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SUMMARY OF GEOTHERMAL EXPLORATION ACTIVITY IN THE STATE OF WASHINGTON FROM 1978 TO 1983

Final Report

By
Michael A. Korosec

January 1984

Work Performed Under Contract No. AC07-79ET27014

State of Washington
Department of Natural Resources
Olympia, Washington

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SUMMARY OF GEOTHERMAL EXPLORATION ACTIVITY IN THE STATE OF WASHINGTON FROM 1978 TO 1983

by

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

Open File Report 84-2

Prepared under U.S. Department of Energy
Contract No. DE-AC07-79ET27014
for Assessment of Geothermal Resources in Washington

January 1984

STATE OF WASHINGTON
DEPARTMENT OF NATURAL RESOURCES
BRIAN J. BOYLE, Commissioner of Public Lands
ART STEARNS, Department Supervisor

DIVISION OF GEOLOGY AND EARTH RESOURCES
Raymond Lasmanis, State Geologist

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INTRODUCTION

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 been released as a Division Open File Report, OFR 81-3 (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 OFR 83-7 (Korosec and others, 1983). Only one other summary report dealing with geothermal resource investigations in the state has been published to date. An Information Circular released by the Division, I.C. 62, (Schuster and others, 1978) compiled the geology, geochemistry, and heat flow drilling results from a project in the Indian Heaven area of the south Cascades.

The progress report for the geothermal program, covering the period up to mid-1980, Open File Report 81-3 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, Geologic Map GM-25, (Korosec, Kaler, and others, 1981). The map is principally a non-technical presentation based on all available geothermal information, presented as data points, tables, and text on a map with a scale of 1:500,000.

The progress report covering the period from mid-1980 through the end of 1982, Open File Report 83-7 presented: chemical analyses for thermal and mineral springs, including available U.S. Geological Survey data; discussions of the regional gravity work conducted in the Cascade Range; results of the heat flow drilling program carried out during 1982; a discussion of the low temperature geothermal resources of the Columbia Basin and surrounding regions of eastern Washington; a progress report for the time-space-composition modeling project for south Cascades Quaternary volcanics; a summary of the findings for the White Pass-Tumac Mountain-Bumping Lake area geologic mapping project; a synopsis of the geohydrologic studies and modeling of the thermal aquifers in the Yakima Valley area; and a summary report on progress and proposals for the state's most significant geothermal resource targets. Since the release of the 1980-1982 progress report, several additional projects have been completed. The results of these projects are available as open file reports, as described below.

The results of the 1983 temperature gradient and heat flow drilling project are discussed in Open File Report 83-12. The two areas examined were the Green River Soda Springs near Mount St. Helens, and the Mount Baker area.

Open File Report 83-10 consists of a soil mercury project report prepared by two geology students who conducted the work as part of the Department of Natural Resources' intern program. The studies were concentrated in the Green River Soda Springs and Marble Mountain areas just beyond the boundaries of the Mount St. Helens National Volcanic Monument.

Geologic mapping for the Wind River area by Dulcy Berri, a subcontractor to the Division, is presented in Open File Report 83-5. A discussion of the geothermal potential of this portion of the Columbia River Gorge is included.

Open File Report 83-11 consists of a geohydrologic study of the thermal aquifers in the Moses Lake-Ritzville-Connell area of the Columbia Basin. The work was carried out by Scott Widness, a graduate student at Washington State University.

Open File Report 83-13 presents geochemical analyses, age dates, and flow estimates for Quaternary volcanic rocks of the southern Cascade Range of Washington. The work was carried out by Dr. Paul Hammond, Portland State University, through a subcontract.

Open file Report 84-1 presents the results of chemical analyses of thermal and mineral springs investigated in 1982-1983. A table of spring geochemistry from the U.S. Geological Survey (not previously reported in other Division progress reports) has been included.

The present report is meant to serve as (1) a summary of project activity, with references to the publications produced, and (2) a summary of the project findings, as they relate to specific geothermal resource target areas. It is recommended that the individual project open file reports and the "annual" program summary open file reports be consulted for details on study area, methods, and specific findings.

PART 1. - SUMMARY OF PROJECTS AND PRODUCTS FOR THE GEOTHERMAL PROGRAM IN THE STATE OF WASHINGTON 1978-1983

During the course of the geothermal program, many different projects were conducted by personnel of the Division of Geology and Earth Resources and by subcontractors working for the division. In the following sections (A and B), brief descriptions of these projects and the publications which have been produced are discussed. Both progress reports and final reports are included, consisting of open file reports (OFR), geologic maps (GM), and university theses. Section C lists the publications which serve as data sets, arranged by major topic. Full references for the reports are presented in Section D, the list of publications.

A. Major Projects of the Geothermal Exploration Program

Thermal and Mineral Spring Chemistry

During the geothermal assessment program, most of the state's known thermal and mineral springs were sampled and analyzed by the division. Major and significant minor anion and cation concentrations were measured and used with various geothermometers to estimate reservoir equilibrium temperatures.

Open File Report (OFR) 80-11 was an early compilation of thermal and mineral spring locations, including information on temperature and conductivity. In Chapter 4 of OFR 81-3, chemical analyses and several site-specific descriptions were presented for springs examined from 1978 through 1980. Chapter 3 of OFR 83-7 serves as a compilation of all available information on thermal and mineral springs up to 1983, including locations, geochemistry (from the Division as well as the U.S. Geological Survey), geothermometers, and several site-specific descriptions. OFR 84-1 presents geochemical analyses for springs examined and analyzed by the Division in 1983. Additional geochemical data from the U.S. Geological Survey are also presented in OFR 84-1.

Heat Flow Drilling

A major portion of the Geothermal Exploration Program has been the drilling of 500 foot temperature-gradient and heat-flow holes within regions and areas where down-hole information had not been previously available.

The first heat flow drilling project was part of a 1975-1976 National Science Foundation-sponsored program to explore the Indian Heaven Quaternary volcanic region of the southern Cascades. Results were presented in Information Circular 62, "Heat Flow Studies in the Steamboat Mountain-Lemei Rock area, Skamania County, Washington".

During the Summer and Fall of 1979, 11 holes were drilled, primarily in the southern Cascades. Sites include Longmire, Randle, Packwood, Ohanapecosh, White Pass, Mount St. Helens (3 sites), and Camas (2 sites). Chapter 4 of OFR 81-3 presents the locations, temperature gradients and heat flow values for these holes.

During the Summer of 1981, 11 temperature gradient heat flow holes were completed, including the sites at Scenic (2 sites near Scenic Hot Springs, Stevens Pass area), Snoqualmie Pass (2 sites), White River, Clear Creek and Sand Ridge (east of White Pass), Tieton, Wind River, Trout Creek Hill, and Klickitat. Locations and results were presented in OFR 81-8 and Chapter 6 of OFR 83-7.

Three temperature gradient heat-flow holes were drilled during the summer of 1983, including one near the Green River Soda Springs northwest of Mount St. Helens, and two holes in the Mount Baker area. The locations and results for these holes are presented in OFR 83-12.

Temperature Gradient Measurements

Besides measuring temperature gradients for the 500-foot holes drilled for heat flow studies, the division measured numerous temperature gradients in existing wells. Most of the wells are located within the Columbia Basin and around its perimeter. Locations and bottom-hole temperatures for many of these wells were shown on the 1981 Geothermal Resource Map of Washington, GM-25. A collection of the best quality gradients up to 1981 are listed and plotted in OFR 80-9. All temperature-gradient information collected from wells since the program began up to 1983 are listed in a computer file called WELLTHERM which is available as a printout in OFR 82-2. Results of the gradient measuring projects are discussed in OFR 82-1 and Chapter 7 of OFR 83-7. Additional gradient information is presented in reports generated by two area-specific hydrologic studies, including OFR 81-7, OFR 82-6, Chapter 10 of OFR 83-7, and the John Biggane thesis for the Yakima area; and OFR 83-11 and the Scott Widness thesis for the Moses Lake-Ritzville-Connell area.

Cascade Range Regional Gravity

The Division supported gravity studies of the north and south Cascade Mountains province through subcontracts with Z. F. Danes of the University of Puget Sound and Danes Research Associates, Tacoma, Washington. The purpose of the work was to gather baseline gravity data for contribution to geothermal resource evaluation, with a goal of achieving a gravity station density of about one gravity station per 5 mi^2.

Information collected as part of the regional gravity survey has been presented in four publications. The principal facts for all of the gravity stations and a discussion of terrain correction methods were released as OFR 83-1. Contoured Bouguer gravity anomaly maps for the north and south sections of the Cascades were published as GM-27 at a scale of 1:250,000. In Chapters 4 and 5 of OFR 83-7, W. M. Phillips described the reductions used to produce the maps, and presented preliminary interpretations of the gravity trends and anomalies. D. Dishberger prepared residual gravity maps for the southern Cascade Mountains using Fourier analysis in OFR 83-4.

Geohydrology Study of the Yakima Area

The geohydrology of the low temperature geothermal resources of the Yakima area was studied by John Biggane of Washington State University. This thesis project was funded by the Division through a subcontract with Biggane. A preliminary report was released as OFR 81-7. Biggane's thesis, "The low temperature geothermal resources and stratigraphy of portions of Yakima County, Washington" was released by Washington State University in 1982. This same publication was released by the Division as OFR 82-6, and a condensed version of this study was presented in Chapter 10 of OFR 83-7. The computer-processed geophysical logs for the area, collected by Washington State University over the past decade, were released as OFR 83-2.

Low Temperature Geothermal Resources of the Moses Lake-Ritzville-Connell Area:

Geohydrologic studies of the Moses Lake-Ritzville-Connell area of the Columbia Basin were carried out by Scott Widness, a graduate student at Washington State University (WSU). The work was supported by the Division through a subcontract.

The first publications dealing with the resources of this region were the geothermal map GM-25 and a report on the potential low temperature geothermal resources throughout the Columbia Basin (OFR 82-1 and Chapter 7 of OFR 83-7). The area-specific project conducted by Scott Widness was summarized in OFR 83-11. The thesis produced for this project is scheduled for release in early 1984. Computer-processed geophysical logs collected by WSU and used in Widness' studies are found in OFR 83-14 and OFR 83-15.

Geology of the White Pass-Tumac Mountain-Bumping Lake Region

The White Pass-Tumac Mountain geologic mapping project was begun in 1978 and expanded to include Bumping Lake to the north and Goat Rocks to the south. Work was carried out by Geoff. Clayton, a graduate student at the University of Washington, and supported by the Division through a subcontract.

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.

A preliminary progress report was presented in Chapter 6 of OFR 81-3. The preliminary map was made available as OFR 80-8, at a scale of 1:24,000. The final report and map comprise a Master of Science thesis at the University of Washington entitled, "Geology of the White Pass Area, South-Central Cascade Range, Washington". Sections of the thesis dealing with Pliocene to Recent volcanic activity and distribution of volcanic centers and products in the area were compiled in Chapter 9 of OFR 83-7.

Wind River Geology

Dulcy Berri, Portland State University, was subcontracted by the Division to map the geology of the lower Wind River drainage and surrounding ridges, from Trout Creek Hill south to the Columbia River Gorge. The results were presented in OFR 83-5. The report includes a map at a scale of 1:24,000, cross sections, petrochemical data, age dates, and a discussion of the geothermal potential of the area.

Geochemistry of Southern Cascade Mountains Quaternary Volcanic Rocks

A geologic and geochemical investigation of the Quaternary volcanic rocks of the southern Cascades was carried out by Paul Hammond, Portland State University, through a subcontract with the Division. The study area extended from the Columbia River north to the Cowlitz River and Goat Rocks Wilderness Area, and from the Klickitat River west to about longitude 122° W. Whole-rock chemical analyses, selected trace element geochemistry, volume approximations, specific gravity determinations, and locations were determined for 103 samples. Radiometric dates were determined for 21 of the basalt and basaltic andesite flows.

Preliminary progress was reported in Chapter 8 of OFR 83-7. Tables of age dates, geochemical data, and volumes, along with a location map, are presented in OFR 83-13.

Soil Mercury Studies

Soil mercury surveys were conducted by two interns working for the Division, Jenny Holmes and Kathleen Waugh. The areas covered were the Green River Soda Springs region northwest of Mount St. Helens, and the Marble Mountain region southeast of Mount St. Helens. The results of their studies, including two maps and a detailed description of the project, are presented in OFR 83-10.

B. Additional Projects

The following reports were completed for projects conducted during earlier years of the geothermal program.

a. Resistivity of the Camas, Washington area: Appendix C of OFR 81-3.

b. Geothermal investigations in the Camas area: Chapter 7 of OFR 81-3.

c. Area-specific studies at Mount St. Helens: Chapter 8 of OFR 81-3.

d. Fault map of Washington: OFR 80-2 and OFR 81-1.

C. Data Sets

Compilations of data generated or collected by the geothermal program over the past five years have been released in several separate publications, many of which have already been mentioned.

a. Gravity: Principal facts for Cascade gravity are listed in OFR 83-1.

b. Temperature Gradients: All good quality temperature gradients up to 1981 are listed and plotted in OFR 80-9. Information collected since then, along with the older data, are listed in a computer file called WELLTHERM (an updated version of OFR 82-2). GM-25, OFR 83-2, OFR 83-14, and OFR 83-15, also include temperature gradient information.

c. Heat Flow Drilling: Results of the various heat flow drilling projects are presented in Chapter 3 of OFR 81-3, OFR 81-8, Chapter 6 of OFR 83-7, and OFR 83-12. All of the information has been drawn together in a report being prepared by David D. Blackwell of Southern Methodist University for the U.S. Department of Energy Geothermal Program, under separate contract, and will be available through the Division.

d. Spring and Well Geochemistry: Chapter 3 of OFR 83-7 and OFR 84-1 contain several tables which present all available data for thermal and mineral springs in Washington.

e. Petrochemistry: Petrochemical data for Cascade Quaternary volcanic rocks are presented in a thesis by Geoff. Clayton for the White Pass-Tumac Mountain Plateau area, and in OFR 83-13 for the south Cascades.

f. Geophysical Well Logs: Well logs are only available for the Columbia Basin area and have been released as OFR 83-2, OFR 83-14, and OFR 83-15.

g. Soil Mercury Values: All soil mercury values collected in the southern Cascade region are presented in OFR 83-10. They are restricted to the specific areas studied around Green River Soda Springs and Marble Mountain.

h. Bibliography: A bibliography of geothermal reports and articles for the State of Washington is presented in OFR 80-4 and Chapter 12 of OFR 83-7.

D. LIST OF PUBLICATIONS

Open File
Report

80-4 Korosec, Michael A., 1980, Bibliography of geothermal resources information for the State of Washington: Washington Division of Geology and Earth Resources Open-File Report 80-4, 17 p. (NOTE: Also released as OFR 81-3, Chapter IX.)

80-8 Clayton, Geoff., 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. (NOTE: Also released as OFR 81-3, Appendix B.)

80-9 Blackwell, David 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.

80-11 Korosec, Michael 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. (NOTE: Also released as OFR 81-3, Table 4.1).

81-3 Korosec, Michael A.; Schuster, J. Eric, with Blackwell, David D.; Danes, Z. Frank; Clayton, Geoffrey 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.

81-7 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 pages, 3 plates.

81-8 Schuster, J. Eric; Korosec, Michael 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 pages.

82-1 Korosec, Michael A.; Phillips, William M.; Schuster, J. Eric, 1982, The low temperature geothermal resources of eastern Washington: Washington Division of Geology and Earth Resources Open File Report 82-1, 20 pages, 2 figures, 1 table, 1 appendix.

82-2 Korosec, Michael A.; Phillips, William 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.

82-3 Korosec, Michael 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 pages.

Open File
Report

82-6 Biggane, John, 1982, The low-temperature geothermal resource and stratigraphy of portions of Yakima County, Washington: Washington Division of Geology and Earth Resources Open File Report 82-6, 136 p., 58 figures, 4 plates, 11 tables.

83-1 Danes, Z. F.; Phillips, W. M., 1983, 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.

83-2 Biggane, John, 1983, Geophysical logs from water wells in the Yakima area, Washington: Washington Division of Geology and Earth Resources Open File Report 83-2, 53 p.

83-4 Dishberger, Debra M., 1983, Preparation of residual gravity maps for the southern Cascade Mountains, Washington, using Fourier analysis: Washington Division of Geology and Earth Resources Open File Report 83-4, 11 pages, 2 appendices.

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

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

83-10 Holmes, Jenny; Waugh, Kathleen, 1983, Targeting geothermal exploration sites in the Mount St. Helens area using soil mercury surveys: Washington Division of Geology and Earth Resources Open File Report 83-10, 13 pages, 3 appendices.

83-11 Widness, Scott, 1983, Low temperature geothermal resource evaluation of the Moses Lake-Ritzville-Connell area, Washington: Washington Division of Geology and Earth Resources Open File Report 83-11, 28 p.

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

83-13 Hammond, Paul E.; Korosec, Michael A., 1983, Geochemical analyses, age dates, and flow-volume estimates for Quaternary volcanic rocks, Southern Cascade Mountains, Washington: Washington Division of Geology and Earth Resources Open File Report 83-13, 36 pages, 1 map.

List of Publications (Cont'd)

Open File
Report

83-14 Stoffel, Keith L.; Widness, Scott, 1983, Geophysical logs of selected wells in Eastern Washington: Washington Division of Geology and Earth Resources Open File Report 83-14, 83 pages.

83-15 Stoffel, Keith L.; Widness, Scott, 1983, Fluid-temperature logs for selected wells in Eastern Washington: Washington Division of Geology and Earth Resources Open File Report 83-15, 353 pages.

84-1 Korosec, M. A., Chemical analyses for thermal and mineral springs examined in 1982-1983: Washington Division of Geology and Earth Resources Open File Report 84-1, 9 pages.

Geologic Maps

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

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

Information
Circular

IC-62 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.

Thesis Biggane, John, 1982, The low-temperature geothermal resource and stratigraphy of portions of Yakima County, Washington: Washington State University Master of Science thesis, 126 p., 4 plates.

Thesis Clayton, G. A., 1983, Geology of the White Pass area, south-central Cascade Range, Washington: University of Washington Master of Science thesis, 212 p., 1 plate.

Thesis Widness, Scott, 1984, Low temperature geothermal resource evaluation of the Moses Lake-Ritzville-Connell area, Washington: Washington State University Master of Science thesis (In preparation).

Part 2. Summary of Progress and Proposals for Washington's Geothermal Resource Targets

Introduction

During the course of conducting the statewide 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 three years, the program has continued to identify new sites, but has concentrated on better defining the resource potential of the best areas. Figure 1 shows the locations of these geothermal areas, and Table 1 presents the level of 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 earlier reports, especially Korosec and others, 1981 and Korosec and others, 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 1. Geothermal Resources of Washington

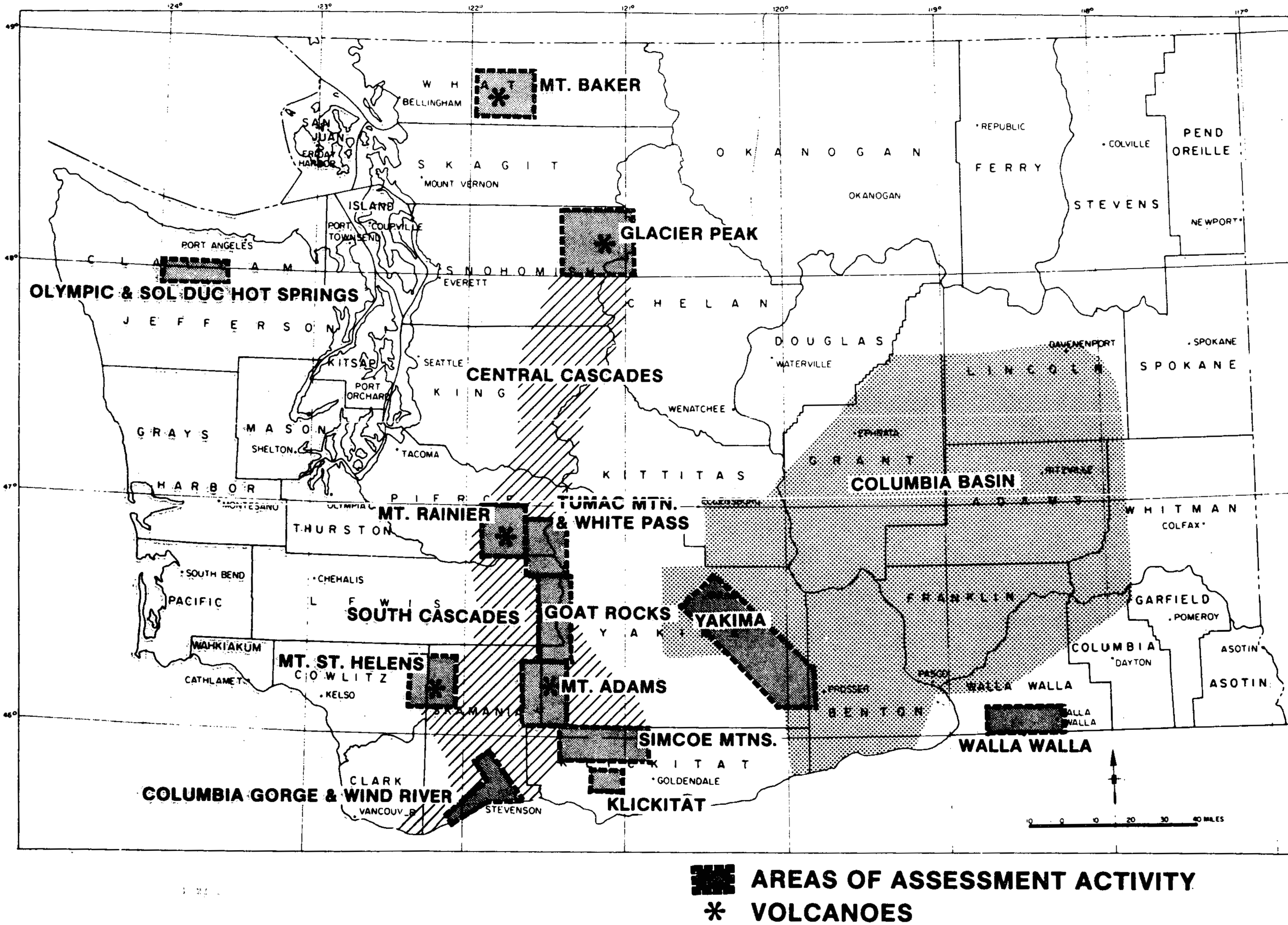

Table 1.
STATUS OF GEOTHERMAL ENERGY ASSESSMENT IN WASHINGTON
6/83

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

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 information void 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 a primarily 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 originate 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 circulation. 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 mudflow 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 has been designated a National Forest 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). There has been some activity within the last 150 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 part of the cone.

The best detailed geologic mapping for the area is provided by McKeever (1977) (south flank only), Blackwell (1983) (region beyond the south and east flanks), 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.

A 140-meter-deep heat-flow hole was drilled about 1/4 km to the southwest of Baker Hot Springs in August, 1983. Hot water similar to the hot spring was encountered, and a bottom hole temperature of 48°C was measured. Two temperature gradients were observed; 200°C/Km in the upper portion of the hole, and 100°C/Km in the lower 1/3 of the hole.

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 Holocene time, younger than about 10,000 years, but older than the 6,700 year old Mazama ash which lies on the surface of some of the distal 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 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 through 1983, 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. It is expected that the information will be released in the near future.

Only one temperature-gradient hole is available for the Mount Baker area, located near the Baker Hot Springs. As such, the drilling of several intermediate depth temperature-gradient/heat-flow holes around the flanks of Mount Baker, especially in the Schrieber's Meadow area, and the region west of Baker Hot Springs, 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 Korosec and others, 1983, for additional information on these springs.

Garland Mineral Spring has a chemistry which suggests a high reservoir equilibrium temperature of 165 to 190°C. It flows from river alluvium and glacial debris in a valley cut through Miocene granite and granodiorite and pre-Tertiary metamorphic rocks. A north-south trending fault thought to be a part of the Straight Creek Fault system has been projected across the valley at Garland (Tabor and others, 1982). The closest Quaternary volcanic centers are the White Chuck and Indian Pass cinder cones about 21 km to the northeast, and Glacier Peak, about 30 km to the northeast. 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 consists 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 is discussed separately in this chapter.

Most of the young volcanics in the South Cascades are monogenetic basalt and basaltic-andesite 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 years old, 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°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 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 east to about the Little White Salmon River, 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. 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, Chapter 4), Rock Creek Hot Springs (35°C) 4.5 km northwest of Stevenson (see Korosec and others, 1983, chapter 3), (St. Martins (Carson) (54°C) and Shipherds Hot Springs (45°C) on the Wind River near its mouth (see Korosec and others, 1983, chapter 3), and Collins Hot Springs, near the base of Wind Mountain. Due to the raising of the water level 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 trending 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 Korosec and others, 1983, chapters 3 and 6), produced a gradient of 366°C/km. A well drilled by a nearby property owner 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 Korosec and others, 1983, chapter 3). 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 Korosec and others, 1983, chapter 6).

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 stratovolcano. 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 Korosec and others (1983, chapter 9) and Clayton (1983).

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 temperature-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. Intermediate 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 andesitic to dacite stratovolcano was a prime target due to a combination of factors, including the young age of the mountain, historic reports of activity during the 19th century, fumarolic activity on its upper flanks, accessibility, 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 suggests 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 belongs both to the state and to 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 an obvious 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.

A 140 meter deep temperature-gradient hole was drilled about 1/2 km east of the Green River Soda Springs in July, 1983. High salinity, bicarbonate, artesian water with a temperature of 14°C and a conductivity of 5,500 umhos/cm (significantly higher than the soda springs) was encountered. A relatively straight-line gradient of 50°C/km was measured in the lower 3/4 of the hole. Work which should be carried out at this prospect includes detailed geological mapping, resistivity surveys, 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 at 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.

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 occurrence 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 (see Korosec and others, 1983, chapter 3).

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. A temperature-gradient hole drilled near the Klickitat Mineral Springs in 1981 gave a gradient of 56°C/km and a heat flow of 78 mW/m^2.

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 U.S. 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 Korosec and others (1983).

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 duration of volcanism, areal extent, and composition of the hornblende andesites and dacites(which appear to be generated from a common source), suggest 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, and high temperature-gradient areas).

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 Korosec and others, (1983). 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 focused on the variations in temperature gradients and aquifer characteristics for the individual basins and valleys in the area (Biggane, 1981, 1982, and Korosec and others, 1983, chapter 7). 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. This region and its low-temperature geothermal potential are treated in greater detail by Widness (1983, 1984).

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 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 work in the Moses Lake-Ritzville-Connell area (Widness, 1983, 1984) should be carried out in all of the anomalous areas before proceeding with development plans. At the very least, well production and 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.

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