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THE 1980–1982 GEOTHERMAL RESOURCE ASSESSMENT PROGRAM IN WASHINGTON

By
Michael A. Korosec
William M. Phillips
J. Eric Schuster

August 1983

Work Performed Under Contract No. AC07-79ET27014

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

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THE 1980-1982 GEOTHERMAL RESOURCE ASSESSMENT PROGRAM IN WASHINGTON

by

Michael A. Korosec, William M. Phillips, and J. Eric Schuster

with contributions from

Z.F. Danes, J.H. Biggane, P.E. Hammond,

and G.A. Clayton

With chapters on
thermal springs, gravity investigations,
heat-flow drilling, low-temperature resources
in eastern Washington, geology of the south Cascades
and White Pass areas, and targets for geothermal
resource exploration

Washington State Department of Natural Resources

Division of Geology and Earth Resources

Olympia, Washington 98504

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by

Michael A. Korosec and J. Eric Schuster

Department of Natural Resources

Division of Geology and Earth Resources

Olympia, Washington

1. INTRODUCTION

by

Michael A. Korosec and J. Eric Schuster

Since 1978, the Division of Geology and Earth Resources of the Washington Department of Natural Resources has participated in the U.S. Department of Energy's (USDOE) State-Coupled Geothermal Resource Program. Federal and state funds have been used to investigate and evaluate the potential for geothermal resources, on both a reconnaissance and area-specific level. Preliminary results and progress reports for the period up through mid-1980 have already been released as a Division Open File Report (Korosec, Schuster, and others, 1981). Preliminary results and progress summaries of work carried out from mid-1980 through the end of 1982 are presented in this report.

Only one other summary report dealing with geothermal resource investigations in the state has been published. An Information Circular released by the Division (Schuster and others, 1978) compiled the geology, geochemistry, and heat flow drilling results from a project in the Indian Heaven area in the south Cascades.

The previous progress report for the geothermal program (Korosec, Schuster, and others, 1981) included information on temperature gradients measured throughout the state, heat flow drilling in the southern Cascades, gravity surveys for the southern Cascades, thermal and mineral spring investigations, geologic mapping for the White Pass-Tumac Mountain area, and area specific studies for the Camas area of Clark County and Mount St. Helens. This work, along with some additional studies, led to the compilation of the Geothermal Resources of Washington map (Korosec, Kaler, and others, 1981). The map is principally a nontechnical presentation based on all available geothermal information, presented as data points, tables, and text on a map with a scale of 1:500,000.

This report contains additional information on projects that were active before mid-1980, previously discussed in Korosec, Schuster, and others, 1981, and includes several new projects. In Chapter 3, new chemical analyses are listed, and detailed reports discuss eleven individual spring systems. Water sample collection and analyses were carried out by Division staff. In addition, all available U.S. Geological Survey spring chemistry for Washington has been compiled.

Chapters 4 and 5 discuss progress on the regional gravity survey for the entire Cascade Range of Washington, and present some preliminary interpretations for the south Cascades. The data were collected by Z. Frank Danes, of Danes Research Associates and the University of Puget Sound, and the interpretations were made by the Division staff.

In Chapter 6, preliminary results of the heat flow drilling project are summarized and discussed. Eleven holes were drilled during the Summer of 1981 by Ponderosa Drilling Company of Spokane, under contract to the Division. Temperature gradient measurements and geologic summaries were made by Division staff, and thermal conductivities were measured out by D. D. Blackwell, Southern Methodist University (SMU). In addition, temperature gradients and a brief discussion of the three holes drilled by the City of North Bonneville are included.

Chapter 7 reports on the low temperature geothermal resources of the Columbia Basin and surrounding regions of Eastern Washington. The data were collected from a number of sources. The newest data came from John Kane, working for the Division, and from two students working for David D. Blackwell (SMU), Sherri Kelley and Walter Barker. The SMU work was also supported by the USDOE Geothermal Program. The data manipulation and interpretations discussed in the chapter were carried out by Division staff.

Chapter 8 is a progress report on Paul Hammond's time-space-composition modeling project for the south Cascades Quaternary volcanics. Hammond, from Portland State University, is working on a subcontract from the Division, which is scheduled to conclude by mid-1983.

Chapter 9 is a summary of the work and findings for the White Pass-Tumac Mountain-Bumping Lake area geologic mapping project. The work, carried out by Geoff Clayton through a subcontract from the Division (from mid-1979 through early 1982), was included in a Master of Science thesis from the University of Washington (1982).

Chapter 10 is also a synopsis of a Master of Science thesis. From mid-1980 through mid-1981, John Biggane worked at Washington State University on geohydrologic studies and modeling of thermal aquifers in the Yakima Valley area. The work was sponsored through a subcontract from the Division.

Chapter 11 discusses the progress made on regional and area-specific studies over the past few years and suggests some directions for future work needed to more completely understand the potential of the state's geothermal resources.

The final chapter consists of a bibliography of geothermal resources information for the State of Washington. The list of publications is only a partial bibliography, meant to serve as an addition to the geothermal resource bibliography presented as an appendix in a previous geothermal program report (Korosec, Schuster, and others, 1981).

The references mentioned in this introduction are listed in the Bibliography in Chapter 2.

2. GEOTHERMAL PROGRAM PUBLICATIONS

Work conducted under the 1980-1981 Geothermal Assessment Program led to the release of the following publications. Portions of this report have been taken directly from several of these publications.

BIBLIOGRAPHY

Biggane, J. H., 1981, The low temperature geothermal resource of the Yakima region--A preliminary report: Washington Division of Geology and Earth Resources Open-File Report 81-7, 70 p., 3 plates.

Biggane, J. H., 1982, The low temperature geothermal resource and stratigraphy of portions of Yakima County, Washington: Washington State University M.S. thesis, 126 p., 11 tables, 4 plates, 58 figures.

Blackwell, D. D.; Steele, J. L.; Korosec, M. A., 1980, The regional thermal setting of the Mount St. Helens volcano : (abstract) EOS (American Geophysical Union, Transactions), v. 61, no. 46, p. 1132.

Clayton, G., 1982, Pliocene and Pleistocene volcanism in the White Pass Area, South Cascade Range, Washington, and its implications for models of subduction beneath the southern Washington Cascades: (abstract) EOS, v. 63, no. 8, p. 175.

Clayton, G., 1982, Geology of the White Pass area, Washington: University of Washington M.S. thesis, 190 p., 1 map, scale 1:24,000.

Danes, Z. F., 1981, Preliminary Bouguer gravity map, southern Cascade Mountains area, Washington: Washington Division of Geology and Earth Resources Open-File Report 81-4, scale 1:250,000.

Korosec, M. A., 1982, Table of chemical analyses for thermal and mineral spring and well waters collected in 1980 and 1981: Washington Division of Geology and Earth Resources Open-File Report 82-3, 5 p.

Korosec, M. A.; Kaler, K. L.; Schuster, J. E.; Bloomquist, R. G.; Simpson, S. J.; Blackwell, D. D., 1981, Geothermal resources of Washington: Washington Division of Geology and Earth Resources Geologic Map GM 25, 1 sheet, map scale 1:500,000.

Korosec, M. A., and Phillips, W. M., 1982, WELLTHERM: Temperature, depth, and geothermal gradient data for wells in Washington State: Washington Division of Geology and Earth Resources Open-File Report 82-2, 3 sheets, 1 table.

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

Korosec, M. A.; Schuster, J., with Blackwell, D. D.; Danes, Z.; Clayton, G. A.; Rigby, F. A.; and McEuen, R. B., 1981, The 1979-1980 geothermal resource assessment program in Washington: Washington Division of Geology and Earth Resources Open-File Report 81-3, 270 p., 1 map, scale 1:24,000.

Schuster, J. E., 1980, Geothermal energy potential of the Yakima Valley area, Washington. In Bloomquist, R. G., editor, 1980, Proceedings of the Geothermal Symposium; Low temperature utilization, heat pump applications, district heating: Washington State Energy Office WAOENG-81-05, section XI.

Schuster, J. E., 1981, A geothermal exploration philosophy for Mount St. Helens (and other Cascade Volcanoes?). In Ruscetta, C. A.; Foley, Duncan, editors, 1981, Geothermal direct heat program, Glenwood Springs Technical Conference proceedings; Volume I, Papers presented, State coupled geothermal resource assessment program: University of Utah Research Institute Earth Science Laboratory ESL-59 and DOE/ID/12079-39, p. 297-300.

Schuster, J. E.; Korosec, M. A., 1980, The Washington State geothermal resources assessment program of the Department of Natural Resources, Division of Geology and Earth Resources. In Bloomquist, R. G., editor, 1980, Proceedings of the Geothermal Symposium; Potential, legal issues, economics, financing, June 2, 1980, Seattle, Washington: Washington State Energy Office WAOENG-80-16, section III.

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

3. SURVEYS AND GEOCHEMICAL ANALYSES OF THERMAL AND MINERAL SPRINGS AND WELLS IN WASHINGTON, 1980-1981

by

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3. SURVEYS AND GEOCHEMICAL ANALYSES OF THERMAL AND MINERAL SPRINGS AND WELLS IN WASHINGTON, 1980-1981

by

Michael A. Korosec

Introduction

During the 1980 and 1981 field seasons, 32 water samples from 20 different thermal and mineral springs and wells were collected. Nearly all of the sampled springs are located in the south and central Cascades, and most of the sampled wells are in the Columbia Basin of eastern Washington.

Analyses of some of the springs have appeared in previous publications, including Campbell and others (1970) and Schuster and others (1978). Because of the age of most of these analyses, and the great discrepancies between results from different labs for the same spring, the quality and validity of these older analyses is suspect. As a result, it is planned that all thermal and mineral springs throughout the state will eventually be resampled and analyzed as part of the Geothermal Assessment Program.

One exception to this problem of quality is the very credible analyses performed by the U.S. Geological Survey (USGS) water chemistry lab at Menlo Park, California. As a result, there is less of a need to resample springs for which USGS analyses exist. A comparison of analyses for water from the same springs and in one case, a split of the same water sample, conducted in the USGS and Division Labs, showed relatively good agreement for all major cations and anions examined.

In this report, all available USGS analyses, analyses previously reported in Korosec and others, 1981, and new chemical analyses are included in the data tables. In addition, 9 spring systems are described in greater detail. The separate reports on each of these spring systems include geothermal features, geology, and available heat flow information.

Methods

At each spring or well, three water samples were collected, including unfiltered, filtered, and filtered-acidified waters. Filtered samples were collected by taking up water in a 50ml plastic syringe and passing it through a 0.4 micron Nuclepore filter, held in a 47 mm Swin-Lok membrane holder. One liter collapsible plastic containers (Cubi-tainers) were used to carry the water. The acidified samples were treated by adding about 3 ml of concentrated nitric acid (with a plastic syringe) to about 1 liter of filtered water.

In the field, temperature, pH, conductivity, and alkalinity were measured directly from the spring or well. 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 about 90°C. Conductivity was measured with a Hach Mini Conductivity Meter model 17250, with built-in temperature compensator. The pH was determined using a combination of ColorpHast Indicator Sticks (+/- 0.2 pH units), portable VWR Mini-pH-Meter (+/- 0.05 pH units) and portable Cole-Palmer Digi-Sense pH Meter (+/- 0.02 pH units). Where wide discrepancies existed between different techniques, the pH was remeasured in the lab as soon as possible (within 2 or 3 days) with an Orion 901 Specific Ion Meter. Alkalinity was determined using a portable kit form Hach with a digital titrator, titrating to color determined end points (Phenolphthalein and Brom Cresol Green -- Methyl Red indicators).

At the Division of Geology and Earth Resources water chemistry lab, the following methods were used:

Cl^-, Br^- F^-	Specific Ion Electrodes and Orion Specific Ion Meter 901
$Si0_2$	Molybdosilicate colorimetric technique with sulfite reduction: Bausch and Lomb Spectronic 710
$S0_4^{-2}$	Turbimetric using Hach Sulfa IV powder pillows and Bausch and Lomb Spectronic 710 (at 450 nm).
Na, K, Ca, Li	Varian AA575 ABQ Atomic Absorption Spectrometer using air-acetylene flame.
Ca, Mg, Fe	Varian AA575 ABQ Atomic Absorption Spectrophotometer using nitrous oxide-acetylene flame.

Results

Spring chemistry results are presented in a series of tables. Within the tables, waters are identified by a three-letter and one-number code. The first two letters are an abbreviation of the common name of the spring or well. The third letter refers to a specific spring within a family of springs. The relative locations of these "sub-springs" are described in the sections on individual spring systems in this publication and a previous geothermal assessment report (Korosec, and others, 1981). The number identifies samples from the same spring or well that were collected at different times. Table 3-1 lists the spring and well identification abbreviations used in the table of chemical analyses.

The results of spring and well geochemical analyses for 1980 and 1981 are presented in Table 3-2. An explanation of the abbreviations and units is included at the end of the table.

Table 3-3 contains analyses conducted by the Division in the past. They have been previously presented in Korosec and others, (1981).

Table 3-4 also contains analyses for Washington springs previously presented in Korosec and others, (1981), but the analyses were conducted by Battelle Northwest Labs. The water had been collected by the Division staff in 1978 and 1979.

Table 3-1. Abbreviations used for identification of thermal and mineral springs and wells.

Code	Spring Name	Data Sample Collected
AHA-1	Ahtanum Soda Springs	8-3-81
BHW-1	Block House Mineral Well	8-19-81
BKA-1	Baker Hot Springs	8-78
BKB-1	Baker Hot Springs	8-78
BRA-1	Bumping River Soda Spring	7-20-81
BVDH-1	Bonneville Drill Hole	5-21-81
BVDH-2	Bonneville Drill Hole	7-11-81
BVA-2	Bonneville Hot Springs	8-30-79
BVA-3	Bonneville Hot Springs	9-11-81
BVB-2	Bonneville Hot Springs	8-30-79
CSA-1	Corbett Station Warm Spring (OR)	10-6-78
EPW-1	Ephrata City Well	3-12-81
FGA-1	Flaming Geyser Mineral Spring	9-15-81
FGW-1	Flaming Geyser Mineral Well	9-15-81
GEA-1	Goose Egg Soda Springs	6-22-79
GMA-1	Goldmeyer Hot Springs	8-2-81
GMB-1	Goldmeyer Hot Springs	8-2-81
GMC-1	Goldmeyer Hot Springs	8-2-81
GMD-1	Goldmeyer Hot Springs	8-2-81
GVA-1	Government Mineral Springs (Iron Mike Well)	3-17-81
KLA-1	Klickitat Mineral Springs	8-20-81
KLB-1	Klickitat Mineral Springs	8-21-81
KLC-1	Klickitat Mineral Springs	8-21-81
KLDH-1	Klickitat Drill Hole	8-18-81

Code	Spring Name	Data Sample Collected
KNB-1	Kennedy Hot Springs	8-25-78
KNC-1	Kennedy Hot Springs	8-25-78
KND-1	Kennedy Hot Springs	8-25-78
LMA-1	Longmire Mineral Springs	7-10-79
LMB-1	Longmire Mineral Springs	7-10-79
LMC-1	Longmire Mineral Springs	7-10-79
LMD-1	Longmire Mineral Springs	7-10-79
LME-1	Longmire Mineral Springs	7-10-79
LMF-1	Longmire Mineral Springs	7-10-79
LMG-1	Longmire Mineral Springs	7-10-79
LMB	Longmire Mineral Springs	8-78
LSA-1	Lester Hot Springs	8-9-79
LSB-1	Lester Hot Springs	8-9-79
LSC-1	Lester Hot Springs	8-9-79
LSD-1	Lester Hot Springs	8-9-79
LSE-1	Lester Hot Springs	8-9-79
LSF-1	Lester Hot Springs	8-9-79
LTA-1	Little Soda Springs	3-17-81
MCA-1	Medicine Creek Mineral Spring	9-8-79
MPW-1	Miocene Petroleum Well	8-4-81
NSA-1	Newskah Mineral Springs	8-79
NSB-1	Newskah Mineral Springs	8-79
OCA-1	Orr Creek Warm Springs	8-7-79

Table 3-1. -Cont.

Code	Spring Name	Data Sample Collected
OHA-1	Ohanapecosh Hot Springs	8-7-79
OHB-1	Ohanapecosh Hot Springs	8-7-79
OHC-1	Ohanapecosh Hot Springs	8-7-79
OHD-1	Ohanapecosh Hot Springs	8-7-79
OHE-1	Ohanapecosh Hot Springs	8-7-79
OHF-1	Ohanapecosh Hot Springs	8-7-79
OHG-1	Ohanapecosh Hot Springs	8-7-79
OHH-1	Ohanapecosh Hot Springs	8-7-79
OLA-1	Olympic Hot Springs	9-78
OLB-1	Olympic Hot Springs	9-78
RCA-1	Rock Creek Hot Springs	8-28-81
SBA-1	Studebaker Mineral Springs	9-16-79
SBB-1	Studebaker Mineral Springs	9-16-79
SCA-1	Summit Creed Soda Springs	7-16-79
SCB-1	Summit Creek Soda Springs	7-16-79
SD1	Sol Duc Hot Springs	8-78
SD2	Sol Duc Hot Springs	8-78
SDA-1	Sol Duc Hot Springs	4-12-79
SDB-1	Sol Duc Hot Springs	4-12-79
SDC-1	Sol Duc Hot Springs	4-12-79
SDD-1	Sol Duc Hot Springs	4-12-79
SEA-1	Scenic Hot Springs	6-24-81
SEB-1	Scenic Hot Springs	6-24-81
SEC-1	Scenic Hot Springs	6-24-81
SED-1	Scenic Hot Springs	6-24-81

Code	Spring Name	Data Sample Collected
SEA-GT	Scenic Hot Springs	8-1-80
SEA-2	Scenic Hot Springs	9-25-81
SED-2	Scenic Hot Springs	9-25-81
SFA-1	Sulphur Creek Hot Springs	8-23-78
SMA-1	St. Martins Hot Springs	9-20-78
SMA-2	St. Martins Hot Springs	6-10-81
SPA-1	Shipherds Hot Springs	3-17-81
SRA-1	Suiattle River Mineral Seep	8-23-78
TWDH-1	Tieton Willows Drill Hole	7-30-81
YMW-1	YMCA Warm Well (Oregon)	10-6-78

TABLE 3-2. — CHEMICAL ANALYSES FOR THERMAL AND MINERAL SPRING AND WELL WATERS COLLECTED IN 1980 AND 1981*

Spring Identification Code	umhos/cm Cond	pH	T(°C)	ppm													
						Alk											
				Cl	SO_4	P	B	Total	SiO_2	Na	K	Ca	Mg	Li	F	Br	Fe
AHA-1	1,100	5.6	12.6	5.6	7	0	650	650	107	83	10.6	73	60	LD	0.2	0.2	47
BHW-1	710	6.4	12.4	4.7	3	0	360	360	100	45	6.0	40	52	0.1	0.6	0.15	4
BRA-1	2,750	6.0	9.7	210	10	0	1570	1570	104	290	5.0	386	63	0.6	1.0	2.5	16
BVA-3	790	9.9	36.3	187	72	-	-	-	50	134	1.0	30	LD	LD	0.6	2.2	LD
BVCH-1	2,800	11.6	27.7	238	92	257	8	265	26	162	2.6	197	LD	LD	0.4	3.2	LD
BVCH-2	1,150	10.9	28.2	238	91	-	-	-	38	155	1.2	62	LD	LD	0.6	2.7	LD
EPW-1	265	-	-	5.8	17	-	-	-	64	27	4.7	19	12	LD	0.5	0.08	LD
FGA-1	180	8.5	10.1	3.1	LD	0	93	93	35	16	1.4	18	11	LD	0.1	0.07	LD
FGW-1	29,000	7.0	12.1	5460	LD	0	1850	1850	12	4150	34	34	27	0.5	2.4	44	LD
GMA-1	600	8.8	47.5	140	46	-	-	-	61	122	3.0	6.2	LD	0.2	0.8	1.8	LD
GMC-1	630	8.8	49.6	137	41	-	-	-	62	119	2.8	6.3	LD	0.2	0.9	1.8	LD
GMD-1	580	8.8	45.3	132	42	-	-	-	59	117	2.7	6.9	LD	0.2	0.8	1.7	LD
GVA-1	3,900	6.0	6.7	640	120	0	1000	1000	68	420	9.0	268	91	0.9	0.05	7.0	15
KLA-1	540	6.3	22.3	4.1	5	0	340	340	110	40	4.6	40	48	0.1	0.9	0.09	5.4
KLB-1	1,500	6.2	26.2	4.6	9	0	860	860	150	68	10.4	118	115	0.1	0.4	0.11	13
KLC-1	1,200	6.2	29.1	4.7	9	-	-	-	147	62	9.5	99	100	0.2	0.3	0.12	12
KLDH-1	1,200	5.8	13.5	2.5	11	-	-	-	114	41	5.7	94	101	0.1	0.5	0.08	22
LTA-1	4,000	6.0	7.7	48	57	0	1350	1350	47	310	3.5	218	200	LD	0.06	6.0	1.6
MPW-1	555	9.3	31.7	88	2	19	101	120	120	123	17.5	2.8	LD	LD	21	0.11	LD
RCA-1	400	9.7	33.5	85	40	4	31	35	41	80	0.1	11.5	LD	LD	0.7	1.2	LD
RCA-2	400	9.3	33.4	85	40	4	35	39	-	-	0.1	11.5	LD	LD	0.7	1.1	LD
SEA-GT	220	9.6	47	24	14	-	-	-	48	50	0.4	2.2	LD	LD	0.9	0.57	LD
SEA-1	180	9.3	39.2	18	14	9	43	52	41	40	0.5	2.3	LD	LD	0.7	0.29	LD
SEA-2	-	-	46.5	23	18	-	-	-	49	51	0.7	2.1	LD	LD	0.8	0.37	LD
SEB-1	200	9.4	42.4	21	16	11	43	54	46	46	0.5	1.9	LD	LD	0.8	0.34	LD
SEC-1	140	9.3	28.2	14	13	6	44	50	37	32	0.5	2.1	LD	LD	0.6	0.26	LD
SED-1	170	9.3	31.0	16	13	7	44	51	38	35	0.5	3.5	0.1	LD	0.6	0.32	LD
SED-2	-	-	32.7	18	15	-	-	-	40	40	1.0	3.5	0.1	LD	0.6	0.31	LD
SMA-2	2,200	8.5	50.0	680	16	0	22	22	51	325	5.2	68	0.4	0.4	0.6	7.3	LD
SPA-1	220	8.5	40.8	38	12	13	30	43	47	43	LD	4.2	0.1	LD	0.4	0.6	LD
TWDH-1	-	-	18	-	6	-	-	-	53	50	1.2	10	5	LD	-	-	4
YKW-1	215	-	28.3	4.5	2	-	-	-	23	52	0.5	1.8	LD	LD	1.2	0.2	LD
BKA-1	820	7.9	42	-	90	-	-	-	-	174	11	5.7	0.1	0.5	-	-	LD
BKB-1	780	8.0	40	-	78	-	-	-	-	154	9	5.8	0.2	0.4	-	-	LD
KNB-1	-	8.2	-	-	LD	-	-	-	-	670	70	185	67	3.9	-	-	7.2
KND-1	3,200	8.2	-	-	LD	-	-	-	-	700	73	197	74	4.1	-	-	7.5
Detection Limit				1	2	1	1	1	1	1	0.1	0.02	0.1	0.1	0.02	0.05	0.5

*Table explanation on following page.

Table 3-2 Explanation

The table of chemical analyses, includes conductivity (Cond), pH, temperature (Temp), chloride (Cl), sulfate (SO_4), alkalinity (Alk), silica (SiO_2), sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), lithium (Li), flouride (F), bromide (Br), and iron (Fe). All analyses were conducted in the Division of Geology and Earth Resources' geochemistry laboratory.

(1) - Temperature is ^{o}C.

(2) - Conductivity is measured in umhos/cm.

(3) - All other analyses are listed as parts per million (ppm), approximately equivalent to milligrams per liter (mg/l).

(4) - "LD" means less than detection limit. The detection limits for the various chemical species are listed in the last row of the table.

(5) - Dashes indicate that analyses were not performed.

(6) - For alkalinity, the Phenolphthalein (P), Brom Cresol Green--Methyl Red (B), and total alkalinity (T) are listed separately and are represented as mg/l Ca CO_3.

(7) - Baker and Kennedy Hot Springs samples were collected in 1978. The results are included here because this is the first analyses of these waters by the Division.

Table 3-3 - Thermal and Mineral Spring Chemistry, 1978-1980, Analyses from Division of Geology and Earth Resources Laboratory (See Explanation for Table 3-2)

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	1.0	1.2	0.01
BVB-2	29.2	790	-	-	78	50	146		28	0.5	-	-	-
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	LD	0.35	-	-
LSE-1	45	-	-	200	-	67	98	2	12	LD	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	LD
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	LD
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	LD	-	-
NSB-1	19	390	-	-	-	52	82	-	5	1.7	LD	-	-
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	LD	29	29	9	3	LD	LD	-	-
SMA-1	32	2350	-	756	-	57	360	6	73	0.5	0.3	4.5	0.02

Table 3-3 - Thermal and Mineral Spring Chemistry, 1978-1980. Analyses from Division of Geology and Earth Resources Laboratory. (See Explanation for Table 3-2) (Continued)

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	81	1	3	LD	0.1	0.2	0.01
SDB-1	50	342	9.2	18	-	65	75	1	1	LD	0.1	0.2	0.01
SDC-1	40	345	9.2	19	-	64	79	1	1	LD	0.1	0.2	0.01
SDD-1	46	305	9.2	18	-	58	75	1	2	LD	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	LD
YMW-1	22.2	-	-	87	-	66	101	9	6	0.3	LD	0.6	LD

Table 3-4 - Thermal and Mineral Spring Chemistry, 1978-1980. Analyses from Battelle Northwest Laboratory. (See Explanation for Table 3-2)

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

Analyses for other Washington thermal and mineral springs conducted by the U.S. Geological Survey are listed in Table 3-5. Sources include the published reports by Newcomb (1972) and Cline (1976) and open file information from R. Mariner and I. Barnes.

Table 3-6 is a list of all springs in tables 3-2, 3-3, 3-4, and 3-5, with temperature information and the results of applied geothermometers. The references for equations used to calculate these predicted reservoir equilibrium temperatures are listed in the next section (see Discussion).

All known thermal and mineral springs in Washington State are listed in Table 3-7. All available information on maximum temperature, conductivity, estimated flow, and location for each of the systems has been included.

Figure 3-1 is a tri-linear plot of percentage reacting anions, divided into bicarbonate, chloride, and sulfate.

Discussion

Most of the discussion of geochemical results is presented in the section on individual spring systems. Table 3-6 summarizes much of the data manipulation, including the results of various geothermometers. Many assumptions are made when applying various geothermometers. Any reader unfamiliar with the assumptions and limitations of geothermometers should consult the references before relying on the results. Formulas used to calculate the geothermometer values from chemical concentrations are as follows:

Silica - Quartz

$$T_Q = \frac{1309}{5.19 - \log(SiO_2)} - 273$$

Chalcedony

$$T_C = \frac{1032}{4.69 - \log(SiO_2)} - 273$$

Na/Li

$$T_{Li} = \frac{1000}{\log(Na/Li) - 0.14} - 273$$

Na-K-Ca

$$T_{Cat} = \frac{1647}{\log(Na/K \times 1.7) + 1/3 \log(115\ Ca/Na) + 2.24)} - 273$$

Magnesium Correction

$$T_{Mgc} = 1066 - 4.7415(R) + 325.87(\log R)^2 - 1.032 \times 10^5 (\log R)^2/T$$
$$- 1.968 \times 10^7 (\log R)^2/T^2 + 1.605 \times 10^7 (\log R)^3/T^2$$

Where T = Temperature in ^{o}K from Na-K-Ca geothermometer ($T_{Cat} + 273^{o}$)

$$R = \frac{3134(Mg)}{9.74(K) + 19.01(Ca) + 31.34(Mg)}$$

Na-K-Ca-Mg

$$T_{Mg} = T_{Cat} - T_{Mgc}$$

Table 3-5. - USGS Analyses of Washington Thermal and Mineral Springs

Part 1. Analyses from Robert Mariner, U.S. Geological Survey, for samples collected from 1977 to 1980.

Spring Name	T	pH	Cl	Alk	SO_2	SiO_2	Na	K	Ca	Mg	Li	F	B	Fe
Kennedy	35	6.27	625	1660	2	175	670	72	190	48	3.5	1.2	7.5	3.0
Garland	29	6.46	3600	2600	160	105	2500	200	390	87	9.4	1.6	64	5.4
Ohanapecosh	48	6.8	880	1060	170	100	920	52	60	4.9	2.9	5.2	12	0.04
Longmire	19	6.35	810	2700	41	125	580	46	540	170	2.2	0.4	3.7	11
Bumping R.	5	6.22	190	1910	1	95	290	5.2	380	52	0.40	1.2	2.2	15
Goose Egg	10	6.25	150	1530	2	92	260	9.2	170	100	0.04	0.15	0.16	18
Summit Cr.	11	6.24	1450	1610	LD	100	1750	85	240	93	5.8	0.24	50	—
Klickitat	22	5.89	4.2	1070	2	140	64	10	120	100	—	0.34	LD	—
Green R.	10	6.58	1250	2715	2	94	1350	79	220	93	—	0.45	28	—
Pigeon	8	8.34	22000	18	280	9.2	6100	—	7100	5.5	—	—	3.0	—
Gov. Bubbling Mike	15	6.41	820	1610	170	75	585	14	360	100	1.0	.16	21	0.06
Gov. Iron Mike Well	18	6.01	570	1250	120	65	420	9.1	260	80	.76	.12	15	13
Gov. Iron Mike Well	6	5.97	550	1230	120	64	420	9	260	75	—	.12	15	—
Gov. Iron Mike Well	—	—	575	—	130	—	—	—	295	76	—	—	17	—
Green River BN	—	6.47	1250	1585	1	96	1320	90	286	24	3.3	.42	25	.25

Table 3-5 - USGS Analyses of Washington Thermal and Mineral Springs

Part 2. Analyses reported in Newcomb (1972)

Spring Name	T	Cl	Alk	SO_4	SiO_2	Na	K	Ca	Mg	Li	F	Br	B	Fe
Klickitat Mineral Well	27	6.4	1060	3.4	129	63	10	120	106	—	0.4	—	—	11
Klickitat Mineral Well	23	3.2	284	0.0	89	30	—	27	25	—	1.1	—	—	2.8

Part 3. Analyses reported in Cline (1976)

Spring Name	T	Cl	Akl	SO_4	SiO_2	Na	K	Ca	Mg	Li	F	Br	Fe
Fish Hatchery Warm	23.8	49	1130	2.6	—	160	16	110	95	—	0.4	—	2.2
McCormick Soda	9.5	150	806	2.6	—	130	2.2	120	78	—	0.2	—	19
Klickitat Meadow Soda	13.8	1.0	279	0.8	—	100	3.5	2.7	0.4	—	0.5	—	0.07
Castile Soda	12.2	92	951	2.2	—	150	16	97	86	—	0.3	—	23

Table 3-6. — Predicted reservoir equilibrium temperatures from selected Washington springs and wells. (See text for explanation)

	Name	Temp.(°C)	Na-K-Ca	Mg-Corr.	Mg-Corr. Na-K-Ca	Na/Li	SiO_2 Quartz	SiO_2 Chalc.
Part 1. Division of Geology Spring Chemistry								
AHA-1	Ahtanum Soda	12.6	170	159	11	-	141	115
BHW-1	Blockhouse Well	12.4	166	163	4	125	137	111
BKA-1	Baker	42.0	168	0	168	143	-	-
BKA-1	Baker	42.0	170	0	170	125	150	125
BKB-1	Baker	40.0	169	7	162	116	131	104
BKB-1	Baker	40.0	162	1	161	136	-	-
BRA-1	Bumping River Soda	9.7	91	5	85	120	138	112
BVA-2	Bonneville	36.2	65	0	65	53	102	72
BVA-3	Bonneville	36.3	69	0	69	-	102	72
BVB-2	Bonneville	29.2	-	-	-	-	102	72
BVDH-1	Bonneville	27.7	85	0	85	-	74	42
BVDH-2	Bonneville	28.2	68	0	68	-	85	59
EPW-1	Ephrata Well	32.0	178	159	19	-	114	85
FGA-1	Flaming Geyser	10.1	145	126	19	-	86	55
FGW-1	Flaming Geyser	12.1	111	82	29	8	45	13
GEA-1	Goose Egg Soda	9.5	124	98	26	-	137	111
GMA-1	Goldmeyer	47.5	119	0	119	105	111	82
GMC-1	Goldmeyer	49.6	117	0	117	107	112	83
GMD-1	Goldmeyer	45.3	115	0	115	108	110	80
GVA-1	Government	6.7	105	57	48	122	117	88
KLA-1	Klickitat Mineral	22.3	157	152	5	133	143	117
KLB-1	Klickitat Mineral	26.2	171	165	7	98	162	138
KLC-1	Klickitat Mineral	29.1	171	165	6	152	160	136
KLDH-1	Klickitat D/Hole	13.5	160	154	6	131	145	119
KNB-1	Kennedy	-	188	141	47	204	-	-
KNB-1	Kennedy	38.0	221	155	66	208	173	151
KND-1	Kennedy	38.0	222	156	66	215	173	151
KND-1	Kennedy	-	188	143	45	205	-	-
LMA-1	Longmire	22.0	164	120	44	164	144	118
LMB-0	Longmire	13.0	215	158	57	122	-	-
LMB-1	Longmire	13.3	143	102	41	118	81	50
LMC-1	Longmire	25.1	162	-	-	164	157	133
LMD-1	Longmire	11.2	162	92	70	173	126	99
LME-1	Longmire	11.0	161	101	60	177	136	109
LMF-1	Longmire	19.1	160	111	49	163	152	126
LMG-1	Longmire	22.0	160	-	-	165	138	112

Table 3-6. — Predicted reservoir equilibrium temperatures from selected Washington springs and wells. (See text for explanation) Cont'd

Name	Temp.(°C)	Na-K-Ca	Mg-Corr.	Mg-Corr. Na-K-Ca	Na/Li	SiO_2 Quartz	SiO_2 Chalc.
	Part 1. Division of Geology Spring Chemistry						
LSA-1 Lester	48.4	122	0	122	156	116	87
LSE-1 Lester	45.0	104	0	104	156	116	87
LSF-1 Lester	45.0	119	0	119	145	115	86
LTA-1 Little Soda	7.7	80	56	24	-	99	69
MCA-1 Medicine Creek	8.7	-	-	-	176	88	57
MPW-1 Miocene Petroleum	31.7	214	0	214	-	148	122
NSA-1 Newskah	17.5	-	-	-	-	103	73
NSB-1 Newskah	19.0	-	-	-	-	104	74
OCA-1 Orr Creek	21.7	233	0	233	-	78	47
OHA-1 Ohanapecosh	39.5	165	26	139	150	141	114
OHB-1 Ohanapecosh	45.0	166	26	139	151	141	115
OHC-1 Ohanapecosh	43.6	165	27	138	157	142	115
OHD-1 Ohanapecosh	50.1	169	28	141	150	141	115
OHG-1 Ohanapecosh	47.8	168	29	139	150	141	114
OHH-1 Ohanapecosh	30.6	165	29	136	151	136	109
OLA-1 Olympic	49.0	-	-	-	-	125	97
OLB-1 Olympic	49.0	142	0	142	-	-	-
RCA-1 Rock Creek	33.5	21	0	21	-	93	62
RCA-2 Rock Creek	33.4	-	-	-	-	93	62
SBA-1 Studebaker	5.3	-	-	-	-	99	69
SBB-1 Studebaker	8.1	-	-	-	-	77	45
SCA-1 Summit Creek	11.6	156	119	37	154	139	113
SCB-1 Summit Creek	9.7	155	140	15	157	79	48
SD-1 Sol Duc	50.0	130	0	130	93	125	97
SD-2 Sol Duc	50.0	139	0	139	93	-	-
SDA-1 Sol Duc	34.0	92	0	92	88	114	85
SDB-1 Sol Duc	50.0	101	0	101	93	115	86
SDC-1 Sol Duc	40.0	99	0	99	90	114	85
SDD-1 Sol Duc	40.0	97	0	97	93	109	80
SEA-1 Scenic	39.2	86	0	86	-	93	62
SEA-2 Scenic	46.5	93	0	93	-	101	71
SEB-1 Scenic	42.4	84	0	84	-	98	68
SEC-1 Scenic	28.2	92	0	92	-	88	57
SED-1 Scenic	31.0	87	0	87	-	89	59
SED-2 Scenic	32.7	109	0	109	-	92	61
SEGT Scenic	47.0	74	0	74	-	100	70

Table 3-6. — Predicted reservoir equilibrium temperatures from selected Washington springs and wells. (See text for explanation) Cont'd

	Name	Temp.(^{o}C)	Na-K-Ca	Mg-Corr.	Mg-Corr. Na-K-Ca	Na/Li	SiO_2 Quartz	SiO_2 Chalc.
	Part 1. Division of Geology Spring Chemistry							
SFA-1	Sulphur Creek	37.0	130	0	130	76	137	111
SMA-1	St. Martins	32.0	102	0	102	67	108	79
SMA-2	St. Martins	50.0	100	0	100	88	103	73
SPA-1	Shipherds	40.8	53	0	53	-	99	69
SRA-1	Suiattle River Seep		227	3	224	172	69	37
TWA-1	Tieton Willows D/H	18.0	103	69	34	-	105	75
YKW-1	Yakima Creamery W	28.3	82	0	82	-	69	37

Table 3-6. — Predicted reservoir equilibrium temperatures from selected Washington springs and wells. (See text for explanation)

Name	Temp.(°C)	Na-K-Ca	Mg-Corr.	Mg-Corr. Na-K-Ca	Na/Li	SiO_2 Quartz	SiO_2 Chalc.
Part 2. — U.S. Geological Survey Spring Chemistry							
Baker	44.0	162	0	162	122	139	112
Bonneville	36.0	64	0	64	-	98	68
Bumping River Soda	5.0	92	0	92	95	135	108
Castile Soda	12.2	168	159	9	-	-	-
Fish Hatchery Warm	23.8	165	155	10	-	-	-
Gamma	65.0	216	18	198	199	157	133
Garland	29.0	191	110	80	165	140	114
Garland	24.0	185	104	80	163	134	107
Goldmeyer	50.0	118	0	118	-	107	78
Goose Egg Soda	10.0	122	98	23	-	133	106
Gov't Bubbling Mike	15.0	112	56	56	108	122	94
Gov't Iron Mike Well	18.0	106	53	53	111	115	86
Gov't Iron Mike Well	6.0	105	50	56	-	114	85
Gov't Iron Mike Well	-	-	-	-	-	-	-
Green River Soda	16.0	166	128	38	-	136	109
Green River Soda	10.0	168	130	37	-	134	107
Kennedy	35.0	189	121	69	194	171	149
Klickitat Meadow Soda	13.8	137	27	110	-	-	-
Klickitat Mineral Well	27.0	172	163	9	-	152	127
Klickitat Mineral Well	23.0	-	-	-	-	131	104
Klickitat Mineral Well	22.0	171	162	10	-	157	133
Little Wenatchee Ford	9.0	205	106	99	-	140	114
Little Wenatchee Soda	7.0	153	72	82	-	91	60
Longmire	19.0	161	116	46	165	150	125
McCormick Soda	9.5	87	58	29	-	-	-
Ohanapecosh	48.0	171	30	140	151	137	111
Olympic	48.5	106	0	106	-	115	86
Pigeon Mineral	8.0	-	-	-	-	37	4
Scenic	47.0	88	0	88	-	96	66
Sol Duc	51.0	101	0	101	-	111	81
St. Martins	48.0	104	0	104	64	100	70
Summit Creek Soda	11.0	162	121	42	154	137	111

Table 3.7 - Basic Data for Thermal and Mineral Springs of Washington State

COUNTY	SPRING NAME	Location T.	Location R.	Sec.	Temperature(1) °C	Estimated(2) Flow l/min	Conductivity umhos/cm
Chelan							
	Medicine Spring	26N	18E	13D	C		
	Little Wenatchee Soda Spring	27N	15E	10B	7°		
	Little Wenatchee Ford Soda Spring	28N	13E	14	9°		
Clallam							
	Olympic Hot Springs	29N	8W	28B	40°- 48°	500	320
	Sol Duc Hot Springs	29N	9W	32	23°- 50°	560	350
	Piedmont Sulfur Spring	30N	9W	11	C		
Cowlitz							
	Pigeon Springs	7N	1E	36BA	8°		
	Green River Soda Springs	10N	4E	2A	13°- 25°		
Grays Harbor							
	Newskah Mineral Springs	16N	9W	9	16°- 19°	400	400
King							
	Lester Hot Springs	20N	10E	21	40° - 49°	200	520
	Diamond Mineral Spring	21N	6E	21C	11°		

COUNTY	SPRING NAME	Location		Sec.	Temperature(1) °C	Flow 1/min	Conductivity umhos/cm
		T.	R.				
King (cont.)							
	Flaming Geyser Springs	21N	6E	27DD	12°	10	22,000
	Goldmeyer Hot Springs	23N	11E	14B	46° - 53°	500	630
	Ravenna Park Sulfur Spring	25N	4E	9	C		
	Skykomish Soda Springs	26N	11E	27B	C		
	Money Creek Soda Springs	26N	11E	30D	C		
	Scenic Hot Springs	26N	13E	28D	23° - 50°	110	200
Kitsap							
	Bremerton Sulphur Spring	24N	1E	3AD	C		
Kittitas							
	Medicine Creek Mineral Spring	21N	17E	22CD	9°	6	300
Klickitat							
	Klickitat Mineral Springs	4N	13E	23, 24	18° - 32°		1,500
	Blockhouse Mineral Springs	4N	15E	9C	12° - 16°	0 - 40	700
	Klickitat Soda Springs	5N	13E	25AD	15° - 17°		
	Fish Hatch Warm Spring	6N	13E	4AD	24°	15	1,660

COUNTY	SPRING NAME	Location T.	 R.	Sec.	Temperature(1) °C	Estimated(2) Flow l/min	Conductivity umhos/cm
Lewis							
	Vance Mineral Spring	12N	7E	22CB	C		
	Alpha Mineral Spring	13N	2E	5	C		
	Packwood Hot Spring	13N	9E	32	38°		
	Packwood Mineral Well(Spring)	13N	10E	6B	C	0	
	Ohanapecosh Hot Springs	14N	10E	4B	50°	110	4,650
	Summit Creek Soda Springs	14N	11E	18CA	12°	100	8,500
Okanogan							
	Poison Lake	39N	27E	5D	40° - 50° (?)		
	Hot Lake	40N	27E	18A	40° - 50° (?)		
Pierce							
	St. Andrews Soda Spring	15N	7E	1	C		
	Longmire Mineral Springs	15N	8E	29D	12° - 25°	250	6,500
	Mt. Rainier Fumaroles	16N	8E	23	52° - 72°		
Skamania							
	Bonneville Hot Springs	2N	7E	16C	28° - 36°	80	800
	Rock Creek Hot Springs	3N	7E	27AB	34°	20	400

COUNTY	SPRING NAME	Location T.	 R.	Sec.	Temperature(1) °C	Estimated(2) Flow l/min	Conductivity umhos/cm
Skamania (cont.)							
	St. Martin Hot Springs	3N	8E	21DD	48° - 53°	65	2,200
	Shipherds Hot Springs	3N	8E	21DB	30° - 45°	100	220
	Collins Hot Springs	3N	9E	31C	40° - 50° (?)		
	Little Soda Spring	4N	7E	5D	8°	100	4,000
	Government Mineral Springs	5N	7E	31	5° - 18°	200	3,900
	Mt. St. Helens Fumaroles	8N	5E	4	88° - 800°		
	Orr Creek Warm Springs	10N	10E	19A	19° - 22°	100	180
Snohomish							
	Garland Mineral Springss	28N	11E	25B	24° - 29°	100	
	Kennedy Hot Springs	30N	12E	1A	38°	60	3,400
	Gamma Hot Springs	31N	13E	24D	65°	15	2,800
	Suiattle River Mineral Seep	31N	15E	18A	10°	8	2,350
	Sulphur Creek Hot Springs	32N	13E	19A	37°	10	500
Walla Walla							
	Warm Springs Canyon Warm Spring	6N	32E	2D	22°		

		Location				Estimated(2)	
COUNTY	SPRING NAME	T.	R.	Sec.	Temperature(1) °C	Flow l/min	Conductivity umhos/cm
Whatcom							
	Dorr Fumarole Field	38N	8E	17BB	90°		
	Sherman Crater Fumaroles	38N	8E	19AC	90° - 130°		
	Baker Hot Springs	38N	9E	20C	40° - 44°		820
Yakima							
	Mt. Adams Fumaroles	8N	10E	1	+ 50°		
	Soda Spring Creek Soda Spring	9N	12E	35AB	C		
	Castile Soda Springs	9N	13E	18CD	12°		1,800
	McCormick Meadow Soda Springs	11N	12E	24CA	10°	8	1,500
	Klickitat Meadow Soda Springs	11N	13E	4DB	14°	25	440
	Simcoe Soda Springs	11N	15E	9C	+ 20°		
	Ahtanum Soda Springs	12N	15E	8	10° - 14°	500	1,100
	Goose Egg Soda Spring	14N	14E	33C	10°	80	2,700
	Indian Mineral Springs	15N	12E	10AA	C		
	Little Rattlesnake Soda Springs	15N	14E	34	C		
	Bumping River Soda Springs	17N	13E	34BB	10°	8	2,750

(1) The letter designation "C" indicates that the temperature of the spring is cold (less than 18° C), but an exact temperature is not known or has not been reported. When temperature ranges are reported, they may indicate that seasonal variations have been observed, that different spring orifices within the same system produce that range of temperature, or both.

(2) The flows reported are rough estimates and represent the total flow from all springs within the system.

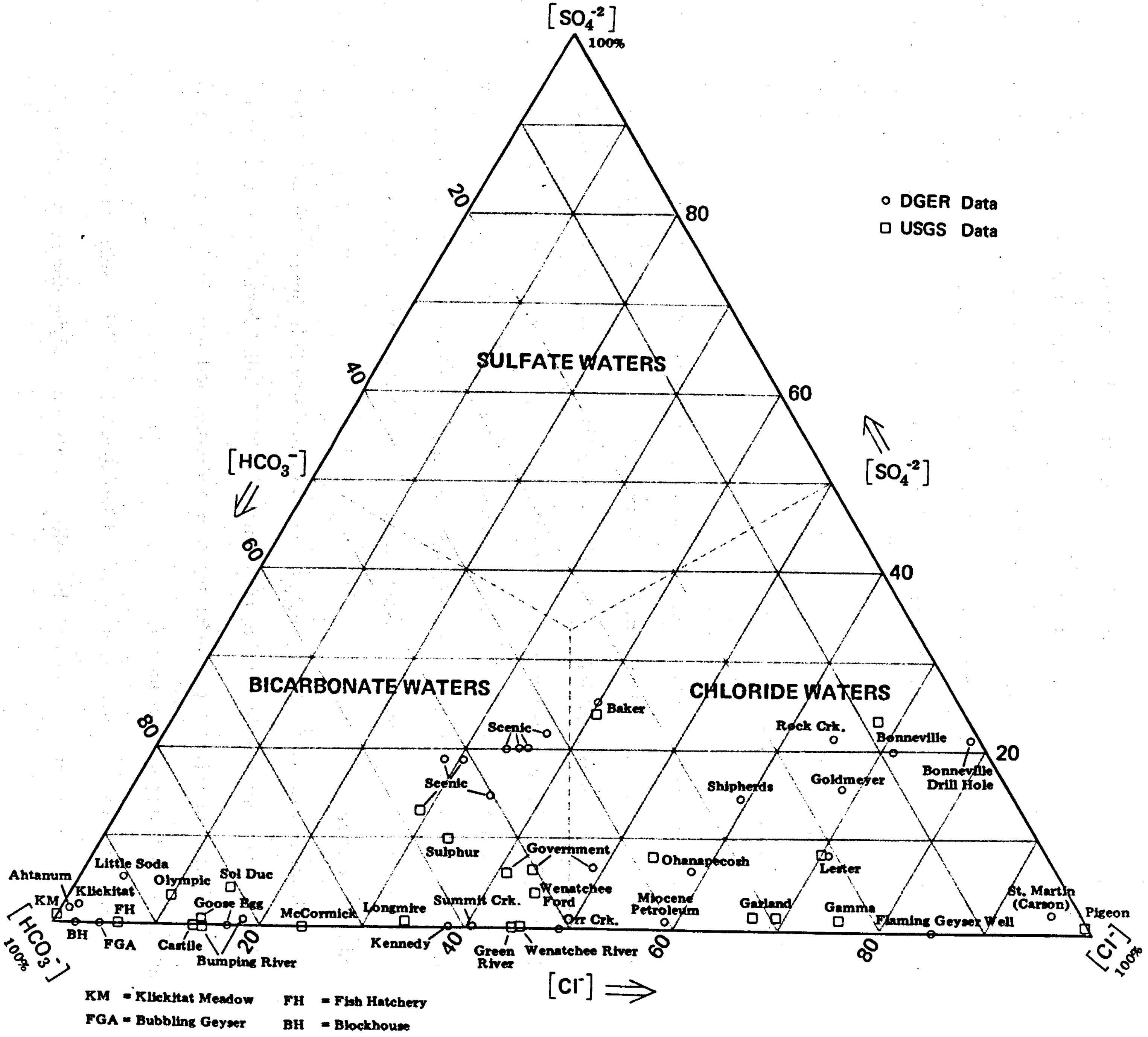

Figure 3-1. — Trilinear plot of percentage of reacting anions for thermal and mineral springs and wells of Washington.

All geothermometer temperatures are in degrees Celsius and cation concentrations are in parts per million. References for these geothermometers are listed below.

Silica-Quartz (T_q)	-	Fournier and Potter, 1979
Chalcedony (T_c)	-	Fournier and Potter, 1979
Na/Li (T_l)	-	Fouillac and Michard, 1981
Na-K-Ca (T_{cat})	-	Fournier and Truesdell, 1973
Mg correction (T_m)	-	Fournier and Potter, 1979

Individual Spring System Investigations

This section contains reports on 9 individual spring systems or groups of springs. Each report has been divided into five sections: an Introduction, which describes directions to reach the area and land ownership information; Geothermal Features, where spring statistics, chemistry, and geothermometer results are presented; Geology, where available geologic information, both regional and site specific, is summarized; Heat Flow, which discusses available information on nearby temperature gradients, thermal conductivities, and heat flow; and Comments, in which the author examines the available information and presents conjectures and interpretations.

Chemical analyses for the springs are presented in Table 3-2. The geothermometer results, listed in each individual report, are compiled in Table 3-6. Thermal conductivities are presented as W/m·K (watts per meter per degree Kelvin), and heat flows are presented as mW/m^2 (milliWatts per square meter).

Some springs are described in greater detail than others. This results from the availability of published information and the realtive time spent studying the spring systems in the field.

Ahtanum Soda Springs

T. 12 N., R. 15 E., Sec. 3, 4, 8, 9, 17, 18

Pine Mountain (1971) 7.5' U.S.G.S. Quad

The Ahtanum Soda Springs area is reached by following the Ahtanum Road (A1000) west from Union Gap, past Tampico, and along the North Fork of Ahtanum Creek on the Middle Fork Road (A2000). The area of interest is located along the North Fork of Ahtanum Creek between the mouths of two tributaries, Nasty Creek to the northeast and Foundation Creek to the southwest. The valley is a patchwork of private ownership, and the surrounding area is both state and private ownership, with checkerboard distribution.

Geothermal Features

Several hundred iron and carbon dioxide rich mineral springs and seeps flow from alluvium throughout this section of the North Fork Ahtanum River valley, with a high concentration of springs in the SW¼ of Section 8. The main spring at an old mineral water resort along the highway is actually a dug well which flows artesian. The well was sunk on the site of a preexisting spring, and was fitted with a well head, porcelain sink, faucet, and catch basin. The water has a temperature of 12.6°C, with a conductivity of 1,100 umhos/cm and a pH of 5.6 units. Analysis AHA-1 in Table 3-2 is from this well.

A 125 foot well was drilled between 1956 and 1958 on the property to the south of the old resort. Several different iron-stained soda water aquifers were encountered, according to the owner, the shallowest reached at 3 meters depth. The well still flows artesian, presumably from several of the different zones. The water has a temperature of 11.8°C. with a conductivity of 1,450 umhos/cm.

Several other springs were examined within the valley, all of which had temperatures and conductivities in the same range as those for the well.

The spring waters are CO_2 saturated bicarbonate, with very little chloride and relatively low sulfate. The silica and potassium/sodium ratio are moderately high, but so is the magnesium. The Li concentration is below the detection limit. The iron concentration, at 47 ppm, was the highest yet observed for a mineral spring in Washington. Using the analyses for sample AHA-1, geothermometers predict the following reservoir equilibrium temperatures:

Geothermometer	AHA-1
Measured Temperature	12.6°C
Na-K-Ca	170
Mg Correction	-159
Na-K-Ca-Mg	11
Na/Li	—
SiO_2 Quartz	141
SiO_2 Chalcedony	115

Geology

The Ahtanum Valley is cut into Grande Ronde basalt flows. The Grande Ronde Formation, composed of basalts of Miocene age, represent the thickest and one of the oldest formations of the Columbia River Basalt Group. Preliminary reconnaissance mapping of the area (Swanson and others, 1979), shows considerable structure, striking northeast, exposed on the ridges north and south of the valley, but nothing in the valley itself. A high angle fault with a downdrop to the northwest occurs to the north, just below the ridge crest which separates Ahtanum and Nasty Creeks. Between Ahtanum Creek and Sedge Ridge to the southeast, the axis of a syncline and the trace of a high angle fault with downdrop to the northwest have been mapped. It is suspected that another high angle fault passes through the valley bottom, parallel to the mapped faults. This is suggested by the strike of the valley and the occurence of the CO_2-rich springs.

Heat Flow

No heat flow or temperature gradient information is available for the area near Ahtanum Soda Springs. On the basis of gradients observed near Yakima and in the Cascades, 20 to 25 km northeast and 15 to 20 km northwest, respectively, the temperature gradient should be greater than 50° C/km. Using a thermal conductivity of 1.59 W/m·K for the Columbia River Basalt, the heat flow should be at least 80 mW/m^2.

Comments

The chemical analysis, results of geothermometers, and geologic setting of the area discourage consideration of the Ahtanum Soda Springs as a possible high temperature geothermal system. In particular, the presence of the high concentration of magnesium, relative absence of lithium, and lack of nearby young volcanic centers suggest low potential. However, the presence of $C0_2$, a high concentration of silica, and a high reservoir temperature predicted by the Na-K-Ca geothermometer without the Mg correction, suggests that the geothermal potential of this system should not be completely dismissed. The next step to further explore this system should be the drilling of shallow holes for temperature gradient information and sampling of spring water from below the point where it may be mixing with cooler ground water.

Bumping River Soda Springs

T. 17 N., R. 13 E., NW¼ of NW¼ of Sec. 34.

Old Scab Mtn. (1971) 7.5' USGS Quad.

Soda Spring Campground on the Bumping River is reached by taking U.S. Forest Service Road 174 about 8 km southwest from its junction with State Route 410. (The two roads intersect near the junction of the American and Bumping Rivers.) The area is part of the Naches Ranger District of the Wenatchee National Forest.

Geothermal Features

An area of iron stained seeps and springs occurs along the east side of the Bumping River, about 80 meters north of where a bridge crosses over from the campground. The two main springs flow from small concrete cisterns which measure about ½ meter across, and whose tops are even with the ground level. The south cistern produced only a trickle, with a bit of bubbling through virtually stagnant water, as observed during the summer of 1981. The other cistern, located a few meters to the north, flowed at about 10 l/m with a temperature of 9.7°C. and a conductivity of 2,750 umhos/cm. No information on seasonal variation of flow or temperature is available. An analysis of water collected from the north cistern is presented in Table 3-2 (see BRA-1)

The water is CO_2 charged bicarbonate, with calcium dominating the cations. The magnesium concentration is relatively high, as is the silica and iron. Geothermometers applied to results of this analysis predict the following reservoir equilibrium temperatures:

Geothermometer	BRA-1
Measured Temperature	9.7 °C
Na-K-Ca	91
Mg Correction	-5
Na-K-Ca-Mg	85
Na/Li	120
SiO_2 Quartz	138
SiO_2 Chalcedony	112

Geology

Bumping River Soda Springs issue from alluvium of undetermined depth. The river in this area cuts through andesitic flows and volcaniclastics of the Early Miocene Fifes Peak Formation. The closest quaternary volcanic centers are located 20 km to the southwest and 17 km to the south-southwest and are known as the Deep Creek Andesites. These 60-120m thick platy and blocky jointed flows are older than 140,000 years, but younger than 690,000 years, (Hammond, 1980). No controlling structure has been identified along the Bumping River in published reports, but the river valley does follow a broad lineament which extends 20 km from Bumping Lake northeast to the American River.

Heat Flow

No temperature gradient or heat flow information is available for the Bumping River area. The few wells and mineral exploration holes drilled in the region are either too shallow or have been destroyed.

Comments

Spring chemistry suggests that the waters from Bumping River Soda Springs may be derived from reservoirs with substantially higher temperatures than the cold observed surface temperature of 9.7°C. While various geothermometers show substantial variation, ranging from 85 to 138°C, (suggesting mixing or possibly non-equilibrium), Na/Li, the geothermometer least affected by mixing, predicts 120°C. But this is also the least tested geothermometer, and the Li concentration relative to total salinity is quite low. Like the other soda springs which occur along the eastern flanks of the Cascades, the origin of the water, especially its $C0_2$, remains a mystery.

Flaming Geyser Springs

T. 21 N., R. 6 E., SE¼ of SE¼ of Sec. 27 (DD)

Black Diamond (1968) 7.5' USGS Quad.

Several cold mineral springs and one well are found along the south side of the Green River within the Flaming Geyser State Park. The Park is reached by taking State Route 18 east from Auburn, and the Green Valley Road east from State Route 18.

Geothermal Features

About ½ km south of the Green River, along a path which follows Christy Creek on the east side of the park, a weakly mineralized, bubbling spring flows from a series of seeps, with a total flow of about 50 l/m. This spring, known as Bubbling Geyser, has a temperature of 10.1°C and a conductivity of 175 to 180 umhos/cm. The pH is 8.6.

The ditch draining the spring to the river is lined with light gray silty material, primarily fine plagioclase and quartz crystals which are carried up by the spring. Filamentous bacteria grows from leaves, rocks, and branches in the ditch. A faint sewer-like odor was detected, proabaly due to decomposition of organics as well as from the organic gases mixed with the CO_2 bubbling through the spring. Analysis of this spring is presented in table 3-2 (see FGA-1).

At the head of the Christy Creek trail, a coal exploration well was drilled in 1911 with cable tools. Total depth was reported to be 1,403 feet (427.6 meters). The hole was 6 inches in diameter, and produced a significant volume of methane gas but not in commercial quantities. In 1925, the highly mineralized water which came up with the gas had a reported temperature of 58.5°F. (about 14.6°C). The well was dynamited in the 1930's, in an attempt to increase the flow of methane, but instead resulted in decreased flow of both water and gas. Cleaning of the well during the last decade has resulted in a small flow of gas, which, when lit, produces a "lazy" flame about 20 cm high. The water flows up from around the well casing, at 12.1°C, with a conductivity of 22,000 umhos/cm and a pH of 7.0. The flow was very difficult to determine because a small pool surrounds the well casing and drains through the surrounding rocks, but is probably less than 40 l/m.

The chemistry of these two waters shows a tremendous difference, suggesting that their aquifers are not related. The spring is a weakly mineralized sodium and calcium bicarbonate water. The well water is a strongly mineralized sodium chloride, with a moderate alkalinity, very high bromide, and very low concentrations of lithium, silica, and sulfate. Geothermometers applied to the waters give the following results:

	FGA-1	FGW-1
Geothermometer	Bubbling Geyser	Flaming Geyser
Measured Temperature	10.1°C	12.1°C
Na-K-Ca	145	111
Mg Correction	126	82
Na-K-Ca-Mg	19	29
Na/Li	--	8
SiO_2 Quartz	86	45
SiO_2 Chalcedony	55	13

Geology

The Flaming Geyser area is underlain by the Puget Group (undivided) of Eocene age. In this region, the Puget Group is at least 6,200 feet (1900 meters) thick, consisting of fine-grained to granular, poorly sorted, feldspathic arenite with lesser amounts of siltstone, claystone, and coal. These strata probably formed in an upper delta plain environment (W. M.

Phillips, personal communication). A roughly north-south striking anticline passes through the area, with the Flaming Geyser Park very near its apex.

A number of oil and gas wells were drilled throughout the area from the late 1930's to the early 1960's. The deepest was drilled to 6000 feet, but did not penetrate through the Puget Group. Although many of these wells had gas and oil shows, nothing of commercial quantity has ever been proven.

Heat Flow

No temperaure gradient or heat flow information is available for the area around Flaming Geyser. The region is suspected to be within a low heat flow region, characterized by gradients less than 35°C/km and heat flow below 50 mW/m^2.

Comments

The chemistry, especially the low geothermometer results, suggest that the spring and the well water are not part of a geothermal sytem. The brine associated with the methane gas from the well probably represents connate water, formation water relatively undiluted by the near-surface ground water. This system is not worth further investigation from a geothermal standpoint, but no doubt continues to hold the interest of oil and gas exploration geologists.

Goldmeyer Hot Springs

T. 23 N., R. 11 E., NW¼ Sec. 14

Snoqulamie Pass (1961) 15' USGS Quad.

Goldmeyer Hot Springs are part of a private inholding within the Snoqualmie National Forest. It is reached by taking Interstate 90 to Tanner, a small town just east of North Bend (on the west side of Snoqualmie Pass). From Tanner, the Middle Fork Road, U.S. Forest Road 2445, is followed north and northeast along the Snoqualmie River to U.S. Forest Service Road 241, which is followed southeast and east along the middle fork. A small parking area has been established in the vicinity of Bruntboot Creek. From the parking area, a well traveled trail follows the creek south and east for about 3 km, leading to the hot springs.

Geothermal Features

The hot springs at Goldmeyer, flow from an old mine adit and from several joints in the bedrock along a ½ km stretch of the creek. Temperatures range from 40° to 50°C and conductivities range from 580 to 630 umhos/cm. Most of the seeps and springs have flows of a few l/m to about 40 l/m. The main spring by volume, but not by temperature, has a flow of about 50 l/m and issues from cracks at the back of an old mine adit which reaches about 10 meters into bedrock.

Water samples were collected from three of the springs, and the results of chemical analyses are presented in Table 3-2. GMA-1 was collected from the main spring flowing from the mine adit. GMC-1 was collected from a group of springs and seeps on the south side of the valley about ½ km upstream from the adit. GMD-1 was collected on the south side of the valley about 200-250 meters back down the creek from the GMC site, a few tens of meters up a large unnamed tributary. The country is very rugged, with steep-sided ravines and dense vegetative cover. There are probably many other thermal springs in the vicinity, but they are likely to be of smaller size with lower temperatures, or would otherwise have been popularized by visiting bathers.

All three analyzed springs have very similar chemistry. The low conductivity and total salinity are unusual for the relatively high temperature. The waters are primarily sodium chloride, with moderately high pH and sulfate concentration and very low magnesium concentration.Geothermometers applied to water analyses from Goldmeyer are presented below:

Geothermometer	GMA-1	GMC-1	GMD-1
Measured Temperature	47.5 °C	49.6 °C	45.3 °C
Na-K-Ca	119	117	115
Mg Correction	0	0	0
Na-K-Ca-Mg	119	117	115
Na/Li	105	107	108
SiO_2 Quartz	111	112	110
SiO_2 Chalcedony	82	83	80

Geology

Goldmeyer Hot Springs issue from the Snoqualmie batholith, a Miocene granitic intrusion about 16 to 18 million years old. Detailed mapping has not been published for this area, but it appears likely that the springs occur along a contact between quartz monzonite to the south and granodiorite, the predominant rock type of the batholith, to the north.

Heat Flow

Temperature gradients measured in two mineral exploration holes a few kilometers northeast of the springs (DDH-1 at T. 23 N., R. 11 E., Section 1C, and DDH-2 in Section 10 DC) are 16.2 and 25.2 °C/km, as determined by straight line segments of temperature vs. depth plots. The holes were uncased, however, and large isothermal zones were measured.

Heat flows calculated using terrain-corrected gradients for the two holes were 58 mW/m^2 for DDH-1 and 56 mW/m^2 for DDH-2, but the actual heat flow may be significantly higher.

Using 18.88 °C measured at the bottom of DDH-2 at 251 meters, and a mean annual surface temperature of 10 °C, a gradient of 34 ° C/km is calculated. A more likely surface temperature for the area is 6° to 8°, which would produce caluculated gradients of about 43 to 51 °C/km. If the measured thermal conductivity value of 3.03 W/m·K is used with gradients of 35 to 50 °C/km, heat flow values of 107 to 152 mW/m^2 are obtained. If a 26 percent terrain correction is applied, the heat flows are still substantially high, with values of 80 to 114 mW/m^2.

At Alpental and Snoqualmie Summit, 7 to 8 km to the south-southwest, two 150m-deep, cased temperature gradient holes were drilled by the Division (see chapter on heat flow drilling). Both holes had gradients (calculated and observed) of about 16 °C/km. Heat flow for the Snoqualmie Summit hole, using a thermal conductivity of 2.97 W/m·K, is 49 mW/m^2, corrected to 44 mW/m^2 with terrain considerations. The Alpental hole produced an uncorrected heat flow of 59 mW/m^2, using a thermal conductivity of 3.69 W/m·K.

Comments

Because of the relatively good agreement between the different geothermometers, the equilibrium reservoir temperature for the system is likely to be in the range of 110 to 120°C. Because the batholith is more than 15 million years old, cooling of the intrusive cannot be the source of heat. There is no recognized evidence of Pliocene or Pleistocene magmatic activity in the area. The hot waters are probably deep-circulating fluids in a moderate temperature gradient and heat flow region.

Government Mineral and Little Soda Springs

Skamania County

T. 5 N., R. 7 E., NW¼, Sec. 31, and T. 4 N., R. 7 E., NW¼, Sec. 5

Wind River 1957, 15' USGS Quad

Located within the Wind River valley, Government Mineral Springs and Little Soda Springs are reached by taking the Wind River Highway (U.S. Forest Service Road 30) north from the town of Carson in the Columbia Gorge. Government Mineral Springs are located along the south side of Trapper Creek, within a campground at the end of Road 30. Little Soda Springs occur within a swampy area west of the Wind River, in a campground reached by taking Road N511 south from its intersection with Road 30. The Wind River Fish Hatchery is located across the river and can be seen from the Little Soda Spring. The two areas, separated by about 2.2 km, are within the Gifford Pinchot National Forest.

Geothermal Features

At Government Springs, on the south side of Trapper Creek, cool orange-tinted mineral water flows into a ditch which parallels and eventually joins Trapper Creek. The hundreds of individual spring orifices are usually under water, and are marked by slow to vigorous bubbling along the bottom of the iron-stained ditch. It was not possible to collect uncontaminated samples of the individual springs during the spring of 1981. Separate areas of springs have been given names by past investigators, including Iron Mike and Little Mike Soda Springs, but the area appeared to the author as a single continuous spring system. Water temperatures ranged from 5.7° to 6.5°C., with conductivities of 700 to 3,900 umhos/cm. A shallow well of unknown depth was drilled several decades ago, and is known as Iron Mike Well. A hand pump brings up cold (6.7°C) $C0_2$ charged, iron-stained water with a conductivity of 3,900 umhos/cm. The water is slightly acidic with a pH of 5.5 to 6.0. There is no noticeable odor associated with any of the springs, and green algae mats cover the bottoms of the quieter pools within the drainage.

Little Soda Springs issue from numerous bubbling orifices along the bottom of a large water-filled depression in a creek drainage. One orifice was located just above the water line of the pond, and permitted the collection of a water sample. The water temperature was 7.7°C, with a conductivity of 4000 umhos/cm and pH of about 6.0.

Most of the orifices produced only periodic bubbling and a faint H_2S smell. It is suspected that the H_2S originates from anaerobic decomposition of organic material within the muds of the pond and surrounding marshy area.

Despite the similarity of temperature, conductivity, and pH for the two spring systems, substantial differences are noted in the major element analyses. Both are sodium-calcium bicarbonate-rich waters, but Government has substantially more chloride (by a factor of 13), and more sulfate (by a factor of 2) than Little Soda. In addition, Government has substantially more silica, potassium, and iron. Both springs have relatively very high bromide and magnesium, with Little Soda having twice as much magnesium as Government. Lithium was below the detection limit (less than 0.1 ppm). Geothermometers for these waters give the following results:

Geothermometer	Government Mineral	Little Soda
Measured Temperature	6.7°C	7.7°C
Na-K-Ca	105	80
Mg-Correction	57	56
Na-K-Ca w/correction	48	24
SiO_2 Quartz	116	99
SiO_2 Chalcedony	88	69

Geology

The springs are near three major quaternary volcanic areas, Trout Creek Hill, Indian Heaven, and the Soda Peaks-Bare Mountain area. Trout Creek Hill, located about 5 km due south, is a polygenetic shield volcano consisting of olivine basalt flows and at least two cinder cones near the summit of the hill. Flows from this volcano traveled southeast through the Wind River Valley about 18 km to the Columbia River. Age of the basalt has been determined to be about 340,000 years old (Hammond, personal communication).

About 12 km to the east and northeast lie the fissure zones, shield volcanoes, and cinder cones of Indian Heaven. The closest and most prominent eruptive center is Red Mountain. The age of the youngest cinder cone on this mountain, the South Red Mountain cinder cone, is between 3,500 and 12,000 years BP. A younger unit, olivine basalt of the Big Lava Bed, located southeast of Red Mountain, is dated between 450 and 3,500 years BP. Quaternary olivine basalt is also found about 1.5 km east of the springs near Tyee Spring and along the Wind River, but this is part of the Rush Creek flow which originated about 25 km to the northeast near Bird Mountain (Hammond, 1980).

About 5 km to the west and northwest, an area of volcanic centers forms several peaks. A center at Soda Peaks gave rise to a hornblende andesite lava flow thought to be as old as 690,000 years BP. A well preserved scoria cone which sits above the andesite flow at Bare Mountain is possibly less than 20,000 years old. A basalt flow which originated at West Crater is probably post glacial, possibly only a few thousand years old (Hammond, 1980). As such, it may be one of the youngest volcanic units in the Cascades, exclusive of the stratovolcanoes.

Government and Little Soda Springs issue from valley fill, thought to consist of a combination of alluvial and lacustrine deposits. During the eruption of the olivine basalt flows from Trout Creek Hill (340,000 years BP), the Wind River Valley was temporarily dammed, probably at a point east or northeast of Bunker Hill (Wise, 1961). The valley itself has been eroded into Tertiary volcanics. These highly altered flows and volcaniclastics are part of the Ohanapecosh Formation of Oligocene age.

Heat Flow

The closest temperature gradient and heat flow holes are at Trout Creek and Carson. They suggest the regional gradient may be as high as 85 to 100°C/km, with heat flows greater than 120 mW/m^2. For details, see the Heat Flow discussion for St. Martins Spring, and Chapter 6 of this report.

Comments

Like so many other cold, CO_2-charged mineral and soda springs in the Cascades, results from geothermometers provide inconsistent predicted temperatures. The waters are dominated by high Ca and Mg which result in very low predicted reservoir temperatures, but contain relatively high concentrations of SiO_2. As a result, the geothermometers should not be too heavily relied upon. More significant however, is the absence of lithium, suggesting that this is not a high temperature sytem. The source of the CO_2, chloride, and high silica is subject to speculation and remains an unanswered question.

Klickitat Mineral Springs

T. 4 N., R. 13 E., Sections 23 & 24

Klickitat (1957) 15 'USGS Quad

Mineral springs and leaky well casings from the abandoned Gas Ice Corporation works produce numerous warm water emanations along the Klickitat River northeast of the town of Klickitat. The area is reached by taking State Route 142 north and east from Klickitat for about 3 km. Most of the land within the valley around the springs and wells belongs to the State of Washington, under the control of the Department of Game.

Geothermal Features

Over a 3 to 4 km stretch of the Klickitat River, warm, iron rich, CO_2 super-charged waters issue from alluvium along the river and, in a few cases, from basalt exposed a few tens of meters (in elevation) above the valley floor. Most of the warm water flows from around well casings or through open wells drilled by the Gas Ice Corporation between 1910 and 1930. Gas Ice Corporation was at one time the leading supplier of dry ice to the west coast area. They were in operation up to a few decades ago, and the wells and structures have been deteriorating since.

The springs have temperatures of 14° to 24°C, and the wells range up to 30°C. The warmest wells were found in the main well field on the east side of the river, across and northeast from the remaining stone building. The wells are reported to have been drilled 300 to 400 feet deep in the area.

The most interesting well was found on the west side of the river, about 100 meters northwest of the stone structure. Every 20 minutes, plus or minus a few minutes, soda water begins to fountain from the pipe. Within a few minutes of the start, the "geyser" builds to a maximum height of about 2½ meters. The temperature reached 26.2°C, and a mild H_2S odor could be detected. The peak flow lasted a few minutes, then slowly declined, coming to a total cessation of flow about 10 minutes after the fountaining had begun. Observations of two additional fountaining cycles for this well showed that timing, height, and duration of flow varied significantly.

This surging of flow was observed at other wells, with periods of increased flow followed by declines and even complete cessation, but the well described above was by far the most significant. Water sample KLB was collected from the "geyser". The other samples from Klickitat presented in Tables 3-2 are KLA, from a spring on the west side of the road (west side of the river) at the northern extension of the well field, and KLC, one of the warmest of the leaky well casings on the east side of the river within the main well field. KLDH was collected from a temperature gradient heat flow hole drilled in 1981 on the southwest side of the well field. The hole is further described below.

The Klickitat Mineral Springs are a slightly acidic (pH of about 6.2), calcium-magnesium bicarbonate water, saturated with dissolved CO_2. The sodium, chloride, and lithium concentrations are all quite low, and the silica and iron concentrations are very high. Geothermometers applied to results from the chemical analyses produced the following predicted reservoir temperatures:

Geothermometer	KLA	KLB	KLC	KLDH
Measured Temperature	22.3°C	26.2°C	29.1°C	13.5°C
Na-K-Ca	157	171	171	160
Mg Correction	-152	-165	-165	-154
Na-K-Ca-Mg	5	7	6	6
Na/Li	133	98	152	131
SiO_2 Quartz	143	162	160	145
SiO_2 Chalcedony	117	138	136	119

Geology

At Klickitat Mineral Springs, the Klickitat River cuts through Grande Ronde Basalt and associated sedimentary interbeds. The Grande Ronde Basalt is part of the Miocene Columbia River Basalt Group. The Warwick Fault has been projected through the area, running northwest-southeast, perpendicular to the main trend of the valley. The occurrence of several parallel lineaments, mostly corresponding to drainages, suggest that the Warwick Fault may actually be a multi-fault system as it crosses the Klickitat River valley and not a single linear feature. No offset has been detected along the Warwick Fault in the vicinity of the mineral springs, but 9 meters of vertical offset and opalization have occurred at the eastern edge of the Camas Prairie, about 20 km to the northwest on the Warwick Fault.

The springs and wells are located southeast of the King Mountain Fissure Zone and south and southwest of the Simcoe Volcanics. The King Mountain fissure zone includes numerous basaltic flows, cinder cones, and shield volcanoes on the south side of Mt. Adams. The closest centers to Klickitat include Quigley Butte, Red Butte, and Shaw Mountain, 25 to 30 km to the northwest, and the Gilmer Shield Volcano and Rattlesnake Creek cones about 25 km to the west (Hammond, 1980). Just south of Quigley Butte, and north of Laurel, an augite-hornblende andesite flow has been identified (Sheppard, 1964). About 22 km west of the springs, between the Gilmer volcano and Snowden, an early Pleistocene dacite volcanic center and related flows form topographic highs on the plains above Rattlesnake Creek (Sheppard, 1964, and Hammond, 1980).

The closest volcanic centers in the Simcoe Volcanic Field the two cinder cones about 4 to 5 km due east in the area called Horseshoe Bend, and a large relatively young appearing cinder cone, Blockhouse Butte, 12 km to the northeast (Sheppard, 1967).

Heat Flow

A temperature gradient hole was drilled in 1981 on the far southeast side of the well field, along the highway and just north of the river. $C0_2$ charged water was encountered at a very shallow depth in the hole, with relatively less mineralized water encountered at deeper depths. At about 14°C, this water was significantly cooler than most of the other springs and wells. The temperature gradient was measured to be about 51 °C/km. Using a thermal conductivity of 1.39 W/m·k, a terrain corrected heat flow of about 52 mW/m^2 was determined. Using the calculated gradient of 56 °C/km and the same thermal conductivity, the heat flow is calculated to be 78 mW/m^2. It is thought that this represents the regional heat flow for the area.

A down-hole temperature measurement was made for the well which geysers (KLB). The hole was virtually isothermal, with temperatures from 25 to 27°C. The deepest depth reached was 100 meters, and the total depth drilled is unknown.

Comments

In spite of the fact that a considerable amount of information is available for Klickitat Mineral Springs and vicinity, including numerous shallow wells, a heat flow hole, several chemical analyses, and good geologic maps, the nature of this hydrothermal system is still open to question. There is very poor agreement between the different geothermometers, with significant variation from spring to spring. There is certainly complex mixing occurring, and the super-saturation of CO_2 is probably contributing to near surface chemical reactions.

The chemistry of this spring system is very similar to other soda springs in the eastern part of the south and central Cascades. This is especially true with respect to Ahtanum Soda Springs (Table 3-2) and Fish Hatchery Warm Springs (Table 3-5).

Rock Creek Hot Springs

T. 3 N., R. 7 E., SE¼ of NW¼ of NE¼ Sec. 27

Bonneville Dam (1957) 15', and (1979) 7.5' USGS Quad.

Rock Creek Hot Springs are located within the Rock Creek drainage, about 4 km northwest of the creek's confluence with the Columbia River. It is reached by taking road CG-2000 from the town of Stevenson along the south side of the Rock Creek Valley to road CG-2030 which descends down to Rock Creek. From the bridge, the creek is followed on foot down valley to the southeast for a distance of about 1 km. An above-ground concrete cistern with a metal rimmed manhole marks the main spring. This structure, and consequently the spring, are submerged during all but the driest months in the summer and fall.

Geothermal Features

Only the main spring was found, located during a sampling trip in 1981, but local residents familiar with the area report that many smaller springs and seeps issue from the creek bed throughout the area around the main spring. Water from the cistern was piped along the valley down to the town of Stevenson in the early 1900's, and was used to supply a hotel.

The water, in mid-summer, had a temperature of 33.5°C and flowed at about 40 l/m, with a conductivity of 400 umhos/cm and pH of 9.7. The concrete cistern measured about 2 meters by 3 meters, and stood about 1 meter above the river bed. Water empties out of the south side of the cistern from old rusty pipes just below stream level. Minor gas bubbling through the alluvium near the cistern was observed, marking additional thermal seeps.

Chemical analyses for samples collected on two different dates during the summer of 1981 are presented in Table 3-2. The analyses produced virtually identical results. The spring is only weakly mineralized, considering its temperature. It is a sodium chloride water, with relatively high sulfate. The concentrations of potassium, lithium, and magnesium are all very low. Geothermometers applied to these waters give the following predicted reservoir temperatures:

Geothermometer	Rock Creek Hot Spring
Measured Temperature	33.5°C
Na-K-Ca	21
Mg Correction	0
Na-K-Ca-Mg	21
Na/Li	—
SiO_2 Quartz	93
SiO_2 Chalcedony	62

Geology

The basalt flows and volcaniclastic rocks which are exposed in Rock Creek Valley have been described in detail by Wise (1961, 1970). Flows were first assigned to the Weigle Formation (Wise, 1961), and have since been included as part of the Ohanapecosh Formation of early and middle-Oligocene age (Wise, 1970). Unlike the silicic subaqueous volcaniclastic rocks which characterize the type section of the Ohanapecosh near Mt. Rainier, the Rock Creek section is chiefly subaerial basalt flows, with interbedded volcaniclastics of fluvial(?) origin. Wise believes this section represents the uppermost portion of the Ohanapecosh Formation. As such, the area may be underlain by as much as 10,000 to 20,000 feet of additional Ohanapecosh volcanics. The closest Quaternary volcanic centers are Rock Creek Butte, a pluglike body of platy olivine basalt, located about 2 km to the northwest. An olivine basalt flow and cinder cone atop the Bonneville landslide, exposed along Red Bluffs and within Greenleaf Basin, occur about 3 km to the southwest. The age of the Rock Creek Butte basalt is not known, but the Bonneville Landslide-Red Bluffs basalt is thought to be post-glacial (Hammond, 1980).

Heat Flow

The closest temperature gradient holes are at Carson and North Bonneville. They suggest that the regional temperature gradient may be as high as 50 to 80 °C/km. See the section on St. Martins (Carson) and Shipherds Hot Springs.

Comments

The chemistry and results from geothermometers are very discouraging for this spring. About the only unusual aspect is the exceedingly high pH. The high pH, measured from 9.3 to 9.7, may be due to chemical weathering of mafic to ultramafic material at depth.

The relatively low salinity of this spring suggests that significant mixing may be taking place. If this is the case, the results of the geothermometer could be disregarded. Mixing would also suggest that the original pH is even higher than the measured 9.7.

By chemical species, Rock Creek Hot Springs appears to be related to Bonneville Hot Springs, 8 km to the south-southwest (Korosec, and others, 1981), and the shallow thermal aquifers encountered during the Bonneville drilling project (see Table 3-2 and Chapter 8, this report). The best guess with the available data would predict a reservoir temperature of less than 100°C.

Scenic Hot Springs

T. 26 N., R. 13 E., SE¼ Sec. 28

Scenic (1965) 7.5' USGS Quad

The Scenic area is reached by taking U.S. Route 2, which follows the South Fork Skykomish River and crosses Stevens Pass. About 8 road km west of Stevens Pass, a few buildings mark the site of the abandoned town of Scenic. Two kilometers to the east, near the west portal of the Burlington Northern Cascade Tunnel, a power line access road traverses upslope to the south. An area of hot springs is reached by following the access road up to the power lines, continuing east along the maintenance road, and by taking the foot path which climbs a few hundred meters further upslope, in a southwesterly direction.

Geothermal Features

At least four distinct areas of hot springs occur on this moderately steep slope above the Skykomish River. Although totally surrounded by U.S. Forest Service land, part of the Snoqualmie National Forest, the main spring area is a private inholding. The four spring areas are aligned roughly northeast-southwest, with the hottest, and most elevated springs on the southwest end and the coolest, lower springs to the northeast.

	Samples Taken	Temperatures	Conductivity
Area 1	SEA	39.2 - 46.5°C	160
	SEB	42.4 - 44.5	195
Area 2	SEC	14 - 36.5	140
Area 3	SED	31.0 - 32.7	160
Area 4	—	15.0 - 27.0	—

The temperature ranges listed in the table are due to two factors. They represent variations observed from spring to spring within an area, and substantial seasonal variations observed over only a portion of the year, in 1981. A more detailed description of each area follows.

The main spring of the area to the southwest (highest in elevation) flows from a joint in exposed granitic bedrock into a plastic-lined wooden tub. The water has a slight H_2S odor, and a small amount of white filamentous bacteria clings to the side of the channel and tub. Temperature and flow changed from late June to late September. Temperature increased from 39.2 to 46.5°C, while flow decreased by roughly 1/3 (estimated at 40 to 50 l/m, down to 25 to 35 l/m). Samples SEA-1 and SEA-2 were collected from this spring.

About 10 meters west of the tub, a small spring issues from under dense brush, at about the same elevation as the tub. This spring, with a flow of only about 15 to 20 l/m, had the highest temperature of all the Scenic Springs in the early summer, at 42.4°C. By late summer its temperature had increased, but was less than the main spring, reaching only 44.5°C. This suggests that this minor spring is less influenced by mixing with the seasonally affected ground waters.

A second thermal area, downslope to the northeast of the first, includes numerous small springs and seeps which issue from a muddy water-saturated slope in a broad, shallow drainage. A small pool had been dug and lined with plastic to catch water from some of the warmest springs. Most of the temperatures ranged from 14° to 30°C, but a maximum of 36.5°C was measured near the bottom of the plastic lined pool. In early summer, the total flow from this area was estimated to be 150 to 200 l/m. Many of the springs and seeps had dried up by late summer, but the warmest springs continued to flow, with somewhat high temperatures, being less influenced by surface and shallow ground waters.

The third thermal area, downhill and northeast of the second area, consists of a single large spring which feeds a shallow rock-dammed pool. The flow was about 100 to 130 l/m, with a temperature of 31.0°C, increasing to 32.7°C by late summer.

The fourth thermal area is located within the power line corridor, and has obviously been disturbed by construction of the corridor. Numerous warm springs issue from alluvium in a poorly defined drainage, forming a marshy area. Temperatures are much cooler than springs in the other areas, ranging up to 27°C. There is a possibility that the water in this area originates from warmer springs upslope, flows downslope through the alluvium, and emerges where the alluvium has been disturbed.

Considering the relatively warm temperatures, the Scenic springs have a very low salinity. The waters are weak sodium bicarbonate, with high sulfate relative to the concentrations of the other anions. The lithium, potassium, and magnesium concentrations are very low, and the silica is relatively low.

Geothermometers applied to water samples from various springs at Scenic give the following results:

Geothermometer	SEA-1	SEA-2	SEB-1	SEC-1	SED-1	SED-2
Measured Temperature	39.2°C	46.5°C	42.4°C	28.2°C	31.0°C	32.7°C
Na-K-Ca	86	93	84	92	87	102
Mg Correction	0	0	0	0	0	0
Na-K-Ca-Mg	86	93	84	92	87	102
Na/Li	--	--	--	--	--	--
SiO_2 Quartz	93	101	98	88	89	92
SiO_2 Chalcedony	62	71	68	57	59	61

Geology

The Scenic Hot Springs issue from granodiorite and quartz diorite, part of the Mount Stuart batholith (Pratt, 1958). Potassium-argon age dates range from 80 to 90 million years before present, with an average of 88 m.y. (Engels and Crowder, 1971). No structural features have been described in the literature for the immediate area of the springs, but the northeast-southwest alignment of the spring groups, roughly paralleling the Skykomish River valley to the north-northwest, suggests possible fault or joint control of the springs.

Heat flow

Two heat flow holes were drilled in the vicinity of the Scenic Hot Springs during the summer of 1981, Scenic No. 1 (T. 26 N., R. 13 E., SE¼ of SW¼ of Section 28), completed to 101.5 meters, was drilled less than ½ km north of the hot springs, downslope about 200 meters in elevation. It produced a gradient of 48 °C/km in the upper one half, and 68 °C/km in the lower portion of the hole. These are very high gradients for granodiorite, and are probably due to the proximity to the hot springs. Using a gradient of 68 °C/km and a thermal conductivity of 2.06 W/m·K, the heat flow (not corrected for topography) would be 140 mW/m^2. A correction for topographic effects lowers the heat flow to 115 mW/m^2.

Scenic No. 2 (T. 26 N., R. 13 E., NE¼ of NW¼ of Section 27), was drilled about 2 km to the east-northeast of No. 1. It was completed to 152 meters and penetrated biotite schist, probably part of the Carboniferous Chiwaukum Schist. The gradient is 36.5 °C/km, and using a thermal conductivity of 2.68 W/m·K, the heat flow is calculated to be 98 mW/m^2. A topographic effect correction lowers the heat flow value to 70 mW/m^2. These heat flows are much higher than had been expected for the central Cascades of Washington.

Comments

The good agreement between different geothermometers and the relatively consistent results for different spring groups suggest that the thermal waters are in equilibrium with reservoir rocks at about 90 to 105°C. The very low concentration of salts, however, and the observed seasonal variations, imply significant mixing.

St. Martins (Carson) and Shipherds Hot Springs

T. 3 N., R. 8 E., Sec. 21

Carson (1979), 7.5' USGS Quad

St. Martins and Shipherds Hot Springs are located within the Wind River Gorge north of the Columbia River. St. Martins Hot Springs, now known as Carson Hot Springs, is a developed resort, located on the southwest side of the Wind River Gorge. It is one of only two hot springs presently being used as developed spas in the State of Washington (the other is Sol Duc Hot Springs on the Olympic Peninsula). The resort is reached by taking Hot Springs Road east from the center of the town of Carson, or by taking the same road north from State Route 14 at the Wind River Bridge.

Shipherds Hot Springs are undeveloped pools along the east bank of the Wind River, about 1 km northwest of the St. Martins spring. They are reached by walking northwest along the east bank of the river from a parking lot at the end of Indian Cabin Road (northwest of Home Valley). Both springs are on private property, and are surrounded by a mixture of private, state, and county land.

Geothermal Features

At Carson/St. Martins Hot Springs, a pump house covers a concrete cistern built over a large joint in the quartz diorite bedrock on the river bank. Water is pumped up to a recently renovated building which includes a bath house, lobby, restaurant, and banquet room. In addition, the water is pumped to many individual cabins and outdoor water faucets (for use by campers). Extending for at least 50 meters northwest from the pump house, hot water flows from the river bottom in a series of seeps. The individual orifices are marked by periodic gas bubbling. The volume of flow for these springs and seeps cannot be easily estimated because of the river flow, and sampling would also be difficult. Water from the main spring has a temperature of about 52 °C, and shows some seasonal variation. In addition, river levels influence static water levels in the main spring cistern and the rate of draw-down from pumping.

Shipherds Hot Springs flows from several orifices in the bedrock near and in the river bed about 1 km northwest of the Carson pump house. Temperatures range widely, with the highest, 42.5 °C, measured from a spring submerged in the river channel. Analyses of water collected at Carson Hot Springs (SMA), and Shipherds Hot Springs (SPA) are presented in Table 3-2. Both springs are predominantly sodium chloride water, but Shipherds has only about 1/10 the conductivity of the Carson Springs, with a higher alkalinity. Both have high pH's, at about 8.5 units, with relatively low concentrations of potassium and lithium and only moderate silica. Geothermometers applied to the results predict the following reservoir equilibrium temperatures.

Geothermometer	SMA-1	SMA-2	SPA-1
Measured Temperature	32.0°C	50.0°C	40.8°C
Na-K-Ca	102	100	53
Mg Correction	0	0	0
Na-K-Ca-Mg	102	100	53
Na/Li	67	88	—
SiO_2 Quartz	108	103	99
SiO_2 Chalcedony	79	73	69

Geology

The Wind River Gorge near St. Martins and Shipherds Hot Springs has been cut into a northwest trending linear structural weakness (possibly a fault) in a quartz diorite intrusive. The rock is a holocrystalline, augite-hypersthene quartz diorite intruded into Tertiary volcanics of the Oligocene Ohanapecosh Formation. The intrusion may be a very large sill. The unit is informally known as the Buck Mountain intrusive, Wind River Gorge intrusive, or Wind River fishway sill. If the quartz diorite correlates with similar rock of the Wind Mountain plug, which intrudes Grande Ronde Basalt about 4 km southeast of Buck Mountain, the Buck Mountain intrusive would be middle Miocene in age, or younger (Wise, 1961 and 1970, and Hammond, 1980).

The closest Quaternary volcanic centers include Rock Creek Butte (5 km west), Trout Creek Hill (9.5 km northwest), basalt of Cedar Creek (5 km north), and Mt. Defiance (5 km southeast in Oregon). Escept for Trout Creek Hill, these centers are probably monogenetic, producing basalt flows and related scoria deposits. A possibly polygenetic volcano, Trout Creek Hill, produced olivine basalt flows of sufficient volume to fill the pre-existing Wind River valley with up to 500 feet of basalt.

A detailed geologic field study of the Wind River area was completed by Dulcy Berri in 1982. The map and report will be released by the Division of Geology and Earth Resources as an Open-File Report in 1983.

Heat Flow

Two heat flow holes were drilled in the Wind River valley in 1981. The first was located near the Wind River Nursery, about 8 km northwest of the hot springs. Drilled primarily in volcaniclastic rocks of the Ohanapecosh Formation, the gradient was about 87°C/km. Excluding any terrain corrections and using a thermal conductivity of 1.22 W/m·K, the heat flow is calculated to be 106 mW/m^2. A terrain correction lowers the heat flow to 92 mW/m^2.

The second hole was drilled on the west side of the Wind River gorge in the vicinity of Shipherds Hot Springs. Passing through Trout Creek basalt and Ohanapecosh volcaniclastic rocks, the hole bottomed in the Buck Mountain intrusive, with a gradient of 365°C/km. If terrain corrections are excluded and a thermal conductivity of 1.60 W/m·K is used, the heat flow is calculated to be 590 mW/m^2. The terrain correction lowers this value by only 2 mW/m^2. If a top to bottom calculated gradient of 166 °C/km is used, the heat flow is calated to be 266 mW/m^2. These values are 5 to 10 times the likely regional heat flow and are due to convective heat flow at depth which is establishing sharp temperature contrasts and consequent high conductive heat flow above the convective system.

Comments

As suggested by the geothermometers, the Carson Hot Springs system probably has a moderate reservoir temperature, at around 100°C. The water is reaching the surface through a fault or fracture zone in the quartz diorite intrusive. If the regional gradient is 80 to 90°C/km, the waters need to circulate downward to only 1 km to obtain the predicted reservoir temperature, but if the regional gradient is actually a more conservative 50 to 60°C/km, the water needs to reach depths of about 2 km.

A relatively high concentration of chloride makes Carson Hot Springs the most extreme sodium chloride spring in the state. High chloride is often suggestive of a high-temperature fluid-dominated geothermal system, but very little other evidence supports this type of interpretation for the Carson springs.

Shipherds Hot Springs are very obviously diluted by ground and surface water. If the hot reservoir water is similar to the water at Carson Hot Springs, then the hot water is being diluted by at least a factor of ten (Suggested by ion ratios for Carson: Shipherds of 18:1 for Cl, 16:1 for Ca, and 8:1 for Na). But if this were true, and the reservoir waters were mixing with near surface ground water (at about 15°C), the reservoir temperature would be predicted to be about 265°C by simple mixing models. This is highly unlikely. The Shipherds system probably has a different "reservoir" chemistry than Carson Hot Springs (due perhaps to a relatively short residence time and/or nonequilibrium), and is probably undergoing complex mixing with ground and river water.

References

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.

Cline, D. R., 1976, Reconnaissance of the water resources of the Upper Klickitat River basin, Yakima Indian Reservation, Washington. U.S. Geological Survey Open-File Report 75-518, 54 p.

Engels, J. C.; Crowder, D. F., 1971, Late Cretaceous fission-track and potassium-argon ages of the Mount Stuart Granodiorite and Beckler Peak Stock, North Cascades, Washington: U. S. Geological Survey Professional Paper 750-D, p. D39-D43.

Fouillac, C., and Michard, G., 1981, Sodium/Lithium ratio in water applied to geothermometry of geothermal reservoirs: Geothermics, v. 10, p. 55-70.

Fournier, R. O., and Truesdell, A. H., 1973, An empirical Na-K-Ca geothermometer for natural waters: Geochemica et Cosmochemica Acta, v. 37, p. 1255-1275.

Fournier, R. A., and Potter, R. W., 1979, Magnesium correction to the Na-K-Ca chemical geothermometers; Geochemica et Cosmochemica Acta, v. 43, p. 1543-1550.

Hammond, P. E., 1980, Reconnaissance geologic map and cross sections of southern Washington Cascade Range, latitude 45°30’ - 47o15’ N., longitude 120o45’ - 122o22.5’W.: Portland State University Department of Earth Sciences, 31 p., scale 1:125,000.

Korosec, M. A.; Schuster, J. E.; Blackwell, D. D.; Danes, Z. F.; Clayton, G. A.; Rigby, J. A.; McEuen, R. B., 1981, The 1979-1980 geothermal resource assessment program in Washington: Washington Division of Geology and Earth Resources Open-File Report 81-3, 270 p., 1 map, scale 1:24,000.

Newcomb, R. C., 1972, Quality of the Groundwater in Basalt of the Columbia River Group, Washington, Oregon, and Idaho; U.S. Geological Survey Water Supply Paper 1999-N.

Pratt, R. M., 1958, The geology of the Mt. Stuart area, Washington; University of Washington Doctor of Philosophy Thesis, 229 p.

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., 1964, Geologic map of the Husum Quadrangle, Washington: U.S.Geological Survey Mineral Investigation Field Studies Map, MF-280.

Sheppard, R. A., 1967, Geology of the Simcoe Mountain Volcanic area, Washington: Washington Division of Mines and Geology Geologic Map GM-3.

Swanson, D. A.; Anderson, J. L.; Bentley, R. D.; Byerly, G. R; Camp, V. E.; Gardner, J. N.; and Wright, T. L., 1979, Reconnaissance geologic map of the Columbia River basalt group in eastern Washington and northern Idaho: U.S. Geological Survey Open-File Report 79-1363, 24 p., 12 plates.

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

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

4. PROGRESS REPORT FOR THE REGIONAL GRAVITY SURVEY OF THE CASCADE MOUNTAIN RANGE, WASHINGTON

by

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4. PROGRESS REPORT ON THE REGIONAL GRAVITY SURVEY OF THE CASCADE MOUNTAIN RANGE, WASHINGTON

by

William M. Phillips

Introduction

Since 1974, the Division of Geology and Earth Resources has supported gravity studies in the Cascade Mountains of Washington State. The purpose of the work has been to gather baseline gravity data for eventual contribution to geothermal resource evaluation. All gravity surveys were carried out by Z. F. Danes[1] Preliminary results of the gravity work are available as Division Open-File reports (Danes, 1975, 1979, 1981; Korosec and others, 1981).

The goal of the gravity program has been to obtain sufficient gravity measurements for preparation of accurate total Bouguer contour maps on a scale of 1:250,000. An average station density of about 1 gravity station per 5 mi^2 is needed to achieve the desired level of accuracy.

Discussion

Collection of gravity data in the field is now reasonably complete (see Figure 4-1). Average station density meets or exceeds the 1 station per 5 mi^2 criterion throughout most of the Cascades south of 47° N. latitude. North of 47°, rugged terrain and limited access have restricted the number of stations that could be established within reasonable time and budget guidelines. Gaining additional gravity coverage in the North Cascades will be an expensive process, as helicopter support is a virtual requirement in many areas.

Observed gravity values have been reduced to the total Bouguer correction, plotted

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[1] Z. F. Danes, Danes Research Associates, 4206 N. 13th St., Tacoma, WA 98406

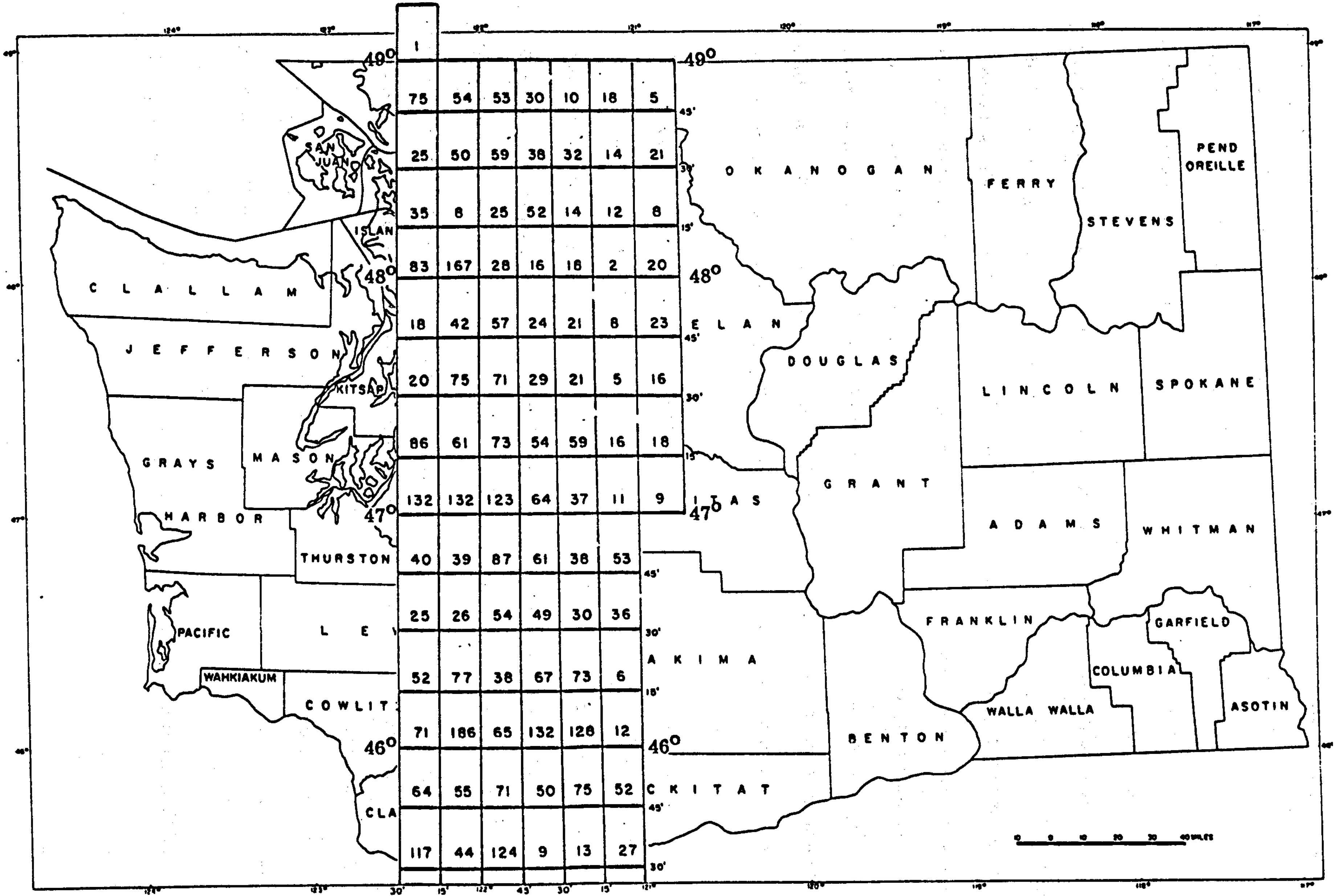

Figure 4-1. — Number of gravity stations per 15' quadrangle in the Cascade Study area.

on base maps of the north and south Cascades, and contoured at a 5 mgal interval (Danes and Phillips, 1983a). A reduction density of 2.67 gm/cc has been used to facilitate qualitative comparison of the Cascade data with other regional gravity surveys. Complete listings of principal facts have been released as an open-file report so that other workers will have the ability to reduce observations with the density most suitable for their application (Danes and Phillips, 1983b).

Work is underway to determine the most appropriate method of residual separation. Under consideration are graphic techniques, polynomal surface fitting, empirical gridding methods, and spectral or Fourier analysis. Each method has limitations as well as advantages. The graphic techniques consist simply of identifying a "regional" component of the total Bouguer field via study of gravity profiles. Residuals are computed by subtracting the regional from the total field. Graphic methods are suitable for profile studies; three-dimensional work is slow and painstaking. In addition, graphic methods are highly subjective and hence difficult to reproduce. However, good results may be obtained if the interpreter is well-versed in the geology of the study area.

Polynomial surface fitting (c.f. trend surfaces, Davis, 1973), is a process of fitting, by a least-squares method, the observed Bouguer gravity anomalies with a surface by a polynomial (Pitts, 1979, p. 61). The surface produced is taken to represent the regional component of the total field. The method offers a rapid, reproducible means of separating regional anomalies from residuals. There is, however, a subjective element in the process in that the order of the polynomial used to represent the regional surface must be chosen. A more complete discussion of polynomial surface fitting and gravity residuals is given in Phillips (see Chapter 5, this volume).

The empirical gridding method (Telford and others, 1976, p. 52) is a simple way of isolating the residual by second-derivative analysis. The regional is considered to be the average value of gravity in the vicinity of the station. It is obtained by averaging observed values of gravity on the circumference of a circle centered at the station. The method is rapid and reproducible, but somewhat subjective in terms of choice of circle radii. If the radius is very small, the residuals will be zero; if the circle is large, the residuals trend toward the total Bouguer values.

Spectral or Fourier analysis separates long wavelength (regional) components from shorter wavelength (residual) components of the total gravity field. The technique involves fitting an infinite series of sinusoidal waves to the gravity data set and calculating the amplitude and phase angle coefficients for the various waves (Pitts, 1979, p. 62). Although Fourier analysis is the most complex of the residual separation methods, it is probably the least subjective and has been widely used by recent investigators (e.g. Pitts, 1979).

The most significant problem faced by the Cascade gravity program has been associated with the calculation of terrain corrections. Terrain corrections are estimates of the gravitational attraction of mass (or lack of mass) ignored in the Bouguer correction. In mountainous country such as the Cascades, terrain corrections are a vital part of gravity data reduction, often contributing from 15 to 20 mgals or more to the Total Bouguer station value. Without terrain corrections, a ficticious correlation between topography and gravity may occur.

In terms of mathematics, terrain corrections offer no special difficulties in computing. A standard method due to Hammer (1939) has long been available. Problems are logistical in nature, as terrain corrections are among the most tedious and cumbersome reductions in all of geophysics. If a gravity survey consists of many hundreds of stations, and topography dictates carrying the terrain correction out to at least 4 miles (Hammer Zone J), hand calculation of the corrections will require weeks to months of work. Although the process is speeded up somewhat with the use of programmable calculators, the time required to select an average elevation for each Hammer Zone sector remains constant.

Plouff (1977) has written a series of computer programs that calculate terrain corrections using digital topographic files. The programs are widely used by the U.S. Geological Survey. An enhanced version of the Plouff programs, developed by S. Pitts at Oregon State University, has been acquired by Danes Research Associates and modified to run on the

University of Puget Sound computer system. In theory, the terrain correction programs offer a rapid and accurate means of eliminating the gravity reduction bottleneck. However, experience in the Cascade Mountains study area has shown the utility of the programs to be limited to distant terrain corrections.

In areas of considerable relief, the computer terrain correction algorithm may underestimate the effect of near-station topography as compared to standard Hammer's method calculations. This effect is most pronounced in the area 3000 feet or less (Hammer Zone F) from the station. The magnitude of the problem is shown in Table 4-1 where computer calculated and hand-calculated terrain corrections for the same stations are presented. (The Variable Density Slab values are discussed later in this report).

Examination of the program documentation (Plouff, 1977; Pitts, 1979, p. 54) and discussions with Plouff (personal communication, 1982), revealed the low terrain corrections to be a consequence of using ½-minute (approximately 2000 by 3000 feet) blocks for constructing digital topographic models in the interval zero to 7500 feet from the station. The topographic model produced by Hammer's method uses pie-shaped blocks that vary in size as a function of the distance from the station (see Figure 4-2). At distances greater than about 3000 feet from the station, the ½-minute blocks are approximately the same size or smaller than the sectors of the corresponding Hammer Zone (Zone G). At distances less than 3000 feet from the station, the ½- minute blocks are much larger than the sectors in Hammer Zone A through F. As the terrain corrections for Zones A through D are usually estimated at the time of the survey, the major source of discrepancy in results comes from under-estimating the gravitational effect of relief in Hammer Zones E and F.

Another factor that can cause potentially large differences in calculating terrain corrections is the accuracy of elevation information. The Plouff programs use elevation data digitized from 1:250,000 scale topographic maps. The contour interval on maps of this scale is usually 200 feet. It is the practice of most geophysicists to calculate terrain corrections from a 1:62,500 to 1:24,000 topographic map base. Contour intervals on these maps range from 80 to 20 feet.

Table 4-1. — Comparison of Hammer's Method, Computer Method, and Variable Density Slab Method for Computing Terrain Corrections.

	TERRAIN CORRECTION (mgals)		
Station No.	Hammer's Method to Zone J	Computer	Variable Density Slab
A1924	9.56	6.68	17.64
A1925	8.64	4.92	11.49
A1926	6.99	4.18	9.78
A1927	7.26	3.81	9.89
7126	6.62	6.72	10.99

Source: Unpublished Gravity Data from Morton 15' Quadrangle, Z. F. Danes, 1982.

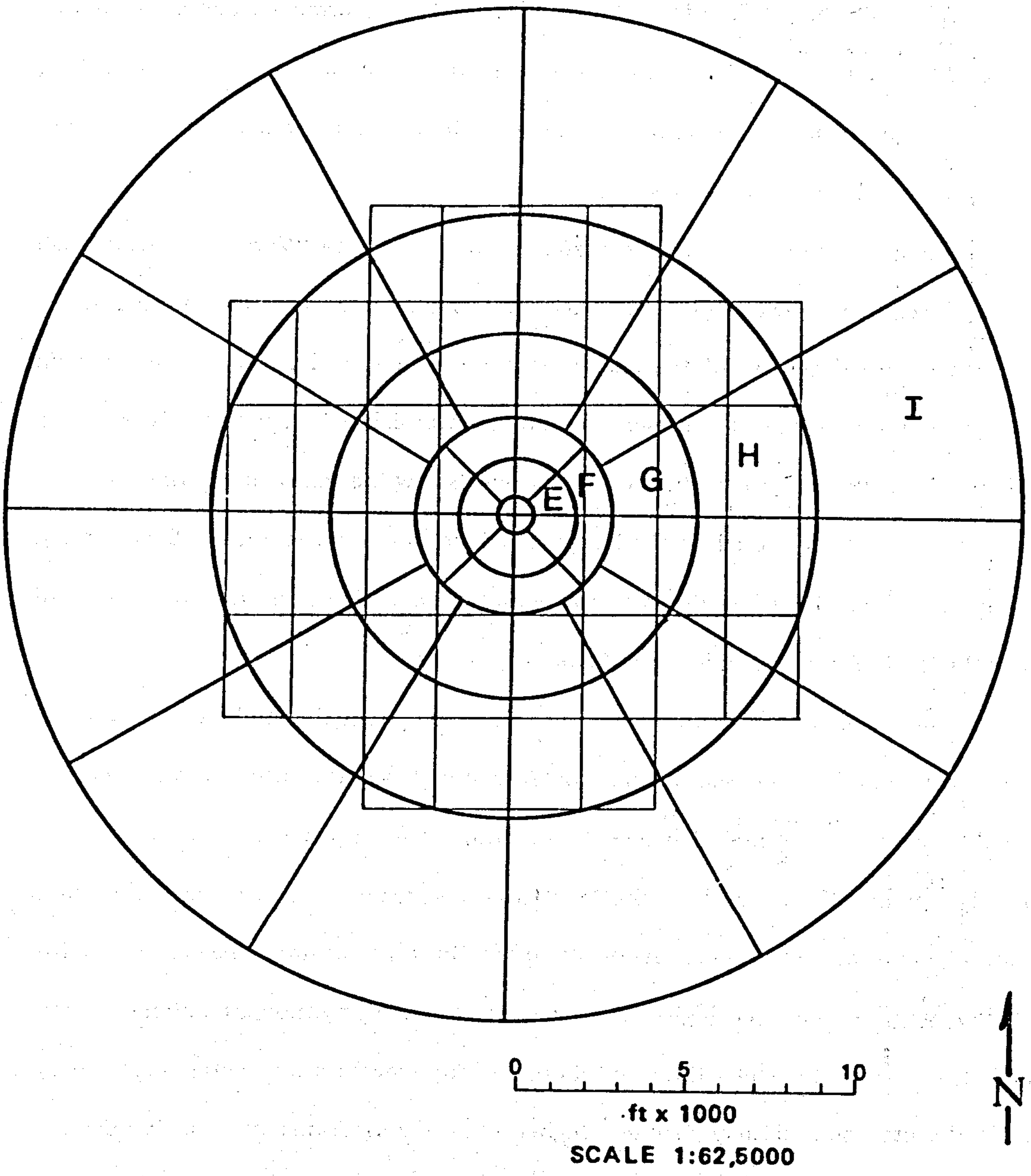

Figure 4-2. — Comparison of Hammer Zone sectors with 30 second digital terrain blocks.

The programs do possess the option of combining near-startion terrain corrections calculated via Hammer's method with distant terrain effects found using the digital files. In practice, this requires manually performing Hammer Zone computations out to at least Zone F. However, Danes has elected to make use of an analytical terrain correction technique for the bulk of Cascade gravity observations. The technique, discussed in some detail below, has the advantage of being implemented on inexpensive programmable calculators rather than requiring use of a large computer system.

The terrain correction method used, referred to here as the "Variable Density Slab Method", was developed by Danes (1982). Near-zone terrain corrections are computed out to Zone J using a modified version of the analytical method described below. Distant terrain effects are estimated by assuming the presence of a horizontal slab of variable density, reaching from the base of valley floors to the tops of mountains. Below the valley floors, the density is assumed to be constant and equal to the Bouguer reduction density (typically 2.67 gm/cc). Within the interval from the valley floors to the mountain tops, slab density decreases toward zero. Above the level of the mountain tops, the density is zero.

By constructing a series of topographic profiles throughout the study area, "average" valley floor and mountain top elevations may be estimated. Given this information, the effect of the variable density horizontal slab may be determined by integrating from some inner radius (usually Hammer Zone I or J; 14,662 or 21,826 feet from the gravity station, respectively) to infinity in a manner directly analogous to the Bouguer infinite plane correction. Results consistent with or somewhat higher than standard Hammer's method are obtained if care is exercised in choosing the valley floor and mountain top elevation parameters (Table 4-1). The variable density method may produce higher terrain corrections because it does not end at an arbitrary outer boundary as do the Plouff computer programs or Hammer's method, and because the range of elevations between mountain tops and valley floors is used rather than mean elevations per sector.

Conclusion

In summary, production of total Bouguer gravity maps at a scale of 1:250,000 for the Washington Cascades is nearing completion. Gravity station density is adequate south of about 47° N. latitude. North of 47°, low station density will limit the resolution of the gravity maps.

Work is underway to determine the most appropriate method of separating residuals from the total Bouguer field. Residual maps will facilitate detailed analysis of the gravity data in terms of relatively near-surface density contrasts.

Terrain corrections remain cumbersome and error-prone despite much work to reduce the labor and increase the accuracy of the calculations. One solution to the problem would involve digitization of elevation data from 1:62,500 or even 1:24,000 topographic maps, and use of available computer programs for automated calculation. The enormous amount of labor required for digitization at such a large scale may preclude such applications for some time to come. An alternative approach is the development of new analytical methods for the calculation of terrain effects, such as Danes' variable density slab method.

Future work should include detailed analysis of the regional-scale gravity data in conjunction with all available Cascade geologic, geochemical, and geophysical data pertinent to geothermal resource evaluation. As a result of this analysis, several areas should be selected for detailed gravity surveys and additional exploration studies.

References

Danes, Z. F., 1975, Bouguer gravity map of Mount Rainier National Park, Washington: Washington Division of Geology and Earth Resources Open-File Report 75-5.

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

Danes, Z. F., 1981, Preliminary Bouguer gravity map, southern Cascade Mountains area, Washington: Washington Division of Geology and Earth Resources Open-File Report 81-4, 1 sheet, scale 1:250,000.

Danes, Z. F., 1982, An analytic method for the determination of distant terrain corrections: Geophysics, vol. 47, no. 10, p. 1453-1455.

Danes, Z. F.; Phillips, W. M., 1983a, Complete Bouguer gravity anomaly map, Cascade Mountains, Washington: Washington Division of Geology and Earth Resources Geophysical Map GM-27, 2 sheets, 1:250,000.

Danes, Z. F.,; Phillips. W. M., 1983b, Principal facts and a discussion of terrain correction methods for the complete Bouguer gravity anomaly map of the Cascade Mountains, Washington: Washington Division of Geology and Earth Resources Open-File Report 83-1, 15 p., 1 appendix.

Hammer, S., 1939, Terrain corrections for gravimetric stations: Geophysics, v. 4, p. 184-194.

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

Pitts, G. S., 1979, Interpretation of gravity measurements made in the Cascade Mountains and the adjoining Basin and Range Province in Central Oregon: M.S. thesis, Oregon State University, 186 p.

Plouff, D., 1977, Preliminary documentation for a FORTRAN program to compute gravity terrain corrections based on topography digitized on a geographic grid: U.S. Geological Survey Open-File Report 77-535, 45 p.

Telford, W. M.; Geldart, L. P.; Sheriff, R. E.; and Keys, D. A., 1976, Applied Geophysics: Cambridge University Press, Cambridge, 860 p.

5. PRELIMINARY INTERPRETATION OF REGIONAL GRAVITY INFORMATION FROM THE SOUTHERN CASCADE MOUNTAINS OF WASHINGTON.

by

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5. PRELIMINARY INTERPRETATION OF REGIONAL GRAVITY INFORMATION FROM THE SOUTHERN CASCADE MOUNTAINS OF WASHINGTON

by

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Introduction

This report presents a preliminary interpretation of a new complete Bouguer gravity anomaly map for the Cascade Mountains of Washington (Danes and Phillips, 1983). The map was constructed by the Division of Geology and Earth Resources as part of a larger program designed to assess the geothermal potential throughout the Washington Cascade Range. A progress report detailing the status of the Cascade gravity survey appears in Chapter 4 of this volume.

In terms of station density and contour interval, the new map is a substantial improvement over previous gravity maps of the area (Danes, 1981; Bonini and others, 1974). The map, together with recent gravity maps of the Oregon Cascades (Couch and others, 1982, 1981a, 1981b; and Pitts and Couch, 1978), offers new opportunities for analysis of the structure of the Cascade Range.

In order to allow preparation of a timely report, this study used a draft, reduced copy of the Bouguer map which had not been fully edited for possible errors. Hence, the conclusions reached in this paper must be regarded as preliminary. In addition, a Bouguer reduction density of 2.67 g/cc was used in preparing the map. As pointed out below, this reduction density may be too high for portions of the southern Cascade Mountains and may mask important gravity features.

Additional work is required to determine the optimum range of reduction densities. Discussion is also restricted in this report to qualitative correlations of gravity features with mapped geological structures. No attempt is made to quantitatively test proposed density models. Despite these limitations, it is hoped that this work will serve as a useful overview of gravity interpretation in the southern Cascade Mountains.

Regional Geology

The location of the study area and the major geologic features of the Cascade Mountain Range are shown in figure 5-1. The following overview of the geology of the southern Cascade Mountains is after Hammond (1979, 1980). Figure 5-2 is a simplified geologic map of the region from the same source.

A very complex stratigraphic nomenclature is in use in the southern Cascades which reflects the area's diverse rock assemblages and long volcanic history. For the purposes of this report, a simple classification of strata based upon age relationships will suffice. Only four major rock units are distinguished: pre-Tertiary rocks; Eocene deltaic and fluvial sediments and associated andesitic volcanic rocks; upper Eocene to lower Pliocene volcanic rocks; and Pliocene to Recent volcanic rocks. Other workers (e.g. Hammond, 1979, 1980) use the terms "Western Cascade Group" and "High Cascade Group" to refer to the Eocene to Pliocene, and Pliocene to Recent volcanic strata respectively. In this report, the terms "Tertiary volcanic rocks" and "Pliocene-Quaternary volcanic rocks" will be used as they better reflect classification based upon age relationships and do not infer any specific geographic distribution. Basalts of the Columbia River Group, although volcanic and Miocene in age, are separated from Cascade volcanic units in order to emphasize their non-Cascade origin and importance as areally extensive stratigraphic marker horizons. Geologic map units are summarized in table 5-1.

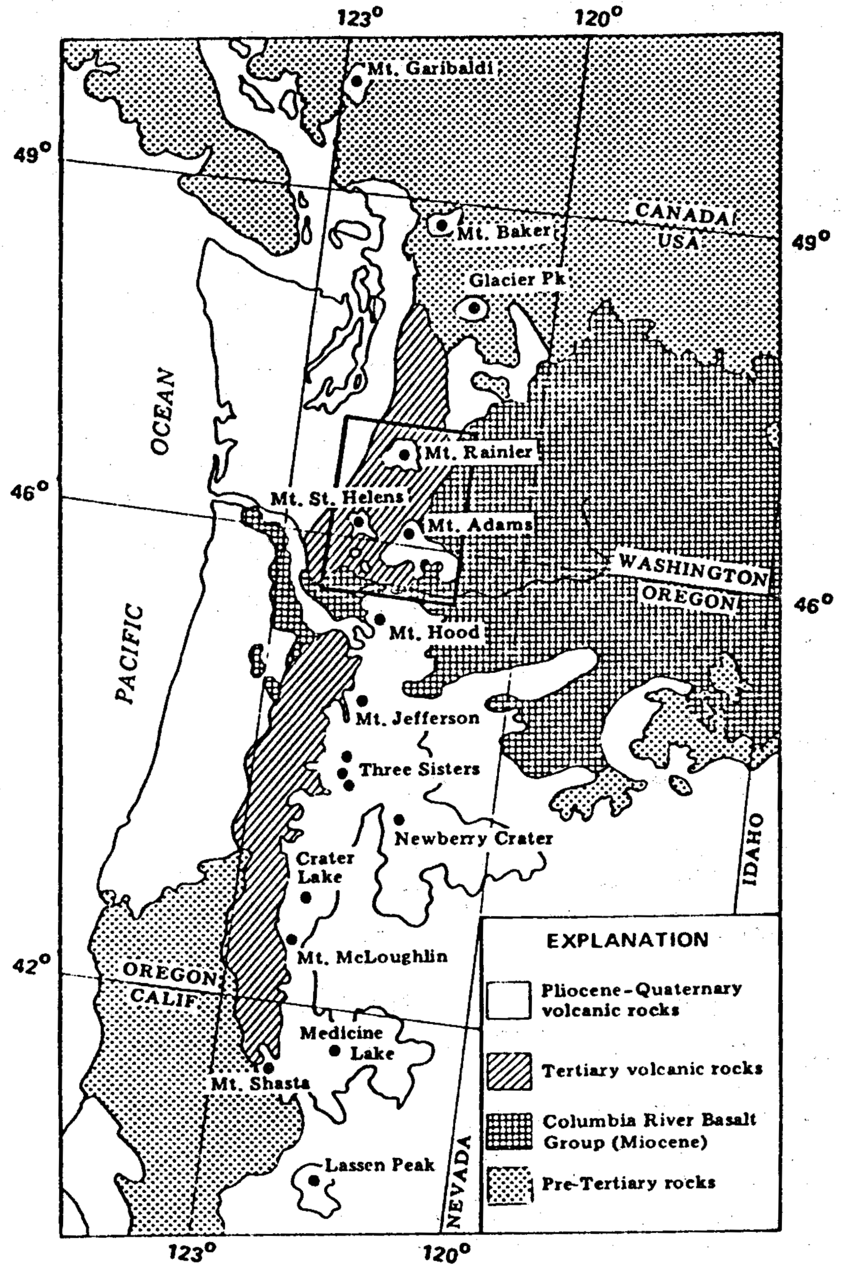

Figure 5-1. — Index map showing location of the Southern Cascade Mountains study area and major geologic elements of the Cascade Mountain Range (after McBirney, 1968). Dots indicate location of Quaternary Cascade stratovolcanoes. Rock units are discussed in text.

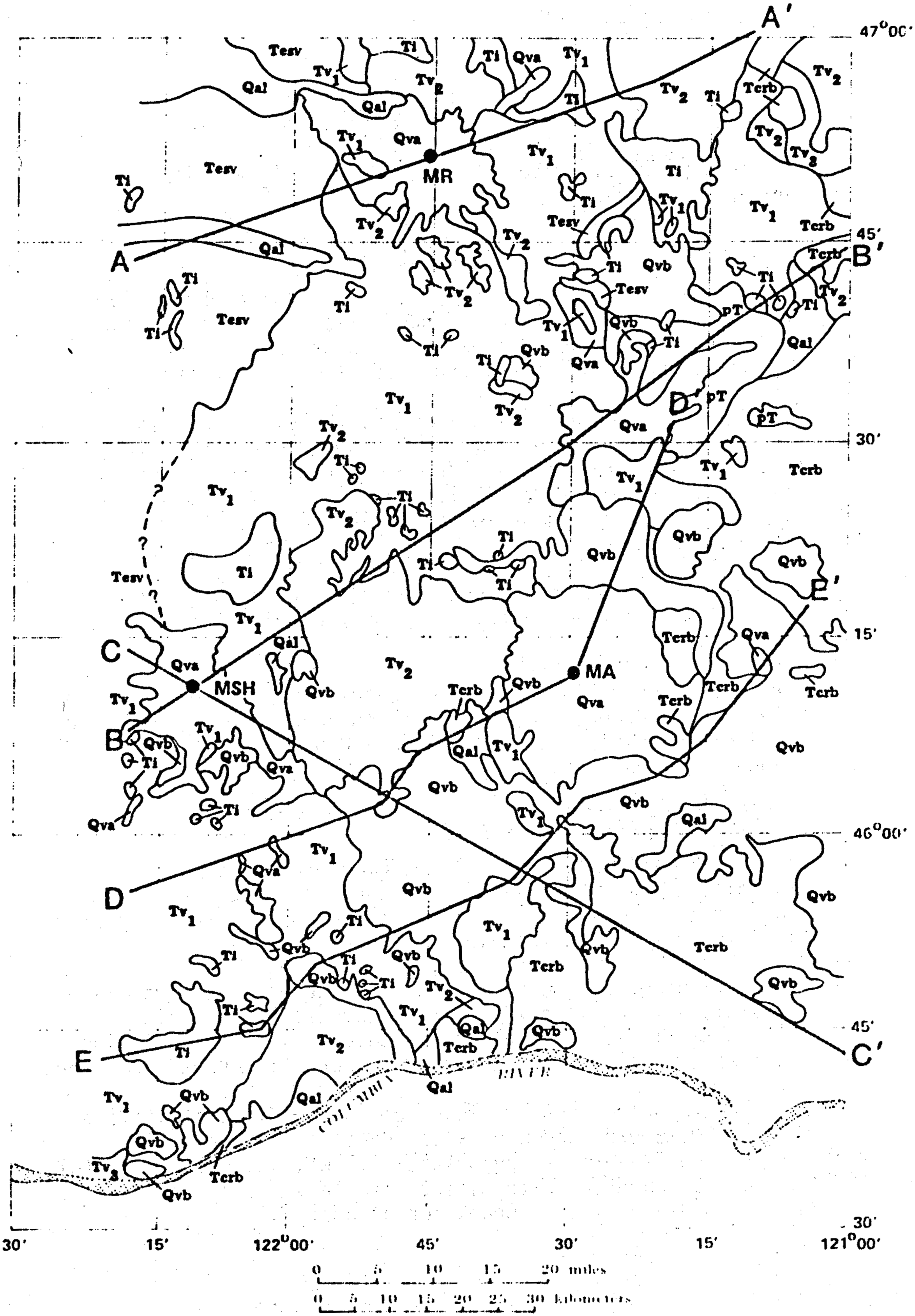

Figure 5-2. — Geologic map of the Southern Cascade Mountains study area (simplified from Hammond, 1980). Table 5-1 identifies map units. Section lines mark location of geologic and gravity profiles shown in Figures 5-9, 5-10, 5-11, 5-12, and 5-13. MR, MSH, and MA mark the locations of Mounts Rainier, St. Helens, and Adams, respectively.

Table 5-1 — Geologic Map Units

Map Symbol	Description
Qal	Quaternary alluvium, colluvium, and glacial deposits, undifferentiated.
	Pliocene - Quaternary Volcanic Rocks
Qva	Quaternary hornblende and/or pyroxene andesite and lesser dacite lava flows, mudflows, and debris avalanche and ash-fall deposits. Erupted from Mt. Rainier, Mt. St. Helens, Mt. Adams, and Goat Rocks, and several minor centers.
Qvb	Pliocene to Quaternary high-alumina, tholeiitic olivine basalt and basaltic andesite lava flows, scoria deposits, pillow lavas, and breccias. Erupted from numerous shield volcanoes and cinder cones along north-south trending fissure zones, including Indian Heaven and King Mountain Fissure Zones.
Ti	Tertiary intrusive rocks, undifferentiated. Mostly of granodiorite, quartz monzonite, quartz diorite, and diorite composition.
Tcrb	Tertiary (middle Miocene) Yakima Basalt Subgroup of Columbia River Basalt Group. Tholeiitic flood lava flows, aphyric to plagioclase-phyric. Includes Saddle Mountains, Wanapum, and Grande Ronde basalts.
	Tertiary Volcanic Rocks
Tv_3	Tertiary (middle Miocene to lower Pliocene) volcanic, plutonic, and metamorphic lithic conglomerates, sandstones, and siltstones. Interstratified at base with Tcrb. Includes the Ellensburg and Troutdale formations.
Tv_2	Tertiary (upper Oligocene to middle Miocene) interstratified andesitic and basaltic lava flows, rhyodacitic-dacitic pyroclastic flows, and volcanic lithic sediments, including mudflows. Includes the Stevens Ridge and Fifes Peak formations.
Tv_1	Tertiary (middle Eocene to lower Oligocene) interstratified, slightly metamorphosed andesitic, dacitic, and basaltic composition lava flows, pyroclastic flows, and volcanic lithic sediments. Base interstratified with Tesv. Includes the Ohanapecosh and Wildcat Creek formations.

Map Symbol	Description
Tesv	Tertiary (middle to upper Eocene) micaceous, lithic feldspathic sandstones, siltstones, shales, and coals. Interstratified with andesitic composition breccias, flows, tuffs, and volcanic lithic sediments. Includes or correlated with the Carbonado, Northcraft, and Spiketon formations of the Puget Group.
pT	Pre-Tertiary (Permian to Jurassic (?)) rocks, undifferentiated. Includes meta-igneous and metasedimentary rocks of the Indian Creek amphibolite and Russell Ranch formations.

The oldest rocks present in the study area are Permian to Jurassic (?) meta-igneous and metasedimentary units exposed in an uplifted structural block in the northeastern portion of the map area. These rocks are labeled "pT" in figure 5-2 and in table 5-1. Compositionally, the meta-igneous rocks are quartz diorites, tonalites, pillow basalts, and gabbros. Metasediments consist chiefly of argillite and graywacke of the flysch facies. Details of the structure within the pre-Cenozoic block have not been fully deciphered. The rocks are extensively faulted and locally sheared to mylonite.

Ringing portions of the uplifted pre-Tertiary block and outcropping along the southern Cascade foothills west and south of Mt. Rainier are micaceous lithic feldspathic sandstones, siltstones, shales and coals. A sequence of predominantly andesitic breccias, flows, tuffs, and volcanic sediments is interstratified with the coal-bearing sediments. On the basis of fossil leaves and lithology, these strata are correlated with the middle to upper Eocene Puget Group, a major rock unit of the Puget Lowlands. Correlations with other non-marine Eocene strata on the eastern slopes of the Cascade Range and within the Puget Lowlands indicate that the Puget Group represents a fluvial-deltaic sequence which prograded westward in Eocene time (Buckavic, 1979). These strata are labeled "Tesv" in figure 5-2 and in table 5-1.

Overlying the Eocene sediments and volcanics is a compositionally diverse assemblage of 5 to 8.5 km of andesite, dacite, rhyodacite, and basalt breccias, flows, and volcanic sediments. Ages of these strata range from middle Eocene to lower Pliocene. In this report, these rocks are termed "Tertiary volcanic rocks". Three major stratigraphic intervals are recognized within the Tertiary volcanic rocks on the basis of regional unconformities and compositional contrasts.

The lower stratigraphic interval, consisting of 1 to 5 km of mudflows, volcanic sediments, lava flows, and pyroclastic flows of andesitic, dacitic, and basaltic composition underlies much of the map area. It is labeled "Tv_1" in figure 5-2 and in table 5-1. Zeolite facies mineral assemblages, characteristic of the lowest grade of regional metamorphism, are typically present in these rocks. The base of the lower division lies conformably on or is interbedded with the micaceous sandstone units discussed above. Radiometric dating indicates an age range of about 45 to 31 m.y. (middle Eocene to Oligocene). The strata include the Ohanapecosh and Wildcat Creek formations. The lower division becomes progressively thinner and contains more distal volcanic facies to the east.

The middle portion of the Tertiary volcanic group, labeled "Tv_2" in figure 5-2 and in table 5-1, contains distinctive, areally extensive, quartz-bearing pyroclastic flows. Volcanic sediments and interstratified andesitic and basaltic lava flows are also present. An unconformity of at least local extent is present between lower and middle division rocks; unconformities may also exist within the middle division. Total thickness of these strata range from 1 to 3 km, with most exposures occurring around Mt. Rainier and in the area between Mount Adams and Mount St. Helens. Radiometric dating gives ages of about 30 to 15 m.y. for the division, which includes two formations, the Stevens Ridge (pyroclastic flows) and the Fifes Peak (andesitic to basaltic flows and associated volcanic sediments). The silicic nature of the Stevens Ridge Formation may reflect an origin at composite volcanoes that developed into calderas, although determination of source volcanic centers is still uncertain.

The upper portion of the Tertiary volcanic rock assemblage consists chiefly of 330 to 550 m of lithic sediments of volcanic, plutonic, and metamorphic origin. These strata unconformably overlie rocks of the middle stratigraphic interval, and have ages ranging from about 15 to 5 m.y. (Miocene to Pliocene). Volcanic sources of upper division strata have not yet been identified; at least some sediments may represent erosional products from older volcanic strata, plutons or metamorphic highlands. Exposures of the upper division strata are limited to the Columbia River Gorge and to the northeast portion of the map area, and include the Ellensburg and Troutdale Formations. The upper division is labeled "Tv_3" in figure 5-2 and in table 5-1.

The Miocene Columbia River Basalt Group is also present in the map area. These chemically and petrologically distinctive lava flows form a widespread and very useful marker horizon in the southern Cascades. The flows are especially important in studies of Cascade Range uplift rates, and in demonstrating the presence of an ancestral Columbia River through which the flows reached the Pacific Ocean. The base of the upper interval of the Tertiary volcanic rock assemblage (Ellensburg Formation) is interbedded with Columbia River basalt flows. The flows reach aggregate thicknesses of up to 600 m within the study area, and are labeled "Tcrb" in figure 5-2 and in table 5-1.

The youngest volcanic rocks in the southern Cascades are grouped in this report as Pliocene to Quaternary volcanic rocks. Although the southern Cascade landscape is visually dominated by the imposing andesite and dacite composite cones of Mount Rainier, Adams, and St. Helens, high-alumina olivine basalts and basaltic andesites are volumetrically more important among youthful volcanic products. The basalts and basaltic-andesites erupted from shield volcanoes and cinder cones typically aligned along north-south trending fissure zones.

In contrast to Tertiary volcanic rocks, Pliocene-Quaternary volcanic rocks are fresh and undeformed, lying with angular unconformity upon older volcanic strata. Ages of the rocks range from about 4.5 m.y. to Recent. Thickness of the strata ranges from 200 m or less to as much as 1 km at volcanic centers. In figure 5-2 and table 5-1, andesitic to dacitic volcanic rocks erupted from stratovolcanoes are labeled "Qva," while basalts and basaltic-andesites are labeled "Qvb".

Figure 5-3 (WPPSS, 1981) is a sketch map showing the approximate location of folds and faults in the southern Cascade Mountains. Structurally, the map area consists of a south-plunging antiform (the Cascade uplift) superimposed on at least two distinctive, earlier-formed fold and fault geometries. Excepting pre-Cenozoic units, where structural details have not been fully defined, earliest folds and faults trend northwest, paralleling the regional structure of the pre-Cenozoic North Cascades. Folds of this generation are typically open, upright, and irregularly spaced. Northwest-trending faults, considered to have been initiated with the fold system, have dip-slip movement and displacements of 300 to 1500.m.

Along the eastern slope of the southern Cascades, a younger fold and fault pattern characteristic of the western Columbia River Basin is superimposed on the earlier structural grain. These structures trend northeast to approximately east-west and principally affect strata of the upper part of the Tertiary volcanic group and basalts of the Columbia River Basalt Group.

The youngest structures in the area are associated with uplift of the Cascade Range about a north-south axis. The magnitude of uplift is progressively greater to the north. Many Quaternary basaltic volcanic centers are aligned on or parallel to north-south trending dip-slip faults thought to have formed as a result of regional uplift about the Cascade trend.

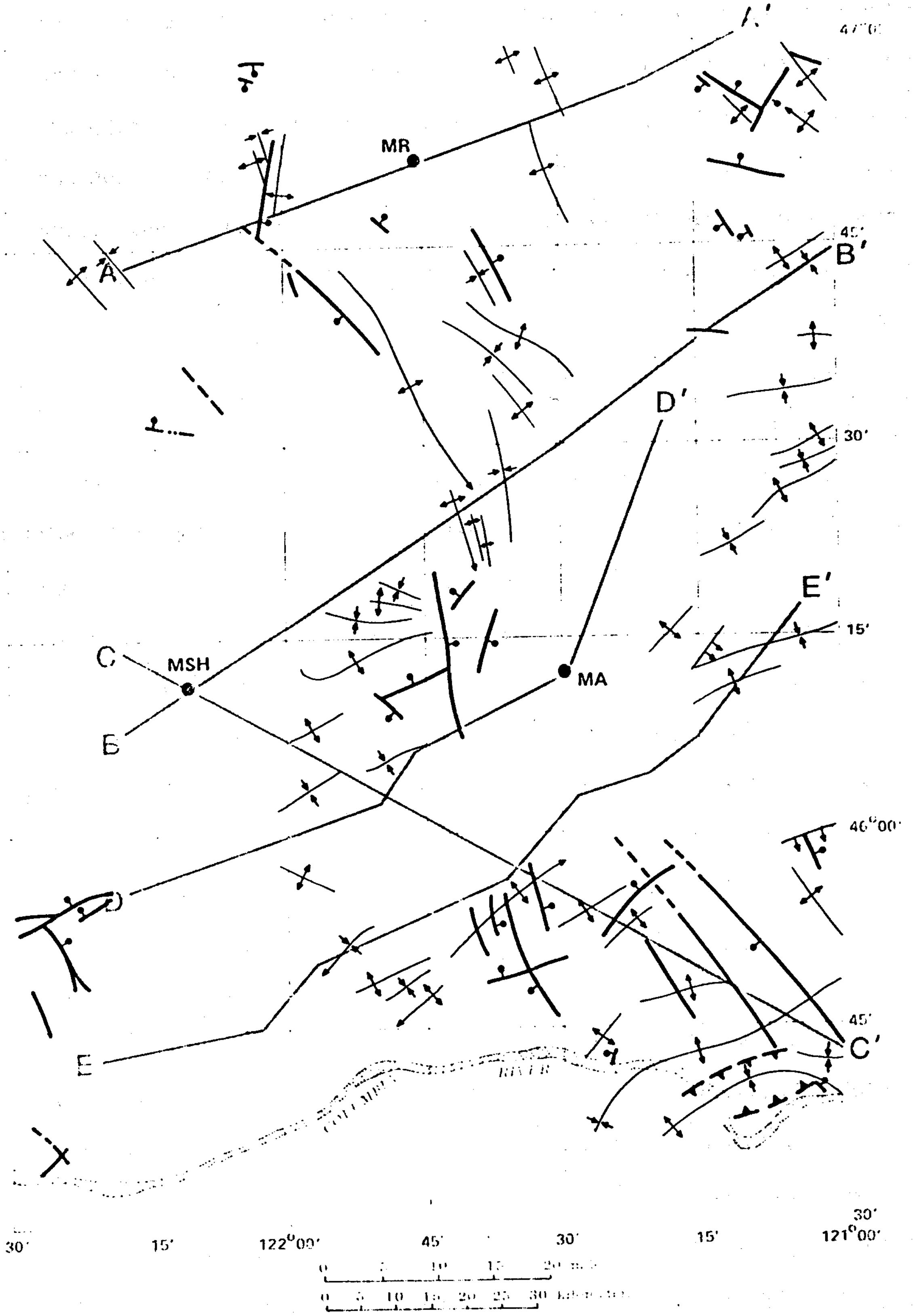

Figure 5-3. — Tectonic map of the Southern Cascade Mountains study area showing location of major faults and fold axes (after WPPSS, 1981). Section lines are same as those shown in Figure 5-2.

Numerous igneous intrusions 50 to 5 m.y. in age are also present in the map area. The map scale of figure 5-2 permitted showing only the largest of the plutons, or, especially near Mt. Rainier, forced depiction of complexly intruded areas as a single, uniform-appearing intrusion. Major plutons range from granodiorite to quartz diorite in composition and appear to have been emplaced at shallow depths within the Tertiary volcanic group between 25 and 10 m.y. ago.

Regional Gravity Patterns

A compilation gravity anomaly map of the Pacific Northwest (Riddihough, 1979) is shown in figure 5-4. Cascade Range Quaternary stratovolcanoes are indicated by solid triangles. A major feature of the map is the north-south trending Bouguer anomaly low coincident with the Cascades from British Columbia to northern California. This low, hereafter termed the "Cascade low", is interrupted at latitude 46° by a Bouguer high. As the Bouguer gravity high lies in the vicinity of the Columbia River, it will be termed the "Columbia River high" throughout this report.

Other major gravity features of the Pacific Northwest include the pattern of negative offshore free-air anomalies, high positive Bouguer anomalies about 100 km inland along the Coast Ranges, and the progressive decrease of Bouguer values eastward through the Puget-Willamette Lowlands. This pattern culminates in the aforementioned Cascade low. East of the Cascade Range, in the Columbia River Basin, Bouguer values rise gradually toward a -50 mgal high centered near the Pasco Basin.

Riddihough (1979) interpreted the gravity features of the Pacific Northwest as evidence for subduction zone geometry in the region. Offshore negative free-air anomalies coincide with the position of a buried submarine trench.

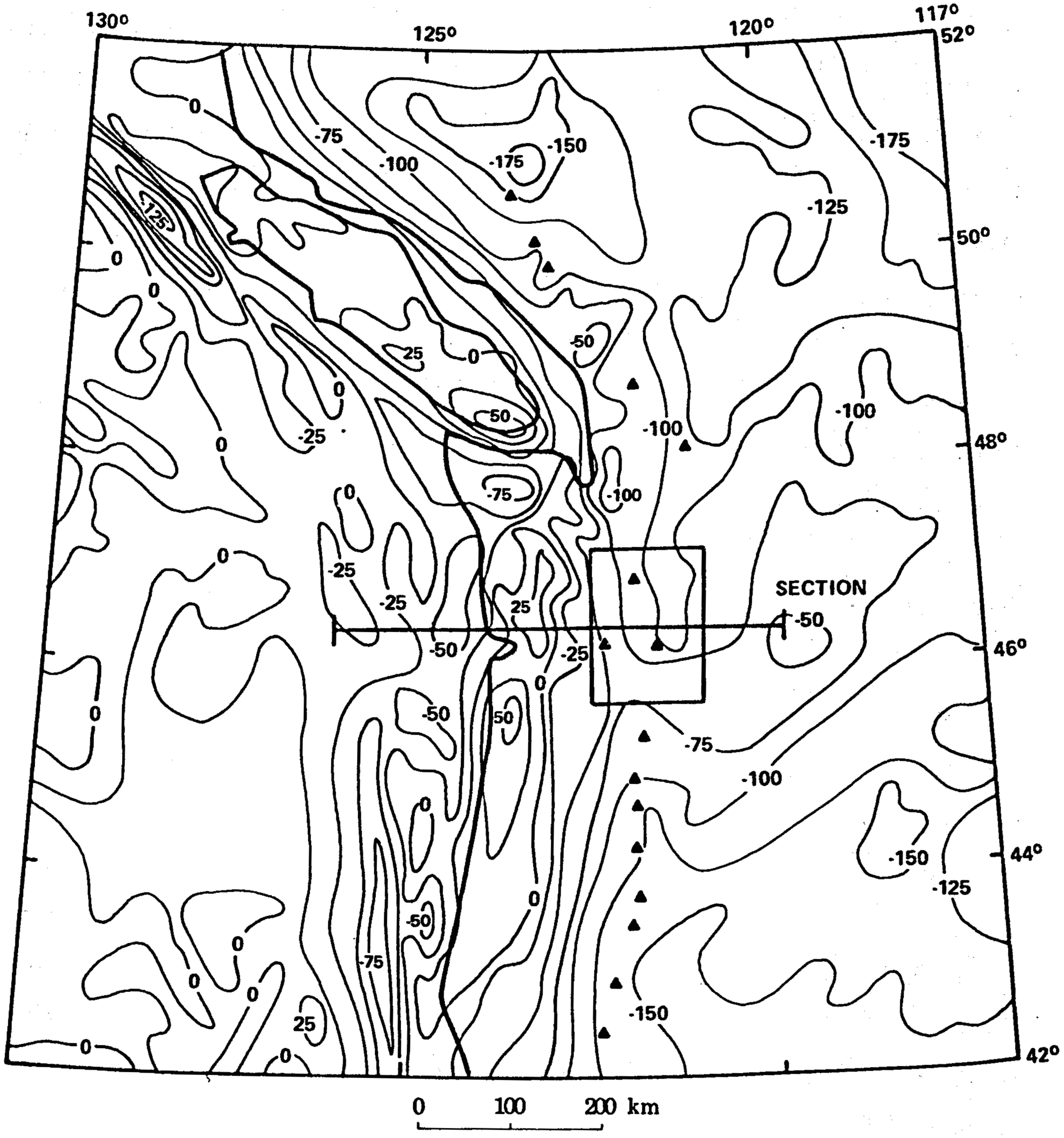

Figure 5-4. — Compilation gravity anomaly map of the Pacific Northwest (after Riddihough, 1979). Contour interval is 25 mgals. Bouguer reduction density is 2.67 g/cc. Anomalies are free-air at sea; Bouguer for land areas. "Section" marks location of profile shown in Figure 5-5. Box shows location of study area.

Inland Bouguer anomalies reflect, at least on a coarse scale, the depth to the dense crust of a subducted oceanic plate. Riddihough's model, shown in figure 5-5, indicates that the subducted plate lies at depths in excess of 100 km within the study area. At these depths, the descending plate is shown as thinning and steepening in dip slightly, presumably in response to density increases and melting associated with the pressure-temperature-chemical regime of the subduction environment The gradual increase of Bouguer values eastward from the southern Cascades across the western Columbia River Basin is ascribed by Riddihough to an east-thickening prism of high density material at lower crustal to upper mantle depths of 25 to 50 km. Note that beneath the southern Cascades, standard densities (Woolard, 1969) of 2.92 g/cc for the crust (33 km thick) and 3.31 g/cc for the mantle are assigned.

Interpretation of Gravity Data

The complete Bouguer gravity anomaly map for the southern Cascades is presented in figure 5-6. Additional gravity data south of the Columbia River is after Couch and others (1981b). The map has been simplified and reduced from the original draft copy, a process which prohibits resolution of many interesting local anomalies. However, the map format is suitable for discussion of major regional-scale trends and correlations.

The first step in analysis of any body of gravity data is selection of a proper Bouguer reduction density. Unfortunately, this is a difficult process, involving knowledge of subsurface densities that usually forms the reason for conducting the gravity survey in the first place. As a substitute for detailed knowledge of regional density variations, figure 5-6, like most regional-scale maps uses a reduction density of 2.67 g/cc. This corresponds to the average density of continental rocks.

Williams and Finn (In Preparation), Finn and Williams (1982), and Couch and Gemperle (1979) present evidence that 2.43 to 2.20 g/cc is a more suitable

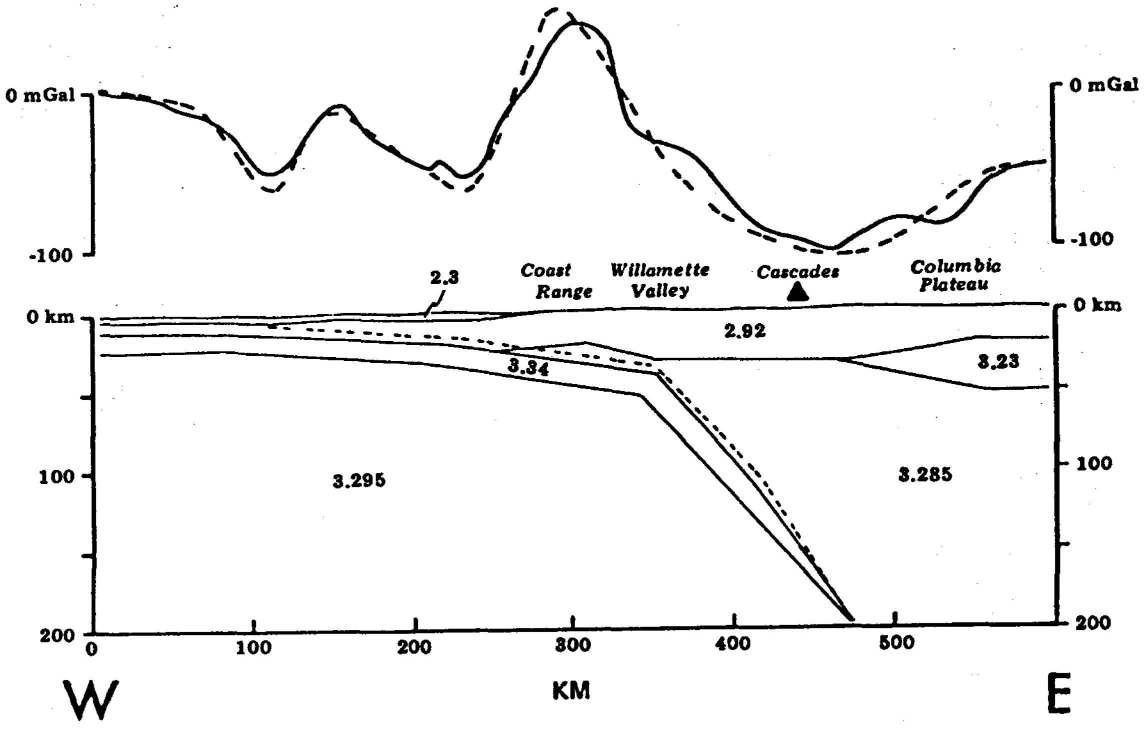

Figure 5-5. — Gravity and structural profile along section line shown in Figure 5-4 (after Riddihough, 1979). Gravity profiles are free-air over sea and Bouguer over land; solid line is observed gravity, dashed line is gravity calculated from structural model. Densities are rock units in g/cc shown in structural profile. Dashed line in structural profile is the upper boundary of oceanic crustal material. The profile is based in part on deep seismic data. No vertical exaggeration.

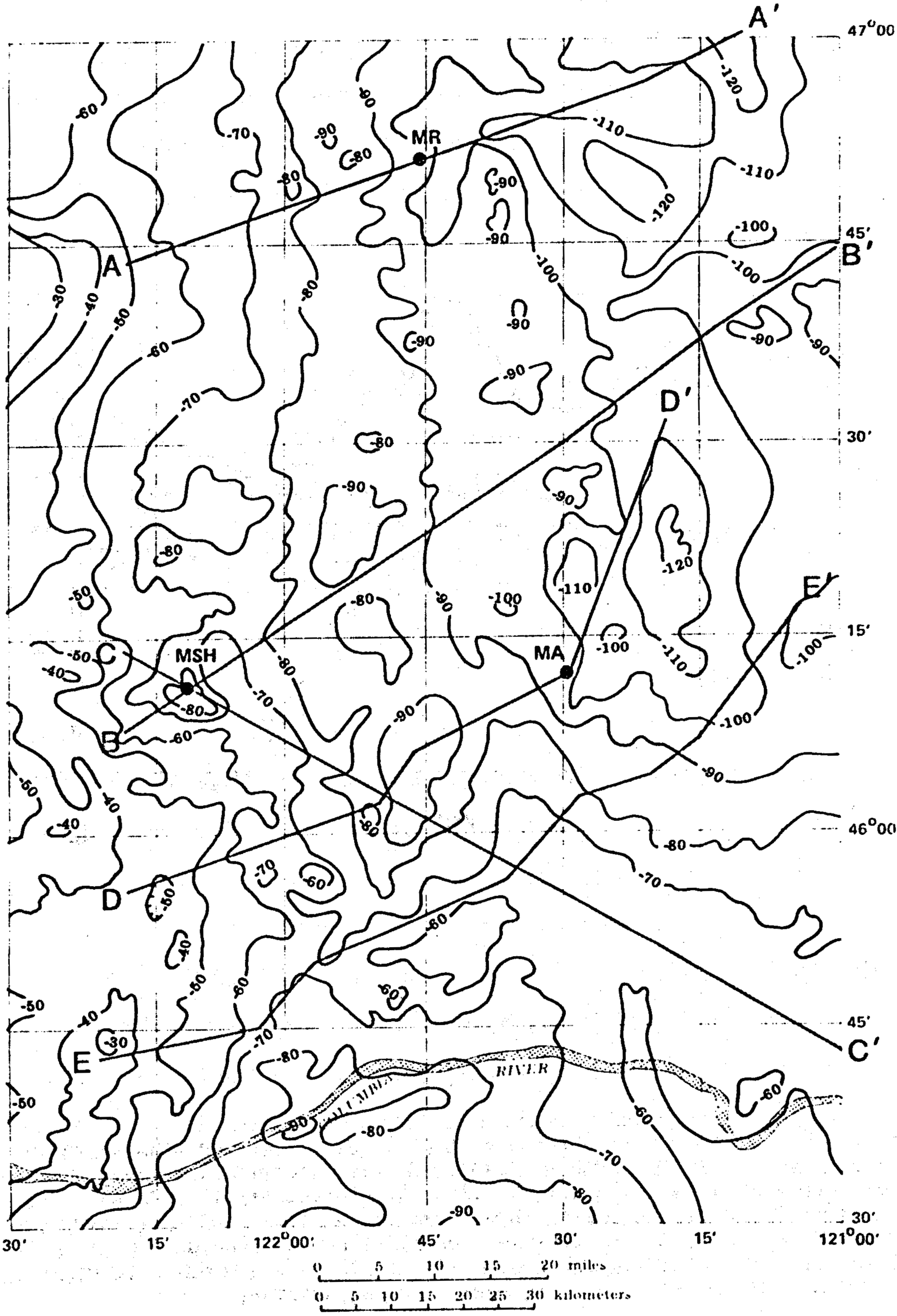

Figure 5-6. — Complete Bouguer gravity anomaly map of the Southern Cascade Mountains (simplified from Danes, in preparation). Contour interval is 10 mgals. Gravity data south of the Columbia River, simplified from Couch and others (1981b). Section lines are the same as those shown in Figure 5-2.

range of reduction densities for volcanic terrain such as that found in the southern Cascades. The effect of using too high a reduction density is especially pronounced in the vicinity of a large volcanic edifice where overcorrection for the topographic expression of the volcano produces a gravity low mimicking the topography (assuming the edifice to be composed of less than average density rocks). While this factor should be kept in mind during the course of interpretation, particularly near the large stratovolcanoes, use of a 2.67 g/cc density reduction is continued in this study. This permits simple comparison of gravity data from the southern Cascades with that of adjacent provinces such as the Columbia Basin (WPPSS, 1981), the Oregon Cascades (Couch and others, 1981a, 1981b) and the Puget Lowlands (Danes, 1969) where data reductions have been performed at 2.67 g/cc. Release of the principal gravity facts for the southern Cascades concurrently with the complete Bouguer map will permit other investigators to experiment with alternate reduction densities.

Previous discussion of Pacific Northwest gravimetry outlined a model explaining the gross variation of Bouguer gravity and free-air gravity values over a very large area. Lateral density variations at lower crustal to mantle depths were ascribed to subduction of a dense oceanic plate. Within the southern Cascades, control of Bouguer values by depth to the subducted plate should also be visible as a "long wavelength signal". Isolation of that portion of the total gravity field due to deep-seated lateral density contrasts from that arising from shallower structures is called regional separation. There are many techniques of regional separation (see Chapter 4, this volume), each possessing individual strengths and weaknesses in terms of computational ease, interpretive bias, and degree of control over the filtering process. Polynomial surface fitting, or trend-surface analysis (Davis, 1973) was used in this report.

In trend-surface analysis, a simple continuous surface which best fits the observed distribution of map data is calculated using the least squares criterion. The trend surface is useful in identifying regional patterns present in complex sets of geographic data. Subtraction of the regional trend from the observed values provides a remainder or residual which represents that portion of the data not contained in or explained by the regional pattern. In gravity work, the trend surface is identified as the regional component of the total anomaly field due to deep-seated density contrasts. The residual Bouguer values reflect density contrasts at shallower crustal levels, and hence are of greater interest in a geothermal exploration project.

A regional Bouguer anomaly map for the southern Cascades is shown in figure 5-7. The map was constructed by sampling the complete Bouguer anomaly map at regular intervals (15 minutes) and using this data matrix as input to a trend surface computer program (after Davis, 1973). The resulting regional trend accounts for 81.9% of the variation in data and is described by a second-order polynomial equation.

Features of the regional Bouguer anomaly map are similar to those noted on the compilation gravity map of the Pacific Northwest (figure 5-4). The rapid decrease of Bouguer values to the east from longitude $122^{o}30'$ to 122^{o} $00'$ is correlated to the depth of a dense, subducted oceanic plate, following the model of Riddihough (1979). The Cascade low is contained in a broad area from longitude $122^{o}00'$ to $121^{o}00'$ and corresponds roughly with the "root" of the mountain range. This low density root provides the means for isostatic compensation of the excess mass of the range (Williams and Finn, In Preparation). Effect of the Columbia River high upon the trend model is indicated by the progressive increase of Bouguer values in the Cascade low from a minimum of -110 mgals at latitude $47^{o}00'$ to a maximum of -75 mgals at the Columbia River.

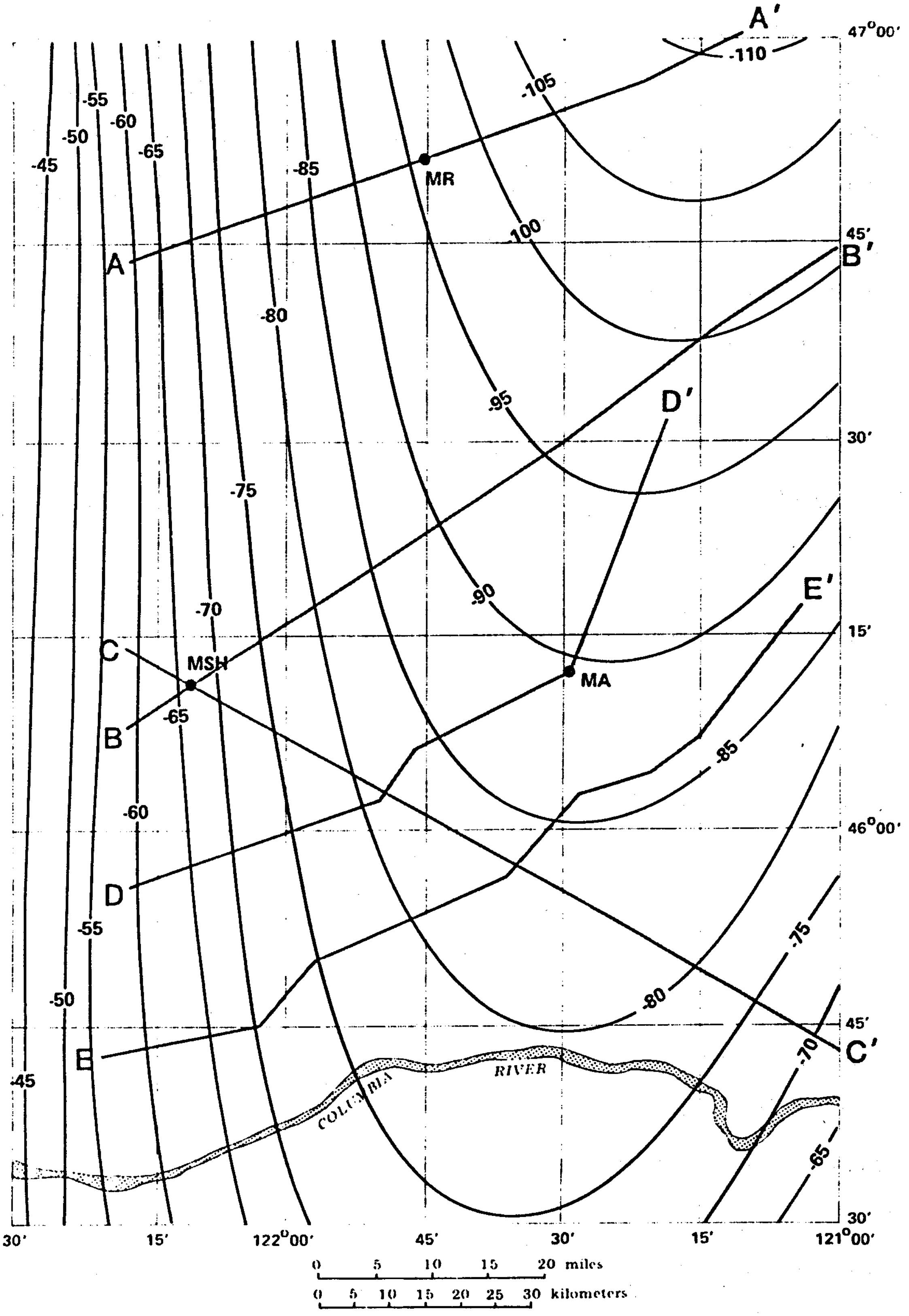

Figure 5-7. — Regional Bouguer gravity anomaly map of the Southern Cascade Mountains. Map constructed by fitting second order polynomial trend surface to complete Bouguer gravity map of Figure 5-6. Contour interval is 5 mgals. Section lines are same as those shown in Figure 5-2.

Interestingly, the change in magnitude of the Cascade Low is in inverse relation to the amount of structural uplift along the north-south Cascade trend. This relationship is also apparent to the north of the study area, in the North Cascade Mountains (Bonini and others, 1974). A possible explanation for this gravity pattern is a thinning to the south of a low density infrastructure composed of granitic plutons and metamorphic rocks.

A residual Bouguer gravity anomaly map (figure 5-8) was produced by graphically subtracting the complete Bouguer map from the regional anomaly map and hand-contouring the residual Bouguer values. Analysis of the residual anomalies was performed on a profile basis. Five geologic cross-sections of the study area (simplified from Hammond, 1980) were prepared along a variety of azimuths, and gravity profiles from the complete, regional, and residual maps plotted over them. There are a number of advantages to using gravity and geologic profiles instead of a map format: first, contour maps, even when colored, are difficult to interpret; second, both the extent and thickness of geologic units are indicated; third, correlations between gravity and topography may be easily detected; and fourth, complete, regional and residual gravity data may be conveniently compared with geology on a single plot. The location of the section lines is indicated on previously referenced geologic and gravity maps of the study area (figures 5-2, 5-3, 5-6, 5-7, and 5-8).

Section A-A' (figure 5-9) is a profile through the northern portion of the map area. The most prominent feature of the section is the negative residual anomaly associated with the Mt. Rainier area. The anomaly is of greatest magnitude northeast of Mt. Rainier in a region underlain by volcanic strata of the lower division of the Tertiary volcanic group. These strata are complexly intruded by the quartz monzonites, diorites, and granodiorites of the Tatoosh and

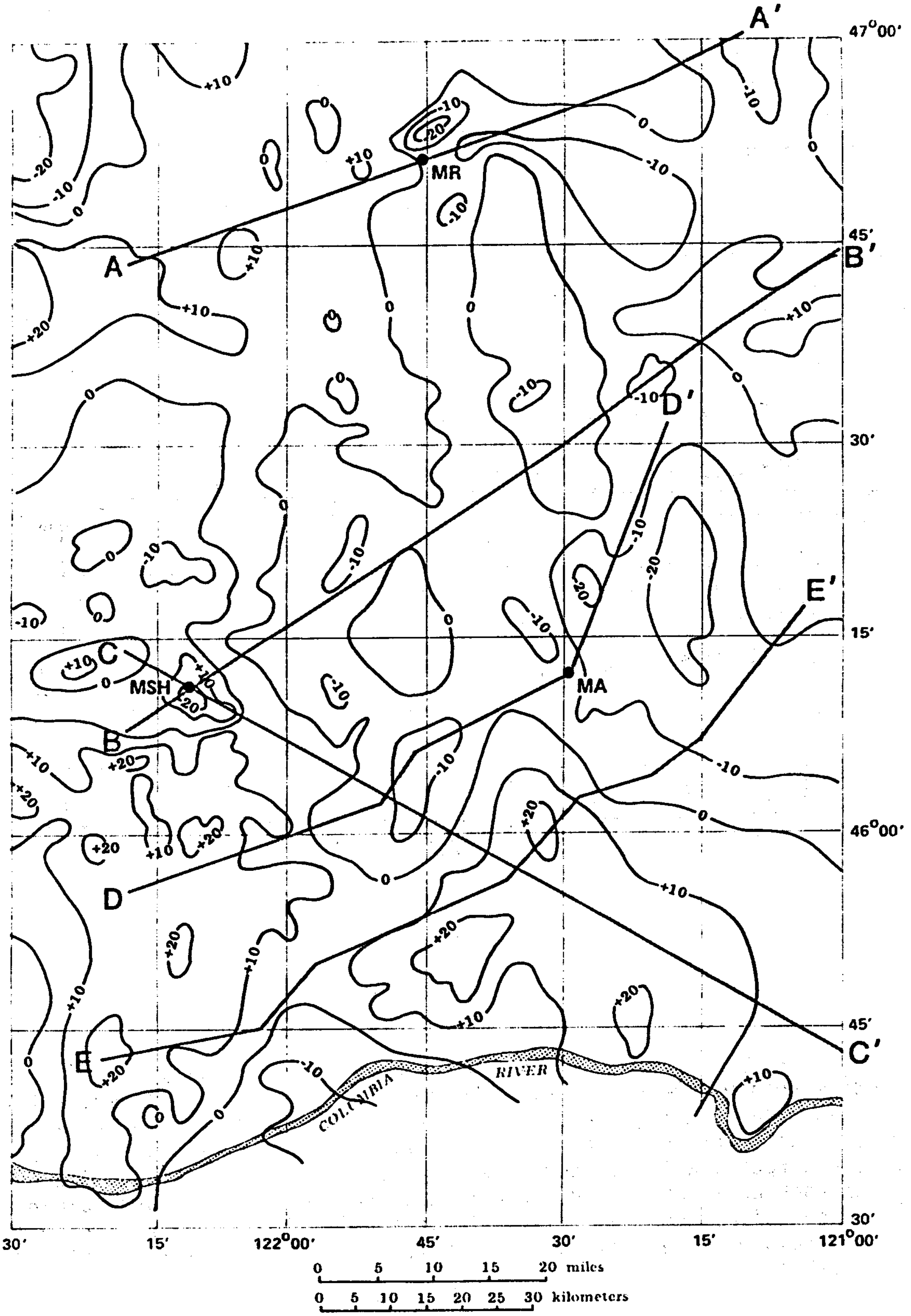

Figure 5-8. — Residual Bouguer gravity anomaly map of the Southern Cascade Mountains. Map constructed by graphically subtracting the complete Bouguer anomaly map (Figure 5-6) from the regional Bouguer anomaly map (Figure 5-7). Contour interval is 5 mgals. Section lines are the same as those shown in Figure 5-2.

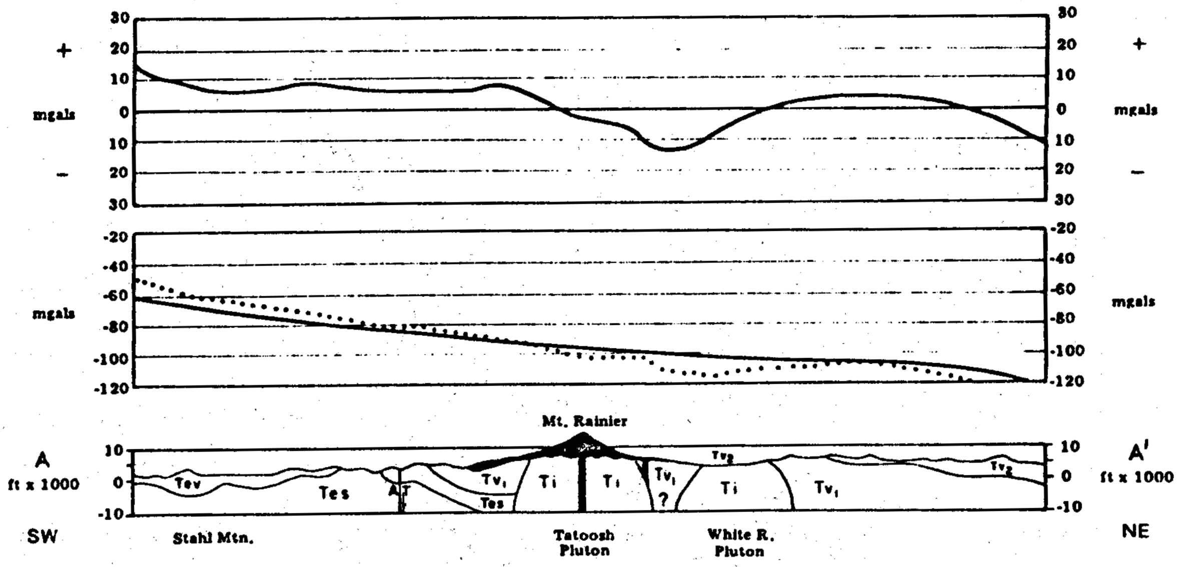

Figure 5-9. — Section A-A'. Geology simplified from Hammond (1980). Uppermost plot is residual Bouguer gravity profile. Middle plot is complete Bouguer (dashed line) and regional Bouguer (solid line). In geologic cross-section, symbols are those used in Figure 5-2 and Table 5-1 except for Tev (Eocene volcanic rocks) and Tes (Eocene sediments). In Figure 5-2 and Table 5-1, these rock units are grouped under Tesv (Eocene sediments and volcanic rocks). Black symbol corresponds to Qva of Table 5-1 and Figure 5-2, Strike-slip fault shown with relative dip-slip movement (arrow), and away (A) and toward (T) symbols.

White River plutons. The composite cone of Mt. Rainier itself does not possess a particularly distinctive gravity signature at the scale of section A-A'. Only a slight positive perturbation in the large residual low marks the position of the stratovolcano. Further interpretation of the anomalies associated with Mt. Rainier and other stratovolcanoes in the study area is deferred until the discussion portion of this paper.

Section B-B' (figure 5-10) extends from Mt. St. Helens northeast through the Goat Rocks area. Unlike Mt. Rainier, Mt. St. Helens possesses a striking residual and complete Bouguer gravity anomaly minimum centered directly over the volcanic edifice. Between Mt. St. Helens and the Cispus River, in a structural basin containing a thick section of middle division Tertiary volcanic rocks, another broad residual gravity low is present. The gravity pattern over the Goat Rocks stratovolcano is subtle, consisting only of a small magnitude residual low. Northeast of Goat Rocks, an interesting -15 mgal residual low occurs in an area underlain by pre-Tertiary metasedimentary lithologies. The metasediments do not appear to differ enough in bulk densities from surrounding volcanic strata to explain the mass deficiency indicated by the gravity low. One possible explanation for the gravity pattern is a large, relatively low density silicic pluton beneath the pre-Tertiary strata. Uplift of the pre-Tertiary block may have been a response to intrusion of the pluton.

Section C-C' (figure 5-11) extends southeast from Mt. St. Helens toward the Columbia River. In addition to providing another view of the Mt. St. Helens residual gravity low, the profile transects a major Quaternary basalt field at Lemei Rock. The Lemei Rock area is shown on the geologic cross-section as a broad syncline capped by a thin (200 m or less) cover of Quaternary basalt.

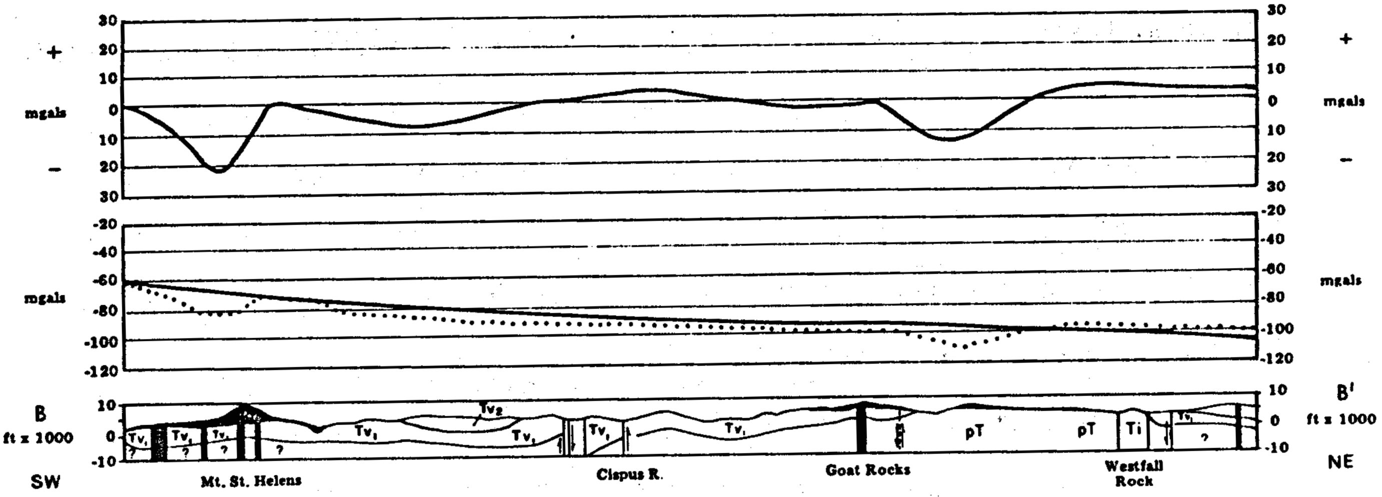

Figure 5-10. — Section B-B'. Geology simplified from Hammond (1980). Uppermost plot is residual Bouguer gravity profile. Middle plot is complete Bouguer (dashed line) and regional Bouguer (solid line). In geologic cross-section, symbols are those used in Figure 5-2 and Table 5-1 except for black, which corresponds to Qva.

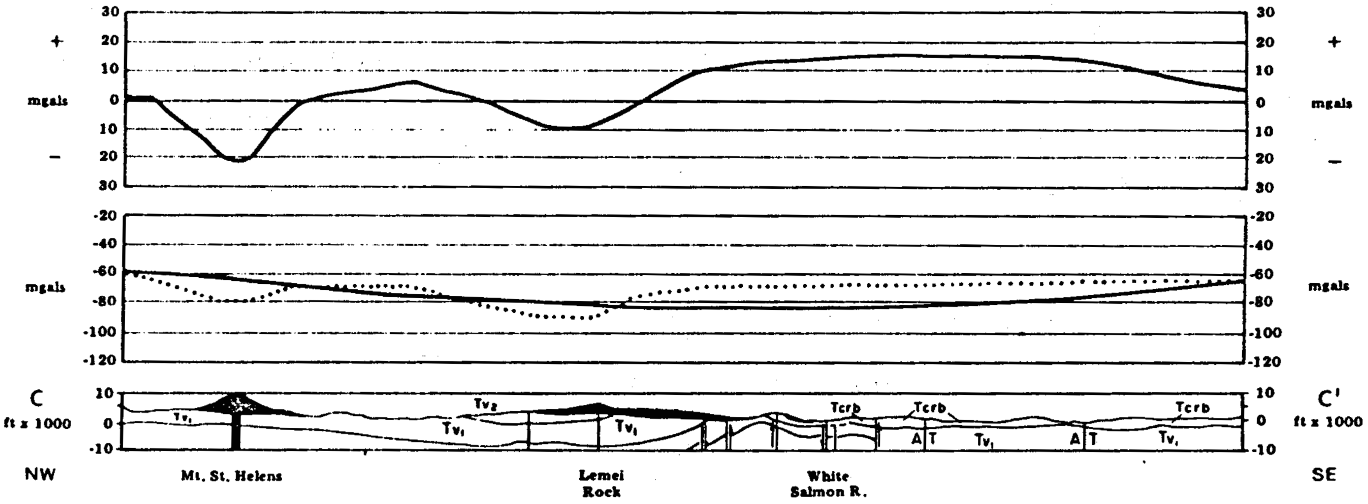

Figure 5-11. — Section C-C'. Geology simplified from Hammond, 1980. Symbols in geologic cross-section and those used in Table 5-1 and Figure 5-2 except for black which corresponds to Qva at Mount St. Helens, and Qvb at Lemei Rock. Dip-slip faults show relative movement with arrows, strike-slip faults show relative movements with away (A) and toward (T) symbols. Upper plot is residual Bouguer profile. Middle plot shows complete Bouguer profile (dashed line) and regional Bouguer profile (solid line).

This structure is apparently a southern continuation of the same sedimentary basin shown in section B-B' between Mt. St. Helens and the Cispus River. As in section B-B', the basin possesses a pronounced residual gravity minimum. Previous workers (Stricklin, 1975; Hammond and others, 1976; and Schuster and others, 1978) also recognized the presence of a large complete Bouguer gravity low in the Lemei Rock area and suggested that the anomaly is due to thickening of Tertiary strata in the syncline, fracturing, brecciation and hydrothermal alteration of pre-Quaternary rocks as a result of basaltic magmatism, and/or presence of a shallow magma chamber 1 to 2 km beneath the surface. However, heat-flow and geothermal gradient data (Schuster and others, 1978) indicate that a large shallow heat source (magma body) is not present in the area.

Section D-D' (figure 5-12) provides a cross-section of the Yale Lake-Mt. Adams-Lakeview Mountain area. Residual gravity anomalies in the profile clearly reflect the Yale Lake anticline (+15 mgal anomaly) and the broad basin containing a thick Tertiary-volcanic group section overlain by Quaternary basalts (-15 mgal anomaly). The basin is the same structure discussed in section C-C' above. The Yale Lake structure possesses a sharp residual gravity peak superimposed on the broad gravity high. The gravity peak may correspond to a local, relatively high-density structure. Given the proximity of the Yale Lake anticline to the Silver Star Pluton and to smaller intrusive bodies south of Mt. St. Helens (figure 5-2), the gravity peak may be due to an unexposed Tertiary pluton (see discussion of the Silver Star Pluton below).

Section D-D' also illustrates the gravity and geological features of the Mt. Adams area. Like Mt. Rainier, Mt. Adams does not possess a distinctive gravity signature. The composite volcano is contained on the southwest side of a prominent residual and complete Bouguer gravity minimum.

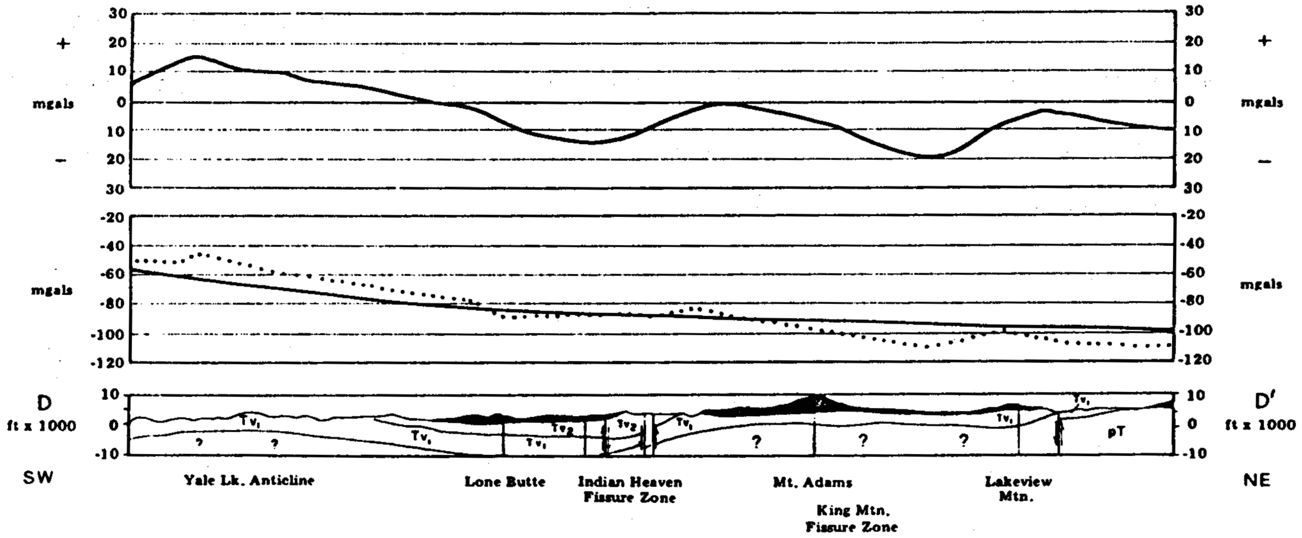

Figure 5-12. — Section D-D'. Geology simplified from Hammond, 1980. Symbols in geologic cross-section are those used in Table 5-1 and Figure 5-2 except for black which corresponds to Qva at Mount Adams and Qvb elsewhere. Dip-slip motion on faults shown with arrows. Upper plot is residual Bouguer profile. Middle plot shows complete Bouguer profile (dotted line) and regional Bouguer profile (solid line).

The maximum magnitude of the minimum occurs in the area between Mt. Adams and Lakeview Mountain, a Quaternary basalt eruptive center. The geological cross-section of section D-D' indicates that the area containing the gravity minimum is underlain by flat-lying Tertiary volcanic rocks topped by Quaternary basalt flows. However, subsurface control in the area is very poor due to the basalt cover, and the cross-section may be too simple. The gravity minimum suggests that one or all of the following features could be present in the area: 1) a sedimentary basin containing a thick section of Tertiary strata; 2) a shallow, low-density magma body; 3) an ancient (solid) low-density pluton; or, 4) extensive brecciation and hydrothermal alteration resulting from Quaternary basaltic volcanism. However, the current level of understanding of the geology of the southern Cascades does not permit a simple selection of a preferred structural model for the Mt. Adams area, or, in fact, for many areas in the southern Cascades containing gravity minima.

The final profile, section E-E', is shown in figure 5-13. This section crosses the area contained in the Columbia River high, and bisects a major pluton and several Quaternary basalt fields. The Miocene(?) Silver Star Pluton is the largest exposed intrusion south of the Spirit Lake area. The striking +20 mgal residual associated with the pluton is puzzling given its granodioritic composition and intrusion into intermediate to basic composition lower division Tertiary volcanic rocks. Two explanations may account for the gravity pattern: first, the bulk density of the lower division strata may be less than expected due to brecciation, vesicularity, and the presence of porosity in sedimentary rocks. Conversely, the Silver Star Pluton may be somewhat denser than a typical granodiorite because of alteration to sulphide-bearing uralite, chlorite, sericite, and kaolinite (Hammond, 1980, p. 24). Secondly, the pluton may possess a dense "root" as a result of magmatic differentiation, although there is no direct evidence to substantiate this.

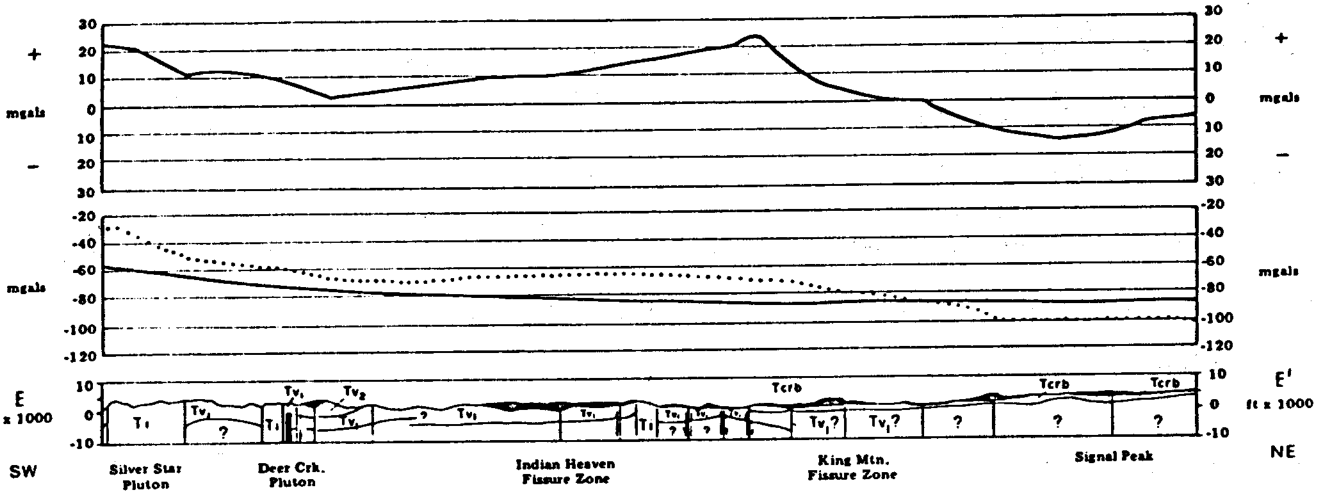

Figure 5-13. — Section E-E'. Geology simplified from Hammond, 1980. Symbols in geologic cross-section are those used in Table 5-1 and Figure 5-2 except for black which corresponds to Qvb. Dip-slip motion on faults shown with arrows. Upper plot is residual Bouguer profile. Middle plot shows complete Bouguer profile (dotted line) and regional Bouguer profile (solid line).

Gravity patterns in the remainder of the section cannot be directly ascribed to mapped geological structures. Of particular interest are the prominent residual high in the vicinity of the King Mountain fissure zone and the broad residual low in the vicinity of Signal Mountain. The geological cross-section does not indicate any structures capable of producing such striking highs and lows. However, subsurface control in the area transected by the profile is poor, and the actual geology may be more complex. While it may be argued that residual gravity highs are to be expected over Quaternary basalt fields such as the Indian Heaven and King Mountain fissure zones, other areas of basalt outcrops, whether of Quaternary age or belonging to the Miocene Columbia River Basalt Group, show no such positive residual patterns, probably because of the thinness of the basalt flows. At this time, the gravity anomalies can only be ascribed to currently unmapped structures below the Quaternary cover, or to more deep-seated features related to whatever high-density lithologies are responsible for the Columbia River high.

Discussion

Residual gravity profiles drawn across the study area reflect, in part, open, irregularly spaced, typically northwest to north-south trending fold structures developed in Tertiary volcanic and sedimentary strata. Over structurally high areas, residual anomalies are often positive; the converse is true over structurally depressed regions. This pattern appears to be a simple consequence of elevating or depressing dense basement rocks upon which the southern Cascade Mountains are built. At this time, little can be said about the nature of the Cascadian basement.

Large igneous intrusions exhibit both positive and negative residual anomalies in the southern Cascades. Positive residuals over at least one pluton (the Silver Star; see section E-E') are ascribed to hydrothermal alteration of granodiorite to sulphide-bearing layer silicates coupled with possible low bulk densities of intruded Tertiary volcanic rocks. A dense gabbroic "root" beneath the exposed granitic body is also a possibility, although no direct evidence exists for such a feature.

The gravity signatures of Quaternary volcanic centers are of special interest to geothermal resource exploration. Quaternary basaltic fields tend to possess negative residual anomalies. Given the high density of basalt (2.7 to 3.30 g/cc), the negative residuals present an apparent problem in interpretation. However, the Quaternary basalts are generally too thin to affect gravity values at the scale of the Bouguer maps used in this report. Geologic mapping suggests that basaltic volcanism is commonly localized at structural lows containing thick sections of middle and upper Tertiary volcanic strata. Residual gravity lows over the basalts are therefore interpreted to be a result of local crustal depression. Hydrothermal alteration and brecciation associated with the volcanism may also contribute to the residual low by reducing bulk density of intruded pre-Quaternary rocks.

Interpretation of the gravity pattern observed at Quaternary stratovolcanoes is complicated by uncertainties regarding choice of reduction densities (see discussion above). In addition, terrain corrections are a special problem near these huge volcanic edifices (see Chapter 4, this volume). The discussion below is meant to emphasize the need for further research in which better descriptions of bulk rock densities at, beneath, and around stratovolcanoes are formulated.

A number of previous workers have investigated gravity patterns at Cascade stratovolcanoes. Regional trends of gravity data have been used to examine the tectonic setting of the Cascade eruptive centers. Danes (1969) associated offsets in the north-south trend of the Cascade low with the position of Cascade composite cones. Hughes and others (1980) cite changes in petrology and eruptive style of Cascade volcanoes that suggest the Cascade Range is broken into segments by transverse faults that strike northeast in the direction of plate convergence. While Hughes and others used changes in the strike of the buried submarine trench of offshore Washington and Oregon to define segment boundaries, it may be that the offsets in gravity trends also reflect transverse faults.

Analyses of gravity data at individual stratovolcanoes have been performed by Braile (1970), Couch and Gemperle (1979), Rowley (1982), Finn and Williams (1982), and Williams and Finn (In Preparation). The work of Braile will be emphasized here because his work at Mt. St. Helens clearly outlines the various problems faced by gravity investigators in the region.

Braile conducted a gravity traverse over Mt. St. Helens in which a sharp negative residual gravity anomaly was found. His conclusions, based upon a reduction density of 2.3 g/cc for the cone, and 2.7 g/cc for the surrounding volcanic terrain, suggested that the residual anomaly could be caused by one or some combination of the following subsurface features:

1) an acidic pluton beneath the mountain of lower density than surrounding rocks;
2) a magma chamber beneath the volcano in which thermal expansion of andesitic-dacitic magma accounts for the mass deficiency;
3) older low density sediments beneath the mountain; and
4) a mass of porous volcanic rock emplaced below the cone by some igneous process.

Braile also calculated the effect of crustal loading by the volcanic edifice and demonstrated that the residual low could not be accounted for by isostatic adjustment.

Because all of the stratovolcanoes in the study area (Mount Rainier, Adams, St. Helens, and Goat Rocks) are near to, or possess a residual gravity low, serious consideration must be given to each of Braile's models. As will become apparent, current levels of understanding of the distribution of rock densities around and beneath stratovolcanoes do not permit simple selection of a preferred model.

Geologic mapping demonstrates that Mt. Rainier is underlain, at least in part, by large granitic plutons (e.g. the Tatoosh and White River plutons). This led Danes (1964) to suggest that the prominent Bouguer low on the north side of the mountain (see figures 5-6 and 5-9) was caused by a silicic pluton. Rowley (1982) also isolated, named, and described four plutons in the area surrounding Mt. Adams on the basis of gravity evidence. However, the details of Rowley's study are not currently available, and it is not clear whether the plutons possess a negative residual gravity signature. The Bouguer gravity data used in this report do not display any indication of prominent gravity signals in the immediate vicinity of Mt. Adams, at least with a reduction density of 2.67 g/cc. Elsewhere in the southern Cascades plutons are relatively common and there is no reason that many more, even several of batholith size, cannot be hidden beneath Quaternary and Tertiary volcanic cover.

The issue of whether negative gravity anomalies at stratovolcanoes are due to low density plutons is complicated by two factors: first, some granitic plutons in the study area possess clear, well-defined gravity highs (see discussion of the Silver Star Pluton in section E-E'). It is this consideration which led Braile to dismiss the model of a low density pluton for Mt. St. Helens.

The second factor is more fundamental and poses serious questions about the applicability of a considerable volume of previous work done in the southern Cascades; namely, that use of a 2.67 g/cc density reduction can impart a negative Bouguer "artifact" to stratovolcanoes. Work by Williams and Finn (In Preparation) at Mt. St. Helens demonstrates that a positive anomaly is present at the mountain when a density reduction of 2.2 g/cc for both the cone and surrounding area is used. They tentatively interpret the positive anomaly to be a subvolcanic intrusion that is denser than surrounding rocks. (Note: gravity data used in this report, and by both Braile and Williams and Finn were collected prior to the May 18, 1980 eruption of Mt. St. Helens. It is possible that the mountain's gravity signature was altered by the eruption).

The principal difference between Braile's and Williams and Finn's work seems to be the choice of reduction densities for rocks surrounding the volcanic edifice, as both agree that the cone itself possesses high porosity. Resolution of this issue is dependent upon measurement of bulk rock densities around and beneath the volcano. As direct measurement is either not feasible or inaccurate, recourse will probably have to be made to indirect methods such as seismic refraction.

Detection of shallow bodies of magma is one of the primary concerns of any geothermal exploration program, hence special interest is assigned to the second of Braile's models. Braile (1970, p.26) dismissed the magma chamber model for the following reasons: "...a magma chamber does not appear to be quantitatively sufficient to produce the entire observed anomaly. A magma chamber, having only a small density contrast with the surrounding basement rock, would have to be very large to produce the observed minimum gravity value and would not be expected to yield such a sharp anomaly."

It may be argued that the catastrophic eruption of Mt. St. Helens in 1980 proved Braile wrong. However, it is not clear whether the magma leading to the eruption was emplaced into the cone from a shallow, large reservoir beneath the mountain, or was derived from a deeper source that would not necessarily produce a residual gravity anomaly.

The third model, that of older, low density sediments beneath Mt. St. Helens causing the residual low, was also dismissed by Braile on the grounds that low density sandstones and mudstones were too thin to account for the gravity feature. Furthermore, Braile deemed it an unlikely coincidence for a sedimentary basin to be circular and centered exactly beneath the mountain. However, several lines of reasoning give some credence to the third model. First, Braile did not account for the low density volcanic facies which are abundant in the Tertiary volcanic strata surrounding Mt. St. Helens. Andesitic breccias and hydrothermally altered or slightly metamorphosed rocks, both characteristic of the lower division Tertiary volcanic rocks, can easily possess the bulk density of many sediments. Secondly, there exists an apparent association between Quaternary basaltic volcanism and structural lows in the southern Cascades that suggests a causal relationship between crustal depression or extension, sedimentation, and volcanic activity. Whether this observation will withstand the test of more detailed geological and geophysical studies, and whether it applies to composite andesitic-dacitic volcanism is not yet clear.

Emplacement of a mass of porous volcanic rock below the cone of Mt. St. Helens by some igneous process was the model favored by Braile to explain the negative residual anomaly. He proposed two mechanisms of emplacement: filling of the central eruptive pipe of the volcano with vesicular and brecciated volcanic material; and caldera formation followed by subsequent rebuilding of the volcanic cone. In detail, the first process requires filling of the central feeding pipe of the volcano to a depth of 9 miles with low density vesicular and brecciated volcanic rock (Braile, 1970, pp.30-31). Braile considers this a reasonable hypothesis given the explosive history of the mountain. However, the increase in rock density with depth of such a breccia plug was not addressed by Braile. It seems unlikely that the high porosities needed to explain the residual low could be maintained for long time periods at such depths.

Braile's caldera hypothesis was prompted by the similarities between the size and shape of the gravity anomaly at Mt. St. Helens, and that of Japanese calderas (Braile, 1970, p. 31). While a geologically reasonable cross-section showing a distribution of relatively low density material can be produced with such a model, no direct geologic evidence exists for caldera formation at Mt. St. Helens, or for the other Quaternary stratovolcanoes of the southern Cascades. However, calderas are hypothesized for eruptive centers of the Miocene Stevens Ridge Formation (Hammond, 1980); it would be valuable to closely examine gravity and supporting rock density data from such proposed centers in order to determine the nature of gravity signatures from calderas within the southern Cascades.

Recent gravity studies performed at Mt. Hood, Oregon suggest that a combination of the above factors may work to produce the observed pattern of gravity minima at or near Cascade stratovolcanoes. At Mt. Hood, Couch and Gemperle (1979) describe a north-south oriented graben-like structure that possesses a complete Bouguer gravity low of -100 mgals or less (Bouguer reduction density equals 2.27 g/cc). Mt. Hood appears to have been built within this depression. The gravity signature of Mt. Hood itself is a local gravity high, indicating either a dense central vent or core to the volcano, or that it was constructed upon a relatively dense structural high within the graben. If the north-south oriented graben was a topographic low for an extended period of time, it is reasonable to expect that relatively low density sediments or volcanic facies may have accumulated within the depression. Intrusion of andesitic-dacitic magma leading to the formation of Mt. Hood could also reasonably lead to a series of subvolcanic plutons with higher bulk densities than surrounding sediments.

Conclusion

Analysis of new complete Bouguer gravity data from the southern Cascades indicates that many gravity anomalies can be correlated reasonably well with mapped geological structures such as folds, sedimentary basins, and large plutons. However, a number of large gravity features, such as gravity minima on the north side of Mt. Rainier, northeast of Goat Rocks, and between Mt. Adams and Lakeview Mountain, cannot be readily explained on the basis of available geologic mapping. Further work, incorporating detailed estimates of rock densities, and gravity modeling of proposed structural models and comparison with observed gravity values, should be performed.

In terms of geothermal resource exploration, greatest interest is attached to understanding gravity patterns over areas of youthful, relatively silicic volcanism. Because incorrect selection of Bouguer reduction densities may mask important gravity features or impart a gravity artifact in such regions, particular effort should be directed toward establishing a more precise estimate of rock densities in target areas. This effort could include field observation such as measuring section and describing compositional variation and degree of vesicularity, brecciation, and alteration of volcanic strata, direct measurement of rock densities in the laboratory using a representative suite of surface samples drill-hole geophysical logging, and indirect means such as seismic profiling.

In addition, a number of theoretical studies should be conducted in order to place some limits on the size, shape, and depth of structural features such as plutons, magma bodies, sedimentary basins, and calderas which have been suggested as sources for observed gravity patterns within the southern Cascades.

References

Bonini, W.E.; Hughes, D.W.; Danes, Z.F., 1974, Complete Bouguer gravity anomaly map of Washington: Washington State Division of Geology and Earth Resources GM-11, 1 map, scale 1:250,000.

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

Buckovic, W.A., 1979, The Eocene deltaic system of west-central Washington. In Armentrout, J.M.; Cole, M.R.; TerBest, Harvey, Jr., editors, Cenozoic paleogeography of the western United States: Pacific Coast Paleogeography Symposium 3, Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 147-163.

Couch, R.W.; Gemperle, M., 1979, Gravity measurements in the area of Mount Hood, Oregon. In Geothermal Resource Assessment of Mount Hood, Final Report, Hull D.A., editor: Oregon Department of Geology and Mineral Industries, Portland, p. 137-189.

Couch, R.W.; Pitts, G.S.; Gemperle, M.; Veen, C.; Braman, D., 1982, Residual gravity maps of the northern, central, and southern Cascade Range, Oregon 121°00' to 121°30' W. by 42°00' to 45°45' N.: Oregon Department of Geology and Mineral Industries GMS-26, 3 maps, scale 1:250,000.

Couch, R.W.; Pitts, G.S.; Veen, C.A.; Gemperle, M., 1981a, Free-air gravity anomaly map and complete Bouguer gravity anomaly map, Cascade Mountain Range, southern Oregon: Oregon Department of Geology and Mineral Industries GMS-16, 2 maps, scale 1:250,000.

Couch, R.W.; Pitts, G.S.; Braman, D.E.; Gemperle, M., 1981b, Free-air gravity anomaly map and complete Bouguer gravity anomaly map, Cascade Mountain Range, northern Oregon: Oregon Department of Geology and Mineral Industries GMS-15, 2 maps, scale 1:250,000.

Davis, J., 1973, Statistics and data analysis in geology: John Wiley and Sons, New York, 550 p.

Danes, Z.F., 1981, Preliminary Bouguer gravity map, southern Cascade Mountain area, Washington: Washington Division of Geology and Earth Resources Open-File Report 81-4, 1 sheet, scale 1:250,000.

Danes, Z.F., 1964, Gravity survey of Mount Rainier, Washington [abstract]: EOS, vol. 45, p. 640.

Finn, C.; Williams, D.L., 1982, Gravity evidence for a shallow intrusion under Medicine Lake volcano, California: Geology, v. 10, p. 503-507.

Hammond, P.E., 1979, A tectonic model for evolution of the Cascade Range. In Armentrout, J.M.; Cole, M.R.; TerBest, Harvey, Jr., editors, Cenozoic paleogeography of the western United States: Pacific Coast Paleogeography Symposium 3, Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 147-163.

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, Portland, 31 p.

Hughes, J.M.; Stoiber, R.E.; Carr, M.J., 1980, Segmentation of the Cascade volcanic chain: Geology, vol. 8, p. 15-17.

McBirney, A.R., 1968, Petrochemistry of the Cascade andesite volcanoes. In Dole, H.M., editor, Andesite conference guidebook: Oregon Department of Geology and Mineral Industries Bulletin 62, p. 101-107.

Pitts, G.S.; Couch, R.W., 1978, Complete Bouguer gravity anomaly map, Cascade Mountain Range, central Oregon: Oregon Department of Geology and Mineral Industries GMS-8, Portland, 1 map, scale 1:125,000.

Riddihough, R.P., 1979, Gravity and structure of an active margin--British Columbia and Washington: Canadian Journal of Earth Sciences, vol. 10, p. 350-363.

Rowley, S.H., 1982, A geophysical investigation of Mt. Adams, Washington [abstract]: EOS,vol. 63, no. 8, p. 174.

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.

Williams, D.L.; Finn, C., (In Preparation), The reduction and interpretation of gravity data in volcanic terrain and gravity anomalies and subvolcanic intrusions in the Cascade Range and at other selected volcanoes.

WPPSS, 1981, Nuclear Project No. 2, Final Safety Analysis Report, Volumes 1 and 2, Amendment 18: Washington Public Power Supply System, Richland, Washington.

Woolard, G.P., 1969, Regional variations in gravity: American Geophysical Union Monograph 13, p. 320-340.

6. HEAT-FLOW DRILLING IN WASHINGTON DURING 1981

by

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Introduction

Ponderosa Drilling and Exploration, Inc. of Spokane, under contract from the Washington Division of Geology and Earth Resources, drilled 10 shallow temperature gradient-heat flow holes in the Cascade Range of Washington during the summer of 1981. This chapter presents some of the preliminary results of this investigation. In addition, data from three holes drilled by the City of North Bonneville and one hole drilled near Snoqualmie Pass by Mr. David Dyer are included.

Figure 6-1 shows the distribution of the heat flow holes. The holes were drilled for two purposes:

(1) To obtain "regional" temperature gradient and heat-flow data in areas where there were no pre-existing wells. These data are incorporated into ongoing efforts to evaluate the geothermal resources of the Cascade Range. The Snoqualmie, White River, Clear Creek, Sand Ridge, and Tieton Willow holes were drilled for this purpose.

(2) To obtain subsurface data on rate of temperature increase, hydrology, and heat flow in the vicinity of known thermal springs. The Scenic, Trout Creek, Carson, Klickitat, and North Bonneville drill holes were drilled for this purpose, but they also contribute to the ongoing regional evaluations mentioned in (1) above.

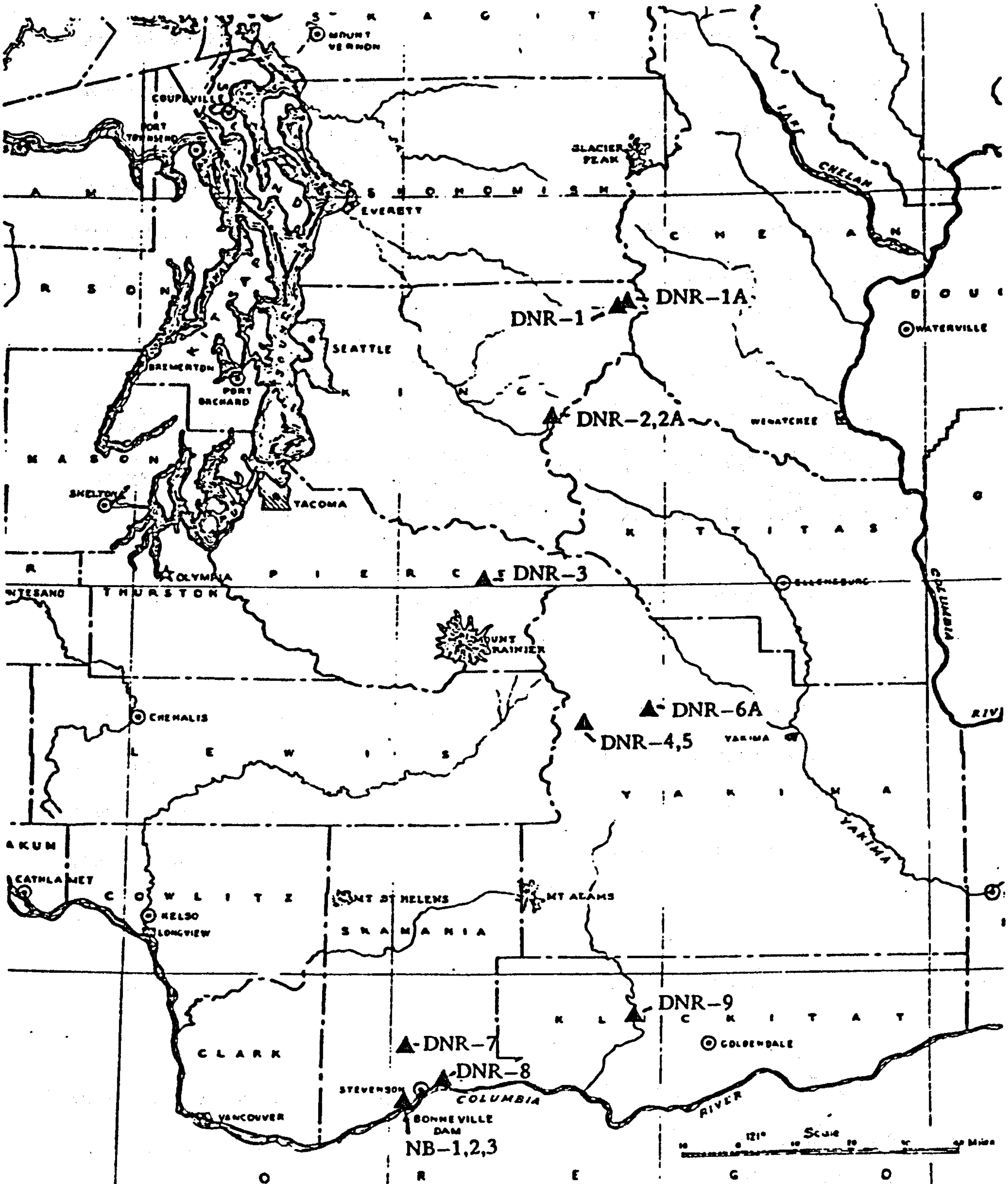

FIGURE 6-1.—Location map for heat-flow drill holes, Cascade Range, 1981. (Drill holes: DNR-1, Scenic No. 1; DNR-1A, Scenic No. 2; DNR-2, Snoqualmie No. 1; DNR-2A, Snoqualmie No. 2; DNR-3, White River; DNR-4. Clear Creek; DNR-5, Sand Ridge; DNR-6A, Tieton Willows; DNR-7, Trout Creek; DNR-8, Carson; DNR-9, Klickitat; NB-1, North Bonneville No. 1; NB-2, North Bonneville No. 2; and NB-3, North Bonneville No. 3.)

Results

Table 6-1A summarizes the results of the drilling project, including hole location, elevation, drilling period, depth, bottom hole temperature, gradients measured within specific intervals, and gradients calculated from bottom hole temperature and estimated mean annual surface temperature. Thermal conductivities and heat flow values are presented in Table 6-1b.

Temperature measurements from the individual heat flow holes are presented in Tables 6-2 through 6-15. They are shown as temperature gradient plots in figures 6-2 through 6-18.

Descripton of units penetrated by drill holes

The following descriptions of downhole lithologies are modified from two reports by Kent and Associates, Consulting Geologists, Lake Oswego, Oregon, to the Washington Division of Geology and Earth Resources and to the City of North Bonneville.

Scenic No. 1

The Scenic No. 1 drill hole penetrated granodiorite and quartz diorite for its full depth. Pratt (1958) assigned these rocks to the Mount Stuart batholith, a large granodiorite and quartz diorite intrusive which becomes locally gneissic in the Stevens Pass area. Potassium-argon ages range from 80 to 90 million years before present, with an average of 88 m.y. (Engels and Crowder, 1971).

Scenic No. 2

This drill hole penetrated landslide deposits to a depth of 33 meters. Quartz biotite schist was encountered from 33 to 82 meters, and the remainder of the hole was in biotite schist. The rock from 33 meters to the bottom of the hole is probably part of the Chiwaukum Schist, of Carboniferous age (Pratt, 1958).

TABLE 6-1A.—*Cascade Range temperature gradients from 1981 drilling*

Drill hole		County	Location			Elev. topo. (m)	Spud completion dates (1981)	Date logged (1981)	T.D. (m)	B.H.T. °C	Est. surface temp. °C	Gradient "A"[1]		Gradient "B"[3] °C/km	USGS topo. quad.
No.	Name			North latitude	West longitude							Depth interval (m)	°C/km ($S_{\hat{\beta}_1}$)[2]		
DNR-1	Scenic No. 1	King	SE¼SW¼ sec. 28 (26-13E)	47°42'39.3"	121°08'30.0"	841	6/23-25	9/25	101.5	9.77	4.7	25-55 65-101.5	47.9 (0.8) 68.0 (0.2)	50	Scenic 7.5'
DNR-1A	Scenic No. 2	King	NE¼NW¼ sec. 27 (26-13E)	47°43'12.0"	121°07'12.7"	841	6/26-29	9/25	151.5	9.97	5.0	35-151.5	36.5 (0.1)	36.5	Stevens Pass 7.5
DNR-2	Snoqualmie No. 1	King	NE¼SE¼NW¼ sec. 4 (22-11E)	47°25'32.4"	121°24'48.0"	908	6/30-7/3	10/13	146.8	7.38	5.6	35-146.8 105-146.8	15.5 (0.2) 16.5 (0.1)	12.1	Snoqualmie Pass 15'
DNR-2A	Snoqualmie No. 2 (D. Dyer well)	King	NW¼NE¼SW¼ sec. 33 (23-11E)	47°26'10.9"	121°24'55.5"	899	7/6-10	10/13	141	7.86	5.6	Disturbed artesian		16.0	Snoqualmie Pass 15'
DNR-3	White River	Pierce	NW¼SW¼ sec. 29 (18-9E)	47°00'32.4"	121°41'42.5"	853	7/13-16	9/15	143.7	8.64	6.0	35-110 110-143.7	17.6 (0.1) 23.3 (0.5)	18	Greenwater 15'
DNR-4	Clear Creek	Yakima	NW¼NW¼ sec. 3 (13-12E)	46°39'09.0"	121°19'49.7"	1006	7/17-22	9/15	153.2	13.78	5.0	60-153.2	65.2 (0.2)	57	White Pass 15'
DNR-5	Sand Ridge	Yakima	NW¼NE¼ sec. 2 (13-12E)	46°38'58.8"	121°17'01.2"	1061	7/22-24	9/15	153.3	12.36	6.5	10-35 35-85 85-153.3	31.8 (1.0) 45.4 (0.3) 41.7 (0.2)	38	White Pass 15'
DNR-6A	Tieton Willows	Yakima	SW¼NW¼ sec. 25 (14-14E)	46°40'26.2"	121°01'42.3"	744	7/27-31	9/15	153.4	24.14	10.5	10-153.4	93.0 (0.3)	89	Tieton Basin 7.5'
DNR-7	Trout Creek	Skamania	SE¼SW¼ sec. 21 (4-7E)	45°48'36.9"	121°57'11.1"	366	8/5-7	9/10	154	19.23	7.0	15-154	84.3 (0.5)	79	Wind River 15'
DNR-8	Carson	Skamania	SE¼SE¼NW¼ sec. 21 (3-8E)	45°44'04.3"	121°48'14.4"	137	8/7-11	9/14	113.2	27.80	9.0	80-113.2	365.8 (14.3)	166	Carson 7.5'
DNR-9	Klickitat	Klickitat	SW¼NW¼ sec. 24 (4-13E)	45°49'24.2"	121°07'43.1"	146	8/18-21	9/14	119.8	20.06	13.5	75-110	51.0 (0.6)	56	Klickitat 15'
NB-1	City of North Bonneville No. 1	Skamania	Sec. 40 (2-7E)	45°38'24.5"	121°58'32.2"	14	4/16-21	5/1	186	16.67	8.0	115.9-179.9	55.5 (0.3)	47	Bonneville Dam 7.5'
NB-2	City of North Bonneville No. 2	Skamania	Sec. 39 (2-7E)	45°38'54.9"	121°57'14.4"	14	4/22-30	9/11	198	35.45	10.5	35-105 105-198	222.9 (3.8) 101.0 (2.7)	126	Bonneville Dam 7.5'
NB-3	City of North Bonneville No. 3	Skamania	Sec. 39 (2-7E)	45°39'09.0"	121°57'36.7"	15	5/11-22	9/11	155	26.38	11.0	70-155	90.0 (0.9)	99	Bonneville Dam 7.5'

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[1] Gradient "A"—Slope of a least-squares straight line fitted to the temperature-depth data for the depth interval indicated.

[2] $S_{\hat{\beta}_1}$ — Standard deviation, expressed

as $$S_{\hat{\beta}_1} = \sqrt{\frac{\sum y_i^2 - n\bar{y}^2 - \hat{\beta}_1\left(\sum x_i y_i - n\bar{x}\bar{y}\right)}{\left(\sum x_i^2 - n\bar{x}^2\right)(n-2)}}$$

where $S_{\hat{\beta}_1}$ = standard deviation of the slope of the regression line

y_i = a temperature reading where $i = 1 - n$.

x_i = the depth where y_i was read

n = number of temperature-depth readings.

$\hat{\beta}_1$ = the estimated slope (temperature gradient)

$\bar{x}$ = mean of depth readings, and

$\bar{y}$ = mean of temperature readings

[3] Gradient "B"—Temperature gradient calculated using an estimated surface or near-surface temperature and a measured bottom hole temperature. Useful especially when straight-line conductive gradients are not present in a hole because of hydrologic disturbances.

Table 6-1B Heat Flow Determinations

Hole Name		Gradient A[1] °C/km	Gradient B[1] °C/km	Average[2] Thermal Conductivity W/m·°K	Corrected[3] Heat Flow mW/m^2	A Gradient[4] Heat Flow mW/m^2	B Gradient[5] Heat Flow mW/m^2
DNR-1	Scenic 1	68.0	57	2.06	115	140	117
DNR-1A	Scenic 2	36.5	37	2.68	70	98	99
DNR-2	Snoqualmie 1	16.5	16	2.97	44	49	48
DNR-2A	Snoqualmie 2	--	16	3.69	--	--	59
DNR-3	White River	23.8	20	2.39	47	57	48
DNR-4	Clear Creek	66.3	57	2.02	91	134	115
DNR-5	Sand Ridge	41.0	42	2.56	108	105	108
DNR-6A	Tieton Willows	93.0	92	1.30	87	121	120
DNR-7	Trout Creek	87.0	79	1.22	92	106	96
DNR-8	Carson	368.8	166	1.60	265	590	266
DNR-9	Klickitat	51.0	56	1.39	52	71	78

[1] See Table 6-1A for explanation of A and B gradients.

[2] The reported average thermal conductivity was determined by measurement of drill cuttings from several selected intervals. The units are watts per meter per degree Kelvin.

[3] Corrected heat flow values have been determined by David D. Blackwell, Southern Methodist University, using A Gradients and corrections for topographic effects. The units are milliwatts per square meter.

[4] These heat flow values were determined by multiplying the A Gradient by the thermal conductivity, with no topographic corrections.

[5] These heat flow values were determined by multiplying the B Gradient by the thermal conductivity, with no topographic corrections.

TABLE 6-2.—Geothermal temperature gradient measurements for Scenic No. 1 drill hole, DNR-1 (date measured 9-25-81)

Depth (m)	Temperature °C	Geothermal gradient °C/km
10	5.08	-42
15	4.87	24
20	4.99	58
25	5.28	42
30	5.49	44
35	5.71	48
40	5.95	50
45	6.20	50
50	6.45	52
55	6.71	58
60	7.00	60
65	7.30	64
70	7.62	68
75	7.96	68
80	8.30	68
85	8.64	68
90	8.98	70
95	9.33	68
100	9.67	67
101.5 T.D.	9.77	

TABLE 6-3.—Geothermal temperature gradient measurements for Scenic No. 2 drill hole, DNR-1A (date measured 9-25-81)

Depth (m)	Temperature °C	Geothermal gradient °C/km
5	8.34	-536
10	5.66	-112
15	5.10	60
20	5.40	4
25	5.42	22
30	5.53	36
35	5.71	30
40	5.86	38
45	6.05	36
50	6.23	34
55	6.40	46
60	6.63	40
65	6.83	26
70	6.96	34
75	7.13	34
80	7.30	34
85	7.47	38
90	7.66	36
95	7.84	40
100	8.04	36
105	8.22	36
110	8.40	36
115	8.58	34
120	8.75	40
125	8.95	38
130	9.14	38
135	9.33	40
140	9.53	38
145	9.72	38
150	9.91	40
151.5 T.D.	9.97	

TABLE 6-4.—Geothermal temperature gradient measurements for Snoqualmie No. 1 drill hole, DNR-2 (date measured 10-13-81)

Depth (m)	Temperature °C/km	Geothermal gradient °C/km
5	7.88	-338
10	6.19	-112
15	5.63	0
20	5.63	0
25	5.63	2
30	5.64	0
35	5.64	16
40	5.72	18
45	5.81	12
50	5.87	12
55	5.93	20
60	6.03	10
65	6.08	8
70	6.12	18
75	6.21	20
80	6.31	24
85	6.43	32
90	6.59	20
95	6.69	-2
100	6.68	4
105	6.70	14
110	6.77	16
115	6.85	16
120	6.93	16
125	7.01	18
130	7.10	16
135	7.18	18
140	7.27	16
145	7.35	17
146.8 T.D.	7.38	

TABLE 6-5.—Geothermal temperature gradient measurements for Snoqualmie No. 2 drill hole, DNR-2A (date measured 10-13-81)

Depth (m)	Temperature °C	Geothermal gradient °C/km
5	7.23	-2
10	7.22	-4
15	7.20	4
20	7.22	0
25	7.22	0
30	7.22	2
35	7.23	0
40	7.23	2
45	7.24	-6
50	7.21	24
55	7.33	10
60	7.38	22
65	7.49	0
70	7.49	4
75	7.51	14
80	7.58	0
85	7.58	16
90	7.66	0
95	7.66	2
100	7.67	0
105	7.67	2
110	7.68	-10
115	7.63	24
120	7.75	2
125	7.76	12
130	7.82	2
135	7.83	4
140	7.85	10
141 T.D.	7.86	

TABLE 6-6.—Geothermal temperature gradient measurements for White River drill hole, DNR-3 (date measured 9-15-81)

Depth (m)	Temperature °C	Geothermal gradient °C/km
5	8.48	-418
10	6.39	-14
15	6.32	22
20	6.43	4
25	6.45	14
30	6.52	8
35	6.56	16
40	6.64	14
45	6.71	16
50	6.79	20
55	6.89	16
60	6.97	16
65	7.05	18
70	7.14	18
75	7.23	18
80	7.32	18
85	7.41	18
90	7.50	18
95	7.59	20
100	7.69	18
105	7.78	20
110	7.88	22
115	7.99	24
120	8.11	28
125	8.25	20
130	8.35	24
135	8.47	26
140	8.60	11
143.7 T.D.	8.64	

TABLE 6-7.—Geothermal temperature gradient measurements for Clear Creek drill hole, DNR-4 (date measured 9-15-81)

Depth (m)	Temperature °C	Geothermal gradient °C/km
5	6.51	-140
10	5.81	58
15	6.10	40
20	6.30	16
25	6.38	12
30	6.44	8
35	6.48	54
40	6.75	48
45	6.99	52
50	7.25	54
55	7.52	52
60	7.78	62
65	8.09	60
70	8.39	64
75	8.71	70
80	9.06	66
85	9.39	62
90	9.70	60
95	10.00	66
100	10.33	64
105	10.65	74
110	11.02	66
115	11.35	66
120	11.68	66
125	12.01	62
130	12.32	66
135	12.65	62
140	12.96	76
145	13.34	54
150	13.61	53
153.2 T.D.	13.78	

TABLE 6-8.—Geothermal temperature gradient measurements for Sand Ridge drill hole, DNR-5 (date measured 9-15-81)

Depth (m)	Temperature °C	Geothermal gradient °C/km
5	8.49	-398
10	6.50	22
15	6.61	36
20	6.79	30
25	6.94	32
30	7.10	38
35	7.29	40
40	7.49	40
45	7.69	50
50	7.94	46
55	8.17	44
60	8.39	46
65	8.62	46
70	8.85	48
75	9.09	44
80	9.31	44
85	9.53	42
90	9.74	44
95	9.96	44
100	10.18	42
105	10.39	42
110	10.60	40
115	10.80	44
120	11.02	40
125	11.22	44
130	11.44	40
135	11.64	42
140	11.85	40
145	12.05	40
150	12.25	33
153.3 T.D.	12.36	

TABLE 6-9.—Geothermal temperature gradient measurements for Tieton Willows drill hole, DNR-6A (date measured 9-15-81)

Depth (m)	Temperature °C	Geothermal gradient °C/km
5	10.89	-18
10	10.80	106
15	11.33	92
20	11.79	110
25	12.34	74
30	12.71	86
35	13.14	86
40	13.57	90
45	14.02	88
50	14.46	96
55	14.94	80
60	15.34	100
65	15.84	90
70	16.29	94
75	16.76	94
80	17.23	96
85	17.71	88
90	18.15	98
95	18.64	106
100	19.17	90
105	19.62	94
110	20.09	92
115	20.55	96
120	21.03	94
125	21.50	96
130	21.98	96
135	22.46	94
140	22.93	94
145	23.40	94
150	23.87	79
153.4 T.D.	24.14	

TABLE 6-10.—Geothermal temperature gradient measurements for Trout Creek drill hole, DNR-7 (date measured 9-10-81)

Depth (m)	Temperature °C	Geothermal gradient °C/km
10	7.52	46
15	7.75	76
20	8.13	84
25	8.55	72
30	8.91	74
35	9.28	64
40	9.60	66
45	9.93	80
50	10.33	86
55	10.76	76
60	11.14	86
65	11.57	90
70	12.02	90
75	12.47	86
80	12.90	100
85	13.40	76
90	13.78	80
95	14.18	90
100	14.63	80
105	15.03	94
110	15.50	78
115	15.89	100
120	16.39	86
125	16.82	92
130	17.28	90
135	17.73	84
140	18.15	90
145	18.60	90
150	19.05	45
154 T.D.	19.23	

TABLE 6-11.—Geothermal temperature gradient measurements for Carson drill hole, DNR-8 (date measured 9-14-81)

Depth (m)	Temperature °C	Geothermal gradient °C/km
5	9.87	-42
10	9.66	108
15	10.20	94
20	10.67	48
25	10.91	82
30	11.32	60
35	11.62	458
40	13.91	870
42	15.65	-100
43	15.55	-815
45	13.92	-62
50	13.61	106
55	14.14	122
60	14.75	114
65	15.32	102
70	15.83	58
75	16.12	-2
80	16.11	310
85	17.66	468
90	20.00	452
95	22.26	354
100	24.03	358
105	25.82	268
110	27.16	200
113.2 T.D.	27.80	

TABLE 6-12.—Geothermal temperature gradient measurements for Klickitat drill hole, DNR-9 (date measured 9-14-81)

Depth (m)	Temperature °C	Geothermal gradient °C/km
5	13.95	-46
10	13.72	-26
15	13.59	182
20	14.50	86
25	14.93	84
30	15.35	26
35	15.48	22
40	15.59	28
45	15.73	42
50	15.94	90
55	16.39	262
60	17.70	48
65	17.94	-40
70	17.74	46
75	17.97	46
80	18.20	50
85	18.45	52
90	18.71	58
95	19.00	48
100	19.24	52
105	19.50	44
110	19.72	86
115	20.15	-19
119.8 T.D.	20.06	

TABLE 6-13.—*Geothermal temperature gradient measurements for City of North Bonneville No. 1 drill hole, NB-1 (date measured 5-1-81)*

Depth (m)	Temperature °C	Geothermal gradient °C/km
0.0	18.22	-236
3.1	17.50	-2623
6.1	9.50	-200
9.1	8.89	-72
12.2	8.67	36
15.2	8.78	36
18.3	8.89	0
21.3	8.89	0
24.4	8.89	16
27.4	8.94	39
30.5	9.06	0
33.5	9.06	16
36.6	9.11	72
39.6	9.33	56
42.7	9.50	72
45.7	9.72	56
48.8	9.89	56
51.8	10.06	0
54.9	10.06	88
57.9	10.33	56
61.0	10.50	56
64.0	10.67	36
67.1	10.78	36
70.1	10.89	36
73.2	11.00	20
76.2	11.06	88
79.3	11.33	20
82.3	11.39	56
85.4	11.56	36
88.4	11.67	72
91.5	11.89	36
94.5	12.00	36
97.6	12.11	36
100.6	12.22	56
103.7	12.39	36
106.7	12.50	56
109.8	12.67	53
112.8	12.83	36
115.9	12.94	56
118.9	13.11	56
121.9	13.28	52
125.0	13.44	56
128.0	13.61	56
131.1	13.78	52
134.1	13.94	56
137.2	14.11	36
140.2	14.22	56
143.3	14.39	72
146.3	14.61	36
149.4	14.72	56
152.4	14.89	72
155.5	15.11	56
158.5	15.28	52
161.6	15.44	56
164.6	15.61	56
167.7	15.78	72
170.7	16.00	56
173.8	16.17	52
176.8	16.33	56
179.9	16.50	36
182.9	16.61	20
186.0 T.D.	16.67	

TABLE 6-14.—Geothermal temperature gradient measurements for City of North Bonneville No. 2 drill hole, NB-2 (date measured 9-11-81)

Depth (m)	Temperature °C	Geothermal gradient °C/km
5	12.16	-236
10	10.98	50
15	11.23	-90
20	10.78	-90
25	10.33	56
30	10.61	64
35	10.93	62
40	11.24	230
45	12.39	340
50	14.09	256
55	15.37	226
60	16.50	198
65	17.49	210
70	18.54	224
75	19.66	310
80	21.21	90
85	21.66	286
90	23.09	220
95	24.19	136
100	24.87	208
105	25.91	90
110	26.36	272
115	27.72	148
120	28.46	98
125	28.95	114
130	29.52	50
135	29.77	16
140	29.85	122
145	30.46	102
150	30.97	118
155	31.56	30
160	31.71	230
165	32.86	106
170	33.39	92
175	33.85	80
180	34.25	88
185	34.69	74
190	35.06	60
195	35.36	30
198 T.D.	35.45	

TABLE 6-15.—Geothermal temperature gradient measurements for City of North Bonneville No. 3 drill hole, NB-3 (date measured 9-11-81)

Depth (m)	Temperature °C	Geothermal gradient °C/km
10	11.50	70
15	11.85	86
20	12.28	62
25	12.59	98
30	13.08	138
35	13.77	132
40	14.43	158
45	15.22	182
50	16.13	130
55	16.78	156
60	17.56	114
65	18.13	146
70	18.86	142
75	19.57	56
80	19.85	76
85	20.23	94
90	20.70	82
95	21.11	86
100	21.54	86
105	21.97	112
110	22.53	102
115	23.04	94
120	23.51	76
125	23.89	82
130	24.30	112
135	24.86	98
140	25.35	86
145	25.78	68
150	26.12	52
155 T.D.	26.38	

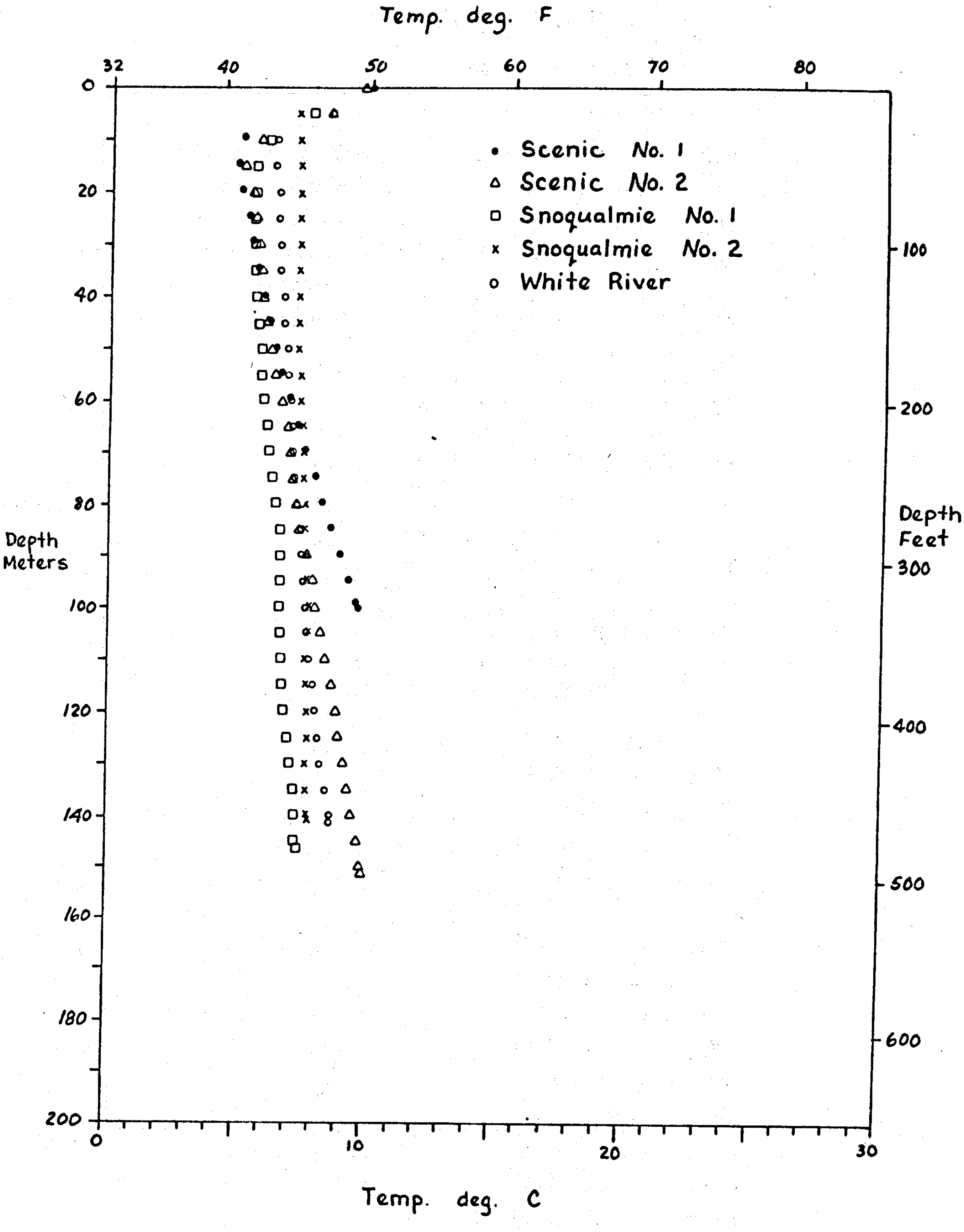

FIGURE 6-2 —Composite temperature-depth plots for Scenic No. 1 (DNR-1), Scenic No. 2 (DNR-1A), Snoqualmie No. 1 (DNR-2), Snoqualmie No. 2 (DNR-2A), and White River (DNR-3) drill holes.

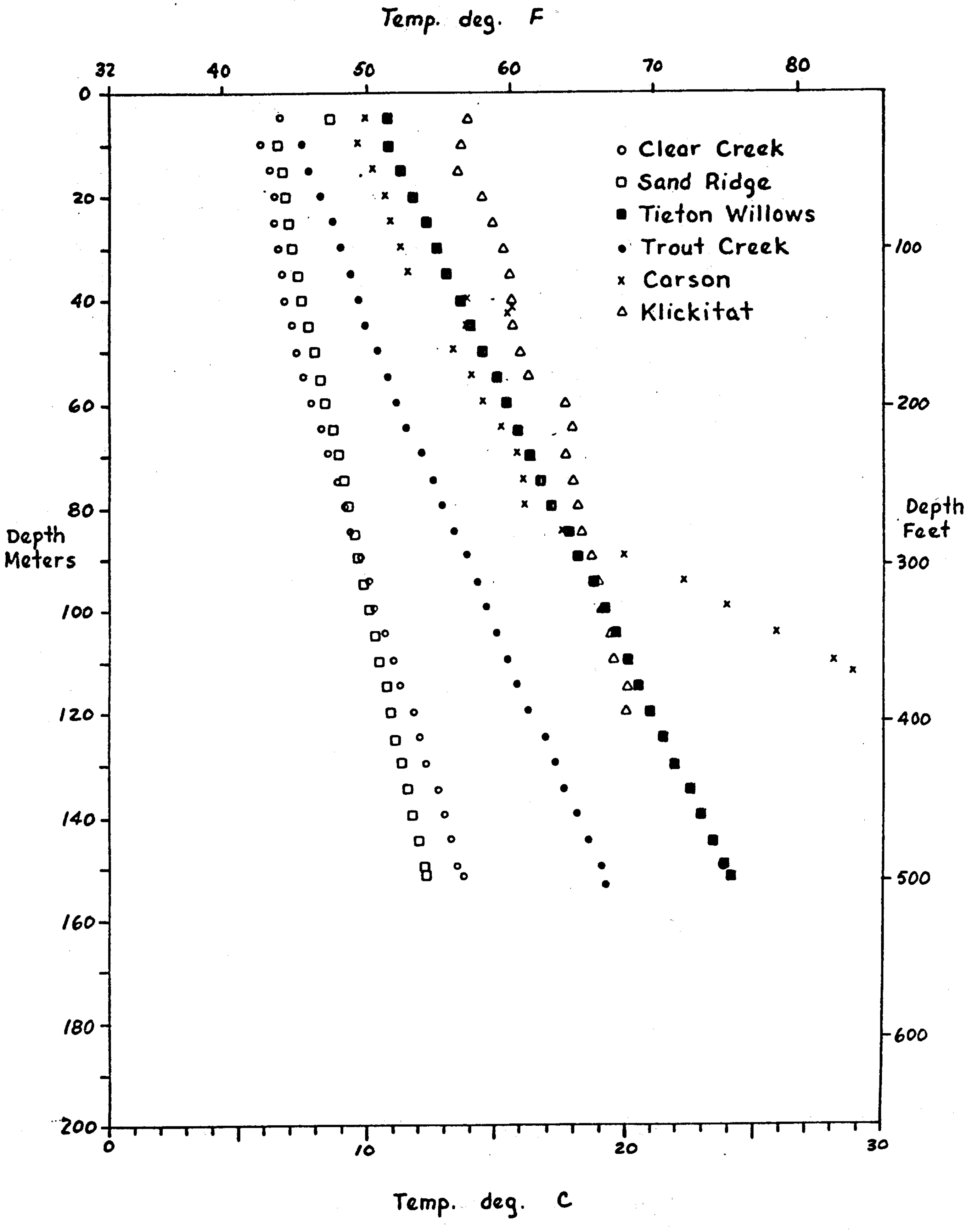

FIGURE 6-3.—Composite temperature-depth plots for Clear Creek (DNR-4), Sand Ridge (DNR-5), Tieton Willows (DNR-6A), Trout Creek (DNR-7), Carson (DNR-8), and Klickitat (DNR-9) drill holes.

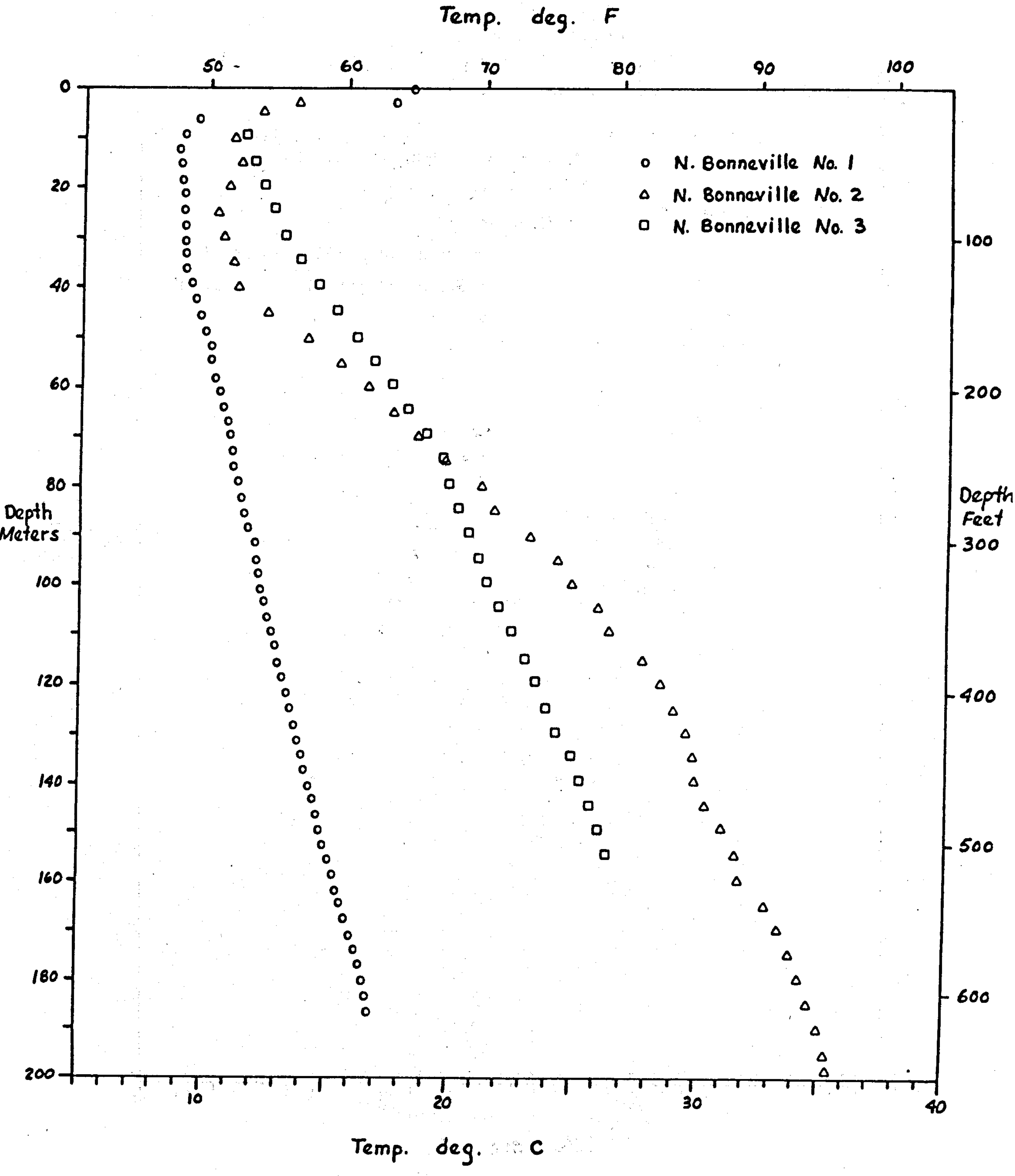

FIGURE 6-4.—Composite temperature-depth plots for North Bonneville No. 1 (NB-1), North Bonneville No. 2 (NB-2), and North Bonneville No. 3 (NB-3) drill holes.

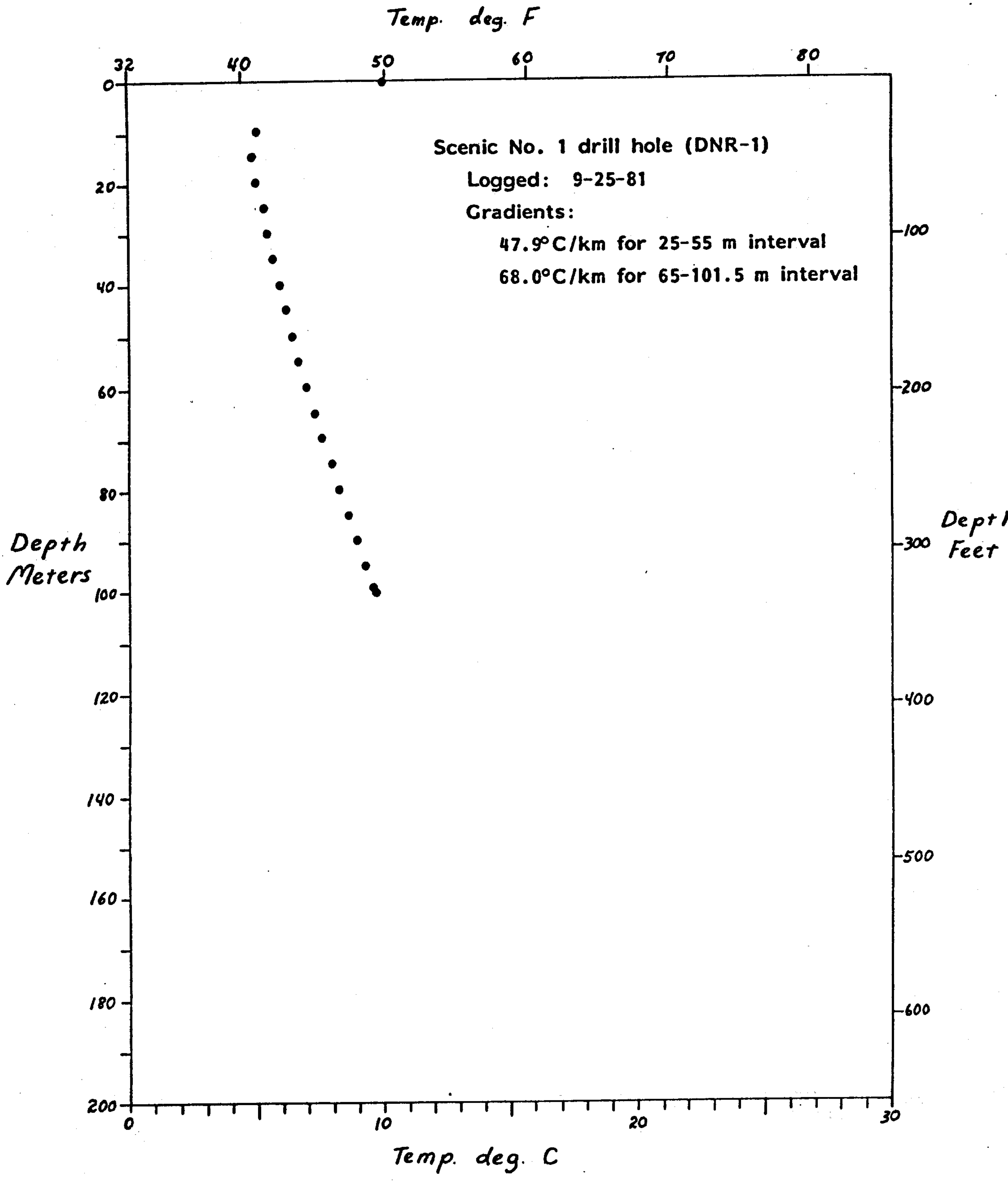

FIGURE 6-5.—Temperature-depth plot for Scenic No. 1 (DNR-1) drill hole.

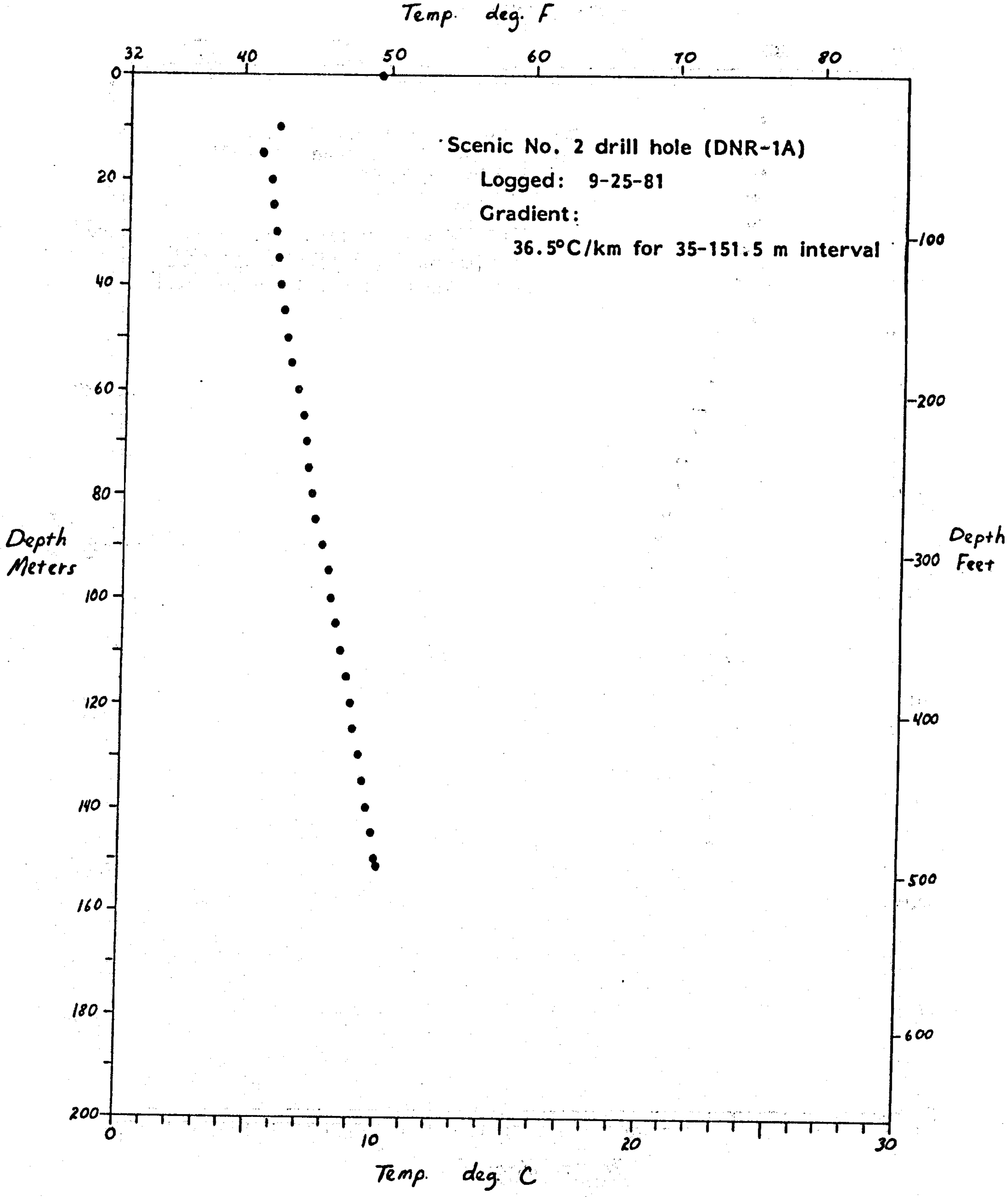

FIGURE 6-6.—Temperature-depth plot for Scenic No. 2 (DNR-1A) drill hole.

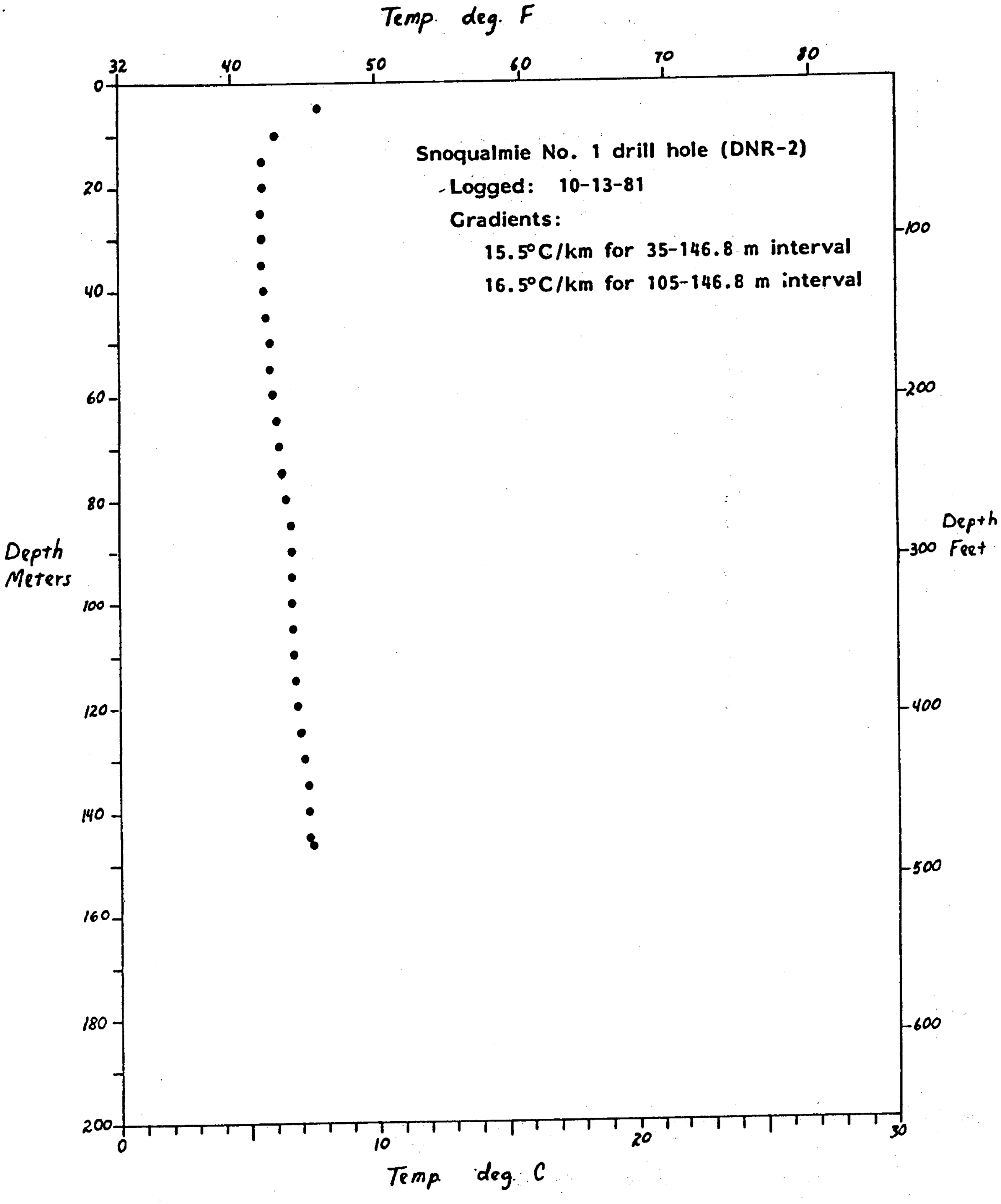

FIGURE 6-7.—Temperature-depth plot for Snoqualmie No. 1 (DNR-2) drill hole.

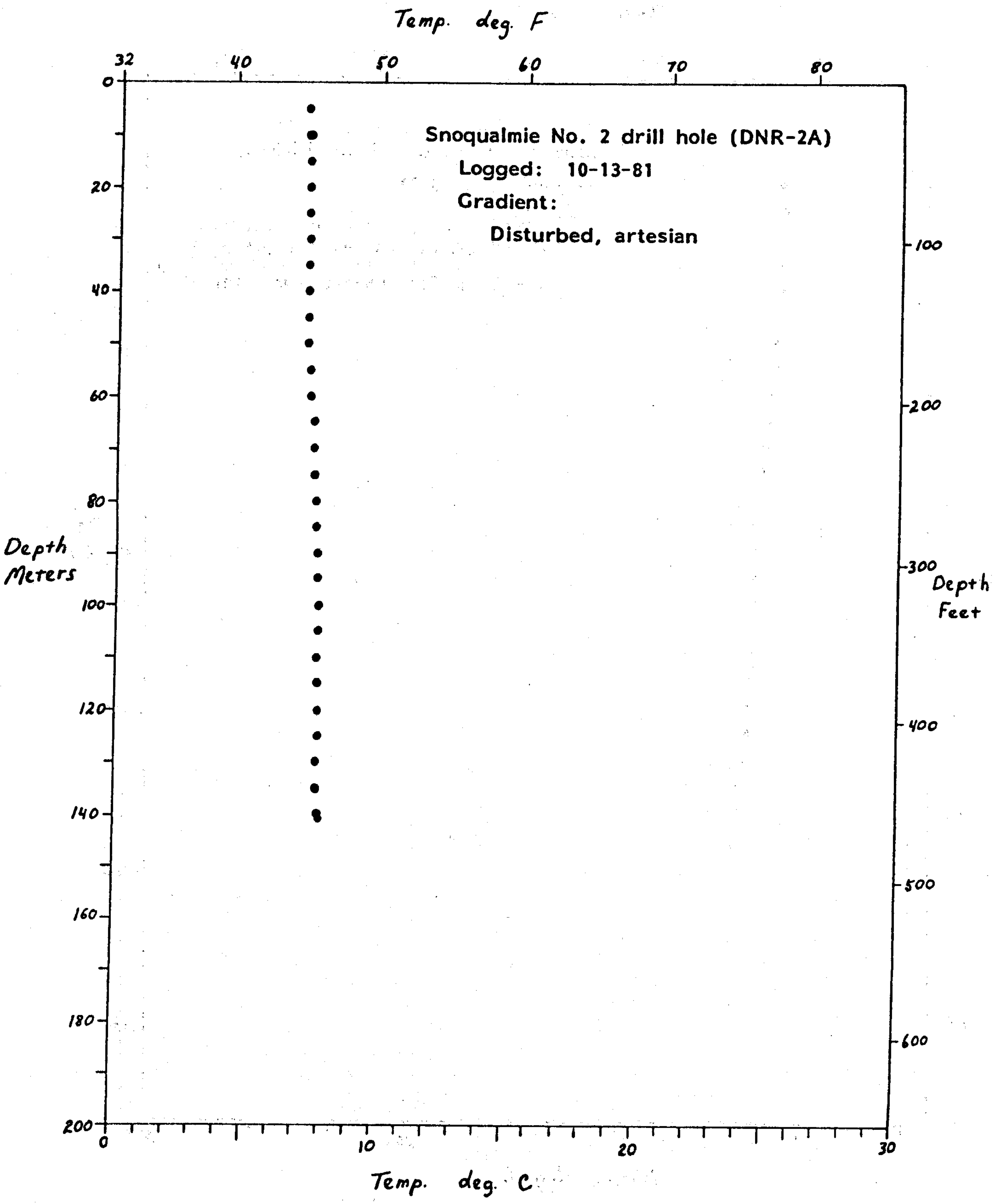

FIGURE 6-8.—Temperature-depth plot for Snoqualmie No. 2 (DNR-2A) drill hole.

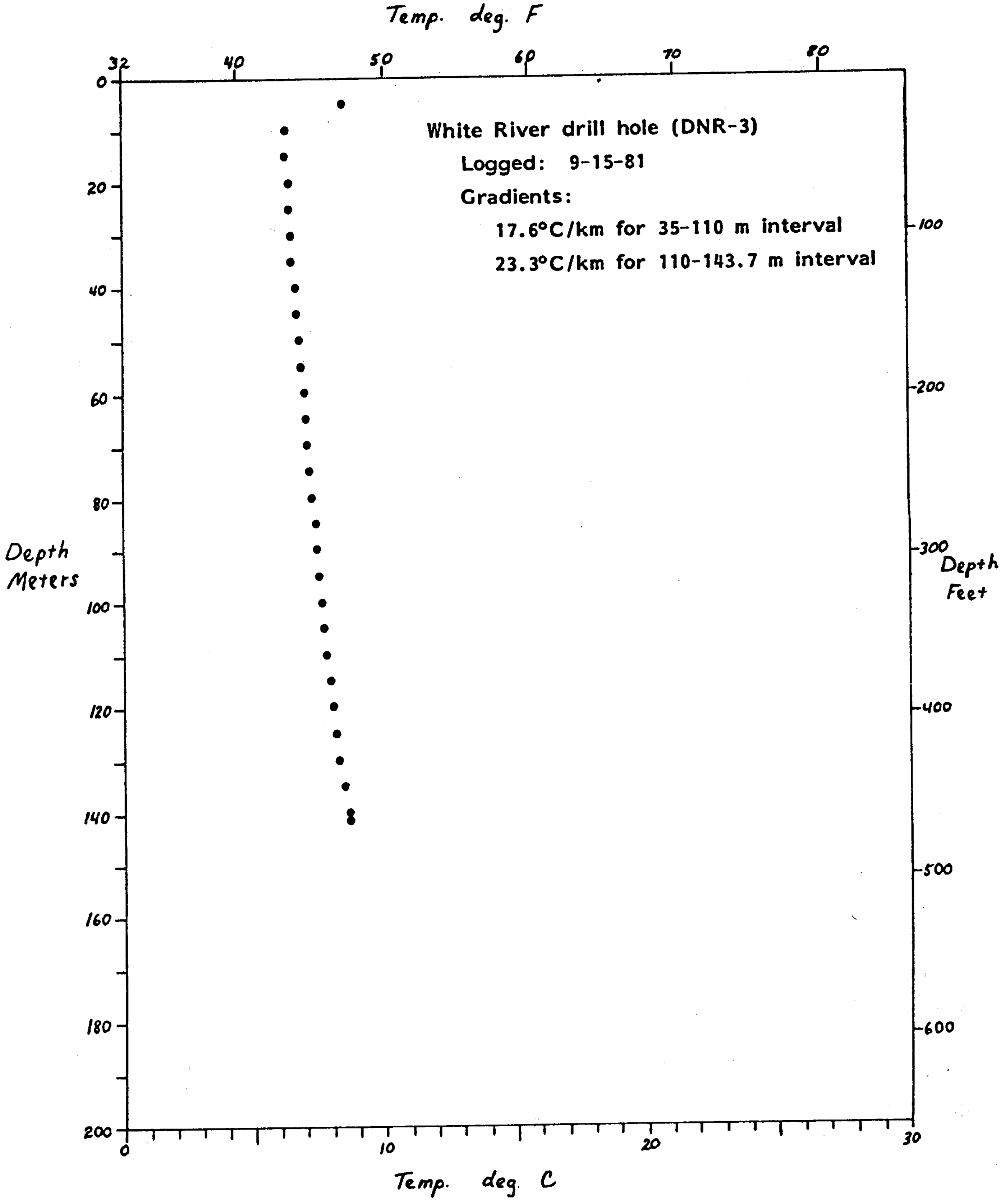

FIGURE 6-9.—Temperature-depth plot for White River (DNR-3) drill hole.

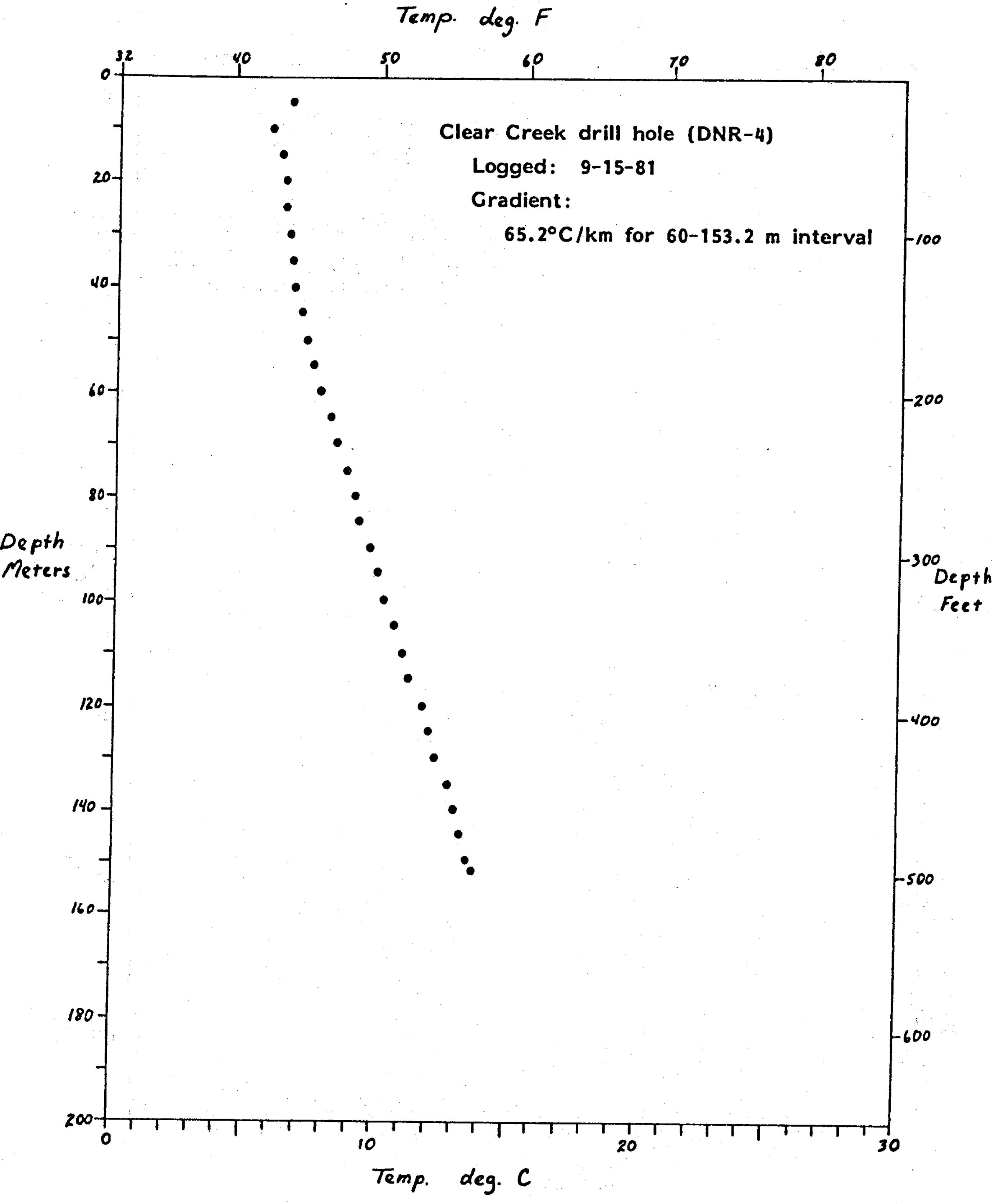

FIGURE 6-10.—Temperature-depth plot for Clear Creek (DNR-4) drill hole.

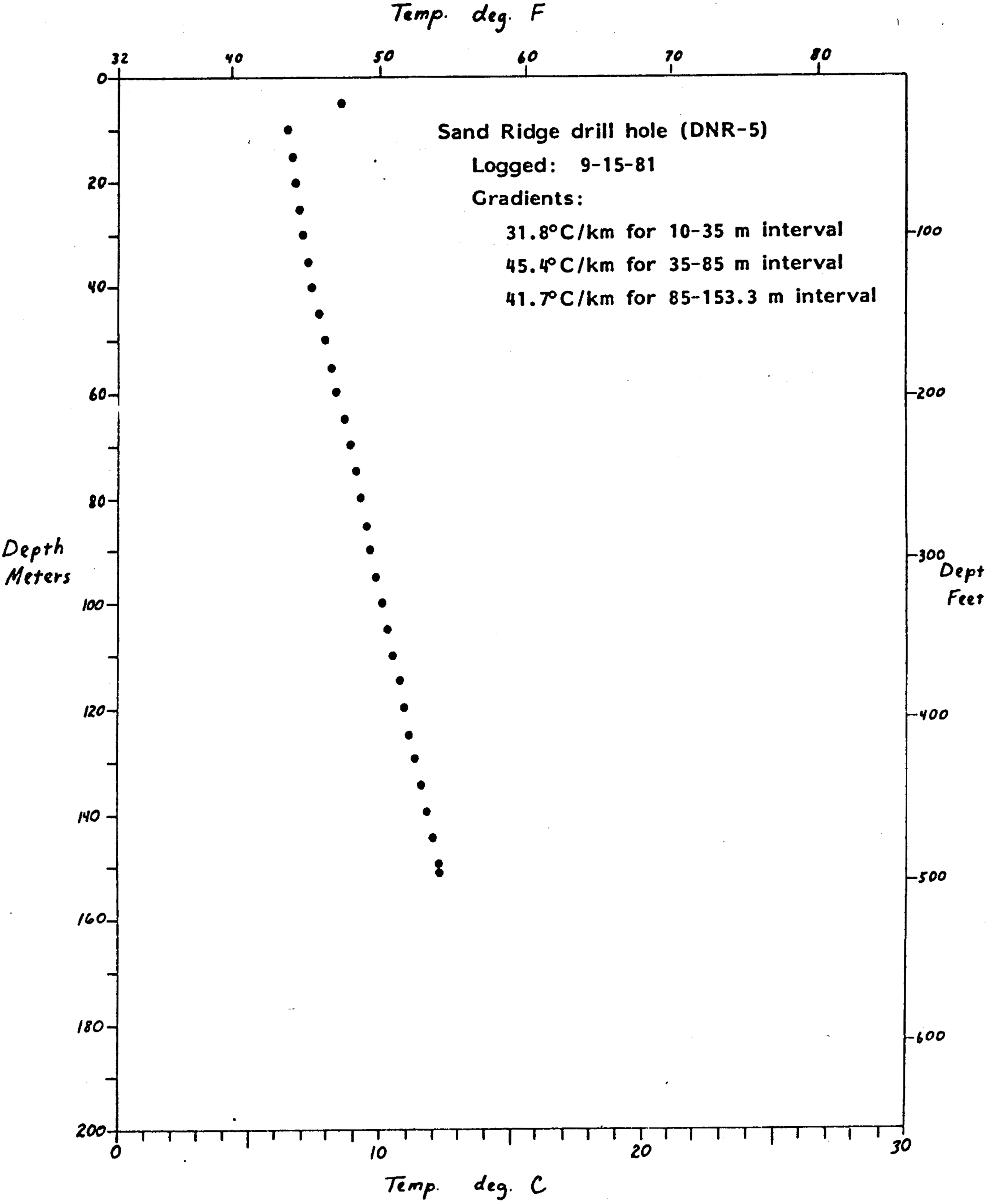

FIGURE 6-11.—Temperature-depth plot for Sand Ridge (DNR-5) drill hole.

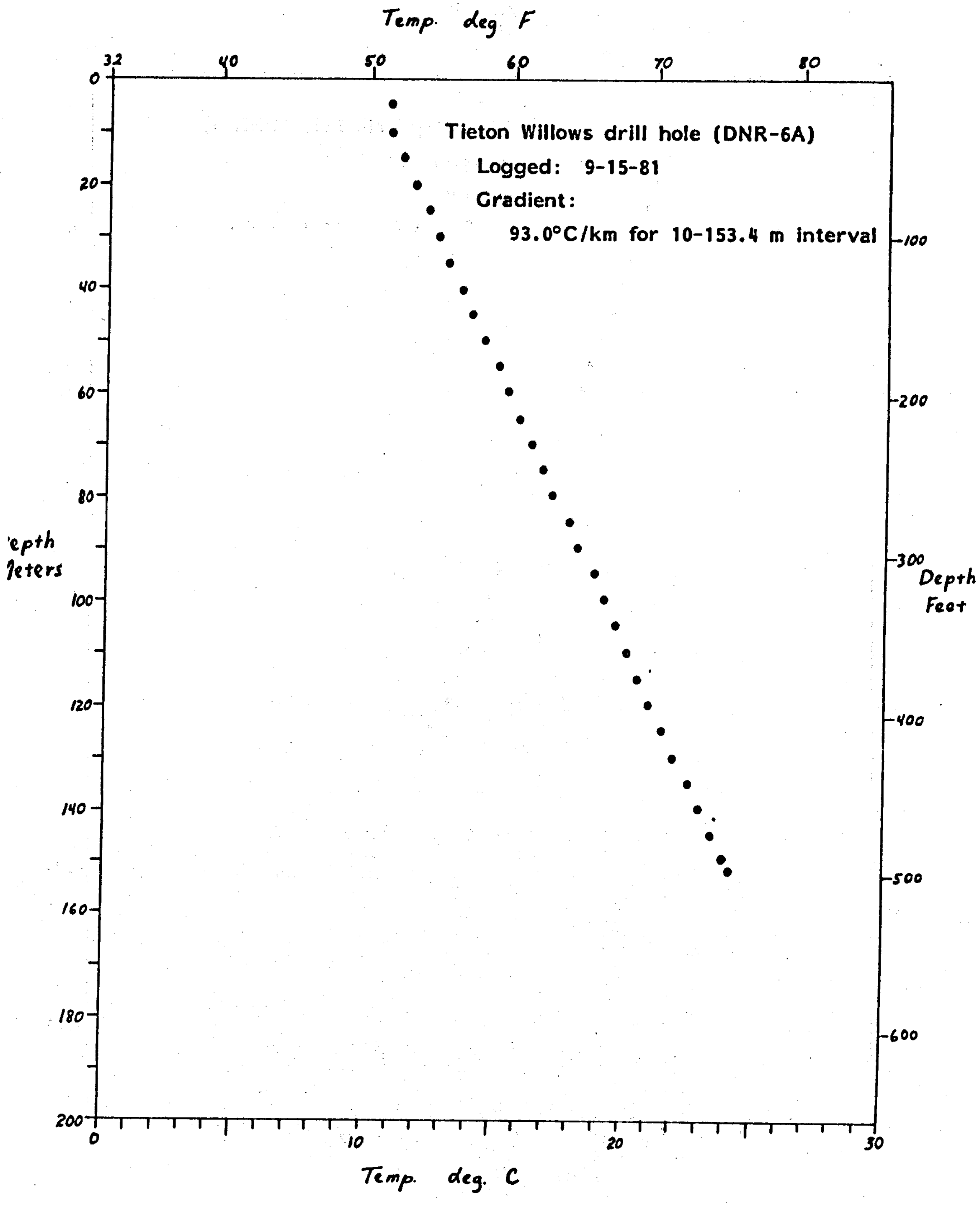

FIGURE 6-12.—Temperature-depth plot for Tieton Willows (DNR-6A) drill hole.

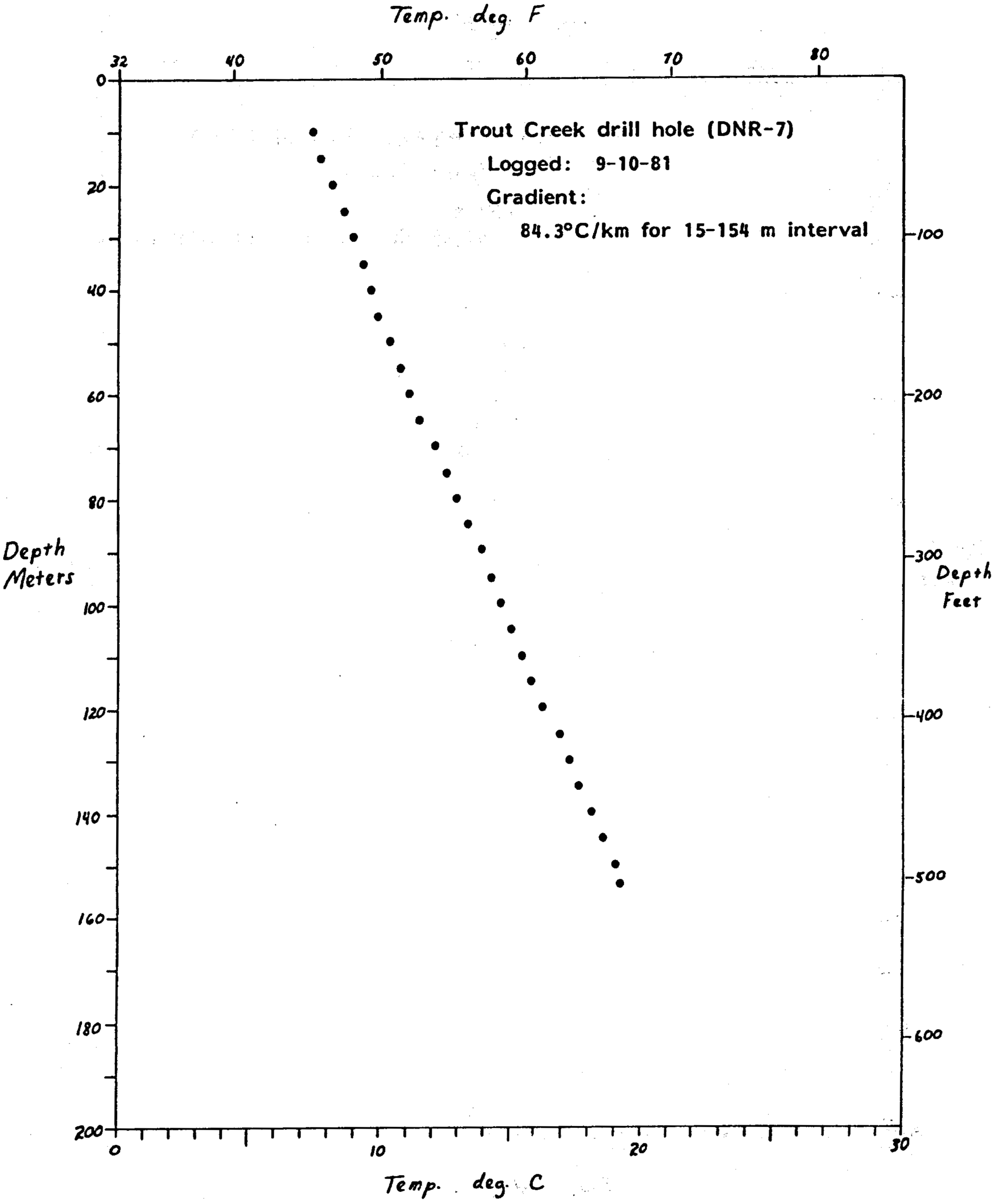

FIGURE 6-13.—Temperature-depth plot for Trout Creek (DNR-7) drill hole.

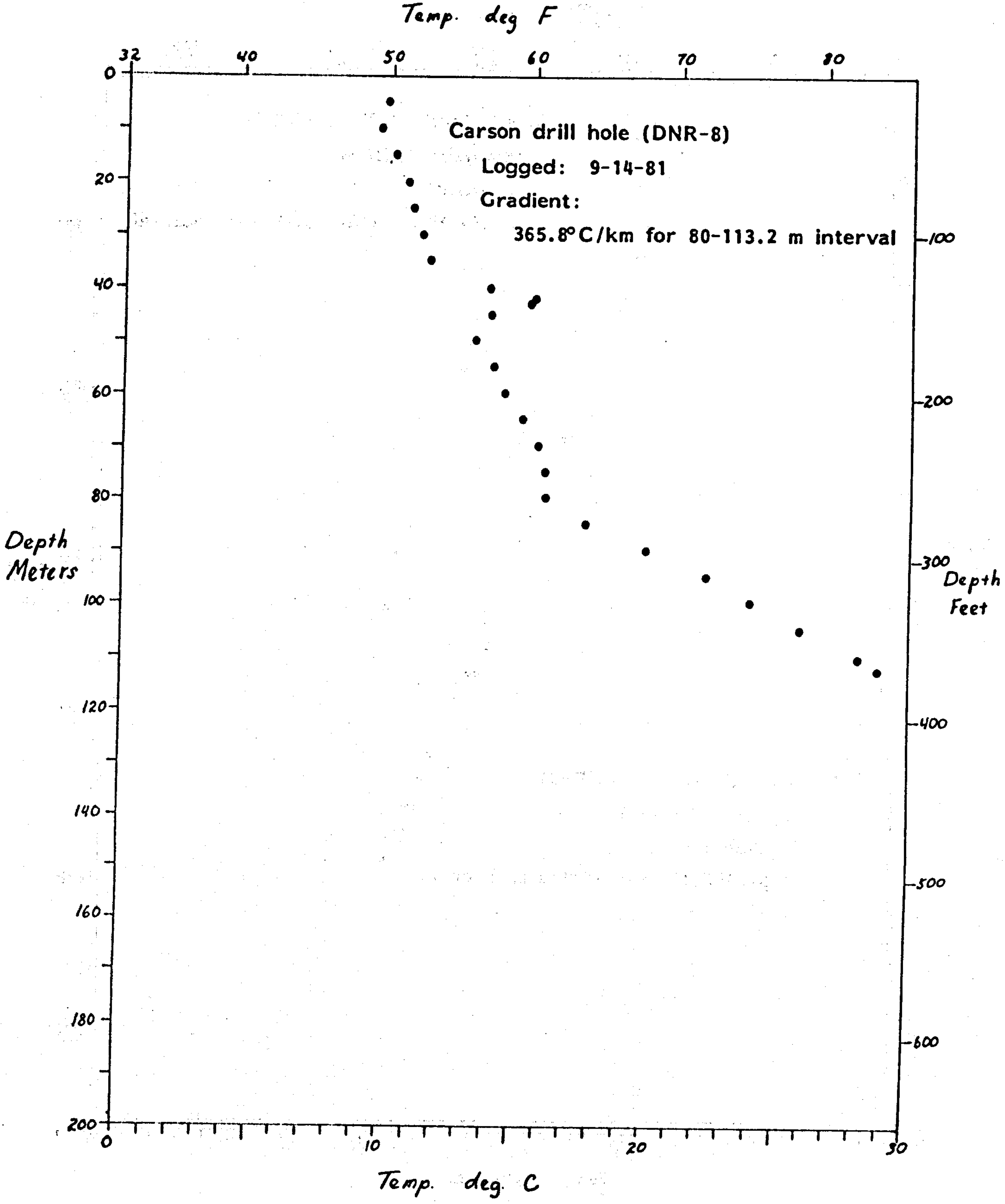

FIGURE 6-14.—Temperature-depth plot for Carson (DNR-8) drill hole.

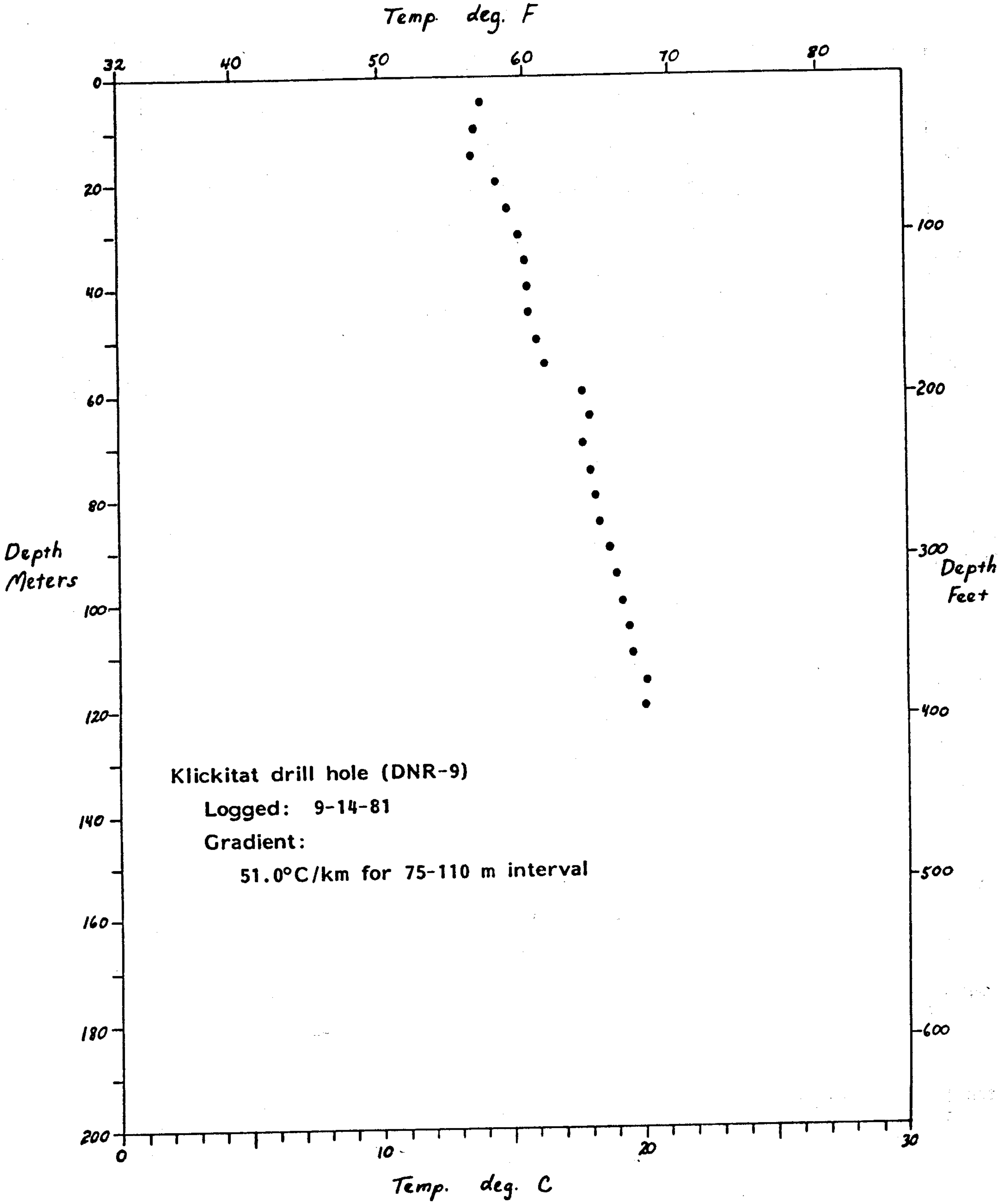

FIGURE 6-15.—Temperature-depth plot for Klickitat (DNR-9) drill hole.

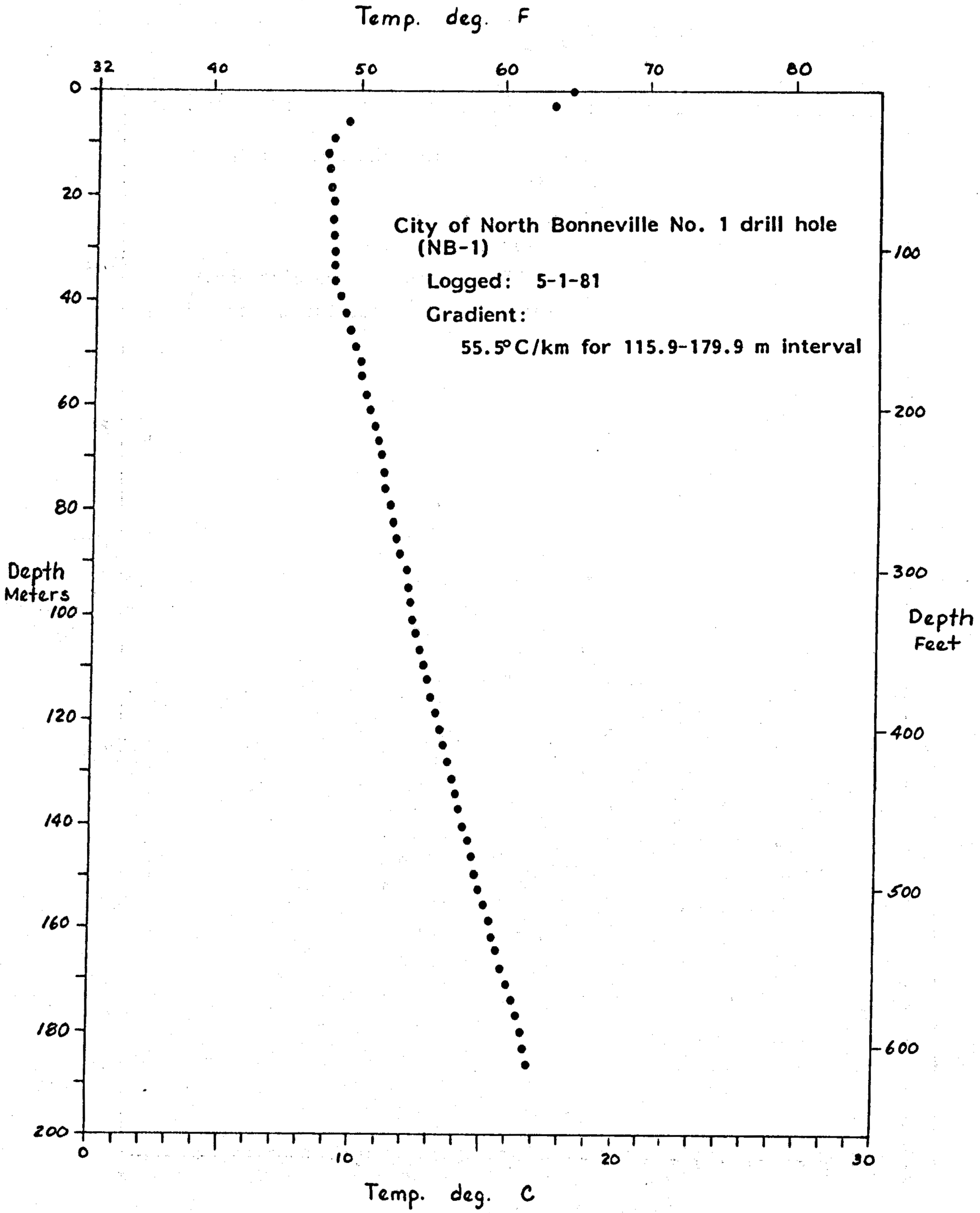

FIGURE 6-16.—Temperature-depth plot for North Bonneville No. 1 (NB-1) drill hole.

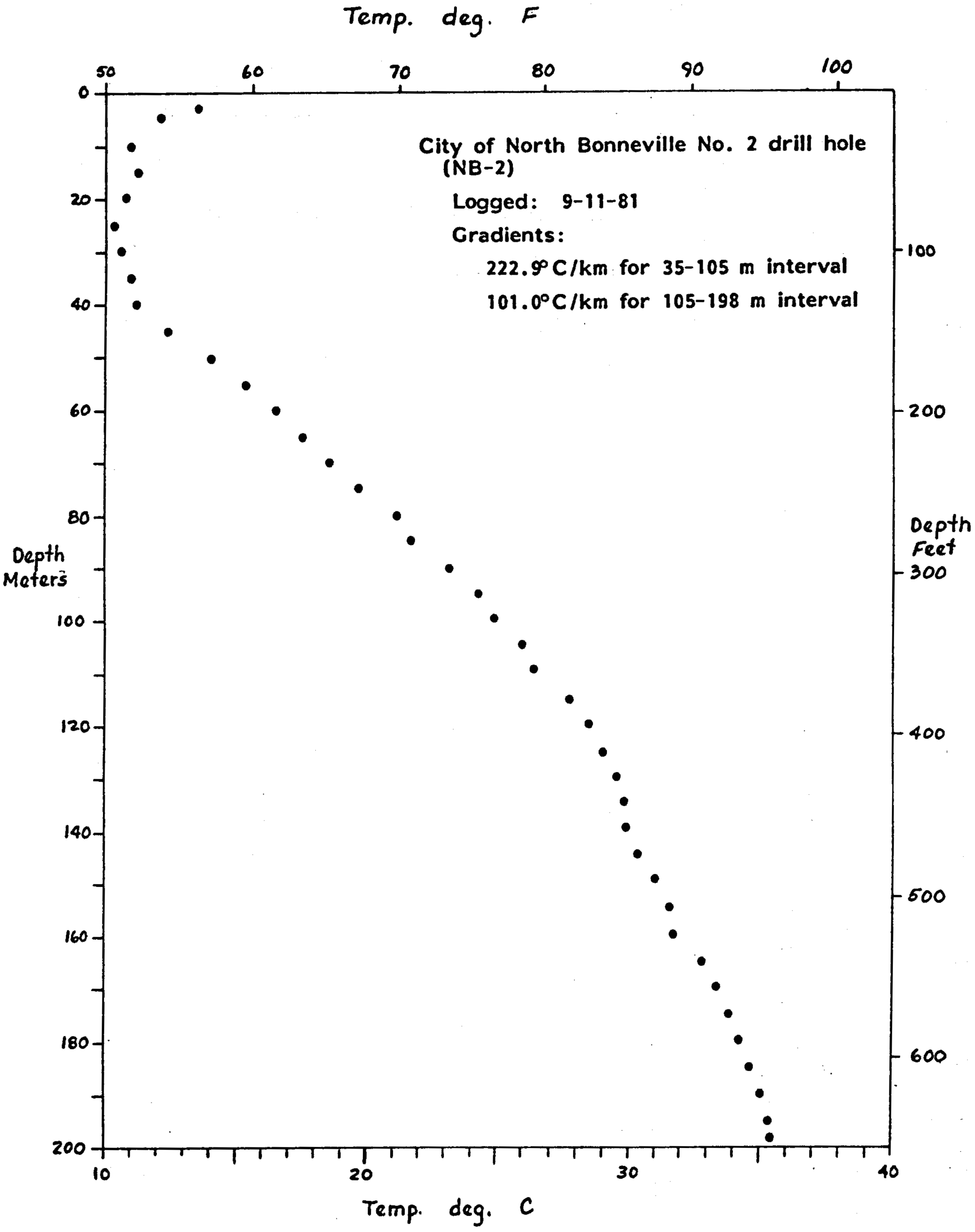

FIGURE 6-17.—Temperature-depth plot for North Bonneville No. 2 (NB-2) drill hole.

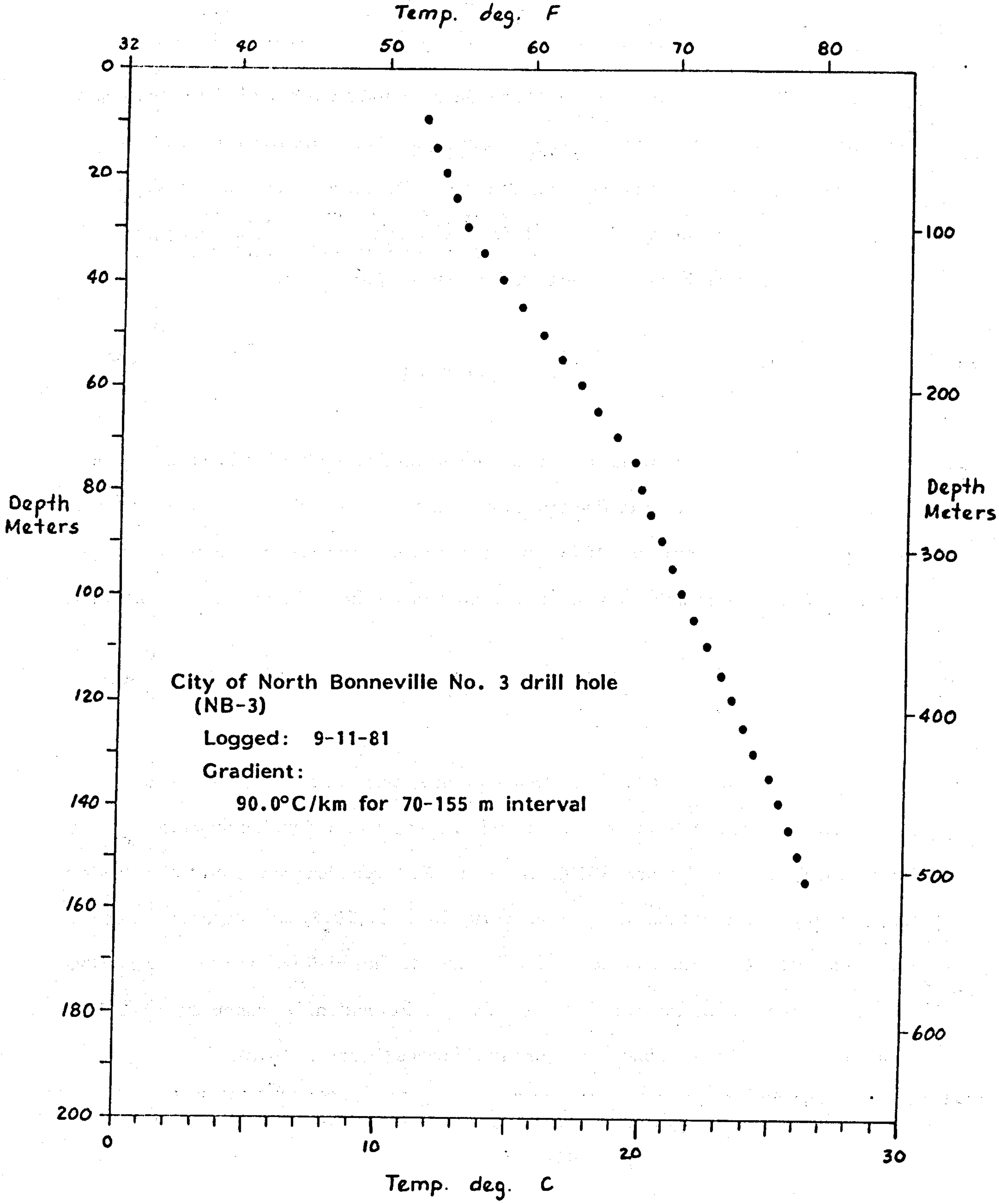

FIGURE 6-18.—Temperature-depth plot for North Bonneville No. 3 (NB-3) drill hole.

Snoqualmie No. 1

This drill hole penetrated argillite with several phyllitic zones for its entire depth. These rocks are part of the Guye Formation, which consists of terrestrial carbonaceous mudstone, shale, sandstone, conglomerate, and breccia of Paleocene or Eocene age (Chitwood, 1976). The rocks penetrated by the drill hole are somewhat metamorphosed, presumably due to the proximity of the Snoqualmie batholith (Miocene) to the north.

Snoqualmie No. 2

The upper 25 meters of this drill hole is in unconsolidated glacial and alluvial materials. The remainder of the hole is in fine-grained quartzite. The quartzite is probably a part of the Guye Formation (Chitwood, 1976), and it was presumably metamorphosed during the intrusion of the Snoqualmie batholith which crops out a short distance to the northwest.

White River

The White River drill hole penetrated banded, devitrified pyroxene rhyolite which is the intrusive phase of the Clear West complex, a hypabyssal rhyolitic ignimbrite and extrusive rheoignimbrite (Fischer, 1970). The Clear West complex may represent a caldera filling or, in part, a very thick sill (Fischer, 1970). Hartman (1973) suggests that the complex may be a plug dome with associated sills. The rhyolites intrude the Eocene-Oligocene Ohanapecosh Formation and the early Miocene Fifes Peak Formation. Potassium-argon age dates indicate an age of 18 to 19 million years, or early Miocene (Hartman, 1973).

Clear Creek

This drill hole intersected sandy siltstone and mudstone of the Russell Ranch Formation, a Jurassic flysch assemblage (Clayton, 1980). The Russell Ranch consists of tectonically deformed and broken argillite and feldspathic graywacke with lenses of greenstone, bedded chert, chert conglomerage, and metatuff (Ellingson, 1972; Swanson, 1978).

Sand Ridge

This drill hole penetrated a portion of the Indian Creek Amphibolite, a Jurassic complex emplaced as a solid mass within the Russell Ranch Formation. Composed of interlayered tectonic lenses of amphibolite, dioritic and tonalitic gneiss, hornblendite, and lesser amounts of quartz diorite pegmatite, cataclastic orthogneiss, and mylonite (Ellingson, 1968, 1972), the Indian Creek Amphibolite has been interpreted to be part of an ophiolite assemblage (Hammond, 1980; Clayton, 1980, unpublished).

Tieton Willows

Two holes were drilled about 80 meters (m) apart at this site. The first hole was lost due to caving. It was collared in landslide materials, and encountered highly weathered and fractured volcanic conglomerates below. This hole was probably drilled into or through a steeply dipping fault or fracture zone.

The second hole, which was successfully completed, encountered competent lava flows at a depth of 10 m, and remained in them to its total depth. The lava flows are thought to be part of Tieton volcano, a Miocene shield volcano, which consists of andesite and basalt lava flows, breccia, and tuff (Swanson, 1966, 1978). Numerous andesitic radial dike swarms are also present. Swanson includes the Tieton volcano as part of the Fifes Peak Formation.

Trout Creek

This drill hole encountered 3 m of overburden, basalt from 3 to 8 m depth, highly variable incompetent materials from 8 to 25 m depth, and variably altered volcaniclastic rocks and flows of the Eocene-Oligocene Ohanapecosh Formation from 25 m to the bottom of the hole.

The basalt from 3 to 8 m depth is part of a Quaternary lava flow which orginated at Trout Creek Hill, a small shield volcano centered about 4.5 kilometers northwest of the drill site (Wise, 1961, 1970). The flow is thought to be older than 35,000 years, but younger than 130,000 years (Hammond, 1980).

The unconsolidated material from 8 to 25 m depth probably represents valley-filling sediments of fluvial or glacial origin; some of the material is weathered bedrock.

Carson

The Carson drill hole was collared in the same Quaternary basalt flow as that encountered in the Trout Creek drill hole. At the Carson site the flow extends to a depth of 35 m. From 35 to 40 m depth a paleosol and glacial or fluvial sediments were encountered. Below this, to about 80 m, altered volcaniclastic rocks and thin lava flows of the Ohanapecosh Formation predominate, but chips of unaltered diorite appeared in several zones, perhaps representing thin dikes.

Below 80 m and extending to total depth at 154 m (the hole is completed to only 113.2 m because of caving), the rock is quartz diorite of the Buck Mountain intrusive (informal name), also informally known as the Wind River Gorge intrusive and Wind River fishway sill (Free, 1976). Free describes the rock as holocrystalline, augite-hypersthene diorite. If the intrusive correlates with the similar rock of the Wind River plug, which intrudes Yakima basalt about 4 kilometers southeast of Buck Mountain, the Buck Mountain intrusive is middle Miocene in age, or younger.

Klickitat

The Klickitat drill hole is in Columbia River basalt for its entire depth. From reconnaissance geologic mapping (Shannon and Wilson, Inc., 1973; Hammond, 1980) it appears that the basalt at the Klickitat drill hole is part of the Grande Ronde Basalt (early and middle Miocene), the most widespread formation of the Yakima Basalt Subgroup.

Several zones of open fractures were encountered in the drill hole, most of which were lined with amorphous opaline silica. Open fracture zones were noted at depths near 10 m, 47 to 50 m, 62 m, 90 m, and 115 m. Carbon dioxide charged artesian water was produced from these zones during drilling, especially from the upper zones. The lower fracture zones may have been relatively underpressured because artesian flow ceased during the drilling of the lower part of the hole. All artesian zones were controlled by casing and/or cementing during the process of completing the hole.

North Bonneville Nos. 1, 2, and 3

The following description of downhole lithologies was taken from an unpublished report to the City of North Bonneville (Kent and Associates, Consulting Geologists, 1981).

Alluvium and landslide debris extend down to about 40 m at NB-1, 48 m at NB-2, and 15 m at NB-3. Below this, conglomerates of the Eagle Creek Formation (early Miocene) extend to depths of about 125 m in NB-1, 115 m in NB-2, and 70 m in NB-3. The conglomerates are predominantly fluvial volcaniclastics.

The lower portions of all three holes, beneath the Eagle Creek Formation, consist of variably altered tuffs and flows. The consultant's report interprets the unit to be part of the Three Corner Rock lava flows, which are estimated to be late Oligocene to early Miocene in age. Hammond (1980) describes the Three Corner Rock lava flows as interstratified pyroxene andesite porphyry, hornblende-pyroxene andesite porphyry, laharic breccia, and minor volcaniclastic rocks.

Because of the extensive alteration reported for cuttings from the lower portions of the North Bonneville holes, we believe it possible that the lower parts of the three holes may have penetrated into the Ohanapecosh Formation instead of the Three Corner Rock lava flows.

References

Chitwood, L. A., 1976, Stratigraphy, structure, and petrology of the Snoqualmie Pass area, Washington: Portland State University M.S. thesis, 68 p., 1 map, scale 1:24,000.

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.

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

Engles, J. C.; Crowder, D. F., 1971, Late Cretaceous fission-track and potassium-argon ages of the Mount Stuart Granodiorite and Beckler Peak stock, north Cascades, Washington: U. S. Geological Survey Professional Paper 750-D, p. D39-D43.

Fischer, J. F., 1970, The geology of the White River-Carbon Ridge area, Cedar Lake Quadrangle, Cascade Mountains, Washington: University of California at Santa Barbara Ph. D. thesis, 200 p., 1 map, scale 1:62,500.

Free, M. R., 1976, Evidence of magmatic assimilation in several diorites of the middle Columbia River Gorge: University of Utah M.S. thesis, 67 p.

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.

Hartman, D. A., 1973, Geology and low-grade metamorphism of the Greenwater River area, central Cascade Range, Washington: University of Washington Ph. D. thesis, 99 p.

Pratt, R. M., 1958, The geology of the Mount Stuart area, Washington: University of Washington Ph. D. thesis, 209 p., 1 map, scale 1:62,500.

Shannon and Wilson, Inc., 1973, Geologic studies of Columbia River basalt structures and age of deformation–The Dalles-Umatilla region, Washington and Oregon. Boardman nuclear project, prepared for Portland General Electric Company: Shannon and Wilson, Inc., 1 v.

Swanson, D. A., 1966, Tieton volcano, a Miocene eruptive center in the southern Cascade Mountains, Washington: Geological Society of America Bulletin, v. 77, no. 11, p. 1293-1314.

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

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

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

7. THE LOW TEMPERATURE GEOTHERMAL RESOURCES OF EASTERN WASHINGTON

by

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7. THE LOW TEMPERATURE GEOTHERMAL RESOURCES OF EASTERN WASHINGTON

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Michael A. Korosec, William M. Phillips, and J. Eric Schuster

Introduction

Relatively deep irrigation wells drilled throughout much of the Columbia Basin of Eastern Washington have often encountered warm water aquifers. As early as the turn of the century, geohydrologists were noting the anomalous temperature gradients suggested by many of these wells, especially the artesian wells in the Moxee Valley, east of Yakima (Smith, 1901). Well temperature information collected during the 1970's further suggested that large portions of the Columbia Basin could provide low temperature geothermal resources. But a closer examination of the available information by the Division of Geology and Earth Resources showed that there was a tremendous amount of variation within the basin, often over relatively short distances (Korosec, Kaler, and others, 1981, and Korosec, Schuster, and others, 1981). In addition wide discrepancies were noted for the values reported for the same well by different sources. Nonetheless, the Division produced the current Geothermal Resource Map of Washington as a preliminary compilation of information, to begin the process of identifying the areas of high potential (Korosec, Schuster, and others, 1981).

Since the completion of the map, the Division has collected additional well information and has further analyzed the entire data set. This chapter will summarize the data-collecting activities of 1980 to 1982, discuss the approaches taken toward data manipulation, and will present an updated picture of the nature and extent of geothermal resources within the Columbia Basin.

Well locations are given in abbreviated from. A well described as 10N 20E 30AB would be in the northwest quarter of the northeast quarter of section 30, in township 10 north and range 20 east. For subsection, A equals northeast, B equals northwest, C equals southwest, and D equals southeast.

Past Work and Some Inherent Problems

The state geothermal map identifies about 330 wells with bottom hole temperatures in excess of 20°C within the Columbia Basin of eastern Washington. In addition, information on about 350 additional wells with cooler temperatures was available and used in the determination of the map's gray areas, which delineate regions potentially underlain by low temperature geothermal resources (i.e., warm aquifers at relatively shallow depths). Within the indicated potential areas, temperature gradients calculated from "bottom hole temperature" and using an average surface temperature of 12°C, were generally greater than 45°C/km. As explained in the map's key, "It is not implied that thermal water will be found everywhere in the gray areas. In southeastern Washington, cold wells are interspersed with warm wells." In addition, "Absence of gray shading does not indicate there is no possibility of finding geothermal resources; it means only that surface and subsurface manifestations are not now known". These cautious statements alluded to the preliminary nature of the map and its designated potential resource areas. Since the compilation of the map, we have identified several causes for some of the variations and inconsistencies suggested by the map and accompanying table of well information.

Data Sources: Well information reported in Korosec, Schuster, and others (1981) and used to construct the geothermal map was compiled form several different sources, representing different degrees of quality, accuracy, and hence, reliability. High quality, reliable data includes well temperature information from Washington State University (J. Crosby and Staff), Southern Methodist University (D. D. Blackwell and Staff), and well logs collected by the Division staff. Questionable information includes unpublished U.S. Geological Survey well logs and WATSTORE data from the Water Resources Division, and information from U.S. Geological Survey water supply papers and Washington State Division of Water Resources water supply bulletins. The lower quality assigned to these sources is due to either temperature probe calibration problems (unpublished USGS well logs) or uncertainties as to whether the temperature is a downhole reading or a well head temperature from a flowing well, possibly representing a mixture of more than one aquifer.

Bottom Hole Temperature: Most wells in eastern Washington are wholly or partially uncased irrigation, municipal, or domestic supply wells. Water flow between aquifers often produces stair-step temperature-depth plots, with large isothermal sections and high gradient "temperature recovery" sections. As a result, the actual temperature increase with depth is not manifested as a straight line gradient. By using the temperature difference between the bottom hole and the surface, an extrapolated gradient can be calculated. But during an examination of data from original driller's reports, it was found that many wells have been logged short of the true bottom of the wells. The probes were blocked by obstructions in the hole, casing step downs, caving zones, etc. If there is inter-aquifer communication extending to depths deeper than the lowest point logged, then the calculated gradient is meaningless. Upflow would produce an artificially high gradient, and vice versa for downflow. A possible example of the first case is the Moon well (7N 26E 5AB, Benton County). With a temperature of 22.1°C at a logged depth of 148 meters, a calculated gradient of 68°C/km results. The well was actually drilled to 326 meters, and upflow is the likely cause of the relatively high temperature at the logged depth. An example of the second case might be the Phillips-11 well (16N 32E 14BB, Adams County). A temperature of 20.0°C was measured at a depth of 314 meters, producing a calculated gradient of 25°C/km. The well was actually drilled to 399 meters. Surrounding wells produce calculated gradients of 45 to 50°C/km. Downflow through the lowest zone logged probably produces the low calculated gradient at Phillips-11.

In some cases, logging to the total drilled depth does not overcome the effects of interaquifer water flow, specifically when the hole bottoms in an underpressured aquifer. Downflow to and into this zone will result in an artificially low bottom hole temperature. The only well in which we are sure this is happening is the City of Ephrata Well No. 10 (21N 26E 15AD) in Grant County. This well produces 30°C water for municipal supply, and will soon be used to heat municipal buildings as part of a Federal Housing and Urban Development funded geothermal project. But the temperature measured at total depth, about 561 meters, was only 21.3°C. The well was virtually isothermal over the lower 400 meters, suggesting strong downflow during static conditions. A gradient calculated from the temperature logged would be 17°C/km, while the actual gradient is about 35°C/km or better. (The pumped water temperature of 30°C, used as a bottom hole temperature, produces a gradient of 32°C/km, but the pumped water is most likely a mixture of a shallow aquifer at about 21°C and a much warmer lower aquifer.) Gradients from shallower wells in the surrounding area are of poor quality but range from 32 to 116°C/km.

Surface Temperature: For the published state geothermal map, an average surface temperature of 12°C was used to calculate gradients. For the Columbia Basin, reported mean annual air temperatures range from 10° to 14°C, with an average of roughly 11.5°C. Variations are controlled primarily by latitude and elevation. Mean annual surface temperatures are usually warmer than mean annual air temperatures, and show more variation, being dependent on slope angle and slope orientation as well as latitude and elevation. The size of the error introduced by using an average mean annual surface temperature for gradient calculations will be dependent on both the depth of the hole and the spread between surface temperature and bottom hole temperature. The deeper and/or warmer the bottom hole temperatures, the less the percentage of error. In an area where the "real" gradient is about 45°C/km, and the mean annual surface temperatures range from 10° to 13°C, calculated gradients using 12°C for holes 100 meters deep may produce errors from 45 percent too low to 25 percent too high (from 25 to 55°C/km). At 200 meters depth the errors range from 22 percent too low, to only 9 percent too high (from 35 to 50°C/km). At 300 meters, the errors are diminished to values from 16 percent too low to 7 percent too high (from 38 to 48°C/km).

New Data Collection

During 1980 and 1981, additional well temperature information was collected by three workers; John Kane, working directly for the Division, and Sherri Kelly and Walter Barker, working for David D. Blackwell, Southern Methodist University, in cooperation with the Division. A total of 180 wells were added to the data set. For many of these wells, drilling depth information was collected. The new data give better coverage of the Columbia Basin, especially the margins, add detail in the Yakima area, and fill in some of the previously blank portions of the map.

In addition, the authors gathered drilling depth information for several hundred holes. The summaries of drillers's reports found in several hydrologic reports were used. Eventually, the total drilled depth for most of the wells in our files will be known, but only after the original driller's reports filed with the State of Washington Department of Ecology are examined.

Data Manipulation

With the additional information collected over the past few years, new approaches to data manipulation have been found. These new approaches have enabled us to overcome many of the problems discussed earlier, and present a somewhat different picture of the extents, boundaries, and temperature gradients of anomalous areas, areas representing the best locations for potential low temperature geothermal resources.

The problem of differing data quality resulting from different information sources was overcome by assigning degrees of confidence to the data sets. We have high confidence in information collected by all individuals associated with Southern Methodist University, Washington State University, and the Division and therefore use primarily these data sets for contouring and the determination of anomalies.

The best quality gradients are straight-line plots of temperature vs. depth, observed over most of the length of the well. These gradients are designated "A". Cased holes, with no intrabore water flow, will produce A gradients, but these conditions are relatively rare in eastern Washington. Straight line gradients can be produced in uncased holes, in zones above, below, and even between aquifers which are being affected by intrabore flow. Since one or both end points are being artificially set by the water flow, the resulting gradient does not represent the true gradient. For these wells, and for any other well with known or suspected intrabore flow, calculated gradients were used.

By knowing the drilled depth at the time of well completion, the quality of the calculated temperature gradient can be roughly determined. Good gradients, designated "G", result when logged depth approximates reported drilled depth. For nearly all of these wells, interaquifer flow has little if any effect on a calculated gradient.

Gradients calculated for wells logged short of the drilled depth were designated "S". The values were assigned a low quality rating. In addition, some wells could have complete caving at depth producing a new bottom which is reached by the probe, but shallower than the reported drilled depth. Not knowing the exact nature of the blockage, especially its effects on water flow to or from lower zones, these wells were still designated S, and considered to be of low quality. Some of these wells may not have had water flow effects on the temperature readings in the lower portion of the hole.

When the drilled depth was not determined, the well was designated "U". The unknown quality of these wells gave them about the same low credibility as S gradients, but overall, these wells have a higher probability of being close to realistic gradients because many of them were undoubtedly logged to the drilled depth. As such, they were often used to influence the contouring of the temperature gradient information.

For wells reported in U.S. Geological Survey water supply papers and State of Washington Division of Water Resources water supply bulletins, which have already been assigned a relatively low quality as a source, gradients calculated from their temperatures were designated "F", for flowing. It is assumed that the temperatures represent a pumped or artesian flowing water, which is either cooled as it rises through the well, warmed as it passed through the pump (if the flow is low), or represents a mixture of lower and upper aquifers. For the most part, these gradients should be minimums. As such, these gradients were only used to influence the position of contours and the designation of anomalous areas where there was otherwise a lack of data.

The problem of errors introduced by using a single mean annual surface temperature for all of eastern Washington was partially overcome by several different methods. By placing more emphasis on the deeper holes, and virtually ignoring the holes less than 120 meters in depth, high-percentage errors were reduced. For holes in the northern portions of the Columbia Basin, where the mean annual air temperature is a few degrees cooler than southern sectors, conservatively lower values were used to generate calculated gradients. For wells with sufficiently detailed near-surface temperature/depth information, where undisturbed by obvious in-hole flow, the mean annual surface temperature was determined from the upper gradient inflection point. This was usually the coolest temperature in the well, if measured during the primary field season, the warm months of May through October. Another method used, especially for wells logged during the cooler seasons, involved determining the general temperature gradient trend of the upper portion of the temperature-depth plot and projecting this trend to the surface. These two methods were used with good success for most of the well temperature information collected during the past two years. Gradients calculated in this manner often produced values relatively close to observed gradients of quality A.

With the newly acquired information, a computerized data base was formed, allowing for quick sorting by parameters such as county, location, depth, temperature, gradient, gradient quality, and information source. For example, a high quality data subset was produced by using Southern Methodist University, Washington State University, and Division data, and using the parameter limits of depth greater than 150 meters and gradients of quality "A" or "G". This reduced the number of wells from over 1000 to about 150 wells.

Computer-run trend surface analysis and contouring programs using this data subset produced a picture of the Columbia Basin very different than previously imagined. However, the complexity suggested by the results, and the very poor percentage of variation explained by the trend surface, at all orders, discouraged our further use of computer manipulation, except for sorting.

The complexity in gradient distribution in the Columbia Basin was not a total surprise. The geohydrologic work conducted by John Biggane in the Yakima area demonstrated that shallow to intermediate depth wells, with depths up to 200-250 meters, could show a tremendous range of high quality gradients over a relatively small area. Biggane suggests that structure and hydrologic controls play an important part in producing these temperature gradient variations.

After plotting all temperature gradients of wells deeper than 120 meters, with quality A and G, and including several gradients with quality U and S (if their values fell within a "reasonable" range), a detailed gradient map with contour interval of 5°C/km was drawn. Figure 7-1 is a simplified and smaller-scale version of this hand contoured map, using a contour interval of 10°C/km. Several areas of above average gradients have been identified. Figure 7-2 shows the locations of the geothermal anomalies, and Table 7-1 presents a listing of some of the best wells within these anomalies.

Cascades: A large portion of the southern Cascades is characterized by gradients in the range of 45 to 55°C/km, or higher. Smaller areas with gradients in excess of 80°C/km are found along the Tieton River east of Rimrock Lake (40km west of Yakima) and along the Columbia and Wind Rivers near the Columbia Gorge (see Figure 7-2). The extent of these high gradient areas, and the extent of areas with gradients between 55 and 80°C/km (as suggested by a few single-point anomalies) is not yet known.

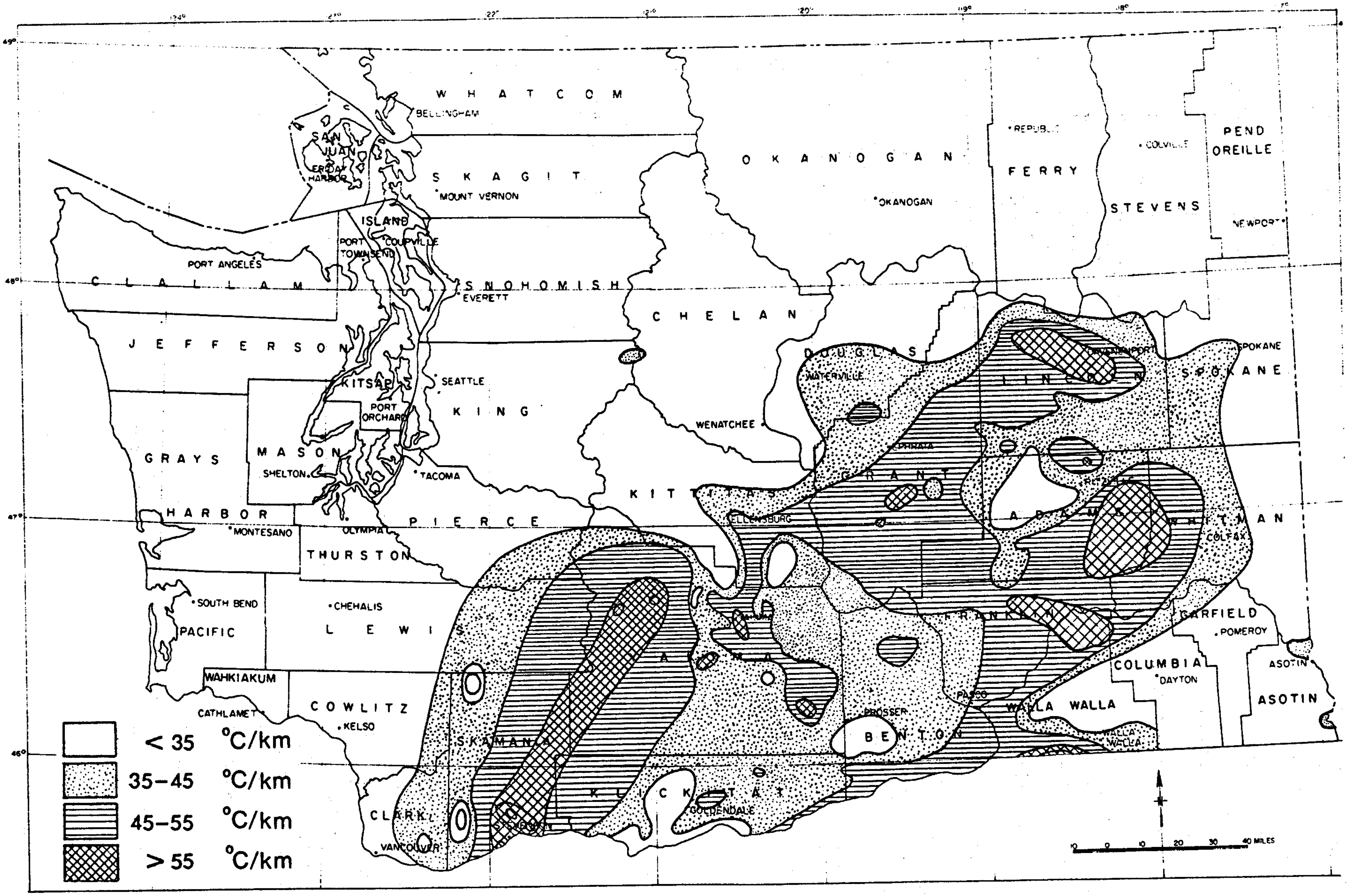

Figure 7-1. — Temperature gradient contour map of Washington.

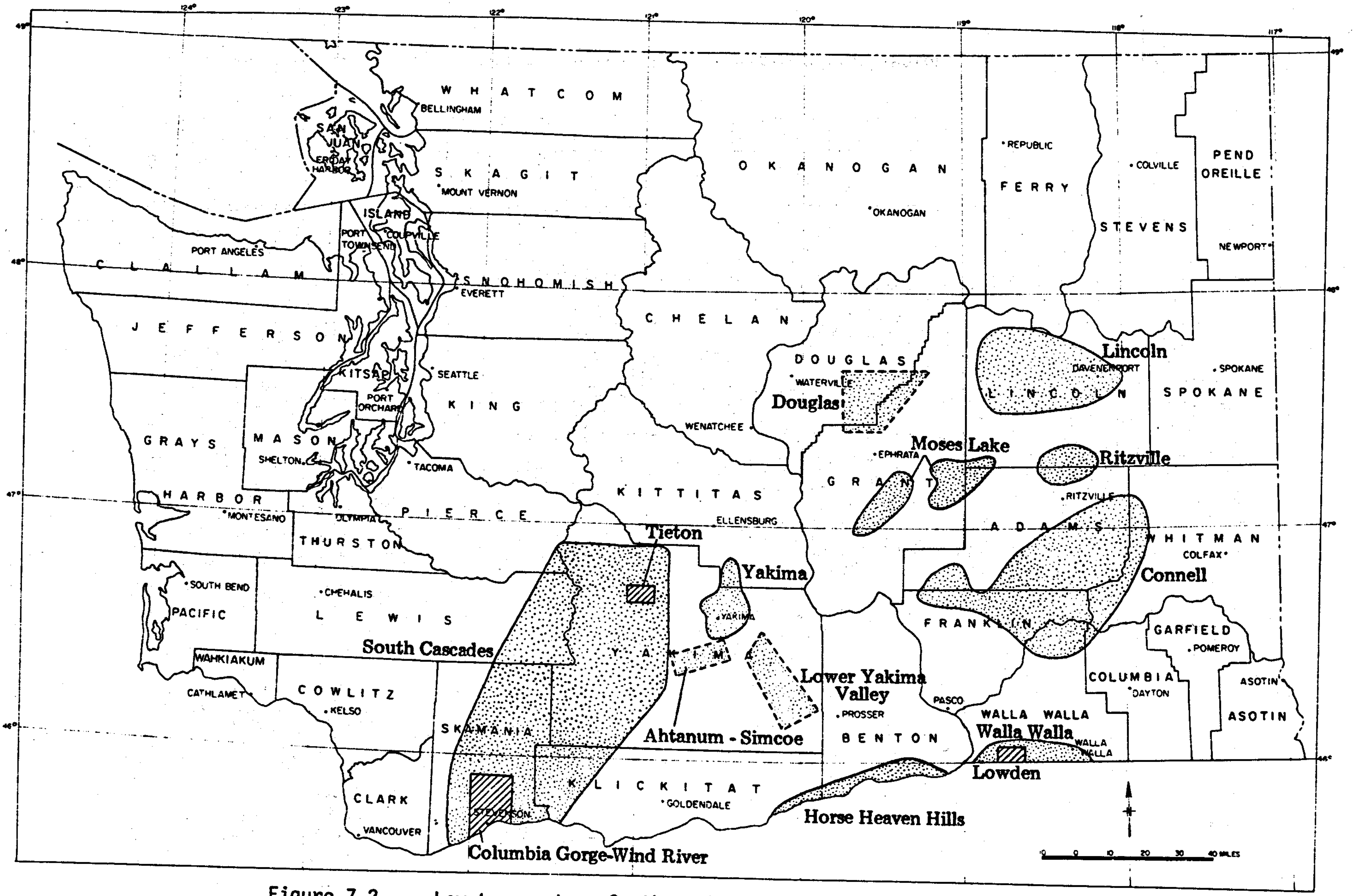

Figure 7-2. — Low-temperature Geothermal Resource Areas in Washington.

Table 7-1. — High-gradient warm wells within Columbia Basin geothermal anomaly areas, from WELLTHERM (see notes at end of table).

Location			Name	Bottom Temp.	Logged Depth	Total Depth	Grad. A	Grad. B	Quality	Surf. Temp.	Source
			YAKIMA								
Yakima-Moxee Valley											
12N	19E	16BB	DNR Gangle	22.0	153	153	--	58	G	13.0	1
12N	20E	16CA	DNR Elephant	29.2	418	?	--	44	U	11.0	2
12N	20E	27CC	Logan	30.4	396	?	--	46	U	12	1
12N	20E	34CC	Estes	33.1	429	?	--	49	U	12	1
12N	21E	16CA	DNR	25.1	235	?	--	55	U	12.2	8
13N	18E	12AA	Carrell	24.8	201	200	--	59	G	13.0	3
13N	18E	24	Creamery Well	33.9	513	?	--	43	U	12.0	1
13N	19E	13DC	Terrace Hts.	24.8	251	?	--	47	U	13.0	1
13N	20E	20BD	Champoux	23.3	215	214	--	52	G	12.2	8
13N	20E	33CA	Coombs	23.2	227	?	--	48	U	12	1
14N	17E	13AD	Murray-3	19.5	132	132	49	61	G	11.5	8
14N	17E	19DC	Mansperger	19.9	150	153	57	57	G	11.4	8
14N	18E	20AC	Zirkle	29.0	324	325	--	52	G	12	1
14N	19E	16CC	Roche	23.2	267	274	--	46	G	11.0	1
15N	19E	22CA	USGS Burbank	23.4		183		62	F	12.0	1
15N	19E	22CD	Larson Fruit	31.5	393	?	--	50	U	12.0	1
Ahtanum-Simcoe											
11N	16E	34DB	Gowdy	21.4	--	139	--	68	F	12	4
11N	17E	2CA	Dekker	25.5	--	265	--	51	F	12	4
11N	17E	16BC	Stephenson	31.6	302	306	--	65	G	12	3
11N	18E	9CC	Siegner	23.0	--	122	--	90	F	12	4
12N	16E	12CC	Shelton	25.2	268	?	--	53	U	11.0	1
12N	16E	13BB	Herke	14.2	70	70	--	58	G	10.2	8
12N	16E	15BC	White	21.5	179	182	--	59	G	11.0	1
12N	18E	27AD	Hansen Fruit	29.6	311	311	--	57	F	12	4
			WALLA WALLA								
6N	33E	10B	Fulgham	31.8	305	312	69.6	67	G	11.5	2
6N	34E	2AB	Miller	25.1	175	?	-	75	U	12	1
6N	34E	6AB	Chuatal	34.4	470	?	-	48	U	12	1
6N	34E	7CD	Gilbert-Merry	40.7	407	408	77.8	71	G	12	2
6N	35E	18AA	Dept. Ecology	36.1	396	399	-	61	G	12	1
7N	33E	31DB	Touchet-3	27.7	268	268	-	58	G	12	1

Table 7-1 (Continued)

Location			Name	Bottom Temp.	Logged Depth	Total Depth	Grad. A	Grad. B	Quality	Surf. Temp.	Source
			MOSES LAKE - RITZVILLE - CONNELL								
Moses Lake											
18N	29E	6DC	Am.Pot.Co.	21.5	205	213	--	47	G	12	1
19N	27E	2BD	Edwards	19.5	80	82	--	91	G	12	1
19N	27E	31BB	Lauzier	25.0	233	?	--	56	U	12	1
19N	29E	4AD	Shinn-2	25.0	280	283	--	46	G	12	1
19N	29E	16CC	Carnation	28.8	191	200	--	88	G	12	1
19N	31E	24AC	Kagele	20.1	165	191	--	49	S	12	1
20N	30E	23BC	Franz	34.8	337	340	--	68	G	12	3
20N	30E	28DD	Jantz	28.5	181	181	--	91	G	12	3
21N	30E	26AC	Schell	20.7	171	172	--	51	G	12	2
21N	31E	25AB	Sahible	28.3	195	195	--	84	G	12	1
Ritzville											
20N	34E	2DC	Weber	20.9	197	200	--	50	G	11.0	1
20N	35E	24BB	Ahern	20.5	157	159	--	61	G	11.0	1
21N	34E	33BA	Hardung	24.0	253	271	--	55	G	11.0	1
Connell											
13N	34E	30CB	Cockrans	32.2	355	358	56	57	G	12	1
14N	32E	2CD	Hart	27.2	242	289	50	63	S	12	1
14N	32E	13BC	Hart	25.6	187	?	--	73	U	12	1
14N	32E	31BB	Connell-6	29.4	303	304	--	57	G	12	1
15N	28E	35CD	ECBID	24.4	253	256	--	49	G	12	1
15N	29E	3CD	Othello 5	29.0	298	307	--	57	G	12	1
15N	32E	35BC	Hart	27.6	310	318	--	50	G	12	1
15N	32E	2AA	Tomkin	25.0	252	253	--	52	G	12	1
15N	36E	34BD	Blauert	25.4	211.5	?	--	63	U	12	1
16N	30E	24BB	Kliphardt	25.9	217	220	65	63	G	12	1
16N	30E	27DA	Andrews-2	25.2	207	?	--	64	U	12	3
16N	30E	36DB	Damon	25.8	241	243	--	57	G	12	1
16N	31E	15BB	Wholman	26.2	230	?	57	57	U	13	9
16N	32E	15BB	Phillips-17	33.4	437	438	--	49	G	12	1
16N	32E	25CC	Phillips-16	31.0	380	380	--	50	G	12	1
17N	32E	14CB	DNR	23.2	189	?	--	54	U	13.0	9

Table 7-1 (Continued)

Location			Name	Bottom Temp.	Logged Depth	Total Depth	Grad. A	Grad. B	Quality	Surf. Temp.	Source
			LINCOLN								
23N	32E	4DA	Weishaar	28.7	212	212	--	83	G	11.0	1
23N	32E	17AC	Weishaar	21.2	206	209	--	49	G	11.0	1
24N	31E	16BC	D.O.E.	21.8	227	229	48	48	G	11.0	10
24N	33E	23CD	Schmierer	25.9	309	312	--	48	G	11.0	1
24N	36E	16AA	USGS Davenport	21.3	221	227	55	51	G	10.0	3
24N	36E	16AA	D.O.E.	21.9	225	229	76	55	G	9.5	10
25N	37E	21CA	Davenport-5	20.0	149	152	--	60	G	11.0	1
25N	37E	21CA	Davenport	24.0	227	297	--	57	S	11.0	1
26N	33E	18AC	Wilber City	14.7	129	137	56	--	-	10.0	10
26N	39E	10CA	Creston	17.7	205	234	56	45	S	8.5	10
			DOUGLAS								
22N	27E	19CC	Soap Lake	27.0	--	142	--	106	F	12.0	4
23N	25E	31CC	Schell-5	18.5	147	152	--	51	G	11.0	1
23N	26E	20BB	Pixlee	29.3	363	401	--	50	S	11.0	1
23N	28E	27BC	Schaffer	22.8	196	?	--	60	U	11.0	1
25N	28E	25AB	Dormaier	23.0	177	177	--	67	G	11.0	3
			HORSE HEAVEN HILLS								
3N	21E	19BA	RB-1	19.0	71	?	54	57	U	12	2
5N	22E	27AA	Matsen	28.1	317	?	--	50	U	12	1
5N	23E	13DA	Powers	26.2	330	?	--	43	U	12	1
5N	23E	29BB	McBride	25.5	266	267	--	51	G	12	1
6N	23E	15AD	Andrews	25.2	275	290	--	48	G	12	1
4N	24E	3AB	Sperry	20.6	-	121	--	71	F	12	5
5N	26E	5BB	Paterson	26.3	305	305	--	47	G	12	1
5N	28E	6DD	Engineers	21.5	-	170	--	56	F	12	4
6N	24E	22AD	Columbia R.	22.5	195	201	--	54	G	12	3
6N	26E	15CB	Craig	24.2	210	?	--	58	U	12	1
7N	25E	36CC	DOE Paterson	30.3	222	230	--	83	G	12	1
			LOWER YAKIMA VALLEY								
8N	22E	11DA	Flower	22.0	162	169	--	62	G	12	1
9N	21E	25CB	Shinn	28.5	295	293	--	56	G	12	3
9N	23E	7BC	Mandrell	17.8	89	89	53	54	G	13.0	10
10N	24E	36BD	DNR-Anderson	29.8	273	460	--	65	S	12	9
10N	25E	25BC	Nakamura	20.6	184	184	--	47	G	12	3
11N	17E	16BC	Stephenson	31.6	302	306	--	65	G	12	3
11N	20E	6AA	Peters	20.2	166	?	--	49	U	12	1
11N	20E	13DD	Soost	29.2	328	366	--	52	S	12	1
11N	21E	6CA	Dahl	29.2	364	?	--	47	U	12	1
11N	21E	20CB	Hanrahan	22.2	191	207	--	54	S	12	1
11N	21E	21AB	Ambrose Farms	27.0	279	283	--	53	G	12	1
11N	32E	29CC	Rowe Farms	29.6	333	337	--	53	G	12	1

TABLE 7-1, (continued)

WELLTHERM is a computerized summary of all well temperature information available to the Washington State Department of Natural Resources, Division of Geology and Earth Resources.

LOCATION: The first 4 columns indicate location, by township, range, section, and partial section. In the two letter partial section code the quarter section is listed first and the quarter-quarter section second, where A = NE, B = NW, C = SW, and D = SE. For example, 23 AB is the northwest ¼ of the northeast ¼ of section 23.

NAME: The well name refers to the name of the owner at the time of drilling, the owner at time of temperature logging, or the project name and number.

BOTTOM TEMP: The temperature (°C) at the lowest point of logging. This may or may not be the bottom-hole temperature.

LOGGED DEPTH: The deepest depth (meters) logged.

TOTAL DEPTH: Depth (meters) at the time of completion, as reported by the drilling logs.

GRAD. A: A relatively straight-line increase of temperature vs. depth (°C/km) observed over a major portion of the temperature log.

GRAD. B: A calculated temperature gradient (°C/km), using the difference between SURFACE TEMP and BOTTOM TEMP, divided by LOGGED DEPTH.

QUALITY: Refers to the quality of Grad B. "G" (good) indicates that the LOGGED DEPTH is approximately equal to TOTAL DEPTH; "S" (short) indicates that LOGGED DEPTH is significantly less than TOTAL DEPTH: "U" (unknown) indicates that the TOTAL DEPTH is not known; "F" (flowing) indicates that the BOTTOM TEMP is probably a flowing temperature, representing the temperature of a single aquifer, or a mixed aquifer, and not necessarily the bottom hole temperature.

SURFACE TEMP: Estimated from mean annual air temperature (usually reported as a whole number) or near-surface inflection points observed in temperature logs. For wells in the Columbia Basin without a listed SURFACE TEMP, GRAD. B was calculated using 12°C, an average surface temperature for southeastern Washington.

SOURCES:

1. Washington State University; James Crosby & Staff, 1972-1981.
2. Southern Methodist University (SMU); David D. Blackwell, & Washington Division of Geology and Earth Resources (DGER), 1971-1979.
3. U.S. Geological Survey (USGS) Tacoma, Washington, Unpublished logs from 1972-1976.
4. USGS WATSTORE computer file.
5. USGS Water Supply Paper 1999-N.
6. Washington State Division of Water Resources Water Supply Bulletin 21.
7. Washington State Division of Water Resources Water Supply Bulletin 24.

TABLE 7-1, (continued)

8. Sherri Kelly, SMU and DGER, 1980.
9. John Kane, DGER, 1980.
10. Walter Barker, SMU and DGER, 1981.
11. Washington Division of Geology and Earth Resources Staff, 1981.

For the middle Cascades, from Mt. Rainier north to Stevens Pass, gradients suggest that this is a relatively low gradient province, but coverage is inadequate. For the northern Cascades, the average temperature gradient is still unknown. The relatively high gradient of 68°C/km at a heat flow hole near Scenic (Stevens Pass area), and the occurrence of two stratovolcanoes, Mt. Baker and Glacier Peak, suggest that there may be substantial areas with relatively high gradients within this province, and further investigations are needed to verify this.

Columbia Basin: The Columbia Basin, an area of relatively higher gradients than surrounding areas to the north, east, and south, shows substantial internal variation. Good to fair quality gradients range from 25 to 90 °C/km, but the average falls between 35 and 45 °C/km. Most anomalously warm wells, with gradients in excess of 45 °C/km, fall within several major and minor areas described below. Unlike the "gray areas" on the Geothermal Resources Map (1981), we need not be as cautious concerning the occurrence of colder gradient wells within these areas. Cooler wells may exist within anomalous area, but they are not recorded in our well temperature data set of more than 1000 wells.

Yakima and Ahtanum-Simcoe areas: The highest degree of variation and complexity occurs around Yakima. This complexity has been brought out by the high density of wells in the area. Investigations by John Biggane confirmed this complexity, and suggest that topographic control of hydrology is responsible for much of the variation (Biggane, personal communications). The best gradients occur along the main Yakima River valley, from Wymer south to Union Gap, and extend into the Moxee Valley (along Roza Creek). Gradients are generally 50 to 60 °C/km within these areas. To the southwest of the city, within the Ahtanum and Simcoe River valleys, a few wells with high quality information, and several wells of marginal to poor quality produce relatively high gradients from 50 to 70 °C/km. Some of these wells may fall within restricted anomalies, with conditions controlled by valley alluvial fill and the

Ahtanum Ridge anticline (which separates the two drainages), but the high gradients on the west side of this area may be representative of a broad high gradient zone associated with the southern Cascades (see the contour map, Figure 7-1).

Moses Lake-Ritzville-Connell Areas: Within the central and eastern portions of the Columbia Basin, several pockets of either high gradients or very low gradients occur. For the warm areas near Moses Lake, many gradients range from 45 to 60 °C/km, with one well at 63-65 °C/km (Kliphardt, 16N 30E 24BB). A very broad anomalous area is located between Connell and Ritzville, and extends east, and southeast from Connell, reaching over 70 km to the east. Many high quality gradients define this anomaly, but the density of coverage is generally poor and very uneven. Most good quality gradients are in the 55-60 °C/km range while fair quality gradients suggest that gradients of 50 to 60 °C/km might be found throughout the area.

A large portion of the Moses Lake-Connell-Ritzville area is the target of a current geohydrologic study by Scott Widness, a graduate student at W.S.U. working for the Division.

Lincoln: A broad area which extends from around Davenport to 50 km west contains many wells with good quality gradients ranging from 50 to 60 °C/km. Only a small gray area appears on the 1981 state geothermal resource map, immediately surrounding the town of Davenport. The acquisition of new temperature gradient information over the last two years, the lack of low gradient wells in the area, and the use of lower surface temperatures for calculating gradients has enabled us to extend the boundaries of this anomaly west and southwest. Many of the wells used for this designation are relatively shallow, with no wells over 250 meters deep, and are spread out over a wide region, with a resulting low density of coverage. More work needs to be done within this anomaly to further define the potential and its full extent.

Douglas: This anomaly is defined by only a few high gradient wells, most of which are of fair to poor quality. The anomaly may extend south to include the Ephrata-Quincy area. The denisty of coverage is very poor in this region, and further work is needed to determine the potential.

Horse Heaven Hills: Numerous wells in eastern Klickitat and southern Benton Counties (just north of the Columbia River) produce warm water from relatively shallow depths. Calculated gradients for these wells range from 45 to 55 °C/km.

Lower Yakima Valley: Throughout the Yakima River valley, south of Yakima from Union Gap to Prosser, temperature gradients range from the lower to upper 40's (°C/km) and a few wells fall between 50 and 55 °C/km. West of Mabton, a small area contains wells with gradients between 50 and 55 °C/km. Northwest of Sunnyside and east of Zillah, a few wells produce gradients in the low 50's (°C/km). Most of the Yakima River valley was included in the Yakima geohydrology project by J. Biggane.

Walla Walla: The Walla Walla River valley, from Walla Walla west to near the Columbia River, contains some of the highest gradients observed in the Columbia Basin for relatively deep wells. Near the city of Walla Walla, especially on the west and south sides, temperature gradients range from 45 to 55°C/km, with most values between 50 and 55°C/km. In the Lowden-Touchet area further to the west, a few wells produce gradients greater than 70°C/km. The best of these wells, Gilbert-Merry (6N 34E 7CD) has a temperature of 41°C at a depth of 407 meters. An observed gradient of 77.8°C/km is supported by the calculated gradient, 71°C/km (assuming a surface temperature of 12°C.) In addition, the only warm spring in the Columbia Basin occurs close to this area, Warm Springs Canyon Warm Springs, with a temperature of 24°C.

Other Areas: In addition to the anomalous areas listed, several single point anomalies show up in the data set, individual wells with good quality information and relatively high calculated gradients. These wells are occasionally surrounded by much cooler wells (with lower gradients), but more commonly, they represent the only well in the vicinity. These isolated occurrences are either due to very local structural and/or hydrologic controls (especially when seemingly contradicted by surrounding wells), or represent additional anomalous areas of unknown extent. Some of these anomalies may be of significant size. This will be determined only when the density of information for these areas is improved.

Conclusion

Despite the lack of fully cased wells and resulting stair-step temperature gradient plots, good quality information can be derived from numerous wells in the Columbia Basin. Gradients calculated from wells logged as deep as they were drilled have enabled us to designate several areas within the Basin which hold high potential for low temperature geothermal resources.

Thus far, the emphasis has been on temperature gradients, with anomalies being determined by the wells with gradients above average (greater than 45 °C/km), and commonly between 50 and 60 °C/km. The next work in these areas should concentrate on characterizing the actual resource, by gathering information on aquifer temperature, depth, extent, chemistry, and productivity. In light of the relatively low costs associated with accumulation of temperature-depth information, our well logging efforts will continue, with the hope of discovering new anomalies and to place better boundaries on the known anomalies.

References

Biggane, John H., 1981, The low temperature geothermal resource of the Yakima region– A preliminary report: Washington Division of Geology and Earth Resources Open-File Report 81-7, 70 p., 3 plates.

Biggane, John H., 1982, The low-temperature geothermal resource and stratigraphy of portions of Yakima County, Washington: M.S. thesis, Washington State University, 126 p.

Korosec, M. A.; Kaler, K. L.; Schuster, J. E.; Bloomquist, R. G.; Simpson, S. J.; Blackwell, D. D., 1981, Geothermal resources of Washington: Washington Division of Geology and Earth Resources Geologic Map GM 25, 1 sheet, map scale 1:500,000.

Korosec, M. A. and Schuster, J. E., 1980, The 1979-1980 geothermal resource assessment program in Washington: Washington Division of Geology and Earth Resources Open-File Report 81-3, 148 p., with 4 appendices.

Smith, G. O., 1901, Geology and water resources of a portion of Yakima County, Washington; U.S. Geological Survey Water Supply and Irrigation Papers No. 55, 65 p.

8. PROGRESS REPORT ON THE TIME-SPACE-COMPOSITION MODEL FOR THE QUATERNARY VOLCANICS OF THE SOUTH CASCADES, WASHINGTON.

by

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8. PROGRESS REPORT ON THE TIME-SPACE-COMPOSITION MODEL FOR THE QUATERNARY VOLCANICS OF THE SOUTH CASCADES, WASHINGTON.

by

Michael A. Korosec and Paul E. Hammond

Introduction

The time-space-composition modeling project for Washington's southern Cascades was begun in early 1981 with U.S. Department of Energy funds through a subcontract to Paul E. Hammond of Portland State University, Portland, Oregon. The aim of the project is to identify and delineate all volcanic rocks younger than about 5 million years and their eruptive centers, characterize the rocks petrographically and chemically, determine their areal extent and volume, and place the individual eruptive events in sequence by stratigraphic interpretation and radiometric age dates. The study area extends from the Columbia River north to the Goat Rocks and Cispus River, and from the Klickitat River west to the Puget-Willamette trough, exclusive of the stratovolcanoes Mount St. Helens and Mount Adams.

The data being gathered should lead to a number of interpretations, including estimates of rates of volcanic activity, and identification of chemical, stratigraphic, and geographic trends of volcanism over time. Plans call for the determination of relative concentrations of eruptive centers (vents per square kilometer), how these concentrations relate to eruptive volumes, spacing patterns, and frequencies, and how all of this relates to the extent, style, and frequency of tectonic deformation in the region. Using chemistry and petrography, evidence of high-level crustal differentiation will be sought. Such differentiation would suggest the possible existence of magma chambers of significantly large size and/or long life. By working from patterns of eruptive volume per unit area per unit of time, estimates of the heat transferred volcanically to the surface in the past will be made and compared to the regional heat flow (determined from drill hole temperature gradients and rock thermal conductivities). The project will contribute to a better understanding and interpretation of the geothermal resource potential of the region, and may lead to new geothermal targets and exploration philosophies.

Work to Date

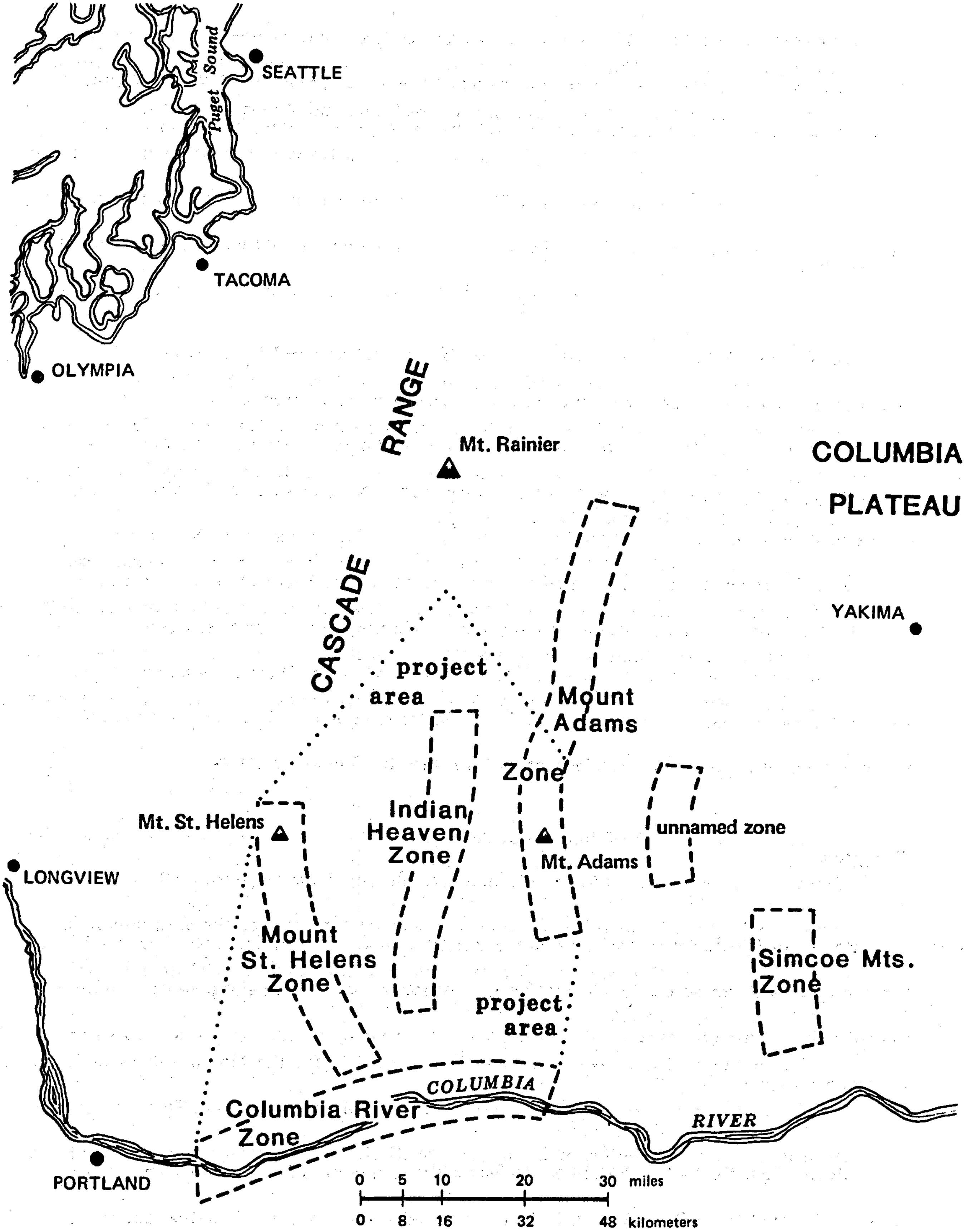
As of early 1982, a major portion of the data collection had been completed. Trace element determinations and specific gravity measurements were finished, and whole rock chemistry had been performed for 50 samples. Only 2 of 14 radiometric age dates had been successfully completed, due to the relatively young age of the rocks and age limitations for the original analytical lab. Petrographic studies for all of the samples were in progress, as were determinations of areal extent and volume calculations for 100 rock units. An overlay map of Quaternary volcanic units has been prepared showing the location and areal extent of the various units and most sample sites by numbered location. The map is an overlay to a reconnaissance geologic map at a scale of 1:125,000 (Hammond, 1980). Limited field collection of samples for further age dating was scheduled for the Summer of 1982.

Discussion

Some preliminary observations and interpretations are already evident. Most of the volcanic activity is younger than 700,000 years, postdating the last magnetic polarity reversal. The volcanic activity appears to have been concentrated in three separate north-south belts and one east-west belt.

North-South belts - The Mount St. Helens belt extends from Mount St. Helens on the north, to Trout Creek Hill on the south. It includes andesite and basalt of Marble Mountain,

Figure 8-1. Index map showing zones of volcanism and project areas in southern Washington Cascade Range.



Soda Peak andesite, West Crater, and Trout Creek Hill basalt. Some of the youngest volcanic activity is included in this belt, most notably at West Crater and Mount St. Helens.

The next north-south belt to the east is the Indian Heaven zone. It extends from the Burnt Peak basalts at Lone Butte and Steamboat Mountain on the north, to the Big Lava Bed on the south end. It includes the numerous basalt flows, shield volcanoes, cinder cones, and fissure zones, known collectively as Indian Heaven. The basalt flows at Spud Hill may be a northern extension of this belt.

The north-south belt which falls between Indian Heaven and the Simcoe Mountains is referred to as the Mount Adams belt. This is the largest belt by area and volume, and includes volcanics of the White Pass-Tumac Mountain area, Goat Rocks volcanic complex, Mt. Adams, and the King Mountain Fissure Zone.

East-West belt - The Columbia River belt consists of a scattering of volcanic centers extending from the Boring basalts and Skamania volcanics (informal name) on the west, to the basalts of Underwood Mountain and White Salmon on the east. The volcanics of the Mount Defiance-Hood River area in Oregon may also be considered to be part of the Columbia River belt.

With the exception of the stratovolcanoes, the volcanic activity has been principally calc-alkalic to tholeiitic basalt to basaltic andesite. Silica contents range from 48 to 56 percent. Expressed as the number of volcanic centers per belt, activity has been the most intense in the Indian Heaven belt, with lesser activity in the Mount Adams, Mount St. Helens, and Columbia River belts, in decreasing order.

Within the Indian Heaven area, and less commonly for the Mount Adams belt, voluminous outpourings of porphyritic plagioclase-rich basalt have occurred. This suggests that there may be an accumulation of magma at a relatively high crustal level under these belts.

Explanation Key for Figures 8-2 through 8-5

The following figures are graphical representations of individual units which constitute the main volcanic zones. The vertical scale represents time, and the horizontal scale represents spatial distribution along the zone (not to scale). The units are represented by boxes, with map unit abbreviation (see Hammond, 1980), sample number(s), and areal extent (km^2).

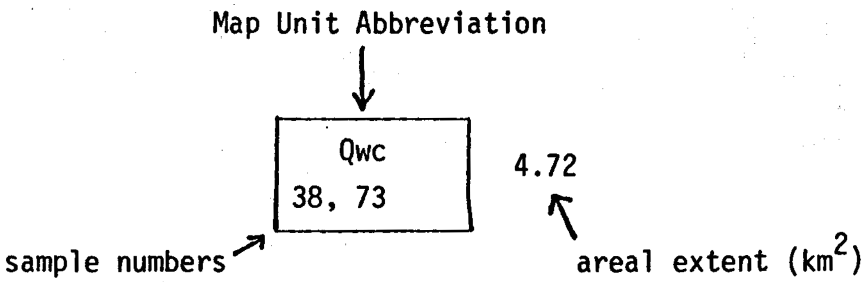


Figure 8-2 MT. ST. HELENS ZONE: Elk Pass – Marble Mtn. – Soda Pks – Trout Cr. Hill – Mowick Butte

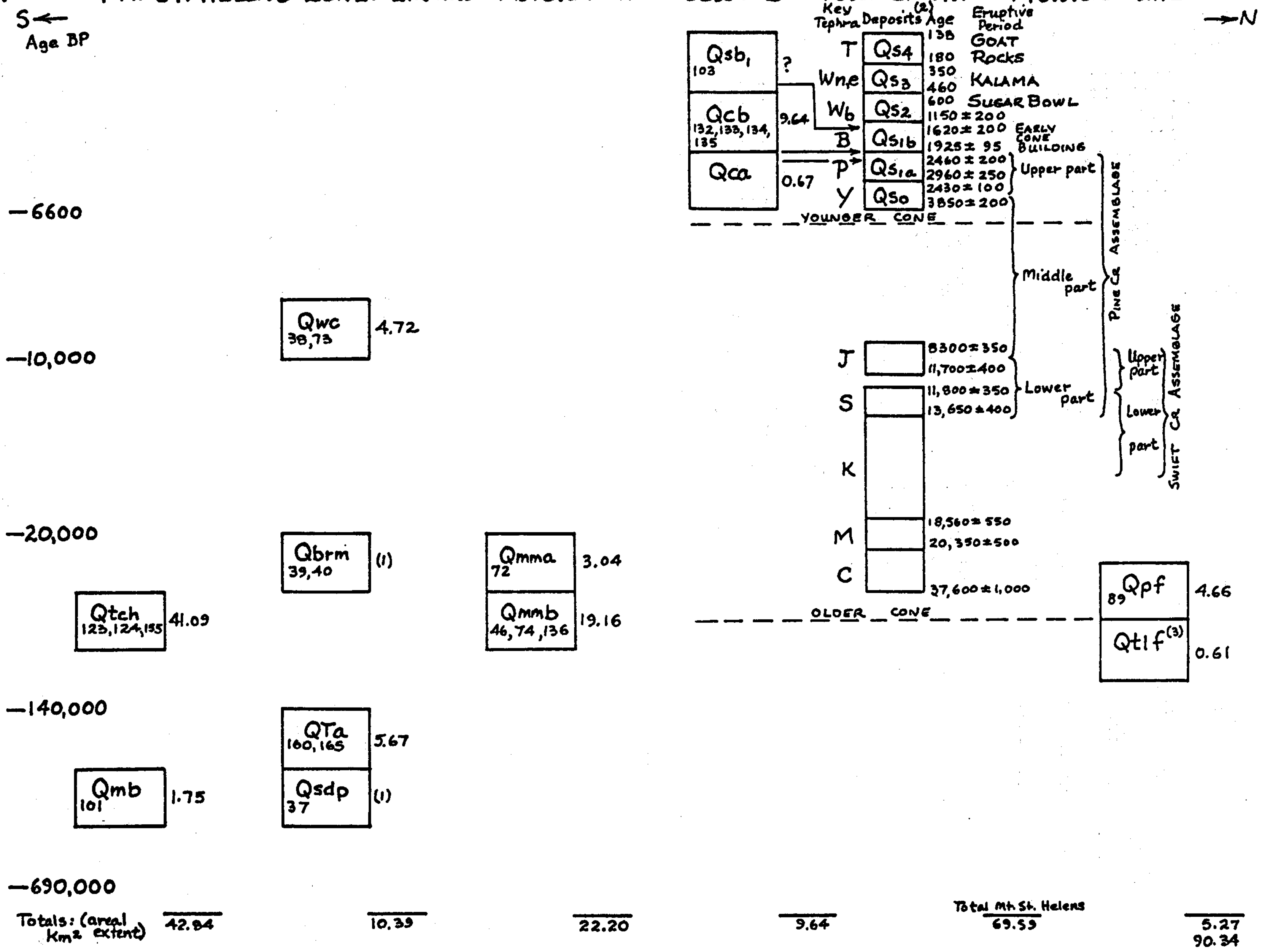


Figure 8-3 INDIAN HEAVEN ZONE: E. Canyon Cr-Steamboat Mtn.—Lemei Rock—Red Mtn.-Cedar Cr.

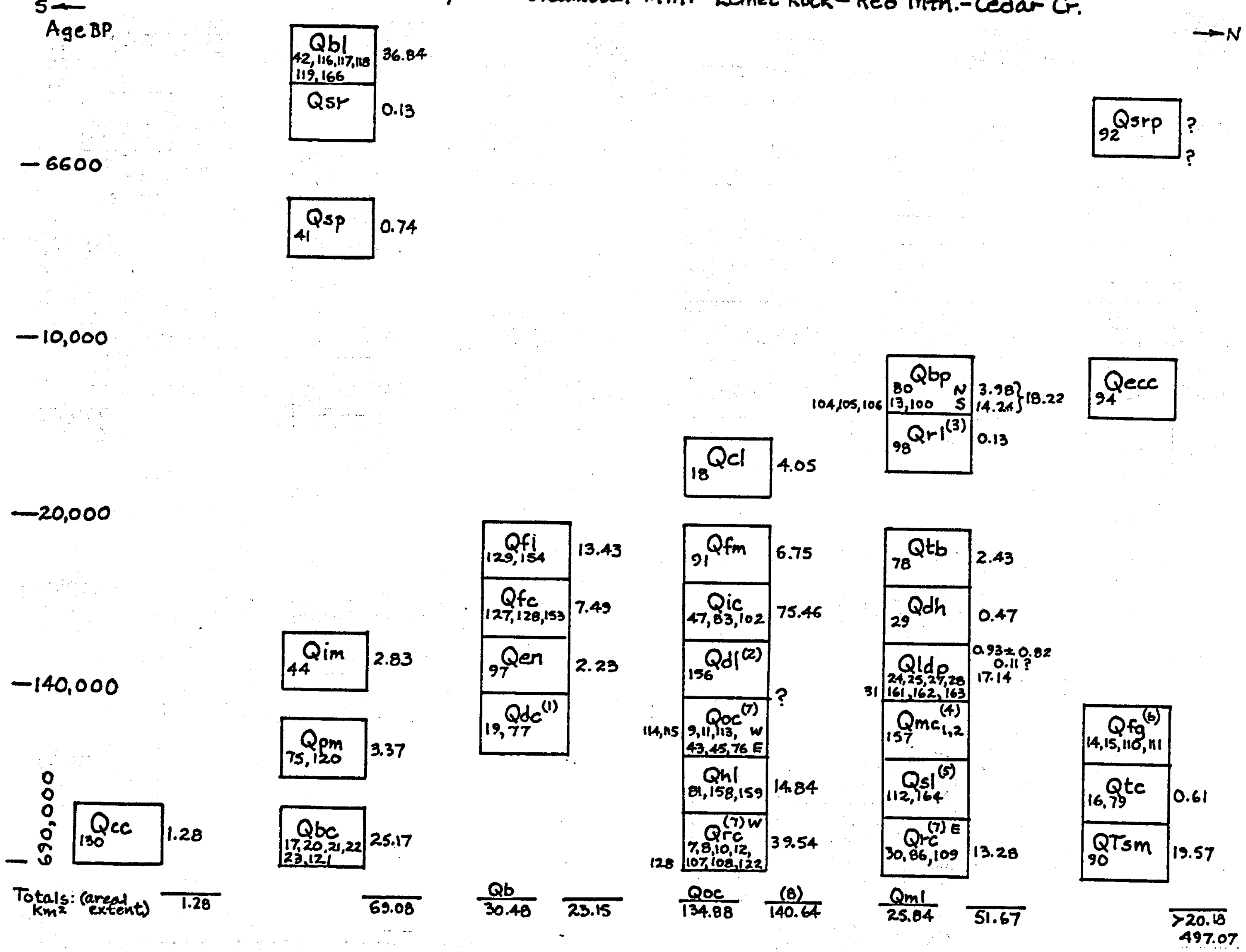


Figure 8-4 MOUNT ADAMS ZONE: Walupt L.-King Mtn.-Quigley Butte-Gilmer-Snowden.

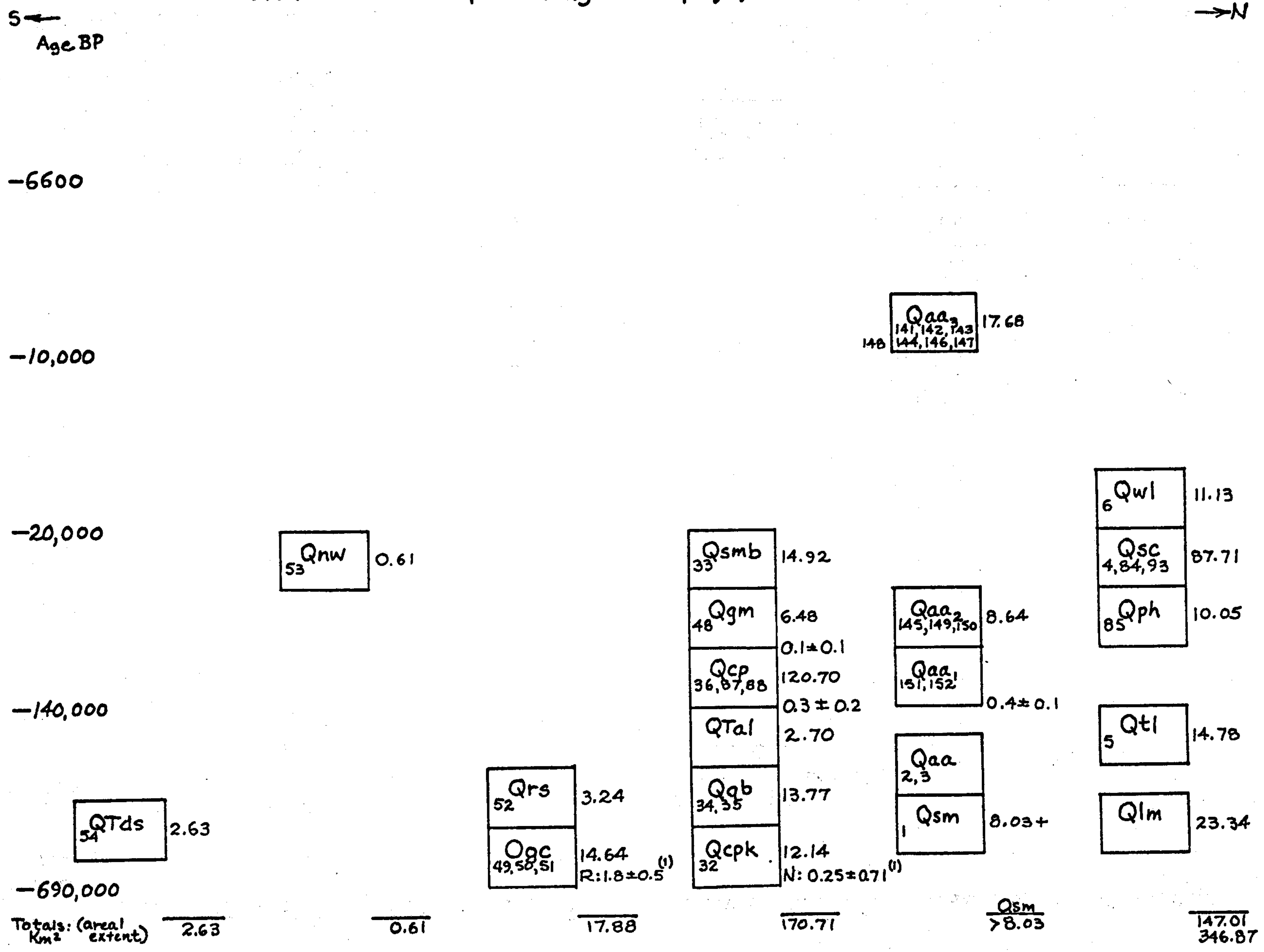
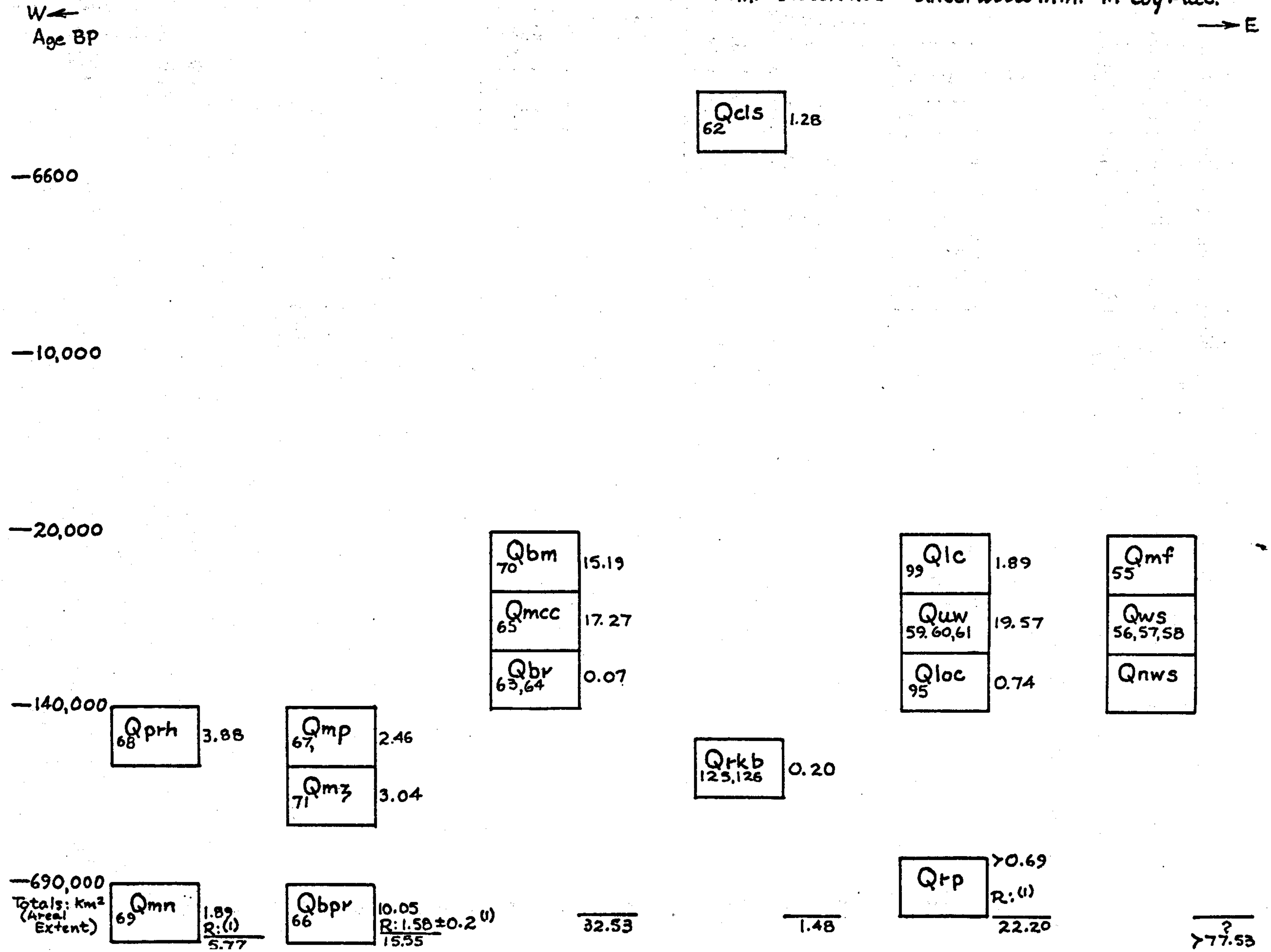


Figure 8-5 COLUMBIA RIVER GORGE ZONE: Prune Hill-Bobs Mtn.-Beacon Rock-Underwood Mtn.-McCoy Flat.



Future Work

Further interpretation will procede when the remaining chemical analyses and age dates are received from outside labs. Tables will be prepared which will include major and trace element compositions of over one hundred samples, volume estimates for each unit, age dates, and various data manipulations.

References

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

9. PLIOCENE AND PLEISTOCENE VOLCANIC HISTORY OF THE WHITE PASS-TUMAC PLATEAU REGION

by

Geoffrey A. Clayton

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Introduction

The White Pass-Tumac Plateau geologic mapping project was begun in 1978 and expanded to include Rimrock Lake to the north and Goat Rocks to the south. The region lies in the northeastern part of the southern Cascades of Washington, which form the crest between the Columbia Basin to the east and the Puget Sound Trough, Cascade foothills, and Mount Rainier to the west.

Detailed field mapping, petrologic and geochemical studies, and radiometric dating of rock units in the area were 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. In addition, it was hoped that detailed subdivision and chronology of the stratigraphic section, identification of zones of crustal weakness, and estimation of displacement along Tertiary and Quaternary faults would allow for correlation and comparison of the volcanic history of the region with volcanic episodes elsewhere in the Cascade Range.

A summary of earlier work and preliminary findings was presented in a previous geothermal program progress report (Korosec and others, 1980), and a preliminary geologic map was released (Clayton 1980). Additional information, including a final map, are being compiled and will be released as a Master of Science Thesis from the University of Washington (Clayton, in preparation). This chapter has been compiled from sections of the thesis dealing with Pliocene to Recent volcanic activity and distribution of volcanic centers and products in the area.

Regional Geology

The Tumac Plateau-White Pass-Rimrock Lake-northern Goat Rocks region in the southern Cascade Range of 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 exposed pre-Tertiary rocks in the southern Cascades of Washington, crop out at altitudes as high as 6,000 ft. (figure 9-1). 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.

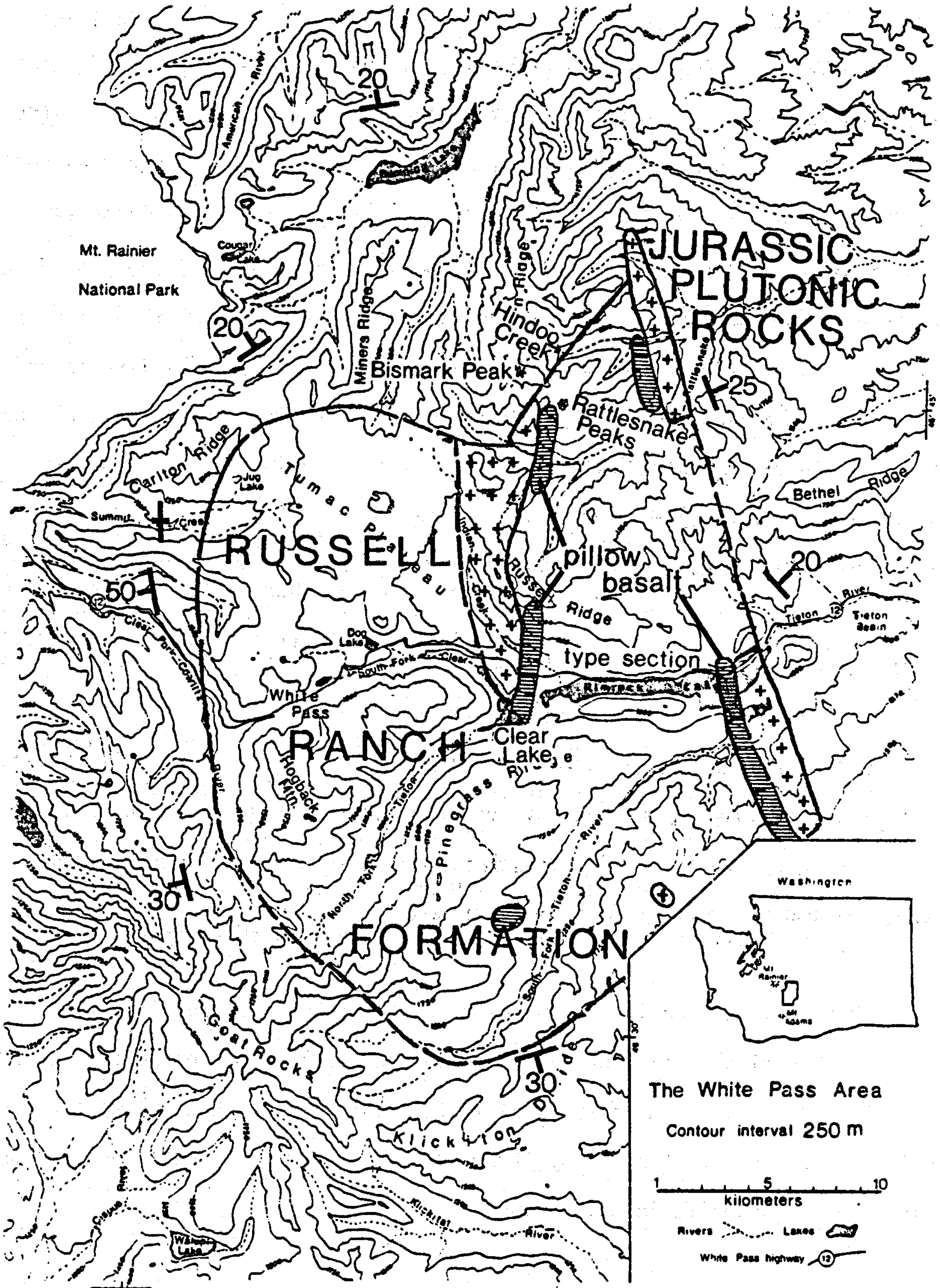


Figure 9-1. — Distribution of Pre-Tertiary Rocks

Pliocene and Pleistocene Volcanism

Pliocene and Pleistocene igneous rocks of the White Pass Area fall into five groups based on their mineralogy (table 9-1), age (figure 9-2 and table 9-1), and geographic occurrence. Variation diagrams based on major element analysis of 140 samples of the five groups of rocks show clusters of data that distinguish four types of rock chemistry within a general calc-alkaline trend. Two of the five groups of rocks have similar chemistry and therefore plot as a single cluster of data in Harker variation diagrams, but each of the other three rock types has distinctive major element chemistry. The overall differences between the igneous rocks are inferred to indicate at least four separate processes and/or source regions of magma genesis.

The five groups of igneous rocks are discussed in roughly geographic-chronologic order starting in the south (the Goat Rocks), where late Pliocene volcanic activity was concentrated, and finishing in the north (the Tumac Plateau area) where late Pleistocene volcanism was centered.

1) Rhyolite flows, breccias, and vitric tuffs of late Pliocene age, erupted from a vent (probably a caldera) between Bear Creek Mountain and Gilbert Peak, in the Goat Rocks Wilderness. The rhyolites are overlain by a small basaltic volcano of late Pliocene age (the Devils Horns). These rocks are referred to as Devils Horn rhyolites and Devils Wash Basin basalt in this report.

2) Porphyritic andesite (pyroxene andesite of Ewart, 1976) lava flows and pyroclastic breccias mainly of late Pliocene and early Pleistocene age, erupted from vents (probably a composite cone) in the Goat Rocks. These flows and breccias are referred to as porphyritic andesite of the Goat Rock's volcano or simply pyroxene andesite in this report.

Table 9-1. Characteristics of Pliocene to Pleistocene Volcanic Rock Groups in the White Pass-Tumac Plateau Region.

	Devils Horns Rhyolites	Devils Wash-basin basalt	Pyroxene andesite	Dacite porphyry	Hogback Mtn. mafic magma	Hornblende andesite
Vent Locations	Goat Rocks	Goat Rocks Devils Horns	Black Thumb Goat Rocks	Twin Peaks to Bumping Lake	Hogback Mtn. to Cougar Lake	Hogback Mtn. to Deep Creek
Age (range)	3.5-3.0 myr	3.0 myr	3.0-0.7 myr	4-2.5 myr	3.0-0.02 myr	2.0-0.03 myr
Volume	60 km^3	0.4 km^3	60 km^3	15-30 km^3	20 km^3	15 km^3
Wt % SiO_2	68-76	50	58-62	65-68	48-55	58-68
Wt % K_2O	4-6	0.6	2-3	1-2	0.5-1.5	1-2
Wt % TiO_2	<0.5	0.75-1.0	0.75-1.5	.5-.75	1.0-1.5	0.5-1.0
Phenocrysts						
Olivine	Absent	20-25	Absent	Absent	10-20	Absent
Augite	Absent	15-20	<10	Absent	<10	Absent
Hypersthene	Absent	Absent	<10	Rare	<10	Rare
Hornblende	Absent	Absent	Rare	5-25	Absent	<10
Biotite	Absent	Absent	Absent	<10	Absent	Absent
Plagioclase	<10	<10	15-40	<15	<15	Rare
Quartz	<10	Absent	Absent	<15	Absent	Absent
Total	<10	35-40	20-50	25-60	10-20	<10

Table 9-1 (Cont'd).

	Devils Horns Rhyolites	Devils Wash-basin basalt	Pyroxene andesite	Dacite porphyry	Hogback Mtn. mafic magma	Hornblende andesite
Eruptive style	high viscosity very explosive	low viscosity explosive	low viscosity explosive	high viscosity explosive ?	low viscosity thin flows	high viscosity 1 flow/volcano
Volcano type	caldera ?	spatter cone	composite	lava-dome	shield	lava-dome
% lava	<15	80	50-70	50-90	95	99
% tuff	>85	20	40	10-50 ?	<5	<1
Other	accretionary lapilli, surge breccias	mafic to ultramafic xenoliths	large near-surface Cispus Pass Pluton	many near-surface intrusions	younger and more silicic northward	concordant altitudes of vent-summits

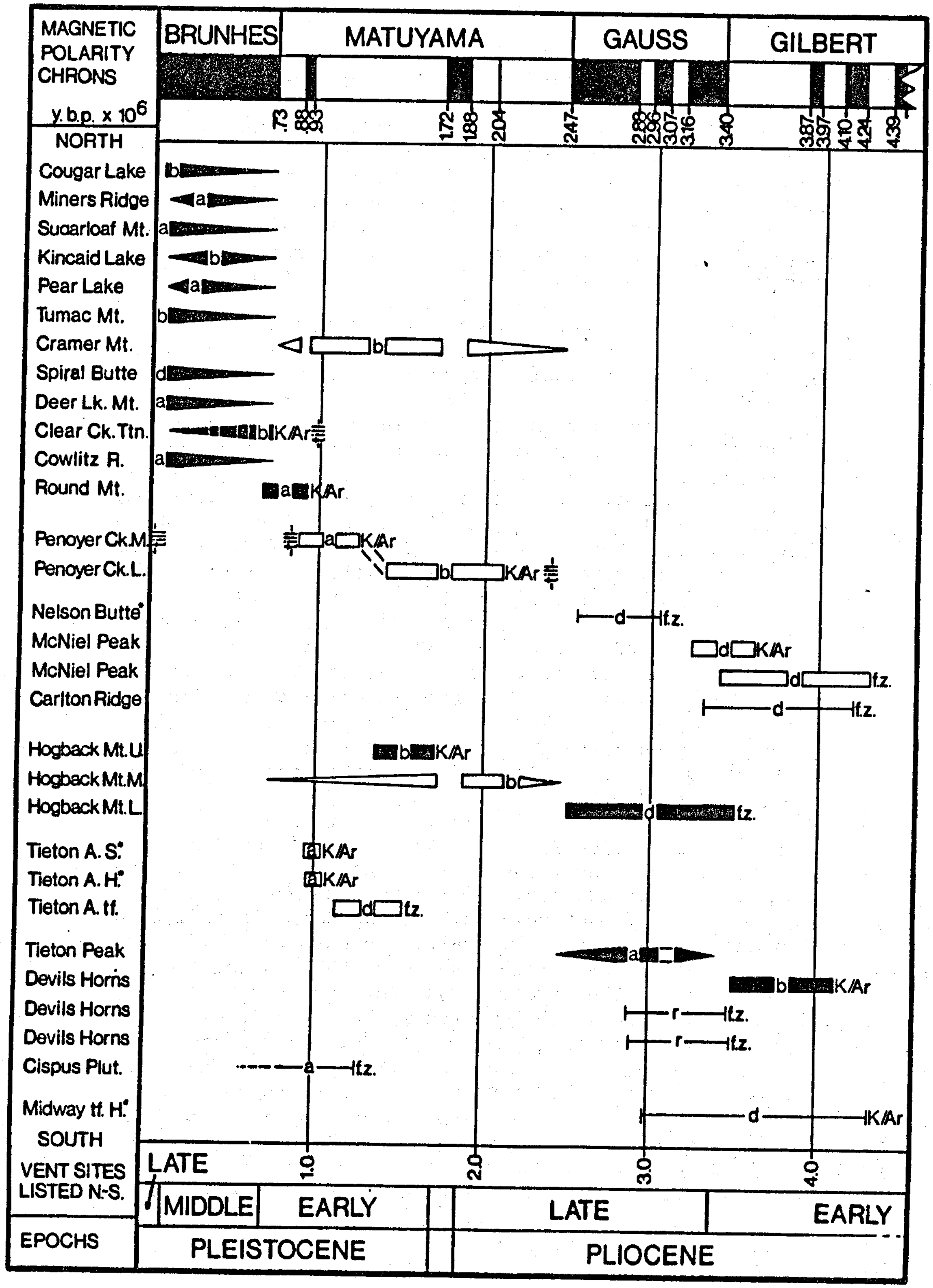


Figure 9-2. — Summary of age data for the Pliocene and Quaternary volcanoes of the White Pass Area.

Figure 9-2 (Continued). — Summary of age data for the Pliocene and Quaternary volcanoes of the White Pass Area.

Volcanoes and sample sites are listed vertically and ordered according to their geographic occurrence from north (top) to south (bottom). Each of the first twelve locales (Cougar Lake to Round Mt.) identifies an individual volcano that is very close to or comprises the named geographic feature. Penoyer Ck. M. and Penoyer Ck. L. (Ck.=Creek, M.=middle, L.=lower) are samples from distal lava flows of Goat Rocks and Hogback Mountain volcano, respectively. They were dated because of their important relations to till. Nelson Butte* (collected by Schreiber, 1981), McNiel Peak, and Carlton Ridge are sites where the dacite porphyry was sampled. McNiel Peak was apparently a vent in a widespread dacite porphyry volcanic field. A single sample from it was dated by both the K/Ar and zircon fission-track techniques. The Hogback Mt. samples are from different stratigraphic levels (U.=upper, M.=middle,L.=lower) of the Hogback Mountain shield volcano. Tieton A. S.* and H.* (A.=Andesite, S.*=Swanson, 1978; H.*=Hammond, 1980) are previously reported dates on a specific anomalously long lava flow extruded late in the eruptive history of the Goat Rocks volcano. Tieton Andesite tf. (tf.=tuff) is from a tuff that directly underlies the Tieton Andesite. Tieton Peak, Devils Horns, and Cispus Pass Pluton samples are from the Goat Rocks volcanic complex. Midway tf. H.* (Hammond, 1980) is a previously reported date on a silicic tuff to the south of the Goat Rocks.

Time before present increases to the right (along the horizontal axis). Isochrons are vertical and labelled in units of millions of years before present. The Pliocene and Pleistocene Epochs and their subdivisions, and magnetic polarity Chrons and events (black is normal, white is reversed) are keyed into the time scale at the bottom and top of the diagram, respectively.

Several dating techniques were used. Radiometric ages are identified by either a K/Ar (for Potassium-Argon dating) or f.z. (for fission-track dating of zircons). Relative ages are based on stratigraphy, morphologic degradation, and remanant magnetic polarity. The composition of the lava flow or volcano that was dated is indicated by a single letter abbreviation (b=basalt, a=andesite, d=dacite, r=rhyolite). The position of the letter also marks the calculated or best estimate of the age of the sample. Bounding the letters marking radiometric dates are statistically calculated age uncertainties (error bars) which are shown as symmetrically paired lines, black rectangles, or white (hollow) rectangles, depending on the remanant magnetic polarity of the sample (no signal, normal, or reversed respectively). The range of uncertainty of relative age estimates is indicated by triangles (black is normal, white is reversed magnetic polarity). The best age estimate lies at the base of (between) the equilateral triangle(s). An age toward the apex is inferred to be less probable.

3) Porphyritic dacite lava flows, hypabyssal intrusive bodies, and tuff of Pliocene age, intruded and erupted from a north-south trending dike system from Twin Peaks (just south of the White Pass Highway), to an unknown distance north of Bumping Lake. The flows, intrusives, and tuff are referred to as dacite porphyry in this report.

4) Olivine-bearing basalts and basaltic andesite flows and tuffs of Pliocene and Pleistocene age, erupted primarily from vents at Hogback Mountain and Tumac Mountain, but also from minor, widely distributed vents as far north as Bumping Lake. These flows and tuffs are referred to as Hogback Mountain mafic magma-type in this report.

5) Sparsely phyric, silicic andesite and dacite lavas (hornblende andesites of Ewart, 1976) mainly of middle and late Pleistocene age, erupted as short, thick flows and domes scattered between Hogback Mountain and Bumping Lake. These lavas are referred to as hornblende andesites in this report.

Because mapping and study of the late Pliocene rhyolites (group 1 above) and the pyroxene andesites of the Goat Rocks volcano (group 2 above) is still in progress as of this writing, only a preliminary summary of their occurrence, age, and composition is presented here.

Rhyolites (and Basalt) of the Devils Horns

Thick sequences of rhyolite tuff, flows, and breccias are exposed beneath the Devils Horns, Bear Creek Mountain, and in the upper South Fork Tieton River drainage basin (figure 9-3). Ellingson (1968) named these rocks and contiguous fragmental andesitic and basaltic rocks the Devils Horns pyroclastics, and inferred they were of Pliocene age. He also mapped younger andesitic and basaltic lahars, lava flows, and breccias around Hogback Mountain as part of this unit. In the present study, The Devils Horns pyroclastics are divided

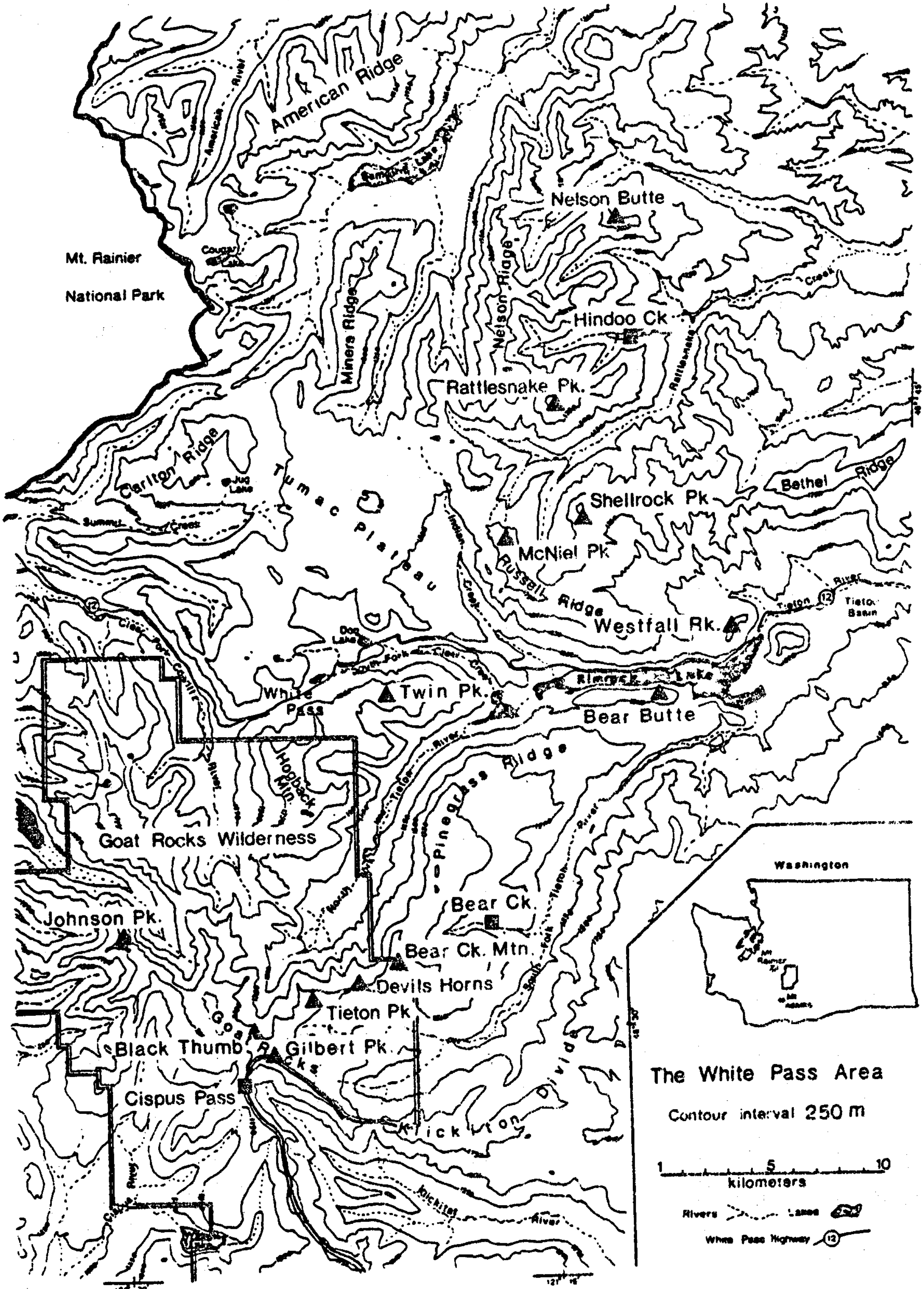


Figure 9-3. — Location map of important outcrops of Pliocene to Pleistocene age igneous rocks (Devils Horns rhyolites, dacite porphyry, pyroxene and andesites).

into units based on their composition and age, but the term Devils Horns pyroclastics, which is poorly defined and groups unrelated rock units, is not further used.

Field Occurrence: The physiographic feature called the Devils Horns is composed of basaltic pyroclastic rocks and lava that directly overlie a thick sequence of rhyolites. The basalts crop out around a tarn named the Devils Washbasin and will therefore be referred to as the Devils Washbasin basalts. The underlying rhyolites, continuously exposed in 650 m thick sections in both the northern and southern slopes of the ridge below the Devils Horns, will be referred to as the Devils Horns rhyolites. Though textural and facies changes cause great variation in the appearance of the rhyolitic deposits, many of these changes are gradational, thus permitting easy correlation of progressively more distant outcrops with the exposures below the Devils Horns. These correlations and geologic mapping indicate that the Devils Horns rhyolites are the only identified post-Oligocene high-silica rhyolites in the White Pass Area.

The westernmost outcrops of the Devils Horns rhyolites occur beneath Tieton Peak, but their contact with older Tertiary rocks is not exposed. The map pattern of these rhyolites and the Ohanapecosh Formation of Oligocene age indicates the western contact is very steep, has greater than 500 m of relief, and may be a caldera boundary fault or a paleo-valley wall. Beneath eastern Tieton Peak, and eastward to Bear Creek and the South Fork Tieton River drainage basin, the rhyolites directly overlie pre-Tertiary Russell Ranch Formation and in many places this contact lies close to the altitude of present valley bottoms. The absence of older Tertiary rocks beneath the rhyolite, in an area where thick remnants of formerly laterally continuous, bedded Oligocene rocks are widely preserved, indicates that the local landscape was deeply eroded or faulted during the Miocene to early Pliocene.

Between the North Fork Tieton River and the Devils Horns, the lower 300 m of the approximately 650 m thick section of rhyolites is composed mainly of flow-banded rhyolite lava, obsidian, and pyroclastic breccias (mostly dense, large-block, flow-banded rhyolite autobreccias and lapilli tuffs with abundant clasts of the Russell Ranch Formation). These rocks may be part of a dome complex and probably mark the vent area for an upper Pliocene rhyolitic volcano (caldera). The middle 200 m of this section consists predominantly of pumiceous lapilli tuffs, vitric tuffs, and obsidian flows. Individual tuff beds are up to 50 m thick and some of the thicker pumiceous tuffs are welded. The upper part of the section is dominated by thinner bedded (0.01 to 10 m thick) tuffs with obsidian lapilli and sets of centimeter thick pumiceous ash layers.

The rhyolitic deposits fine eastward as well as upwards. Another approximately 650 m thick section of rhyolites is exposed in a southern slope of Bear Creek Mountain 2 to 3 km east of the Devils Horns. This sequence contains more thin-bedded, nonwelded, and blocky pyroclastic flow (surge) deposits than the near-vent rhyolites previously described. The basalt portion of this section is composed of a massive, 100 to 200 m thick, brilliant white, pumice lapilli, vitric ash tuff which is overlain by decimeter thick beds of vitric ash tuff. The middle portion is characterized by textures resulting from rapid and violent lateral transport of rhyolitic pyroclasts, including crossbedded vitric-lapilli and ash tuffs, and a 200 to 300 m thick sequence of graded obsidian block breccias (with blocks up to several meters across) that have scoured and filled channels in the bedded vitric tuffs. Obsidian-lapilli ash tuff, obsidian-block tuff (with clasts less than 20 cm across), thin-bedded (0.1 to 1 m thick) pumice-lapilli tuffs, and vitric ash layers (1 to 10 cm thick) predominate in the upper portion of this exposure.

Outcrops of rhyolite 7 to 8 km east of the Devils Horns, in Bear Creek (a western tributary of the South Fork Tieton River), are mainly composed of 0.01 to 5 m thick beds of vitric ash tuff, and vitric tuffs with clasts of obsidian, flow-banded rhyolite, pumice, and/or accretionary lapilli. Laminae of volcanic ash, soft-sediment deformation, and intercalated andesitic and basaltic lahars and fluvial sediments indicate that ponded water, valley walls composed of more mafic lavas, and streams were locally present.

Rock Description: Petrographic studies have not yet been completed but the high glass content of these rocks is evident in hand specimen. Vitric ash, pumice, and black to gray obsidian comprise more than 95 per cent by volume of most rock samples. Quartz, feldspar, other crystals and exotic lithic fragments are minor to rare in most hand specimens. Chemically, these rocks are rhyolites and high-silica rhyolites.

Geologic Relations and Significance: Some preliminary conclusions emphasize the importance of these previously undescribed rhyolites. First, their volume is large. More than 20 cubic km of pyroclastic material accumulated in the study area. However, the total volume of rhyolite erupted was probably much greater because the thick, distal, air-fall deposits in the South Fork Tieton River basin may be part of a widespread tephra blanket. Second, few volcanoes of late Pliocene age have been recognized in the Washington Cascades. Samples from high in the rhyolite section 200 m north of the Devils Washbasin, and the middle part of the section approximately 1 km west of the Devils Washbasin, gave zircon fission-track ages of 3.20 ± 0.2 myr and 3.17 ± 0.2 myr, respectively (figure 9-2). The closeness of these ages and the absence of alteration, paleosols or other deposits resulting from weathering or long surface exposure suggest that the duration of this highly silicic volcanism was relatively brief, probably less than 0.5 myr. Third, the cropping out of late Pliocene rhyolite tuff near the base level of present day rivers implies a Pliocene terrain of high relief and deep erosion or structural down-dropping of the rhyolites.

Devils Washbasin Basalt: The Devils Washbasin basalt occurs as agglomerate, agglutinate, flows, dikes, and tuff, and though volumetrically small (approximately 0.4 cubic km are preserved) it is important for four reasons. First, the eruption of these basalts marked an abrupt change from rhyolitic volcanism to more mafic volcanism. Devils Washbasin basalts overlie the Devils Horns rhyolites and are intercalated with the basal pyroxene andesite flows of the Goat Rocks volcano. It probably represents a short-lived parasitic vent that was subsequently overwhelmed by the major outpouring of andesite that built the main Goat Rocks composite volcano. Though andesitic volcanism persisted into the Pleistocene, neither basalt nor high-silica rhyolite were again erupted in this area.

Second, the Devils Washbasin basalt is characterized by inclusions of rounded, less than 5-cm-diameter xenoliths of mafic and ultramafic plutonic rocks. Modal olivine, pyroxene, and plagioclase in these inclusions vary greatly. One xenolith was observed in which mafic gabbro graded into cumulate-textured, nearly mafic-free anorthosite or leuco-gabbro across a narrow linear contact. These inclusions, and the abundance of up to 1.5 cm long olivine and clinopyroxene megacrysts and crystal clusters, suggest that fractional crystallization or fragmentation of a compositionally variable mafic to ultramafic pluton was occurring in the magma chamber or conduit system of this vent. Further study is required to determine the exact relation of these megacrysts and xenoliths to the basalt.

Third, glacial dissection of the Devils Horns provides excellent exposures of the internal structure of a small volcano. The pyroclastic rocks composing the Devils Horns are welded basaltic bombs, blocks, scoria, and spatter. Erosion of red oxidized agglomerate has formed the bizarre spires which are aptly named the Devils Horns. Quaquaversal dips measured among the horns indicate the vent was probably located over what is now the Devils Washbasin. Dikes and a small stock intrude and underlie the agglomerate.

Fourth, a northwest trending fault with a minimum of 50 m of offset separates the main vent complex from the distal deposits of Devils Washbasin basalt capping a ridge 0.5 km southwest of the Devils Horns. The ridge-capping sequence is composed of three basalt flows and an underlying basaltic tuff which contains exotic lithic blocks all of which contain ultramafic to mafic xenoliths and large olivine and clinopyroxene phenocrysts that are typical of Devils Washbasin basalt. The bulk of the ridge underlying the distal basalts is composed of an early, 20 m thick, pyroxene andesite flow of the Goat Rocks volcano and silicic tuffs. This western rock sequence is faulted against massive Devils Washbasin basalt. The original distance between the ridge-capping basalts and the Devils Horns spatter cone is uncertain because a 100 m wide zone without outcrops of these rocks parallels the fault. The fault is vertical, but neither the relative motion nor the most recent activity could be determined.

The Devils Washbasin basalt has a K/Ar whole-rock age of 3.8 ± 0.31 myr. However, this age is not in agreement with the two 3.2 ± 0.2 myr fission-track dates on the underlying Devils Horns rhyolites. A younger age for the basalt, and thus an error in the K/Ar date rather than the fission-track ages seems probable for three reasons. First, detailed paleomagnetic studies demonstrate the Devils Horns vent complex, the three ridge-capping basalt flows, and a continuous sequence of about 25 andesite flows that overlies a distal Devils Washbasin basalt flow at Tieton Peak, all have normal remnant magnetization. The large volume of the andesite sequence and the development of strong paleoweathering horizons between some of these andesites implies a long period of normal magnetic polarity. Therefore, these rocks were probably deposited during the Gauss Chron, between 2.47 and 3.40 myr ago (figure 9-2). Second, the basalt may be contaminated with argon from older plutonic mafic to ultramafic inclusions. Third, the basalt has low potassium (0.6 weight percent K_2O) and is mainly composed of crystalline phases that exclude potassium (35 to 45 volume percent olivine and augit phenocrysts). Thus, the small amount of potassium must be concentrated in the glassy groundmass and scattered clusters of plagioclase, a distribution not well suited for precise K/Ar dating. However, the basalt is very fresh, and therefore appeared to be the best rock to K/Ar date in the area.

Porphyritic Andesites of the Goat Rocks Volcano

Pyroxene andesite, now known to have been erupted from a Pliocene to Pleistocene volcano in the Goat Rocks, was first mentioned by Russell (1893). Smith (1903) mapped remnants of an intracanyon lava flow from the Goat Rocks composite volcano in a paleochannel of the Tieton River and named it the Tieton Andesite. Warren (1941) and Becraft (1950) clarified the stratigraphic position of the Tieton Andesite in the Tieton River Canyon. Becraft (1950) also described the lava flow physically, petrographically, and mapped it sourceward on the Pinegrass Plateau (figure 9-3). Swanson (1964; 1978) reported on the petrography, composition, and the radiometric age of the Tieton Andesite between Windy Pont and Pinegrass Ridge. Ellingson (1968; 1972) correlated Tieton Andesite mapped by Becraft at the west end of Pinegrass Ridge with a volcanic plug at Black Thumb in the Goat Rocks. He inferred that Black Thumb was the vent for porphyritic andesite lavas and pyroclastic rocks composing a Pliocene to Pleistocene stratovolcano that he named the Goat

Rocks Volcano (Ellingson, 1968.) Because the andesites of Pinegrass Ridge (mapped by Becraft as Tieton Andesite) were part of a more widespread apron of the Goat Rocks volcano, he named all Pliocene and Pleistocene porphyritic andesites vented in the Black Thumb area Tieton Andesite.

In the present study, the name Tieton Andesite is applied in its original sense (Smith, 1903; Warren, 1941; and Becraft, 1950) and it refers only to the intracanyon porphyritic andesite lava flow exposed along the Tieton River. It is the only lava erupted from the Goat Rocks volcano that is preserved east of Westfall Rocks (the western margin of the Tieton Basin). It has a total length of 80 km between the vent at Black Thumb and its terminus at Cowiche Canyon, 3 km northwest of Yakima, making it perhaps the longest pyroxene andesite lava flow ever reported (Hammond and others, 1977). The Tieton Andesite is one of many porphyritic andesite deposits erupted from vents in the Black Thumb area, which in this report will be referred to collectively as the andesites of the Goat Rocks volcano. Clarification of this nomenclature is necessary to minimize confusion between early Miocene andesites forming the Tieton volcano (Swanson, 1966), which have been zircon fission-track dated at about 23 myr old, and the Pliocene and Pleistocene andesites of the Goat Rocks volcano. Lavas composing the Tieton volcano are referred to as Fifes Peak Formation andesites.

Field Occurrence: The pyroxene andesites of the Goat Rocks volcano crop out as up to 500 m thick sequences of 5 to 130 m thick, platy jointed, pinch-and-swell lava flows and intercalated, less than 20 m thick pyroclastic breccias. Quaquaversal dips range up to 30°. Lava that spilled down the flanks of the volcano into valleys formed sequences of nearly flat lying, columnar jointed lavas that are interbedded with lahars, boulder conglomerate, and other fluvial deposits. Inversion of relief around these valley filling lava flows repeatedly placed younger rocks below slightly older rocks forming the valley walls. Lavas are rarely traceable for more than 0.5 km laterally. Outcrops of andesite break up into platy or blocky, gray to reddish-brown talus. The lavas are more resistant to erosion than the intercalated clastic rocks and therefore stand out as cliffs, creating a step-like topography. A subparallel system of northeast trending linear dikes (2 to 5 m wide and up to 1.5 km long) of pyroxene andesite cut through the eastern portion of the volcano. Lavas in the central portion of the volcano weather to a deep red-brown to orange stain, possibly due to propylitic alteration which probably occurred during emplacement of the Cispus Pass pluton.

Rock Description: Only a few rock samples have been studied petrographically, but these data and inspection of hand specimens indicate that the Goat Rocks volcano is built almost entirely of typical orogenic, pyroxene andesite (Ewart, 1976; Gill, 1981). Plagioclase is the dominant and conspicuous phenocrystic phase, constituting 10 to 40 percent by volume, and two pyroxenes, hypersthene, and augite are each generally present at less than 10 percent by volume (Becraft, 1950; Ellingson, 1968; Swanson, 1964; 1978). Chemically, these are high-potassium andesites (Gill, 1981).

Geologic Relations and Significance: Radiometric dating and paleomagnetic polarity studies bracket the age of the main mass of porphyritic andesites composing the Goat Rocks volcano between approximately 3.2 and 1.0 myr (figure 9-2). The maximum age is set at 3.17 ± 0.2 myr and 3.2 ± 0.2 myr by zircon fisson-track dates on Devils Horns rhyolites underlying a 300 m thick sequence of pinch-and-swell, porphyritic andesite flows, with normal remnant magnetization, that compose Tieton Peak. The basal andesite flows at Tieton Peak are intercalcated with the normally magnetized Devils Washbasin basalts and are inferred to have been erupted during the Gauss Chron. However, a more than 400 m thick sequence of porphyritic andesites forming a western remnant of the Goat Rocks volcano in the vicinity of Johnson Peak (above Heart Lake) has reversed remnant magnetic polarity. These lava flows have pinch-and-swell morphology, dip gently westward (the quaquaversal dips of the lava flows are subparallel to the dip slopes of the underlying Ohanapecosh Formation), and are less altered than the andesites at Tieton Peak, but are not as fresh as the approximately 1.0 myr old Tieton Andesite. These western andesites were probably erupted during the early Matuyama Chron.

Younger limiting ages for activity of the Goat Rocks volcano are set by K/Ar dates from the Tieton Andesite of 1.0 ± 0.1 myr (Swanson, 1978) and 0.99 myr (Hammond, 1980), a 1.3 ± 0.2 myr zircon fission-track date from a tuff directly underlying the Tieton Andesite at Bear Butte, and a switch of paleomagnetic polarity (inferred to be the Matuyama Chron to Brunhes Chron reversal) in the sequence of late-stage lava flows of the Gilbert Peak-Black Thumb massif.

The Tieton Andesite is one of the least altered Goat Rocks volcano lavas. Its plagioclase and pyroxene are fresh and the groundmass contains only trace devitrified glass and limonite. It was erupted after the main cone-building activity of the Goat Rocks volcano and flowed down a northeast-trending valley deeply incised into the volcano. Between the Devils Horns and Bear Creek Mountain, this valley was eroded into locally deformed Devils Horns rhyolites and Devils Washbasin basalt with steep quaquaversal dips, thus the contact of the flow with the underlying Pliocene rocks may be strongly discordant. At Bear Creek Mountain, the Tieton Andesite cannot be distinguished from other gently eastward dipping distal andesite flows of the Goat Rocks volcano. From Bear Creek Mountain to Westfall Rocks, the andesite flowed across a landscape largely stripped of Tertiary rocks, following a valley that passed around the north side of the Westfall Rocks. This paleovalley lies 100 m above and is cross-cut by the Tieton River, which now passes south of the

Westfall Rocks. Outcrops of the Tieton Andesite in the Tieton Basin (where it overlies Fifes Peak-age andesites of the Tieton volcano) and eastward to Yakima are well described by Warren (1941), Becraft (1950), and Swanson (1964).

A sample of one of several small intrusions of granodiorite (total area of about 2 km^2 (D. Swanson, personal communication, 1982), found within a broad area of porphyritic volcanic rocks and mapped as the Cispus Pass pluton (Ellingson, 1968) gave a zircon fission-track age of 1.1 ± 0.1 myr (due to the high uranium content of these zircons and consequent problems counting the induced tracks, this is presently regarded as a maximum age and the pluton may be less than 1 myr old). The granodiorite has suffered only minor mafic-destructive propylitic alteration and it crosscuts and is coarser grained than rocks of the Ohanapecosh Formation. It may represent a shallow intrusive phase of the magmatism that produced the anomalously large Tieton Andesite lava flow of about the same age, or it may be an intrusive core of the Goat Rocks composite volcano. Pyroxene andesite lavas overlying the Cispus Pass pluton form the precipitous peaks of the Gilbert-Black Thumb massif. They are younger than 700,000 years old (based on normal magnetism) and flowed mainly to the southeast down a paleovalley of the Klickitat River.

In summary, eruptions of high-potassium pyroxene andesite from vents centered in the Goat Rocks built a large composite volcano between approximately 0.7 and 3 myr ago. Formation of the volcano began soon after the complete cessation of a major episode of rhyolitic volcanism in the same area, and contemporaneously with the development of a small parasitic basalt volcano at the Devils Washbasin. More than 60 cubic kilometers of pyroxene andesite are inferred to have been erupted from the Goat Rocks volcano. For comparison, Mount Rainier is composed of approximately 100 cubic kilometers of medium-potassium pyroxene andesite and was built from a base level of approximately 500 m lower than that of the Goat Rocks volcano. Therefore, the height and form of the Goat Rocks volcano may have been similar to present-day Mount Rainier.

Dacite Porphyry

Dacite with phenocrysts of plagioclase, hornblende, ± biotite, and ± quartz, forms distinctive outcrops in the White Pass area (figure 9-3). Abbott (1953) first described the rock type in the Mount Aix quadrangle as Oligocene or possibly Miocene intrusions of dacite porphyry, unconformably overlain by Fifes Peak Formation. Ellingson (1968) mapped several large dikes of dacite porphyry that crop out 3 km due east of White Pass as the Twin Peaks Pluton and described the rock as a diorite porphyry. Simmons (1974) referred to the dacite as rhyodacite porphyry and noted that some outcrops have well developed columnar jointing or a poorly indurated crystal-tuff-like texture. However, he concurred with Abbott regarding its age and intrusive character. Armstrong (1976) obtained a K/Ar date of 6.3 ± 0.2 myr from an alteration zone where a "rhyolite" intruded the Bumping Lake granodiorite, thus raising the possibility that dacite porphyry was intruded during a previously unrecognized late Miocene episode of silicic igneous activity. Schreiber (1981) mapped ridge-capping, flow-banded, and microvesicular dacite porphyry east of Nelson Ridge and dated a sample from Nelson Butte at 3.2 ± 0.3 myr (this same sample was dated by this author as 2.8 ± 0.2 my, the youngest age so far recorded on this rock type). Schreiber concluded that ridge-top dacite porphyries at Nelson Butte and the Rattlesnake Peaks were remnants of Pliocene valley-filling lava flows preserved due to inversion of relief around paleovalleys.

Field Occurrence: The dacite porphyry occurs as lava, tuff, laharic breccia, stocks, plugs, dikes, and sills. Outcrops of the dacite are scattered over a large area. The southernmost remnant of the hypabyssal system is the Twin

Peaks pluton, but the northern limit is not known. Abbott (1953) and Schreiber (1981) mapped large bodies of dacite porphyry beyond the northern and eastern boundary of the present study area, respectively. However, these rocks have not been reported west of Cougar Lake (Fiske and others, 1963) or east of Shellrock Peak (Swanson,1964; 1978). The area of outcrops and many elements of the hypabyssal system trend north-south.

As both Abbott (1953) and Simmons (1974) report, outcrops of the dacite porphyry have a distinctive appearance and are easily recognized by their light color and the voluminous talus which partially or wholly engulfs columnar and/or platy jointed cliffs and covers basal contacts. Most outcrops form peaks or occur on ridge crests and are overlain only by Quaternary deposits.

Rock Description: In hand specimen, distinctive subhedral to euhedral phenocrysts of plagioclase, hornblende, and/or biotite (up to 2 cm in length) and/or bipyramidal quartz (up to 7 mm in diameter) are set in a fine-grained, gray, quartz-bearing, holocrystalline to holohyaline groundmass. The phenocryst assemblages range from predominantly plagioclase or hornblende porphyry to plagioclase, quartz, minor biotite, and hornblende porphyry. The wide variation in phenocryst mode caused previous workers to assign the dacite names ranging from diorite (Ellingson, 1968) to rhyodacite (Simmons, 1974) and "rhyolite" (Armstrong, 1976). However, at a number of sites (including Twin Peaks, McNiel Peak, and the Rattlesnake Peaks) "dioritic" hornblende and/or plagioclase porphyries grade into plagioclase, quartz, and biotite porphyritic dacite. Abbott (1953) provides a good general microscopic description of this rock type, and Ellingson (1968) and Schreiber (1981) describe some local variations in the petrography.

In the present study, classification of these rocks as dacite is based on a) the abundance of quartz in the groundmass or as phenocrysts, and b) the surprisingly constant values of 65 to 68 weight percent SiO_2 for samples representing the full range of phenocryst assemblages.

Geologic Relations and Significance: Previous workers did not recognize the extrusive occurrence of this rock type because vent deposits were not found and talus covers basal contacts. Evidence for the extrusion of porphyritic dacite has now been found at several sites, and inferences based on data from these outcrops lead to the conclusion that such deposits were widespread and volumetrically significant.

Field relations establishing that the dacite porphyry was erupted as lava are exposed in a tributary of Rattlesnake Creek, 2 km due south of Bismark Mountain. At this site, massive to subhorizontally columnar-jointed dacite grades into flow-banded rubble and flow-bottom breccia that overlies alluvium. This dacite crops out along the northern side of the valley for approximately 0.5 km as remanents of a lava flow which is inferred to have filled a paleochannel of Rattlesnake Creek. Erosion has enlarged the valley to the south, leaving the dacite clinging to the northern wall of the valley.

Poorly indurated, tuffaceous-textured rocks are characteristic of many massive outcrops of the dacite porphyry. A 1 km^2 occurrence of tephra with this lithology on Carlton Ridge has a zircon fission-track age of 3.7 ± 0.2 myr. At Hogback Mountain a 0.5 m thick, crystal, lithic lapilli tephra layer of porphyritic dacite is interbedded with sandy sediments between pillowed basalt flows with normal remanent magnetization. In decreasing order of abundance, phenocrysts in the tuff are plagioclase, bipyramidal quartz, hornblende, and biotite. This phenocryst assemblage, the pyroclastic texture, major element composition, age of 3.1 ± 0.2 myr (or 3.7 ± 0.2 myr if the sample is not contaminated with older zircons from the lithic fragments), and normal (Gauss Chron) magnetization (figure 9-2) indicate that his tuff resulted from explosive dacite porphyry volcanism.

Vents for dacite porphyry volcanism have not yet been definitely identified, but at McNiel Peak and Rattlesnake Peak, up to 300 m thick bodies of dacite are characterized by dense, hornblende, and/or plagioclase porphyry, grading into a porous, plagioclase, bipyramidal quartz, biotite porphyry. This possibly indicates a change from a hypabyssal environment to microvesicular lava flows. At McNiel Peak, this change of phenocrysts is paralleled by a change from subhorizontal to more vertical columnar jointing and the development of a basal, flow-banded, glassy dacite. This "plug" has a zircon fission-track age of 4.0 ± 0.3 myr and a biotite K/Ar age of 3.42 ± 0.19 myr for the same sample. Between McNiel Peak and Pear Butte the map pattern, orientation of columnar joints, and gradually decreasing altitude of the outcrops of the basal vitric zone of dacite porphyry suggest that they are remnants of a single lava flow that filled a valley in the Pliocene landscape. Other volcanic deposits are tuffaceous laharic breccias up to 50 m thick that cap ridges south of Hindoo Creek and appear to have had their source at a volcano at the Rattlesnake Peaks.

The altitudes of outcrops of dacite porphyry inferred to have an extrusive origin show a remarkable concordance. Lavas at Nelson Butte (Schreiber, 1981), the Rattlesnake Peaks, and McNiel Peak are all approximately 300 m thick, and their basal contacts occur at an altitude of approximately 1800 m (6,000 ft). The north-trending paleovalley filled with lava from McNiel Peak is estimated to have been incised about 300 m into pre-Tertiary basement. To the west, the basal contacts of the dacite porphyry tuff at Hogback Mountain and porous dacite porphyry on Carlton Ridge occur at altitudes of about 1580 m (5,200 ft). Thus, the upper Pliocene landscape in the northern portion of the study area, appears to have had a minimum of 600 m of relief and a gentle westward slope across what is now the Tumac Plateau. Plutons of dacite porphyry at Twin Peaks, on American Ridge, and north of Pear Butte, intruded to the average surface-level of this paleolandscape.

The eruptive style and morphology of the dacite porphyry volcanoes may have closely resembled that of the well-preserved hornblende andesite lava flows and domes of the Tumac Plateau area (late and middle Pleistocene age). Relatively nonexplosive volcanism, the formation of domes and thick valley-filling lava flows, and the distribution of monogenetic vents over a large area characterizes both volcanic episodes. The morphology of McNiel Peak and Rattlesnake Peaks volcanoes appears to have been similar to the shape of the 300 m thick lava dome and flow that forms Deer Lake Mountain (see Hornblende Andesites, Field Occurrence). Furthermore, although these two rock types differ in mineralogy and texture, their major element compositions are very much alike, suggesting the hornblende andesites may represent a resurgence of the magmatic system which generated the dacite porphyry. The younger rocks generally have lower silica, but their range of 59 to 68 percent SiO_2 overlaps that of the dacite porphyry, and variation of K_2O vs. SiO_2, TiO_2 vs. SiO_2, and to a lesser extent, CaO vs. SiO_2, for the hornblende-bearing rocks are very similar and distinctively different from those of the pyroxene andesites. However, all three andesitic to dacitic rock types show a similar degree of differentiation and iron enrichment, and similar trends in CaO vs. MgO, and FeO vs. SiO_2.

In summary, the field occurrence of the dacite porphyry is distinctive as light-colored cliffs with voluminous aprons of talus. Hand specimens have large phenocrysts of plagioclase, hornblende, bipyramidal quartz, and biotite, set in a fine grained to glassy, quartz-rich groundmass. Though substantial variations occur in the phenocryst mode, major element chemistry is surprisingly constant. Silica ranges from 65 to 68 weight percent SiO_2, and K_2O is relatively low at 1 to 1.5 weight percent. Radiometric dating and remnant paleomagnetic polarity studies indicate that these rocks formed during the Pliocene, with the main pulse of magmatism occurring during the late Gilbert and Gauss Chrons.

The dacite porphyry crops out as scattered remnants of a formerly widespread system of hypabyssal intrusions and volcanoes which had a volume of 15 to 30 cubic kilometers.

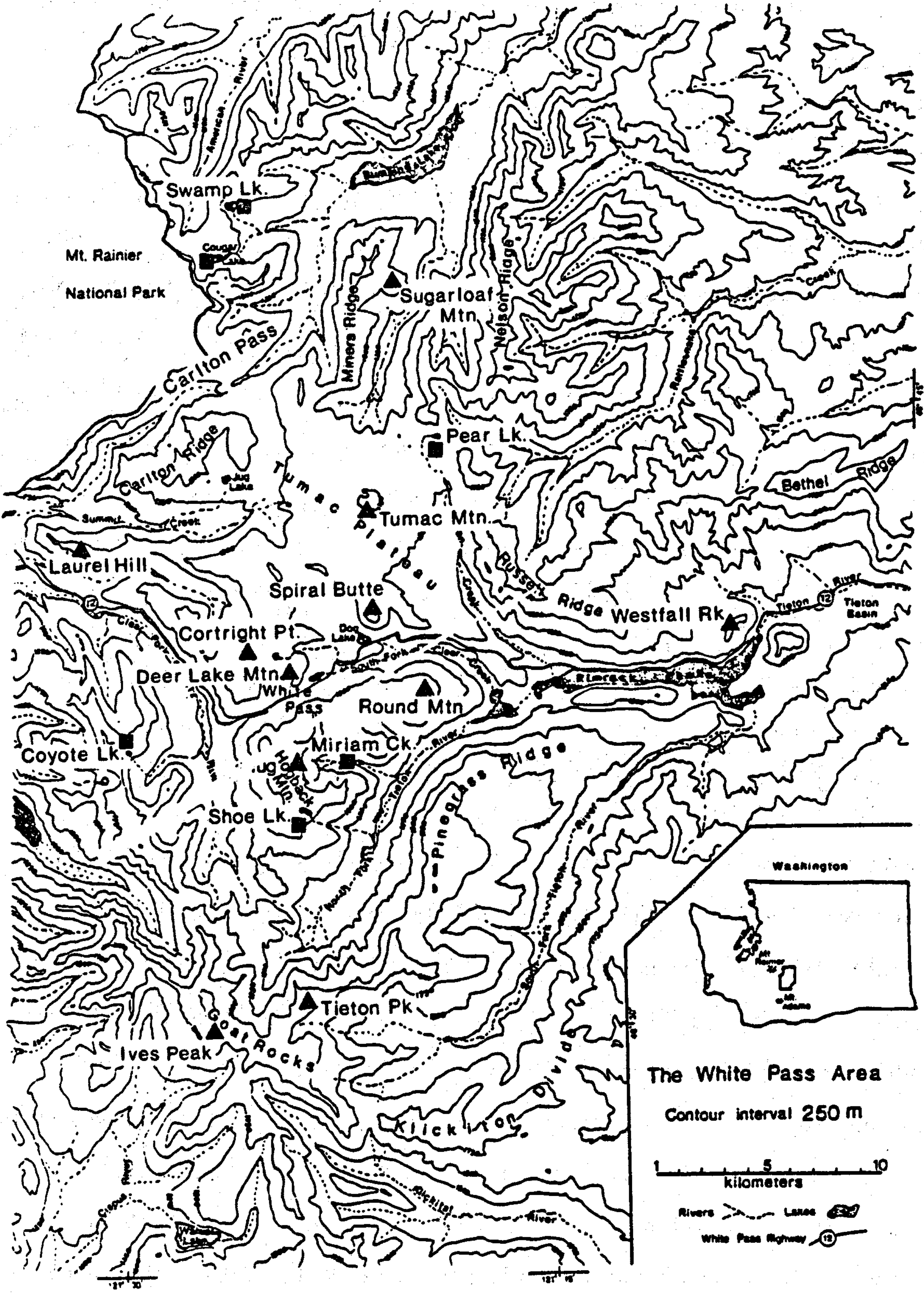
Hogback Mountain Mafic Magma Type: Olivine-bearing Basalts and Basaltic Andesites

Basalts and basaltic andesites, which commonly bear olivine phenocrysts, were erupted from widely distributed vents in the White Pass area during the Pliocene and Pleistocene (figure 9-4). These lavas formed small shield volcanoes and flowed down valleys for distances of as much as 30 km. Inversion of relief around lavas confined to paleovalleys has resulted in good exposures of sequences of basalt in present-day topographic highs. The altitude at which these sequences crop out is related to their age, such that Pliocene lavas cap ridges, while younger lavas occur on lower ridges or as benches at respectively lower altitudes.

Abbott (1953) first described these lavas:

> ". . . basaltic flows that occur as tongues in the present-day valleys are . . . called Valley flows . . . the largest exposure of the Valley flows occurs as a plateau . . . a post glacial cinder cone . . . rests on the Valley flows which cap the plateau of Tumac Mountain . . . an early Pleistocene age seems likely and the upper age limit is pre-Wisconsin glaciation."

Abbott also mentions Valley flows exposed in the vicinity of Cougar Lake and Swamp Lake, but he did not locate the vents for these lavas or for those forming the Tumac Plateau. Ellingson (1972), Simmons (1974), and Hammond (1980) concurred with the age relations inferred by Abbott, but they recognized that Tumac Mountain marks the vent for pre-cinder cone valley flows that could



igure 9-4. — Location map of hornblende andesite and Hogback Mountain mafic magma-type vents and significant outcrops of these associated rock types.

be traced to the Tumac Plateau.

Along the western boundary of the Tumac Plateau, Ellingson mapped ridge-capping sequences of lava up to 330 m thick which formerly "filled valleys and ran out on an ancient lowland" and named them the Ridge Top andesite (Ellingson, 1959). However, the hornblende andesite he described as the characteristic rock type of these sequences is volumetrically minor compared to basalt. After further fieldwork, Ellingson (1968) changed the name Valley flows (Abbott, 1953) to Tumac Mountain olivine basalt and recognized that the Ridge Top andesite was composed of both basalt and andesite. He grouped the andesites into a unit named after Spiral Butte, a conspicuous hornblende andesite (dacite) volcano. In addition, he traced the basalts back to a vent near Shoe Lake and named them the Hogback Mountain olivine basalts.

> "The basalt just north of Shoe Lake...surrounds the exposed volcanic neck...and apparently partially filled a crater that was 1 mile in diameter...The individual flows range in thickness between two and four feet and are very vesicular with scoriaceous tops. The lavas have pillow structure where they flowed over snow or ice patches."

Ellingson (1968) initially included the volcanic rocks beneath these thin basalt flows in the Devils Horns pyroclastics, but later remapped them as Tieton Andesite (Ellingson, 1972). Several pyroxene andesite flows occupying northwest-trending paleovalleys are intercalated with the basal basalts of the Hogback Mountain volcano, but they clearly cannot be Tieton Andesite, a fact recognized by Hammond (1980), who mapped the lower sequence as undifferentiated andesites of the Goat Rocks volcanic complex.

In the present study, Pliocene and younger lavas characterized by olivine phenocrysts and 49 to 55 weight percent SiO_2 are recognized as a distinct rock type. Their consistent petrographic and chemical characteristics correspond to rocks grouped as orogenic basalts (Ewart, 1976). They were erupted from two major volcanoes, Hogback Mountain (basalt) and Tumac Mountain (basaltic andesite), and several other minor vents. Contemporaneous, but separately vented (except at Pear Lake) hornblende andesite lavas are associated with them. Because the best exposures of these rocks occur at Hogback Mountain they will be collectively referred to as rocks of the Hogback Mountain mafic magma-type. However, volcanic sequences that form distinct mappable units and can be traced to a specific vent are identified by the name of a geographic feature which marks the vent site (e.g. Cougar Lake basaltic andesite).

Field Occurrence: Exposed at Hogback Mountain are remnants of the largest and oldest volcano of the Hogback Mountain mafic magma-type. The southwest tributaries of Miriam Creek and cirques near the summit of Hogback Mountain reveal portions of an approximately 700 m thick sequence of basalt flows with shallow quaquaversal dips. These lavas apparently overwhelmed a valley cut into Russell Ranch Formation and spilled out to form a shield volcano against the northern flank of the Goat Rocks composite volcano. Northward-flowing pyroxene andesites from the Goat Rocks volcano and basalts of Hogback Mountain initially invaded the same valleys, but as the basaltic volcano grew, pyroxene andesite flows were diverted to other channels.

Lavas forming the lower 350 m of the Miriam Creek section are slightly altered, have very vesicular tops, and are 2 to 10 m thick. Although thick vegetation obscures contacts laterally, a step-like topography and outcrops in waterfalls provide evidence that the sequence consists mainly of poorly consolidated flow-bottom breccias that grade upward into massive cliff-forming lava. Pillow palagonite breccias, diamictons, fluvial sands, laminated silts, and silicic tuff are locally intercalated between lava flows. At the approximate altitude of Miriam Lake, a 50 m thick hornblende andesite flow and remnants of a basaltic tephra cone interrupt the monotonous sequence of basalts. The hornblende andesite lava forms a much thicker and less laterally extensive flow than the surrounding basalts.

The upper 310 m of the Miriam Creek section, well exposed in cirques above Miriam Lake, is the Hogback Mountain olivine basalt that Ellingson (1968; 1972) described. The strikingly uniform sequences of as many as 120 flows of 0.5 to 1.5 m thick, red-oxidized, laterally continuous, but very rubbly lavas, are locally disrupted by comagmatic sills and dikes which are lighter colored due to the growth of groundmass plagioclase More detailed mapping is needed before the Hogback Mountain volcanic complex can be accurately reconstructed, but considerable understanding of it can result from study of the Tumac Plateau, where a very similar volcano is in a constructional phase.

During the early Pleistocene, volcanism in the White Pass area shifted northward and eruptions of olivine-bearing basaltic andesite built the Tumac Plateau, a well preserved shield volcano with an area of approximately 40 square kilometers. These lavas initially filled valleys eroded into the Russell Ranch Formation and ponded behind contemporaneous hornblende andesite flows. The paleotopography is now almost completely buried, and only a few islands of older rock pierce the shield. The gentle slopes of the Tumac Plateau are composed of flow units that are 2 to 10 m thick and have vesicular pahoehoe tops and rubbly flow bottoms. Lava overwhelmed ponds, glacial drift, and tephra layers (which also cover much of the present surface of the plateau), forming sequences of lava with intercalated pillow-palagonite breccia, diamicton, laminated silts, fluvial sands, and tephra that are similar to exposures at Hogback Mountain.

Small remnants of three additional vents for mafic magmas were found north of the White Pass Highway and are named after nearby geographic features. Cramer Mountain lies 4 km southwest of Tumac Mountain and is capped by basaltic andesite agglomerate and welded bombs up to 0.5 m long. The extensive erosion and reversed magnetic polarity of this volcanic sequence indicates the vent is probably of early Pleistocene age. Kincaid Lake, 8 km northwest of Tumac Mountain, lies in a small cirque scoured into fresh olivine basalt agglomerate with normal remnant magnetic polarity. A lava flow apparently ponded on the ridge crest to a depth of 40 m and then spilled down towards Carlton Pass. Cougar Lake and Swamp Lake, approximately 15 km northwest of Tumac Mountain, are both dammed by lava flows with fresh olivine phenocrysts and normal remnant magnetic polarity. Severe glacial erosion and vegetation make locating vents in this area difficult, but the distribution and volume of lava suggests that several middle to late Pleistocene vents may occur there.

Rock Description: Hand specimen and petrographic descriptions of Hogback Mountain type mafic lavas are included in reports by Abbott (1953) and Ellingson (1968). The predominance of olivine as an easily recognizable phenocryst in hand-sample is diagnostic of the rock type. In general, other phenocryst phases are not abundant, though glomeroporphyritic augite, plagioclase, and/or hypersthene may be conspicuous. The color of hand samples varies from gray to black to rusty brown or hematite-red, depending on the degree of crystallinity and oxidation. Darker samples generally contain more glass and are not necessarily less silicic. The rusty brown color appears to be an alteration phenomenon peculiar to certain sequences of lava. Ellingson (1968; 1972) mapped nearly holocrystalline basalts which crop out between Cartright Point and Crystal Springs Camp as Spiral Butte andesite because their light color and platy jointing more closely resembled hornblende andesite than the thin, dark, highly vesicular lavas of Hogback Mountain. However, some of those "andesites" are among the most silica-poor (50 ±1 weight percent SiO_2) and olivine-rich basalts in the White Pass area.

Petrographic changes that accompany increasing silica from basalt to basaltic andesite (49 to 55 weight percent SiO_2) include resorption of olivine phenocrysts, elimination of groundmass olivine, the appearance of hypersthene in the groundmass and as a phenocryst, and a change in the rim composition of plagioclase phenocrysts from labradorite to andesine. Petrographic data based on study of more than 60 thin sections are summarized below.

Fosteritic olivine, (optical angle 2V = 90^o +/- 5^o) occurs as phenocrysts up to 9 mm long. It is skeletal to euhedral in glassy rocks, fresh and subhedral to euhedral in hypocrystalline basalts, and resorbed or rimmed by pyroxene and/or magnetite in hypocrystalline basaltic andesites. In older rocks, iddingsite commonly rims grains, penetrates phenocrysts along fractures and completely replaces microphenocrysts. Study of samples from the same lava flow but with different degrees of crystallinity indicate olivine was the first mineral to crystallize and that it grew rapidly before becoming unstable as groundmass pyroxene and magnetite developed.

Plagioclases are the most abundant constituent of the groundmass and are common as microphenocrysts. They are also abundant as 5 mm long prismatic phenocrysts. Patchy, normal, and oscillatory zoning; spongy, skeletal, and resorbed textures; Carlsbad and albite twins; and synneusis and glomeroporphyritic clusters are common.

Augite (2V = 45^o to 60^o) is the main groundmass pyroxene of the basalts, and it occurs as minor, stubby phenocrysts up to 3 mm long. Augite crystallized after olivine and plagioclase, and its abundance as microphenocrysts, microlites, and subophitic and intersertal grains increases with increasing crystallinity and/or decreasing silica.

Hypersthene ($2V = 45^{0}$ to 60^{0}) is the dominant pyroxene in the groundmass of some basaltic andesites and though rare as phenocrysts, it may be conspicuous in glomeroporphyritic masses containing stubby to prismatic crystals up to 3 mm long.

Magnetite began crystallizing soon after olivine, it occurs as prismatic, octahedral, and irregular granules less than 1 mm in diameter.

Pigeonite composes approximately 10 percent of some lava flows (Ellingson), 1968).

Abbott (1953) reports up to 5 percent apatite in some Tumac Mountain cinders.

Glass is brown to black and appears murky or opaque when riddled with fine magnetite and alteration products. Vesicular lava flow tops may be as much as 90 volume percent glass. Hyalopilitic and pilotaxitic textures are common, but some dikes and portions of some lavas are holocrystalline and diabasic. Quartz, hornblende, and igneous and sedimentary lithic fragments are rare accidental inclusions.

Geologic Relations and Significance: The Hogback Mountain volcano was active during the late Pliocene and early Pleistocene and was roughly contemporaneous with the Goat Rocks composite volcano. South of Shoe Lake, lavas erupted early in the history of the two volcanoes are complexly intercalated due to repeated cycles of erosional enlargement and lava infilling of valleys. The slopes of the White Pass ski area expose several Goat Rocks pyroxene andesite lavas that flowed down a north-trending valley eroded into the pre-Tertiary Russell Ranch Formation. They are overlain by Hogback Mountain basalts. Because the oldest andesites of the Goat Rocks volcano are inferred to be less than 3.2 myr old, the Hogback Mountain basalts must also be of late Pliocene or younger age.

The lower 400 m of the Miriam Creek section of Hogback Mountain basalts, up to and including the hornblende andesite that crops out southeast of Miriam Lake at an altitude of about 1765 m (5780 ft), has normal remnant magnetic polarity. A bipyramidal-quartz-bearing, lithic-lapilli, dacitic tuff that crops out in sediments between two pillowed basalt flows approximately 120 m above the base of this sequence, gave a zircon fission-track date of 3.1 ± 0.3 myr. Thus, the lower portion of the Hogback Mountain volcano probably formed during the Gauss Chron (2.47 to 3.40 myr old) and is contemporaneous with the oldest sequence of Goat Rocks volcano andesites exposed at Tieton Peak.

More than 40 basalt flows with reversed magnetic polarity (total thickness 150 to 200 m) overlie the Miriam Lake hornblende andesite. The thickness of individual flows tends to decrease upward in this sequence, from massive, 2 to 15 m thick lavas near the base, to rubbly, highly vesicular, 0.5 to 3 m thick flows at the top. The paleosurfaces of the thin flows show no significant modification due to weathering, indicating the time interval between eruptions of these basalts was brief. These lavas are inferred to be of early Matuyama Chron age (1.88 to 2.47 myr old).

More than 130 basalt flows, 0.5 to 2 m thick, with normal remnant magnetization, form the upper 140 ± 10 m thick portion of the Hogback Mountain volcano. A massive, 3 to 4 m thick basalt flow that caps a 2045.5 m (6711 ft) high peak 450 m due north of Shoe Lake, near the stratigraphic top of the shield, gave a whole rock K/Ar age of 1.53 ± 0.18 myr. Because the only period of normal remnant magnetic polarity close in age to this radiometric date is the Olduvai event, dated at 1.72 to 1.88 myr, these lavas are inferred to have been erupted during this period of time.

The reversal of paleomagnetic polarity that marks the base of the Olduvai event can be exactly located in a sequence of thin basalt flows in a north-facing cirque about 650 m due north of Shoe Lake at an altitude of 1930 ± 10 m (6340 ± 30 ft). It can be traced as a nearly horizontal time line around the northeast side of Hogback Mountain (just below the Cascade Crest trail) to a site (1.4 km to the north-northwest) where the Cascade Crest trail crosses the Cascade Crest (altitude 1930 ± 5 m). There the contact enters the cinder cone facies of the Hogback Mountain volcano which is centered around a peak-forming plug (mapped as 6375 ft high) about 250 m to the east. By calculating the average frequency of eruption of Hogback Mountain volcano during the Olduvai event (once every 1230 yr given a minimum of 130 flows erupted in, at most, 160,000 years) and recognizing that paleoweathering between the thin basalt flows was insignificant, it may be inferred that the Earth's magnetic field switched polarities during a time interval of less than 1500 years. If the missing sequence of younger Olduvai age lavas eroded from the top of Hogback Mountain was substantial or the eruptions were bunched in time, then it is likely that the magnetic reversal took place in only decades or centuries. The lavas that bound the geomagnetic polarity reversal have dipole vectors that are parallel (and parallel with those in the rest of the sequence) but opposite in direction (as determined on a portable fluxgate magnetometer). Thus, the magnetic polarity reversal at the base of the Olduvai event appears to have occurred rapidly and without a significant change in the location of the magnetic poles.

Because erosion has stripped away upper Olduvai event (and younger ?) lavas at Hogback Mountain, an upper age limit for the volcanoe's activity cannot be determined. However, basalts of late Matuyama Chron age that are preserved in a valley eroded into the Tieton Andesite near Westfall Rocks (Becraft, 1950; and Swanson, 1964; 1978) may have been erupted at Hogback Mountain.

Other sequences of basalt of Matuyama age, that crop out on ridge crests between Laurel Hill, Crystal Springs Camp, and Cortright Point, and west of Twin Sister Lakes, formed when lavas flowed down a north- to northeast-trending drainage system from Hogback Mountain. Erosion and inversion of relief around these basalts has locally exposed ponded lava, pillow-palagonite complexes, and contacts with paleovalley walls. A topographically lower and more westerly trending paleovalley (which is cut by the White Pass Highway 3 km east of the Palisades Viewpoint) is filled with Hogback Mountain basalts with normal remanent magnetization that may be of Brunhes Chron age (Hammond, 1980).

The lavas of the surface of the Tumac shield volcano have not been severely affected by glacial erosion and thus appear to be of late Pleistocene age. All portions of the volcano found so far have normal remanent magnetization indicating they are less than 700,000 yr old. Tephra studies (Clayton, in preparation) around the Tumac Plateau indicate the most recent eruption of Tumac Mountain occurred 20,000 to 30,000 yr B.P. Thus, the Tumac volcano is of middle to late Pleistocene age.

Hornblende Andesites

In this report, the term hornblende andesite refers to volcanic rocks with 59 to 68 weight percent SiO_2 and hornblende as the most conspicuous phenocryst phase. However, it should be noted that in terms of silica content, some are dacites (63 to 68 weight percent SiO_2) and, in these rocks, hornblende is generally minor, resorbed, and rimmed or pseudomorphed by opacite (an opaque intergrowth of pyroxene and magnetite). Were it not for the sparse but ubiquitous hornblende, this rock type would best be classified as an aphyric, aphanitic, hyalopilitic, silicic andesite. Ewart (1976) defined hornblende andesite as "rocks containing hornblende and/or biotite or identifiable pseudomorphs after these phases".

In the White Pass area, the hornblende andesites form an essentially monogenetic volcanic field, mainly of Plesitocene age, characterized by dome-like vents that grade into thick, narrow lava flows. Selection of a type volcano is difficult because most of the widely distributed vents appear to have produced only one lava flow, and thus each is unique. Spiral Butte is one of the youngest and best preserved volcanoes, but its composition is dacitic and its spiraling morphology is anomalous. Vents and lavas in Clear Fork Cowlitz Creek and Deep Creek are also well preserved and are probably better type examples of hornblende andesite volcanoes.

The first mapping of the hornblende andesite lava type in the White Pass area was done by Becraft (1950) who mapped a 1000 ft. thick section of these rocks at Round Mountain as basalt. Abbott (1953) first described the hornblende andesites, defined a type area for them at Sugarloaf Mountain on the east side of Miners Ridge, and named them the Deep Creek andesite. He recognized their occurrence as valley-filling flows but incorrectly inferred that the present outcrops are erosional remanents of a once continuous sheet of Miocene and Pliocene age lavas that extended from Round Mountain to Bumping Lake. West of the Tumac Plateau, Ellingson (1959) mapped sequences of Hogback Mountain mafic lavas with minor intercalated hornblende andesite flows as Ridge Top andesite and correlated them with the Deep Creek andesite. Subsequently, Ellingson (1968) remapped areas south and west of the Tumac Plateau, identified Spiral Butte as a hornblende andesite vent, and grouped lava sequences containing hornblende andesite into a unit he named the Spiral Butte andesite (except for a lava flow in the Clear Fork Cowlitz River which he mapped as a late Pleistocene unit, the Clear Fork dacite). Ellingson (1968; 1972) and Simmons (1974) concurred with Abbott's interpretation of the age and distribution of these lavas and failed to recognize the monogenetic style of hornblende andesite volcanism. Hammond (1980) who compiled his maps of this portion of the south Cascades based on these previous studies, was the first to suggest late and middle Pleistocene ages for these rocks.

Field Occurrence: Outcrops of hornblende andesite are commonly the source of extensive, light-colored talus and in some places they are completely engulfed by scree. Lava domes are conspicuous as 100 to 650 m high sugar-loaf shaped hills ringed by large, arcuate aprons of talus. The lava flows are 25 to 200 m thick, up to 14 km long, and filled valleys or formed long lobate lava streams less than 1 km wide that are confined by levees of their own rubble. Original volcanic structures preserved at several volcanoes show that the vent-domes grade into lava flows and that the core of the dome was quite fluid. Thus, these volcanoes are not the result of upheaval of congealed lava like plug-domes or spines (McBirney and Williams, 1979) and they will therefore be referred to as lava domes.

From a distance, dacite porphyry and hornblende andesite occurrences may appear similar, but the latter have talus that is more tabular or distinctively fissile (due to pervasive platy jointing). Furthermore, the hornblende andesites are generally younger, and therefore crop out at lower altitudes (as benches or knobs in present drainage systems) than the dacite porphyry, which (due to inversion of topography) caps ridges.

The southernmost hornblende andesite vents occur at Ives Peak and 1 km northwest of Tieton Peak. Contact relations at the latter locality are ambiguous, but it appears that remnants of a late Pliocene dome are preserved there. Mutual inclusion of country rock in the dome and fragments of hornblende andesite in the surrounding rhyolitic tuffs may have resulted from brecciation during forceful intrusion of a semi-solid plug. This is the oldest hornblende andesite volcano and it may have had atypically high viscosity. Ives Peak is a lava-dome-dike and vent complex of middle to late Pleistocene age that was the source for several lava flows in the upper Cispus River drainage.

Two kilometers southwest of Shoe Lake, a 200 m high, radially jointed hornblende andesite dome and an approximately 75 m thick lava flow that moved eastward from the dome, were partially buried by thin flows of Hogback Mountain basalts. This andesite volcano formed early in the history of the Hogback Mountain volcano (it is probably of late Pliocene age), has normal remanent magnetization, 60 to 66 weight percent SiO_2, and may have acted as a dam to southward flowing basalts much like Spiral Butte has dammed Tumac basaltic andesite flows. Outcrops of other hornblende andesite lavas at Hogback Mountain are not sufficiently well exposed to determine their vent or morphology.

Round Mountain is capped by a 250 m thick sequence of hornblende andesite lavas and tuff (60 to 64 weight percent SiO_2) that Becraft (1950) mapped as Round Mountain basalt and Ellingson (1968; 1972) included in his Hogback Mountain basalts. Steeply dipping contacts between rubbly lava flow-bottoms and the Russell Ranch Formation indicate that molten rock poured down the slopes of a high ridge into valleys both north and south of Round Mountain. The Twin Peaks area to the west apparently formed a higher portion of the ridge and was not covered by lava. Glacial erosion has severely eroded the eastern flank of the volcano and basal deposits of pumiceous to lithic-lapilli tuff and tuff breccia are exposed in the core. Round Mountain is one of the few hornblende andesite vents in the White Pass area which extruded several lava flows from a single vent and where evidence of explosive, tephra-producing eruptions was found. All lavas of the volcano have normal magnetization, but deep erosion and a K/AR date of 0.79 ± 0.13 myr from lava at the summit indicate an early Brunhes Chron age.

Three of the four best-preserved hornblende andesite vent-lava-flow systems are contiguous to the White Pass Highway. These volcanoes include Spiral Butte, 4 km northeast of White Pass (it towers above and probably dammed Dog Lake), Deer Lake Mountain, 1.5 km northwest of White Pass (named after the small lake on its northern flank), and Coyote Lake hill, the source of the Clear Fork andesite (Clear Fork dacite of Ellingson, 1972). The other well preserved volcano is Sugarloaf Mountain in Deep Creek, 4 to 5 km south of Bumping Lake. This is the type area of Abbott's (1953) Deep Creek andesite and though it is traversed and bounded by mining roads that provide excellent access, thick vegetation prevents detailed study.

Spiral Butte, the best preserved and perhaps youngest hornblende andesite volcano, is a 550 m high lava dome that grades into a 4 to 5 km long lava flow. Chemically it is dacitic and the most silicic (64 to 66 weight percent SiO_2) and differentiated lava erupted during the last 1.5 myr in the White Pass area. It may be supposed that high viscosity, related to the high silica content, may have caused the lava to build up as a cylindrical to conical lava-dome and steep-sided lava flow. In addition, lateral spreading may have been further inhibited by viscosity increases due to loss of volatiles and cooling at the flow margins.

However, the core eventually became so swollen with liquid lava that the semi-solid walls and rubble buttress ruptured on the north side, partially draining the dome, and forming the ramp-like lava flow that spirals remarkably back around the flanks of the dome. The fluid nature of the core is manifested by lava drain-down structures preserved at the top of the butte and lava flow, and by the symmetrically paired lava levees that bound the spiral flow (similar features are visible on the Deer Lake volcano). This fluidity contrasts sharply with the explosive and brittle behavior of lava extruded in semi-solid plug domes (Williams, 1932; Rose, 1973). Thus, though the magma appears to have been confined by high viscosity walls and rubble levees of its own making, the flow structures and gentle gradient of the overall longitudinal profile of the lava flow indicate that the viscosity of the lava was low.

An alternative explanation for the compressed morphology of the Spiral Butte volcano is that low viscosity magma was forced to build up vertically and flow in a tightly coiled lava stream because it was confined in a cavity melted into a Tumac Plateau ice cap. This hypothesis is supported by the presence of thin, waterlaid, nontuffaceous sediments among eruption breccias cropping out along the White Pass highway below Spiral Butte. However, these sediments may be the result of local interaction between hot rock and snow.

Patches of fresh vent and flow-top block breccia crop out on the Spiral Butte volcano where glacial erosion, talus, or vegetation have not obliterated them. Significant amounts of tephra or pumice have not been found. The Spiral Butte lava dome apparently overwhelmed the terminus of the Deer Lake lava flow, thereby impounding Dog Lake. The eastern portion of the volcano and much of the southeastern corner of the Tumac Plateau is underlain by hornblende andesite lavas for which source vents are not known.

In summary, Spiral Butte is a small (2 cubic kilometer), well-preserved dacite volcano with an anomalous shape that was caused by the high viscosity of its lava, ice confinement, and/or paleotopography buried under the onlapping Tumac basaltic andesite shield.

The Deer Lake Mountain lava dome is 250 m high and grades into an approximately 1 km wide and 4 to 5 km long lava flow. It is composed of fresh, silicic hornblende andesite (61 to 62 weight percent SiO_2), and although it suffered some modification during the Fraser Glaciation, primary flow structures are well preserved. Leech Lake is situated between, and impounded by, two branches of the flow. A small lobe of lava turned south, spiraled back toward the vent, and now forms the short ridge that bounds Leech Lake to the west. The main lava stream moved east and now forms a ridge on the north side of Leech Lake and can be traced to Dog Lake. The outlet of North Fork Clear Creek from Dog Lake crosses the terminus of the flow forming a waterfall as it plunges down into the older, glacially-broadened Clear Creek valley.

Approximately 1 km east of Leech Lake, Deer Lake lava overlies the basalt of Clear Creek (Hammond, 1980). A gorge, cut by South Fork Clear Creek provides excellent exposures of the basalt, an underlying till up to 5 m thick with abundant clasts of porphyritic igneous rocks and graywacke, and Russell Ranch Formation basement. The contact of the basalt with the hornblende andesite is not exposed, but may be located to within a few meters under the bridge where the White Pass Highway crosses South Fork Clear Creek. The basalt has a K/Ar age of 0.65 ± 0.08 myr and a normal magnetic polarity.

Approximately 1.5 km east of Leech Lake a roadcut of the White Pass Highway provides a cross section through the margin of the main Deer Lake Mountain lava flow. Textures transitional between loose rubble and dense lava are well exposed. Distal rubble is poorly consolidated, locally bedded, brown to red colored, and sand to cobble sized. This grades into gray or red, partially welded block breccia. Deeper into the flow, zones of flow-stretched breccia and hematite-streaked lava increase until lava predominates and incorporated rubble is partially digested or plastically deformed. The interior is dense, gray, and pervasively broken by centimeter-scale platy jointing that rapidly changes orientation. The outcrop appears to have been randomly shattered by blasting, but careful inspection reveals that fractures occur in swirling fluidal patterns that were controlled by late-stage viscous flowage.

The Clear Fork dacite (Ellingson, 1968; 1972) occupies the valley of the Clear Fork Cowlitz River. Its bench-like form distorts the otherwise "U"-shaped profile of the lower 13 km of this valley. It has a silica content ranging from 59 to 62 weight percent, slightly lower than many of the other hornblende andesites of the White Pass area, and apparently also had lower viscosity. Evidence for low viscosity includes poor development of the lava dome north of Coyote Lake (which may also have been severely eroded by glaciers), spectacular columnar jointing of ponded lava (best seen at the Palisades Viewpoint along the White Pass Highway), and the unusual length and low gradient of the lava flow. The morphology of the lava flow is well preserved, even though it has been overridden by glacial ice (Hammond, 1980).

Sugarloaf Mountain is a 650 m high lava dome that grades northward into a 5 km long lava flow. This volcano bulges conspicuously into the otherwise broad "U"-shaped valley of Deep Creek and erupted a silicic hornblende andesite flow (63 to 64 weight percent SiO_2) in a style similar to that of the Deer Lake and Spiral Butte volcanoes. The terminus of the flow merges with that of another hornblende andesite flow along the southern shore of Bumping Lake. The lava dome of this other flow lies 3 km northwest of Sugarloaf Mountain between Miners Ridge and Bumping River. Glacial modification and thick vegetation prevent detailed reconstruction of these two volcanoes.

There are a number of hornblende andesite occurrences which are portions of partially eroded or buried volcanoes. Small hills around Jess Lake in Cowlitz Pass contain hornblende andesite lava (including unusual highly vesicular glassy lava) and vent breccia, but this volcano has been almost completely overwhelmed by Tumac basaltic andesite. Remnants of hornblende andesite lavas are also intercalated among basalts at Cramer Mountain and between Crystal Springs Camp and upper Cortright Creek. A volcano north of Indian Creek Meadows impounds Pear Lake. It is composed of olivine, quartz, hornblende, and plagioclase porphyritic lava that has anomalous chemistry, and may represent a mixed magma.

A hornblende andesite dike (and flow ?) has been mapped on Russell Ridge (Swanson, 1978). It has the lowest silica (59 weight percent) of any hornblende andesite analyzed thus far.

Rock Description: A typical hand specimen of hornblende andesite is composed mostly of aphanitic groundmass, which is a glossy gray, bluish gray, pinkish gray, or gray with reddish hematite streaks, and it contains less than 5 percent phaneritic crystals. Hornblende is the principal and ubiquitous phenocryst phase and it commonly appears fresh and euhedral, even when petrographic study reveals extensive alteration to opacite. Plagioclase and pyroxene are visible in some hand specimens. At Round Mountain and several other localities, plagioclase occurs in peculiar clusters that give the rock the appearance of having included snowflakes. Small round or stretched vesicles and platy partings are abundant in flow margins and are commonly lined with glass or crystals (quartz and analcite ?). Fluidal textures are also characteristic of flow margins where digested rubble, contrasting zones of oxidation, and vesicles are stretched and streaked out.

The hornblende andesites have a distinctive petrographic appearance characterized by dense hyalopilitic to pilotaxitic textures (dominated by myriad uniformly shaped plagioclase microlites) and flow-aligned hornblende phenocrysts that are partially or wholly replaced by opacite. Though silica ranges from 59 to 68 weight percent, the only petrographic change that definitely correlates with increasing silica is a decrease in the abundance of pyroxene microlites. The small size of the microlites prevented petrographic determination of their composition. Most of the hornblende andesite lava flows in the White Pass area were sampled and examined petrographically. The resulting data (based on 40 thin sections) are summarized below.

Hornblende, up to 1 cm long,is the most abundant phenocryst phase and generally comprises 1 to 5 volume percent (rarely more than 10 volume percent) of these rocks. Most lavas contain euhedral to subhedral oxyhornblende

($2V = 85^{\circ} \pm 5^{\circ}$) with golden-brown to red-brown (to deep-red) pleochroism that is rimmed or replaced by opacite. A few lavas have hornblende with green to brown pleochroism ($2V = 85^{\circ} \pm 5^{\circ}$). This hornblende is acicular, glomeroporphyritic, and mostly replaced by opacite. Some opacite pseudomorphs are themselves resorbed so that only a faint ghost of magnetite dust remains and little evidence of a mafic phenocryst phase survives. Skeletal crystals and glomeroporphyritic masses (which may include plagioclase phenocrysts) were observed in some lavas. Hornblende does not occur in the groundmass.

Plagioclase phenocrysts up to 5 mm long rarely comprise more than 5 volume percent of this rock type, and modes of less than 1 percent are common. Many phenocrysts are resorbed, show oscillatory zoning, or have a broad rim that is reversely zoned. Uniform normal or reverse zoning is not common. Albite and Carlsbad twinning, skeletal and spongy crystals, and small glomeroporphyritic and synneusis clusters are characteristic of plagioclase in many lavas. Opacite pseudomorphs of hornblende were observed as inclusions in several phenocrysts.

Pyroxene phenocrysts up to 4 mm long are present but rare (less than 2 volume percent) in most rocks. Orthopyroxene ranges in composition from bronzite ($2V = 80^{\circ}$) to hypersthene ($2V = 60^{\circ}$) and it is much more abundant than very rare augite, ($2V = 40^{\circ} \pm 5^{\circ}$). Crystals are generally fresh, skeletal or subhedral to euhedral prisms, though some are resorbed or anhedral and glomeroporphyritic.

The groundmass ranges from crystallite-rich brown to clear glass to a dense microlitic matte of flow-aligned plagioclase and orthopyroxene and/or clinopyroxene. Fine, amoeboid to euhedral magnetite crystallized early with plagioclase. Pyroxenes formed later and are intersertal in some samples. Hematitic alteration rimming mafic phases gives hand specimens a patchy, pink to reddish coloration. Polycrystalline quartz grains with reaction rims of pyroxene and kink bands resulting from late stage movement of highly viscous lava were found in several flows.

Geologic Relations and Significance: The frequency and volume of eruptions of hornblende andesite appear to increase both northward and with decreasing age. Remnants of only five or six relatively small hornblende andesite volcanoes have been found intercalated with the more than 300 lava flows erupted from the Goat Rocks and Hogback Mountain volcanoes of late Pliocene and early Pleistocene age. Brunhes Chron age hornblende andesite volcanoes have larger volumes and occur mainly in the northern portion of the study area. Round Mountain volcano, of middle Pleistocene age (based on its moderately eroded appearance, normal remnant magnetization, and a K/Ar date of 0.79 ± 0.13 myr) is larger than, and lies to the north of the older hornblende andesite volcanoes. The five largest hornblende andesite volcanoes (Ives Peak complex to the south, Spiral Butte, Deer Lake, Clear Fork Cowlitz River, and Deep Creek to the north) are inferred to be of late Pleistocene age and the latter four occur in an area where earlier Pliocene and Pleistocene volcanism was less active.

Lava domes and flows of hornblende andesite appear to be spatially and temporally related to shields and cones of olivine-bearing basalts and basaltic andesites (Hogback Mountain mafic-lava-type). Older volcanoes of both rock types are located near Hogback Mountain and younger hornblende andesite vents are associated with contemporaneous centers of basaltic andesite volcanism near Ives Peak, at Tumac Mountain, and between Cougar Lake and Sugarloaf Mountain. However, only one small volcano (0.5 km south of Pear Lake) has erupted both types of lava. This vent is also anomalous because it produced the only mixed-magma lava found in the study area. Thus, the two rock types are associated in time and space, but the absence of lavas having compositions transitional between their different mineralogies and chemical compositions, except for lava resulting from the obvious disequilibrium mixing at Pear Lake, is evidence that they are not derived from a common parent magma, or related by fractionation preocesses involving the observed phenocryst phases.

Hornblende andesite and pyroxene andesite lavas of the White Pass area have similar ranges of silica content (most have 59 to 64 weight percent SiO_2), but they differ in age, geographical occurrence, weight percent K_2O, TiO_2, and H_2O, and possibly other volatiles, mode and composition of phenocrysts, eruptive style, and volcano morphology. The latter two differences indicate that the viscosities of the two types of lava were dissimilar. The two magma types cannot be derived from each other or a common parent magma by fractional crystallization involving the observed phenocryst phases; neither do iron enrichment of the modified Larsen index show magmatic affiliation. Their separate occurrence in time and space is further evidence against a common genetic process.

Hornblende andesites and pyroxene andesites do occur together at other Quaternary volcanoes of the Cascade Range, as at Mount Hood where the hornblende andesites are interpreted as late-stage volcanic activity (Wise, 1969; White, 1980), but significant volumes of these two types of lava are not present together in the volcanoes of Washington State. Mount Rainier, Mount Adams, and Mount Baker are composed almost entirely of pyroxene andesite (mainly lavas) while Mount St. Helens and Glacier Peak consist of a more divergent suite of rocks including basalt, silicic hornblende andesite and dacite (as domes and pyroclastic flows) and relatively small volumes of pyroxene andesite lavas (lavas with abundant plagioclase phenocrysts and generally 5 to 15 volume percent augite and/or hypersthene phenocrysts). Thus, these two types of orogenic andesite are inferred to have been derived from different primary magmas and/or source regions and neither is parental to, nor necessarily associated with the other.

The hornblende andesites and dacite porphyries have very similar chemical trends in major element variation diagrams. Graphs of SiO_2 vs. K_2O and K_2O vs. TiO_2 (which distinguish hornblende andesites from pyroxene andesites) show overlapping clusters of data for the two hornblende-bearing rock types. Their styles of eruption and their occurrence as widely distributed monogenetic vents are also similar. Dacite porphyry volcanism ended between 2.5 and 3 myr ago, about the time hornblende andesite volcanism began. It is therefore possible that the hornblende andesites are much less porphyritic, younger products of the processes that generated dacite porphyry magmas.

Summary of Pliocene and Pleistocene Volcanism

In the White Pass area, more than 25 volcanoes of Pliocene to Pleistocene age have produced a total of more than 175 cubic kilometers of calc-alkaline lavas and tuff ranging in composition from picritic basalt to high-silica rhyolite. Petrographic and major element data from approximately 100 lava flows, representative of the more than 400 flows that issued from these volcanoes indicate that five distinct types of lava were erupted (table 9-1). These are olivine-bearing basalts and basaltic andesites (Hogback Mountain mafic magma-type), high-potassium pyroxene andesites, high-potassium porphyritic dacites. The latter two have very similar chemistry. Interpretation of the volcanic history is based on geologic mapping, radiometric dating, and paleomagnetic correlations (figure 9-2).

Volcanism began 3 to 4 myr ago with the eruption of the two most silicic rock types. Rhyolite in the south and the dacite porphyry to the north were deposited on a landscape that was deeply dissected by late Miocene and early Pliocene erosion. Thick, widespread sequences of Tertiary rocks, including the Ohanapecosh and Stevens Ridge Formations and westward-flowing Columbia River Basalts which buried or lapped onto highlands of pre-Tertiary rock and the Tieton volcanoes of the Fifes Peak Formation (Swanson, 1966), are absent from almost 40 percent of the study area. The absence of late Miocene and early Pliocene volcanic rocks suggests that a period of magmatic quiescence may have accompanied the deep erosion that preceded the outburst of rhyolitic and dacite porphyry volcanism in this area.

Silicic volcanism ended about 3 myr ago and for the next two million years eruptions of pyroxene andesite built the Goat Rocks composite volcano and outpourings of olivine-bearing basalt constructed the Hogback Mountain shield volcano. During the early Pleistocene, volcanic activity waned at these two volcanoes and the eruptive center for basaltic lavas shifted northward to the Tumac Plateau. A schematic stratigraphic cross section for this area is presented in figure 9-5. Tumac Mountain lies at the center of a Brunhes Chron age volcanic field which is composed of hornblende andesites and olivine-bearing basaltic andesites. At least five volcanoes are inferred to be of late Pleistocene age and they have larger volumes and are more chemically differentiated than the middle Pleistocene lavas. No volcanic rocks have been dated or determined to be of post-Fraser glaciation age in the White Pass area. However, further volcanism can be expected in the area. A relatively nonviolent eruption of Tumac Mountain, or the formation of a new hornblende andesite or olivine-bearing basaltic andesite volcano (somewhere between the White Pass Highway and Bumping Lake) will probably occur during the next 10,000 years.

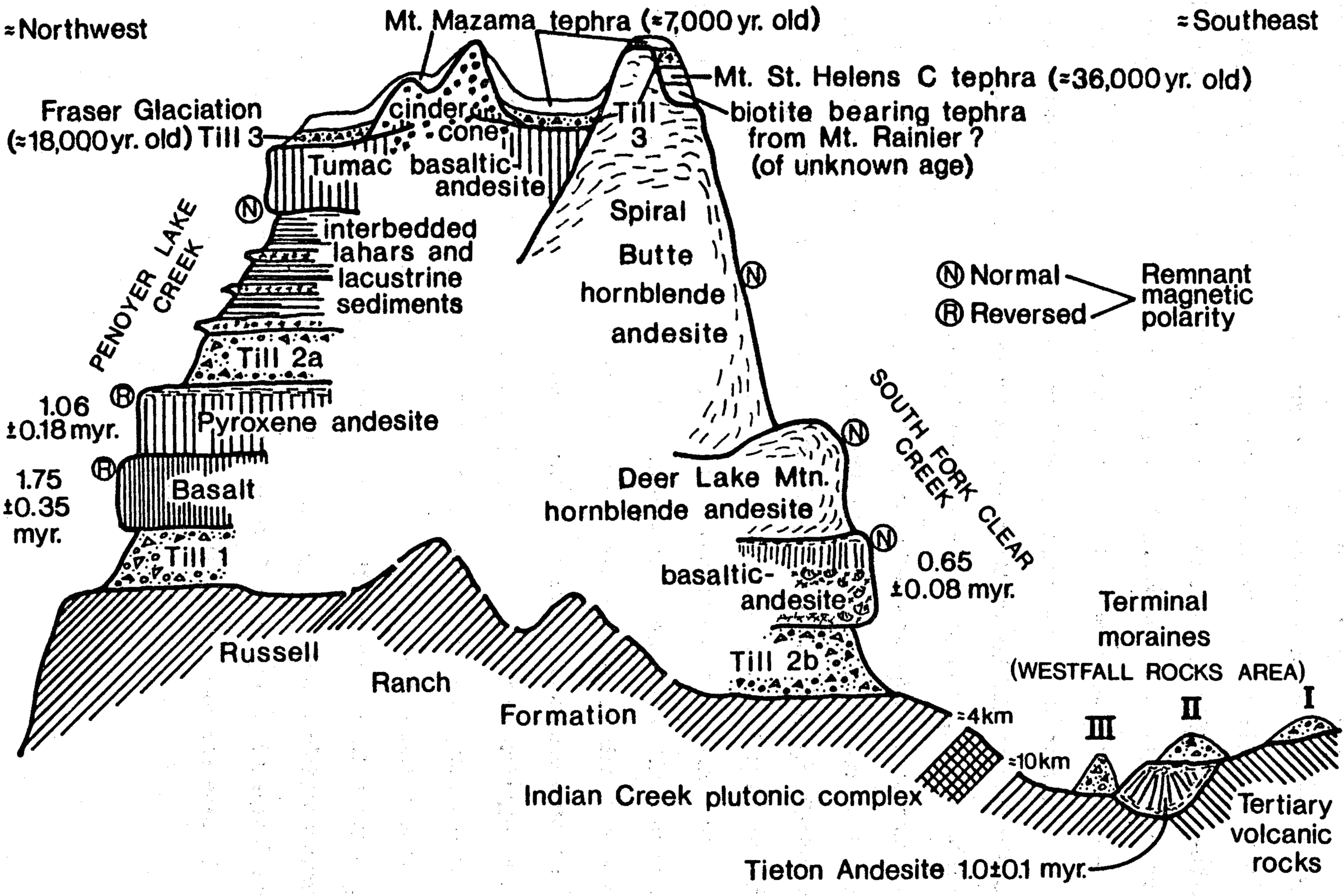


Figure 9-5. — Schematic cross section through the Pleistocene volcanic rocks in the White Pass-Tumac Plateau area.

The absence of transitional rock types between the Devils Horns rhyolites, Hogback Mountain mafic magma-type, high potassium pyroxene andesites of the Goat Rocks volcano, and low potassium hornblende andesites and porphyritic dacites, and their separate geographic and/or chronologic occurrence, indicates that these lavas were generated as separate batches of magma. It is not possible to relate these rock types to a common parent magma by fractional crystallization of the observed phenocryst phases. Furthermore, the phenocryst-poor nature of rapidly chilled samples of the basalts and basaltic andesites (which commonly contain only skeletal olivine that crystallized rapidly as the lava was erupted), the eruption of large volumes of highly differentiated rocks first, and the lack of whole-rock iron enrichment throughout the rock suite are evidence that fractional crystallization of basalt did not control the compositional variation between the main volcanic rock types.

The duration of the rhyolitic volcanism was probably less than 0.5 myr, but each of the processes that generated the other rock types operated for one to two million years and repeatedly produced very similar lavas. Lavas do not show substantial evolution towards more silicic differentiates over the lifespan of the volcanic systems (except possibly for the hornblende andesites), and they reached the surface without being contaminated by other contemporaneous magmatic systems. These late Pliocene and Pleistocene igneous rocks appear to be the result of one of the volumetrically largest and most compositionally diverse recognized episodes of volcanism in the White Pass area (compared to any other 4 myr interval of time) since the inception of the Cascade arc about 38 myr ago.

The White Pass-Bumping Lake area appears to be the northern termination of the Pliocene- and Pleistocene-age south Cascade volcanic province. This province is characterized by scattered basalt, basaltic andesite, hornblende andesite and rhyolite vents (Hammond, 1980). It has roughly the shape of an equilateral triangle with its apex at Bumping Lake and a base that is approximately 140 km wide at the latitude of Vancouver, Washington. The general northward decrease in age of vents within the White Pass area suggests that the apex of the triangle has shifted 15 to 20 km northward in the last three million years. Late Pliocene and Pleistocene volcanism in the Cascade Range of Washington north of Bumping Lake is volumetrically insignificant compared to that in the south Cascade volcanic province. This major change in the volcanic regime which occurs at about latitude 47^{o}N (and coincides with the southernmost occurrence of pre-Tertiary basement in western Washington), deserves more attention in models of the Quaternary and Pliocene tectonics of Washington State.

REFERENCES

Abbott, A. T., 1951, Tumac Mountain, A Post-Glacial Cinder Cone in Washington State (abstract): Geol. Society of America Bull., v 62, p 1495.

Abbott, A. T., 1953, The Geology of the Northwest Portion of the Mount Aix Quadrangle, Washington: Unpub. Ph.D. dissertation, Univ. of Washington, Seattle, 256 pp.

Armstrong, R. L., J. E. Harakel, and V. F. Hollister, 1976, Age Determination of Late Cenozoic Porphyry Copper Deposits of the North American Cordillera: Trans. Inst. Min. Metall. Sec. B, v 85, pp B239-B244.

Bates, R. G., M. E. Beck Jr., and R. F. Burmeister, 1981, Tectonic Rotations in the Cascade Range of Southern Washington: Geology, v 9, pp 184-189.

Becraft, G. E., 1950, Definition of the Tieton Andesite on Lithology and Structure: Unpub. M.S. Thesis, Washington State Univ., Pullman, 26 pp.

Berggren, W. A., and others, 1980, Towards a Quaternary Time Scale: Quaternary Research, v 13, pp 277-302.

Buckovic, W. A., 1979, The Eocene Deltaic System of West-Central Washington: In "Cenozoic Paleogeography of the Western United States" (J. M. Armentrout, M. R. Cole, and H. TerBest, Jr., eds.), 335 pp, Pacific Section, Society of Economic Paleontologists and Mineralogists, pp 147-163.

Campbell, N. P., 1975, A Geologic Road Log over Chinook, White Pass, and Ellensburg to Yakima Highways: Dept. of Natural Resources, Division of Geology and Earth Resources, Olympia, Washington, 81 pp.

Campbell, N. P., and R. D. Bentley, 1981, Late Quaternary Deformation of the Toppenish Ridge Uplift in South-Central Washington: Geology, v 9, pp 519-524.

Ellingson, J. A., 1959, General Geology of the Cowlitz Pass Area, Central Cascade Mountains, Washington: Unpub. M.S. Thesis, Univ. of Washington, Seattle, 60 pp.

Ellingson, J. A., 1968, Late Cenozoic Volcanic Geology of the White Pass - Goat Rock Area, Cascade Mountains, Washington: Unpub. Ph.D. Dissertation, Washington State Univ., Pullman, Washington, 112 pp.

Ellingson, J. A., 1969a, Geology of the Goat Rocks Volcano, Southern Cascade Mountains, Washington: Geol. Society of America Abstracts with Program,: v 1, n 3, p 15.

Ellingson, J. A., 1969b, Paleozoic Sedimentary and Metamorphic Rocks in the Southern Cascade Mountains, Washington: Geol. Society America Abstracts with Programs, v 1, n 3, pp 15-16.

Ellingson, J. A., 1972, The Rocks and Structure of the White Pass Area, Washington: Northwest Science, v 46, n 1, pp 9-24.

Ewart, A., 1976, Mineralogy and Chemistry of Modern Orogenic Lavas-Statistics and Implications: Earth and Planetary Science Letters, v 31, pp 417-432.

Fisher, R. V., 1957, Stratigraphy of the Puget Group and Keechelus Series in the Elbe-Packwood Area of Southwest Washington: Unpub. Ph.D. Dissertation, Univ. of Washington, Seattle, 153 pp.

Fisher, R. V., 1961, Stratigraphy of the Ashford Area, Southern Cascades, Washington: Geol. Society of America Bull., v 72, pp 1395-1408.

Fiske, R. S., 1960, Stratigraphy and Structure of Lower and Middle Tertiary Rocks, Mount Rainier National Park, Washington: Unpub. Ph.D. Dissertation, Johns Hopkins Univ., Baltimore, Maryland, 162 pp.

Fiske, R. S., 1963, Subaqueous Pyroclastic Flows in the Ohanapecosh Formation, Washington: Geol. Society of America Bull., v 74, pp 391-406.

Fiske, R. S., C. A. Hopson, and A. C. Waters, 1963, Geology of Mount Rainier National Park, Washington: U. S. Geol. Survey Prof. Paper, n 444, 93 pp.

Fiske, R. S., and T. Matsuda, 1964, Submarine Equivalents of Ash Flows in the Tokiwa Formation, Japan: American Journal of Science, v 262, pp 76-106.

Gill, J., 1981, Orogenic Andesites and Plate Tectonics; Minerals and Rock Series: Springer Verlag, New York, v 16, 300 pp.

Hammond, P. E., R. D. Bentley, J. C. Brown, J. A. Ellingson, and D. A. Swanson, 1977, Volcanic Stratigraphy and Structure of the Southern Cascade Range, Washington: In "Geological Excursions in the Pacific Northwest" (field trip 4), (Brown, E. H., and R. C. Ellis eds.), Geol. Society of America Annual Meeting, Publications of

Western Washington State Univ., Bellingham, pp 127-169.

Hammond, P. E., 1979, A Tectonic Model for the Evolution of the Cascade Range: In "Cenozoic Paleogeography of the Western United States" (J. M. Armentrout, M. R. Cole, H. TerBest, Jr., eds.), 335 pp, Pacific Section, Society of Economic Paleontologists and Mineralogists, pp 219-237.

Hammond, P. E., 1980, Reconnaissance Geologic Map and Cross Sections of Southern Washington Cascade Range: Publications of the Department of Earth Sciences, Portland State Univ., Portland, Oregon.

Harker, A., 1909, The Natural History of the Igneous Rocks: Macmillan and Co., New York, 384 pp.

Hopson, C. A., and J. M. Mattinson, 1973, Ordovician and Late Jurassic Ophiolitic Assemblages in the Pacific Northwest: Geol. Society of America Abstracts with Programs, v 5, n 1, p 57.

Irvine, T. N., and W. R. A. Baragar, 1971, A Guide to the Chemical Classification of the Common Volcanic Rocks: Canadian Journal of Earth Sciences, v 8, pp 523-548.

Larsen, E. S., 1938, Some New Variation Diagrams for Groups of Igneous Rocks: Journal of Geology, v 46, pp 505-520.

Long, W. A., 1951, Glacial Geology of the Tieton Valley, South-Central Washington: Northwest Science, v 25, pp 142-148.

Mullineaux, D. R., 1974, Pumice and Other Pyroclastic Deposits in Mount Rainier National Park, Washington: U. S. Geol. Survey Bull. 1326, 83 pp.

Mullineaux, D. R., J. H. Hyde, Rubin, Meyer, 1975, Widespread Late Glacial and Postglacial Tephra Deposits from Mount St. Helens Volcano, Washington: U. S. Geol. Survey Journal of Research, v 3, n 3, pp 329-335.

Mullineaux, D. R., R. E. Wilcox, W. F. Ebaugh, R. Fryxell, M. Rubin, 1978, Age of the Last Major Scabland Flood of the Columbia Plateau in Eastern Washington: Quaternary Research, v 10, pp 171-180.

Naeser, C. W., 1978, Fission-Track Dating: U. S. Dept. of the Interior, Geol. Survey, Open-File Report 76-190.

Porter, S. C., 1976, Pleistocene Glaciation in the Southern Part of the North Cascade Range, Washington: Geol. Society of America Bull., v 87, pp 61-75.

Porter, S. C., 1978, Hawaiian Glacial Ages: Quaternary Research, v 12, pp 161-187.

Rose, W. I. Jr., 1973, Pattern and Mechanism of Volcanic Activity at the Santiaguito Volcanic Dome: Guatemala, Bull. Volcanology, v 37, pp 73-94.

Rubin, M., Alexander, and Corrine, 1960, U. S. Geological Survey Radiocarbon Dates V: Radiocarbon Supplement, v 2, pp 129-185.

Russell, I. C., 1893, A Geological Reconnaissance in Central Washington: U. S. Geol. Survey Bull. 108, 108 pp.

Schreiber, S. A., 1981, Geology of the Nelson Butte Area South-Central Cascade Range, Washington: Unpub. M.S. Thesis, Univ. of Washington, Seattle, 81 pp.

Simmons, G. C., 1950, The Russell Ranch Formation: Unpub. M.S. Thesis, Washington State Univ., Pullman, 26 pp.

Simmons, G. C., R. M. Van Noy, and N.T. Zilka, 1974, Mineral Resources of the Cougar Lakes - Mt. Aix Study Area, Yakima and Lewis Counties, Washington: U. S. Geol. Survey Open-File Report, 73-243, 22 pp.

Smith, G. O., 1903, Description of the Ellensburg Quadrangle, Washington: U. S. Geol. Survey Geol. Atlas, Folio 86, 7 pp.

Swanson, D. A., 1964, The Middle and Late Cenozoic Volcanic Rocks of the Tieton River Area, South-Central Washington: Unpub. Ph.D. Dissertation, Johns Hopkins Univ., Baltimore, Maryland, 329 pp.

Swanson, D. A., 1966, Tieton Volcano, a Miocene Eruptive Center in the Southern Cascade Mountains, Washington: Geol. Society of America Bull., v 77, pp 1293-1314.

Swanson, D. A., 1967, Yakima Basalt of the Tieton River Area, South-Central Washington: Geol. Society of America Bull., v 78 pp 1077-1110.

Swanson, D. A., 1978, Geologic Map of the Tieton River Area, Yakima County, South-Central Washington: U. S. Geol. Survey, Misc. Field Studies Map, MF-968.

Waitt, R. B., Jr., 1979, Late Cenozoic Deposits, Landforms, Stratigraphy, and Tectonism in Kittitas Valley, Washington: U. S. Geol. Survey Prof. Paper 1127, 16 pp.

Warren, W. C., 1941, Relation of the Yakima Basalt to the Keechelus Andesite Series: Journal of Geology, v 49, pp 795-814.

White, C., 1980, Geology and Geochemistry of Mount Hood Volcano: State of Oregon Dept. of Geology and Mineral Industries, Special Paper 8, 26 pp.

Wilcox, R. E., 1979, The Liquid Line of Descent and Varition Diagrams: In "The Evolution of the Igneous Rocks: Fiftieth Anniversary Perspectives." (H. S. Yoder, Jr., ed.), 588 pp, Princeton University Press, Princeton, New Jersey, pp 205-232.

Williams, H., 1932, The History and Character of Volcanic Domes: Univ. of California Pub. Geol. Science, 21, pp 51-146.

Williams, H., and A. McBirney, 1979, Volcanology: Freeman, Cooper and Co., San Francisco, California, 391 pp.

Wise, W., 1969, Geology and Petrology of the Mount Hood Area; A Study of High Cascade Volcanism: Geol. Society of America Bull., v 80, pp 969-1006.

Wright, T. L., 1974, Presentation and Interpretation of Chemical Data for Igneous Rocks: Contributions to Mineralogy and Petrology, v 48, pp 233-248.

Vance, J. A., 1979, Early and Middle Cenozoic Arc Magmatism and Tectonics in Washington State: Geol. Society of America Abstracts with Programs, v 11, p 132.

Vance, J. A., and R. B. Miller, 1981, The Movement History of the Straight Creek Fault in Washington State: Geol. Association of Canada, Cordilleran Section, Programme and Abstracts, p 39.

10. GEOHYDROLOGIC STUDIES OF THE YAKIMA VALLEY AREA, WASHINGTON

by

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10. GEOHYDROLOGIC STUDIES OF THE YAKIMA VALLEY AREA, WASHINGTON

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Introduction

The low temperature geothermal resource within the aquifers of the Columbia Basin has become the focus of attention as a significant potential energy source. The Yakima region in particular has been determined to be a favorable target for the exploration and development of low temperature geothermal resources. Present commerical use is limited to irrigation (soil warming) and as a source of warm water for a car wash. As other energy sources become scarce or more costly, an increasing number of municipalities, businesses, and private residences may turn to geothermal energy for space heating, using the warm aquifers either directly or in conjunction with heat pumps. As a result, it becomes very important to be able to understand the geologic and hydrologic nature of these aquifers.

Since mid-1980, the Washington State Division of Geology and Earth Resources has supported thesis work at Washington State University aimed at describing the nature of the low-temperature geothermal resources in the Yakima region. The study area is located in the south-central portion of the state, within the Yakima folds geomorphic province on the western edge of the Columbia Basin (see figure 10-1). The topography is characterized by a series of east to southeast-trending anticlinal ridges and synclinal valleys. The near surface stratigraphy consists of lava flows of the Miocene Columbia River Basalt at depth, with interbeds and overlying sediments of the Miocene Ellensburg Formation. Aquifers occur within fracture zones of the basalt, permeable interbeds, and permeable zones of the overlying sedi-

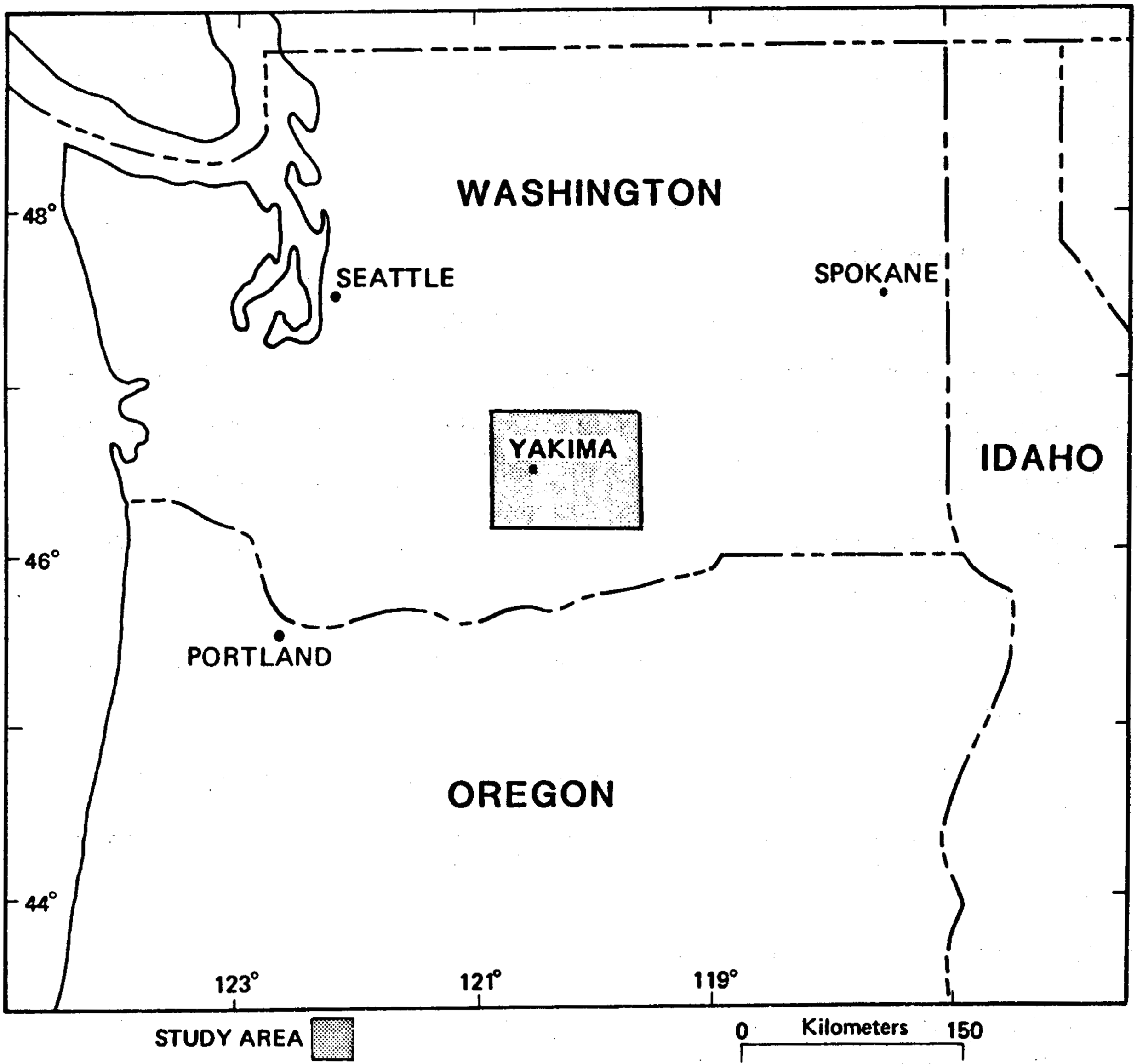


FIGURE 10-1 LOCATION OF STUDY AREA

ments of the upper Ellenburg Formation. The relatively high number and good density of wells penetrating to these aquifers provides an excellent opportunity to characterize the individual aquifers, with respect to depth, temperature, and areal extent.

Preliminary results from the study were released in a Division open-file report (Biggane, 1981). This report is a synopsis of the thesis entitled, "The Low Temperature Geothermal Resource and Stratigraphy of Portions of Yakima County, Washington". The thesis was released in mid 1982.

Previous Geothermal Work

Previous geothermal research in the Yakima region has been quite limited and has focused primarily on temperature gradient determinations. Foxworthy (1962) reported an average geothermal gradient of 40.5°C/km in water wells greater than 15 m deep in the Ahtanum Valley and suggested that the rock type had little effect on the gradient. Schuster (1980) noted that geothermal gradients of 50 to 70°C/km were commonly measured in water wells of the region and that relatively warm temperatures (20 to 27°C) were recorded in several wells.

Most of the geothermal gradients listed by Schuster (1980) and Korosec and others (1981) for the Yakima region are in the 35 to 45°C/km range. Depths to the 20°C isotherm in water wells of the Yakima region were reported to range from 9 to 471 m, with the majority from 100 to 200 m (Schuster, 1980).

Ground-Water Hydrology of the Yakima Region

The Sedimentary Aquifer --- The ground water in the upper Ellensburg Formation and Quaternary sediments, which comprise the sedimentary aquifer, is recharged by direct infiltration from precipitation, irrigation, and the influent reaches of the rivers, streams, and canals of the region. This aquifer is also recharged by upward flow from the basalt aquifer. The sedimentary aquifer discharges directly to the effluent reaches of the streams and rivers of the region and to the basalt aquifer by downward flow.

The lithologic heterogeneity of the sedimentary aquifer results in a wide range of horizontal and vertical transmissivities. The gravel and sand-rich sediments are much more permeable than the clay and silt-rich sediments. As a consequence, ground water in the sedimentary aquifer occurs under perched, unconfined (water table), and confined conditions.

The Basalt Aquifer --- Ground water in the basalt aquifer is recharged directly by infiltration along the anticlinal ridges and along the influent reaches of the rivers and streams of the region where the basalt is at the surface. The basalt aquifer is also recharged by downward flow from the sedimentary aquifer. The basalt aquifer discharges to the overlying sedimentary aquifer and to the effluent reaches of streams and rivers of the region when the basalt is at the ground surface. Direct recharge and discharge from the Yakima River to the basalt aquuifer is significant in the upper Yakima River basin.

The transmissivity of the basalt aquifer can vary by several orders of magnitude both horizontally and vertically. The typical basalt flow has zones of much higher effective porosity at both the top and the bottom as compared with the central portion of the flow. Horizontal transmissivity within the basalt aquifer is influenced greatly by the presence of these high porosity zones. Cooling joints and tectonic fractures also contribute to horizontal transmissivity. These high porosity zones may be areally extensive but often exhibit large variations in productivity, primarily because of changes in aquifer thickness and secondary mineralization or clay infilling. Vertical transmissivity within the basalt aquifer is controlled largely by the presence of cooling joints and tectonic fractures. The central portion of a basalt flow may act as an aquitard in the absence of these features.

The Sedimentary Interbeds (Selah, Mabton, Quincy(?), Squaw Creek, and Vantage members)-- Sedimentary interbeds also influence the horizontal and vertical transmissivities of the basalt aquifer. Both horizontal and vertical transmissivities should increase where the interbeds are composed of porous sands and gravels. Conversely, the transmissivities should decrease where there are less porous clayey or tuffaceous sediments.

There seems to be a high degree of vertical conductivity on a regional scale in at least the younger basalt flows of the Yakima region. Ground-water levels in the basalt aquifer have shown a general decline in the Toppenish basin because of irrigation withdrawals which would suggest that the horizontal, high porosity zones are hydraulically connected on a regional scale.

Temperature Data

Subsurface temperature data from the Yakima region have been collected primarily by three research groups or agencies. These groups are the Geological Engineering Section at Washington State University (WSU), the Washington State Department of Natural Resources Division of Geology and Earth Resources and Southern Methodist University (DNR-SMU), and the U. S. Geological Survey (USGS). The USGS data and the pre-1979 DNR-SMU data were obtained from Korosec and others (1981). Post-1979 DNR-SMU data were compiled by the DNR and made available for this investigation. Temperature-depth information has been collected from 184 wells, most of which are domestic supply and irrigation water wells.

The quality of the temperature data ranges from excellent to poor or "disturbed'. Drilling and pumping operations and intra-borehole flow often disturb the borehole temperature gradient so that it does not represent the actual geothermal gradient.

WSU and DNR-SMU bottom-hole temperatures (BHT's) are actually temperatures at a maximum logging depth, several of which were not from the bottom of the well. When identified, these "intermediate depth temperatures" were treated as such. Obstructions in the well or an inadequate probe cable length prohibited logging to the total depth in these wells.

The quality of the USGS data is unknown, and may, in fact, include "intermediate depth temperatures" and maximum temperatures measured in water flowing from wells during pumping tests or well development operations (Korosec, personal communication, 1982).

The errors involved with the BHT vs. botton-hole depth (BHD) linear regression analysis can be assumed to decrease as the geographic size of the well sample area decreases and as the number of available BHT's increases. The geographic area encompassed by a well data group and the depth interval that yields an accurate definition of the geothermal regime will be limited by the magnitude of the rate of change of the geothermal gradient within the well data group.

Discussion of Results

Bottom-hole temperatures of water wells in the Yakima region were separated into 14 well data groups based on four criteria: geographic proximity of the BHT data, similar land slope azimuth and dip in the area, position of the group within the conceptualized regional groundwater flow system, and BHD's over 50 m.

Geographic proximity was used as a standard on the assumption that the geothermal regime within small areas and depth intervals would be nearly constant. Land slope azimuth and dip were used in an attempt to segregate BHT's into well data groups that are similarly affected by land surface temperature (LST) and ground-water flow.

An example of BHT vs. BHD and the results of the least squares regression analyses for a well data group is presented in Figure 10-2. Locations, geothermal gradients, projected LST's, and depth to the 20°C isotherm for the well data groups have been compiled in Table 10-1 and on a map plate 10-1. Geothermal gradients for the groups range from 24.9 to 52.5° C/km. The projected LST's range from 10.6 to 14°C, and the depth to the 20°C isotherm ranges from 142 to 346 m.

Determination of Geothermal Gradients in the Yakima Region.

Rather than calculating the geothermal gradient from BHT, depth, and assumed land

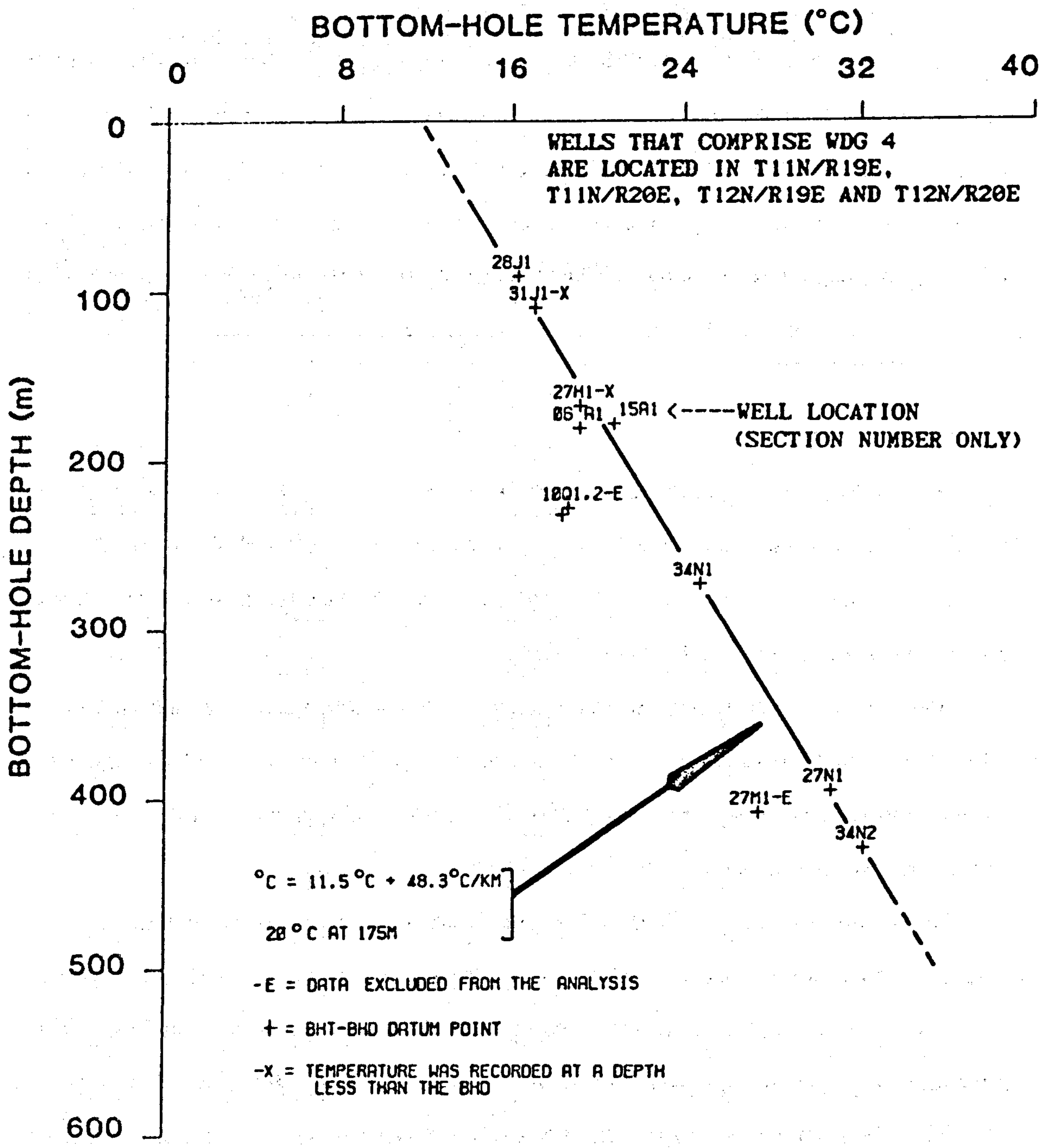


FIGURE 10-2 PLOT OF BOTTOM-HOLE TEMPERATURE VS. BOTTOM-HOLE DEPTH FOR WELL DATA GROUP 4

Table 10-1. Geothermal Gradients Determined by Regression Analysis, Predicted LST's, and Depth to 20° Isotherm For the Well Data Groups.

Well Data Group	Quality Designation	Geothermal Gradient (°C/km)	Land Surface Temperature (°C)	Depth to 20°C Isotherm (m)
1	A	38.7	11.8	212
2	C	33.7	14.0	179
3	C	52.2	12.6	142
4	A	48.3	11.5	175
5	A	40.3	12.9	175
6	A	36.5	13.8	171
7	A	34.1	12.5	220
8	B	40.7	11.6	207
9	B	43.4	11.4	199
10	A	40.5	12.9	176
11	A	42.3	10.6	223
12	C	24.9	11.4	346
13	A	29.8	11.3	292
14	B	39.8	12.7	184

(See Plate 10-1 for location of Well Data Groups) surface temperature, average gradients were determined using a least squares linear regression analysis of the relationship between the BHT and the "bottom-hole depth" of two or more water wells. Ideally, the BHT's of wells belonging to a particular well data group (WDG) would all be affected, in a similar manner, by the factors that influence the geothermal gradients of the area in which the water wells are located. The equation relating the BHT's and BHD's in such an area would define an average geothermal gradient and the projected LST of an area.

The linear regression analysis may introduce errors that result from an uneven distribution of data, and an "eyeball" fit of the line of well data group predicted temperature curve may be more accurate in some cases. The linear regression analysis was used in this study in order to eliminate this investigator's bias towards the recognition of higher than normal geothermal gradients.

Plots of BHT's vs. BHD's show an excellent correlation for the water wells grouped within the 14 well data groups. The accuracy of the geothermal information provided by this analysis increases as the density of the BHT data increases and/or as the area of the well data group decreases.

A subjective quality designation has been assigned to the different well data groups to provide a sense of the information's reliability, as perceived by the principal investigator. The letters "A", "B", and "C" have been assigned to the groups, with "A" designated the highest quality.

To check the accuracy of the individual well data groups, an analysis of the relationship between the predicted geothermal data and the actual borehole temperature logs was conducted. Borehole temperature logs from water wells of several groups were plotted along with the group temperature curves predicted by the BHT vs. BHD regression analysis. The plots indicated that, in most cases, the predicted geothermal data can be used not only to predict aquifer temperatures but also to determine borehole flow direction (uphole or downhole flow). The direction of borehole flow, interpretation of the flowmeter log, and pump test temperatures, if available, are noted in each plot of the combination borehole temperature logs and well data group predicted temperature curves in Biggane (1982).

When the regression-analysis-determined "depth to 20°C" isotherms of the well data groups are plotted against mean elevations for the groups, a fair correlation results. It suggests that the depth to the 20°C isotherm increases as the land surface elevation increases. However, the predicted geothermal gradients do not appear to be related to the mean elevations of the well data groups. In addition, the projected LST's, the depths to the 20°C isotherm, and predicted geothermal gradients do not appear to be related to the land slope azimuths of the groups. The apparent lack of correlation between the land slope azimuths and the predicted geothermal data of the groups may be caused, in part, by the simple method (linear) by which these relationships were examined. Other possible causes include the BHD's considered (i.e., greater than 50 m) and the size of the geographic area included in each group.

The apparent correlation between the mean elevations and the depths to the 20°C isotherm and between the mean elevations and the projected LST's of the well data groups may be explained by the ground-water flow system of the Yakima region. The direction of groundwater flow in the region is from higher elevations towards lower elevations. The difference in the overall ground-water flow direction in the recharge portion (higher elevations) and discharge portion (lower elevations) and the increase in the residence time of the water in the flow system towards the lower elevations may be the cause of elevated temperatures at the lower elevations.

Conclusions

The low temperature geothermal resources of the Yakima region were described by analyzing the relationship between the BHT's and BHD's of two or more water wells in each of fourteen geographic areas. The fact that the BHT vs. BHD analysis could be successfully applied in the relatively large geographic areas encompassed by the well data groups was not expected at the onset of this study.

Differences in the heat flow, thermal conductivity, and topography within a WDG might be expected to be great enough to produce a large variation in the geothermal regime of the individual wells and therefore cause a scatter of data on the plots of BHT vs. BHD. It should be apparent that the geothermal gradient and projected LST vary within the well data group, but the excellent correlation between the BHT and BHD data from the Yakima region suggest that the areal variation in the geothermal regime of a groups is very small.

The ground-water flow system is at least partially responsible for the variation within well data groups being as small as it appears to be. The effects of the flow system, especially the horizontal component, would tend to dampen the variation that results from differences in the heat flow, thermal conductivity, and topography. Topographic effects are also greatly reduced, if not eliminated, at the BHD's considered. In addition, the contrast in thermal conductivity was limited by the fact that most of the BHT's were obtained from the basalt aquifer.

Perhaps the greatest disadvantage of the BHT vs. BHD analysis is the requirement that at least three BHT's be available from any region under consideration before the assessment can be made with confidence. The results of any geothermal assessment which uses less than three BHT's by assuming an LST or by some other means could be subject to large errors. This is especially true when the calculated geothermal gradient must be projected to greater depths in order to reach production temperatures.

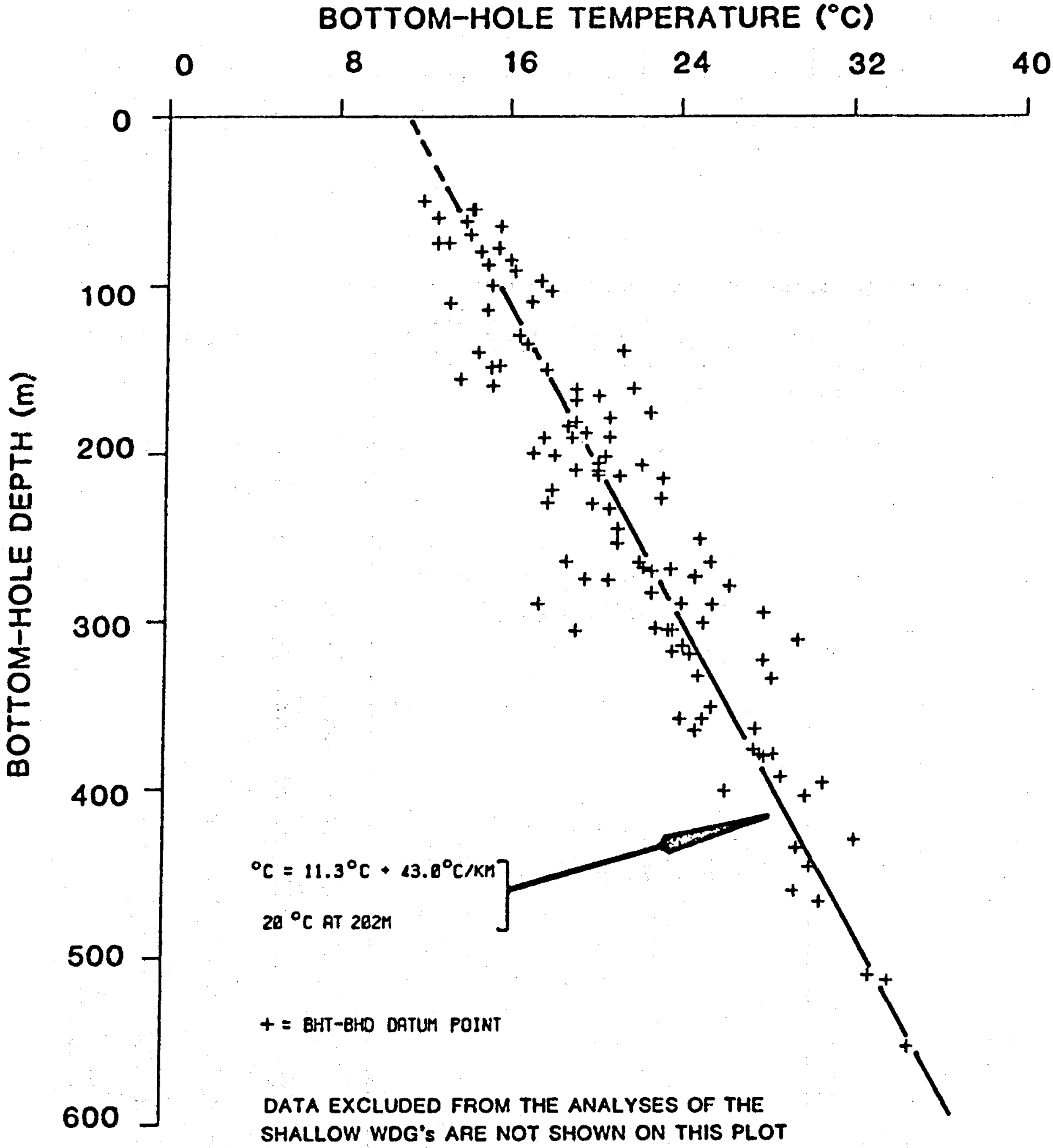
The BHT vs. BHD analysis should be applicable over even larger areas of the Columbia Basin, considering the size of the WDG's of the Yakima region and the relatively small topophic relief of the Columbia Basin. If an LST must be assumed in order to calculate a geothermal gradient, then the BHT vs. BHD analysis should at least provide a guide to the assumed or projected LST.

Judging the geothermal resources potential strictly on the basis of temperature gradients, the best areas for finding low temperature geothermal resources are within groups 3, 4, 9, and 11. Groups 3 is that part of the Yakima Valley southwest of Sunnyside. It has a gradient of 52.5^{o}C/km and predicted depth to the 20^{o}C isotherm of 142 meters. However, this group has a quality designation of C, (relatively poor quality) because of the data sources and their reliability.

Group 4 is located between Union Gap and Wapato and extends east to Parker Heights. It has a gradient of 48.3°C/km, a predicted depth to the 20°C isotherm of 175 meters, and a high quality designation of A.

Group 9 falls mostly within the Yakima city limits. It has a gradient of 43.4°C/km, a predicted depth to the 20°C isotherm of 199 meters and a quality designation of B.

Group 10, in the Black Rock Valley, has a gradient of 42.3°C/km, but because of its relatively cool surface temperature, the depth to the 20°C isotherm is relatively deep (223 meters). Group 10 data are of good quality and have been assigned an A designation.



DATA EXCLUDED FROM THE ANALYSES OF THE SHALLOW WDG's ARE NOT SHOWN ON THIS PLOT

FIGURE 10-3 PLOT OF BOTTOM-HOLE TEMPERATURE VS. BOTTOM-HOLE DEPTH FOR THE WELL DATA OF ALL GROUPS

Table 10-2. Well Data Group Geothermal Gradients, Mean Geothermal Gradients G1 and G2, Errors in Geothermal Gradient G2, and Corrected Mean Geothermal Gradient G2

Well Data Group	Well Data Group Geothermal Gradient (C/km)	Mean Geothermal Gradient G1 (C/km)	Mean Geothermal Gradient G2 (C/km)	Error in Geothermal Gradient G2 (C/km)	Corrected Mean Geothermal Gradient G2 (C/km)
1	38.7	38.8	37.9	0.8	38.7
2	33.7	35.0	43.4	-7.5	35.9
3	52.2	52.1	55.2	-2.9	52.3
4	48.3	48.6	45.8	2.2	48.0
5	40.3	40.8	43.7	-2.6	41.1
6	36.5	36.3	42.8	-5.6	37.2
7	34.1	34.0	35.9	-1.7	34.2
8	40.7	40.9	37.8	2.4	40.2
9	43.4	45.0	38.8	2.9	41.7
10	40.5	40.0	45.8	-4.2	41.6
11	42.5	40.7	33.8	5.7	39.5
12	24.9	24.9	19.4	3.9	23.3
13	29.8	30.3	25.0	3.1	28.1
14	39.8	39.7	41.6	-1.9	39.7

geothermal gradient as predicted by the WDG regression analysis

$$\text{mean geothermal gradient G1} = \frac{\text{BHT - WDG Projected LST}}{\text{BHD}} \text{ /number of wells}$$

$$\text{mean geothermal gradient G2} = \frac{\text{BHT - }12^{\circ}\text{C}}{\text{BHD}} \text{ /number of wells}$$

$$\text{error in geothermal gradient G2} = \frac{12^{\circ}\text{C - WDG projected LST}}{\text{Mean WDG BHD}}$$

corrected mean geothermal gradient G2 = mean geothermal gradient G2 + error in geothermal gradient G2

References

Biggane, J. H., 1981, The low temperature geothermal resource of the Yakima region--A preliminary report: Washington Division of Geology and Earth Resources Open-File Report 81-7, 70 p., 3 plates.

Biggane, H. H., 1982, The low temperature geothermal resource and stratigraphy of portions of Yakima County, Washington: Washington State University M.S. thesis, 126 p., 11 tables, 4 plates, 58 figures.

Foxworthy, B. L., 1962, Geology and ground-water resources of the Ahtanum Valley, Yakima County, Washington: U.S. Geological Survey Water Supply Paper 1598, 100 p.

Korosec, M. A., Schuster, J. E., with Blackwell, D. D.; Danes, Z.; Clayton, G. A.; Rigby, F. A.; and McEuen, R. B., 1981, The 1979-1980 geothermal resource assessment program in Washington: Washington Division of Geology and Earth Resources Open-File Report 81-3, 270 p., 1 map, scale 1:24,000.

Schuster, J. E., 1980, Proceedings of the Geothermal Symposium; Low temperature utilization, heat pump applications, district heating: Washington State Energy Office WAOENG-81-05, section XI.

11. Geothermal Resource Targets: Progress and Proposals

by

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Division of Geology and Earth Resources

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Introduction

During the course of conducting the state-wide reconnaissance study of Washington's potential geothermal resources, several specific areas and broader regions have been identified as targets which warrant a more concentrated effort. Over the past two years, the program has continued to identify new sites, but has concentrated on better defining the resource potential of the best areas. Figure 11-1 shows the locations of these geothermal areas, and Table 11-1 presents the progress for each area, expressed as a percentage of completion for the various exploration tasks.

In the following section, descriptions of the geothermal target areas are presented. Much of this material has been summarized from other chapters in this report and from earlier reports, especially Korosec and others, 1981. Refer back to these chapters and earlier reports for details on location, temperatures, gradients, etc. The gravity observations were made from Bouger gravity maps prepared by Danes and Phillips (1983).

Geothermal Target Area Descriptions

Olympic and Sol Duc Hot Springs: Because these hot springs are within the Olympia National Park, very little attention has been paid to them despite their 50 °C surface temperature. The water chemistry and regional geology suggest that the temperature is the result of deep circulation through permeable structures, probably faults. Equilibrium reservoir temperatures as indicated by chemical geothermometers, are about 100 °C. See Korosec and others, 1981, for further information on the Sol Duc Hot Springs area.

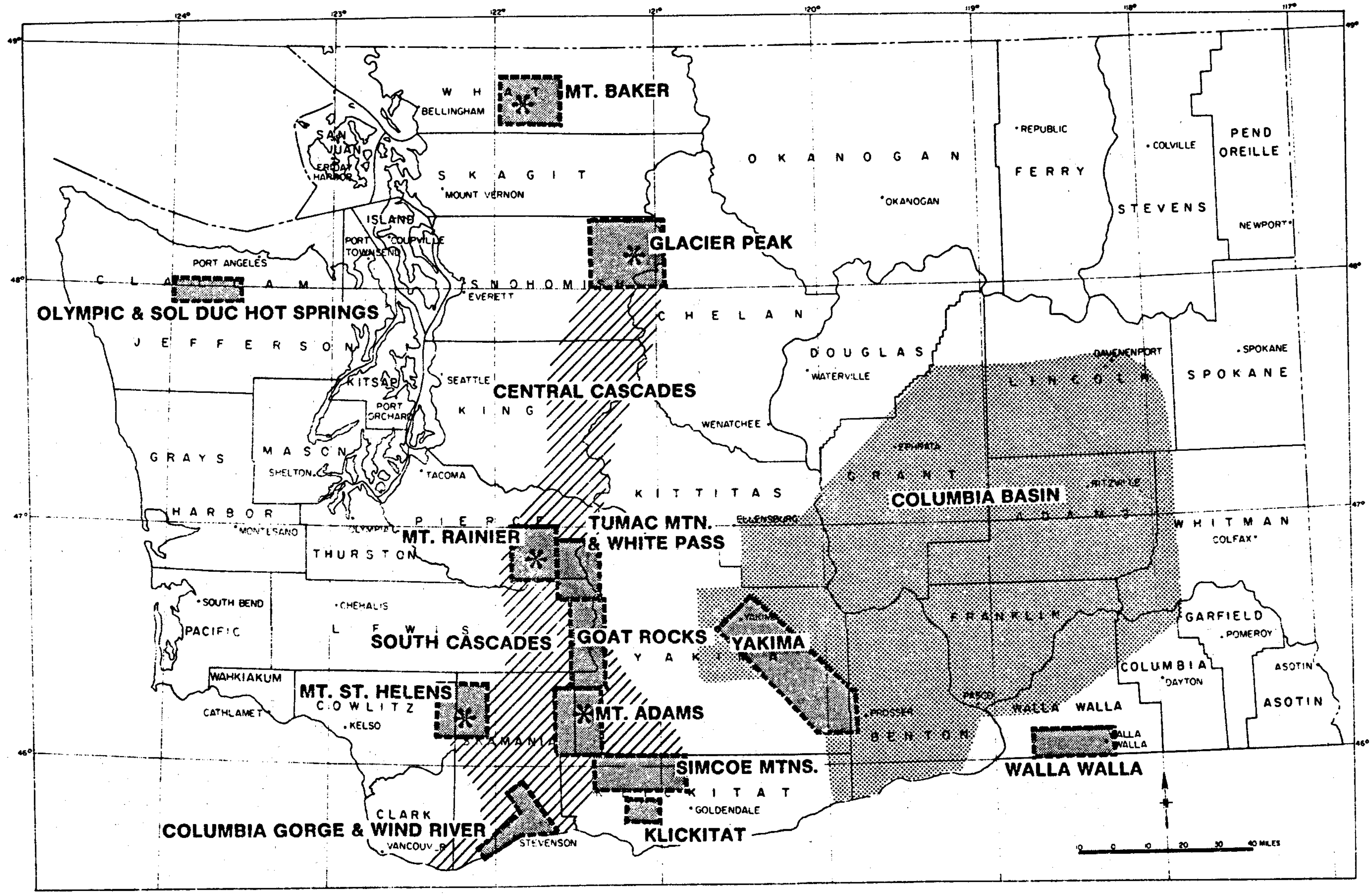

FIGURE 11-1. – Geothermal Resource Target Areas of Washington. All boundaries are approximate or indefinite.

STATUS OF GEOTHERMAL ENERGY ASSESSMENT IN WASHINGTON 6/82 NA = Not Applicable Numbers represent percent of work completed ● = 100% complete	PHASE I—Regional Reconnaissance	Literature search	Temperature gradient measurement in existing wells — wide spacing	Spring & well sampling of ground water — wide spacing	Broad reconnaissance geologic mapping, 1:100,000 scale or smaller.	Regional geophysical studies —wide spacing. Includes gravity, seismic, and aeromagnetic surveys.	Regional heat flow	PHASE II—Initial direct exploration of identified resource	Temperature gradient measurement in all available wells	Spring and well sampling of water in all available wells and springs	Detailed geologic mapping. 1:62,500 scale or larger	Shallow drilling of 500' temperature gradient wells to define heat flow anomalies	Detailed geophysical exploration —close spacing. Includes gravity, seismic, and aeromagnetic surveys	Qualitative and quantitative hydrologic analysis	PHASE III—Direct exploration of thermal anomalies	Intermediate depth drilling of 2000' wells to define thermal anomalies	Geophysical exploration	Quantitative hydrologic modeling of the geothermal system	PHASE IV—Direct testing of geothermal resource at depth	Deep drilling of 3000' to 6000' wells to test geothermal aquifers	Reservoir testing engineering evaluation including pump testing	Quantitative reservoir estimation
Olympic & Sol Duc Hot Springs	60	●	NA	●	●	0	0	15	NA	75	0	0	0	0	0	0	0	0	0	0	0	0
Glacier Peak	60	●	NA	80	●	10	0	30	NA	60	●	0	0	0	0	0	0	0	0	0	0	0
Mt. Baker	60	●	NA	80	60	40	0	10	NA	40	20	0	0	0	0	0	0	0	0	0	0	0
Central Cascades	65	50	NA	80	●	60	30	20	NA	60	40	0	0	0	0	0	0	0	0	0	0	0
South Cascades	85	●	NA	●	●	80	40	30	NA	80	40	20	5	0	0	0	0	0	0	0	0	0
Columbia Gorge, Wind River	85	●	60	●	●	80	80	50	50	80	80	40	40	0	5	10	0	0	0	0	0	0
Goat Rocks	65	●	NA	0	●	50	0	10	NA	0	20	0	20	0	0	0	0	0	0	0	0	0
Klickitat	75	●	50	●	●	50	50	15	40	40	0	20	0	0	0	0	0	0	0	0	0	0
Mt. Adams	55	60	NA	20	●	60	0	5	NA	0	20	0	0	0	0	0	0	0	0	0	0	0
Mt. Rainier	80	●	NA	●	●	60	40	40	NA	80	●	20	0	0	0	0	0	0	0	0	0	0
Mt. St. Helens	90	●	NA	●	●	●	40	60	NA	●	●	30	60	10	0	0	0	0	0	0	0	0
Simcoe Mtns.	45	●	NA	0	●	20	0	10	NA	0	60	0	0	0	0	0	0	0	0	0	0	0
Tumac Mtn., White Pass	80	●	NA	●	●	60	40	45	NA	80	●	40	0	0	0	0	0	0	0	0	0	0
Columbia Basin	75	80	80	●	●	50	50	30	40	20	60	NA	20	30	0	0	0	0	0	0	0	0
Walla Walla	90	●	●	●	●	90	50	45	60	60	80	NA	20	10	0	0	0	0	0	0	0	0
Yakima	95	●	●	●	●	90	●	70	●	60	●	NA	20	80	0	0	0	0	0	0	0	0

TABLE 11-1. – *Status for the Geothermal Resource Target Areas, as of June, 1982.*

The development of these resources will need to be consistent with the philosophy of the National Park Service, and will likely include a greater use of the Sol Duc resource for pool and space heating than is currently taking place. Olympic Hot Springs will be left in a "natural" state, with no development planned for the future.

For a better understanding of the geologic nature of these systems, an important void of information to fill is the lack of temperature gradient and heat flow data for the area. The entire Olympic Peninsula is suspected to be a relatively low heat flow province, with gradients less than 40 °C/km, but very little downhole temperature information exists in support of this. In addition, a shallow drilling program in the vicinity of the hot springs will provide information on the depth and extent of the shallow aquifers, thought to be the lower portion of the valley filling alluvium, and could better define the structure which controls these hot springs.

Glacier Peak: Glacier Peak, part of the North Cascade Range, is an andesitic Quaternary stratovolcano. While the most significant period of recent activity occurred between 5,000 and 14,000 years ago, smaller tephra eruptions have occurred as recently as 100 to 300 years ago (Beget, 1982). The volcano is part of the Glacier Peak Wilderness Area in the Mount Baker-Snoqualmie National Forest.

Good Geologic mapping exists for the area (Tabor and Crowder, 1968), and the recent eruptive history of the volcano has been documented in detail (Beget, 1982).

Fossil and possibly still active solfataric areas on the upper slopes of the volcano suggest that a high temperature reservoir exists within the upper part of the cone. Hot springs on the lower flanks suggest that a substantial high temperature reservoir exists below the cone, especially on the northeast and west sides.

Kennedy Hot Springs (38 °C) is located about 5 km west of the peak and about 3 km inside the Wilderness Area Boundary. The springs may arise from a reservoir with an equilibrium temperature from 170 to 220 °C, based on the water chemistry and geothermometers.

Gamma Hot Springs (65 °C), located about 5 km northeast of the peak, has one of the highest surface temperatures of any hot spring system in the State of Washington. Water chemistry suggests that it may origniate in a reservoir with a temperature of 200 to 215 °C.

Within the valley of the Suiattle River, about 11 km northeast of the peak, a group of cold mineral seeps flow from alluvium on the east side of the river. The water is sodium chloride-type, similar to Gamma Hot Springs. The water chemistry suggests a reservoir equilibrium temperature in the range of 170 to 225 °C. The Suiattle River Mineral Seeps are possibly related to Gamma Hot Springs (4.5 km southwest and upslope from the seeps) and may be part of the volcano's geothermal system.

Sulphur Creek Hot Springs (37 °C) is located about 17 km north of the peak. Its water chemistry suggests that the spring is part of a moderate temperature system, probably the result of deep ciruculation. On the basis of its chemistry and distance from Glacier Peak, Sulphur Creek Hot Springs is probably not related to the stratovolcano's geothermal system.

Despite the high potential of the Glacier Peak systems, very little geothermally oriented geologic work has been completed. To date, no shallow drilling for temperature gradients and heat flow determinations have been performed, and no information from geophysical surveys, such as gravity and resistivity, is available. The principal reason for this is the wilderness status of the Glacier Peak area, which precludes most types of exploration.

The area outside of the western boundary of the wilderness area deserves further attention. It is only 3 km from Kennedy Hot Springs, and is easily accessible by existing logging and recreational roads. The land is part of the Mount Baker-Snoqualmie National Forest. Recommended preliminary work includes geochemical sampling of springs in the area, soil mercury surveys, and shallow drilling for temperature gradient information, especially in the White Chuck River and North Fork Sauk River drainages. It may be found that holes deeper than 150 meters will be needed to adequately test the temperature gradients in the river valleys, due to possibly deep river deposits, glacial debris, and mud flow deposits.

Mount Baker: Mount Baker is a Quaternary stratovolcano on the western front of the North Cascades. It is located within the Mount Baker-Snoqualmie National Forest, and lies within a specially designated recreation area. The bulk of the mountain's edifice was formed prior to the last glaciation, with the earliest activity extending as far back as 400,000 years ago (Black Buttes volcanics)(Swan, 1980). The latest volcanic activity occurred within the last few hundred years, according to numerous historic accounts. Fumarolic activity at the Dorr fumarole field and within the Sherman crater suggests that a high temperature geothermal system exists within the upper cone of the volcano.

The best detailed geologic mapping for the area is provided by McKeever (1977) (south flank only) and Swan (1980), while regional reconnaissance geology is presented by Moen (1969). Studies which pertain to surficial expressions of the upper cone hydrothermal reservoir include Friedman and Frank (1974), Frank and Friedman (1975), and Hyde and Crandell (1978). The volcanic hazards aspects of this volcano are addressed by Hyde and Crandell (1978).

The occurrence of Baker Hot Springs (45 °C), about 11 km east of the peak, suggests that a geothermal system may extend at depth well beyond the topographic limits of the volcanic pile. The water chemistry at Baker Hot Springs suggests that the reservoir equilibrium temperature of this system may range as high as 150 to 170 °C. There are also reports of other hot springs in the area, including submerged thermal springs in the Swift Creek drainage north of Baker Hot Springs. Along the North Fork Nooksack River to the north of the volcano, several mineral and possibly thermal springs and seeps are rumored to exist.

About 8 km south of the peak, in Schrieber's Meadow, a cinder cone and several water-filled boccas mark the vent area which produced the numerous andesite flows of the Sulphur Creek and Rocky Creek drainages. The vent was active in Recent time, younger than about 10,000 years, but older than the 6,700 year old Mazama ash which lies on the surface of the flows. While no present-day thermal manifestations have been found in the vicinity, the relatively young age of this vent, the volume of andesite produced, and the comparatively easy access to Schrieber's Meadow (in comparison to the upper slopes and crater areas of the peak) make this area a prime target for further geothermal exploration.

Additional features of interest in the Mount Baker area include relatively young volcanic centers on Ptarmigan Ridge and in the upper Boulder Creek drainage, a deep elongate gravity low on the west and south-southwest sides of the volcano (about 50 to 60 mgals) extending from the Schrieber's Meadow area to the Glacier Creek Valley to the northwest, and a slight gravity high near the Baker Hot Springs area.

During late 1981, Nevin, Sadlier-Brown, Goodbrand, Ltd., conducted a preliminary reconnaissance survey of the Mount Baker area for Seattle City Light. This was followed up by further reconnaissance and area-specific tasks in a number of target areas. The work included resistivity surveys, soil mercury measurements, and water conductivity determinations. As of this writing, much of the results of the work were proprietary, and therefore confidential. However, it is expected that the information will be released in the near future.

No heat flow or temperature gradient information is available for the Mount Baker area. As such, the drilling of several shallow to intermediate depth temperature gradient/heat flow holes around the flanks of Mount Baker, especially in the Baker Hot Springs and Schrieber's Meadow areas, should be carried out as part of any further exploration program. In addition, detailed gravity surveys and resistivity measurements in the Schrieber's Meadow area should be conducted in an effort to identify the underlying structure and determine the cause of the deep gravity low. This could be followed up by seismic profiling which would also define structure, but the rugged terraine would make such surveys difficult to conduct.

Central Cascades: The central Cascades region of Washington, informally defined as the area extending from Mount Rainier north to about Glacier Peak, is characterized primarily by Tertiary volcanics and sediments, interrupted by numerous Oligocene (?) to Miocene intrusives. The ownership is primarily U.S. Forest Service (Mount Baker-Snoqualmie National Forest), with lesser private ownership concentrated in the foothills and major valleys. The only suggestion of geothermal potential in this region is the occurrence of four isolated thermal springs. They include Garland Mineral Springs (29 °C) in the Skykomish River valley, Scenic Hot Springs (50°C) on the southern slope of the Skykomish River valley near Stevens Pass, Goldmeyer Hot Springs (53 °C) near the Middle Fork of the Snoqualmie River drainage, and Lester Hot Springs (49 °C) in the Green River valley.

Scenic and Goldmeyer systems have chemistries which suggest that their reservoir equilibrium temperatures are near 100 °C. The springs are likely the result of deep circulation of meteoric water. See Chapter 3 of this report for additional information on these springs.

Garland Mineral Spring has a chemistry which suggests a high reservoir equilibrium temperature of 165 to 190 °C. Little else is known about this spring system, but on the basis of its chemistry, Garland is probably the best geothermal target in the central Cascades.

Lester Hot Springs may also have a moderately high reservoir temperature, about 120 to 150 °C, but its location within the City of Tacoma Watershed complicates exploration and eventual development. See Korosec and others (1981) for further information on Lester Hot Springs.

Very little heat flow and temperature gradient information has been collected from the central Cascades. The area just north of Mount Rainier and the Snoqualmie Pass area produced very low heat flow, about 50 mW/m^2, but two holes near Scenic and Stevens Pass produced relatively high heat flows of about 100 to 140 mW/m^2. As such, the general character of the heat flow for the bulk of the central Cascades has yet to be determined. The temperature gradients at the holes near Scenic are 35 and 65 °C/km.

In addition to reconnaissance heat flow drilling in this region, deeper drilling may be warranted in the Garland and Lester areas as part of future exploration activity. There should be an attempt to collect geothermal fluids from deeper portions of the spring systems with these deeper holes, along with the determination of gradients at depth.

South Cascades: The southern portion of Washington's Cascades consist of uplifted Tertiary volcanics, capped in places by Quaternary stratovolcanoes, cinder cones, shield volcanoes, and lava flows. There are several specific targets within this geographic province, including Mount Rainier, Mount St. Helens, Mount Adams, and the Columbia River Gorge--Wind River areas. Each of these targets are discussed separately in this chapter.

Most of the young volcanics in the South Cascades are monogenetic basaltic flows and cones and polygenetic basaltic shield volcanoes, with only minor occurrences of more silicic products. The best targets within this volcanic province should be judged by a combination of a) age of volcanic centers, b) density of volcanic centers and/or volume of volcanics in the area, and c) composition of volcanics, with the more silicic centers being most favorable.

The best combination of density and relative youth of volcanic centers occurs in the Indian Heaven area of the Gifford Pinchot National Forest. North-south oriented fissure zones have produced basalts which cover 2,200 km^2. The oldest flows are from about 140,000 to 690,000 BP, but the majority of flows are 20,000 to 130,000 years old (Hammond, 1980). Several flows are of recent age, perhaps only a few thousand years old, including the very large Big Lava Bed. Individual centers and their ages are discussed in Schuster and others (1978), and Hammond (1980). The Indian Heaven area is also the location of a large, relatively deep (about 25 mgals) gravity low, centered near the main fissure zones.

Despite the concentration of young volcanics, no thermal or mineral springs occur in the vicinity of Indian Heaven. It is suspected, however, that any upwelling thermal fluids would be rapidly diluted by the deep penetrating meteoric-ground water in this region of high precipitation.

During 1975, a shallow drilling project found temperature gradients of 45 to 60 ^{o}C/km, and heat flows of about 50 to 70 mW/m^2 (Schuster and others, 1978). The drill holes were only 150 meters deep, and were obviously influenced by ground water flow to depths of 50 to 90 meters. Because there are doubts as to whether or not this adequately characterizes the area's temperature gradients and heat flow, deeper holes, of 600 meters or greater, should be drilled before the Indian Heaven area is removed from further geothermal consideration.

A similar concentration of basaltic centers occurs within the King Mountain fissure zone, east of Indian Heaven and south of Mount Adams. These volcanics are older than those of Indian Heaven on the average, but some of the centers may be only a few tens of thousands of years old. Very little is known about the King Mountain area's geologic nature and geothermal potential. Geologic maps of the area are provided by Sheppard (1964), Hopkins (1976), and Hammond (1980). Because of its proximity to Mount Adams and favorable land status (primarily U.S. Forest Service land designated for multiple use), future exploratory efforts should be conducted in the area, with an emphasis on shallow and intermediate drilling, age dating, and structural mapping.

Another area of concentrated volcanic centers, south of Mount St. Helens and northwest of Trout Creek Hill, includes West Crater and Soda Peak. The land is part of the Gifford Pinchot National Forest. West Crater is a basaltic cinder cone with two intra-canyon lava flows of Recent age. It may be one of the youngest volcanic centers in the state, aside from the five main stratovolcanoes (Paul Hammond, personal communications). Timbered and Soda Peaks are volcanic centers which produced hornblende andesite flows. They are significantly older than West Crater, probably of Middle to Late Pleistocene age. Bare Mountain crater, however, which consists of andesitic scoria atop the flows northwest of Soda Peak, is well-preserved and probably of Recent age.

No temperature gradient or heat flow information is available for the region around Soda Peak and West Crater, and no occurrences of thermal or mineral springs have been reported for the immediate area. The Government Mineral Springs and Little Soda Springs occur 5 to 6 km east of Soda Peak, and may be related to the Quaternary volcanics which surround the area. Published geologic mapping for the area is very crude, but it should be greatly improved by a thesis mapping project currently being carried out by Dave Polivka at Portland State University.

Future work in the West Crater-Soda Peak area should include drilling of shallow and intermediate holes for temperature gradient and heat flow information, and age dating of the volcanics. Geophysical surveys such as resistivity and seismic profiling might be effective exploration techniques for later stage exploration in this area. Because of the extensive logging operations which have persisted in this portion of the National Forest for many decades, an extensive road system exists which should greatly facilitate exploration activities.

Columbia Gorge--Wind River Area: Along a section of the Columbia Gorge, extending from about Skamania on the west to about the Little White Salmon River to the east, several warm springs and wells with relatively high temperature gradients occur. These are especially concentrated in the area of Carson, where the Wind River flows into the Columbia River. Within the Wind River valley to the north of the Columbia River, there are several mineral springs and high temperature gradient holes. Consequently, the Wind River valley has been included as part of the Columbia Gorge geothermal target area.

Land ownership in the region is a combination of federal, state, and private. Along the Columbia River and through the lower portion of the Wind River valley, the land is primarily under private ownership, and includes individual holdings, small businesses, and logging companies. Above the rivers, valleys, and through the upper portion of the Wind River valley, the ownership is primarily Federal (Gifford Pinchot National Forest). The State of Washington owns lands along the periphery of the National Forest and scattered throughout some of the private land. The entire region of the Columbia Gorge is under study for some type of preservation, such as a National Monument, which may influence development activity in the future.

Geologic mapping in the area is quite good, with coverage provided by Hammond (1980), Wise (1961 and 1970), and Berri (1983). The area of the Gorge has a relatively low density of Quaternary volcanic centers compared to areas to the north and south. The closest volcanic centers are monogenetic basalt cones and flows at or near Red Bluffs (Greenleaf Basin), Rock

Creek Butte, Cedar Creek, Beacon Rock, and Mt. Defiance (Oregon). The Wind River Valley cuts close to the Trout Creek Hill volcano, whose basalt covers the floor of the valley down to the Columbia Gorge. Trout Creek Hill is close to the relatively young West Crater and Soda Peak volcanic centers (see section on South Cascades).

The springs along the Gorge include Bonneville Hot Springs (38 °C) near the town of North Bonneville (see Korosec and others, 1981), Rock Creek Hot Springs (35 °C) 4.5 km northwest of Stevenson (see chapter 3, this report), St. Martins (Carson) (54 °C) and Shipherds Hot Springs (45 °C) on the Wind River near its mouth (see chapter 3, this report), and Collins Hot Springs, near the base of Wind Mountain. Due to the raising of the water levels behind Bonneville Dam, Collins Hot Springs is submerged, but from historic accounts, the springs at Collins were similar to St. Martins Hot Springs.

The chemistries of these springs suggest that they have reservoir equilibrium temperatures of about 100 °C or less, not significantly warmer than their surface temperatures. They occur along suspected north-northwest faults, where these faults intersect the major northeast trending lineament of the Columbia River and Little Wind River (Hammond, 1980).

Wells drilled in the vicinity of the hot springs have produced spectacular temperature gradients, as would be expected, and have encountered the warm aquifers at relatively shallow depths. In the Bonneville area, the town of North Bonneville drilled three shallow temperature holes, followed by an intermediate depth exploration-production well. Gradients ranged from 55 to 120 °C/km in the 150 to 190 meter-deep holes. The production well, 680 meters deep, encountered several different aquifers which produced a combined flowing temperature of 40 °C, and had a bottom hole temperature of 44 °C, with an average gradient of only 50 °C/km. The effects of cooler water entering the well from shallower depths may be significant, but have not been fully assessed.

A shallow (150 meter) heat flow hole near Shipherds Hot Springs, drilled by the Division in 1981 (see chapters 3 and 6, this report), produced a gradient of 366 °C/km. A well drilled by the property owner next to this hole in 1982 penetrated to a depth of 190 meters, encountered 32 °C water at about 170 meters, and continued to have an increase in temperature below the hot aquifer. The gradient determined for this well was about 153 °C/km.

Only a few other wells have been measured in the surrounding area, with mixed results. Most are uncased and too shallow to produce good gradients, but some give indications of gradients as low as 35 °C/km and as high as only 55 °C/km. However, a 250-270 meter water well southwest of Home Valley along the Columbia River reportedly produced about 28 to 30 °C mineralized water, which suggests a temperature gradient of at least 65 °C/km, and perhaps much higher.

About 20 to 22 km up the Wind River, two spring groups, Government Mineral Springs and Little Soda Springs, produce cool mineralized water. Their chemistries suggest they arise from reservoirs of 100 to 150 °C at best (see chapter 3 of this report). A heat flow hole drilled about 5 km south of the springs and southeast of Trout Creek Hill produced a gradient of 84 °C/km (see chapter 6 of this report).

Other interesting features and observations for this area include the occurrence of a broad east-west trending gravity high north of the Columbia River which interrupts the large north-south trending Cascade Range gravity low; a small gravity low superimposed on the regional high in the vicinity of North Bonneville; high chloride content of the St. Martins Hot Springs water; and very high pH values for all of the spring waters, especially for waters from the Bonneville Hot Springs, Rock Creek Hot Springs, and Bonneville Drill Hole.

The Columbia Gorge and Wind River area is one of the best areas for low to intermediate temperature geothermal resources, because of the combination of confirmed resource, favorable economics, nearby users, and currently favorable land status and ownership. Additional exploration activities which would add to the understanding of these geothermal resources include the drilling of additional shallow temperature gradient holes and intermediate depth holes (600 meters) in the vicinity of thermal springs and existing high temperature -gradient wells, and hydrological studies of the shallow warm aquifers. Resistivity should be tested as a method to trace the extent of the mineralized warm water aquifers. The best target appears to be the St. Martins Hot Springs area. This target may extend southeastward to the Wind Mountain-Collins Hot Springs area, as suggested by the warm well southwest of Home Valley.

Goat Rocks: The Goat Rocks are high elevation volcanic ridges south of White Pass and north of Mount Adams. This roadless area has been preserved as a National Wilderness Area.

The Goat Rocks should be considered Washington State's sixth Quaternary strato-volcano. After explosive rhyolitic volcanism during the late Pliocene, activity shifted to calc-alkaline cone-building volcanism in the early Pleistocene. This strato-volcanic activity continued until at least 1 million years ago. Most of the edifice, which at one time may have been as large as Mount Adams, has been eroded and deeply dissected, primarily through glacial activity. Additional geological information for this area is presented in chapter 9 of this report.

No surface manifestations exist which suggest the presence of active geothermal systems, except for a few reported mineral springs southeast of Cispus Pass in the upper reaches of the Klickitat River (Geoff Clayton, personal communication). Cispus Pass is also an area of hydrothermal alteration.

While no measurements have been made in the vicinity, it is suspected that the area is characterized by above normal heat flow. This is suggested by high temperature gradients and heat flows measured in surrounding regions, and the presence of Quaternary volcanic centers throughout the region.

Because the Goat Rocks are part of a Wilderness Area, and closed to most exploration and development, it is unlikely that further work will be conducted in the near future, except for ongoing geological mapping and potential mineral resources assessment for the region being carried out by the U.S. Geological Survey.

Mount Adams: Mount Adams is a pyroxene andesite Quaternary volcano surrounded by a number of monogenetic, basaltic volcanoes. The eastern portion of the mountain is part of the Yakima Indian Reservation. The rest of the volcano and much of the surrounding region are part of the Mount Adams Wilderness Area.

Because of the land status (Wilderness Area and Indian Reservation), very little exploration has taken place in the region. The only areas that could be easily explored and eventually developed would be the Gifford Pinchot National Forest lands beyond the boundaries of the Wilderness Area on the west, southwest, and south sides. The only thermal manifestation in this region is Orr Creek warm springs (Korosec and others, 1981). Water chemistry from this 20 °C spring system suggests that the equilibrium reservoir temperature may be as high as 200 °C, but the water has a relatively low total dissolved solids content and probably represents a highly diluted thermal seep. The springs may have no relationship to the Mount Adams volcano, but for lack of additional information, Orr Creek should be considered a prime geothermal target worthy of further consideration and exploration. There is no temperture gradient information for the region, and as such, the drilling of shallow to intermediate exploration holes should be carried out as part of an exploration program, especially near Orr Creek and in the vicinity of Potato Hill north of Mt. Adams. Potato Hill may be the youngest of the numerous basalt volcanoes extending between Mount Adams and Goat Rocks, with a possibly post glacial age (Hammond, 1980).

On the south and southeast sides of Mount Adams, several basaltic shield volcanoes and cinder cones of the King Mountain fissure zone occur. These volcanic centers are primarily late Pleistocene in age. No thermal manifestations occur in the area, and no temperature gradient or heat flow information has been collected in the region. Shallow drilling for temperature gradient information might be the best means to assess whether this area holds any potential for geothermal resources.

Mount Rainier: This Quaternary volcano, located within Mount Rainier National Park, is the largest of the state's stratovolcanic mountains. It is considered temporarily dormant, with the last minor eruptions reported in the mid to late 1800's. Ice caves formed by fumarolic activity in the summit crater area and thermal seeps which occur near the terminus of several of the major glaciers suggest that a significant hydrothermal system exists within the upper cone. The occurrence of hot springs beyond the main edifice of the mountain, at Longmire and Ohanapecosh, suggest that there may also be a hydrothermal system which extends beyond the topographic bounds of the volcano. Chemistry of the waters from both Longmire (28 °C) and Ohanapecosh (50 °C) Hot Springs suggest the temperature of the systems may be as high as 150 to 175 °C.

Very little geothermal exploration has taken place at Mount Rainier, primarily because it is within a National Park whose boundary extends about 12 to 25 km out from the peak. Preliminary work outside of the Park boundary has not produced any high potential prospects, but the occurrence of a mineralized spring along the Puyallup River near the Park boundary (Pigeon Soda Springs) may warrant further attention. The proximity of the Ohanapecosh Hot Springs to the southeast corner of the Park suggests that this boundary area may be a prime target for further studies, including intermediate depth drilling and various geophysical work, such as resistivity surveys.

Mount St. Helens: Mount St. Helens is, without question, the most obvious geothermal manifestation in the State of Washington, as a consequence of its continuing eruptive activity since early 1980. Prior to that time, this stratovolcano was a prime target due to a combination of factors, including the relatively young age of the mountain, historic reports of activity during the 19th century, fumarolic activity on its upper flanks, accessibility by existing roads, and land status. Ownership of the surrounding land was divided between the U. S. Forest Service (Gifford Pinchot National Forest), the State of Washington, and private concerns, primarily large timber companies. Decades of logging in the area were responsible for the construction of an extensive road system.

In the wake of the major eruptions of the volcano, a National Volcanic Monument was established, which removes the mountain and immediate surrounding countryside from further exploration and specifically precludes any type of development of geothermal resources. There are a few areas outside of the monument's boundaries, however, which should be considered for further exploration.

The Green River Soda Springs occur where a projection of a linear distribution of earthquake epicenters extending north-northwest from Mount St. Helens crosses the Green River valley. This linear zone, which suggest the presence of a large fault or fracture zone related to the volcano, was evident before 1980. Seismic activity from the latest eruptions and from aftershocks associated with the 1981 Elk Lake earthquake (Richter magnitude 5.5), has better defined this structure. It extends for at least 30 km and is seismically disturbed at depths as shallow as a few kilometers. The land ownership belongs to both state and private timber companies. The land immediately surrounding the soda spring is part of three patented mining claims..

The Mount St. Helens fault zone becomes an intriguing target for geothermal exploration because it is intimately related to volcanic activity, represents a probable permeable zone which would allow fluid movement, shows seismic activity to drillable depths, and extends beyond the bounds of the preserved monument. The Green River Soda Springs mark the logical area to concentrate future activity. Chemistry of this cool mineral spring, reported to have been significantly warmer several decades ago, suggests that the equilibrium reservoir temperature may be as high as 140 to 150 °C. Because the spring is flowing from valley fill, it is very likely that the spring waters represent a mix of the upwelling thermal fluids and the shallow ground water. No temperature gradients or heat flow information exist for the area, and the geologic map coverage is poor. Work which should be carried out at this prospect includes detailed geologic mapping, shallow temperature gradient drilling, drilling of a hole to isolate and collect the spring water from deeper depths (below the depth of mixing with the shallow ground water), soil mercury surveys to better define the structure of the area, resistivity work, and the drilling of an intermediate depth hole (600 meters or deeper) to test the gradient at depth.

On the south-southeast extension of the suspected fault zone, beyond the southern boundary of the monument, a collection of Quaternary volcanic centers has built up Marble Mountain. The volcanics are primarily mid to late Pleistocene basalts, but one center, probably the youngest, produced a hornblende andesite flow. This flow has been K-Ar age dated to be about 160,000 years old. No thermal manifestations occur within the immediate area, and no temperature gradient or heat flow information has been collected. For many of the same reasons mentioned for the Green River Soda Springs area, Marble Mountain should be further investigated, primarily through shallow and intermediate drilling work.

Simcoe Mountains and Klickitat Area: The Simcoe Mountains are a collection of Pliocene to Pleistocene olivine and pyroxene-olivine basalt shield volcanoes and cinder cones in south central Washington. The northern portion of the area is within the Yakima Indian Reservation, while the rest is a combination of private and state ownership.

Although the area has been mapped at scales of 1:125,000 (Sheppard, 1960 and 1967) and 1:62,500 (Shannon and Wilson, 1973), the Simcoe mountains are poorly understood. Only a few age dates have been determined for the volcanics, and the results suggest ages of late Pliocene to early Pleistocene. But the geomorphology of many of the cinder cones suggests that some of the volcanics may be significantly younger. A few cinder cones are thought to be as young as 10,000 to 100,000 years old.

Many of the cones, particularly those in the southern portion of the area, are arranged in linear clusters, suggesting fault and/or fissure zone control. The centers are aligned roughly north-south, as well as northwest-southeast.

The only recognized silicic products of the Simcoes occur near Indian Rock, atop and along the flanks of a very large shield volcano. The dacite domes and rhyolite flows are only minor in volume, but their presence suggests the occurence of shallow crustal accumulations of magma sometime during the history of the Simcoe volcanics.

There are 4 mineral springs associated with the Simcoes, including Klickitat Mineral Springs (warm spring and wells up to 32 °C), Klickitat Soda Springs (cold), Blockhouse Mineral Springs (cold), and Fish Hatchery Warm Springs (24 °C). Klickitat Mineral Springs has the highest reservoir equilibrium temperature predicted by geothermometers, at about 160 to 170 °C.

Most temperature gradient information for the area comes from water wells on the south side of volcanic field, clustered around the Goldendale area. The gradients range from 30 to 55 °C/km. There are no high-quality data from wells located within the main volcanic province.

The best recognized geothermal targets within the Simcoes are Klickitat Mineral Springs, Fish Hatchery Warm Springs, and the dacite domes near Indian Rock. Intermediate drilling in these areas may be the only means of demonstrating any geothermal potential for these targets beyond that suggested by the presently available information, such as spring chemistry. Temperature gradient drilling in the other portions of the Simcoe volcanic field is needed to characterize the local gradients and heat flow, and possibly find otherwise blind geothermal systems in the region.

Tumac Mountain-White Pass Area: This area forms the Cascade crest east of Mt. Rainier, west of Yakima, and north of the Goat Rocks Wilderness Area. Ownership is primarily National Forest Service. Relatively young volcanic centers occur within the area, surrounded by volcanic products produced during the Pliocene through late Pleistocene. A detailed mapping, geochemical, and petrologic study of the area was conducted by Geoff Clayton from 1978 through 1982 (Clayton, 1982) and is summarized in chapter 9 of this report.

The youngest volcanic center is Tumac Mountain, estimated to be between 40,000 and 10,000 years old. The products are flows and cinders of basaltic-andesite composition. A number of relatively young monogenetic volcanoes consisting of hornblende andesite and dacite may be of greater geothermal significance than Tumac Mountain. This volcanism is estimated to span a period from about 2 million years to 30,000 years B.P., and involves the area from Sugarloaf Mountain near Bumping Lake on the north to Clear Fork on the southwest to Spiral Butte to the east. The long period of volcanism, areal extent, and composition of the hornblende andesites and dacites appear to be generated from a common source (Clayton, 1982, and chapter 9, this report), suggesting that a significant upper crustal magma chamber may underlie the entire area.

Only two shallow temperature gradient holes exist within this area, one at White Pass summit, the other in the Clear Creek valley just south of Spiral Butte. The first produced a temperature gradient of 52 °C/km, with a heat flow of about 90 mW/m^2. The Clear Creek hole produced a gradient of 65 °C/km and a heat flow of about 130 mW/m^2. The only mineralized spring in this area is Summit Creek Soda Springs, a series of springs and seeps which have built up several tufa mounds (Korosec and others, 1981). The chemistry of this spring system suggests that it may arise from a reservoir with an equilibrium temperature of 150 to 155 °C.

Future work in the area should start with further shallow drilling throughout the region. Shallow drilling should be followed up by intermediate depth drilling (600 meters and deeper), in the most promising areas, especially near Spiral Butte, the youngest hornblende andesite-dacite volcanic center. Additional work should also be designed to help interpret the complex structural nature of the area suggested by the surficial geology, including close-spacing gravity surveys, seismic profiling (where terrain and access permit) and possibly resistivity work (targeted around the volcanic centers and major faults).

Columbia Basin, Yakima Valley, and Walla Walla Valley: From numerous temperature gradient measurements for wells throughout the Columbia Basin province, several areas have been identified where above average gradients occur, resulting in warm aquifers at relatively shallow depth. The best areas are discussed in chapter 7 of this report, and are identified on maps in figures 7-1 and 7-2. They include the Yakima-Ahtanum-Simcoe areas, Moses Lake-Ritzville-Connell region, portions of Lincoln and Douglas Counties, Horse Heaven Hills, lower Yakima Valley, the Walla Walla Valley, and several other smaller anomalous areas.

In the Yakima area, a detailed, statistically oriented study focussed on the variations in temperature gradients and aquifer characteristics for the individual basins and valleys in the area (Biggane 1981, 1982, and chapter 7, this report). A similar study is in progress for the Moses Lake-Ritzville-Connell region. These studies have shown that significant variations exist within the broad anomalous areas, identified in earlier studies. In addition, they have shown that individual warm aquifers may be somewhat limited in extent.

The best areas around Yakima include the city proper, Moxee Valley to the east, and the Yakima River Valley to the north and to the south of the city. Gradients are generally in the 45 to 60 °C/km range. Many irrigation and domestic wells produce 20 to 35 °C water from depths generally less than 400 to 500 meters.

Within the central and eastern portions of the Columbia Basin, several pockets of very high temperature-gradient wells occur. Near Moses Lake, gradients range from 45 to 60 °C/km. North of Ritzville, anomalous gradients range from 50 to 65 °C/km. A broad anomalous area extends northeast, east, and southeast from Connell, extending over 70 km to the east, with gradients ranging from 55 to 60 °C/km, but the density of coverage within this area is low.

In Lincoln County, an area which extends 50 km west from Davenport contains many wells with good quality gradients ranging from 50 to 60 °C/km. Most of the wells are less than 250 meters deep, and very little information is available on the temperature and production of the aquifers within the anomaly. The same could be said of the anomaly in Douglas County, where only a few wells suggest above normal gradients.

In the Horse Heaven Hills in eastern Klickitat and southern Benton Counties, wells produce warm irrigation water from relatively shallow depths. The gradients range from 45 to 55 °C/km.

In the lower Yakima Valley area, from about Union Gap south to Prosser, several wells have gradients of 50 to 55 °C/km, but there are a number of cooler wells interspersed, Concentrations of warm wells or high temperature gradient wells occur west of Mabton and northeast of Sunnyside.

In the Walla Walla River Valley, temperature gradients range from 45 to 55 °C/km, and higher. In the Lowden-Touchet area, several wells produce gradients greater than 70 °C/km. Because of the relatively high gradients in the area, and the deep depths of many of the wells, water temperatures of 30 to 40 °C are common.

In summary, the collection of downhole temperature gradient information for the Columbia Basin, and the contouring of the data on maps, has lead to the identification of specific areas of anomalous temperature-gradients. However, for most of these areas, very little is known about the number, characteristics, and extent of the aquifers encountered by these wells. Many high gradient wells may be "dry holes". Studies similar to the Yakima area project (Biggane, 1982) and the current work in the Moses Lake-Ritzville-Connell area should be carried out in all of the anomalous areas before proceeding with development plans. At the very least, well-production temperature information should be collected, to identify existing wells which could be used for low temperature geothermal applications right away. In addition, the continued collection of downhole temperature information in new wells and previously unmeasured wells will better define the extent of the identified anomalies, and perhaps locate new anomalies in areas of poor coverage.

References

Begct, J. E., 1982, Postglacial volcanic deposits at Glacier Peak, Washington, and potential hazards from future eruptions: U.S. Geological Survey Open-File Report 82-830, 77 p.

Berri, D. A., 1983, Geological and geothermal investigations of the lower Wind River valley, southern Cascade Range, Washington: Washington Division of Geology and Earth Resources Open-File Report (in preparation).

Biggane, J. H., 1981, The low temperature geothermal resource of the Yakima region–A preliminary report: Washington Division of Geology and Earth Resources Open-File Report 81-7, 70 p., 3 plates.

Biggane, J. H., 1982, The low temperature geothermal resource and stratigraphy of portions of Yakima County, Washington: Washington State University M.S. thesis, 126 p., 11 tables, 4 plates, 58 figures.

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

Clayton, G. A., 1982, Geology of the White Pass area, Washington: University of Washington M.S. thesis, 190 p., 1 map, scale 1:24,000.

Danes, Z. F.; Phillips, W. G., 1983, Complete bouguer anomaly map, Cascade Mountains, Washington: Washington Division of Geology and Earth Resources Geophysical Map GM-27, 2 sheets, scale 1:250,000.

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

Friedman, J. D.; Frank, David, 1980, Infrared surveys, radient flux, and total heat discharge at Mount Baker Volcano, Washington, between 1970 and 1975: U.S. Geological Survey Professional Paper 1022-D, 33 p.

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° 22.5W: Portland State University Department of Earth Sciences, 31 p., 2 sheets, scale 1:125,000.

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

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

Korosec, M. A.; Schuster, J. E.; with Blackwell, D. D.; Danes, Z. F.; Clayton, G. A.; Rigby, F. A.; and McEuen, R. B., 1981, The 1979-1980 geothermal resource assessment program in Washington: Washington Division of Geology and Earth Resources Open-File Report 81-3, 270 p., 1 map, scale 1:24,000.

McKeever, Douglas, 1977, Volcanology and geochemistry of the south flank of Mount Baker, Cascade Range, Washington: Western Washington State College M.S. thesis, 126 p.

Moen, W. S., 1969, Mines and mineral deposits of Whatcom County, Washington: Washington Division of Mines and Geology Bulletin 57, 134 p., plate 1.

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 Inforamtion Circular 62, 56 p.

Shannon and Wilson, 1973, Geologic studies of Columbia River Basalt structures and age of deformation, The Dalles-Umatilla region, Washington and Oregon, Boardman Nuclear Project: Report to Portland General Electric Company from Shannon and Wilson, Inc., unpublished.

Sheppard, R. A., 1960, Petrology of the Simcoe Mountains area, Washington: Johns Hopkins University Ph. D. thesis, 153 p.

Sheppard, R. A., 1964, Geologic maps of the Husum Quadrangle, Washington: U.S. Geological Survey Mineral Investigation Field Studies Map MF-280.

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.

Swan, V. L., 1980, The petrogenesis of the Mount Baker volcanics, Washington: Washington State University Ph. D. thesis, 630 p.

Tabor, R. W.; Crowder, D. F., 1968, Batholiths and volcanics in north Cascades, Washington--History of Glacier Peak volcano: Geological Society of America Special Paper 115, p. 354.

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, 258 p.

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

12. ADDITIONS TO THE BIBLIOGRAPHY OF GEOTHERMAL RESOURCE INFORMATION FOR THE STATE OF WASHINGTON

by

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In the previous geothermal resource assessment program report (Korosec, et al, 1981), a bibliography was presented which included all known references concerning both general and site-specific geothermal studies for the State of Washington. Since the compilation of that bibliography in 1980, several new studies have been published. The following list of references is presented as an update to the geothermal bibliography.

Biggane, J. H., 1982, The low temperature geothermal resource and stratigraphy of portions of Yakima County, Washington: Washington State University M.S. thesis, 126 p., 11 tables, 4 plates, 58 figures.

Biggane, J. H., 1981, The low temperature geothermal resource of the Yakima region--A preliminary report: Washington Division of Geology and Earth Resources Open-File Report 81-7, 70 p., 3 plates.

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

Blackwell, D. D.; Steele, J. L.; Schuster, J. E.; Korosec, M. A., 1980, The regional thermal setting of the Mount St. Helens volcano abstract: EOS (American Geophysical Union, Transactions), v. 61, no. 46, p. 1132.

Bloomquist, R. G., 1980, Washington State Geothermal leasing status, January 1981: Washington Division of Geology and Earth Resources Open-File Report 80-10, 5 sheets.

Bloomquist, R. G., ed., 1981, Proceedings of the Geothermal Symposium; low temperature utilization, heat pump applications, district heating: Washington State Energy Office WAOENG 81-05, 1 vol.

Bloomquist, R. G., 1981, Geothermal energy policy in Washington--An overview. In Geothermal potential of the Cascade Mountain Range--Exploration and development: Geothermal Resources Council Special Report No. 10, p. 65-67.

Bloomquist, R. G.; Basescu, Neil; Higbee, Charles; Justus, Debra, and Simpson, S. J., 1980, Washington; A guide to geothermal energy development: Oregon Institute of Technology, 1 vol.

Bloomquist, R. G.; Wonstolen, Ken, eds., 1980, Proceedings of the Geothermal Symposium; potential, legal issues, economics, financing, June 2, 1980, Seattle, Washington: Washington State Energy Office WAOENG 80-16.

Brown, J. C., 1980, Stratigraphy and ground-water hydrology of selected areas, Columbia Plateau, Washington: Washington State University College of Engineering Research Report 80/15-39, 52 p., 1 plate.

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

Clayton, G. A., 1982, Pliocene and Pleistocene volcanism in the White Pass area, south Cascade Range, Washington, and its implications for models of subduction beneath the southern Washington Cascades, EOS, v. 63, no. 8, p. 175.

Clayton, G. A., 1982, Geology of the White Pass area, Washington: University of Washington M.S. thesis, 190 p., 1 map, scale 1:24,000.

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.

Danes, Z. F., 1981, Preliminary Bouguer gravity map, southern Cascade Mountains area, Washington: Washington Division of Geology and Earth Resources Open-File Report 81-4, scale 1:250,000.

Jhaveri, A. G., and Miller, J. A., 1980, Geothermal resources in the Yakima area--Potential low temperature utilization. In Bloomquist, R. G., ed., Utilization, heat pump applications, district heating: Washington State Energy Office WAOENG-81-05, Section XII.

Kent Associates, 1981, Geothermal Exploration Project--Phase I, temperature gradient drilling: prepared for the City of North Bonneville, Washington: Kent Associates [Lake Oswego ,]1 vol.

Kent, R. C., 1982, Thermal water encountered in lava flows at North Bonneville, Washington: EOS, v. 63, no. 8, p. 174.

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., 1980, Table of thermal and mineral spring locations in Washington: Washington Division of Geology and Earth Resources Open-File Report 80-11, 6 p.

Korosec, M. A., 1982, Table of chemical analyses for thermal and mineral spring and well waters collected in 1980 and 1981: Washington Division of Geology and Earth Resources Open-File Report 82-3, 5 p.

Korosec, M. A.; Kaler, K. L., 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, K. L.; Schuster, J. E.; Bloomquist, R. G.; Simpson, S. J., 1981, 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. G., 1980, Quaternary volcanics in the State of Washington: Washington Division of Geology and Earth Resources Open-File Report 80-6, scale 1-500,000.

Korosec, M. A.; Phillips, W. M., 1982, WELLTHERM: Temperature, depth, and geothermal gradient data for wells in Washington State: Washington Division of Geology and Earth Resources Open-File Report 82-2, 3 sheets, 1 table.

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

Korosec, M. A.; Schuster, J. E., 1980, The 1979-1980 geothermal resource assessment program in Washington: Washington Division of Geology and Earth Resources Open-File Report 81-3, 148 p., 4 appendices, 1 map, scale 1:24,000.

Lipman, P. W.; Mullineaux, D. R., 1981, The 1980 eruption of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, 844 p.

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.

McLucas, G. B., 1981, Detailed fault maps; Hoquiam, Vancouver, Yakima, and The Dalles quadrangles: Washington Division of Geology and Earth Resources Open-File Report 81-1, 5 sheets.

McLucas, G. B., 1981, Lineament and fault maps of the south Cascades, Washington: Washington Division of Geology and Earth Resources Open-File Report 81-2, 6 sheets, scale 1:100,000.

Schuster, J. E., 1980, Geothermal energy potential of the Yakima Valley area, Washington. In Bloomquist, R. G., ed., 1980, Proceedings of the Geothermal Symposium; low temperature utilization, heat pump applications, district heating: Washington State Energy Office WAOENG 81-05, Section XI.

Schuster, J. E., 1981, A geothermal exploration philosophy for Mount St. Helens (and other Cascade volcanoes?). In Ruscetta, C. A.; Foley, Duncan, eds., 1981, Geothermal direct heat program, Glenwood Springs Technical Conference proceedings; Volume I, Papers presented, State coupled geothermal resource assessment program: University of Utah Research Institute Earth Science Laboratory ESL-59 and DOE/ID/12079-39, p. 297-300.

Schuster, J. E.; Korosec, M. A., 1980, The Washington State geothermal resources assessment program of the Department of Natural Resources, Division of Geology and Earth Resources. In Bloomquist, R. G., ed., 1980, Proceedings of the Geothermal Symposium; potential, legal issues, economics, financing, June 2, 1980, Seattle, Washington: Washington State Energy Office WAOENG 80-16, Section III.

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.

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

U.S. Geological Survey, 1981, Aeromagnetic map of the Mt. Margaret area, Washington: U.S. Geological Survey Open-File Report 81-926, 1 sheet, scale 1:62,500.

U.S.. Geological Survey, 1981, Aeromagnetic map of the Indian Heaven area, Washington: U.S. Geological Survey Open-File Report 81-928, 1 sheet, scale 1:62,500.

U.S. Geological Survey, 1981, Aeromagnetic map of the Mt. Adams area, Washington: U.S. Geological Survey Open-File Report 81-929, 1 sheet, scale 1:62,500.

U.S. Geological Survey, 1981, Aeromagnetic map of the Mt. St. Helens area, Washington: U.S. Geological Survey Open-File Report 81-932, 1 sheet, scale 1:62,500.

Youngquist, W., 1980, Pacific Northwest Geothermal: Geothermal Energy, v. 8, no. 10 & 11, p. 3-11.

Youngquist, W., 1981, Geothermal potential of the Cascades. In Geothermal potential of the Cascade Mountain Range--Exploration and development: Geothermal Resources Council Special Report No. 10, Davis, California, p. 25-29.

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