STATE OF OREGON
Department of Geology and Mineral Industries
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FINAL TECHNICAL REPORT

OREGON LOW TEMPERATURE RESOURCE ASSESSMENT PROGRAM

By

George R. Priest, Gerald L. Black, and Neil M. Woller

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ABSTRACT

Numerous low-temperature hydrothermal systems are available for exploitation throughout the Cascades and eastern Oregon. All of these areas have heat flow significantly higher than crustal averages and many thermal aquifers. In northeastern Oregon low temperature geothermal resources are controlled by regional stratigraphic aquifers of the Columbia River Basalt Group at shallow depths and possibly by faults at greater depths. In southeastern Oregon most hydrothermal systems are of higher temperature than those of northeastern Oregon and are controlled by high-angle fault zones and layered volcanic aquifers. The Cascades have very high heat flow but few large population centers. Direct use potential in the Cascades is therefore limited, except possibly in the cities of Oakridge and Ashland, where load may be great enough to stimulate development. Absence of large population centers also inhibits initial low temperature geothermal development in eastern Oregon. It may be that uses for the abundant low temperature geothermal resources of the state will have to be found which do not require large nearby population centers. One promising use is generation of electricity from freon-based biphase electrical generators. These generators will be installed on wells at Vale and Lakeview in the summer of 1982 to evaluate their potential use on geothermal waters with temperatures as low as 80° C (176° F).

It is clear also that the low temperature geothermal resources identified here and others like them elsewhere in the state must be viewed in a broader context which considers the very favorable geologic setting for geothermal potential in general. Thus, low temperature resources identified today really constitute part of a data base which may lead to the discovery of a larger temperature resource base tomorrow, technology and economics permitting.

INTRODUCTION

This report is the summary and conclusions of an investigation of low-temperature (20 to 90° C) geothermal resources begun May 23, 1979 by the Oregon Department of Geology and Mineral Industries (DOGAMI) with support from the United States Department of Energy (USDOE) under Cooperative Agreement No. DE-FC07-79ET27220. The report summarizes low-temperature resource assessment data generated for the following project areas (Figure 1):

1. Corbett-Moffett
2. Parkdale
3. Milton-Freewater
4. La Grande (Craig Mountain-Cove area)
5. Belknap-Foley Hot Springs
6. Willamette Pass
7. Powell Buttes
8. Northern Harney Basin
9. Southern Harney Basin
10. Western Snake River Plain
11. Lakeview
12. Alvord Desert
13. McDermitt

Raw data and preliminary conclusions for these areas are included in the following published DOGAMI reports and maps and will not be included here:

1. Heat flow of Oregon: Special Paper 4, 1978, includes 1 map.
2. Geothermal gradient data for Oregon: Open-File Report 0-78-4, 1978.
3. Chemical analyses of thermal springs and wells in Oregon: Open-File Report 0-79-3, 1979.
4. Geology of the La Grande area, Oregon: Special Paper 6, 1980, includes 1 map.
5. Preliminary geology and geothermal resource potential of the Belknap-Foley area: Open-File Report 0-80-2, 1980, includes 1 map.

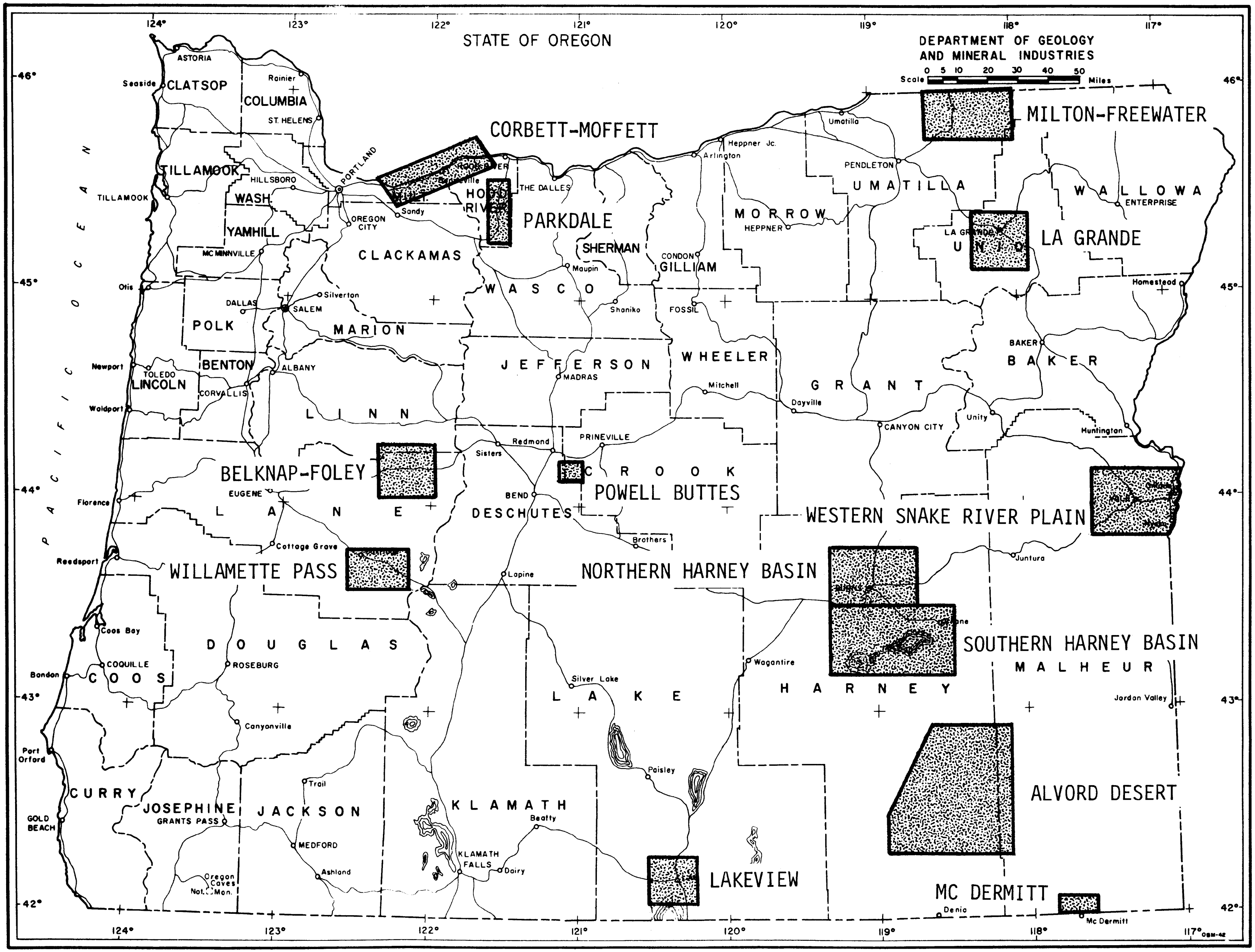

Figure 1. Location of project areas.

6. Preliminary geology and geothermal resource potential of the Willamette Pass area: Open-File Report 0-80-3, 1980, includes 1 map.
7. Preliminary geology and geothermal resource potential of the Craig Mountain Cove area: Open-File Report 0-80-4, includes 1 map.
8. Preliminary geology and geothermal resource potential of the western Snake River Plain: Open-File Report 0-80-5, 1980, includes 4 maps.
9. Preliminary geology and geothermal resource potential of the northern Harney Basin: Open-File Report 0-80-6, 1980, includes 4 maps.
10. Preliminary geology and geothermal resource potential of the southern Harney Basin: Open-File Report 0-80-7, 1980, includes 8 maps.
11. Preliminary geology and geothermal resource potential of the Powell Buttes area: Open-File Report 0-80-8, 1980, includes 1 map.
12. Preliminary geology and geothermal resource potential of the Lakeview area: Open-File Report 0-80-9, includes 2 maps.
13. Preliminary geology and geothermal resource potential of the Alvord Desert area: Open-File Report 0-80-10, 1980, includes 2 maps.
14. Progress report on activities of the low-temperature resource-assessment program 1979-80: Open File Report 0-80-14.
15. Geothermal gradient data for Oregon for 1978: Open-File Report 0-81-3A.
16. Geothermal gradient data for Oregon for 1979: Open-File Report 0-81-3B.
17. Geothermal gradient data for Oregon for 1980: Open-File Report 0-81-3C.
18. Map showing geology and geothermal resources of the southern half of the Burns 15' Quadrangle: GMS 20, in press.
19. Map showing geology and geothermal resources of the Vale East 7 1/2' Quadrangle, Oregon: GMS 21, in press.

20. Geothermal gradient data for Oregon for 1981: Open-File Report 0-82-4.

The Department is continuing its resource assessment efforts in other areas throughout Oregon with concentration on the Cascades. Resource assessment data will soon be available in open file for the low-temperature resources of Ashland, Oregon when a 1982 drilling program is completed under contract DE-FC07-79ID12044. Preliminary conclusions concerning the Klamath Falls and Bend areas will also be available in an upcoming special paper on the geology and geothermal resources of the Oregon Cascades (DOGAMI Special Paper 15). A preliminary summary of this paper will be included in the conference proceedings volume for the 1982 USDOE-sponsored conference at Salt Lake City, Utah. A similar paper, aimed primarily at a summary of the data gathered at Powell Buttes, was presented in the 1981 USDOE conference at Glenwood Springs, Colorado (see DOE/ID/120-79-39, ESL-59, published by the Earth Science Laboratory, University of Utah Research Institute, Salt Lake City, Utah).

CORBETT-MOFFETT

The Corbett-Moffett area extends from Cascade Locks in the Columbia Gorge to the lower Sandy River-Troutdale area (Figure 1). Hot springs at Carson (49°C) and North Bonneville (36°C) on the Washington side, a warm well at the new site of North Bonneville (37°C) and three slightly warm springs in the Troutdale area are the main surface manifestations of the geothermal resources. These springs are in a northeast-southwest line in a distinct lineament on high altitude SLAR and ERTS imagery. The cause of this lineation and spring alignment has, as yet, not been determined.

Cascade Locks (population 835) is the largest city within the Columbia Gorge. Several smaller communities lie between Cascade Locks and Troutdale. Lumber mills at Bridal Veil and Cascade Locks and tourism are the economic bases for the population. There is also a sizable number of local residents who work at Bonneville Dam.

At the western end of the Corbett-Moffett area the population is considerably larger. Troutdale (population 5,940) and Gresham (population 33,250) are the centers of lush farming and light industrial areas. Near Troutdale, a warm artesian well at Camp Collins (23°C), a slightly anomalous spring at Corbett Quarry (18°C), and a warm spring across the Columbia River at Camas suggest that a possible resource may lie at depth.

DOGAMI undertook study of the Corbett-Moffett area under the current USDOE low-temperature grant. The aims of the study were: 1) to investigate the possibility of geothermal resources occurring on the south side of the Columbia Gorge; 2) to investigate the low-temperature manifestations at Camp Collins and Corbett Quarry; and 3) to see if the main source of geothermal waters was: a) a deep-seated northeasterly geologic structure; b) several northwesterly or northerly cross-cutting geologic structures (such as the Lacamas Fault in the Camas area) which could cause localization of geothermal waters; or c) the deep incission of the Columbia River interacting with the regional heat flow to yield higher than ambient temperature.

DOGAMI began a vigorous spring sampling and water well "scrounge" program to identify promising sites for drilling of geothermal heat flow test holes. Although many springs were tested, only in the immediate area of Camp Collins were new thermal waters discovered. None of the thermal found in the Camp Collins area exceeded the Camp Collins well in temperature or ion/mineral content.

Six holes were drilled by DOGAMI in the Corbett-Moffett area in 1981. Locations and results are as follows:

1) Dry Creek Falls - This hole was located at the foot of the cliffs south of Cascade Locks. Although the site was over 1 mile from Cascade Locks, the site was the nearest available with the possibility of yielding good results. The gradient was 35.4° C. The gradient at this site was below the expected regional gradient. This may be due to a downflow groundwater system at the site.

2) Tanner Creek - This site is across the Columbia River from thermal anomalies at Moffett Hot Springs and North Bonneville. Hammond (1980) mapped a northwesterly fault crossing the Columbia Gorge in this area. The gradient was 77° C/km. The results at this site were slightly higher than the expected regional gradient.

   The Tanner Creek site is located close to the Bonneville Dam complex, with its fish hatchery, maintenance shops, administration buildings, and tourist facilities. However, unless still warmer waters are encountered (by either deeper drilling or striking a still higher heat flow anomaly in the same vicinity), it is not likely that low temperature utilization will be feasible in this area.

3) Corbett Quarry - located at the site of a slightly warm spring. The gradient was 29.3° C/km down to 110 m, where it became isothermal. The gradient is isothermal at approximately the same temperature as the nearby spring and is probably the product of upflow from the same source which feeds the spring.

4) Howard Canyon - This site was chosen to hit the Columbia River Basalt in an area where it may have fracture permeability. It is on the hinge of a monoclinal fold of the permeable basalts, on the projected strike of the Lacamas Fault. The gradient was 40.5° C/km. The results were consistent with heat flow modeling of the northern Oregon Cascades of Blackwell and others (1978). The gradient indicates that the site is outside of the High Cascades heat flow anomaly.

5) Sandy River - This site is also in the trend of the Lacamas Fault which has been mapped in southern Washington. It is also across the Sandy River from Camp Collins. The gradient was 42° C/km which is again consistent with regional background values outside the High Cascade heat flow anomaly.

6) Camp Collins - This hole was expected to determine the nature of the resource at nearby Camp Collins. Unfortunately, the hole had to be terminated before reaching its scheduled depth because of drilling problems and budget limitations. However, the gradient was 124° C/km to a depth of 74 m. Deeper drilling needs to be done to evaluate this extremely anomalous result.

The Camp Collins site remains attractive for investigation although no evidence of a large-scale shallow hydrothermal system was revealed which might be utilized by the nearby population center of Gresham. While it does not seem likely that other than very low-temperature resources occur in this area, based on the low gradients in adjacent wells, the very high local temperature gradient suggests that deeper drilling might have a chance of encountering higher temperature water than currently utilized at Camp Collins.

Thermal aquifers may occur in Columbia River Basalt Group (CRBG) rocks at unknown depths (perhaps 1000 m?) beneath the Gresham area, although drilling for such aquifers in the Mt. Hood area has not been successful. If water is present in CRBG at 1 km in the Gresham area, it will be at about 50° C, assuming the heating of the Camp Collins water occurs at depth within the area. Perhaps more likely is the possibility that thermal waters migrated laterally within an aquifer of the CRBG from the Cascade thermal anomaly to the east, and rose to shallow levels in the lower Sandy River area via local fracture zones associated with folding of the CRBG. This is supported by the general vertical impermeability of the volcanic pile in the Mt. Hood area, the hydrostatic head of wells penetrating the CRBG in the Camp Collins area, and the absence of young local Quaternary volcanic centers. Engineering studies should be pursued to evaluate whether further exploration for a low-temperature resource is justified. The study should take into account the probable low-temperature of the resource, high risk of finding inadequate fluid, and high costs of drilling deep wells, as well as the high potential load available.

Based on the results of the studies undertaken for this report, the best model explaining the occurrence of thermal phenomena in the Corbett-Moffett area would be the localization of low-temperature geothermal waters by the intersection of the Columbia Gorge with cross-cutting northwesterly and northerly geologic structures. Future recognition of additional geologic structures in the Columbia Gorge would merit further geothermal investigation.

PARKDALE

The Parkdale area is located at the south end of Hood River Valley (Figure 1). The area is noted for its lush farmland and orchards. Local population centers include Parkdale, Dee and Odell.

Interest in low-temperature geothermal energy in the Parkdale area is based on the existence of a warm well, a young lava flow whose estimated age is 500 years, and youthful faults to promote convective circulation that may allow thermal water from the Mt. Hood heat flow anomaly to rise to shallow depths.

Heat flow data from the area is sparse. There is an abundance of spring water and runoff available to meet most of the needs of the population and agribusiness. Those not so fortunate have found ground water at shallow depths in the valley fill of river sediments. Consequently there are few water wells drilled in the valley, and those present do not penetrate the sediments to any substantial depth.

The abundant rainfall and the permeability of the river deposits create a masking effect in which shallow cold ground water tends to conceal regional gradients in wells that do not penetrate through the shallow aquifers.

The warm well that provides the Dee Fish Hatchery with 24° C has been temperature logged by DOGAMI. The temperature log shows two shallow aquifers; one at 60 to 110 m yields water of 24.2° C, and one at 110 to 175 m yields 22° C water. Geothermetric calculations using data from geochemical analysis suggest reservoir temperatures of approximately 125° C.

DOGAMI undertook an assessment of the low-temperature geothermal resources of the Parkdale area for this report. The investigation was a three-pronged study involving geochemical water sampling, regional "scrounging" for available open wells for temperature gradient logging, and geologic mapping.

Nineteen springs were sampled in 1981. Some of the springs were located on maps and used for local water supplies. Others were located during the course of the geologic mapping project and were possibly related to structural geologic features. However, none of the sampled springs showed any geothermal component, and measured temperatures were invariable low. The lone exception was the resampled well at Dee's fish hatchery, already mentioned.

The effort to locate additional wells available for temperature logging was only moderately successful. DOGAMI's files now include a total of 15 wells in the area with temperature logs. Many of these are isothermal or have negative gradients, indicating that these wells did not penetrate through the cold water "blanket" generated by recharge from Mount Hood. Two of the 15 wells were drilled by DOGAMI in previous years for heat flow determination and encountered the same problem. The few good quality gradients that exist for the area are in the range of 25° C - 55° C/km, with a high heat flow maximum of 87 mW/m^2. However, the gradient of this well (yielding a heat flow of 87 mW/m^2), was not clear and the calculated heat flow is regarded as a maximum value.

Geologic mapping was intended to identify faulting and determine the age of the episodes. The Parkdale scarp, the fault that terminates the east side of the valley, was studied by Department staff. The major movement on the fault occurred between 2.66 ± 2.0 m.y. and 2.08 ± 0.24 m.y.B.P., with a displacement of greater than 2,000 feet. Last movement of the fault postdates 2.08 ± 0.24 m.y., making this fault one of the youngest known faults in the Oregon Cascade Range.

Although available regional gradient and spring sampling data do not indicate geothermal resources in the Parkdale area more promising than for the region in general, the identification of young faulting and the proximity to Mt. Hood suggests that further work should be done in the area. Available gradient data is not sufficient to analyze the potential adequately. Lack of a large urban population in the area probably precludes development of a district heating system, should adequate geothermal resources be found. Other, smaller-scale uses, such as the aquaculture system, already being utilized at the Dee Fish Hatchery, and food processing, might be possible on a much larger scale than currently in utilization.

MILTON-FREEWATER

The Milton-Freewater area, as defined for purposes of this report, is composed of that part of the Walla Walla Basin which lies in Oregon (Figure 1). The Walla Walla Basin is a triangular shaped area which lies astride the Oregon-Washington border approximately 30 miles (48 km) northeast of Pendleton, Oregon. The only significant population centers in Oregon are Milton-Freewater (pop. 5,110) and the small unincorporated town of Umapine. Agriculture is the main source of income for the region.

The Walla Walla Basin is a structural depression located in the Columbia Plateau physiographic province of eastern Oregon and Washington, which is composed mostly of flood basalts of the Miocene Columbia River Group. That part of the plateau located in Oregon is known as the Deschutes-Umatilla Plateau. The basin is bordered on all sides by anticlines. To the east is the northeast trending Blue Mountains Anticline, to the south the west-northwest trending Horse Heaven Anticline, to the west the north-south trending Divide Anticline, and to the north in Washington is a low east-west trending arch.

As has been previously mentioned, the Columbia Plateau is underlain by a thick sequence of Miocene tholeiitic flood basalts, the Columbia River Group. In the Walla Walla Basin, the basalts are exposed only in the bottoms of streams flowing into the basin, and on the flanks of the anticlines bordering the basin. Within the basin the basalts are covered by a series of unconsolidated Pleistocene and Holocene deposits which are as much as 650 feet (198 m) in thickness. The deposits include gravels, clays, loess, silts, siltstones, glacio-fluviatile deposits, and alluvium.

There are no surface thermal phenomena in the Walla Walla Basin. Early interest in the area was generated by rumors of warm irrigation wells, some of which were artesian at temperatures in excess of 38° C, though most fall into the range 15-27° C. The warmest wells all turned out to be located in the center of the basin near the town of Touchet, in Washington.

The Department of Geology and Mineral Industries (DOGAMI) effort in the region has been quite limited. To this date temperature gradients have been measured in only seven open water wells in Oregon, though a larger data set exists for the Washington side of the Walla Walla Basin. No well sampling program has been instigated, but limited geochemical data is available from groundwater studies which have included the Walla Walla Basin. Silica geothermometers indicate minimum reservoir temperatures in the range 100°-120° C for some of the warmer wells in the area.

Based on the limited temperature gradient data available, it appears that the heat flow averages about 55 mWm^{-2} in the Walla Walla Basin. Typical gradients are 35° Ckm^{-1} in the basalts and 50° Ckm^{-1} in the lower thermal conductivity sediments overlying the basalts.

According to ground water studies, there are major sets of aquifers in the area. The first is associated with older Pleistocene gravels. The water from wells drilled into these aquifers is typically cold and unconfined. The second is associated with flow contacts in the Columbia River Basalt. Waters from these aquifers are typically warm and artesian, and the wells commonly produce several thousand gallons per minute of water.

It is clear that there is a low-temperature resource in the Walla Walla Basin with abundant fluid and temperatures adequate for space heating and other lower temperature direct-use applications (most probably agricultural applications). The high temperatures, in most cases, result from a combination of the somewhat high regional heat flow (55 mWm^{-2}) and the insulating cap of low thermal conductivity unconsolidated sediments. Where temperatures in excess of 38° C occur, as in the Touchet area of Washington, it is probable that the fluids are derived from convection systems associated with mapped normal faults.

It appears, given the nature of the Columbia River Basalts in the Oregon portion of the Columbia Plateau, that adequate quantities of warm fluids can be obtained at any specific site. The temperature obtained in a specific well will depend primarily upon the depth drilled. Therefore, future efforts should be directed primarily toward site specific engineering studies, to determine if the resource is adequate to supply the expected load. In certain areas detailed geologic mapping and geophysical studies may be useful for locating faults. Convective systems associated with the faults could provide higher temperatures than would normally be expected at a given depth.

LA GRANDE

The La Grande area is located within the Blue Mountains physiographic province of northeastern Oregon (Figure 1). It is bordered by the Blue Mountains on the north and west, and by the Wallowa Mountains on the east. The three main population centers of La Grande (pop. 11,140), Union (pop. 2,160) and Cove (pop. 500), all lie within the Grande Ronde Valley.

The Grande Ronde Valley is a structural depression which is bordered on all sides by normal faults with displacements of several thousand feet. The floor of the valley is composed of unconsolidated Plio-Pleistocene lacustrine and fluvial sediments, landslide deposits, and alluvial fans. The bedrock making up the valley margins is composed exclusively of rocks of the Miocene Columbia River Basalt Group.

Hot springs are common throughout the study area, particularly along the southern and eastern margin of the Grande Ronde Valley. The hottest spring is the Hot Lake Resort Spring, 11.7 km southeast of La Grande, with a surface temperature of 85°C. Most of the other springs possess surface temperatures in the range 20-30°C. All of the springs are fluid-dominated deep circulation systems which are associated with the normal faults at the margins of the Grande Ronde Valley.

The Department of Geology and Mineral Industries (DOGAMI) commenced its geothermal effort in the Grande Ronde Valley in the summer of 1977 with the measurement of temperature gradients in existing water wells. In the spring of 1980 a spring sampling program was completed, and in the winter of 1979/1980 three heat flow holes were drilled in the city of La Grande. Originally 4 holes with a 152 meter (500 ft) nominal depth were scheduled, but extreme drilling problems resulted in the completion of only three holes, the deepest of which was completed to 120 m.

During the DOGAMI sampling program, twenty-five thermal springs and wells were sampled and analyzed. These, when combined with previously published data, resulted in a total of seventy-five analyses available for evaluation. It is felt that the chalcedony and 4/3B Na:K:Ca geothermometers probably give the best estimates of minimum reservoir temperature. For most of the springs and wells, these estimates fell in the range 100-125°C. The highest calculated temperatures were for those springs associated with the basin-bounding normal faults. The highest estimated minimum reservoir temperature for the Hot Lake Resort Well was 100°C.

Heat flow data for the Grande Ronde Basin is sparse, and the quality of most of the data that has been obtained is not good. Because most of the holes were measured in the unconsolidated sediments of the La Grande Basin, where the effects of refraction, sedimentation, and groundwater circulation tend to depress temperatures, the measured temperature gradients were often anomalously low or even isothermal. Of the three holes drilled by DOGAMI in the city of La Grande, one was totally useless for heat flow determinations (due to a negative temperature gradient) and there were significant problems in interpretation associated with the other two. These two holes resulted in heat flow values of 42 mWm^{-2} and 84 mWm^{-2}. Based on the total data set, the best estimate for heat flow in the Grande Ronde Valley is 60-80 mWm^{-2}, and the best gradient is $50 \pm 20°Ckm^{-1}$.

One of the DOGAMI holes, drilled adjacent to the city hospital, encountered 15-21°C water flowing at 114 lpm; a temperature and flow rate adequate for space heating applications using a heat pump.

It appears that the areas with the highest potential for the direct use of low temperature geothermal fluids are those adjacent to thermal convection systems associated with valley bounding normal faults. Of the many warm springs in the Grande Ronde Valley, those associated with the Craig Mountain fault and its extensions along the southern margin of the valley appear to be the most promising. Normal faults are also present in La Grande, and the warm water encountered in one of the DOGAMI drill holes is evidence that thermal convection anomalies may be associated with these faults. At the present time the City of La Grande is drilling a 1700-ft hole near one of the DOGAMI drill sites. Although it is being drilled primarily as a city water supply, DOGAMI will be allowed to temperature log the hole. If the temperatures are adequate, serious consideration will be given to forming a geothermal heating district to supply the many public loads in the area (three schools, city and county offices, and the Eastern State College Campus).

There is also considerable low temperature geothermal potential toward the center of the Grande Ronde Valley, where deep irrigation wells (900-1700 ft) commonly encounter large (often artesian) flow rates of several hundred to several thousand gallons per minute of water in the temperature range 19-32°C. The aquifers in these wells are the flow contacts between basalts of the Columbia River Group, and the heat is provided by the regional geothermal gradient. Although the temperatures in the wells are not particularly high, the large volumes of water available should make them an attractive economic target.

BELKNAP-FOLEY

The Belknap-Foley area is located at the eastern margin of the central Western Cascade Range of Oregon, approximately 80 km (50 mi) east of Eugene (Figure 1). McKenzie Bridge, Rainbow, and Blue River are the only towns in the study area. They are very small unincorporated communities. Because few people live in the area, there is little likelihood that a large-scale heating district could be economically installed. For this reason, no drilling was done for this study, although five temperature-gradient wells were drilled to about 150 m by the Department for regional heat flow measurement in the Cascades project (Cooperative Agreement DE-FC07-79ID12044). All hot springs were sampled and a geologic map was prepared in conjunction with both the Cascades and low-temperature projects. In addition, temperature gradients in five existing wells were measured, and a geologic map at a scale of 1:62,500 was prepared.

The geology of the area is dominated by its location at the boundary between the Western Cascades and the High Cascades. Rocks at the east margin of the area are chiefly Pliocene and younger basaltic lavas of the High Cascades, but most of the area is composed of Oligocene to Miocene lavas and tuffs characteristic of the Western Cascade physiographic province.

Although there is minor folding in rocks older than about 9 m.y.B.P., the major structures in the area are a series of north-south trending normal faults. These faults are concentrated at the High Cascade-Western-Cascade physiographic boundary at Horse Creek and the upper McKenzie River and in the South Fork of the McKenzie River at Cougar Reservoir. Rocks older than about 4 m.y. are consistently offset downward toward the east in both areas. Offset at Cougar Reservoir is at least 300 m and cumulative offset across Horse Creek is about 620 m.

The Horse Creek fault zone does not cut intracanyon lavas of the High

Cascades dated at 2.05 to 3.4 m.y.B.P. The Cougar Reservoir fault zone cuts rocks dated at 13.2 m.y. but does not cut Pleistocene gravels.

Hot springs and areas of anomalously high heat flow are associated with the north-south trending faults. The hottest springs are Belknap (86.7 to 71.0°C), Bigelow (61.0°C), and Foley (80.6°C) which are along the Horse Creek fault zone. Terwilliger Hot Springs (also called Cougar Reservoir and Rider Hot Springs) is adjacent to the Cougar Reservoir fault zone and has a temperature of between 42 and 44°C. Drilling near Terwilliger Hot Springs has shown that hydrothermal water also occurs at 150 m depth about 1/2 km east of the springs in an Oligocene(?) lava.

The most reliable geothermometric calculations for the Horse Creek fault zone group indicate reservoir temperatures in the 100 to 143°C range. Similar calculations for Terwilliger Hot Springs indicate reservoir temperatures of 95 to 103°C.

Of the five wells drilled in the Belknap-Foley area, three were located along the Horse Creek fault zone and two were adjacent to the Cougar Reservoir fault zone. Where heat flow was not obviously disturbed by nearby thermal springs, regional heat flow conforms to the pattern demonstrated by Blackwell and others (1978). Heat flow increases abruptly from values of about 70 to 83 mW/m^2 (terrain-corrected gradients of 53°C/km to 52°C/km) in the Cougar Reservoir area to about 111 to 114 mW/m^2 (terrain-corrected gradients of 71 to 74°C/km) in the Horse Creek area. The area thus lies on the transition zone between low heat flow (55 mW/m^2 or below) characteristic of the Western Cascades-Willamette Valley provinces and very high heat flow (over 100 mW/m^2) characteristic of the High Cascades province. These regional gradients and heat flow values indicate that hot springs in the area probably ascend from depths of about 1.2 to 2.0 km in the Horse Creek area and about 1.6 to 1.8 km in the Cougar Reservoir area.

The best target for furhter exploration is the Horse Creek fault zone. Drilling should be aimed at intercepting either the shallow aquifers near the hot springs or possible aquifers within the fault zone at depths appropriate for the temperatures desired. At depths of about 3 km, temperatures of about 200°C can be expected. Should fluid also be present, perhaps in fractured rocks near the fault zone, then electrical generation by direct-flash technology might be possible. Electrical generation from the hot spring waters is probably possible utilizing Rankine-cycle technology. For example, 40 kilowatts of electricity will be generated at Lakeview in the summer of 1982, using freon as a working fluid, from 80°C (176°F) water. This use, and small-scale local space heating uses near the hot springs are probably the most cost-effective means of exploiting the low-temperature resources of the area. Lack of a large population or industrial base precludes large-scale district heating systems unless it is possible to pipe thermal waters to the population centers of Springfield and Eugene. An engineering study is recommended to evaluate all of these possibilities.

WILLAMETTE PASS

The Willamette Pass area is located in the central Western Cascade Range of Oregon approximately 80 km (50 mi) southeast of Eugene, Oregon, up the Willamette River drainage (Figure 1). The only town in the area is the city of Oakridge (population of 4,300).

Because it is a significant population center a substantial effort was directed at defining geothermal resources near Oakridge. Toward that goal, a 122 m city water well was deepened to 344 m, and a 150 m temperature gradient well was drilled at a fault intersection 4 km southeast of Oakridge. A geologic map at a scale of 1:62,500 and complete sampling and temperature measurement in all available springs and wells was also completed. Eighteen water samples were analyzed and seventeen temperature gradients were measured and recalculated to heat flow. Seven of the gradients were measured in holes drilled for the Cascades project.

Rocks in the area are chiefly Oligocene(?) to late Miocene lavas and tuffs with minor Pleistocene or late Pliocene intracanyon basalt flows. The Pleistocene to late Pliocene basalts come from vents in the High Cascades to the east. The lack of youthful faulting makes the location of significant fractured rocks, which could hold thermal water, very difficult. Early Miocene tholeiitic (very iron-rich) lavas which have been mapped immediately outside of the map area near Lookout Point, may, however, be permeable. These rocks, together with buried intrusive rocks may provide the best aquifers for geothermal fluids in the area. Unfortunately, owing to the complexity of the geology of the area and the short time available for mapping, the depth to these potential reservoir rocks cannot be predicted with certainty throughout much of the area. It is highly probable, however, that neither of these rock types occur beneath Oakridge. Oakridge is located in a valley cut into rocks which appear to lie stratigraphically below the tholeiitic sequence. There is also no evidence of a major volcanic or plutonic center in or adjacent to the city. Lack of significant permeability at Oakridge is underscored by the insignificant fluid found in the 344 m city well. It is however, possible that permeability may exist in areas east of Oakridge since, as discussed below, hydrothermal fluids are obviously able to circulate enough to form warm springs in three areas within 6 to 15 km east of town. These warm springs are all in or adjacent to major faults and lineations. It is thus entirely possible that similar hydrothermal systems occur in or adjacent to unexplored faults between Oakridge and the hot spring belt. One temperature gradient well in such a fault zone at Hills Creek dam, however, did not reveal any anomalous gradients or heat flow indicative of circulating hydrothermal fluids.

Three warm spring areas occur east of Oakridge. Water is 62 to 73°C at McCredie Hot Springs, 40 to 41°C at Wall Creek Hot Springs and 30 to 44°C at Kitson Hot Springs. Most reliable geothermometric calculations for the three springs indicate possible reservoir temperatures of 112-126°C, 118-125°C, and 97-110°C, respectively.

Temperature gradient and heat flow measurements in the area show that the hot springs are in the transition zone between high (over 100mW/m^2) heat flow characteristic of the High Cascades and low (55mW/m^2 and less) heat flow characteristic of the Western Cascades and Willamette Valley. Heat flow in the hot springs belt is roughly 69 to 101 mW/m^2, with a terrain-corrected gradient of about 60°C/km. Heat flow east of the hot springs belt high as 115 mW/m^2 with terrain-corrected gradients as high as 67°C/km. West of the hot springs belt at Oakridge the heat flow is about 66 to 74mW/m^2 and the terrain-corrected gradient is between 36 to 40°C/km. Oakridge is thus on the westernmost edge of the heat flow anomaly generated by the High

Cascades. The gradients at Oakridge are, however, about half as high as gradients within the main High Cascades anomaly. The transition is very sharp, occurring over a distance of about 20 km. This is an additional reason to focus exploration as far east of Oakridge as is economically feasible.

In order to attain the reservoir temperatures calculated for the warm springs, waters would have to reach depths of about 1.0 to 1.5 km in the hot springs belt. In order to encounter similar temperatures (97-125°C) under Oakridge, meteoric water would have to circulate to depths of about 2.3 to 3.0 km. If potential circulation occurs only to 1.0 to 1.5 m at Oakridge, then water with temperatures of between about 48 and 57°C should be expected at depth. If rapid circulation of water occurs laterally from the High Cascades heat flow anomaly, then higher temperature water might be found near the city. No evidence of rapid lateral circulation has, as yet, been found.

Further exploration for low-temperature at Oakridge is warranted if potential uses can justify the capital outlay. There is a high probability that potential resources will be located at least a few km east of the city. Feasibility studies should be conducted which evaluate the viability of piping thermal water to Oakridge for various end uses. Known thermal spring areas have temperatures adequate for many uses, although the high content of dissolved salts in the water at Kitson Hot Springs may preclude many uses. Similarly high salt content was noted in the small amount of water found in the 344 m well drilled at Oakridge.

POWELL BUTTES

Powell Buttes is a large elliptically shaped topographic high located in the High Lava Plains physiographic province of east central Oregon, approximately 18 km southeast of Redmond and 29 km northeast of Bend, Oregon (Figure 1).

Powell Buttes is a volcanic vent complex composed of rhyolitic, rhyodacitic, and dacitic plugs, domes, flows, and tuffs of the Oligocene John Day Formation. Although colluvium mantles the flanks of the buttes, drill holes indicate that volcaniclastic sediments, ash-flow tuffs, and basalt flows of the late Miocene to Pliocene Deschutes Formation unconformably overlie the John Day Formation over large portions of the flanks. Powell Buttes lies at the western end of the Brothers Fault Zone, a major structural feature which is considered by some writers to mark the northern terminus of the Basin and Range physiographic province in the western United States.

Although several springs are present on Powell Buttes, the warmest of these is only 18°C. The lack of naturally occurring surface thermal phenomena makes the area a true "blind" geothermal anomaly. Several warm domestic water wells are present on the north, northwest, and western sides of the buttes. The highest water temperature measured in a domestic well was 33°C, in a well located on the west flank of the buttes in the zone of highest heat flow.

The Oregon Department of Geology and Mineral Industries (DOGAMI) first became interested in the Powell Buttes area during the summer of 1978, when temperatures measured in three open holes resulted in gradients in excess of 100°C km^{-1} and bottom hole temperatures as high as 37°C. Several more holes logged during the summer of 1979 confirmed the presence of a thermal anomaly along the north and west flanks of the buttes. In 1980 DOGAMI completed an extensive water sampling program and made an intensive effort to locate and log every open well in the vicinity of Powell Buttes. In the fall of 1980 DOGAMI drilled 9 heat flow holes, mostly along the west flank of the buttes.

The drilling program culminated in February 1981 with the completion of a 460-meter borehole centered in the zone of highest heat flow. In addition to the above efforts, complete Bouguer and residual gravity and aeromagnetic maps of the Powell Buttes area were completed for DOGAMI by the Oregon State University Geophysics Group.

A total of twenty-five wells and springs were sampled and analyzed during the course of the project. The waters are unusual when compared to waters from other geothermal areas in that they are relatively "clean". Total dissolved solids are low; and Cl, which is usually present in abundance in thermal waters, is nearly nonexistent. Also somewhat unusual is the presence of high amounts of trace metals such as Cu, Ba, Zn, and Sr. Minimum reservoir temperatures, calculated using Si geothermometers, are in all cases less than 100°C.

Several conclusions can be derived from the chemical analyses of the waters at Powell Buttes. First, the waters sampled were probably never much warmer than the temperature recorded during sampling. Second, because of the very low concentrations of constituents normally associated with thermal waters, the waters at Powell Buttes have not been deeply circulated. It is more likely that they have been heated conductively by a source that lies at greater depths.

Third, the waters sampled are most probably meteoric waters which have infiltrated through the buttes, the local recharge area. The high trace metal concentrations were probably acquired from zones of hydrothermal alteration as the fluids migrated down the hydrologic dip to where they were intercepted by domestic water wells.

The geophysical anomalies associated with Powell Buttes are somewhat difficult to interpret. There are large positive Bouguer and residual gravity anomalies centered over the buttes paralleling its northeast trend. Neither block faulting nor the presence of an intrusive beneath the buttes seem sufficient in themselves to provide the mass excess required to explain the large magnitude of the anomaly. It is likely that both mechanisms are in operation.

The most surprising aspect of the aeromagnetic study at Powell Buttes is the lack of an anomaly associated with the buttes, implying that either the buttes are underlain by nonsusceptible rocks, or that the rocks are very hot. Again it is probable that both mechanisms are in operation, particularly given the silicic nature of the volcanism that has occurred at Powell Buttes and the high heat flow measured on its flanks.

Since 1978, temperature gradients have been measured in 43 drill holes in the vicinity of Powell Buttes, and heat flow values have been determined for 32 of the sites. The data delineates a closed elliptical anomaly paralleling the west side of the butte. The zone of highest heat flow lies directly downslope from a large rhyolitic exogenous dome.

Although the early data collected at Powell Buttes indicated that temperature gradients in excess of 160°C km^{-1} and heat flow values in excess of 376 mWm^{-2} were present in the high heat flow zone, later data from deeper holes (particularly the 460-meter hole drilled by DOGAMI) indicate that the average heat flow in the vicinity of Powell Buttes is 125-167 mWm^{-2} and the average temperature gradient is about 80°C km^{-1}.

There are two possible explanations for the very high temperature gradients measured at shallow depths on the west side of the butte: (1) the high gradients are the result of a combination of heat flow refraction and very low thermal conductivities in the unconsolidated colluvium mantling the flanks of the buttes, and (2) there is a slow flow of warm water in a shallow aquifer beneath the zone of highest heat flow. In this second case fractures in the rhyolitic dome just east of the high heat flow zone could be acting as a conduit for thermal fluids.

There are problems with both hypotheses. Heat flow in the Powell Buttes area is conductive. There is no evidence of large-scale convective fluid movement in any of the holes in the data set, and only rarely is there any evidence of intraborehole fluid movement. In the 9 heat flow holes drilled by DOGAMI, no aquifer of the type described was encountered, and the geochemistry of the various water samples indicates that the waters have not been deeply circulated. Finally, groundwater supply in the Powell Buttes area is a serious problem. Wells are often totally dry, and those that do produce do so at rates of only 5-10 gpm. Producing wells seem to be situated along fairly narrow fracture zones, arguing against the presence of large stratigraphic aquifers. The hypothesis is still viable, however, as the flow rates in the aquifer could be extremely low and still produce the anomaly.

The temperature-depth profile at Powell Buttes has been successfully reproduced by computer using a finite difference thermal conductivity model. The problem with this model is that to account for the high temperature gradients, extremely low thermal conductivities are required for the surface layers. The conductivities are lower than can be produced with water-rock combinations alone, requiring that the pore space in the rock be only about 70% saturated; the remaining space filled with air. While certainly possible, given the arid nature of the region, the phenomenon has not been identified in other holes in east central Oregon.

Whatever mechanism is operative, it is obvious that temperatures adequate for many direct use applications can be found at relatively shallow depths in the Powell Buttes area. The temperature at 460 meters in the DOGAMI deep test (PB-1) was 56°C. Projections of the temperature gradient indicate that 80°C would be encountered at about .8 km, and 150°C at 1.7 km.

The problem is the availability of adequate fluids. Although the temperature-depth curve for PB-1 did show one small aquifer at 425 m, significant amounts of fluids were not encountered in the hole. In general, the John Day Formation and the underlying Clarno Formation are composed of large amounts of tuffaceous rocks, which are relatively impermeable.

It is clear that efforts to produce a viable low temperature resource in the Powell Buttes area must center around the location of adequate fluids. Detailed geologic mapping and geophysics, to locate fracture permeability, and the deepening of PB-1 to locate stratigraphic aquifers (probably associated with lava flows) are the most obvious steps to take in this direction. At this point in time, the PB-1 drill site has been turned over to Francana Corporation, which plans to deepen the hole sometime in the near future. Although private industry will probably continue to explore for high temperature geothermal resources, the position of Powell Buttes within piping distance of three important towns, Bend (16 km), Prineville (8 km), and Redmond (8 km), make it a viable exploration target for direct use resources. Future exploration should be aimed at deeper drilling not only at Powell Buttes but also on youthful faults known to exist in the vicinity of Bend and Redmond (e.g. see Peterson and others, 1976). Additional temperature measurement and possible drilling should be accomplished at Prineville as well. Engineering studies should be pursued to define the amount of exploration expenditure which can be justified by expected loads and end uses.

NORTHERN HARNEY BASIN

The study area is located at the northern end of a large, circular topographic depression in the central portion of eastern Oregon known as the Harney Basin (Figure 1). The major population center is the city of Burns (a population of 3,525) and the nearby community of Hines (population of 1,575). Fifteen springs and wells were sampled, four temperature logged to a depth of 800 m, and geologic maps at both the 1:62,500 and 1:24,000 scale were produced for the area. A soil mercury survey and ground magnetometer survey were also completed. All of the raw data, except the mercury and magnetometer surveys, was published in various open file reports and in one high quality colored 1:24,000 scale geologic map of the Burns area.

The northern Harney basin was a major silicic volcanic center during the late Miocene and probably during the middle Miocene as well. Major cauldron subsidence blocks formed during eruption of voluminous soda rhyolite ash-flow sheets which covered hundreds of square miles of eastern Oregon. Interfingering with the ash flows are smaller amounts of soda rhyolite lava and basaltic lava. Volcanism since about 3.0 m.y.B.P. has been dominated by eruption of small volumes of alkaline high-alumina tholeiite. Holocene eruptions of alkali basalt at Diamond Craters near the southern margin of the study area was the last volcanic activity.

Faulting in the area follows three general trends. The first is the trend of the Brothers fault zone (N25°W to N55°W), which is exhibited most strongly immediately west of Burns. These are dip-slip faults which cut 2.3 to 2.9 m.y.B.P. basaltic andesites near Burns Butte. The second trend is that of north-south to north-northwest dip-slip faults of the Basin and Range which cut all bedrock units except the Holocene basalts. Dip-slip faults at a N40°W to N50°W in the east-central part of the area are transitional between the Brothers and Basin and Range trends.

Many of the faults have evidence of some relation to strike-slip motion. This is particularly true of faults of the Brothers fault zone which, according to Lawrence (1976) may be related to right lateral wrenching at depth. A large north-south trending fault in the Soldier Creek area at the northern margin of the basin also has evidence of lateral movement. The Soldier Creek fault is notable for its large opalized breccia zones, and because the hottest geothermal well in the area (the O.J. Thomas well) occurs 3 km east of the presumed extension of this fault at the northern margin of the basin. Brown and others (1980a) conclude that the O.J. Thomas water emanates from this fault. The Soldier Creek zone loses its aeromagnetic and gravity signature at about the latitude of Hines where a west-northwest trending structure appears in geophysical maps.

Folding of bedrock units is generally in the form of broad, shallowly dipping anticlines and synclines plunging toward the center of the basin. Exceptions are sharply folded rocks adjacent to major fault zones.

The Harney Basin appears to be the result of downwarping over a broad area. Some parts of the basin may be bounded by caldera faults, but much of the northern half of the area appears to be a broad zone of subsidence requiring very little deformation at the basin boundaries. D. D. Blackwell (personal communication) has speculated that much of this broad subsidence may be due to cooling and contraction following late Miocene silicic volcanism.

Most warm springs in the Burns area are in the 22 to 28.5°C range with calculated minimum reservoir temperatures of between 70°C and 11°C. Thermal water near the Soldier Creek fault zone possesses both higher surface temperatures (71°C) and higher calculated minimum reservoir temperatures (99-139°C).

The best example of thermal water from the Soldier Creek system is the O. J. Thomas well, which is 15.3 km east-northeast of Burns. This well yielded 11,400 liters per minute (about 3,000 gpm) of 72°C water in a pump test (this was the capacity of the pump). The Harney Development well, an old oil well south of the O. J. Thomas well (14.5 km southeast of Burns), flows about 380 liters per minute (100 gpm) of 46°C to 50°C thermal water, similar in composition to the water of the O. J. Thomas water (e.g. high total dissolved solids and boron). No pump test data is available for the Harney Development well to establish its ultimate potential flow.

Four shallow (140 m to 187 m) temperature gradient wells and one deep oil well (the Poteet well 2 km east of Burns) provided the most definitive data about temperatures and aquifers in the area. The Poteet well was temperature logged to 800 m and revealed that the background gradient at Burns is about 60° C/km with an estimated heat flow of about 92 mW/m^2. The well also showed disturbances in the conductive gradient indicative of definite thermal aquifers at 210-230 m (32°C) and 550-600 m (48°C) and a possible small aquifer at about 750 m (55°C). A 187-m well at the Hines Lumber Mill encountered a 3,800 liter per minute (1,000 gpm), 27°C aquifer at 15 to 50 m. A 164-m well drilled on the Hotchkiss Ranch, about 2.4 km (1.5 m) southwest of Hines was targeted on a soil mercury anomaly and encountered a 4- to 8-liter per minute (lpm) aquifer at 126 m, a 20-lpm aquifer at 140 m, and ~ 20-lpm aquifer at 160 to 164 m. All of these aquifers were between 34 and 35°C and were located in ash flow tuff, loose volcanic sands, or basaltic interflow areas. Discharge rates are estimated from water blown from the well during air drilling.

Comparing the data from the above holes, it is apparent that abundant thermal water in the temperature range of 27°C to 35°C occurs at depths of 15 m to 230 m between Hines and Burns. This is also the temperature of most of the thermal springs in the area which no doubt issue from these same aquifers. Data from the Poteet well suggests that the background temperature gradient is high enough to produce this 27 to 35°C water from conductive heating at between 140 and 340 m. Water encountered in the Hines area is thus ascending from at least these depths and then flowing laterally in the layered volcanic rocks. A mapped fault at the Hotchkiss site was encountered in the drill hole and may have provided a conduit for rise of warm water there. Because the Hotchkiss site is 114 m higher in elevation than the Hines area, some water around Hines could be explained by lateral flow of water from the Hotchkiss area. The high flow rate at the Hines Lumber Mill site, however, suggests that water must be coming from other areas as well, perhaps other faults. Additional drilling will be necessary to determine the circulation pattern of these shallow aquifers at Hines. Drilling should be focused on mapped faults and probable extensions of mapped faults under the valley sediments.

The city of Burns probably has thermal aquifers at 32°C at about 210 to 230 m and at 48°C at about 550 to 600 m, based on data from the Poteet well. There is definitely abundant (380 lpm) 14°C water at Burns High School at a depth of 37 m, and an 18°C aquifer of unknown volume occurs at about 140 m at the same site. The Poteet well should be cleaned out and temperature logged below 800 m, in order to discover if other higher temperature thermal aquifers are present at depth beneath Burns. The well has a drilled depth of 1975 m. Temperatures of 100°C at about 1.5 km (5,000 ft) and 200°C at about 3.2 km (10,400 ft) would be expected beneath Burns, based on the Poteet data. There is no guarantee of fluids at these depths, however.

One way of mitigating the high cost of drilling deep at Burns for hot water would be to take advantage of possible areas of upwelling thermal water. Fault zones are often sites of upwelling. The probable southerly extension of the Soldier Creek fault between 10.5 and 14.5 km (6 to 9 mi) east of Burns apparently contains large quantities of thermal water, based on data from the O. J. Thomas well (at least 11,400 lpm, of 72°C water). Water found in this well would have to ascend from at least a depth of 1 km (3,280 ft), based on the 60° C/km Poteet gradient. If the O. J. Thomas water is from a conductively heated source at the geochemically calculated reservoir temperature (99 to 135°C), the water would have to ascend from depths of about 1.5 km to 2.0 km. This is a clear indication that a major hydrothermal circulation system must be operating east of Burns. Drilling between the O. J. Thomas well and Burns should be pursued to determine the lateral extent of the circulation system toward Burns.

Another particularly interesting site for drilling is the area approximately due east of Hines and due south of Soldier Creek, where geophysical anomalies indicate a possible intersection of the Soldier Creek structure with a west-northwest trending structure. Possible high fracture permeability in this area might allow convection of large quantities of thermal water to shallow depths.

Engineering studies should be pursued which evaluate the feasibility of drilling beneath Burns for the thermal aquifers noted in the Poteet well. Additional studies should focus on the maximum distances that resources associated with the Soldier Creek hydrothermal system could be piped. The shallow thermal aquifer at Hines should be evaluated for heat pump and cogeneration applications.

SOUTHERN HARNEY BASIN

The Harney Basin is a roughly circular basin with interior drainage to Malheur, Harney and Mud Lakes. The basin covers approximately 8,100 square miles. The small unincorporated farming communities of Crane, Princeton, and Diamond are the only population centers.

DOGAMI's study of the south Harney Basin (Figure 1) involved extensive spring sampling, gradient data accrual through the location and logging of all available open water wells, a literature search, reconnaissance mapping of eight 15' quadrangles, and the drilling of a 135 m heat flow hole at Crane School.

Thermal spring and well water geochemistry generally indicates reservoir temperatures of 100°C to 140°C by the quartz geothermometer and 100°C to 170°C by the Na-K-Ca geothermometer. Numerous thermal springs occur in the area, 22 of which were sampled for this study. The highest spring temperatures, located near Crane, were 80°C. On the basis of the chemistry, the springs can be split into two groups. The first group is centered near Crane, the second near Harney Lake. Chemical differences probably stem from the nature of the rocks these fluids are associated with at depth and subsurface residence time.

The basin was formed by regional collapse due to the eruption of voluminous ash-flow sheets from within the area. Harney Lake was one of the eruptive centers, active about 9 m.y.B.P. The last silicic volcanism occurred approximately 8 m.y.B.P., but a Holocene basaltic center, Diamond Crater, was active as recently as 15,000±2,000 years ago (Norm Peterson, 1980, personal communication, cited in Brown and others, 1980b).

The area is also in the Brothers Fault Zone, which represents the northern termination of the Basin and Range physiographic province. Basin and Range faulting occurred predominantly in the middle and late Miocene and represents east-west extension on numerous north-south trending faults. The Brothers Fault Zone trends northwesterly through the area. Fault activity associated with the Brothers Fault trend is younger than that of the Basin and Range trend in the area. The fabric of the area is predominantly northwesterly. Northwest trending faults cut the 15,000±2,000 year-old basalts of Diamond Crater (Brown and others, 1980b).

The background gradient for the south Harney Basin is 60-80°C/km, the background heat flow is 60-80 mW/m^2. These values are based on previous DOGAMI and USGS heat flow studies (Hull and others, 1977, DOGAMI 0-77-3; Sass and others, 1976) and new data from open water wells.

The deepest well logged for temperature in the area is the Poteet oil well, in the northern Harney Basin. The well is 800 m deep with a gradient of 59.8°C/km and a heat flow of 92 mW/m^2. The heat flow value is consistent with the modeling of Blackwell and others (1978) and corroborates predictions of anomalous heat flow and geothermal potential along the Brothers Fault Zone. This high-quality heat flow and gradient may be more representative of the regional background heat flow than the 60-80 mW/m^2 value, since the lower values are based on shallower measurements. Only deeper drilling will test this hypothesis adequately.

The background heat flow predicts that spring waters probably ascend from a minimum depth of one km. This indicates that hydrothermal circulation may reach at least this depth in other parts of the basin as well.

DOGAMI identified a potential geothermal resource at Crane. A heat flow hole was drilled by DOGAMI in 1981 at Crane School. The gradient was 96°C/km and the bottom hole temperature was 24.5°C at 135 m. The heat flow for the hole is approximately 148 mWm^2. Additional drilling would be needed for utilization because no large water-bearing aquifer was encountered in the hole. This gradient and heat flow are obviously very anomalous with respect to both of the above regional background estimates. It is probably necessary for background heat flow to be redistributed by convection to produce heat flow this high. Either magmatic or hydrothermal convection would suffice. It is likely that hydrothermal convection is responsible for this anomaly, since Crane is not a young volcanic center. Should this hypothesis prove correct, there could be a major hydrothermal circulation system beneath Crane. Additional shallow drilling around the Crane area should be done to determine the width of the anomaly, in order to determine its extent and to do half width calculations which can predict the depth of the anomalous heat source. Deeper drilling should then be done if the predicted drilling depths can be economically justified. Alternatively, deeper drilling could be pursued immediately to determine if the anomaly is caused by a relatively shallow aquifer of warm water.

Anomalous geothermal areas, other than hot spring locations, were found near Coyote Buttes and west of Diamond Valley, where gradients of 130-160°C/km and 88°C/km, respectively, and heat flow of 125-155 and 146 mW/m, respectively, were found. However, population densities in these areas are too low to justify exploitation unless industrial interests decide to lcoate at these sites. In terms of risk, the existing hot springs are a better choice, since hydrothermal water is readily accessible if hot spring temperatures are adequate.

DOGAMI recommends site-specific resource evaluation of several locales within the basin. Low temperature utilization would possibly be feasible for the population center of Crane and for possible light industrial/agricultural purposes elsewhere in the basin. Methods that should be used are detailed geologic mapping at large scales; detailed sampling and analysis of thermal springs and wells to determine fluid flow direction, provenance and reservoir conditions; and a drilling program to outline thermal anomalies and test geothermal aquifers. Several intermediate-depth wells (600 m) will be required to give stratigraphic control, identify aquifers at depth and enable informative pump test data to be acquired. These steps should only be taken after engineering feasibility studies have shown that development of potential resources is economically justified.

WESTERN SNAKE RIVER PLAIN

The Western Snake River Plain, as defined in this report, includes approximately 1100 square miles of eastern Oregon located in the extreme northeastern corner of Malheur County, adjacent to the state of Idaho (Figure 1). Major population centers include Ontario (and Payette, immediately across the Snake River in Idaho) in the extreme east-central portion of the area; Vale, in the west-central part of the area; and Nyssa, in the southern part of the area.

The Snake River Plain is a broad structural downwarp which extends across southern Idaho and at its western terminus into east-central Oregon. In Oregon the downwarp is filled with a series of Pliocene-Pleistocene lacustrine and fluvial sediments (often tuffaceous) which are intercalated with a few thin olivine basalt flows. These sediments, which are over 914m (3000 ft) thick throughout most of the study area, are underlain by a thick sequence of Miocene flood basalts (the Owyhee Basalt) which are considered to be time-stratigraphic equivalents with the Columbia River Group in the Columbia Plateau and the Steens Mountain Basalt in south-central Oregon.

Hot springs are common throughout the study area, with the highest temperatures being reported for Vale Hot Springs (90^{o}C), Neal Hot Springs (88^{o}C), Deer Butte Hot Springs (79^{o}C), Baschon Well (69^{o}C), and Snively Hot Springs (57^{o}C). Nearly all of the springs are associated with normal faulting, and they appear to result from typical deep circulation systems.

The Oregon Department of Geology and Mineral Industries (DOGAMI) has gathered a considerable amount of data in the Western Snake River Plain over the last several years. The measurement of temperature gradients in open water wells has been an ongoing process since the early 1970's. In the summers of 1972 and 1973 a series of (2-3 meter) wells was drilled to investigate the possibilities of identifying geothermal anomalies by using temperature measurements from very shallow holes, and in 1975 DOGAMI drilled 5 deeper holes (62-152 m) to investigate geothermal anomalies in Cow Hollow, Willow Creek, and South Fork Jacobsen Gulch. For the present study, no new heat flow holes were drilled in the Western Snake River Plain. Instead, the emphasis was placed on spring sampling and the measurement of temperature gradients in open water wells. In addition, a detailed geologic map of the Vale East 7 1/2' quadrangle was produced. The map will be published in the summer of 1982.

A large geochemical data base, which includes all of the major hot springs in the area, now exists for the Western Snake River Plain. Geochemically the waters are typical of eastern Oregon Basin and Range fluid-dominated deep circulation systems. Calculated minimum reservoir temperatures cover a wide range, with several of the springs having at least one method of calculation resulting in a minimum temperature of greater than 150°C. The most promising of of these are Vale Hot Springs (160^{0}C), Neal Hot Springs (180^{0}), Bully Creek Warm Spring (188^{0}C), Harper Warm Spring (208^{0}C), and BLM Vine Hill well (162^{0}C).

As a result of DOGAMI efforts since the early 1970's, a considerable body of heat flow data now exists for the Western Snake River Plain. By 1980, temperature gradients had been measured in 45 holes. Additional holes, mostly in the vicinity of Vale Hot Springs, have been added since that time. These serve to give a fairly accurate picture of heat flow within the province. The average heat flow is approximately 119 mWm^{-2} and the average temperature gradient is 97.5^{0} Ckm^{-1}. The heat flow is nearly twice the worldwide average, and the temperature gradient is greater than twice the worldwide average. This is due to the insulating effect of the low thermal conductivity tuffaceous sedimentary rocks which crop out throughout the study area.

As is the case throughout much of eastern Oregon, local convective thermal anomalies are superimposed on an overall high regional heat flow. In these systems, meteoric waters penetrate to great depths and are heated by the regional geothermal gradient. When the heated waters encounter significant fracture permeability in the normal faults which cut the area, they rise rapidly with little cooling to the surface, where they emerge as hot springs.

Because of the combination of the above factors, the Western Snake River Plain has a great deal of low temperature geothermal potential. There are significant population centers, an overall high population density, and a large agricultural industry to provide loads. Because of the high regional temperature gradient ($60^{0}Ckm^{-1}$ is the minimum gradient encountered in the region), it can be expected that moderate temperature resources ($80^{0}C$-$130^{0}C$) will be encountered in the depth range 1-1.5 km. In areas where convective anomalies are present, moderate temperatures exist at depths of only a few hundred meters. Temperatures suitable for heat pump applications may be found at depths of a few tens of meters throughout the study area.

At the present time, several large-scale direct-use projects are in the operation; including greenhouses, mushroom nurseries, and an alcohol plant. The one potential problem with the development of low to moderate temperature geothermal resources in the Western Snake River Plain may be the lack of adequate fluids at depth beneath large portions of the study area. The tuffaceous sedimentary rocks which cover the area tend to be relatively impermeable. The Ore-Ida Food Comapny drilled a deep exploration hole to greater than 3000 meters in the city of Ontario; and although temperatures in excess of $175^{0}C$ were encountered at the bottom of the hole, there was no fluid production below 2000 meters. It appears that future exploration will be more concerned with locating aquifers rather than locating temperatures. The Ore-Ida well might, in fact have been successful had more attention been paid to permeability during site selection.

Vale Hot Springs is probably the best site in the area for direct-use. In a crude pump test, conducted in cooperation with the landowner, R. Butler, a shallow (30 m) well near the old swimming pool at the springs produced about 1,500 lpm (400 gpm) of 110°C (230°F) water for about ten hours. Additional drilling and pump testing around Vale Hot Springs should be done to estimate the ultimate volume and temperature of the waters. This resource could probably produce enough water to significantly offset space heating loads at the city of Vale which is within 1/4 km of the springs.

There has also been considerable high-temperature resource exploration in the area. To this point in time, private industry has concentrated its energies primarily in three areas: Bully Creek, Willow Creek, and the Cow Hollow Geothermal Anomaly. This last anomaly is a fault-controlled system extending southeastward from Vale Hot Springs, which was discovered during one of the early phases of the Oregon geothermal programs. At this time, there are plans to install a small biphase electrical generation system on a well in the Cow Hollow anomaly near Vale Hot Springs by the summer of 1982.

LAKEVIEW

The Lakeview area is located in the Basin and Range physiographic province of south-central Oregon (Figure 1). A typical Basin and Range graben-horst pair, the Goose Lake Valley on the west and the Warner Mountains on the east, make up the area. Lakeview (pop. 2,770), the only town in the region, is located in the center of the area at the foot of the Warner Range.

The geology is typical of most of the rest of the Basin and Range province in Oregon. The Goose Lake Valley is composed of unconsolidated Pleistocene to Holocene lacustrine and fluvial sedimentary deposits which are as much as 1,524 m (5,000 ft) thick in the center of the basin. The Warner Range, in the vicinity of Lakeview, is composed of volcanic and volcaniclastic rocks which range in age from Oligocene(?) to Pleistocene(?) rhyodacitic exogenous domes and flows and mafic vent complexes.

The dominant structure in the area is the essentially north-south normal fault that separates Goose Lake Valley from the Warner Mountains. It is vertical or steeply westward dipping and, where exposed in the vicinity of Lakeview, is characterized by a breccia zone as much as 50 feet in width. The earliest fault movement probably occurred in the early Pliocene, and most of the movement on the fault took place before glaciation affected the higher peaks in the Warner Range, although Pleistocene terrace material is faulted north of Lakeview.

Surface or near surface thermal phenomena are associated with this normal fault in three separate parts of the study area. The hottest is the Leach Hot Well area just north of Lakeview, where a bottom hole temperature of 112.7°C was measured in a 120-m hole. At Barry Ranch Warm Spring in the central part of the study area, a temperature of 75.7°C was measured in a 73-m hole, and at the Rockford Ranch, in the southern part of the study area, a temperature of 69.9°C was measured in a 415-m hole.

The Oregon Department of Geology and Mineral Industries' (DOGAMI) effort in the Lakeview area consisted of a limited spring sampling program, the measurement of temperature gradients in existing, open drill holes, and a nine-hole drilling program. In addition, a complete Bouguer anomaly map was completed for DOGAMI by the Oregon State University Geophysics Group.

Twenty thermal springs were sampled, and these, when combined with existing published analyses, resulted in a total of 27 analyses available for the calculation of minimum reservoir temperatures. In general, the calculated minimum reservoir temperatures fall in the 100-150°C range.

Of the nine holes drilled by DOGAMI in the Lakeview area, three were located in Hammersly Canyon adjacent to the Leach Hot Well thermal area, three were located in Bullard Canyon, immediately west of the town of Lakeview, one was near the Precision Pine Company just north of the town, one was in the town itself, and one was near Barry Ranch Hot Springs.

In addition to the nine holes drilled by DOGAMI specifically for heat flow purposes, temperature gradients were measured in 31 open water wells. The heat flow pattern which emerges is typical of the Basin and Range Province throughout the western United States. The high regional heat flow (approximately 100 mW/m^2) is modified by thermal refraction, erosion, sedimentation, and hydrologic effects. These factors interact in a complex manner, with the overall result being that higher heat flow values are typically measured in the range blocks immediately adjacent to the bounding normal faults than are measured in the adjacent valleys. Superimposed on the high regional heat flow are local, higher temperature anomalies which result from the circulation of thermal fluids up permeable zones in the normal faults. Frequently the higher temperature anomalies are localized by the intersection of cross faults with the range bounding normal faults.

The holes in the Leach Hot well area demonstrated that the actual upflow of geothermal fluids occurs within the range block, and that heat flow is at least three times the regional value for a distance of 1 1/2 km into the range. One of the holes encountered 99°C water at a depth of 45 m. A later hole drilled to 208 m by Northwest Geothermal Corporation adjacent to this hole found no increase in temperature at the deeper depth.

In the town of Lakeview itself, temperature gradients and heat flow values are lower, only about 50% greater than regional values.

It appears that the heat requirements of the town of Lakeview may possibly be satisfied with water from geothermal systems located within 8 km of the town. The Northwest Geothermal Corporation (a subsidiary of Northwest Natural Gas Company) was given a 30-year franchise by the city to build and operate a district geothermal heating system. The company has been waiting for some large year-round industrial loads or a construction subsidy before beginning construction.

In addition to low temperature uses, there are temperatures in the Lakeview area adequate for the generation of electricity using biphase technology. A 40-kw Ranking Cycle generator utilizing 80°C fluid has recently commenced operation on the Rockford Ranch.

ALVORD VALLEY

The Alvord Valley lies in the Basin and Range physiographic province of southeastern Oregon and northeastern Nevada (Figure 1). It is a north- to northeast-trending graben valley that is flanked on the west by the Steens Mountains in Oregon and the Pueblo Mountains in Nevada, and on the southeast by the Trout Creek Mountains. The valley is approximately 113 kilometers long and has a maximum width of about 16 kilometers near the Alvord Desert.

The rocks of the Steens Mountains are composed of a series of volcanic flows and volcaniclastic rocks which range in age from lower Miocene to early(?) Pliocene. The Alvord Valley is composed of a series of Pliocene-Pleistocene to Holocene unconsolidated lacustrine and fluvial deposits.

Structurally the area is dominated by the large north- to northeast-trending vertical to steeply eastward dipping normal fault which separates the Steens Mountains from Alvord Valley. Displacements on the fault are estimated to be as much as 1000 feet, most of which occurred before the onset of glaciation. The slight uplift of some Quaternary alluvial fans is an indication faulting is an ongoing process.

Surface thermal phenomena are associated with the range-bounding normal fault at Mickey Hot Springs, in the northern part of the area, at Alvord hot spring west of the Alvord Desert in the central part of the area, at Borax Lake Hot Springs in the south central portion of the area, and at Pedro Springs in the southern part of the area just west of Fields, Oregon.

The Department of Geology and Mineral Industries (DOGAMI) effort in Alvord Valley was confined to limited spring sampling and the measurement of temperature gradients in existing wells. In all, six springs were sampled and their waters analyzed. When combined with previously published data, a total of twenty-seven analyses was available for evaluation. Calculated minimum reservoir temperatures covered a wide range, with the maximums being a 330°C estimate for Mickey Hot Springs and a 252°C estimate for Alvord Hot Springs.

Due to the sparsely settled nature of the study area, there are few open holes available for the measurement of temperature gradients. The heat flow, however, appears to be typical of other parts of the Basin and Range Province in the western United States, where local convective thermal anomalies are superimposed on high regional heat flow values of approximately 100 mWm^{-2}. The convective anomalies result from the rapid ascent of thermal waters in zones of fracture permeability in the range bounding normal faults. The fracture permeability often results from the intersection of cross faults with the range-bounding normal faults. This appears to be the situation in the Alvord Valley, where previously published geophysical data indicate the presence of faults beneath Mickey Hot Springs, Alvord Hot Springs, and Borax Lake Hot Springs.

Given the sparsely settled nature of the Alvord Valley (less than 1 person per square mile), the potential for the use of low temperature geothermal fluids is not significant. Although the required temperatures and fluid flow rates are present for direct use applications, the population densities required to attract industrial users or establish heating districts are not.

This is not the case with respect to electrical generation potential. The high minimum estimated reservoir temperatures at Mickey Hot Springs and Alvord Lake Hot Springs have attracted considerable industry interest over the last few years, and exploration by the private sector is still pressing forward at the present time.

McDERMITT

The McDermitt area is located in the extreme southeast corner of Oregon (Figure 1). The town of McDermitt just across the state line in Nevada is the only population center in the area.

The McDermitt caldera was a major Miocene eruptive center. Five large overlapping collapse structures with resurgent domes and ring dikes have been identified by workers in the area. Two of the calderas partially extend into Oregon's extreme southeast corner. Volcanism centered in the area was very silicic. Rhyolites, alkali rhyolites, trachyandesites, quartz latites, dacites and ash-flow sheets of these compositions were all erupted in the area. Volcanic activity occurred between 15 and 18 m.y.B.P.

Thermal springs with recorded temperatures of 53.5^{O}C, 52^{O}C, 32^{O}C, 25^{O}C, and 35^{O}C and an artesian well flowing at 46^{O}C are associated with the caldera structures within Oregon. Geochemical analysis of the springs indicates reservoir temperatures of approximately 100-130^{O}C.

Mineral deposits of mecury, uranium, and lithium are found at the caldera margins. None of the Oregon deposits are currently being worked, but others in Nevada associated with the same McDermitt caldera structures are the largest mecury deposits in the United States and are currently in production. Chemical analyses of rocks of the area indicate rhyolitic and alkali rhyolitic magmas enriched in mecury, uranium and lithium were probably the source for subsequent mineralization by epithermal hydrothermal fluids. The highest uranium concentrations are located in rhyolitic ring dikes and domes although there are also anomalous concentrations of uranium associated with mercury deposits.

Local heat flow is greater than 100 mW/m^2 (Blackwell and others, 1978). The thermal anomaly and springs of the McDermitt area may be generated by a combination of the locally high radioactivity with the very low conductivity of the silicic pyroclastic rocks. Thermal springs may occur where faulting or fracturing has provided channelways for heated waters to rise to the surface.

Low temperature geothermal utilization in the McDermitt area has low potential due to the very low population density of the area. Distances between residences preclude formation of a heating district, and light industry is not likely to locate in an area so remote with relatively little transportation access and through-traffic. Potential utilization of thermal waters in the McDermitt area seems to be restricted to individual ranch resources and needs, unless high-temperature fluids, adequate for electrical generation, can be found. The high heat flow and faulted nature of the rocks in the area are favorable for such resources.

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