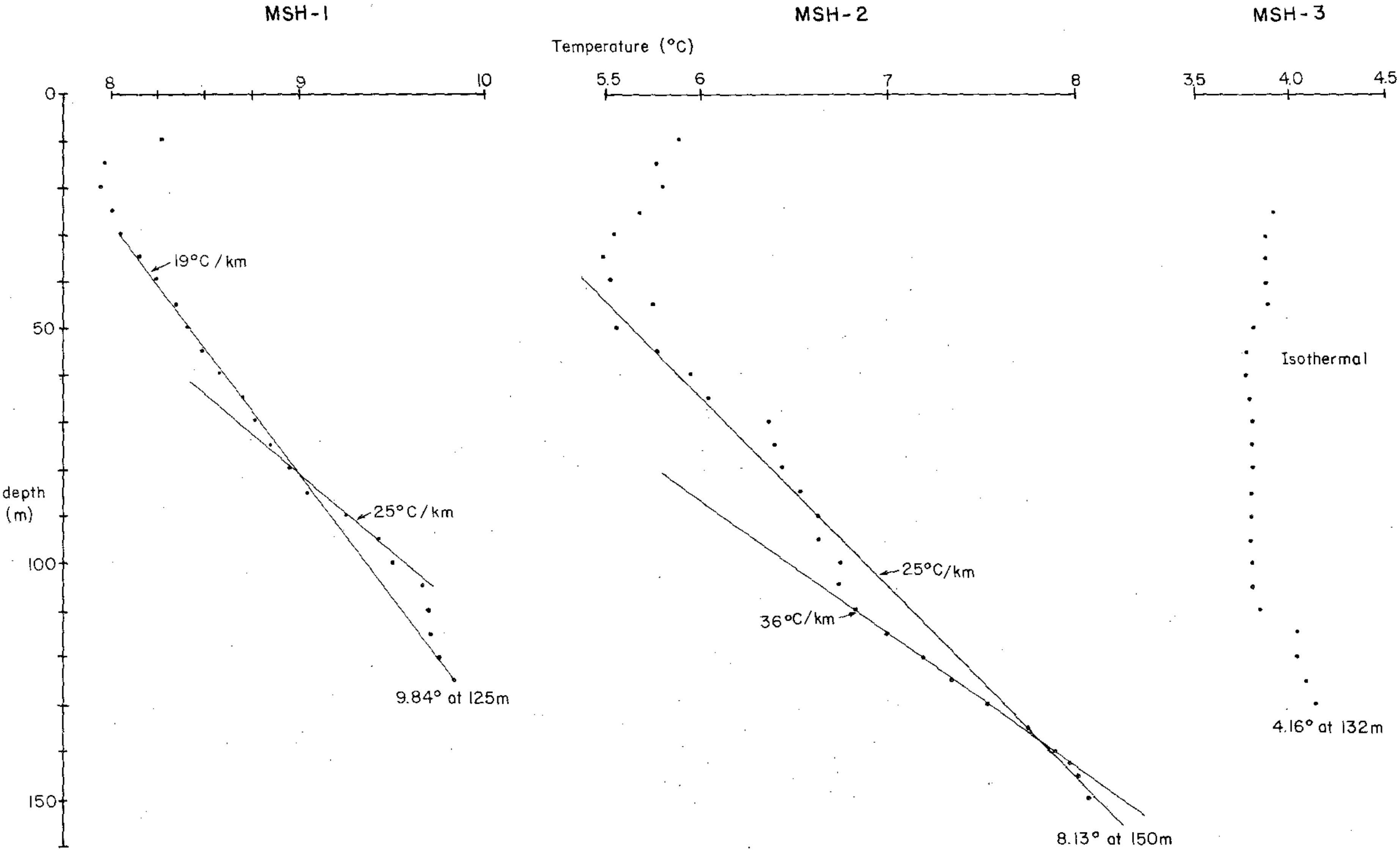

FIGURE 8.1.—Temperature vs. depth profiles for Mount St. Helens drill holes.

From mid-September 1979 through mid-November 1979, three heat flow holes were drilled around Mount St. Helens. St. Helens Drill Hole No. 1 (SHDH 1) was located along the north side of State Route 504 (also known as the Spirit Lake Road) at the Studebaker Creek Road turnoff (T. 9 N., R. 5 E., NW1/4NW1/4 section 18), about 8 km north-northwest of the park. The hole was finished and cased to a depth of 125 meters. The bottom hole temperature was measured to 9.9°C and a relatively straight line temperature gradient was determined to be 19°C/km. The site was destroyed by the May 18, 1980 eruption and now lies below 50 to 80 meters of debris and pyroclastic flows.

St. Helens Drill Hole No. 2 (SHDH2) is located above Goat Marsh on USFS Road N847, 8 km southeast from the former summit. The hole was completed at a depth of 154 meters, producing a bottom hole temperature of 8.2°C and a gradient of 38°C/km. This drill site seems to have been spared by the first year of eruptive activity.

St. Helens Drill Hole No. 3 (SHDH3) is located near the west end of an unnamed marsh, south-southeast of the summit, in a borrow pit quarry along the Marble Mountain Road (USFS Road N809). The site is about 8 km from the former summit. The hole was completed at a depth of 131 meters, but only after considerable difficulties because of poor drilling conditions. The first temperature measurements were made May 3, 1980, just over one month after the initial phreatic eruptions (March 27) and two weeks before the catastrophic eruption of May 18. The temperature measured at depth varied by only about 1°C the entire length of the hole (virtually isothermal), at the very cold temperature of about 4°C. The site is probably still preserved, but access by roads has been cut off by mudflows from the volcano's flanks.

Discussion

The relatively low temperature gradients of the Mount St. Helens drill holes resulted in similarly low heat flow. Hole SHDH 2 has a calculated heat flow of 54 mW/m^2, representing an expected regional value. The SHDH 1 heat flow of 38 mW/m^2

is more typical of the Puget Lowland than the Cascade Mountains. There is still a high degree of doubt as to whether these holes represent the true regional heat flow regime (unaffected by anomalous conditions in the area), or whether the values are the result of local hydrological problems.

All three holes were thought to be collared in Tertiary Ohanapecosh volcanic rocks (Eocene to Oligocene age). The rocks in the surrounding outcrops are zeolitized basalt and andesite lavas, with a smaller percentage of volcanoclastics than the younger material from the nearby Quaternary stratovolcano. As a result, these Tertiary rocks are ideally less permeable to vertical flow of ground water. The Ohanapecosh outcrops just beyond the lower flanks of Mount St. Helens are topographic highs or islands above the Quaternary rocks.

SHDH 1 was definitely drilled through Tertiary rock, but its proximity to possibly deep Quaternary valley fill of the North Fork of the Toutle River could have resulted in hydrologic complications. This situation could be taken care of, in part, with terrain corrections which treat the area as an open valley, cut down to some assumed depth. But considering that the source of much of this water is likely very cold glacial melt water that flows through the Tertiary rocks as well as Quaternary rocks, and noting the existence of several cold springs within the valley near the drill site (suggesting vertical flow), any anomalous heat flow in the area would be wiped out, and the actual regional heat flow would be greatly reduced, at least when measured in drill holes that fail to penetrate below the "blanket" of cold ground water and its sphere of influence.

The results at SHDH 2 most likely represent the actual thermal regime existing in the area, not significantly affected by hydrologic conditions. But the absence of any other nearby heat flow measurements makes it difficult to give a fair evaluation of SHDH 2 in the context of regional heat flow.

The same hydrologic conditions which are possibly at work near SHDH 1 are definitely occurring at SHDH 3. In addition, despite believing that the hole was drilled into the Ohanapecosh formation, it is likely that the hole was actually collared in Marble Mountain volcanics, a mid-Quaternary unit known to occur throughout the area to the southwest and southeast of SHDH 3. Rubbly volcanoclastics encountered beneath coherent flow rocks may be ancient deposits from a very early Mount St. Helens or some other neaby Quaternary volcanic center.

Assuming that the results from SHDH 1 and 2 are close to the actual heat flow of the area, the regional heat flow setting of Mount St. Helens can be discussed with respect to the rest of the southwest Cascades. The map in Figure 3.4 (in chapter 3), presents a contoured picture of the regional heat flow. A sharp transition exists between the Western Washington Region (Puget Lowland Province) and the South Cascades Region. This transition runs roughly north-south, from the Skamania area on the Columbia River, crossing the Cowlitz River valley between the towns of Morton and Randle, and extending further north on the west side of Mount Rainier National Park. Mount St. Helens appears to fall within this transition zone. Results from a few drill holes on the east side of Mount St. Helens would be needed to confirm this.

At Mount St. Helens itself, the three drill holes had only begun to examine the local heat flow regime. The discouraging results by no means preclude the possible existence of geothermal resources beyond the flanks of the volcano. The area involved is roughly 200 to 300 square kilometers, most of which is virtually untested. The potential for anomalous thermal conditions or geothermal reservoirs is conceptually quite high, especially in light of the volcano's 1980 eruptions.

Conclusions

The 1979-80 geothermal assessment effort added greatly to the relatively scant geothermal and hydrologic data bases for Mount St. Helens, but did not identify a geothermal resource or indicate the impending eruption of the volcano. There may indeed be large hot water reservoirs associated with this volcanic system, but their existence has yet to be demonstrated.

In addition, the 1980 eruptions of the volcano have provided a wealth of information which has helped develop a better understanding of the structural, thermal, and hydrologic systems associated with the volcano. This enhanced understanding will provide new ways of viewing other Cascade stratovolcanoes, and will have an important impact on how their hydrothermal systems will be explored.

Some of the developing concepts include: (1) A volcano continues to be active through geologic time only because it keeps its conduit "open" to some shallow depth between eruptions. That is, the conduit remains in a semi-molten or plastic condition. Each eruption re-supplies heat to the upper portion of the conduit, heat which is slowly dissipated through conduction and convection to the surrounding country rock. Preliminary indications from the seismic information provided by Mount St. Helens are that these "plastic" conditions existed to within 5 km of the surface under the volcano. Therefore, very high temperatures are maintained through time at a relatively shallow depth without the formation of a shallow magma chamber. (2) Probably all of the Quaternary stratovolcanoes maintain a hydrothermal system within the edifice of the cone itself. The existence of fumaroles on most of the cones confirms this. These systems may be very small and probably cool quite rapidly through time. Because of the problems of access (difficult terrain and closures due to land status), and because of the geologic hazards associated with many of the stratovolcanoes (the constant threat of eruption, for example) it is unlikely that these intra-cone hydrothermal systems will ever become viable commercial resources. (3) The Mount St. Helens eruptions have provided evidence that the volcano's location may be structurally controlled. Even before the current activity, a plot of the epicentus for microearthquakes in the vicinity suggested a north-northwest trending structure running through the stratovolcano (see figure 8.2). Epicentus of earthquakes associated with the 1980 eruptions have confirmed this, delineating a right-lateral strike-slip fault system. Crustal structures associated with volcanoes may provide a means by which geothermal fluid associated with deep systems beneath the volcano could migrate laterally out from the volcanic system and possibly vertically to relatively shallow depths beyond the flanks of the volcano. The resulting hydrothermal reservoirs will have a much greater practical and economic value, but the true energy potential of such a resource has yet to be demonstrated in the Cascades.

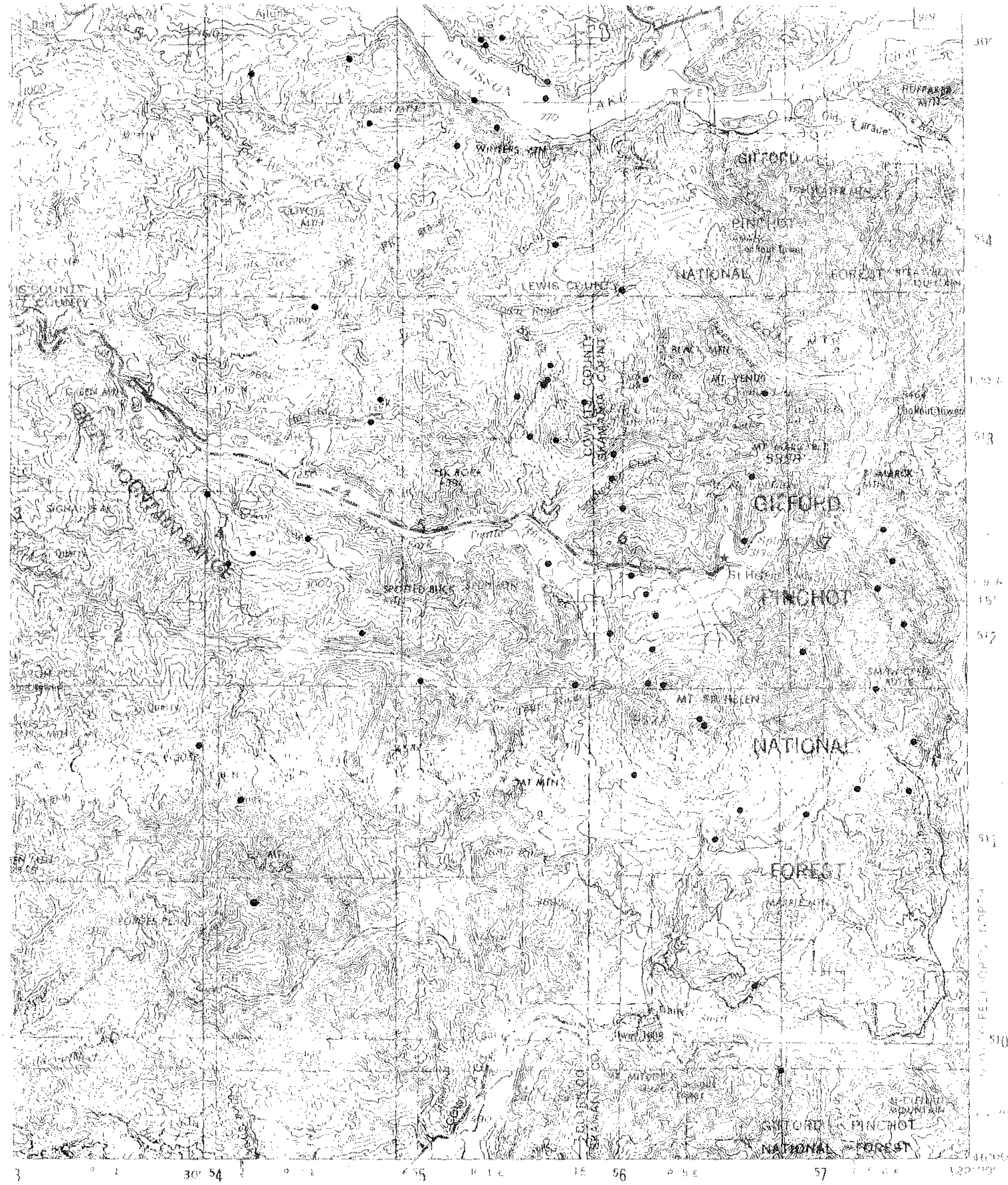

FIGURE 8.2.—Earthquake hypocenters near Mount St. Helens from 1971 through 1978
Data from Robert S. Crosson (University of Washington)

IX. BIBLIOGRAPHY OF GEOTHERMAL RESOURCE INFORMATION FOR THE STATE OF WASHINGTON

by

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1980

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Chapter IX
Bibliography of Geothermal Resource Information for the State of Washington

Armstrong, J. E.; Crandell, D. R.; Easterbrook, D. J.; Noble, J. B., 1965, Late Pleistocene stratigraphy and chronology in southwestern Washington: Geological Society of America Bulletin, v. 76, no. 3, p. 321-330.

Banks, N. G.; Bennett, C. A.; Schmidt, J. M., 1978, Maps of photo lineaments and geomorphic features in the Spirit Lake quadrangle, Washington: U.S. Geological Survey Open-File Report 78-505, 2 sheets.

Blackwell, D. D., 1969, Heat-flow determinations in the northwestern United States: Journal of Geophysical Research, v. 74, no. 4, p. 992-1007.

Blackwell, D. D., 1974, Terrestrial heat-flow and its implications on the location of geothermal reservoirs in Washington. In Energy resources of Washington, Washington Division of Geology and Earth Resources Information Circular 50, p. 21-33.

Bloomquist, R. G., 1979, Geothermal energy in Washington - Site data base and development status: Oregon Institute of Technology Geo-Heat Utilization Center, U.S. Department of Energy, DE-AC03-79SF1049, 192 p.

Bockheim, J. G.; Ballard, T. M., 1975, Hydrothermal soils of the crater of Mount Baker, Washington: Soil Science Society of America Proceedings, v. 39, no. 5, p. 997-1001.

Bonini, W. E., 1965, Gravity surveys in the northwestern United States: American Geophysical Union Transactions, v. 46, no. 3, p. 563-569.

Bonini, W. E.; Hughes, W. D.; Danes, Z. F., 1974, Complete Bouguer gravity anomaly map of Washington: Washington Division of Geology and Earth Resources Geologic Map GM-11, scale 1:500,000.

Braile, L. W., 1970, The isostatic conditions and crustal structure of Mount St. Helens as determined from gravity data: University of Washington M.S. thesis, 37 p.

Campbell, K. V.; Miers, J. H.; Nichols, B. M.; Oliphant, J.; Pytlak, S.; Race, R. W.; Shaw, G. H.; Gresens, R. L., 1970, A survey of thermal springs in Washington State: Northwest Science, v. 44, p. 1-11.

Cantwell, T.; Nelson, P.; Webb, J.; Orange, A., 1965, Deep resistivity measurements in the Pacific Northwest: Journal of Geophysical Research, v. 70, no. 8, p. 1931-1937.

Cantwell, T.; Orange, A., 1965, Further deep resistivity measurements in the Pacific Northwest: Journal of Geophysical Research, V. 70, no. 16, p. 4068-4072.

Condie, K. C.; Swenson, D. H., 1973, Compositional variations in three Cascade strata volcanoes - Jefferson, Rainier, and Shasta: Bulletin Volcanologique, v. 37, no. 2, p. 205-230.

Coombs, H. A., 1936, The geology of Mount Rainier National Park: University of Washington Publications in Geology, v. 3, no. 2, p. 131-212.

Coombs, H. A., 1939, Mount Baker, a Cascade volcano: Geological Society of America Bulletin v. 50, no. 10, p. 1493-1509.

Crandell, D. R., 1969, Surficial geology of Mount Rainier National Park, Washington: U.S. Geological Survey Bulletin 1288, 41 p.

Crandell, D. R., 1969, The geologic story of Mount Rainier: U.S. Geological Survey Bulletin 1292, 43 p.

Crandell, D. R., 1971, Post-glacial lahars from Mount Rainier volcano, Washington: U.S. Geological Survey Professional Paper 677, 75 p.

Crandell, D. R., 1973, Map showing potential hazards from future eruptions of Mount Rainier, Washington: U.S. Geological Survey Map I-836, scale 1:250,000.

Crandell, D. R., 1976, Preliminary assessment of potential hazards from future volcanic eruptions in Washington: U.S. Geological Survey Map MF-774, scale 1:1,000.

Crandell, D. R.; Mullineaux, D. R., 1973, Pine Creek volcanic assemblage at Mount St. Helens, Washington: U.S. Geological Survey Bulletin 1383-A, 23 p.

Crandell, D. R.; Mullineaux, D. R., 1978, Potential hazards from future eruptions of Mount St. Helens volcano, Washington: U.S. Geological Survey Bulletin 1383-C.

Crandell, D. R.; Mullineaux, D.R.; Miller, R. D.; Rubin, M., 1962, Pyroclastic deposits of Recent age at Mount Rainier, Washington. In Short Papers in the Geologic and Hydrologic Sciences, U.S. Geological Survey Professional Paper 450-D, p. D64-D68.

Crandell, D. R.; Mullineaux, D. R.; Rubin, M., 1975, Mount St. Helens volcano: recent and future behavior: Science, v. 187, p. 438.

Crandell, D. R.; Waldron, H. H., 1956, A Recent volcanic mudflow of exceptional dimensions from Mount Rainier, Washington: American Journal of Science, v. 254, p. 349-362.

Crosby, J. W., III, 1971, New developments in geothermal exploration. In Cole, B. L., Papers presented at First Northwest Conference on Geothermal Power: Washington State Department of Natural Resources.

Crosson, R. S.; Mayers, I. R., 1972, Report on geothermal ground noise measurements in Washington State: Washington Division of Mines and Geology Open-File Report, 16 p.

Crowder, D. F.; Tabor, R. W.; Ford, A. B., 1966, Geologic map of the Glacier Peak quadrangle, Snohomish and Chelan Counties, Washington: U.S. Geological Survey Geologic Quadrangle Map GQ-473, scale 1:62,500.

Cullen, J. M., 1978, Impact of a major eruption of Mount Rainier on public service delivery systems in the Puyallup Valley, Washington: University of Washington M.S. thesis, 195 p.

Danes, Z. F., 1964, Gravity survey of Mount Rainier , Washington [abstract]: American Geophysical Unions Transactions, v. 45, p. 640.

Danes, Z. F., 1969, Gravity results in western Washington: American Geophysical Union Transactions, v. 50, p. 548-550.

Dehlinger, P.; Chiburis, E. F.; Collver, M. M., 1965, Local travel time curves and their geologic implication for the Pacific Northwest states: Bulletin of the Seismological Society of America, v. 55, no. 3, p. 587-607.

Easterbrook, D. J., 1975, Mount Baker eruptions: Geology, v. 3, no. 12, p. 679-682.

Easterbrook, D. J., 1976, Pleistocene and Recent volcanic activity of Mount Baker, Washington: Geological Society of America, Abstracts with Programs, v. 8, no. 6, p. 849.

Ellingson, J. A., 1968, Late Cenozoic volcanic geology of the White Pass, Goat Rocks area, Cascade Mountains, Washington: Washington State University Ph. D. thesis, 112 p.

Ellingson, J. A., 1969, Geology of the Goat Rocks volcano, southern Cascade Mountains, Washington: Geological Society of America Abstracts with Programs, Part 3, Cordilleran Section, p. 15.

Ellingson, J. A., 1972, The rocks and structure of the White Pass area, Washington: Northwest Science, v. 46, p. 9-24.

Fiske, R. S., 1960, Stratigraphy and structure of lower and middle Tertiary rocks, Mount Rainier National Park, Washington: Johns Hopkins University, Ph. D. thesis, 163 p.

Fiske, R. S.; Hopson, C. A.; Waters, A. C., 1963, Geology of Mount Rainier National Park, Washington: U.S. Geological Survey Professional Paper 444, 93 p.

Ford, A. B., 1957, Petrology of the Sulphur Mountain area, Glacier Peak quadrangle, Washington: University of Washington M.S. thesis, 103 p.

Ford, A. B., 1959, Geology and petrology of the Glacier Peak quadrangle, northern Cascades, Washington: University of Washington Ph. D. thesis, 374 p.

Fowler, C. S., 1935, The origin of the sulfur deposits of Mount Adams: M.S. State College of Washington, M. S. thesis, 23 p.

Frank, D.; Meir, M. F.; Swanson, D. A., 1977, Assessment of increased thermal activity at Mount Baker, Washington: U.S. Geological Survey Professional Paper 1022-A, 49 p.

Frank, D.; Post, A.; Friedman, J. D., 1975, Recurrent geothermally induced debris avalanches on Boulder Glacier, Mount Baker, Washington: Journal of Geophysical Research, v. 3, no. 1, p. 77-87.

Friedman, J. D., 1972, Aerial thermal surveillance of volcanoes of the Cascade Range, Washington, Oregon, and northern California: E.O.S., v. 53, no. 9, p. 533.

Friedman, J. D.; Frank, D., 1980, Thermal surveillance of active volcanoes using the Landstat-1 DCS: Part 2, IR Surveys, radiant flux, and total heat discharge from Mount Baker volcano, Washington, between 1970 and 1975, Final Report: U.S. Geological Survey for Goddard Space Flight Center [in press].

Friedman, J. D.; Frank, D., 1977, Thermal surveillance of active volcanoes using the Landstat I data collection system: Part 3, Heat discharges from Mount St. Helens, Washington: U.S. Geological Survey Open-File Report 77-541, 30 p.

Gizienski, S. F.; McEuen, R. B.; Birkhahn, P. C., 1975, Regional evaluation of the geothermal resources potential in central Washington state: Washington Public Power Supply System, 113 p.

Hammond, P. E., 1974, Brief outline to volcanic stratigraphy and guide to geology of southern Cascade Range, Washington, and northern Cascade Range, Oregon: Geothermal Field Trip, Oregon Department of Geology, June 24-29, 1974.

Hammond, P. E., 1975, Preliminary geologic map and cross sections with emphasis on Quaternary volcanic rocks, southern Cascade Mountains, Washington Division Geology and Earth Resources Open-File Report 75-13, scale 1:24,000.

Hammond, P. E., 1980, Reconnaissance geologic map and cross sections of southern Washington cascade range, latitude 45° 30 - 47° 15 N, longitude 120° 45 - 122° 22.5 W: Portland State University Department of Earth Sciences, 31 p., 2 sheets, scale 1:125,000.

Hammond, P. E., Bentley, R. D.; Brown, J. C; Ellingson, J. A.; Swanson, D. A., 1977, Volcanic stratigraphy and structure of the southern Cascade Range, Washington: Field Trip No. 4, Geological Society of America, 90th Annual meeting, Seattle, Washington.

Hammond, P. E.; Pedersen, S. A.; Hopkins, K. D.; Aiken, D.; Harle, D. S.; Danes, Z. F.; Kohicek, D. L.; Stricklin, C. R., 1976, Geology and gravimetry of the Quaternary basaltic volcanic field, southern Cascade Range, Washington. In Pezzotti, C. (editor), Proceedings, Second U.N. Symposium on development and use of geothermal resources, San Francisco, 1975, p. 397-405.

Harris, S. L., 1976, Fire and ice: the Cascade volcanoes: Pacific Search Press, Seattle, Washington, 320 p.

Harle, D. S., 1974, Geology of the Baby Shoe Ridge area, southern Cascades, Washington: Oregon State University M.S. thesis, 71 p.

Hopkins, K. D., 1976, Geology of the south and east slopes of Mount Adams volcano, Washington: University of Washington Ph. D. thesis, Seattle, 143 p.

Hopson, C. A.; Waters, A. C.; Bender, V. R.; Rubin, M., 1962, The latest eruption from Mount Rainier volcano: Journal of Geology, v. 70. p. 635-646.

Hopson, C. A., 1971, Eruptive sequence at Mount St. Helens, Washington: Geological Society of America Abstract with Programs, vol. 3, no. 2, p. 138.

Hyde, J. H., 1970, Geologic setting of Merrill Lake and evaluation of volcanic hazards in the Kalama River valley near Mount St. Helens, Washington: U.S. Geological Survey Open-File Report, 15 p.

Hyde, J. H., 1973, Late Quaternary volcanic stratigraphy of the south flank of Mount St. Helens, Washington: University of Washington Ph. D. thesis, Seattle, 114 p.

Hyde, J. H., 1975, Upper Pleistocene pyroclastic-flow deposits and lahars south of Mount St. Helens volcano, Washington: U.S. Geological Survey Bulletin 1383-B, 20 p.

Hyde, J. H.; Crandell, D. R., 1975, Origin and age of post-glacial deposits and assessment of potential hazards from future eruptions of Mount Baker, Washington: U.S. Geological Survey Open-File Report 75-286, 22 p.

Hyde, J. H.; Crandell, D. R., 1978, Post-glacial volcanic deposits at Mount Baker, Washington, and potential hazards from future eruptions: U.S. Geological Survey Professional Paper 1022-C, 17 p.

Johnson, S. H.; Couch, R. W., 1970, Crustal structure in the north Cascade Mountains of Washington and British Columbia from seismic refraction measurements: Bulletin of the Seismological Society of America, v. 60, no. 4, p. 1259-1269.

Kiver, E. P., 1975, Washington's geothermal ice caves: Pacific Search, v. 10, no. 3, p. 11.

Kiver, E. P., 1978, Geothermal ice caves and fumaroles, Mount Baker volcano: 1974-1977 [abstract]: Geological Society of America Abstracts with Programs, v. 10, no. 3, p. 112.

Kiver, E. P., 1978, Mount Baker's changing fumaroles: The Ore Bin, v. 40, no. 8, p. 145.

Kiver, E. P.; Snavely, J.; Snavely, D. F., 1977, Hydrogen sulfide fumes at the summit of Mount Rainier volcano, Washington: Northwest Science, v. 51, no. 1, p. 31-35.

Konicek, D. L., 1974, Geophysical survey in south-central Washington: University of Puget Sound M.S. thesis, 35 p.

Konicek, D. L., 1975, Geophysical survey in south-central Washington: Northwest Science, v. 49, no. 2, p. 106-117.

Lange, I. M.; Avent, J. C., 1975, Ground-based thermal infrared survey of Mount Rainier volcano, Washington: Geological Society of America Abstracts with Programs, v. 7, no. 5, p. 619.

Livingston, V. E., Jr., 1972, Geothermal energy in Washington. In Geothermal overviews of the western United States, First National Conference: Geothermal Resources Council, El Centro, California, February 16-18, 1972, Section L, 17 p.

Malone, S. D., 1976, Deformation of Mount Baker volcano by hydrothermal heating: E.O.S. v. 57, no. 12, p. 1016.

McEuen, R. B.; Birkhahn, P. C.; Pinckney, C. J., 1976, Predictive regionalization of geothermal resource potential. In Pezzotti, C. (ed.), Proceedings, Second U.N. Symposium on development and use of geothermal resources, San Francisco, 1975, p. 1121.

McLane, J. E.; Finkelman, R. B.; Larson, R. R., 1976, Mineralogical examination of particulate matter from the fumaroles of Sherman Crater, Mount Baker, Washington (abstract): E.O.S., v. 57, no. 2, p. 89.

Moxham, R. M., 1970, Thermal features of volcanoes in the Cascade Range as observed by aerial infrared surveys: Bulletin Volcanologique, v. 34, no. 1, p. 77-106.

Moxham, R. M.; Boynton, G. R.; Cote, C. E., 1973, Satellite telemetry of fumarole temperatures, Mount Rainier, Washington: Bulletin Volcanologique, v. 36, no. 1, p. 191-199.

Moxham, R. M.; Crandell, D. R.; Mariott, W. E., 1965, Thermal Features at Mount Rainier, Washington, as revealed by infrared surveys: U.S. Geological Survey Professional Paper 525-D, p. 93-100.

Mullineaux, D. R.; Crandell, D. R., 1962, Recent lahars from Mount St. Helens, Washington: Geological Society of America Bulletin v. 73, p. 855-970.

Mullineaux, D. R.; Hyde, J. H.; Meyer, R., 1972, Preliminary assessment of upper Pleistocene and Holocene pumaceous tephra from Mount St. Helens volcano, southern Washington: Geological Society of America, Abstracts with Programs, v. 4, no. 3, p. 204-205.

Mullineaux, D. R.; Sigafoos, R. S.; Hendricks, E. L., 1969, A historic eruption of Mount Rainier, Washington: U.S. Geological Survey Professional Paper 650-B, p. 315-318.

Mundorff, M. J., 1964, Geology and ground water conditions of Clark County, Washington, with a description of a major alluvial aquifer along the Columbia River: U.S. Geological Survey Water Supply Paper 1600, 268 p.

Phillips, K. N., 1942, Fumaroles of Mount St. Helens and Mount Adams: Mazama, v. 23, no. 12, p. 37-42.

Radke, L. F.; Hobbs, P. V.; Stith, J. L., 1976, Airborne measurements of gases and aerosols from volcanic vents on Mount Baker: Geophysical Research Letters v. 3, no. 2, p. 93-96.

Russell, R. H., 1972, Geothermal energy potential of Washington State: Washington Department of Ecology, 23 p.

Russell, R. H., 1973, Geothermal Energy; potential of Washington State: Geothermal Energy Magazine, v. 1, no. 4, p. 39-48.

Sato, M.; Malone, S. D.; Moxham, R. M., 1976, Monitoring of fumarolic gas at Sherman Crater, Mount Baker, Washington (abstract): EOS v. 57, no. 2, p. 88.

Schuster, J. E., 1973, The search for hot rocks - Geothermal exploration, Northwest: Washington Division of Geology and Earth Resources Reprint 11, p. 4.

Schuster, J. E., 1974, Geothermal energy potential of Washington: In Energy resources of Washington, Washington Division of Geology and Earth Resources Information Circular 50, p. 5.

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.

Sheppard, R. A., 1967, Petrology of a late Quaternary potassium-rich andesite from Mount Adams, Washington: U.S. Geological Survey Professional Paper 575-C, p. 55-59.

Sheppard, R. A., 1967, Geology of the Simcoe Mountains volcanic area, Washington: Washington Division of Mines and Geology Geologic Map GM-3, scale 1:250,000.

Stavert, L., 1971, A geochemical reconnaissance investigation of Mount Baker andesite: Western Washington State College M.S. thesis, 60 p.

Stricklin, C. R., 1975, Geophysical Survey of the Lemei Rock - Steamboat Mountain area, Washington: University of Puget Sound M.S. thesis, 23 p.

Swan, V. L., 1978, Mount Baker volcanics: (abstract) American Geophysical Union meeting, Tacoma.

Swanson, D. A., 1964, The middle and late Cenozoic volcanic rocks of the Tieton River area, south-central Washington: Johns Hopkins University Ph. D. thesis, 329 p.

Swanson, D. A., 1966, Tieton volcano, a Miocene eruptive center in the southern Cascade Mountains, Washington: Geological Society of America Bulletin, v. 77, p. 1293-1314.

Swanson, D. A., 1978, Geologic map of the Tieton River area, Washington: U.S. Geological Survey Miscellaneous maps, MF-968, scale 1:48,000.

Swanson, D. A.; Wright, T. L.; Zietz, I., 1979, Aeromagnetic map and geologic interpretation of the west-central Columbia Plateau, Washington and adjacent Oregon: Geophysical Investigations, Map GP-917.

Swenson, D. H., 1973, Geochemistry of three Cascade volcanoes: New Mexico University of Mining and Technology M.S. thesis, 101 p.

Tabor, R. W., Cady, W. M., 1978, The structure of the Olympic Mountains, Washington - Analysis of a subduction zone: U.S. Geological Survey Paper 1033, 38 p.

Tabor, R. W., Cady, W. M., 1978, Geologic map of the Olympic Peninsula, Washington: U.S. Geological Survey, 2 maps, scale 1:125,000.

Tabor, R. W.; Crowder, D. F., 1969, On batholiths and volcanoes - Intrusion and eruption of late Cenozoic magmas in the Glacier Park area, north Cascades, Washington: U.S. Geological Survey Professional Paper 604, 50 p.

U.S. Geological Survey, 1977, Aeromagnetic maps of part of northern Washington: U.S. Geological Survey Open-File Report 77-254, 2 sheets, scale 1:62,500.

Unger, J. D.; Decker, R. W., 1970, The microearthquake activity of Mount Rainier, Washington: Seismological Society of America Bulletin, v. 60, p. 2023-2035.

Unger, J. D.; Mills, K. F., 1972, Microearthquakes at Mount Rainier - 1969: Seismological Society of America Bulletin, v. 62, p. 1079-1081.

Unger, J. D.; Mills, K. F., 1973, Earthquakes near Mount St. Helens, Washington: Geological Society of America Bulletin, v. 84, no. 3, p. 1065-1067.

Valentine, G. M., 1960, Inventory of Washington minerals - Part I, Nonmetallic minerals, revised by M. T. Huntting: Washington State Division of Mines and Geology Bulletin 37, 2 volumes, text and maps, 175 p. plus 83 p.

Verhoogan, J., 1937, Mount St. Helens - A recent Cascade volcano: California University Publications in Geological Science, v. 24, no. 9, p. 263-302.

Washington Division of Geology and Earth Resources, 1974, Energy resources of Washington: Information Circular 50, 158 p.

Waters, A. C., 1973, The Columbia River Gorge Basalt Stratigraphy, ancient lava dams, and landslider dams. In Beaulieux, J. D., chairman, Geologic field trips in northern Oregon and southern Washington: Oregon Division of Geology and Mineral Industries, Bulletin 77, p. 133-162.

Weaver, C. S., 1976, Seismic events on Cascade volcanoes, Ph.D. dissertation, University of Washington, Ph. D. thesis, 158 p.

Weaver, C. S., 1976, Seismic events on Cascade volcanoes [abstract]: University of Washington Ph. D. thesis, Seattle: In Dissertation Abstracts International, v. 37, no. 3, p. 1157-B.

Wise, W. S., 1961, The geology and mineralogy of the Wind River area, Washington, and the stability relations of celadonite: Johns Hopkins University, Ph. D. thesis, p. 258.

Wise, W., 1970, Cenozoic volcanism in the Cascade mountains of southern Washington: Washington Division of Mines and Geology Bulletin 60, 45 p.

APPENDIX A

WELL TEMPERATURE INFORMATION AND LOCATIONS

IN THE STATE OF WASHINGTON

by

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APPENDIX A

WELL TEMPERATURE INFORMATION AND LOCATIONS IN THE STATE OF WASHINGTON

The following table includes all wells on record with the Division of Geology and Earth Resources. They have been divided by county, and ordered by increasing township and increasing range. Information includes township-range location, 1/4 of 1/4 of section, bottom hole temperature (°C), depth (m), two types of gradients (°C/km), and source reference. Gradient A are those gradients actually observed from a well log over a significant depth interval through the well. Gradient B are calculated gradients using bottom hole temperatures and mean annual surface temperature, calculated from elevation, slope angle, and slope orientation.

The references key as follows:

1. Washington State University well logs - Dr. James Crosby
2. Southern Methodist University and Division of Geology and Earth Resources well logs and thermal gradient holes, Dr. David D. Blackwell, SMU, and J. Eric Schuster, DGER.
3. U.S. Geological Survey Tacoma Office, well logs.
4. U.S. Geological Survey Tacoma Office, WATSTORE computer file.
5. U.S. Geological Survey Water Supply Paper 1999R.
6. Washington State Division of Water Resources, Water Supply Bulletin #21.
7. Washington State Division of Water Resources, Water Supply Bulletin #24.

ADAMS COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
15N	28E	SW	NW	8	20.0	126		63	4
15N	28E	NW	NW	15	24.2	264		46	4
15N	28E	SE	SW	35	23.0	253		43	1
15N	29E	NE	NW	3	22.8	212		51	4
15N	29E	NE	SE	3	20.8	276		32	4
15N	29E	SE	SW	3	29.0	297.8		57	1
15N	29E	NE	NE	4	24.3	365.1		34	1
15N	30E	NE	SW	1	7.1	206.6			1
15N	30E	SE	NE	2	14.3	277.4			1
15N	30E	NW	SE	12	17.9	408.4			1
15N	31E	NE	SW	5	26.4	403.5		36	1
15N	31E	SW	NW	11	20.1	214	32.2	38	3
15N	31E	NE	NE	19	25.5	338.6		40	1
15N	32E	NW	NE	4	21.8	266.4		52	1
15N	32E	NW	SW	16	15.0	335.3			1
15N	32E	NW	NW	20	17.8	214.3			1
15N	32E	SW	NW	35	27.6	309.7		50	1
15N	33E	NE	NE	2	25.0	68.9		185	1

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Reference
15N	33E	SW	SE	15	18.4	202.1			1
15N	34E	SE	SE	27	20.9	243.8		36	1
15N	36E	SE	NW	34	25.4	211.5		63	1
16N	29E	SE	SE	34	23.0	275		40	4, 7
16N	30E	NW	NW	24	25.9	219.4	64.8	63	1
16N	30E	NE	NE	26	26.2	192	34	74	3
16N	30E	NE	SE	27	25.2	207	91	64	3
16N	30E	NW	SE	36	20.3	208.8		40	1
16N	30E	NW	SE	36	25.8	240.8		57	1
16N	31E	NW	NE	15	22.7	200.5		53	1
16N	31E	SW	SE	15	26.9	408.7		37	1
16N	32E	NW	NW	11	27.7	310.3		51	1
16N	32E	NE	NW	14	20.7	155.1		56	1
16N	32E	NW	NW	14	19.8	313.9			1
16N	32E	NW	NW	15	32.8	437.1		48	1
16N	32E	SE	SE	16	17.8	355.7			1
16N	32E	SW	SW	20	22.8	214.3		50	1
16N	32E	SW	SW	20	29.2	372.1		46	1

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
16N	32E	SW	NW	21	27.4	158.8		97	1
16N	32E	NW	NW	25	28.7	431.6		39	1
16N	32E	SW	SW	25	30.4	709.2		26	1
16N	32E	SW	NW	34	42.8	771	69.5	40	1
16N	32E	NW	NW	35	24.0	270.6		44	1
16N	32E	NW	NW	35	24.0	192		63	1
16N	33E	NE	NE	20	18.8	443.8			1
16N	35E	NE	SE	22	15.33	315.0			2
16N	35E	SW	SE	31	22.2	599.5		17	1
17N	31E	NW	NW	12	27.8	590.4		27	1
17N	31E	SW	SW	13	16.4	232.6			1
17N	32E	SE	SW	12	21.0	227		40	3
17N	33E	SW	SE	12	17.3	225.5			1
17N	33E	NE	NE	23	16.8	200.9			1
17N	34E	SW	SW	7	17.4	201			3
17N	35E	NE	SW	12	18.8	125			1
17N	36E	SW	SW	7	13.4	273.4			1

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
17N	37E	NW	NW	27	21.9	167.9		59	1
18N	31E	NE	NW	18	21.5	237.7		40	2, 3
18N	31E	NW	SE	30	14.7	188			1
18N	31E	NW	NW	33	30.0	771		23	1
18N	36E	NE	NE	4	14.6	279.8			1
18N	34E	SW	SE	32	16.2	183			3
19N	31E	SW	NW	24	17.9	190.6			3
19N	31E	SW	NE	24	20.1	164.6		49	1
19N	32E	SW	SW	15	15.4	205.8			3
19N	32E	NW	SE	24	20.6	243.2		35	1
19N	32E	SW	SW	24	31.5	680.3		29	1
19N	32E	SW	SW	30	19.2	165			3
19N	33E	SW	SE	8	20.3	229.8		36	1
19N	33E	SW	SE	8	39.3	736.7		37	1
19N	34E	NW	NE	20	19.4	341.4			1
19N	35E	SE	SW	14	16.4	186			3
19N	36E	NW	SE	9	20.4	228.9		37	1

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
19N	36E	NE	NE	15	15.5	378.2			1
19N	36E	NE	SE	22	13.1	58.5			1
19N	36E	NE	SE	22	16.1	197.2			1
19N	36E	NW	SW	34	18.7	334.3			1
19N	36E	SW	SW	34	20.7	100.6		86	1
19N	38E	SE	NW	13	21.1	201.2	82.8	45	2
20N	33E	NE	NE	13	17.8	173			3
20N	34E	SW	SE	2	20.9	197.2		45	1
20N	34E	SE	NW	10	17.8	238			3
20N	34E	SW	NE	25	12.8	167.6			1
20N	35E	NW	NW	17	20.9	231.6	90	39	2
20N	35E	NW	NW	24	20.5	156.7		55	1
20N	35E	NE	NE	27	15.4	363.3			1
20N	35E	SW	NE	27	13.11	240.8			2
20N	36E	NE	NE	8	13.5	139.9			1

ASOTIN COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
6N	43E	SW	SW	12	13.01	70			2
7N	46E	NE	NE	2	15.31	275	27.6		2
7N	46E	NE	NW	13	13.01	70	53		2
8N	44E	SE	NE	2	10.93	140.2	13.1		2
10N	46E	SW	SE	5	23	554		20	4, 7
11N	45E	NW	NE	32	17.5	192	31.3		2
11N	46E	NW	NW	19	12.63	160			2
11N	46E	SW	SE	30	23.3	406		28	4, 5
11N	46E	NE	SW	32	26.17	405		35	2
11N	46E			32	23.4	387.7		29	1

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
4N	24E	NW	NE	3	20.6	121		71	5
5N	26E	NW	NW	5	25.9	304.8		46	1
5N	28E	SE	SE	6	21.5	170		56	4
6N	24E	SE	NE	22	22.5	195		54	3
6N	24E	NW	NW	23	19.6	198.1			1
6N	26E	NW	SW	15	24.2	209.7		58	1
6N	30E	SW	SE	12	21.1	305	31	30	3
6N	30E	SW	SW	19	20	176.8		45	1
7N	24E	NW	NW	8	22.9	332.5		33	1
7N	25E	NW	SW	35	18.6	307.2			1
7N	25E	SE	NW	36	17.5	263.3			1
7N	25E	SW	SW	36	22.5	253.9		41	1
7N	25E	SW	SW	36	30.3	221.6		83	1
7N	25E	SW	SW	36	21.8	262		37	4
7N	26E	NW	NE	5	22.1	148.1		68	1
7N	26E	NW	NE	5	19.2	326			3
7N	27E	SW	SE	29	14.9	142			3

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
8N	24E	NE	SE	1	25	378.5		34	1
8N	27E	SW	SE	29	19.4	221.6			1
8N	29E	NE	NE	22	23	244		45	4
9N	25E	NW	NE	6	25.2	364.2		36	1
9N	26E	NW	SE	27	21.5	204		47	4
9N	28E	SE	NE	34	21.1	271.3		34	1
10N	25E	SW	NW	25	20.6	184	36	47	3
10N	25E	SW	SW	33	21.8	275.5		36	1
10N	26E	SW	SE	27	17.3	236.2			1
10N	28E	SW	SW	14	47.78	1079.9	34.6	33	2
11N	24E		SE	15	96.29	2500	37.1	34	2
11N	25E	SW	SW	33	19	204.2			1
11N	26E	SE	SE	34	24	305		39	4
12N	24E	SW	SW	20	26	366		38	4
12N	26E	SW	SW	4	21.4	117		80	4
12N	26E	NW	NE	7	20.7	126		69	4

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
12N	26E	SW	SE	7	20.4	99		85	4
12N	26E	SE	SW	8	21.2	98		94	4
12N	26E	SE	NE	12	21	158		57	4
12N	26E	NW	NW	14	21.1	117		78	4
12N	26E	NE	NW	15	21.7	134		74	4
12N	26E	SW	NW	18	20.5	177		48	4
12N	26E	SW	NE	18	20.8	85		103	4
12N	27E	NW	SW	16	20.5	65		131	4
12N	28E	SE	NW	19	16.4	176			4
13N	24E	SW	NW	25	24.2	237		51	4, 7
13N	24E	SW	NE	26	20	215		37	7
13N	24E	NW	NW	36	24	333		36	4, 7
13N	25E	SW	SW	1	23	241		46	4, 5
13N	25E	SE	NE	11	39.1	32		847	4
13N	25E	SW	NE	30	26.8	339		44	4, 7
13N	26E			25	21.89	183	37.2	54	2
13N	26E	SW	NE	35	25	1726		7.5	4

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
14N	26E	NW	SW	14	32.5	24		854	4
14N	26E	SW	NE	28	20.7	24		363	4

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
22N	20E	NW	NW	26	35.68	900	26.8	26	2
24N	17E	NE	SW	23	10.9	75.6			1

CLARK COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
1N	3E	NW	SE	2	14.43	151	29.9		2
1N	3E	SE	SW	6	11.4	57.5			2
1N	3E	SE	SW	6	11.4	76			2
1N	3E	SW	SE	11	12.58	73			2
1N	4E	SE	NE	5	11.01	65			2
1N	4E	SW	SW	6	10.93	49			2
2N	3E	SE	NE	12	11.95	127	27.5		2
2N	3E	SW	SE	21	12.68	72	43.8		2
2N	3E	SW	NE	26	10.77	54			2
2N	3E	SW	NE	30	9.7	76.2			1
2N	3E	NW	NE	31	9.7	33.5			1
2N	4E	NW	NW	29	10.61	52			2
2N	4E	NW	SW	29	11.49	61.5			2
3N	3E	NW	NE	21	11.59	103	26.7		2
3N	3E	SE	NW	21	14.29	188	28.7		2
3N	3E	NW	SE	23	12.47	183.5	22.3		2
4N	1E	SE	SW	21	14.57	236	24.7		2

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
4N	2E	NW	NE	10	11.3	201	28		3
4N	3E	NW	SW	18	12.29	109	31.1		2
4N	3E	SE	SE	20	16.74	221	38.3		2
5N	1E	SW	SE	5	13.27	177.5	21.5		2
5N	1E	NE	NW	23	17.02	246	32.1		2
5N	2E	NE	SE	24	10.54	104	14		2
5N	2E	SW	NW	25	13.31	158	33.1		2
5N	3E	SW	SW	28	10.05	96.5	20.4		2

COLUMBIA COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
10N	39E	NE	NE	30	11.86	32.5			2
10N	41E	SE	NW	3	11.35	106.7	22.1		2
12N	38E	SW	NW	1	21.6	241.1		40	1
13N	38E	SW	NW	26	20	74		108	4, 5

COWLITZ COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
8N	4E	SE	SE	14	7.98	153.5	34.4		2
9N	2W	NW	SE	1	10.43	135	13.5		2

DOUGLAS COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
23N	25E	SW	SW	31	18.5	146.6			1
23N	25E	NE	SW	32	13.5	252.1			1
23N	26E	NW	NW	20	27.8	244.4		65	1
23N	26E	NW	NW	20	29.3	362.7		48	1
23N	26E	NW	NW	20	18.3	403.8			1
24N	25E	SW	SE	30	10.4	114.3			1
25N	22E	SE	NE	21	13	183			4
25N	22E	SW	SW	22	16.6	169.1			1, 3
25N	22E	NW	NE	28	16.2	184.5			3
27N	26E	NW	NW	25	17.5	228.3			1, 4

FERRY COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
30N	33E	SE	SE	31	9.49	170	19.5		2
30N	33E	NW	NE	31	9.82	255	17.7		2
30N	33E	SW	NE	31	14.79	475	16.6		2
37N	32E	SW	NE	33	14.39	260	31.1		2
37N	32E	NW	NE	34	11.44	195	18.8		2
37N	32E		NW	34	9.13	95	24.5		2
37N	32E		NW	34	9.46	55			2
40N	33E	SE	SW	2	10.82	205	22.7		2
40N	33E	NW	NW	2	9.39	150	26.5		2
40N	33E	NW	NW	2	9.38	155	22.4		2
40N	33E	NW	NW	2	10.78	215	24.4		2

FRANKLIN COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
9N	30E	SE	NE	18	21	315		29	4
9N	31E	SW	NW	7	24.6	167.6	33.4	75	1
11N	31E	SE	NE	21	24.2	354.8		34	1
12N	29E	SE	NW	28	20	213		38	4
12N	32E	NW	NE	28	19.5	242			4,5
13N	28E	SW	SW	13	27.6	341		46	4
13N	32E	NW	NE	17	17.8	203.9			1
13N	34E	NW	SW	30	31.3	355.1	56.4	54	1
14N	29E	NE	NE	9	22.3	263		39	4, 7
14N	29E	NE	NE	9	22.2	215	57.6	47	3
14N	31E	NE	SE	9	21.2	330.1		28	1
14N	31E	NE	SE	36	25	337		39	4
14N	32E	SE	SW	2	27.2	242.3	50.2	63	1
14N	32E	SW	NW	13	25.6	187.1		73	1
14N	32E	SE	SW	30	17.7	251.7			1
14N	32E	NW	NW	31	29.4	303	38	57	1, 3
14N	33E	SW	SW	21	27.3	349.3		44	1
14N	36E	SW	SW	19	22.5	262.7		40	1

GARFIELD COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
12N	40E	SE	NE	14	13.54	74.1	33.9		2
12N	40E	NE	SE	17	14.71	150	9.2		2
12N	42E	NE	SW	31	23	304		36	4, 7

G R A N T   C O U N T Y

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
14N	25E	NW	NW	1	27.5	285		54	4, 7
14N	25E	NW	NE	21	22	159		63	4, 7
14N	27E	NE	NW	24	30	426		42	4, 7
15N	27E	SW	NW	32	16.5	343			4
15N	27E	NE	SW	34	21.5	194		49	4, 7
16N	24E	SW	NE	1	23.5	244		47	4, 7
16N	24E	SW	NE	1	24.5	279		45	4, 7
17N	25E	SE	NW	1	25.3	239		56	1
17N	26E	SE	SW	8	18	97.6			3
17N	27E	NW	NW	31	20.8	247		36	4
17N	30E	SW	NE	1	23	299		37	7
17N	30E	SE	SW	10	14.3	253			1
17N	30E	NW	SE	33	22.2	306		33	4, 7
17N	30E	NW	SE	33	23.5	222		52	4
18N	25E	SW	NW	15	25.6	297		46	4
18N	25E	SW	NW	15	22.4	270.3		39	1
18N	25E	SW	NW	15	29.3	488	35.2	35	1

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
18N	25E	NE	SE	23	21.2	190.2		48	1
18N	25E	SW	SW	27	21.2	228		40	3
18N	25E	NW	NE	28	22.4	211.5		49	1
18N	26E	NW	SE	31	22.5	214.6	46	49	1, 3
18N	29E	SW	SE	6	20.6	202.4		43	1
19N	27E	SE	NW	2	19.2	79.6			1
19N	27E	NW	NW	31	23.3	233.2		49	1
19N	28E	SE	SW	4	14.4	229			4
19N	28E	SW	SE	15	22.2	277		37	4
19N	28E	NW	NW	23	23.7	280.4		42	1
19N	28E	NW	NW	23	20.6	292		30	4, 5
19N	28E	NE	SE	23	17.1	210.3			1
19N	28E	NW	SE	28	15.8	305			4
19N	28E	NW	SE	28	22.6	294.4		36	1, 3
19N	28E	NW	SW	29	19.6	137.2			1
19N	28E	NW	SW	29	19.7	232			3
19N	29E	SE	NW	3	22.5	321.2		33	1
19N	29E	SE	NE	4	24.6	280.4		45	1

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
19N	29E	NE	SE	9	20.5	97.5		88	1
19N	29E	NE	NE	15	17.9	288			1
19N	29E	SW	SW	16	28.4	190.5		86	1
19N	30E	SE	NW	13	20.2	201		41	3
19N	30E	NE	SW	15	15.8	113.4			1
19N	30E	NE	SE	16	15.3	278.6			1
19N	30E	NW	SW	16	18.2	288.3			1
19N	30E	NW	SW	17	20.3	220.6		38	1
19N	30E	NW	NW	20	25.8	310.9		44	1
20N	24E	SE	SE	7	21	131		69	4
20N	28E	SW	NW	33	15.6	241			4
20N	29E	SE	NE	7	20.1	213.3		38	1
20N	29E	SE	NE	15	14.7	159.1			1
20N	29E	NE	NW	25	21.8	400.8		25	1
20N	29E	NE	NE	35	25	292.6		44	1
20N	30E	SE	NW	21	26.44	322.7	53.7	45	2,3

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
20N	30E	SW	NE	21	22	351.7		28	1
20N	30E	SW	NE	21	28	466.3		34	1
20N	30E	NE	NW	22	13.5	124	47		3
20N	30E	NE	NE	23	21.5	219.4		43	1
20N	30E	SW	NW	23	34.8	337	101	68	1, 3
20N	30E	SE	SE	28	20.4	178.3		47	1
20N	30E	SE	SE	28	28.5	181		91	3
20N	30E	NW	SE	32	21.2	381		24	1
21N	26E	NW	SW	8	30	305		59	4
21N	26E	SW	SW	8	16.2	131.7			1, 4
21N	26E	SE	NE	15	20.9	561.4		16	1
21N	26E	SW	NW	21	25.5	188		72	4
21N	30E	SW	NW	3	15.5	199			4
21N	30E	NW	SW	10	30	640		28	3
21N	30E	SW	NE	26	20.72	170.7		51	2
22N	27E	SW	SW	19	27	142		106	4
22N	30E	SW	NE	26	17.7	475.5	25.8		1
22N	30E	SW	NE	26	23.5	239.9	34.7	48	1

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
22N	30E	SW	NW	35	19.06	194.2	91		2, 3
23N	28E	SW	NW	27	22.4	195.7		53	1
24N	28E	NW	SW	11	15.4	107			1
24N	29E	NE	NE	1	19.3	318.2			1
25N	28E	SE	SW	13	14.1	109.7			1
25N	28E	SE	SW	14	14.7	132.9			1
25N	28E	NE	SW	24	29.2	189		91	1
25N	28E	SW	SE	24	13.8	101.8			1
25N	28E	NW	NE	25	11.6	173.7			1
25N	28E	NW	NE	25	23	177		62	3
25N	28E	SE	SW	26	14.7	113.4			1
25N	30E	SW	SE	5	16.6	195			1, 3

GRAYS HARBOR COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
16N	12W	SE	NE	24	14.29	155	26.5		2

KING COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
21N	4E	NW	SW	32	12.4	342	20		3
21N	6E	SE	SE	27	13	446			4
23N	11E		SW	1	6.79	130	12.6		2
23N	11E	NE	SW	10	18.88	290	18.6		2
25N	9E	SE	NE	4	2.98	130			2
25N	9E	NE	SE	4	3.36	68			2

KITTITAS COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
15N	19E	NE	SW	22	22.8	183		59	4
15N	19E	NE	SW	22	23.4	121.9		93	1
16N	19E	NE	NW	28	27.9	309.7		51	1, 4
17N	20E	SW	NE	5	13.4	136.5			1
17N	21E	NE	SW	21	18.4	193.8			1
18N	18E	SW	NW	35	20.8	272.4		32	1
18N	18E	NW	NE	36	28.4	262.2		63	3
18N	20E	SW	NW	23	16	70.1			1
18N	20E	NE	NE	27	19.3	140.8			1
20N	15E	SE	SE	18	11.61	200	21		2

KITSAP COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
24N	1E	SW	SE	25	9.8	339			3

KLICKITAT COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
2N	15E	NW	SW	17	18.1	145			4
3N	12E	SE	SW	28	17.89	185	33.9		2
3N	14E	SW	SE	9	13.1	123.4			1
3N	14E	NW	NE	29	11.2	101.8	26.8		1
3N	15E	SE	SE	2	13.7	122	41		1
3N	15E	SE	NE	22	18.1	182	36		3
3N	15E	NW	NE	29	16.3	184			3
3N	15E	NW	SW	34	15.4	149	27.4		2
3N	17E	NE	NE	29	18	235			4
3N	21E	NW	NE	19	19.03	71	50		2
4N	13E	SE	NE	24	27.2	90		167	4, 5
4N	14E	NE	NW	19	22.8	61		177	5
4N	14E	NE	NW	21	14.7	291.7			1
4N	15E	SE	NW	2	14.5	145.1	37.9		1
4N	15E	NW	SE	13	14.5	112.8			1
4N	15E	NW	SE	13	11	159			4
4N	15E	SE	NW	16	18.5	179			3
4N	15E	SE	NW	27	14.1	132.6	22.6		1

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
4N	16E	NW	NW	11	17.8	187.4			1
4N	16E	NE	SW	16	14	103.6	26		1, 3
4N	16E	SW	SE	16	19.9	267			1
4N	16E	NE	SE	17	12.2	93			1
4N	16E	NW	NE	21	18	150.6			1,3
4N	16E	SE	NW	22	14.5	135.6			1
4N	16E	SE	SW	22	13.5	123.4			1
4N	16E	NE	NE	28	19.5	163			3
4N	16E	SW	NE	29	14.4	115.8	38.2		1
4N	16E	SE	NE	34	18.5	154			3
4N	17E	SE	SE	20	12.9	102.1			1
4N	17E	NE	SE	21	13	154.5	42		1
5N	14E	NW	SW	22	15.76	137.5	31.2		2
5N	14E	NW	NE	36	15.2	186.2			1
5N	15E	NW	SE	25	19.7	214			3
5N	20E	NW	NE	27	22.8	276	41	40	3

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
5N	20E	NE	NW	27	23.1				1
5N	20E	SE	SE	28	10.2	64			1
5N	22E	NE	NE	27	28.2	321	42	50	1, 3
5N	23E	NE	NE	3	14.5	91.4			1
5N	23E	NE	SE	13	26.2	329.8		43	1
5N	23E	NW	NW	29	25.5	61		221	1
6N	20E	SE	NE	13	12.6	99.1			1
6N	21E	NW	NW	28	7	92.6			1
6N	21E	SE	NW	31	12.8	92.7			1
6N	21E	SE	SW	35	14	91.4			1
6N	23E	SW	SW	11	22	272		37	4
6N	23E	SW	SE	11	21	204		44	4, 5
6N	23E	SE	NE	15	25.2	275		48	1
6N	23E	SE	NE	15	21	193		47	4
6N	23E	NE	SE	22	21.3	141.7		66	1

LEWIS COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
11N	2W	SW	SE	26	14.86	261.5	13.6		2
12N	1W	NW	NE	7	25.21	565	33.2	30	2
12N	1W	SW	SW	8	24.66	540	30.8	31	2
12N	1W	SE	NE	8	21.31	409	34.6	33	2
12N	1W			17	30	792	26	27	3
12N	1W	SW	SW	37	25.72	578	21.5	31	2
12N	1E	NW	SW	12	11.78	125.3	21		2
12N	2E	SE	SW	5	10.87	155	25.4		2
12N	2E	SE	NE	9	13.18	205	23		2
12N	2E	SE	NE	11	10.85	88			2
12N	2E	NE	NE	16	11.08	106	18.2		2
12N	2E	SW	SE	16	10.02	59.8			2
12N	2E	SW	SW	20	11.37	57	25.6		2
12N	3E	NW	SE	7	11.06	86	19.1		2
12N	3E	NW	SW	17	11.7	138.5	20.5		2
12N	3E	SE	NW	19	14.33	232.5	27		2
12N	3E	NE	SW	19	11.58	156.5	28.1		2
12N	3E	SW	SW	23	10.1	84.5			2

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
12N	3E	NW	NE	25	9.65	152			2
12N	4E	SE	SW	3	8.93	84			2
12N	4E	NW	NE	4	9.78	42.5	17.4		2
12N	7E	SW	SW	16	14.07	129	41.6		2
12N	7E	NW	NE	27	10.05	34.3	38.5		2
12N	8E		SE	3	7.88	147	5.4		2
13N	1W	NE	SE	17	10.19	54			2
13N	1W	NW	SE	17	14	486			4
13N	1W	NW	NW	18	11.1	91	11.5		2
13N	1W	SE	SW	19	15.14	225	21.3		2
13N	1W	SW	SW	29	10.37	67.5			2
13N	2W	NE	NE	25	11.27	30	18.2		2
13N	3W	NW	NE	35	11.56	136.5	29.4		2
13N	4W	NE	NW	7	11.06	122.5	20.6		2
13N	2E	NE	NW	17	9.87	100.8			2
13N	5E	SE	NW	18	8.95	57	23		2

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
13N	9E	NE	SW	16	14.32	152	43.5		2
13N	11E	SW	SE	2	11.7	148.5	52.4		2
14N	1W	NE	SE	23	10.21	74.5			2
14N	1W	NE	NE	26	10.84	92.3			2
14N	2W	SE	NW	4	12.06	150.5	20.8		2
14N	2W	SE	NE	22	14	366			4
14N	5E	SE	NE	4	9.34	49.7			2
14N	5E	SE	NE	4	9.38	49.2			2
14N	8E	SW	SW	6	8.86	99.5	28		2
14N	10E	NW	SW	8	11.36	116	49.8		2

LINCOLN COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
21N	31E	NW	SW	10	65.8	1342.5	40	40	1, 2, 3
21N	31E	NW	SW	10	30.4	229		80	4
21N	31E	SW	NW	22	19.8	232	60		3
21N	31E	SE	NW	23	16.3	227			3
21N	31E	NW	NE	25	28.3	194.8		84	1
21N	31E	NW	SE	27	18.4	200	41		3
21N	31E	NE	SW	30	14	14.3			1
21N	31E	SE	SE	30	22.8	263.6		41	1
21N	31E	NW	NW	32	21.1	211		43	1, 3
21N	31E	NW	NW	32	18.9	341.4			1
21N	32E	SE	NW	23	22	298.7		33	1, 2
21N	33E	NE	SE	17	18.3	207.3			3
21N	34E	NE	NW	33	24.4	252.7		49	1
21N	35E	SW	NE	7	20.1	128		63	3
21N	35E	SW	NE	7	16.17	134.1			2

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
22N	31E	SW	NE	24	17.9	210	55		3
23N	32E	NE	SE	4	28.7	211.8		79	1
23N	32E	SW	NE	10	16.9	125			1
23N	32E	SW	NE	17	21.2	206.3	36.5	45	1
23N	33E	NE	SE	10	21.6	231.6		42	1
23N	33E	SW	NW	14	18.5	204.8			1
23N	34E	NE	NW	30	11.1	167.9			1
23N	37E	NE	NE	35	12.7	86.9			1
24N	31E	SW	NW	16	20.1	227		36	1, 3
24N	32E	NW	SW	30	19.4	229			3
24N	33E	SE	SW	23	25.9	308.7		45	1
24N	34E		SW	23	17.5	132.3			1
24N	34E	SE	SW	30	19.9	231			1
24N	36E	NE	NE	16	12.6	229			3
24N	36E	NE	NE	16	17.1	227			4
25N	33E	NW	NE	7	10.6	114.6			1

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
25N	37E	NE	SW	21	19.1	149.3			1
25N	37E	NE	SW	21	24	226.5		53	1
25N	39E	NW	NW	15	19.4	255.4	28.3		1
26N	32E	SE	NE	10	16.3	225.5			1
26N	32E	SE	NE	10	19.2	182			2, 3
27N	37E	NW	NW	2			24.8		2
27N	37E	NE	NE	27			26.5		2

OKANOGAN COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
33N	31E	NW	SW	14	11.44	270	25		2
33N	31E	NE	SE	14	9.86	230	19		2
33N	31E	SW	SE	14	9.35	200	15.2		2
36N	20E	NW	NW	19	11.68	170			2
36N	20E	SW	SE	19	14.41	275			2
36N	20E	NW	NE	19	14.94	360	26.5		2
37N	26E	SW	NW	8	16.48	435	21.6		2
40N	27E		NW	6	14.62	210	30.2		2
40N	27E		NW	6	13.91	140	21.3		2
40N	27E		NW	6	15.41	225	23.6		2
40N	27E		NW	6	14.96	200	25.5		2
40N	27E	SW	SE	6	15.31	180	25.2		2

PIERCE COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
15N	4E	NE	SE	14	8.58	122	14.6		2
15N	6E	SE	NW	22	6.76	68	137		2
16N	4E	NW	NE	22	9.75	74			2
16N	4E	SE	SE	23	9.13	86.5			2
17N	2E	NE	NE	2	12.21	177	25.4		2
18N	3E	SE	NW	12	11.19	85			2
18N	5E	NE	SE	6	9.11	68	21.4		2
20N	2E	NW	NE	32	17.7	387	12.8		3

S K A G I T   C O U N T Y

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
34N	1E	NW	NW	1	11.61	220	12.6		2

SKAMANIA COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
1N	5E	SE	SE	1	11.62	46.5	22.4		2
2N	5E	SW	NW	35	8.37	103			2
2N	5E	NE	SE	36	12.78	92	51.5		2
2N	5E	NW	SE	36	14.79	129	52.7		2
2N	7E	SW	NW	22	11.35	68.8	82		2
2N	7E	NE	NW	22	12.45	82	50		2
2N	7E	NE	NW	22	12.29	80.5	34.8		2
2N	7E	NE	NW	22	11.72	68	24.6		2
2N	7E	NE	NW	22	11.98	63	.6		2
2N	7E	NE	NW	22	12.77	68.7			2
2N	7E	SW	NW	22			50		2
2N	7E	SE	NW	22	13.05	80			2
3N	5E	NE	SW	4	13.66	305	23		2
3N	5E	NW	SW	4	11.35	240	24.6		2
3N	5E	NE	SW	4	13.19	280	20.3		2
3N	5E	NE	SE	4	9.42	265	23		2
3N	5E	NW	SE	4	13.52	300	23		2

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
3N	5E	SW	SE	4	9.26	155.5	15.5		2
3N	5E	SW	SE	4	11.51	215	23.2		2
3N	5E	NW	NE	4	14.2	290	24.4		2
3N	5E	SW	NE	4	11.52	210	23		2
3N	7E	SE	SE	36	17.93	290	24.4		2
3N	8E	SE	SW	27	10.21	84	28.6		2
5N	8E	SW	NW	22	2.71	55	2		2
6N	7E	SW	NE	23	11.5	150	49.8		2
6N	9E	SW	SW	25	12.19	150	52.7		2
7N	8E	SE	SW	2	9.1	152.5	44.5		2
7N	8E		SW	36	3.55	25	58		2
7N	9E	NE	NE	17	12.98	150	46.9		2
9N	5E	NW	NW	18	9.84	124.6	20.2		2
10N	6E	NE	SE	8	6.51	265	12.5		2
10N	6E	NW	SE	18	10.56	210	18.5		2

STEVENS COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
27N	38E	NW	NW	28		150	33.8		2
28N	37E	SE	NW	9		135	26		2
29N	37E	SE	SE	36		400	28.4		2
35N	39E	SE	SE	12	11	45.4			1
35N	39E	SE	SE	12	11.5	41.8			1
39N	41E	SE	SE	2	13.34	340	20.3		2
39N	41E	NE	NW	2	12.37	240	21		2

SPOKANE COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
23N	41E	SW	NW	13	14	187			3
23N	41E	SW	SE	14	29.1	341.4		50	1
23N	41E	SW	SE	14	31.9	648.6		31	1
23N	41E	SW	SE	1	12.6	27.4			1
23N	42E	SE	NW	2	16.4	189			3
24N	41E	SW	SW	3	13.9	123			3

THURSTON COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
15N	1W	NW	NW	21	11.83	78.5			2

WALLA WALLA COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
6N	33E	SE	NW	1	31.78	305	69.6	65	2
6N	33E	SE	NE	10	16.39	90	104.1		2
6N	34E	SW	NE	1	15.8	207.3			1
6N	34E	NW	NE	2	25.1	175.3		75	1
6N	34E	NW	NE	6	28.8	470		36	1
6N	34E	NW	SE	7	40.7	407.2	77.8	71	2, 3
6N	35E	SW	SW	3	20	416		20	6
6N	35E	SE	SW	10	25	350		37	6, 7
6N	35E	SE	NE	12	21	214		42	6
6N	35E	SW	SW	12	22	180		56	5, 6
6N	35E	NE	NE	18	20.3	154.8		54	1
6N	35E	NE	NE	18	21.3	177.7		52	1
6N	35E	NE	NE	18	36.1	396.2	41.8	61	1, 3, 4
6N	36E	NE	SW	4	13.88	57.5			2
6N	36E	NW	SW	5	21	188		48	6

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
6N	36E	SE	SE	5	27	554		27	6
6N	36E	NW	SW	6	22	186		54	6
6N	36E	NW	NW	7	22	171		58	6
6N	36E	NE	SW	9	22	352		28	6
6N	36E	SE	SW	9	23	629		17	6
6N	36E	NE	NE	14	14.4	276.7			1
7N	32E	SW	SE	36	24	310		39	4
7N	33E	SW	SE	24	23.2	433.7	19.3	26	1
7N	33E	SW	SE	24	17.01	235			2
7N	33E	NW	SE	31	27.7	268.8		58	1
7N	34E	SW	SW	25	20	336		24	6
7N	34E	SE	NE	36	13.39	32.5			2
7N	35E	NW	SW	23	20	157		51	5
7N	35E	NW	SW	23	20	175		46	6

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
7N	35E	SW	NE	25	12.72	70			2
7N	35E	NE	NW	25	19.7	260	24.4		2
7N	35E	SE	NW	25	20	207		39	6
7N	35E	SE	SW	25	20	189		42	6
7N	35E	SE	NE	33	24	217		55	5
7N	35E	NE	SW	34	24	219.4	47.4	55	1,3
7N	35E	NE	NE	35	20	183		44	6
7N	35E	NE	NE	35	20.54	310	22.1	27	2
7N	35E	NE	NW	36	20	195		41	6
7N	35E	SE	NW	36	20.4	247		34	4, 6
7N	35E	SE	NW	36	21	186		48	6
7N	35E	SE	NW	36	20	216		37	4, 6
7N	35E	SE	SE	36	21	189		48	6
7N	36E	SE	SW	14	25.9	406.9		34	1
7N	36E	NE	SW	17	18.55	160	33.3		2
7N	36E	NE	SW	17	39.1	716		38	2

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
7N	36E	SW	SW	18	18.6	171	22		3
7N	36E	NW	NW	19	18.3	178	27		3
7N	36E	SE	NW	19	30.2	468.8		39	1, 3
7N	36E	SE	SE	19	28.0	485		33	4, 6
7N	36E	SW	NE	20	22	367		27	4, 6
7N	36E	SE	SE	28	23.5	333		22	4, 7
7N	36E	NE	SE	31	21	523		17	6
7N	36E	NW	NW	33	25.9	185.9		75	1
7N	36E	NW	NW	33	28.64	425	74.7	39	2, 3
8N	31E	SE	NW	14	24.5	335.9	36.5	37	1
8N	31E	SE	NE	34	25.4	146		92	4
8N	33E	SW	SE	21	17.3	188.7			1
8N	33E	SE	SE	21	18.5	236.5	21.6		1
8N	33E		SE	21	24.05	290	37.7	42	2
8N	36E	NE	NW	30	10.98	65			2
9N	32E	NE	NW	13	22.2	215		47	2
11N	35E	SW	SE	14	28.4	282.5		58	1
12N	36E	SE	NE	26	22.2	182		56	1

WHITMAN COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
14N	44E	NE	SE	2	11.5	60	17.9		1
14N	44E	SE	SW	14	16.2	183			4
14N	45E	SE	NW	1	16.5	297.2			1
14N	45E	SE	SE	2	12.9	118.9			1
14N	45E	NW	NE	5	20	50		160	5
14N	45E	NW	NW	5	21	51		176	5
14N	46E	NE	NE	5	12	99.4			1
15N	44E	SE	SE	10	9.7	24.7			1
15N	45E	SW	NE	25	12.4	115.8			1
15N	45E	SW	SW	32	14.5	291			4
16N	39E	SW	SE	24	15.6	143.2			1
16N	43E	SW	NE	11	23.5	183		63	5
16N	43E	SW	SW	14	18	229			4
19N	41E	SW	SE	36	14.7	141.1			1
19N	44E	NE	SE	22	12.2	146.3			1
20N	39E	SE	NW	28	17	211	14.8		1

YAKIMA COUNTY

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
7N	19E	NW	NE	10	14.4	119			3
7N	19E	SW	SW	14	14.2	128			3
7N	22E	NW	NE	23	23.4	299.9	34.9	38	1
7N	23E	SE	SE	36	19.8	245.4			1
8N	22E	SW	NE	1	23	329	36	33	3
8N	22E	NE	SE	11	21.4	161.5		58	1
9N	21E	NW	SW	26	28	295		54	3
9N	21E	SE	SE	27	22	35		286	4
9N	22E	NE	SE	11	20.3	166	43.1	50	3
9N	23E	SW	NE	23	16	350			4
10N	17E	NW	NW	14	20.5	23		370	4
10N	17E	NE	SW	23	20.3	213		39	4
10N	17E	NE	SE	26	23.8	305		39	4
10N	17E	SW	SE	27	26	460		24	4
10N	17E	NW	NE	28	22.4	268		39	4
10N	17E	NW	NE	35	21.2	245		38	4
10N	18E	SW	SE	5	20.6	202		43	3
10N	18E	SW	SW	31	23.8	318		37	4
10N	20E	NW	SW	3	14.8	244			4

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
10N	20E	NE	SW	4	22.6	312		34	4
10N	20E	NE	NE	9	20.5	256		33	3
10N	22E	SE	NW	25	20	480		17	4
10N	23E	NE	SW	4	17.1	150.3			1
10N	23E	NW	NE	17	17.7	359.6			1
10N	23E	NE	NE	36	22.9	352.9		31	1
10N	23E	NE	NE	36	26.7	400.8		37	1
10N	23E	SW	NE	36	22.3	284.1		36	1
11N	16E	SE	SW	25	25.4	259.1		52	1
11N	16E	NW	SE	34	21.4	139		68	4
11N	17E	SE	NW	1	24.2	358		34	4
11N	17E	NE	SW	2	25.5	265		51	4
11N	17E	NE	SW	3	25.2	301		44	4
11N	17E	SE	NW	16	31.6	302		65	3
11N	17E	SE	NE	16	20.8	233		38	4
11N	17E	SW	SE	30	19.7	275			4

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
11N	18E	SW	SW	9	23	122		90	4
11N	18E	NW	NE	17	17.7	191			4
11N	18E	NE	SW	26	26.4	16		900	4
11N	18E	SE	NE	30	18	103.7			3
11N	19E	SW	SE	10	18.4	233			4
11N	19E	SW	SE	10	18.7	229			4
11N	19E	NE	NE	15	20.8	179.2		49	3
11N	20E	NW	SW	1	28.1	457.1		35	1
11N	20E	SE	SE	1	21.5	350.8		27	1
11N	20E	NE	NE	6	20.2	166.1		49	1
11N	20E	SE	SE	13	28.5	328.6		50	1
11N	21E	NW	NE	5	25.8	378.8		36	1
11N	21E	NE	SW	6	29.2	364.2		47	1
11N	21E	SW	SE	6	29.6	392		45	1
11N	21E	NW	SW	20	21.6	190.5		50	1
11N	21E	NW	NE	21	26.9	279.2		53	1
11N	21E	SW	NE	22	23.7	299.3	33.2	39	1
11N	21E	NW	SE	22	25.6	319.4	7.5	43	1

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
11N	21E	NE	NW	34	19.5	173.7			1
11N	21E	NW	SE	36	21.5	213.3		45	1
11N	22E	SW	SW	21	22.3	207		50	3
11N	22E	NE	NE	28	17.8	347.5			1
11N	22E	NE	NE	28	18.8	259	18.4		1
11N	22E	SW	SW	29	21.6	340.4		28	1
11N	22E	SW	NE	30	20.3	206.3		40	1
12N	16E	SW	SW	12	24.9	268.2		48	1
12N	16E	NE	NE	18	19.2	108.2			1
12N	17E	SW	NE	2	16.1	85	34		3
12N	17E	NE	SE	2	19	27.4			1
12N	17E	SW	NW	7	11.6	191.1	7.9		1
12N	17E	SW	NE	7	19.5	79.3			3
12N	17E	NW	SW	7	19	201.5			1
12N	17E	NW	SW	7	12.3	155.7			1
12N	17E	NE	NE	16	22.2	265		39	4
12N	17E	SE	SE	16	17	329			4

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
12N	18E	SW	NE	27	23.6	305		38	4
12N	18E	SE	NE	27	29.6	311		57	4
12N	18E	SE	SE	31	22.2	479		21	4
12N	18E	SE	NE	32	25.2	358		37	4
12N	18E	NE	SW	32	27.9	379	39	42	3
12N	18E	NE	NE	33	25.6	290		47	4
12N	18E	NW	NE	33	28	312.7		51	1
12N	19E	SW	SE	1	30	404		45	4
12N	19E	SE	SE	27	19.8	163	42.3		1
12N	19E	NE	SE	28	16.9	90.8	45		1
12N	20E	SW	SE	13	27.9	374.9	35.9	42	1
12N	20E	NW	NW	16	21	153.9		58	1
12N	20E	SE	NW	27	13.8	76.2			1
12N	20E	SW	SW	27	30.4	396.2		46	1
12N	20E	NW	SW	27	27.5	409	48	38	3

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
12N	20E	SW	SW	34	25.9	274		51	1
12N	20E	SW	SW	34	33.1	429		49	1
12N	21E	NE	SW	17	27.8	472.7		33	1
12N	21E	NE	NE	20	16.7	143.9			1
12N	21E	SE	SW	20	25	313.6		42	1
12N	22E	SE	SE	2	23.1	267		42	1
12N	22E	NE	NW	14	15.2	149			3
12N	22E	NW	NE	29	19.4	374.9			1
12N	22E	NW	NE	29	23	430.1		26	1
12N	23E	NE	NE	19	19	229.5			1
13N	17E	NW	NE	28	14.3	171			1
13N	18E	NE	NE	12	24.8	201		64	3
13N	19E	SW	SE	13	24.8	250.8		51	1
13N	19E	NW	SW	22	20	82	70	98	3
13N	19E	NE	NE	24	19.95	230	26.4	35	2
13N	19E	NW	NE	31	19	191			4
13N	20E	SW	SW	18	16.9	292.3	8.9		1

Township	Range	1/4	1/4	Section	Bottom Hole Temperature	Depth	Gradient A	Gradient B	Source Reference
13N	20E	SW	SW	19	22	253.3	19.3	40	1
13N	20E	NW	NW	29	22.65	176		61	3
13N	20E	NE	SW	33	22.9	227.1	39.3	48	1
13N	21E	SE	NE	34	21.7	310.9		31	1, 3
14N	16E	NW	SE	13	16	147.8	19.8		1
14N	16E	NW	SE	24	15.6	209.1			1
14N	17E	SE	NE	4	14.4	305			4
14N	17E	SW	SW	15	14.3	155.7	19.3		1
14N	17E	NE	NE	27	18.1	159.7	39.8		1
14N	17E	SE	NE	35	18.4	289.2			1
14N	18E	SW	NE	20	28.4	324		51	1
14N	19E	SW	SW	16	23.2	267.3		42	1
14N	19E	NW	NE	28	21	183		49	4, 7
14N	20E	SW	SW	20	17	183.5			3
15N	17E	NE	NE	24	9.8	158.5			1
15N	18	SW	NE	30	9.6	144.8			1

APPENDIX B

GEOLOGY OF WHITE PASS - TUMAC MOUNTAIN AREA, WASHINGTON

by

Geoff Clayton

University of Washington
Seattle, Washington
1980

Note: Geologic Map, Scale 1:24,000, found in pocket of back cover

APPENDIX C

RESISTIVITY STUDY OF CAMAS, WASHINGTON:

FINAL REPORT

January 5, 1981

for

Geology and Earth Resources Division
Washington State Department of Natural Resources
Olympia, Washington 98504

by

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TABLE OF CONTENTS

1. PURPOSE

The purpose of the survey described in this report was to determine regions along the trend of the Lacamas fault where lower electrical resistivity can be expected at depth. Once located, these regions of lower resistivity are to be further evaluated by drilling shallow depth heat-flow holes.

2. GENERAL DISCUSSION OF RESULTS OF MODELING

Figures 1, 2, and 3, respectively, are the apparent resistivity pseudosection for line AA', the apparent resistivity pseudosection for line BB', and a map for the Camas area showing the placement of lines AA' and BB'. Figure 4 shows the plotting convention used to obtain these pseudosections. These pseudosections were previously discussed in our preliminary report issued on 14 September 1979, which appears as an appendix at the back of this report.

2.1 PSEUDOSECTION AA'

The pseudosection for profile AA' displays a distinct transition in resistivity from values of the order of 30 ohm-meter in a region 3 kilometers south of the northern end of the profile to values of the order of 120 ohm-meter in a region extending to a point 9 to 10 kilometers from the northern end. This transition appears to occur at a point approximately 4 kilometers from the northern end of the profile.

Figure 5 displays the two-dimensional earth model developed by the University of Utah Research Institute to fit the data on line AA'. The pseudosection that would be measured for such an earth model is also shown. Most of the major features of pseudosection AA' derived from the field data are reasonably well reflected in the model. This "best fit" model places the transition from low to high resistivity at a point 3.75 kilometers south of the starting point of the profile. The 10 ohm-meter resistivity block at the northern end of the profile is open ended to the north. This is consistent with the observed data's open 20 ohm-meter contour enclosing values of approximately 10 ohm-meter at the northern end of the pseudosection (Figure 1).

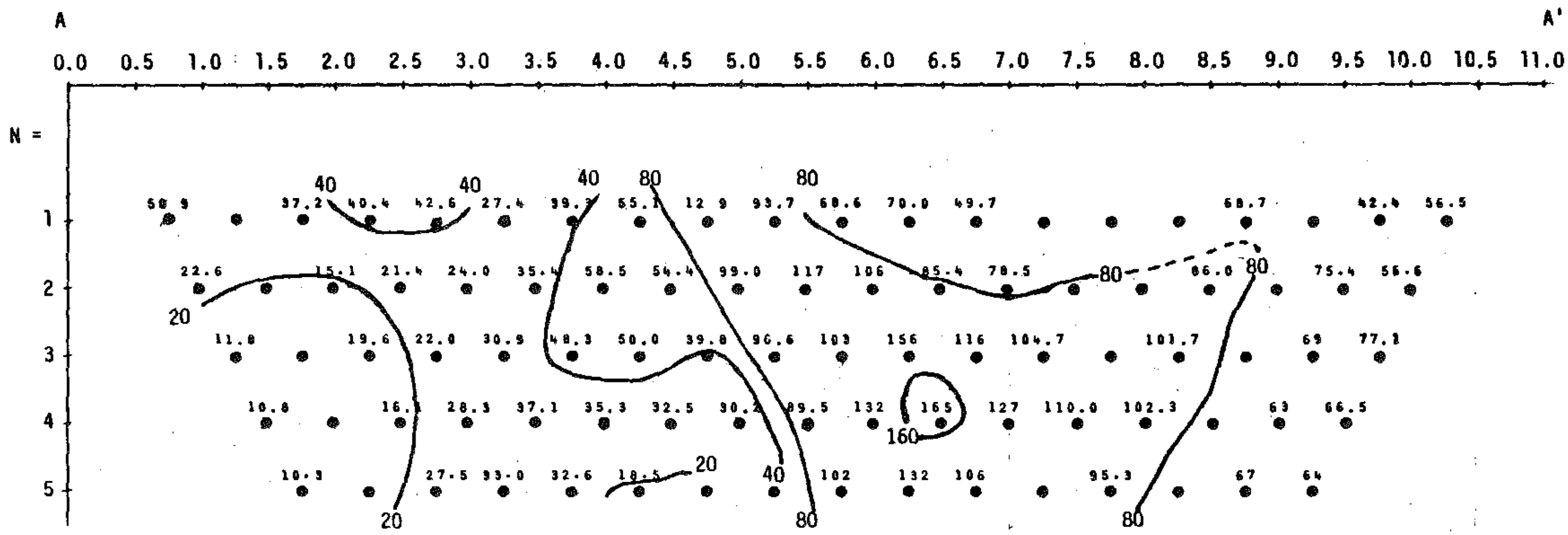

Figure 1. Pseudosection for line AA'. Dipole length was 0.5 km. Resistivities are in ohm-meters. The vertical scale is exaggerated by a factor of two.

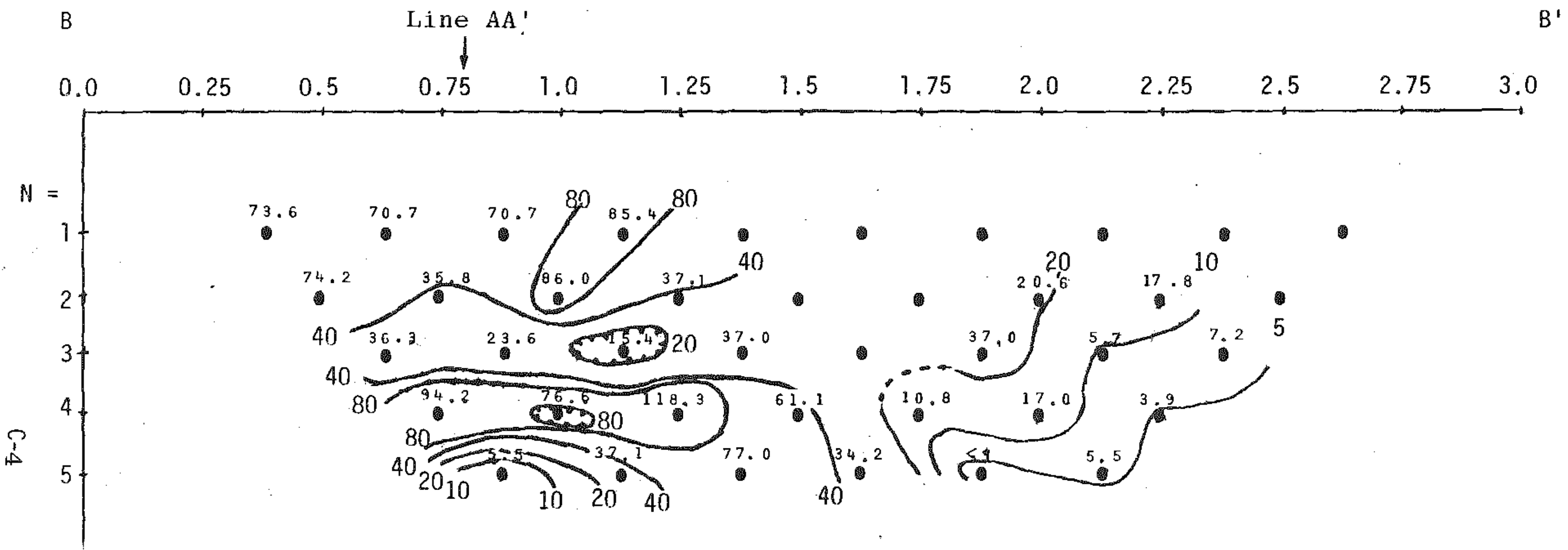

Figure 2. Pseudosection for line BB'. Dipole length was 0.25 km

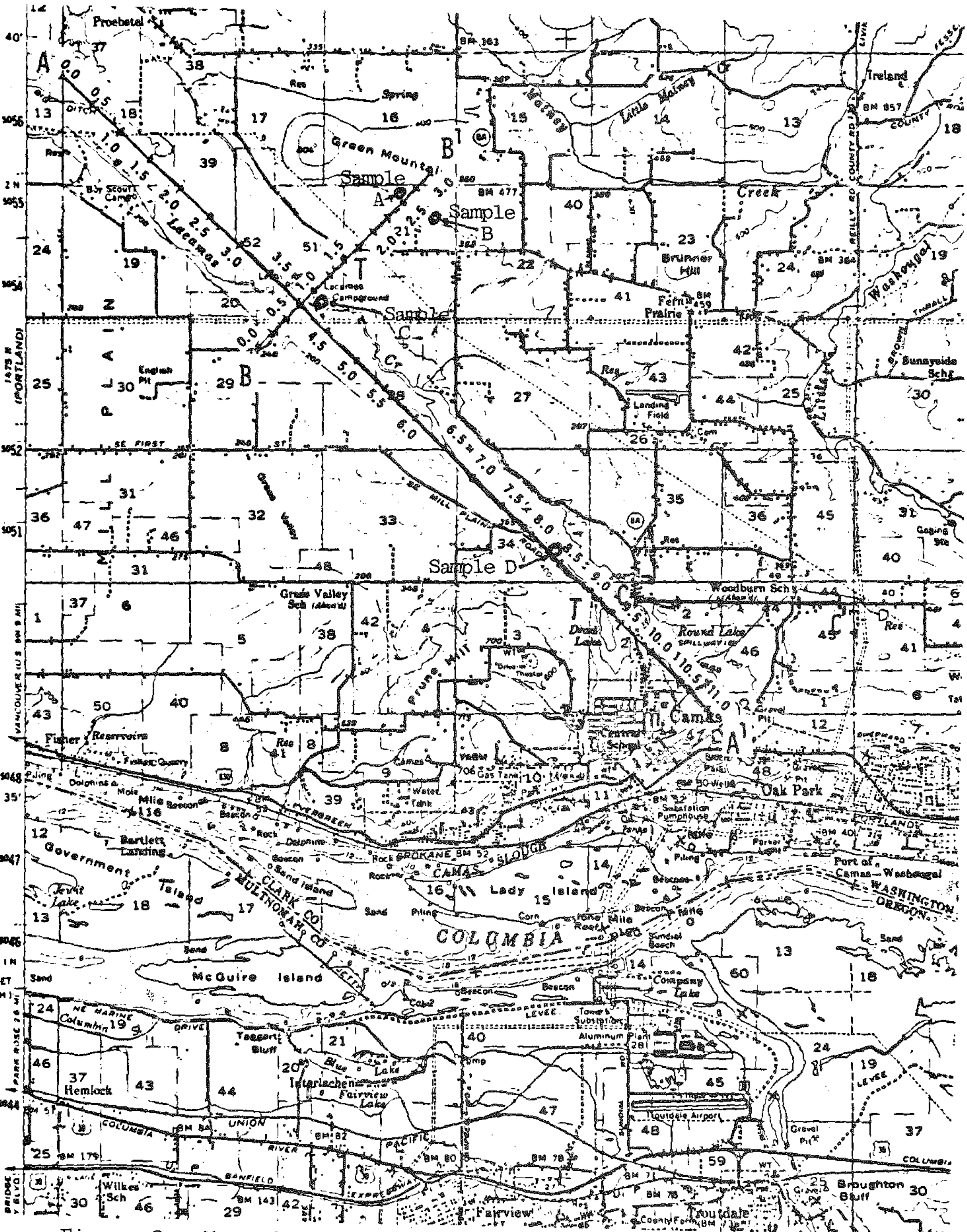

Figure 3. Map of the Camas area showing resistivity lines. Two suggested test hole sites are marked with the letter "T".

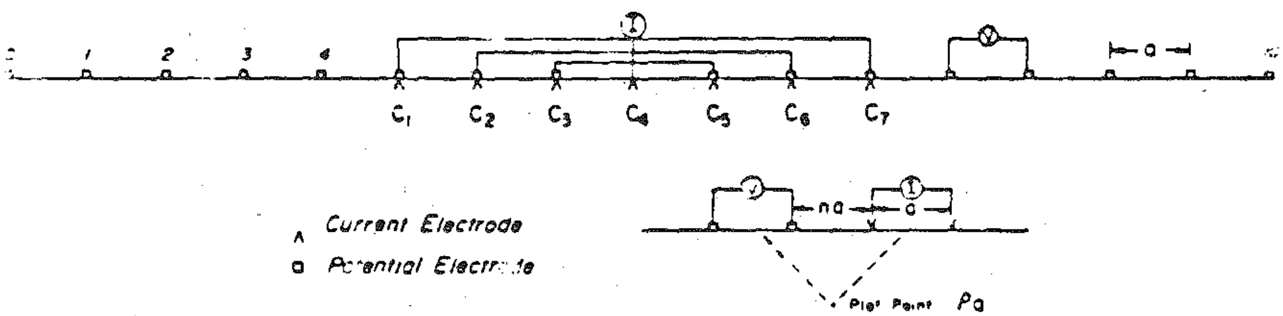

Figure 4. Electrode Geometry

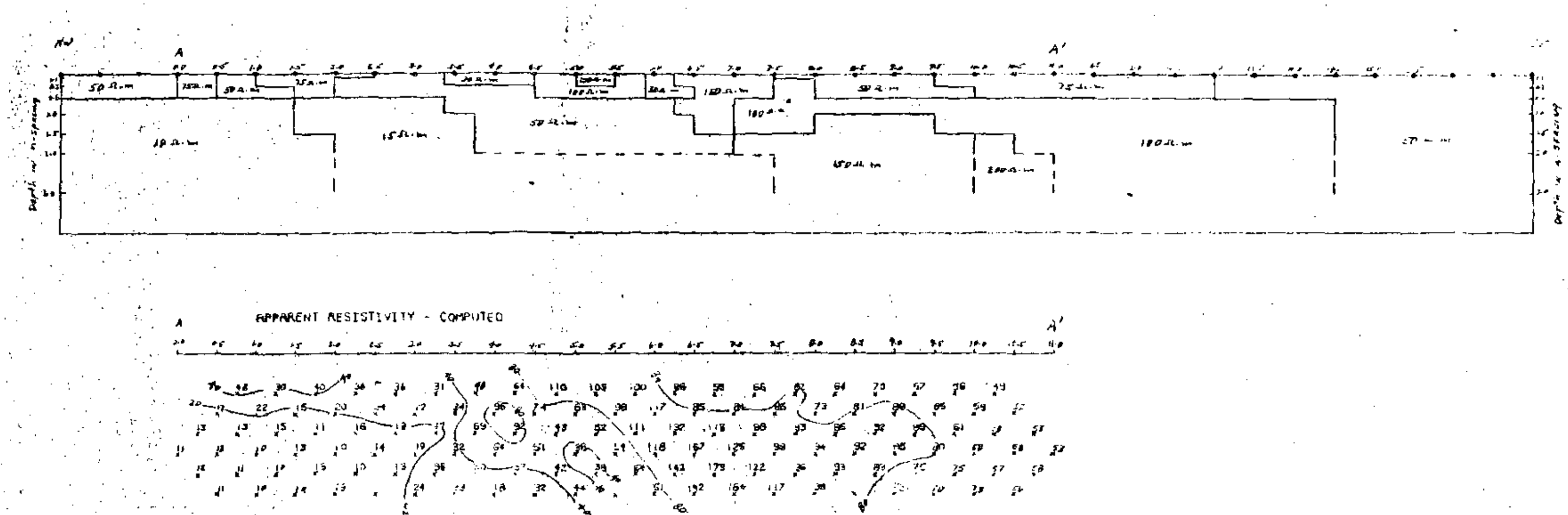

Figure 5. UURI Resistivity Model for Line AA' and Apparent Resistivity Pseudosection That This Model Would Produce

At the southern end of profile AA', the resistivities shown in the pseudosection decrease from values near 100 ohm-meter to values near 65 ohm-meter, this transition occurring approximately 9.5 kilometers from the northern end of the profile (Figure 1). The modeling for this portion of the field data suggests an increased thickness of a 100 ohm-meter unit (low resistivity material relative to deeper 150 and 200 ohm-meter units) occurs at this point. The position of this change in thickness corresponds to the position of a fault mapped by Mundorff that crosses the line AA' about this point and that is downthrown on the south side. Such a downthrown block would account for the greater thickness of the 100 ohm-meter material. The values of about 50 ohm-meter measured at the extreme southern end of the profile require the model to contain a 50 ohm-meter unit at the extreme southern end, although the evidence for this unit is clearly tenuous.

2.2 PSEUDOSECTION BB'

Figure 2 shows the apparent resistivity data as measured along profile BB'. The dipole length used to collect these data was 250 meters as opposed to the 500 meter length used for profile AA'. This shorter dipole length increased the spatial resolution but had the effect of decreasing, by a factor of two, the depth of penetration.

BB' is perpendicular to AA', the two lines intersecting about the 4 kilometer point on AA' and the 0.75 kilometer point on BB'. Line BB' is thus a further investigation of the formations at the north end of AA'. It proved to be very difficult to obtain a satisfactory fit for line BB'. Figures 6 and 7 show pseudosections obtained for differing earth models. The difficulty of the computer analysis indicates that a two-dimensional model cannot be derived that will adequately fit the observed field data for the western portion of pseudosection BB'. We have

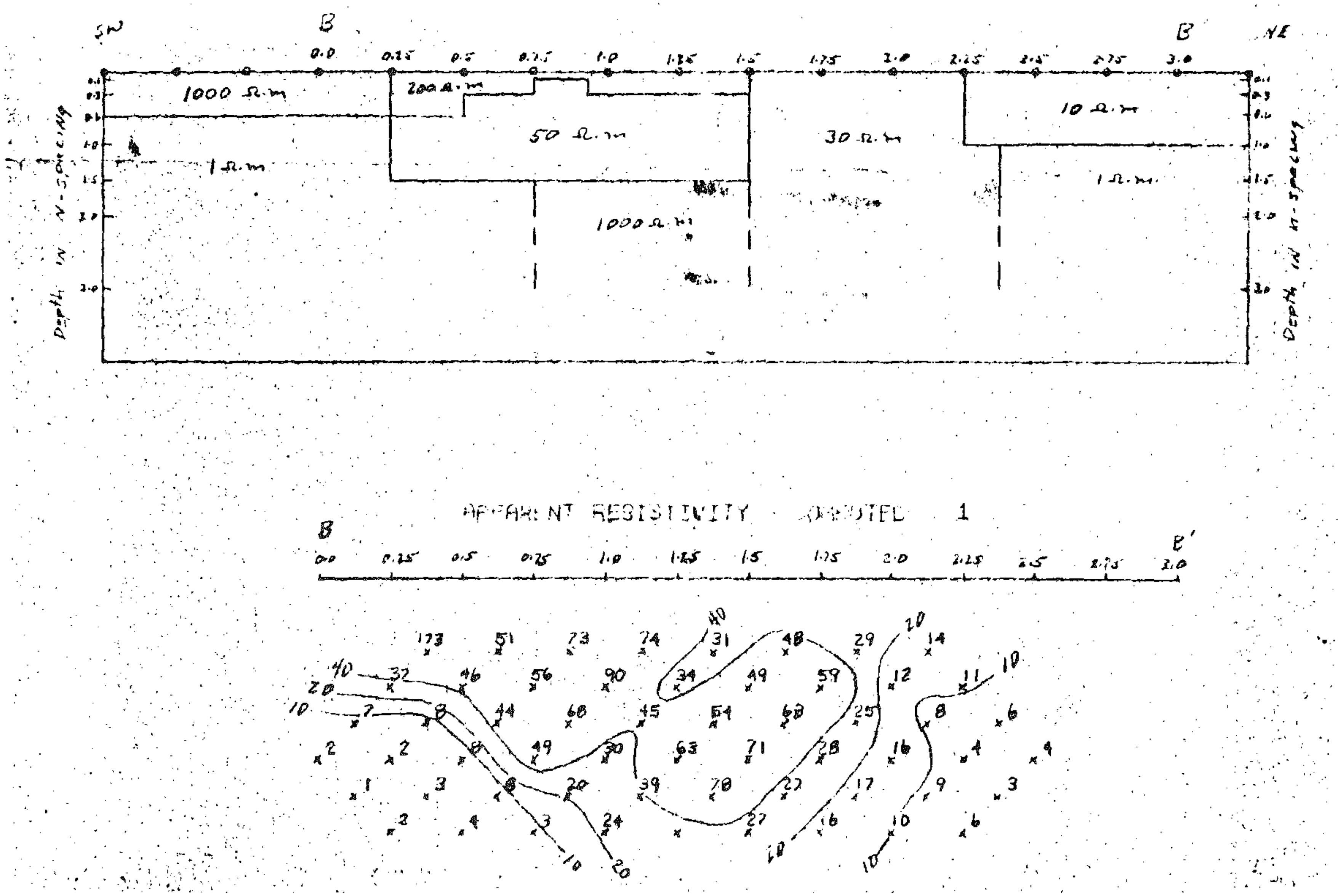

Figure 6. One Alternative UURI Model for Line BB' with the Apparent Resistivity Pseudosection It Would Produce

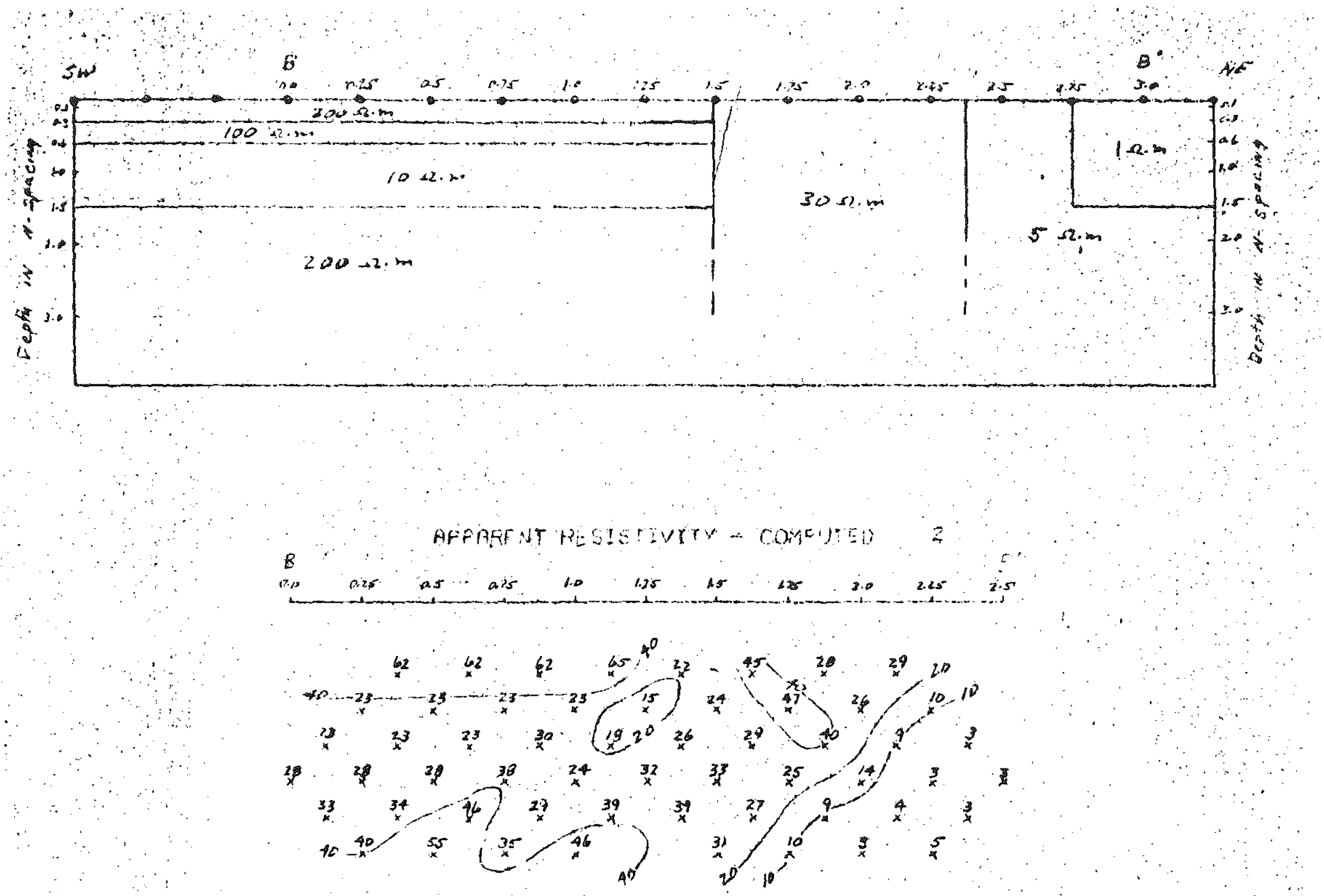

Figure 7. Second Alternative UURI Model for Line BB' with the Apparent Resistivity Pseudosection This Model Would Produce

studied the variability of the field data shown in Figure 2 and conclude that the pseudosection for computed models 1 and 2 fit the data equally well. The two models are, however, substantially different. It can be concluded that features common between the two models have a high probability of reflecting actual geologic features, while other features must be regarded as doubtful. Both models have major boundaries at 1.5 and 2.4 kilometers NE of the profile origin. These boundaries most probably represent, respectively, the Lacamas fault and the contact with the volcanics ics of Green Mountain.

2.3 UURI COMMENTS ON MODELING RESULTS

Below is a discussion of the modeling results by C. E. Mackelprang. Mr. Mackelprang was responsible for the modeling carried out by UURI.

> "Results of the modeling for line A-A' suggest a surface layer of fairly moderate apparent resistivity extending over the entire line. This layer increases in thickness in the central portion of the line. A conductive media is present at a fairly shallow depth on the northwest end of the line but deepens to the southeast and is absent at the southeast end of the line.
>
> "Model results of line B-B' are questionable but tend to suggest a layering of resistive - conductive - resistive medias of unknown configuration and thicknesses on the southwest half of the line. To the northeast the models are less complex showing a trend into fairly conductive ground.
>
> "The attached models are two-dimensional (i.e. infinite strike length). If the survey lines have been run at some angle other than normal to the geologic structure then the model interpretation will not approximate the true resistivity distribution. The presence of three dimensional resistivity distributions would also detract from the applicability of the model solutions. We understand that line A-A' runs subparallel to a major geologic structure and topographic features. This may reduce the applicability of the resistivity model submitted here."

2.4 IMPACT OF MODEL RESULTS ON PREVIOUSLY RECOMMENDED DRILL SITE LOCATIONS

Two drilling locations are recommended in our Preliminary Report. Both are in regions along the Lacamas fault having lower resistivity and reasonable proximity to Camas. Subsequent to our report, the southern drilling location was moved further south due to problems associated with land availability. The model that approximates the field data for profile AA' suggests that this placement of the second location at a point near the 10.25 km on line AA' is in a region where low resistivity units are thickening. As already mentioned, this thickening may be associated with faulting resulting in thicker units within the southernmost down faulted block. In addition, this new location places the drilling site nearer the crest of the interesting gravity positive mapped by Z. F. Danes. Thus the final placement of the drill site near the southern end of line AA' would seem to be excellent.

The other drillsite recommendation, a point a short distance southeast of the 1.5 km point on line BB', also appears to be supported by the inversion models. This location would place the test hole near one of the major vertical contacts shown on both the alternative models of section BB', the contact that may be associated with the Lacamas fault. It must be noted however that substantial, open-ended, low resistivity zones exist at the northeast end of line BB', perhaps associated with the volcanic rock of Green Mountain, and at the northwest end of line AA'. It seems clear that further determination of the extent of these regions of very low resistivity would be worthwhile if further study of the geothermal potential of this area is to be persued.

3. FIELD METHODS AND PROCEDURES

The profiles along which apparent resistivity data were collected were surveyed using a compass and chain. Each electrode position was staked and properly identified. The distance between electrode locations was 500 meters along profile AA' and 250 meters along profile BB'.

The dipole-dipole electrical prospecting method requires the injection of controlled current into the ground at the ends of a grounded dipole. The current source for this survey consisted of a truck-mounted gasoline generator. The output from the generator was fed to a "transmitter" which controlled the amplitude and wave form of the injected current. Maximum current was 20 amps, although it was not always possible to achieve this; frequencies of 0.01 H_z and 0.1 H_z were employed on each measurement to allow detection of electromagnetic coupling if it significantly affected results. Clusters of metal stakes driven into the ground provided satisfactory current electrodes. Non-polarizing electrodes for the receive dipole were made using a copper sulfate solution in porous porcelain cups.

Receive and transmit dipoles were of equal length and were co-linear (all four electrodes in a single line). The distance between the nearest electrodes of the receive and transmit dipoles was used as the dipole separation and was recorded in terms of multiples of the dipole length. For each transmit position, measurements were made with the receive dipole at separations ranging from one to five times the dipole length, if possible. Problems of access prevented collection of data in a few cases. The major gap in the BB' pseudosection was the most severe case.

Portable Esterline-angus strip chart recorders were used as the voltage measuring device on the receive dipoles. Figure 7 shows some typical field data.

The measured voltage and the known value of the injected current are used to determine the apparent resistivity using the formula

$$\rho = 2\pi N(N+1)(N+2)\mu\Delta V/I$$

where

N = the number of dipole lengths of the gap between dipoles,

ΔV = the potential difference measured at the receive dipole,

μ = is the dipole length and

I = the injected current.

A listing of the field data is given in the next section.

The calculated values for apparent resistivities are plotted and contoured on the pseudosections shown in Section 2. The actual dipole locations for several of the measurements near the 2.0 km point on BB' had to be offset slightly due to access problems. In preparing the pseudosection, corrections were applied for these offsets by computing apparent resistivity based on individual electrode separations. These data were also analyzed for appropriate two-dimensional earth models by the Earth Science Laboratory of the University of Utah Research Institute.

4. LISTING OF RAW DATA

Electrode Configuration Dipole Dipole

Date (9)(4)(79)

Spread Length T 500 m R 500 m 3

Area (1) Lacamas

Line AA'

Sheet (1)

Location No. Transmit	Receive	f		N	Voltage (mV)	CRNT AMPS	ρa	Remarks
0.0-0.5	1.0-1.5	.01	.1	1	47.4	12	37.2	
0.0-0.5	1.5-2.0	.01	.1	2	4.8	12	15.1	
0.5-1.0	2.5-3.0	.01	.1	3	2.8	12	22.0	
0.0-0.5	2.5-3.0	.01	.1	4	1.025	12	16.1	
0.0-0.5	2.0-2.5	.01	.1	3	2.05	12	19.6	
0.5-1.0	1.5-2.0	.01		1	51.5	12	40.4	
0.5-1.0	2.0-2.5	.01	.1	2	6.8	12	21.4	
0.0-0.5	3.0-3.5	.01	.1	5	1.0	12	27.5	
0.5-1.0	3.0-3.5	.01	.1	4	1.8	12	28.3	Charts misread initially, correct value =
0.5-1.0	3.5-4.0	.01	.1	5	3.1	12	85.2	33.0 check See
1.0-1.5	3.5-4.0	.01	.1	4	6.3	16	74.2	37.1 check data sheet
1.5-2.0	3.5-4.0	.01	.1	3	20.5	20	96.6	48.3 check for V
1.0-1.5	2.5-3.0	.01	.1	2	13.3 11.0	20 18	25.1 23.0	24.0
1.5-2.0	2.5-3.0	.01	.1	1	58.8	20	27.7	
1.5-2.0	3.0-3.5	.01	.1	2	18.8	20	35.4	
1.0-1.5	3.0-3.5	.01	.1	3	5.25	16	30.9	
1.0-1.5	2.0-2.5	.01	.1	1	81.3	18	42.6	
1.0-1.5	4.0-4.5	.01	.1	5	1.78	18	32.6	
1.5-2.0	4.0-4.5	.01	.1	4	3.75	20	35.3	
1.5-2.0	4.5-5.0	.01	.1	5	1.12	20	18.5	
2.0-2.5	4.0-4.5	.01	.1	3	10.6	20	50.0	Repeat checks
2.0-2.5	4.5-5.0	.01	.1	4	3.45	20	32.5	31.8 Repeat
2.0-2.5	4.0-4.5	.01	.1	3	3.38 10.6	20	49.9	
2.0-2.5	4.5-5.0	.01	.1	3	3.38	20	31.8	
2.5-3.0	4.0-4.5	.01	.1	2	46.2	16	54.4	
2.5-3.0	4.5-5.0	.01	.1	3	6.75	16	39.8	
3.0-3.5	4.0-4.5	.01	.1	1	27.5	2	129.6	
3.0-3.5	4.5-5.0	.01	.1	2	5.25	2	98.9	
3.0-3.5	5.0-5.5	.01	.1	3	2.05	2	96.6	
3.0-3.5	5.5-6.0	.01	.1	4	.95	2	89.5	
3.0-3.5	6.0-6.5	.01	.1	5	1.85	3	101.7	
4.5-5.0	6.5-7	.01	.1	3	3.7	3	116	
4.0-4.5	6.0-6.5	.01	.1	3	6.6	.5 .4	156	
4.5-5.0	6.0-6.5	.01	.1	2	6.8	3	85.5	
4.0-4.5	6.5-7	.01	.1	4	.35	.4	165	
4.0-4.5	7.0-7.5	.01	.1	5	.45	.7x2=1.4	106	
4.5-5.0	7.0-7.5	.01	.1	4	2.7	4	127.3	

Electrode Configuration Dipole - Dipole

Date (8) (12) (79)

Spread Length T 500 m R 500 m

Area (1)

Line AA'

Sheet (2)

Location No.								
Transmit	Receive	f		N	Voltage (mV)	CRNT AMPS	ρa	Remarks
4.0-4.5	5.5-6.0	.01	.1	2	4.5	.8x2=1.6	106	
4.5-5.0	5.5-6.0	.01	.1	1	33.7	.9x5=4.5	70.7	
4.0-4.5	5.0-5.5	.01	.1	1	2.33	.8x2=1.6	68.6	
3.5-4.0	4.5-5.0	.01	.1	1	9.9	1	93.7	
3.5-4.0	5.0-5.5	.01	.1	2	3.1	1	116.8	
3.5-4.0	5.5-6.0	.01	.1	3	1.1	1	103	
3.5-4.0	6.5-7.0	.01	.1	5	1.0	2.5	132	
3.5-4.0	6.0-6.5	.01	.1	4	1.75	2.5	132	
3.5-4.0	2.0-2.5	.01	.1	2	3.88	2.5	58.5	
3.5-4.0	2.5-3.0	.01	.1	1	14.6	2.5	55.1	
3.0-3.5	2.0-2.5	.01	.1	1	33.4	8	39.3	
5.0-5.5	6.0-6.5	.01	.1	1	47.5	9	49.7	
5.0-5.5	6.5-7.0	.01	.1	2	18.75	9	78.5	
5.0-5.5	7.0-7.5	.01	.1	3	10.0	9	104.7	
5.0-5.5	7.5-8.0	.01	.1	4	5.25	9	110.0	
5.0-5.5	8.0-8.5	.01	.1	5	2.6	10	95.3	
5.0-5.5	2.5-3.0	.01	.1	4	1.6	10	30.2	
8.0-8.5	5.5-6.0	.01	.1	4	3.8	7	102.3	
8.0-8.5	6.0-6.5	.01	.1	3	7.55	7	101.7	
8.0-8.5	6.5-7.0	.01	.1	2	18.25	8	86.0	
8.0-8.5	7.0-7.5	.01	.1	1	51.0	7	68.7	
9.0-9.5	8.0-8.5	.01	.1	1	4.5	1	42.4	
9.0-9.5	7.5-8.0	.01	.1	2	2.5	1.25	75.4	Amps misrecorded on strip chart
9.0-9.5	7.0-7.5	.01	.1	3	1.1	1.5	69	
9.0-9.5	6.5-7.0	.01	.1	4	0.5	1.5	63	?Terrain effects? Ravine edge//To Transmit
9.0-9.5	6.0-6.5	.01	.1	5	0.3+	1.5	66+	Barely detectable
9.5-10.0	8.5-9.0	.01	.1	1	16.5	2.75	56.5	Offset to SW of line ≈ 100 yards to avoid cemetary
9.5-10.0	8.0-8.5	.01	.1	2	5.0	3.0	62.8	
9.5-10.0	7.5-8.0	.01	.1	3	2.7	3.3	77.1	
9.5-10.0	7.0-7.5	.01	.1	4	1.2	3.4	66.5	
9.5-10.0	6.5-7.0	.01	.1	5	0.7- 0.65	3.5	66 61 } 64	
-1.0-0.5	0.0-0.5	.01	.1	1	54.0	10.0	50.9	
-1.0-0.5	0.5-1.0	.01	.1	2	6	10.0	22.6	
-1.0-0.5	1.0-1.5	.01	.1	3	1.5	12.0	11.8	Traces are terrible, high noise.
-1.0-0.5	1.5-2.0	.01	.1	4	0.8	14.0	10.8	
-1.0-0.5	2.0-2.5	.01	.1	5	0.5	16.0	10.3	

Electrode Configuration Dipole - Dipole

Date (8) (19) (79)

Spread Length T 250 m R 250 m

Area (1)

Line BB'

Sheet (3)

Location No.							
Transmit	Receive	f	N	Voltage (mV)	CRNT AMPS	ρa	Remarks
0.0-0.25	0.5-0.75	.01 .1	1	125	8	73.6	Amps ran up to 10 at beginning of record
0.0-0.25	0.75-1.0	.01 .1	2	31.5	8	74.2	
0.25-0.5	0.75-1.0	.01 .1	1	120	8	70.7	
0.0-0.25	1.0-1.25	.01 .1	3	7.7 8.0	10 14	36.3 26.9	Step up to 14 amps on last part of .1 frequency
0.0-0.25	1.25-1.5	.01 .1	4	10.0 14.0	10 14	94.2	
0.25-0.5	1.0-1.25	.01 .1	2	20 19	10	37.7 35.8	Strong anisotropy between transmit electrodes
0.25-0.5	1.25-1.5	.01 .1	3	5.0	10	23.6	
0.0-0.25	1.5-1.75	.01 .1	5	0.15 0.1 0.5	15	5.5 1.6 1.1	
0.0-0.25	1.75-2.0	.01 .1	?6?	0.85	15	15.0	
0.25-0.5	1.5-1.75	.01 .1	4	13	16	76.6	
0.25-0.5	1.75-2.0	.01 .1	5	3.6	16	37.1	
0.50-0.75	1.0-1.25	.01 .1	1	120	8	70.7	Ran up to 10 amps when starting up
0.0-0.75	1.25-1.50	.01 .1	2	36.5	8	86.0	Ran up to 10 amps when starting up
0.75-1.0	1.25-1.50	.01 .1	1	145	8	85.4	
0.50-0.75	1.50-1.75	.01 .1	3	4	12	15.7	Very bad trace
0.50-0.75	1.75-2.0	.01 .1	4	15.5	14	104.3	Offset 300 yards SE (receiver)
0.75-1.0	1.50-1.75	.01 .1	2	24.0	12	37.7	
0.75-1.0	1.75-2.0	.01 .1	3	9.0	14	30.3	Receiver offset 300 yards SE
0.50-0.75	2.0-2.25	.01 .1	5	6	14	70.7	Off the line 300 yards SE (receiver)
0.75-1.0	2.0-2.25	.01 .1	4	8.0	14	5.4/53.9	5mv scale is open to question receiver offset
0.75-1.0	2.25-2.5	.01 .1	5	2.9	14	34.2	
2.25-2.5	1.50-1.75	.01 .1	2	7.0	7	18.8	
2.25-2.5	1.25-1.50	.01 .1	3	5.5	7	37.0	Power down after 2 minutes of .01 frequency side of hill
2.25-2.5	1.0-1.25	.01 .1	4	0.8	7	10.8	
2.5-2.75	1.0-1.25	.01 .1	5		8/7		Current was 8 on 1st try, 7 on 2nd try
2.5-2.75	1.25-1.5	.01 .1	4	1.3	7.2	17.0	
2.75-3.0	1.25-1.5	.01 .1	5	0.2	6	5.5	Very faint
2.5-2.75	1.5-1.75	.01 .1	3	0.6	5.2	5.4	Started at 6 amps dropped to 5.2 after a minute
2.75-3.0	1.5-1.75	.01 .1	4	0.2	5.0	3.8	Extremely bad trace
2.5-2.75	1.75-2.0	.01 .1	2	2.5	4.0	11.8	Receiver offset 300 yards SE
2.75-3.0	1.75-2.0	.01 .1	3	0.5	4.0	5.9	Receiver offset 300 yards SE

APPENDIX

PRELIMINARY REPORT ON DIPOLE-DIPOLE RESISTIVITY STUDY NEAR CAMAS, WASHINGTON*

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and

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5202 College Gardens Ct.
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During the past month (August) DC resistivity studies have been carried out in Washington in the area immediately north and a little east of Camas for the purpose of investigating possible indications of geothermal potential in the area. The first portion of the study consisted of resistivity measurements covering 11-line kilometers on a line oriented NW-SE running along the southwestern shore of Lacamas Lake. This line ran from the northern edge of the town of Camas, along the SW side of the Lake, and extended NW beyond the north end of the Lake along the valley of Lacamas Creek, as shown on the enclosed map (Figure 1, line AA'). This line lies approximately on the trace of the Lacamas Fault. This fault zone has been identified as a possible conduit for the circulation of hot fluids associated with the hypothesized geothermal heat source.

The measurements were made using a 500 meter dipole with a maximum N-spacing of N=5 (separation of near electrodes of the transmitter and receiver dipoles ranging from a distance equal to the dipole length, up to five times the dipole length). The data obtained are shown on the pseudosection in Figure 2.

* Funding for this effort was provided by the U.S. Department of Energy under Contract DE-AC03-79ET27014 under contract to the Washington State Department of Natural Resources.

As can be seen, resistivity values are not uniform along the line. Sharp resistivity contrasts present along the apparent fault zone may be evidence of the presence of hot, conductive fluids.

The most significant feature on the pseudosection in Figure 2 is the transition from low-resistivity values on the order of 30 ohm-meters or less to resistivities in excess of 100 ohm-meters. Examination of the pseudosection suggested the boundary between these zones to be about at a point 4.25 kilometers from the north end of the line. Accordingly, a cross line perpendicular to the first line was laid out through this point (line BB' on Figure 1). To gain greater detail, measurements were made along this line using a dipole length of 250 meters and a maximum spacing of N=5 (the low resistivities encountered reduced signal strength to such a point that data could not be reliably obtained for larger N). The pseudosection for the second line is shown in Figure 3. The left side of the pseudosection in Figure 3 suggests a layered geology with high resistivities similar to those in the center portion of the pseudosection for line AA' (Figure 2). Near the intersection with line AA', sharply reduced resistivity values were found. This may mark the point at which line BB' crossed the Lacamas Fault or some other geologic boundary. The most distinct resistivity contrasts on the pseudosection for line BB' suggest the minimum resistivities are in the vicinity of the 1.5 kilometer point. The author's feel some skepticism regarding the very low N=5 measurement of 5.5 ohm-meters occurring at the point at which the two lines cross. At N=5, the signal strength for this small a resistivity was at the limit of detection, and the contrast between the N=4 and 5 values seems extreme. There may, therefore, be some question regarding the quantitative measure at this point, but the presence of a pronounced resistivity drop seems clear.

Line BB' could not be extended farther to the southwest (left on Figure 3) because of the intervention of a new housing development. The line was carried farther to the northeast, up the slope of Green Mountain, which has the appearance of a volcanic feature. As can be seen from the right side of Figure 3, low resistivities were found as the measurements approached Green Mountain. Although several points were not obtained in this area because of the refusal of one local property owner to allow access to his land, it is nonetheless clear that this area displays some of the lowest resistivities encountered in the course of the study, even when allowance is made for terrain affects.

The area at the north end of Lacamas Lake clearly commands primary attention based on the results of the resistivity study. However line AA' was also extended as far southeast into the vicinity of Camas as was feasible. It is worth noting that a second resistivity contrast was detected at the southern limit of the line. While this change in resistivities is much less pronounced than those at the north end, the proximity to Camas enhances its significance. Unfortunately this area could not be fully investigated within the constraints of this project.

The question of the implications of the resistivity results for the siting of the planned thermal gradient holes remains to be discussed. Selecting one site from the available data is straightforward. As already discussed, the vicinity of the 1.5 km point on line BB' near the intersection of lines AA' and BB' marks a sharp resistivity contrast with very low resistivity values. Since the resistivity lines were selected to try to follow the Lacamas Fault and the Boundary (possibly another fault) of the low resistivity zone found along the northern section of line AA', it would be reasonable to hope that hot fluids at depth should be able to rise toward the surface in the vicinity of the intersection. A block of land at the north end of the Lake, owned by Crown Zellerbach Corporation, could provide a feasible site for test drilling within a few hundred yards southeast of the 1.5 kilometer point of the cross-line, BB'. This site would also place the test hole on the steep gradient in the gravity measurements just north of the end of Lacamas Lake, as shown on the gravity map prepared by Danes (Figure 4). The hole would thus be in an area marked by both gravity and resistivity contrasts. This site should also help to minimize any institutional problems that might be encountered (including being outside the shoreline zone of Lacamas Creek).

Selection of a site for the second thermal gradient test hole is not as straightforward. The resistivity study gives evidence of several interesting areas. As can be seen from Figure 2, resistivity values remain low along line AA' from Lacamas Lake on northwest to the limit of the area measured. A strong case could be made for further investigation of this area. Green Mountain also represents an area of considerable interest, as has already been discussed. Finally, there is the area at the southeast end of the line where the resistivities again decline with the transition apparently occurring about 9 to 9.5 kilometers along line AA'.

The selection of the site for the second test hole is complex. Based on available data and four considerations, discussed below, the authors favor a site near the south end of Lacamas Lake around the small lake called Dead Lake. (1) Given that one test hole is to be sited on the anomalous area at the north end of line AA', it seems reasonable to site the second on a different anomaly. If there is a geothermal feature in the area northwest of Lacamas Lake, then it is unlikely that the several zones in that area having low resistivities are unrelated. The area at the south end of the lake, however, represents a second anomaly that could mark a geothermal resource even if the anomalies at the north end do not. (2) Selection of a test hole site near Dead Lake will also have the affect of placing the second test hole on the margin of the major positive gravity trend that runs northeast-southwest through Camas, a feature that may also be associated with one of the major lineaments identified from the aeromagnetic data. (3) The proximity of the south end to Camas must also be considered. If only a low temperature resource is present, the prospect for development requires it be close to potential users. (4) Dead Lake is itself an interesting feature. Called "Dead Lake" because it has no streams feeding it or draining it; it is not a small, stagnant pond. Conversations with local residents indicate that it is exceptionally deep. Reportedly, an attempt a number of years ago to sound it was unable to reach the bottom with 1500 feet of cable. More than one person raised the question of whether or not this lake could be a volcanic feature.

The recommendations as to the drilling locations are shown as "T"s on Figure 1.

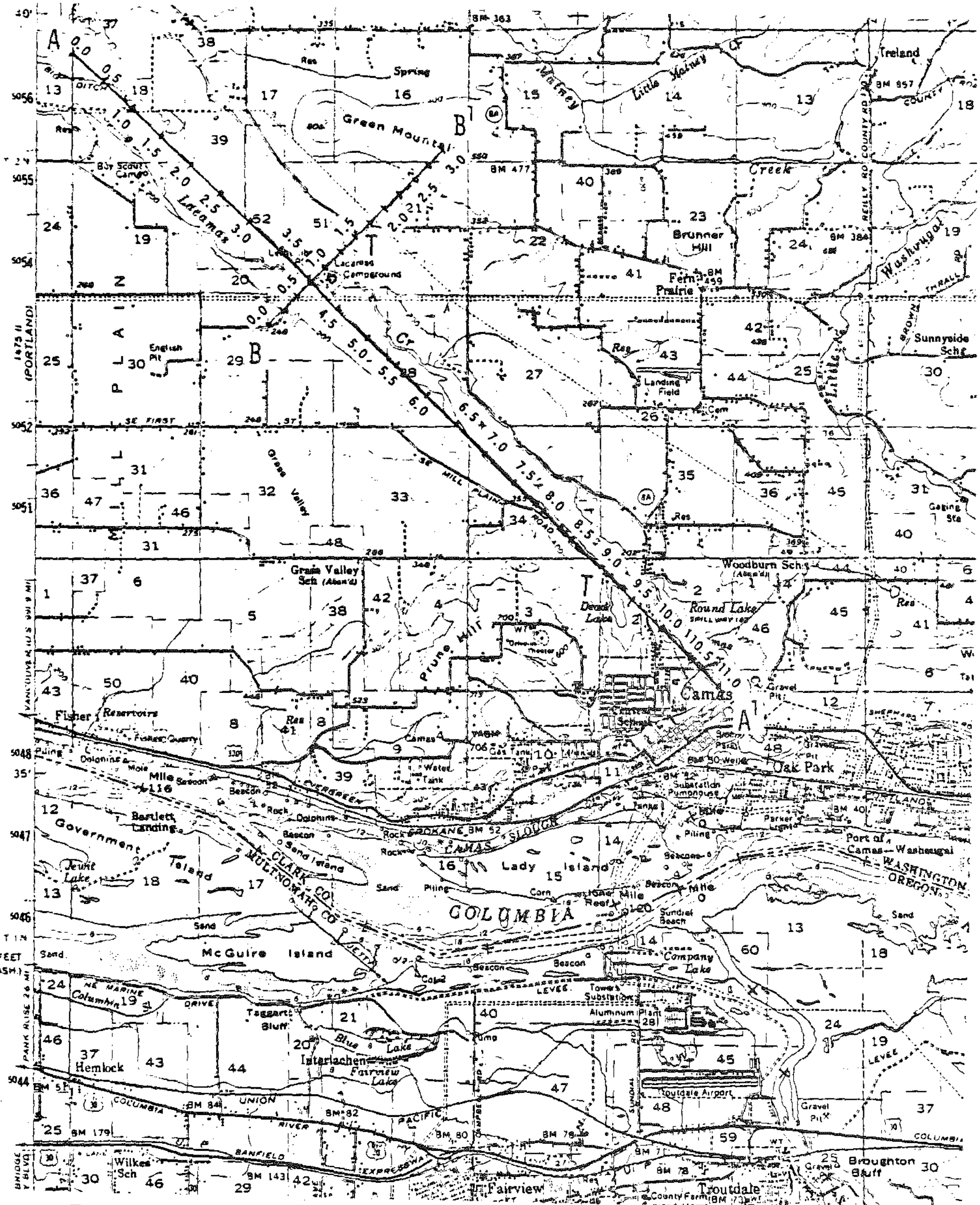

Figure 1. Map of the Camas area showing resistivity lines. Two suggested test hole sites are marked with the letter "T".

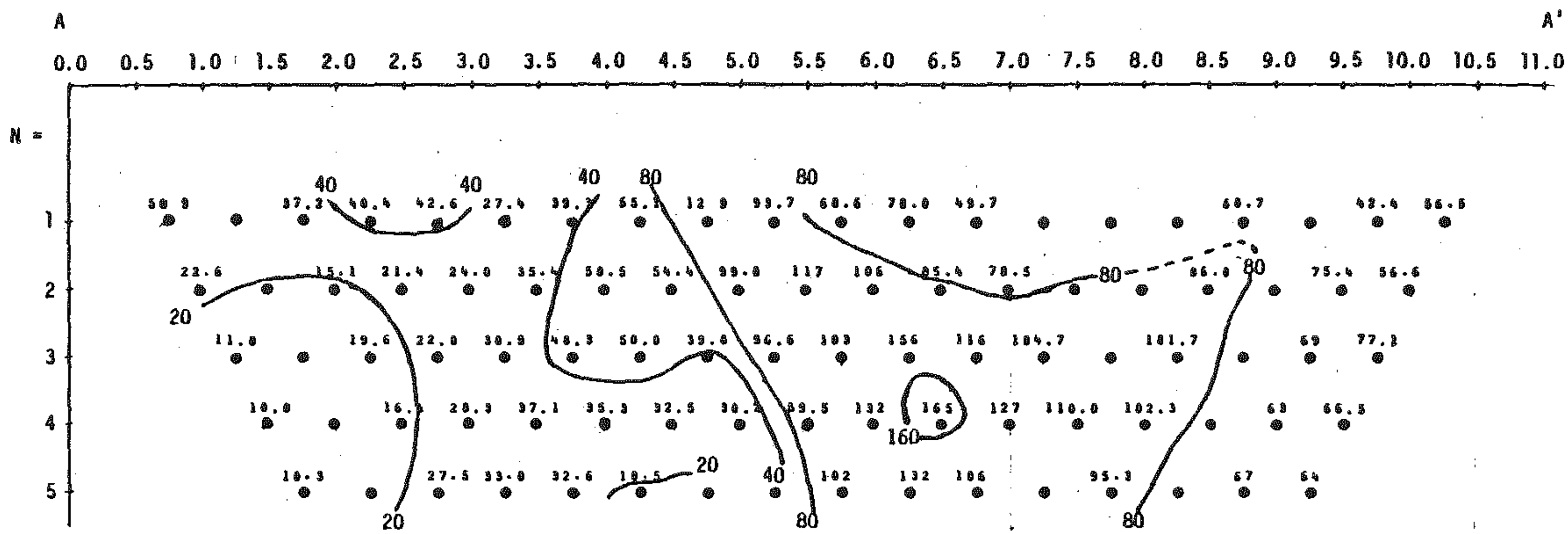

Figure 2. Pseudosection for line AA'. Dipole length was 0.5 km. Resistivities are in ohm-meters. The vertical scale is exaggerated by a factor of two.

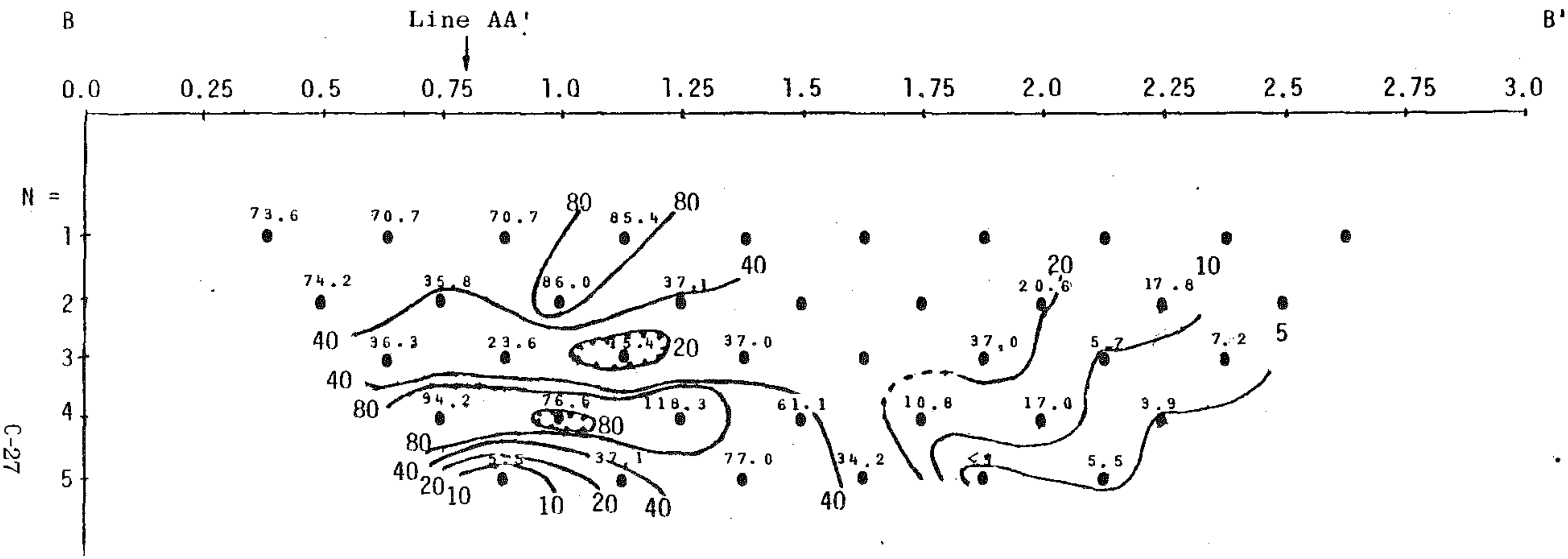

Figure 3. Pseudosection for line BB'. Dipole length was 0.25 km

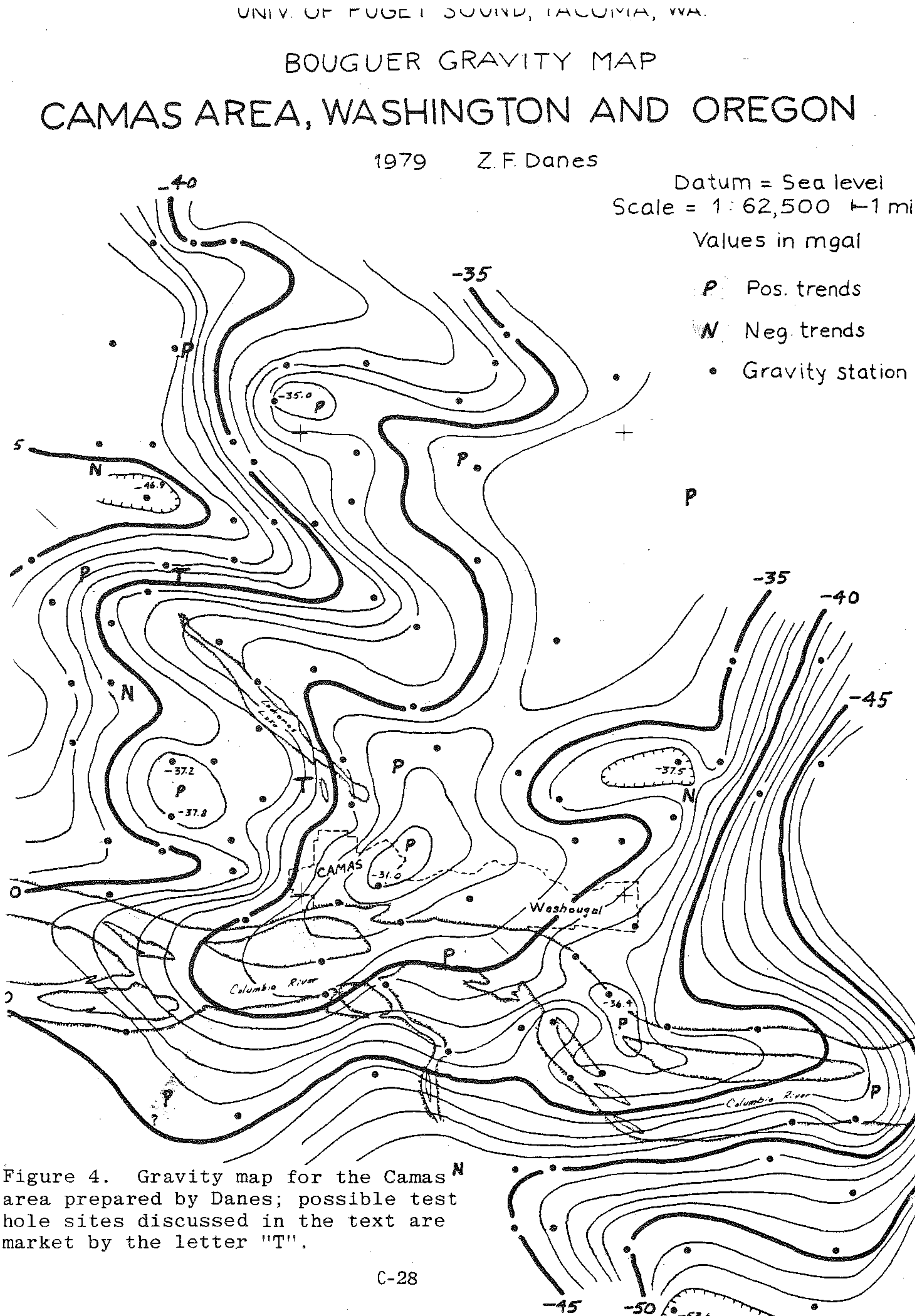

Figure 4. Gravity map for the Camas area prepared by Danes; possible test hole sites discussed in the text are market by the letter "T".

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DIVISION OF GEOLOGY AND EARTH RESOURCES

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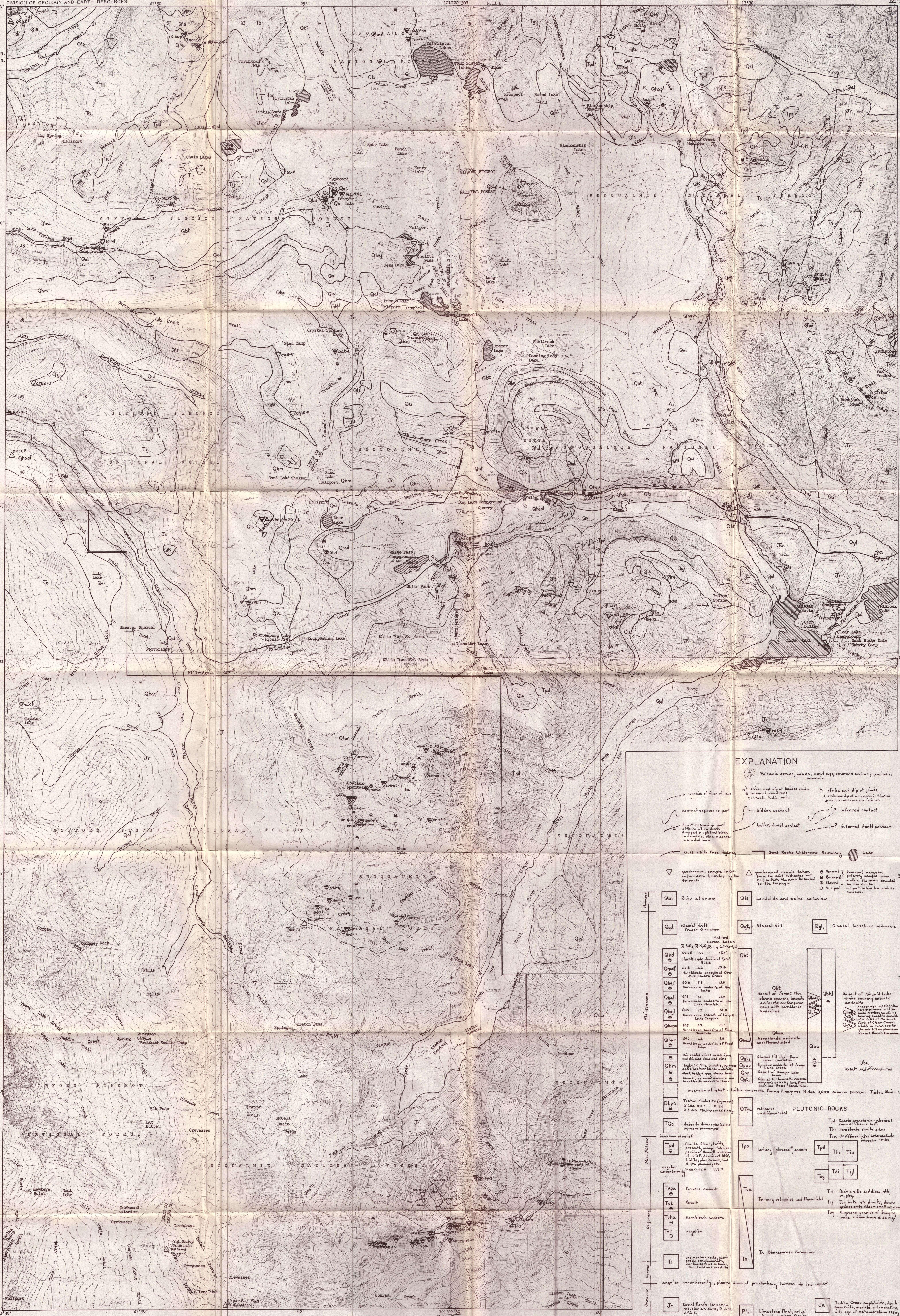

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