A SUMMARY OF GEOTHERMAL POTENTIAL IN WYOMING

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INTRODUCTION

This report summarizes the geothermal potential of Wyoming exclusive of Yellowstone National Park. The main body of the report discusses basic geologic, hydrologic, and thermal character of geothermal resources in the State. Included in this discussion are general definitions of geothermal systems, a brief discussion of application and the distribution of geothermal resources, methods of geothermal assessment, identified resource areas in Wyoming, and potential resource areas. Also included is a summary of permitting procedures and agencies involved with the regulation of geothermal energy.

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GEOTHERMAL SYSTEMS

In general, geothermal systems vary from high temperature steam to warm water being pumped from a drill hole. The type of system depends on how the heat flowing out of the earth is modified by geologic and hydrologic conditions. Most places in the crust of the earth warm up about 14° F for every 1,000 feet of depth (Anderson and Lund, 1979). An attractive geothermal resource may exist where the thermal gradient is significantly higher than 14° F/1,000 ft.

Heat flow studies in Wyoming basins (Decker et al., 1980; Heasler et al., 1982) have reported heat flows of about 33 to 80 mW/m^2 (milliwatts per square meter) (see Figure 1). The only

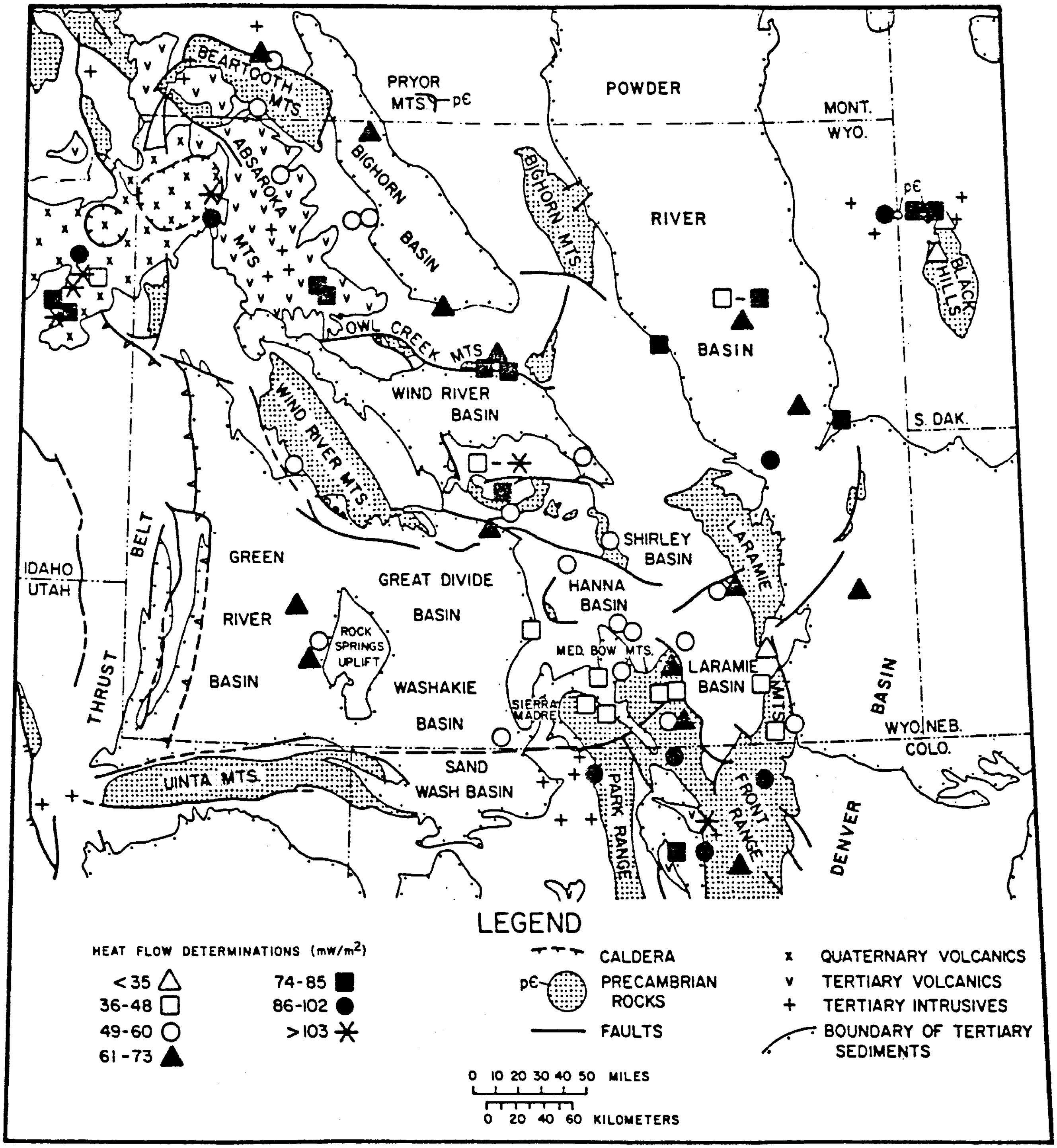

Figure 1. Generalized geology and heat flows in Wyoming and adjacent areas. From Heasler et al., 1982.

exception is in the northwest corner of Wyoming, in Yellowstone National Park, where high-temperature water exists at shallow depth due to very high heat flows of over 105 mW/m^2 (Morgan et al., 1977). By itself, a background heat flow of 33 to 80 mW/m^2 would not suggest a significant geothermal resource.

In Wyoming basins, the primary mechanism for the translation of moderate heat flow into above-normal temperature gradients is ground-water flow through geologic structures. Figures 2 and 3 illustrate systems based on two mechanisms. The temperatures listed in the lower portions of the diagrams reflect normal temperature increase with depth. Since the rocks through which the water flows are folded or faulted upwards, water at those same high temperatures rises to much shallower depth at the top of the fold or above the fault. If water proceeds through such a system without major temperature dissipation, a highly elevated thermal gradient is developed. In other words, a fold or fault system provides the "plumbing" to bring deep-heated water to a shallow depth. Any natural or man-made zone through which water can rise, such as an extensive fracture system or deep drill hole, serves the same purpose.

TEMPERATURE, DISTRIBUTION, AND APPLICATION OF RESOURCES

White and Williams (1975) of the U.S. Geological Survey divide geothermal systems into three groups: (1) high-temperature systems, greater than 302°F (150°C); (2) intermediate-temperature systems, 194-302°F (90-150°C); and (3) low-temperature systems, less than

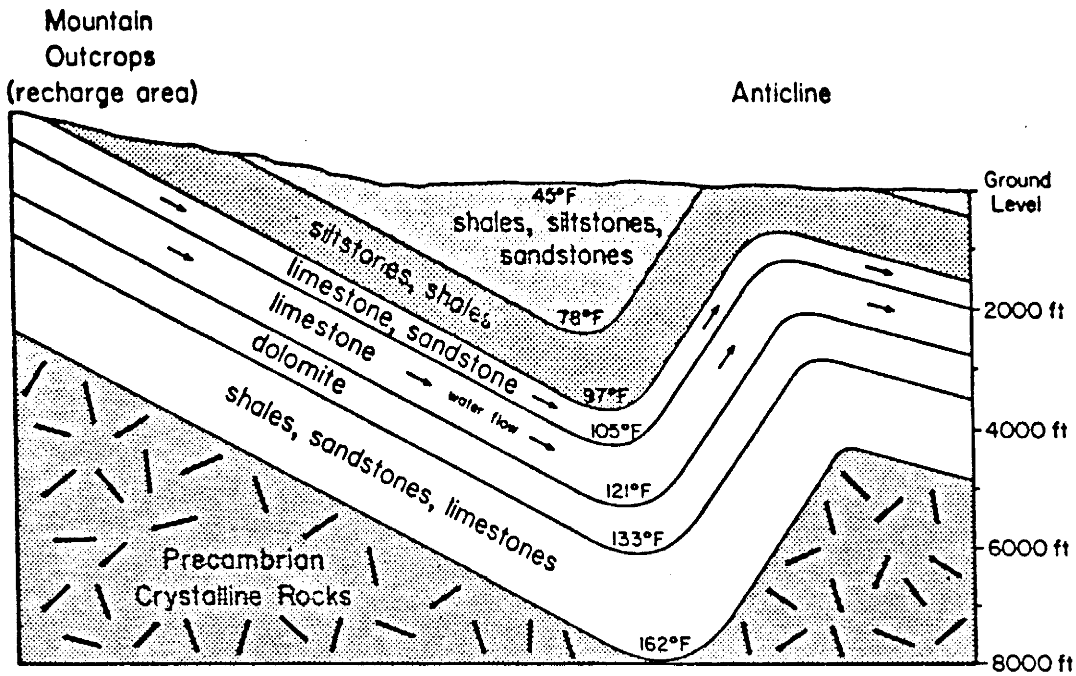

Figure 2. Simplified cross section of a fold-controlled geothermal system in Wyoming. From Hinckley and Heasler, 1984.

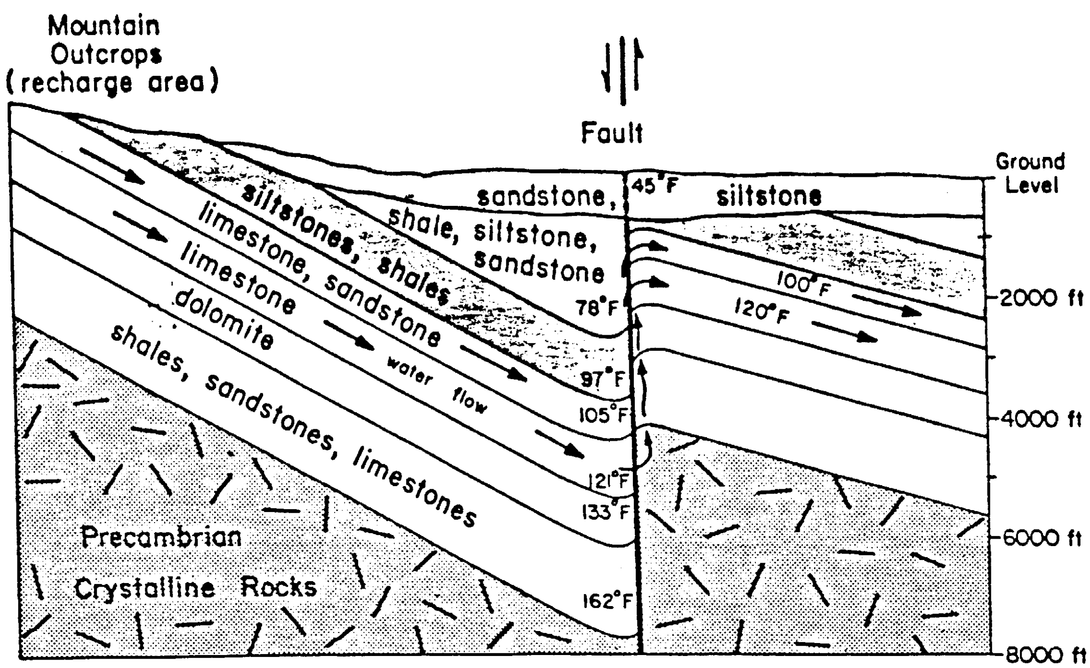

Figure 3. Simplified cross section of a fault-controlled geothermal system in Wyoming. From Hinckley and Heasler, 1984.

194°F (90°C). While Yellowstone National Park is a high-temperature system, the sedimentary basins of Wyoming fall mostly into the low-temperature and intermediate-temperature groups.

Due to the great depth of many Wyoming basins, ground water at elevated temperature exists beneath vast areas of the State as shown in Figure 4. Where a system like those described above (Figures 2 and 3) creates a local area of high gradient, it may be feasible to develop the shallow geothermal resource directly. Outside these scattered areas of high thermal gradients, it is likely that geothermal development will depend upon much deeper drilling, such as that provided by oil and gas exploration.

The geothermal resources in Wyoming's sedimentary basins are suited to relatively small-scale, direct-use projects. Energy uses include a wide range of space heating, agricultural, aquacultural, and low-temperature processing applications. (See Anderson and Lund, 1979, for a discussion of direct-use geothermal appliations). Below 100°F, uses are limited to such applications as soil and swimming pool warming, deicing, and fish farming. Through the use of ground-water heat pumps, energy can be extracted from natural waters as cool as 40°F (Gass and Lehr, 1977).

The presently documented thermal springs in the State's basin areas as shown in Figure 5 (Breckenridge and Hinckley, 1978; Heasler et al., 1983) release 3.5 trillion British thermal units (Btu's) of heat per year in cooling to ambient temperature. Like the oil springs and seeps that led developers to Wyoming's vast petroleum fields, thermal springs are simply the surface manifestation of the

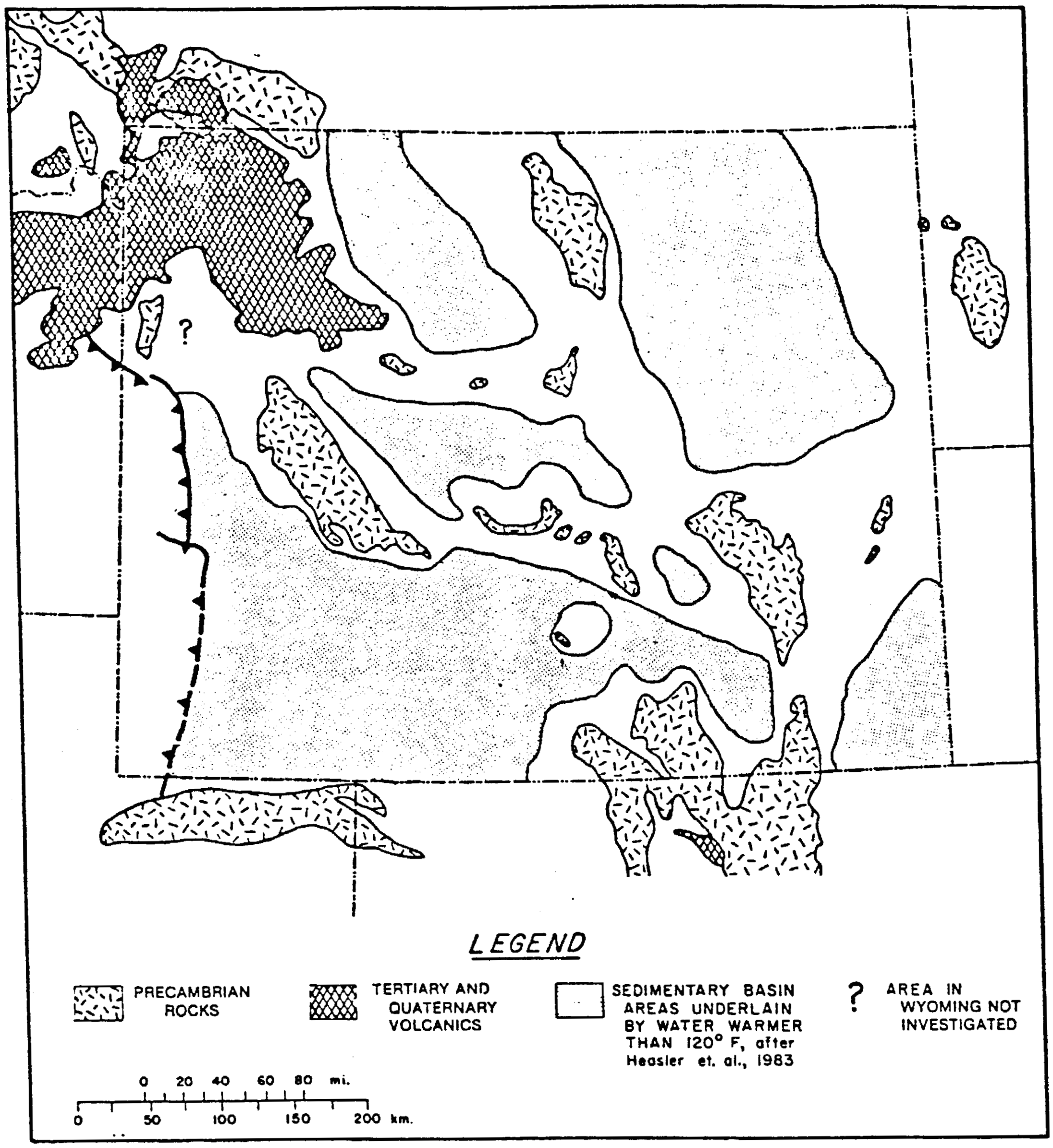

Figure 4. Simplified geologic map of Wyoming showing area of sedimentary basins potentially containing water warmer than 120° F (50° C).

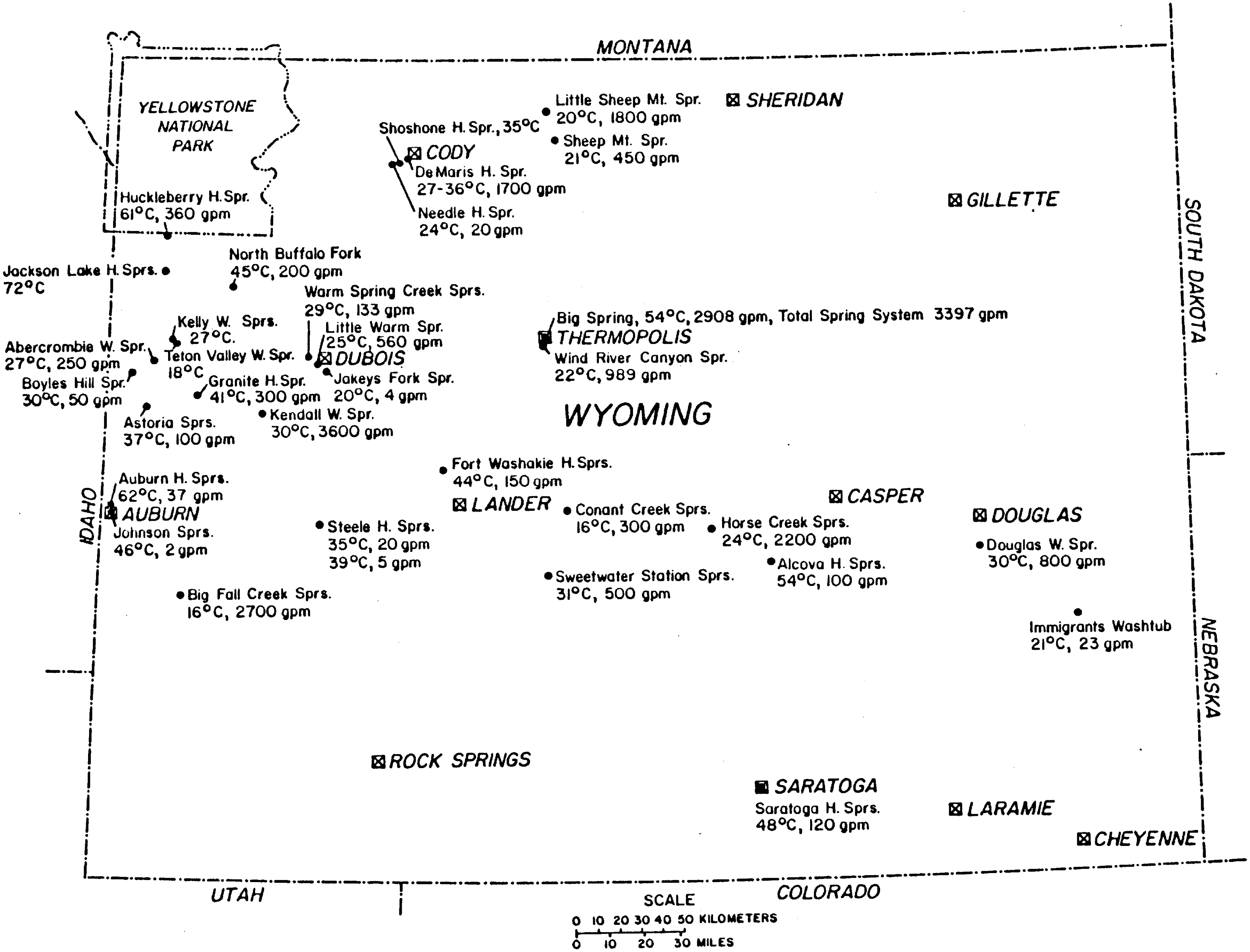

Figure 5. Hot springs in Wyoming exclusive of Yellowstone National Park.

much larger, unseen geothermal resource. For example, Hinckley (1983) has calculated that approximately 24 trillion Btu's of heat would be released per year if all the thermal water produced as a by-product in Wyoming oil fields were cooled to 70° F.

METHODS OF ASSESSMENT

Sources of subsurface temperature data in Wyoming are (1) thermal logs of wells, (2) oil and gas well bottom-hole temperatures, and (3) surface temperatures of springs and flowing wells.

(1) The most reliable data on subsurface temperatures result from direct measurement under thermally stable conditions. Using thermistor probes precise to $\pm 0.005°C$ (Decker, 1973), over 380 holes across Wyoming have been measured (Heasler et al., 1983). Temperatures were measured at intervals of 32 feet or less in holes up to 6,500 feet deep. Many of the logged holes had years to equilibrate, so temperatures of sampled intervals approached true rock temperatures. With these temperature-depth data, least squares statistical analysis was used to determine gradients at depths below the effects of long-term and short-term surface temperature fluctuations. These values are accepted as the most reliable thermal gradients, to which other temperature and gradient information is compared.

Where rock samples from a logged hole were available for testing, laboratory determinations of rock thermal conductivity were made. This information was coupled with the measured gradients to calculate the local heat flow.

(2) The most abundant subsurface temperature data are the bottom-hole temperatures (BHT's) reported with logs from oil and gas wells. Over 14,000 oil and gas well bottom-hole temperatures have been collected for study areas in Wyoming (Table I). Thermal gradients were calculated from BHT information using the formula

$$\text{Gradient} = \frac{(\text{BHT}) - (\text{MAAT})}{\text{Depth}}$$

where MAAT is the mean annual air temperature.

The use of oil field bottom-hole temperatures in geothermal gradient studies is the subject of some controversy among geothermal researchers. These are problems associated with the thermal effects of drilling and with operator inattention in measuring and reporting BHT's which cast doubt on the accuracy of individual temperature reports. Drilling fluids may transfer heat to the bottom of a drill hole, either warming or cooling the rock depending on the drilling fluid temperature and the depth of the hole. The magnitude of the thermal disturbance depends on the temperature difference between the drilling fluid and the rock, the time between the end of fluid circulation and temperature measurement, the type of drilling fluid used, the length of time of fluid circulation, and the degree to which drilling fluids have penetrated the strata.

Theoretical analysis of the deviation of a reported BHT from true formation temperature may be possible on a detailed, well-by-well basis, but is an overwhelming task basin-wide. Therefore, for studies of large areas it is assumed that such factors as time of

Table I. Summary of geothermal data on Wyoming sedimentary basins.

Basin:	Bighorn	Great Divide and Washakie	Green River	Laramie, Hanna, & Shirley	Southern Powder River	Wind River
Number of bottom-hole temperatures analyzed	2,035	1,880	1,530	445	6,100	1,740
Number of wells thermally logged	70	68	47	57	60	67
Background thermal gradient in °F/1,000 ft (°C/km)	16 (29)	15 (27)	13 (24)	12-15 (22-28)	14 (25)	15 (28)
Highest recorded temperature and corresponding depth	306°F at 23,000 ft (152°C at 7,035 m)	376°F at 24,000 ft (191°C at 7,300 m)	306°F at 21,200 ft (152°C at 6.453 m)	223°F at 12,000 ft (106°C at 3,600 m)	275°F at 16,000 ft (135°C at 4,900 m)	370°F at 21,500 ft (188°C at 6,555 m)
Basin depth in feet (km)	26,000 (8.0)	28,000 (8.5)	30,200 (9.2)	12,000; 39,000; 8,200 (3.7; 12.0; 2.5)	16,400 (5.0)	25,800 (7.6)

year, operator error, time since circulation, and drilling fluid characteristics are random disturbances which "average out" because of the large number of BHT's. The fact that drilling fluids are circulating, acting to homogenize temperatures within the hole, is, on the other hand, a systematic effect. With sufficient data at all depths, anomalous gradients may be identified despite the fact that they may be depressed in value.

The following procedures are used to assess geothermal resources in a basin from oil and gas well bottom-hole temperatures: First, all available BHT's are compiled and gradients calculated. The gradients are then plotted on a map and contoured for the basin. Thermally logged holes define fixed points in the contouring.

(3) The third source of subsurface temperature data is measurements in springs and flowing wells. Since the amount of cooling which waters have undergone between an aquifer and its surface discharge is generally unknown, these sources provide only a minimum temperature estimate. There is also commonly some uncertainty about the depth and source of flow. One can assume that all flow is from the bottom of a flowing well to obtain a minimum gradient. The most useful subsurface temperature data from springs and wells come from those whose source aquifer can be determined.

The most important aspect of any geothermal resource is the temperature and flow that can be delivered to the surface. In this sense, flowing wells and springs give excellent data, leaving no need for prediction.

IDENTIFIED GEOTHERMAL RESOURCE AREAS

Two low-temperature geothermal resource areas in Wyoming have been investigated in detail. These two areas are the Cody and Thermopolis hydrothermal systems in the Big Horn Basin (Figure 6).

Both geothermal systems are controlled by folds. Basically, regional water movement is such that water flows through deep synclines and then up over asymmetrical anticlines. This creates an area of elevated temperature on the crest of the anticline. The magnitude of the thermal anomaly depends on the velocity of water flow, the geometry of the geologic structure, the thermal conductivities of the rocks, and the regional heat flow.

The Cody hydrothermal system extends from the DeMaris Hot Springs which are west of Cody, to 7 miles (11 km) south of Cody along the Horse Center anticline. Maximum temperatures in the convecting part of this system may be 110 to 130°F (45 to 55°C) at depths of 850 to 1600 feet (260 to 500 meters). Thermal waters exist at shallower depths in the northwestern portin of the system. The main aquifers for this system are the Tensleep Sandstone, Madison Limestone, and Bighorn Dolomite. For additional data and discussion, see Heasler, 1982.

The Thermopolis hydrothermal system covers an area of approximately 50 miles^2 (130 km^2) along the crest of the Thermopolis anticline. The principal surface discharge of the hydrothermal system is in Hot Springs State Park. Six private flowing wells north of the State Park have temperatures of 115 to 130°F (46 to 54°C). Maximum temperatures of this system may be as high as 176°F (80°C)

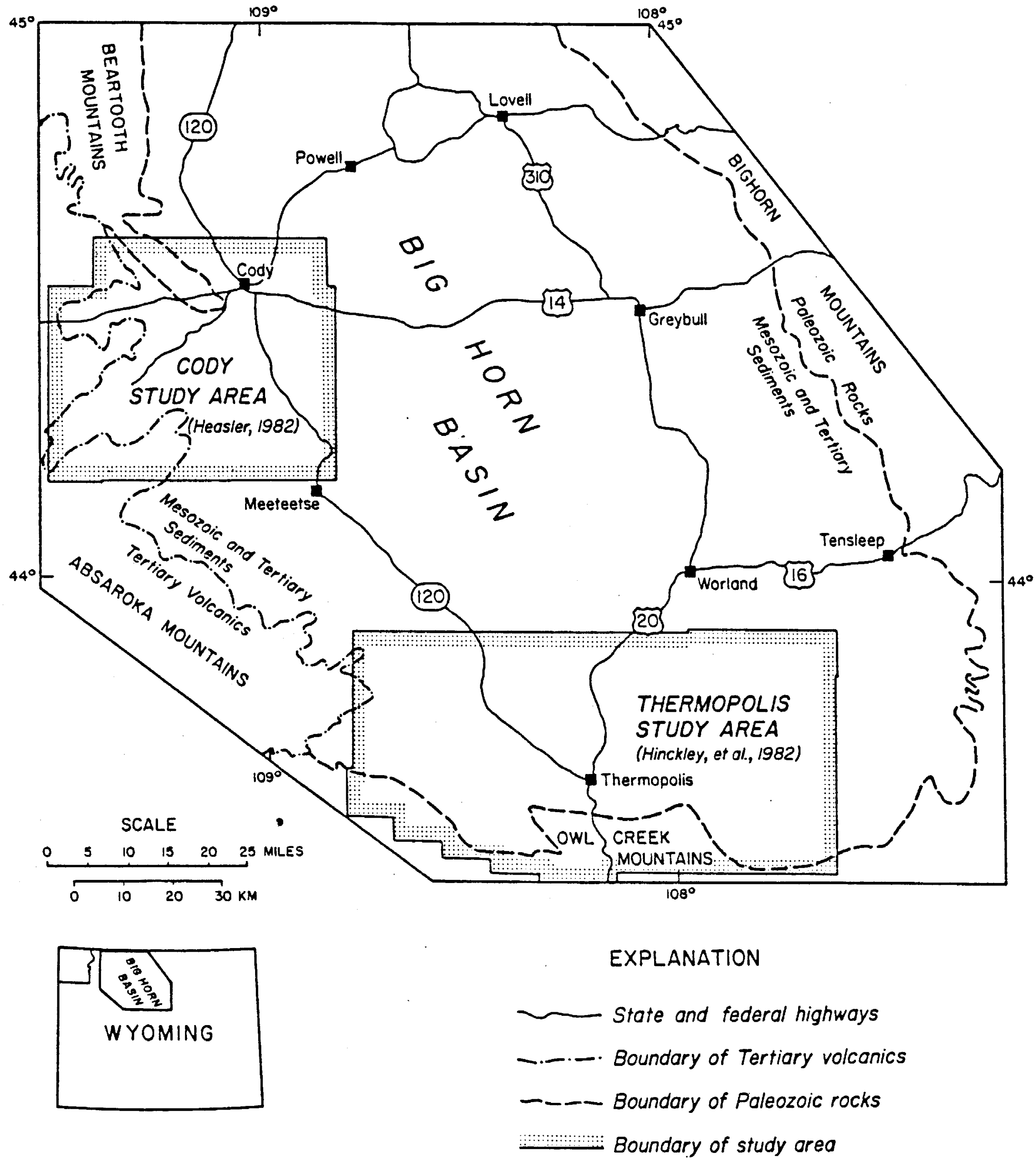

Figure 6. Location of the Cody and Thermopolis study areas.

with the maximum measured temperature being 162°F (72°C). Additional details of this system may be found in Hinckley et al., 1982, and Heasler, 1984.

POTENTIAL GEOTHERMAL RESOURCE AREAS

A vast amount of Wyoming has the potential to yield water from major aquifers warmer than 120°F (50°C) (see Figure 4). Thus, wherever a drill hole encounters this warm water, a useable geothermal resource may exist. Many oil and gas wells encounter and presently produce warm water. For example, Hinckley (1983) estimates that if the total water production of Wyoming's 52 largest water producing oil fields were cooled to 70°F (21°C), approximately 800 megawatts of thermal power would be released. Such oil and gas wells represent existing sources of hot water which could be used for heating purposes.

Other potential geothermal resources may exist in areas associated with hot springs (see Figure 5). Hot springs are merely surface manifestations of much larger subsurface hydrothermal systems. Critical geologic questions which may need to be answered before using water from a hot spring or hydrothermal system include: the areal extent of the system; the maximum temperature of the system; hydrologic information about the system; geochemistry of the water; and the heat source for the system.

Only one potential geothermal resource area in Wyoming (exclusive of Yellowstone National Park) may be capable of yielding high temperature water (greater than 302°F (150°C). This is the general area of Jackson Hole which includes eight hot springs. At the northern end of Jackson Hole near Yellowstone National Park there exists the possibility of volcanic and magmatic activity which may act as a heat source. However, considerable research needs to be conducted before such an idea can be substantiated.

REGULATION OF GEOTHERMAL RESOURCES

Three Wyoming Statutes directly deal with the regulation of geothermal development. Wyoming Statute 41-3-90 concerning the definition of underground water states that "underground water means any water, including hot water or geothermal steam, under the surface of the land or the bed of any stream, lake, reservoir, or other body of surface water, including water that has been exposed to the surface by any excavation such as a pit." Therefore, since geothermal resources are considered underground water, the Wyoming State Engineer controls geothermal resources and must be contacted prior to any exploration or development.

Wyoming Statute 41-3-101 states that the extraction of heat is a beneficial use of water. Since water in Wyoming must be beneficially used in order to have a valid water appropriation, this law defines the use of water for its heat content as a valid beneficial use.

Wyoming statute 41-1-109 gives the State Engineer "the authority to abolish, correct, discontinue or stop any condition which interfers with the natural flow of any thermal spring on state lands."

The Wyoming State Engineer is also responsible for protecting the flow of Big Horn Hot Springs at Thermopolis (Hot Springs State Park).

The type of permits needed for geothermal exploration or development will partially depend on the land ownership of the potential site. Listed on Tables II, III, and IV are the various agencies and permits pertaining to geothermal development in Wyoming. The Tables list the agency, type of permit and address for local (Table II), State (Table III), and Federal (Table IV) agencies potentially involved in the geothermal permitting process. Data contained in the Tables are primarily from Aspinwall et al., 1980.

Shown in Table V is a summary of Tables II, III, and IV. Table V lists the agencies involved in the geothermal leasing, the mandatory state permits, and conditional permits which depend on land ownership of the drill site.

Although the tables are believed to represent the agencies and permits necessary for geothermal development in Wyoming, it would be wise to reconfirm with each agency the list of permits necessary before beginning any geothermal exploration or development.

Table II

Local Agencies and Permits Involved
in Geothermal Development in Wyoming

City Agency	Permit	Required Prior To	Estimated Time for Issuance	Note
City Planning Commission	Zoning	Construction	Several Weeks	Extensive review by many people and public hearings
City Building Inspector	Building Permit	Start of Costruction	Several Days	
	Certificate of Occupancy	Use of Building	Several Days	

County Agency	Permit	Required Prior To	Estimated Time for Issuance	Note
County Planning Commission/ Board of Adjustment	Zoning	Construction	Several Weeks	May not be required; extensive review by many people and public hearings
County Engineer	Business License	Sale of Utility	Several Days	
County Clerk	Building Permit	Start of Construction	Several Days	May not be required

TABLE III

State Agencies and Permits Involved in Geothermal Development in Wyoming

State Agency	Permit	Required Prior To	Estimated Time for Issuance	Note
Board of Land Commissioners	Exploration Permit	Exploration	30-60 days	Only required of exploration or development is on
	Land Lease	Development	30-60 days	
Wyoming Department of	Encroachment	Building Utility Lines	Several days	Required to build utility lines or place steam pipe in highway right of way
	Oversize Vehicle Permit	Moving Oversize/Over weight Equipment	One day	
State Engineer	Permit to Appropriate Ground-water	Drilling Geothermal Well	3-5 weeks	
	Exploratory Permit to Appropriate Groundwater Production	Operation of Plant	3-5 weeks	
Department of Environmental Quality				
Air Quality Division	Construction Permit	Start of Construction	120-175 days	May require public hearings
Land Quality Division	"Reclamation" Permit	Start of Construction	168-233 days	May require extensive site studies

TABLE III (continued)

State Agency	Permit	Required Prior To	Estimated Time for Issuance	Note
Department of Environmental Quality				
Solid Waste Management Program	Industrial Solid Waste Disposal Permit	Start of Construction Operation of Plant	75-150 days	Site inspections required but may be waived by the agency
Water Quality Division	Construction Permit	Start of Construction	45 days	
	National Pollution Discharge Elimination System Permit	Start of Plant Operation	180 days before plant begins operation	
Public Service Commission	Certificate of Public Convenience and Necessity	Sale of Utility	12-18 months	Rarely disapproved
Industrial Siting Council/ Administration	Industrial Siting Permit	Start of Construction	90-450 days	May require extensive socio-economic and site studies. For projects over $67,400.00 in 1979 dollars

TABLE III (continued)

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TABLE IV

Federal Agencies and Permits Involved in Geothermal Development in Wyoming

Federal Agency	Permit	Required Prior To	Estimated Time for Issuance	Note
U.S. Department of the Interior U.S. Geological Survey	Conduct Site Specific Environmental analyses and Approval of Operation and Development Plans	Exploration and development (after lease by surface management agency	5-8 years	
	Exploration	Exploration		Requires many letters of permission and site easements
	Environmental Baseline Data	Gathering of 1 years environmental data		Must be complete before development plan is submitted
	Development	Drilling of production wells		Development, utilization, and production plans can be submitted and processed concurrently
	Utilization	Construction of power plants or area heat plants, injection systems, etc.		
	Production	Commercial Utility Use		Includes production data from wells and delivery timelines

TABLE IV (continued)

Federal Agency	Permit	Required Prior To	Estimated Time for Issuance	Note
U.S. Department of the Interior Bureau of Land Management	Permit for prelease Operation	Exploration	30 days	Extensive geophysical studies before approval
	Lease for BLM Lands	Major exploration construction	6 months	
	Plant Siting Permit	Plant Construction	6 months-1 year	
	Approval of Operation Plans with U.S. Geolog-			
U.S. Park Service	Unknown, although geothermal legislation allows Park development			No development in Yellowstone, carefully regulated
U.S. Fish and Wildlife Service	Advise and Consent on Environmental mental Impact Statements	Development	varies	Essential veto power over development based upon environmental
U.S. Department of Agriculture U.S. Forest Service	Special Use Permit for Pre-lease Operations	Exploratory Activities	30 days	Extensive geophysical studies before approval

TABLE IV (continued)

Federal Agency	Permit	Required Prior To	Estimated Time for Issuance	Note
	Leasing of Forest Major Exploration Service Lands		app. 18 months	Lease grants all rights to the geothermal resource
U.S. Department of Agriculture U.S. Forest Service	Approval of Operation Plans with U.S. Geological Survey			
U.S. Environmental Protection Agency	Review and Approval of Environmental Impact Statements		Exploration and/or Construction	varies
U.S. Department of Energy	Financial Services			
	State Co-operative Program			
	Geothermal Loan Guarantee Program			1 year
	Research and Demonstration Projects			varies

TABLE IV (continued)

Federal Agency	Permit	Required Prior To	Estimated Time for Issuance	Note
	Assistance to other agencies to develop geothermal lease stipulation			

TABLE V

Summary of Permits for Geothermal Development in Wyoming

Requirement	Agency	See Table
Land Purchase or Lease		
Federal Lands	B.L.M., U.S. Forest Soc., U.S. Park Service	IV
State Lands	Board of Land Comm.	III
Local Public Lands	City or County	II
Private Lands	Individuals	
Mandatory State Permits		
Permit to Appropriate Groundwater: Exploratory	Wy. State Engineer	III
Permit to Appropriate Groundwater: Production	Wy. State Engineer	III
Water Quality Constructio Permit	D.E.Q., Water Quality	II
National Pollution Discharge Elimination System Permit	D.E.Q., Water Quality	III
Land Quality Construction "Reclamation" Permit	D.E.Q., Land Quality	III
Air Quality Construction Permit	D.E.Q., Air Quality	III
Industrial Solid Waste Disposal Permit	D.E.Q., Solid Waste	III
Conditional Permits		
Local		
Zoning Permit	Wy. City or County	II
Building Permit	Wy. City or County	II

TABLE V (continued)

Summary of Permits for Geothermal
Development in Wyoming

Requirement	Agency	See Table
Conditional Permits (Cont.)		
State		
Permit to Prospect for Geothermal Resource	Wy. Board of Land Commissioners	III
Industrial Siting Permit	Wy. Industrial Siting Commissioners	III
Certificate of Public Convenience and Necessity	Wy. Public Service Commission	III
Oversize Vehicle Permit	Wy. Dept. of Highways	III
Encroachment Permit	Wy. Dept. of Highways	III
Federal		
Easements for Passage across abutting lands	Abutting Land Owners	IV
Pre-Lease Operation Permit	B.L.M., U.S Forest Service, U.S. Park Service	IV
Geothermal Operation and Development Plans	U.S. Geological Survey	IV

SUMMARY

The geothermal resources of Wyoming are widespread as shown in Figures 4 and 5. The large areal extent of warm, underground water results primarily from the deep circulation of water in aquifers. Much of this water is too deep to be economically tapped solely for geothermal uses. The heat source for this water is primarily the normal temperature increase with depth in the earth (the temperature gradient). Only in and near Yellowstone National Park does there appear to be high temperature heat sources associated with volcanism.

Isolated areas of Wyoming have high temperature gradients due to geologic structure and hydrologic flow patterns as shown in Figures 2 and 3 (also see Hinckley and Heasler, 1984, and Heasler and Hinckley, 1985). These areas represent geothermal systems which might be developed economically. However, additional work is needed in most of these areas to define the extent and magnitude of the systems.

The geothermal systems of Wyoming are directly intertwined with the State's water resource. Water is the transporting medium for the heat in all the geothermal and hot springs systems in Wyoming. Consequently, geothermal exploration and development is primarily controlled by the State Engineer who controls the State's water resources.

Present uses of warm water in the State are primarily recreational. Other existing uses are; ground water heat pumps for space heating; thermal wells for space heating; and shallow wells for highway bridge de-icing (Heasler et al., 1983). With additional time, the potential of Wyoming's geothermal resources may be increasingly recognized and used.

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