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GEOTHERMAL RESEARCH PROGRAM
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~~1) Send Dave all~~ T profiles, Roosevelt,

2) Preliminary Findings of an Investigation of the Dunes Thermal Anomaly Imperial Valley, Calif

State of Californ
The Resources Agency
Dept of Water Resources
849 S Broadway
P.O. Box 6598
L.A. 90055

3) Interpretation of Electromagnetic Soundings Using a Layered Earth Model, J. J. Daniels ~~MS.~~ Ph.D Thesis. Col Sch. Mines. Dr. G.V. Keller.

~~4) Abstract for UN mtg S.F. by Oct. 1~~

5) Review Panel for Project.

3 guys, - write to Ritchie

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3) Jirard
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6) Combs
7) Ty Copeland, Elders Petrology Riverside
8) Helgeson

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U.S. Geological Survey
Revised August 1980

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GTHM
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THE MOST PROMISING GEOTHERMAL FIELDS IN THE WESTERN UNITED STATES (EXCLUDING THE GEYSERS GEOTHERMAL FIELD)

BY
DAVID N. ANDERSON
EXECUTIVE DIRECTOR
GEOTHERMAL RESOURCES COUNCIL

Presented at the
Geothermal Resources Council
Special Short Course No. 9
San Francisco, California
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TABLE OF CONTENTS

ABSTRACT

This paper contains a brief summary of each of the most promising geothermal fields in the Western United States. The summaries contain data on size, ownership, discoveries, number of wells, involved utilities and operators, estimated power production potential, reservoirs, load centers, geology, geothermal phenomena and other important information concerning recent and ongoing activities.

DISCUSSION OF TERMS

Numerous terms have been used on the summary sheets in this report that may not have meaning to a casual acquaintance of geothermal energy. Therefore, a list of the less obvious terms, with a brief explanation of each, follows:

1. KGRA - Known Geothermal Resource Area. This term was originated by the U.S. Geological Survey.

2. AREA - Area is used to define that part of the state in which a specific field is located.

3. SIZE AND LAND OWNERSHIP - Figures are always in acres.

4. DISCOVERY AND TOTAL WELL DATA - Year, refers to year of the discovery; Operator, to who made the discovery; and Deep Wells to the number of wells drilled into the reservoir. Note: Some of the wells in the count may have been abandoned or converted to injection service.

5. UTILITY AND POWER POTENTIAL - Involved Utility, refers to that company which is involved directly in the development of power generation facilities or as otherwise noted, Estimated MWe, means the amount of electrical power in MW's that could be produced for a 30 year period. A MW is equal to 1,000 kilowatts (KW). Note: All power estimates are from U.S.G.S. Circular 790.

6. PRINCIPAL OPERATORS - Names of the most active operators in the field. In some cases not all of the operators in a field have been listed. Wells refers to the number of wells drilled or controlled by the operator that penetrate the reservoir (some of the wells may have been abandoned or converted to injection). Tests refers to the kinds of tests made.

7. FIRST POWER PLANT - Type considered refers to the type of plant design e.g. double flash, single flash, binary, etc. Size refers to the size of the plant in MW's. Status means where the plant development presently sits in time. Scheduled on Line means the date when the plant is expected to start producing power.

8. RESERVOIR DATA - Type refers to what kind of reservoir is present - dry steam (vapor) or hot water (all of the reservoirs covered in this report are hot water types). Temp. refers to the reservoir temperature in degrees Fahrenheit. Depth refers to the distance from the surface to the top of the reservoir. Salinity depicts the amount of dissolved chemicals in parts per million. Max. Flow Rate is the maximum rate of

fluid that a well produced during a flow test. Flows from geothermal wells are usually measured in thousand pounds per hour.

9. RESERVOIR TEMPERATURE - All areas in this report have reservoir temperatures in excess of 300°F (149°C or nominal 150°C) except Raft River, Idaho which has a reservoir temperature of 295°F. Although the Raft River reservoir temperature is below 300°F (the generally agreed threshold for economic power production is 375°F) it has been included because of the construction of two research power plants, a 60 KW and a 5 MW unit.

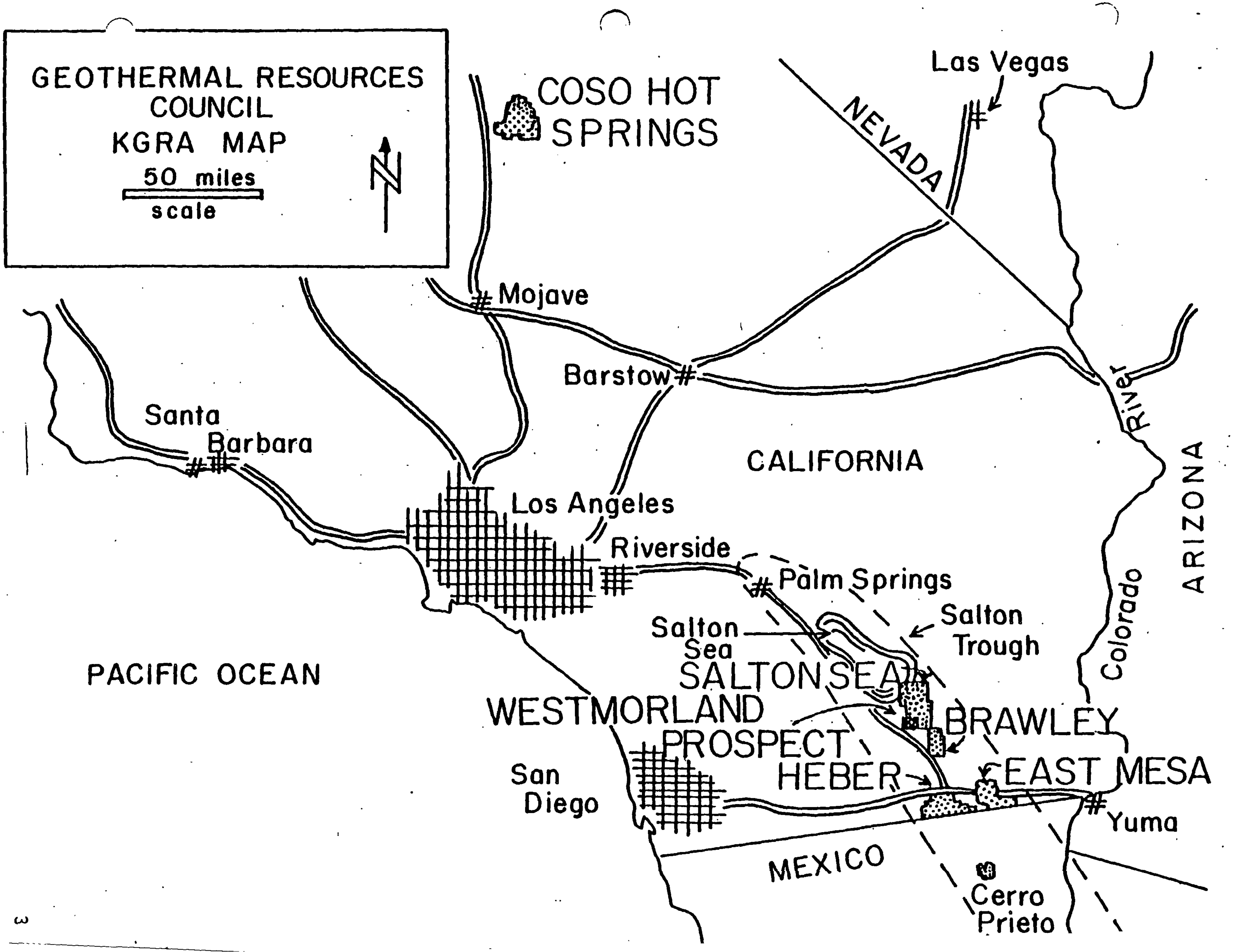
10. LOAD CENTERS - This listing shows the population and the power line distance from the field to the closest city or metropolitan area.

11. GEOLOGY AND GEOTHERMAL PHENOMENA - These terms are self explanatory.

It should be noted that The Geysers geothermal field has been omitted from the following summaries because it is now under production and its details have been widely published. However, this dry steam field is now producing 663 gross MW's of electricity and an additional 600 MW's are now being planned or are under construction.

PRODUCTION RECAP

The total estimated electrical potential of the 13 fields covered in the summaries is 12,684 MWe for 30 years. The estimates are taken from U.S. Geological Survey Circular 790 (1978). It should also be recognized that the fields covered are only a small percentage of the more than 57 Known Geothermal Resource Areas (KGRA's) that have convection systems with temperatures greater than 300°F (150°C) which have been identified by the U.S. Geological Survey.



GEOTHERMAL RESOURCES COUNCIL
KGRA MAP
50 miles
scale
N
COSO HOT SPRINGS
Las Vegas
NEVADA
Mojave
Barstow
Santa Barbara
CALIFORNIA
River
ARIZONA
Los Angeles
Riverside
Palm Springs
Salton Trough
Salton Sea
Colorado
PACIFIC OCEAN
SALTON SEA
WESTMORLAND
BRAWLEY
PROSPECT
HEBER
EAST MESA
San Diego
Yuma
MEXICO
Cerro Prieto

KGRA SALTON SEA   AREA IMPERIAL VALLEY   STATE CALIFORNIA

KGRA

SIZE: 95,824 acres

LAND OWNERSHIP:

Federal: 18,644 acres
State and Private: 77,180 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1958

OPERATOR: Kent Imperial Corp.

DEEP WELLS: 30

INVOLVED UTILITY: Southern California Edison and San Diego Gas & Electric Co.

ESTIMATED POWER POTENTIAL: 3,400 MW

PRINCIPAL OPERATORS

NAME: Magma Power Co.
WELLS: 11
TESTS: Production and injection

NAME: Union Oil Co.
WELLS: 6
TESTS: Production and injection

FIRST POWER PLANT	SCE	Magma/SDG&E
TYPE CONSIDERED:	Flash	Double Flash
SIZE (NOMINAL):	10 MW	49 MW
STATUS:	Under design	Preliminary design
SCHEDULED ON LINE:	1982	--

RESERVOIR DATA

TYPE: Hot water   *TEMPERATURE:* 640°F+   *SALINITY:* 250,000-330,000 ppm

DEPTH (TOP OF RES.): 3,000 ft   *MAXIMUM FLOW RATE:* 500,000 lbs/hr

LOAD CENTERS

CITY: Los Angeles area
POPULATION: 9 million
DISTANCE: 185 miles

CITY: San Diego area
POPULATION: 1.5 million
DISTANCE: 130 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Tertiary and quaternary marine sands and shales, non marine fluvial and lacustrine sediments and interbedded evaporites; field is traversed by five rhyolite volcanoes trending NE-SW; numerous mud pots and mud volcanoes; minor CO_2 surface vents; major faults strike at high angle to trend of volcanic cones. Area underlain by an active spreading center (the east Pacific rise).

REMARKS

Presence of field known prior to 1925; CO_2 produced from shallow wells during the 1940's; major drilling effort (12 wells) in the early 1960's, which was accompanied by an attempt to reclaim potash from the produced brine; drilling activity renewed in early 1970's; SDG&E and ERDA funded and constructed a 10 MW equivalent (no turbine generator) pilot flash binary power plant in 1975 which is not included under first power plants; high salinity (20 to 30%) will hamper full development due to corrosion and scaling problems. Techniques are being developed to lessen the corrosion problems by a three party association: Union Oil Co., Mono Power Co. (a subsidiary of Southern California Edison), and Southern Pacific Land Company. In addition, Magma Power Co. is also active in corrosion and scaling research.

KGRA WESTMORLAND PROSPECT (Salton Sea) AREA IMPERIAL VALLEY STATE CALIFORN

KGRA

SIZE: approx. 20,000 acres

LAND OWNERSHIP:
- Federal: 0
- State: 0
- Private: 20,000 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1976

OPERATOR: Republic Geothermal, Inc.

DEEP WELLS: 6

INVOLVED UTILITY:
Imperial Irrigation District service area

ESTIMATED POWER POTENTIAL:
1710 MW

PRINCIPAL OPERATORS

NAME: Westmorland Geothermal Associates (Republic Geothermal, Inc. and MAPCO)

WELLS: 6

TESTS: Production and injection

FIRST POWER PLANT

TYPE CONSIDERED: Double Flash

SIZE (NOMINAL): 50 MW

STATUS: Under design

SCHEDULED ON LINE: 1983

RESERVOIR DATA

TYPE: Hot water

TEMPERATURE: 500°F

SALINITY: 20,000-70,000

DEPTH (TOP OF RES.): 4,000 ft

MAXIMUM FLOW RATE: 580,000 lbs/hr

LOAD CENTERS

CITY: Los Angeles area

POPULATION: 9 million

DISTANCE: 185 miles

CITY: San Diego area

POPULATION: 1.5 million

DISTANCE: 130 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Tertiary and quaternary marine sands and shales and lacustrine lake bed and deltaic sediments; no surface volcanic expression or geothermal indicators; vertical strike slip faulting controls distinct fault block salinities; distinct gravity and thermal anomalies. Area underlain by an active spreading center (the east Pacific rise).

REMARKS

Area is jointly leased and operated by Westmorland Geothermal Associates (Republic Geothermal, Inc. and MAPCO); a federal loan guarantee for reservoir evaluation and development drilling was obtained in 1979 and work on two additional wells is under way; area lies to the SW of the Salton Sea anomaly.

KGRA BRAWLEY AREA IMPERIAL VALLEY STATE CALIFORNI

KGRA

SIZE: 28,885 ACRES

LAND OWNERSHIP:
Federal: 0
State: 0
Private: 28,885 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1975

OPERATOR: Union Oil Co.

DEEP WELLS: 10

INVOLVED UTILITY: Southern California Edison

ESTIMATED POWER POTENTIAL: 640 MW

PRINCIPAL OPERATORS

NAME: Union Oil Co.

WELLS: 8

TESTS: Production and injection

NAME: Chevron Resources Co.

WELLS: 2

TESTS: Short term production

FIRST POWER PLANT SCE

TYPE CONSIDERED: Single Flash

SIZE (NOMINAL): 10 MW

STATUS: Under construction

SCHEDULED ON LINE: 1980

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 500°F *SALINITY:* 100,000 ppm

DEPTH (TOP OF RES.): 3,000 ft *MAXIMUM FLOW RATE:* 70,000 lbs/hr

LOAD CENTERS

CITY: Los Angeles area

POPULATION: 9 million

DISTANCE: 200 miles

CITY: San Diego area

POPULATION: 1.5 million

DISTANCE: 115 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Tertiary and quaternary marine sands and shales and non marine fluvial and lacustrine sediments; no surface volcanic expression or geothermal indicators; field in close proximity to active Brawley fault. Area is underlain by an active spreading center (the east Pacific rise).

REMARKS

Field was identified by University of California at Riverside field studies in late 1960's and early 1970's; high salinity due to close proximity to lowest portions of northern landward extension of Salton Trough (evaporite sink); high salinity will cause problems in the design, construction and operation of power plants; the Union 10 MW power plant is approximately 85% complete.

KGRA HEBER AREA IMPERIAL VALLEY STATE CALIFORNIA

KGRA

SIZE: 58,568 acres

LAND OWNERSHIP:
Federal: 0
Private: 58,568 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1972

OPERATOR: Magma Power Company

DEEP WELLS: 17

INVOLVED UTILITY: Southern California Edison and San Diego Gas & Electric Co.

ESTIMATED POWER POTENTIAL: 650 MW

PRINCIPAL OPERATORS

NAME: Chevron Oil Company
WELLS: 8
TESTS: Extensive production and injection

NAME: Union Oil Company
WELLS: 7
TESTS: Short term, production

FIRST POWER PLANT

	SCE	SDG&E (see remarks)
TYPE CONSIDERED:	Double Flash	Flash Binary
SIZE (NOMINAL):	50 MW	65 MW
STATUS:	In final design	Design complete
SCHEDULED ON LINE:	Late 1982	1984

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 350-375°F *SALINITY:* 14,000 ppm

DEPTH (TOP OF RES.): 3,200 ft *MAXIMUM FLOW RATE:* 440,000 lbs/hr

LOAD CENTERS

CITY: Los Angeles area
POPULATION: 9 million
DISTANCE: 225 miles

CITY: San Diego area
POPULATION: 1.5 million
DISTANCE: 100 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Tertiary and quaternary marine sands and shales and non marine fluvial and lacustrine sediments, minor volcanic sills; no surface volcanic expression or geothermal indicators. Area is underlain by an active spreading center (the east Pacific rise).

REMARKS

In 1977-78 the field was considered by U.S. Department of Energy as a possible site for a 50 MW binary power plant (the plant was subsequently awarded to Union Oil Co. at their Baca location in northern New Mexico). In December of 1979 Chevron Resources Company (the major operator) signed a contract with Southern California Edison, who will construct a 50 MW power plant. The completion date is late 1982. San Diego Gas & Electric is contemplating the co-sponsoring of a 50 MW binary type demonstration power plant with the U.S. Department of Energy.

KGRA EAST MESA AREA IMPERIAL VALLEY STATE CALIFORNI

KGRA

SIZE: 38,365 ACRES

LAND OWNERSHIP:

Federal: 32,725
Federal leased: 11,770 acres
State and Private: 4,840 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1972

OPERATOR: U.S. Bureau of Reclamation

DEEP WELLS: 18

INVOLVED UTILITY: San Diego Gas and Electric Co.

ESTIMATED POWER POTENTIAL: 360 MW

PRINCIPAL OPERATORS

NAME: Republic Geothermal, Inc.
WELLS: 8
TESTS: Production and injection

NAME: Imperial Magma
WELLS: 5
TESTS: Production and injection

FIRST POWER PLANT	Republic	Magma
TYPE CONSIDERED:	Double Flash	Binary
SIZE (NOMINAL):	48 MW (net)	10 MW
STATUS:	Plant designed	Construction completed
SCHEDULED ON LINE:	Late 1982	Spring 1980

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 400°F *SALINITY:* 2,500 ppm

DEPTH (TOP OF RES.): 2,450 ft *MAXIMUM FLOW RATE:* 740,000 lbs/hr

LOAD CENTERS

CITY: Los Angeles area
POPULATION: 9 million
DISTANCE: 245 miles

CITY: San Diego area
POPULATION: 1.5 million
DISTANCE: 120 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Tertiary and quaternary marine sands and shales and non marine fluvial and lacustrine sediments; no surface volcanic expression or geothermal indicators; area is slightly westward sloping, sandy mesa with a minimum elevation a few feet above the valley floor; major faults trend NW-SE. Area is underlain by an active spreading center (the east Pacific rise)

REMARKS

In the early 1970's the U.S. Bureau of Reclamation drilled and tested 5 wells and constructed and tested multi-stage flash and vertical tube desalination units; a facility (operated by U.S. DOE) at the site is available for the testing of various prototype energy conversion machines; loan guarantee granted to Republic Geothermal, Inc. for reservoir development; a shallow, slightly brackish aquifer is present over most of the mesa. Magma's 10 MW binary power plant will be the first binary type plant in the United States and the first hot water plant in the United States.

KGRA COSO HOT SPRINGS AREA MOJAVE STATE CALIFORN

KGRA

SIZE: 51,760 acres

LAND OWNERSHIP:

Federal: 43,330 acres
(BLM: 16,690 acres)
(Navy: 26,640 acres)
State and private: 8,430 acres

DEVELOPMENT

Numerous shallow temperature wells have been drilled and a deep reservoir test was completed by U.S. Department of Energy in December 1977.

INVOLVED UTILITY: Mono Power Co. (a subsidiary of Southern California Edison)

ESTIMATED POWER POTENTIAL: 650 MW

PRINCIPAL OPERATORS (see remarks)

NAME:
WELLS:
TESTS:

NAME:
WELLS:
TESTS:

FIRST POWER PLANT

TYPE CONSIDERED: Decision pending confirmation of a reservoir
SIZE (NOMINAL):
STATUS:
SCHEDULED ON LINE:

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 390°F+ *SALINITY:* 6,000 ppm
DEPTH (TOP OF RES.): 2,000 ft *MAXIMUM FLOW RATE:* well was not tested

LOAD CENTERS (see remarks)

CITY: Los Angeles area
POPULATION: 9 million
DISTANCE: 160 miles

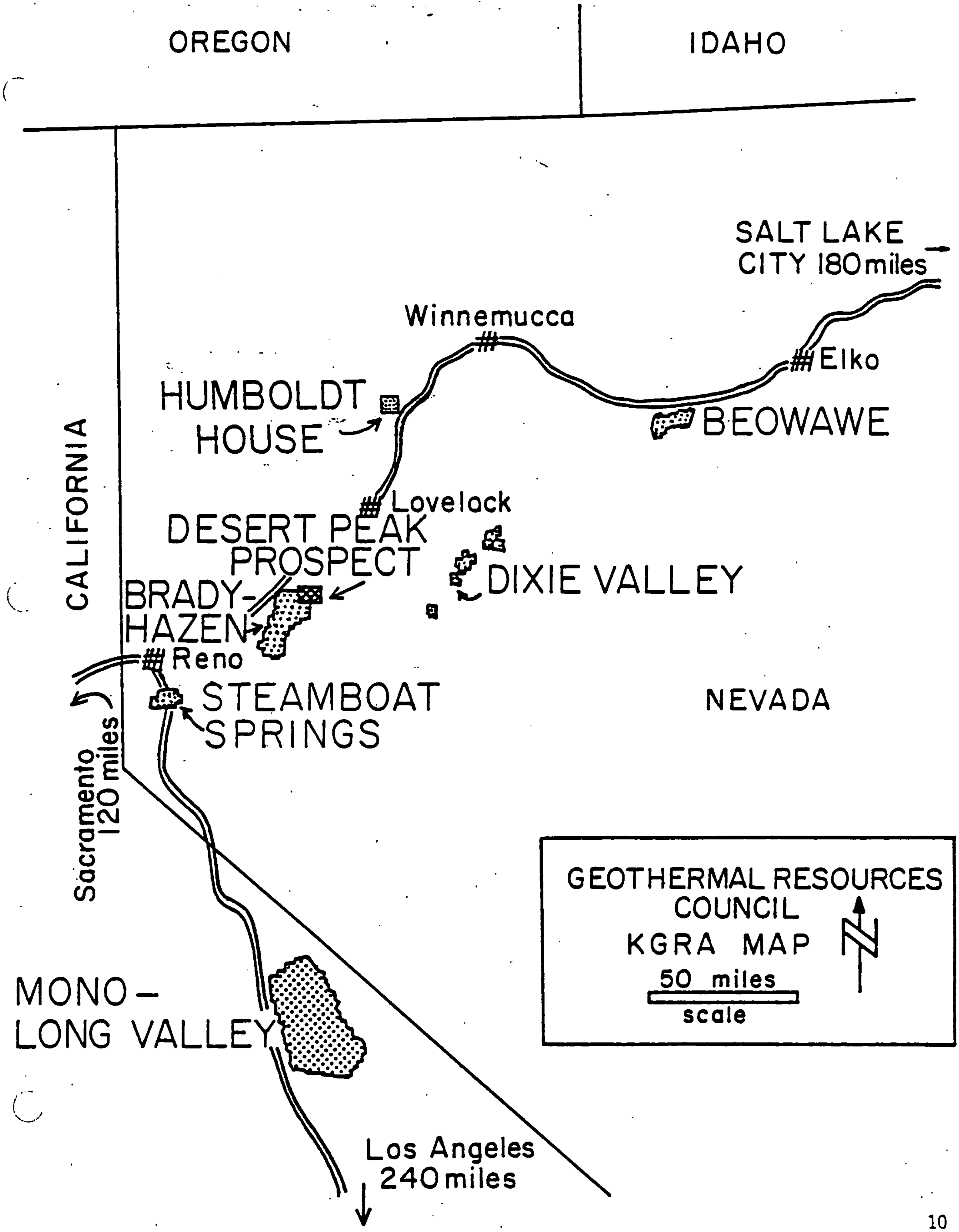
CITY: Bakersfield area
POPULATION: 86,000
DISTANCE: 60 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Granitic, metasedimentary and metavolcanic rocks extruded and overlaid by rhyolites and andesites in the form of cinder cones, pierlitic domes and flows. Volcanic s flows and air falls are interbedded with lacustrine and fanglomerate deposits. Structurally the area appears to have been under tension throughout the late Cenozoic which caused a fault pattern to develop that served as volcanic conduits. Fumaroles and hot springs are common in some parts of the KGRA.

REMARKS

Major portion of KGRA land is controlled by the federal government and is partially overlain by instrumented bombing ranges operated by the U.S. Navy. This aspect, in the past, has caused a general reluctance by the Navy to lease or allow the land to be opened for leasing by the U.S. Bureau of Land Management. Recently the Navy has developed a program to contract directly for the development of several square miles of land owned in fee and to allow the U.S. BLM to commence leasing procedures on other lands. In late 1979 the U.S. Navy and California Energy Company (CEC) signed a contract to develop the Navy fee land. The contract calls for CEC to ultimately develop 75 MW's of electrical power. The power produced on the Navy fee land would go to power Navy installations in the west.


OREGON
IDAHO
SALT LAKE CITY 180 miles
Winnemucca
Elko
HUMBOLDT HOUSE
BEOWAWE
CALIFORNIA
Lovelack
DESERT PEAK PROSPECT
DIXIE VALLEY
BRADY-HAZEN
Reno
STEAMBOAT SPRINGS
NEVADA
Sacramento 120 miles
GEOTHERMAL RESOURCES COUNCIL
KGRA MAP
50 miles
scale
MONO-LONG VALLEY
Los Angeles 240 miles

KGRA STEAMBOAT SPRINGS AREA WESTERN NEVADA STATE NEVADA

KGRA

SIZE: 8,914 acres

LAND OWNERSHIP:

Federal: 4,457 acres
Private: 4,457 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: Unknown

OPERATOR: Unknown

DEEP WELLS: 1

INVOLVED UTILITY:

Sierra Pacific Power Co. service area

ESTIMATED POWER POTENTIAL:

350 MW

PRINCIPAL OPERATORS

NAME: Phillips Petroleum Co.

WELLS: 1 deep, 20+ temp. grad. and four 800-2,000 ft observation wells

TESTS: None

NAME: Gulf Mineral Resources Co. (Gulf has extensive land interests in the area.)

WELLS: None

TESTS: None

FIRST POWER PLANT (see remarks)

TYPE CONSIDERED:

SIZE (NOMINAL):

STATUS:

SCHEDULED ON LINE:

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 400°F+ *SALINITY:* 3,000 ppm

DEPTH (TOP OF RES.): 2,000 ft+ *MAXIMUM FLOW RATE:* --

LOAD CENTERS

CITY: Reno

POPULATION: 150,000

DISTANCE: 12 miles

CITY:

POPULATION:

DISTANCE:

GEOLOGY AND GEOTHERMAL PHENOMENA

Sierra Nevada granitic rocks, highly fractured; fractures related to the eastern Sierra frontal fault system; hot springs and siliceous sinter terraces common.

REMARKS

Phillips Petroleum Co. drilled a deep test in mid 1979 and the test results looked promising. A follow-up exploration program which includes three 2,000 ft. temperature test holes is in progress.

A utility group consisting of Sierra Pacific Power Co. (the lead agency), Sacramento Municipal Utility District, Pacific Power and Light, Portland General Electric and the Eugene Water and Electric Board is considering the co-funding of a 50 MW plant at Desert Peak, Beowawe or Dixie Valley provided that a suitable reservoir can be developed and an agreement can be reached with the operator(s). In addition, the group is considering a 10 MW pilot plant at any one of five sites (the three mentioned above plus Steamboat Springs and Humboldt House).

KGRA DESERT PEAK PROSPECT (Brady-Hazen) AREA RENO STATE NEVADA

KGRA

SIZE: 98,508 acres

LAND OWNERSHIP:
Federal: 59,358 acres
Federal leased: 26,049 acres
State and private: 39,150 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1976

OPERATOR: Phillips Petroleum Co.

DEEP WELLS: 4

INVOLVED UTILITY: Sierra Pacific Power Co. service area

ESTIMATED POWER POTENTIAL: 750 MW

PRINCIPAL OPERATORS

NAME: Phillips Petroleum Co.

WELLS: 4

TESTS: Production

NAME:

WELLS:

TESTS:

FIRST POWER PLANT (see remarks)

TYPE CONSIDERED:

SIZE (NOMINAL):

STATUS:

SCHEDULED ON LINE: unavailable

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 400°F+ *SALINITY:* 6,000-8,000 ppm

DEPTH (TOP OF RES.): 2,000+ ft *MAXIMUM FLOW RATE:* Test program under way

LOAD CENTERS

CITY: Reno

POPULATION: 150,000

DISTANCE: 55 miles

CITY:

POPULATION:

DISTANCE:

GEOLOGY AND GEOTHERMAL PHENOMENA

Faulted tertiary volcanics (basalts, rhyolites) overlying a metamorphosed basement complex; hot springs, sinter and travertine deposits.

REMARKS

Desert Peak area lies just north of the Brady-Hazen KGRA and will eventually be included. Preliminary meetings have taken place between the operator, utility and an engineering firm concerning the design and construction of a power plant. Additional exploration and development work is under way.

A utility group consisting of Sierra Pacific Power Co. (the lead agency), Sacramento Municipal Utility District, Pacific Power and Light, Portland General Electric and the Eugene Water and Electric Board is considering the co-funding of a 50 MW plant at Desert Peak, Beowawe or Dixie Valley provided that a suitable reservoir can be developed and an agreement can be reached with the operator(s). In addition the group is considering a 10 MW pilot plant at any one of five sites (the three mentioned above plus Steamboat Springs and Humboldt House).

KGRA DIXIE VALLEY AREA CENTRAL NEVADA STATE NEVADA

KGRA

SIZE: 38,989 approx. acres

LAND OWNERSHIP:

Federal: 38,989 approx. acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1978

OPERATOR: Sunoco Energy Devel. Co. (Sunedco)

DEEP WELLS: 4

INVOLVED UTILITY: Sierra Pacific Power Co. service area

ESTIMATED POWER POTENTIAL: --

PRINCIPAL OPERATORS

NAME: Sunedco

WELLS: 4

TESTS: Production

NAME: Natomas/Thermal Power Co. / Southland Royalty

WELLS: 2

TESTS: Preliminary testing

FIRST POWER PLANT (see remarks)

TYPE CONSIDERED:

SIZE (NOMINAL):

STATUS:

SCHEDULED ON LINE:

RESERVOIR DATA

TYPE: --

TEMPERATURE: --

SALINITY: --

DEPTH (TOP OF RES.): --

MAXIMUM FLOW RATE: --

LOAD CENTERS

CITY: Reno

POPULATION: 150,000

DISTANCE: 110 miles

CITY:

POPULATION:

DISTANCE:

GEOLOGY AND GEOTHERMAL PHENOMENA

Jurassic metasedimentary rocks overlain by tertiary sediments, which are overlain by volcanic deposits including basalt and andesitic rocks, rhyolitic flows and ash deposits, and younger alluvial fans. Early structural history consists of complexed folding and thrust faulting. Active structure consists of normal faults bounding a north-northeast trending graben with horst blocks. Numerous hot springs present.

REMARKS

In November 1978, Sunedco completed and production tested the first deep well in the area. Results from the test have been encouraging and have caused the drilling of two additional wells. In addition, a two company association (Natomas/Thermal Power Co. and Southland Royalty) have drilled two additional wells. Although the area was discovered over two years ago, none of the involved operators have made a formal press release concerning the potential.

A utility group consisting of Sierra Pacific Power Co. (the lead agency), Sacramento Municipal Utility District, Pacific Power and Light, Portland General Electric and the Eugene Water and Electric Board is considering the co-funding of a 50 MW plant at Desert Peak, Beowawe or Dixie Valley provided that a suitable reservoir can be developed and an agreement can be reached with the operator(s). In addition, the group is considering a 10 MW pilot plant at any one of five sites (the three men-

FIELD HUMBOLDT HOUSE AREA BATTLE MOUNTAIN STATE NEVADA

FIELD

SIZE: Unknown

LAND OWNERSHIP:

DISCOVERY AND TOTAL WELL DATA

YEAR: 1978

OPERATOR: Phillips Petroleum Co.

DEEP WELLS: 3

INVOLVED UTILITY: Sierra Pacific Power Co. service area.

ESTIMATED POWER POTENTIAL: 47 MW

PRINCIPAL OPERATORS

NAME: Phillips Petroleum Co.

WELLS: 2

TESTS: Production tests only

NAME: Union Oil Co.

WELLS: 1

TESTS: Preliminary

FIRST POWER PLANT (see remarks)

TYPE CONSIDERED:

SIZE (NOMINAL):

STATUS:

SCHEDULED ON LINE:

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 360°F+ *SALINITY:* 6,000 ppm

DEPTH (TOP OF RES.): 1,800 ft *MAXIMUM FLOW RATE:* Unavailable

LOAD CENTERS

CITY: Reno

POPULATION: 150,000

DISTANCE: 120 miles

CITY:

POPULATION:

DISTANCE:

GEOLOGY AND GEOTHERMAL PHENOMENA

Mesozoic metamorphosed volcanic and sedimentary rocks overlain by tertiary lake beds in the valleys; large hydrothermally altered areas, old tuffa mounds and other hot springs deposits; structure is high angle faults bounding basins and mountain ranges.

REMARKS

Phillips Petroleum Co. feels that they have only penetrated a shallow auxiliary reservoir and that the main reservoir exists at depth and will contain water at temperatures of approximately 430°F. The Humboldt House area is not an official KGRA, however, it is near the Rye Patch KGRA.

A utility group consisting of Sierra Pacific Power Co. (the lead agency), Sacramento Municipal Utility District, Pacific Power and Light, Portland General Electric and the Eugene Water and Electric Board is considering the co-funding of a 50 MW plant at Desert Peak, Beowawe or Dixie Valley provided that a suitable reservoir can be developed and an agreement can be reached with the operator(s). In addition, the group is considering a 10 MW pilot plant at any one of five sites (the three mentioned above plus Steamboat Springs and Humboldt House).

KGRA BEOWAWE AREA BATTLE MOUNTAIN STATE NEVADA

KGRA

SIZE: 33,225 acres

LAND OWNERSHIP:

Federal: approx. 16,000 acres
State and private: approx. 1,600 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1959

OPERATOR: Magma Power Co.

DEEP WELLS: 8

INVOLVED UTILITY: Sierra Pacific Power Co. service area

ESTIMATED POWER POTENTIAL: 127 MW

PRINCIPAL OPERATORS

NAME: Chevron Oil Co.
WELLS: 4
TESTS: Limited production

NAME: Getty Oil Co.
WELLS: none
TESTS: none

FIRST POWER PLANT (see remarks)

TYPE CONSIDERED:

SIZE (NOMINAL):

STATUS:

SCHEDULED ON LINE:

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 412°F *SALINITY:* 1,400 ppm

DEPTH (TOP OF RES.): 700 ft *MAXIMUM FLOW RATE:* 1,500,000 lbs/hr ±

LOAD CENTERS

CITY: Reno
POPULATION: 150,000
DISTANCE: 220 miles

CITY: Elko
POPULATION: 10,000
DISTANCE: 40 miles

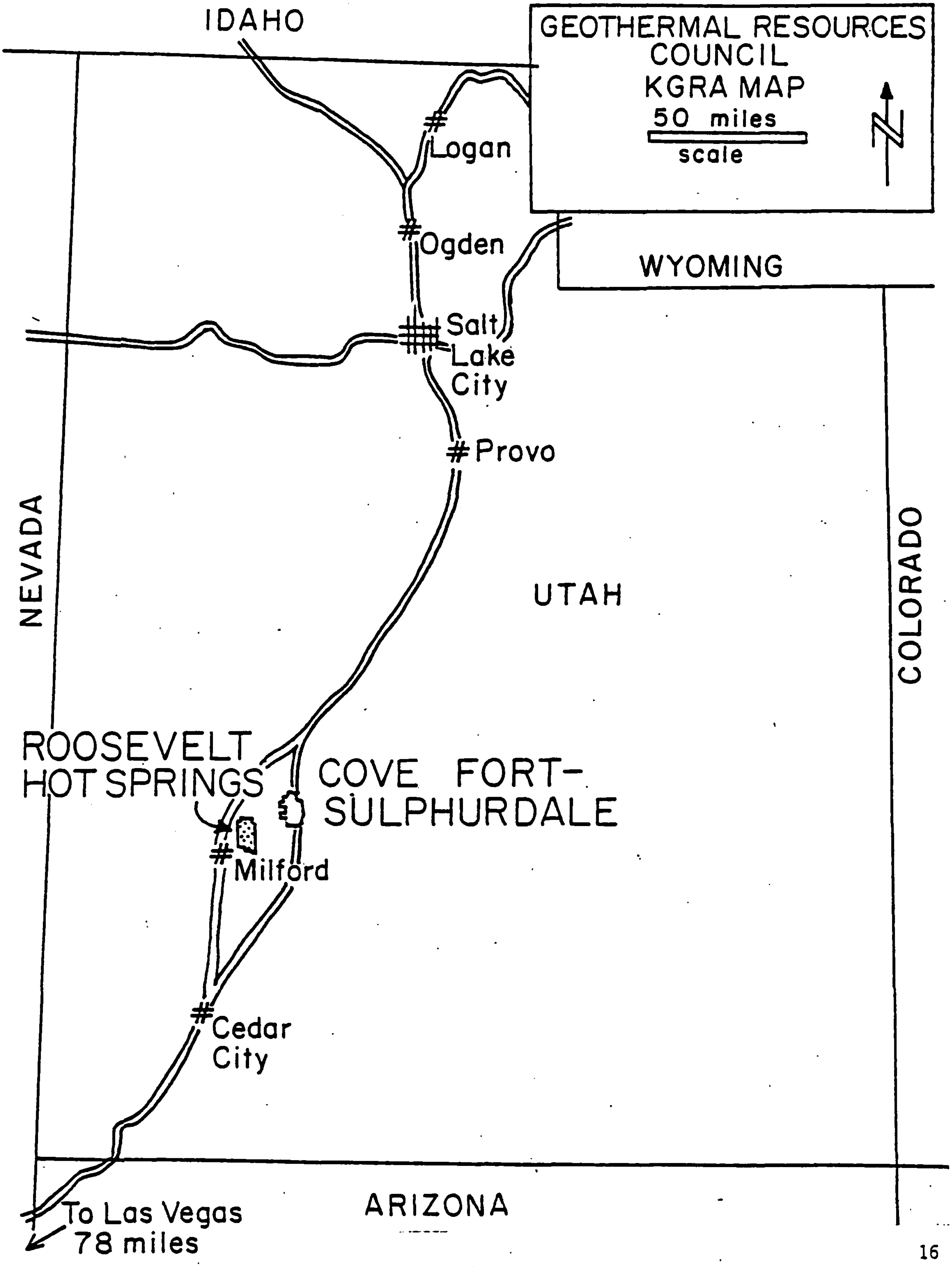
GEOLOGY AND GEOTHERMAL PHENOMENA

Paleozoic sediments overlaid by tertiary volcanics, principally basaltic flows; area centered along a major normal, NE-SW trending fault; numerous hot springs, geysers, fumaroles and sinter deposits.

REMARKS

Chevron Oil Co. has an extensive exploration program under way which includes the drilling of several wells. Getty Oil Co. has started a temperature gradient well program. The field area has been unitized (Chevron and Getty Oil Cos.)

A utility group consisting of Sierra Pacific Power Co. (the lead agency), Sacramento Municipal Utility District, Pacific Power and Light, Portland General Electric and the Eugene Water and Electric Board is considering the co-funding of a 50 MW plant at Desert Peak, Beowawe or Dixie Valley provided that a suitable reservoir can be developed and an agreement can be reached with the operator(s). In addition, the group is considering a 10 MW pilot plant at any one of five sites (the three mentioned above plus Steamboat Springs and Humboldt House).


GEOTHERMAL RESOURCES COUNCIL
KGRA MAP
50 miles
scale
N
IDAHO
Logan
Ogden
WYOMING
Salt Lake City
Provo
NEVADA
UTAH
COLORADO
ROOSEVELT HOT SPRINGS
COVE FORT-SULPHURDALE
Milford
Cedar City
ARIZONA
To Las Vegas 78 miles

KGRA ROOSEVELT HOT SPRINGS AREA MILFORD STATE UTAH

KGRA

SIZE: 29,791 acres

LAND OWNERSHIP:

Federal leased: 24,592 acres
State and private: 5,199 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1975

OPERATOR: Phillips Petroleum Co.

DEEP WELLS: 9

INVOLVED UTILITY: Utah Power and Light service area

ESTIMATED POWER POTENTIAL: 970 MW

PRINCIPAL OPERATORS

NAME: Phillips Petroleum Co.

WELLS: 7

TESTS: Extensive production and injection

NAME: Thermal Power Co.

WELLS: 2

TESTS: Production

FIRST POWER PLANT

TYPE CONSIDERED: Several power plant proposals are now being considered

SIZE (NOMINAL):

STATUS:

SCHEDULED ON LINE:

RESERVOIR DATA

TYPE: Hot water

TEMPERATURE: 500°F

SALINITY: 7,800 ppm

DEPTH (TOP OF RES.): 2,700 ft

MAXIMUM FLOW RATE: 1,000,000 lbs/hr

LOAD CENTERS

CITY: Salt Lake City area

POPULATION: 820,000

DISTANCE: 200 miles

CITY: Las Vegas, Nevada

POPULATION: 160,000

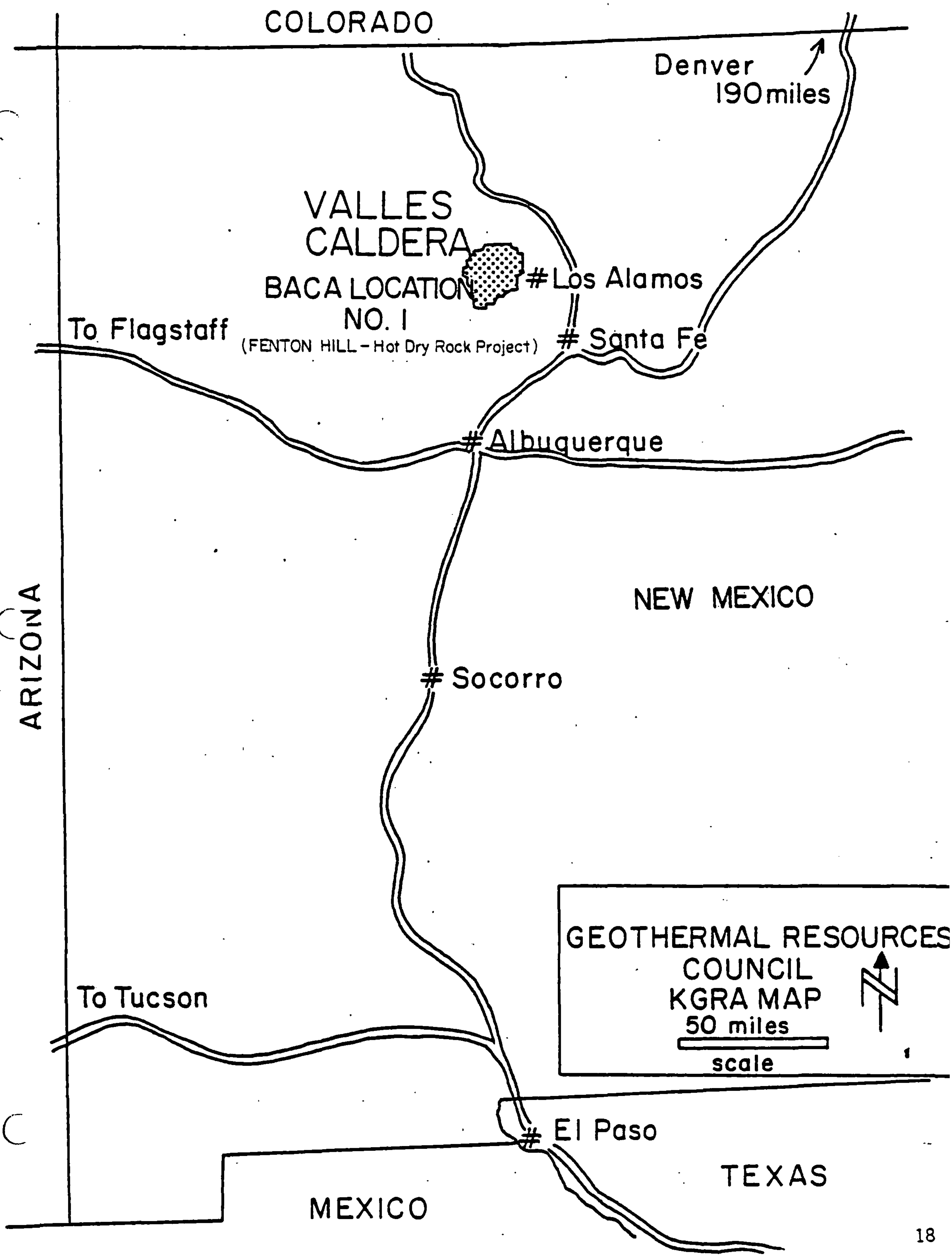
DISTANCE: 240 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Precambrian (?) metamorphics overlaid by unconsolidated tertiary and quaternary sediments; quaternary volcanics are present on the surface three miles east of the field; sinter deposits in KGRA area.

REMARKS

Large percentage of KGRA has been unitized; cooling water may be difficult to obtain.


COLORADO
Denver
190miles
VALLES
CALDERA
BACA LOCATION
NO. 1
(FENTON HILL - Hot Dry Rock Project)
Los Alamos
Santa Fe
To Flagstaff
Albuquerque
ARIZONA
NEW MEXICO
Socorro
GEOTHERMAL RESOURCES
COUNCIL
KGRA MAP
50 miles
scale
N
To Tucson
El Paso
TEXAS
MEXICO

KGRA BACA LOCATION NO. 1 (Valles Caldera) AREA -- STATE NEW MEXI

KGRA

SIZE: 168,761 acres

LAND OWNERSHIP:

Federal: 30,000+ acres
Federal leased: 18,000 acres
State and private: 120,700+ acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1970

OPERATOR: Pat Dunigan

DEEP WELLS: 14

INVOLVED UTILITY: New Mexico Public Service Co.

ESTIMATED POWER POTENTIAL: 2,700 MW

PRINCIPAL OPERATORS

NAME: Union Geothermal Co. of New Mexico (a subsidiary of Union Oil Co.)

WELLS: 14

TESTS: Extensive production and injection

FIRST POWER PLANT

TYPE CONSIDERED: Double Flash

SIZE (NOMINAL): 50 MW

STATUS: Preliminary design under way by Bechtel National Corp.

SCHEDULED ON LINE: 1982

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 530°F *SALINITY:* 6,000 ppm

DEPTH (TOP OF RES.): 3,200 ft *MAXIMUM FLOW RATE:* 50,000 lbs/hr

LOAD CENTERS

CITY: Santa Fe, New Mexico

POPULATION: 50,000

DISTANCE: 65 miles

CITY: Albuquerque, New Mexico

POPULATION: 409,000

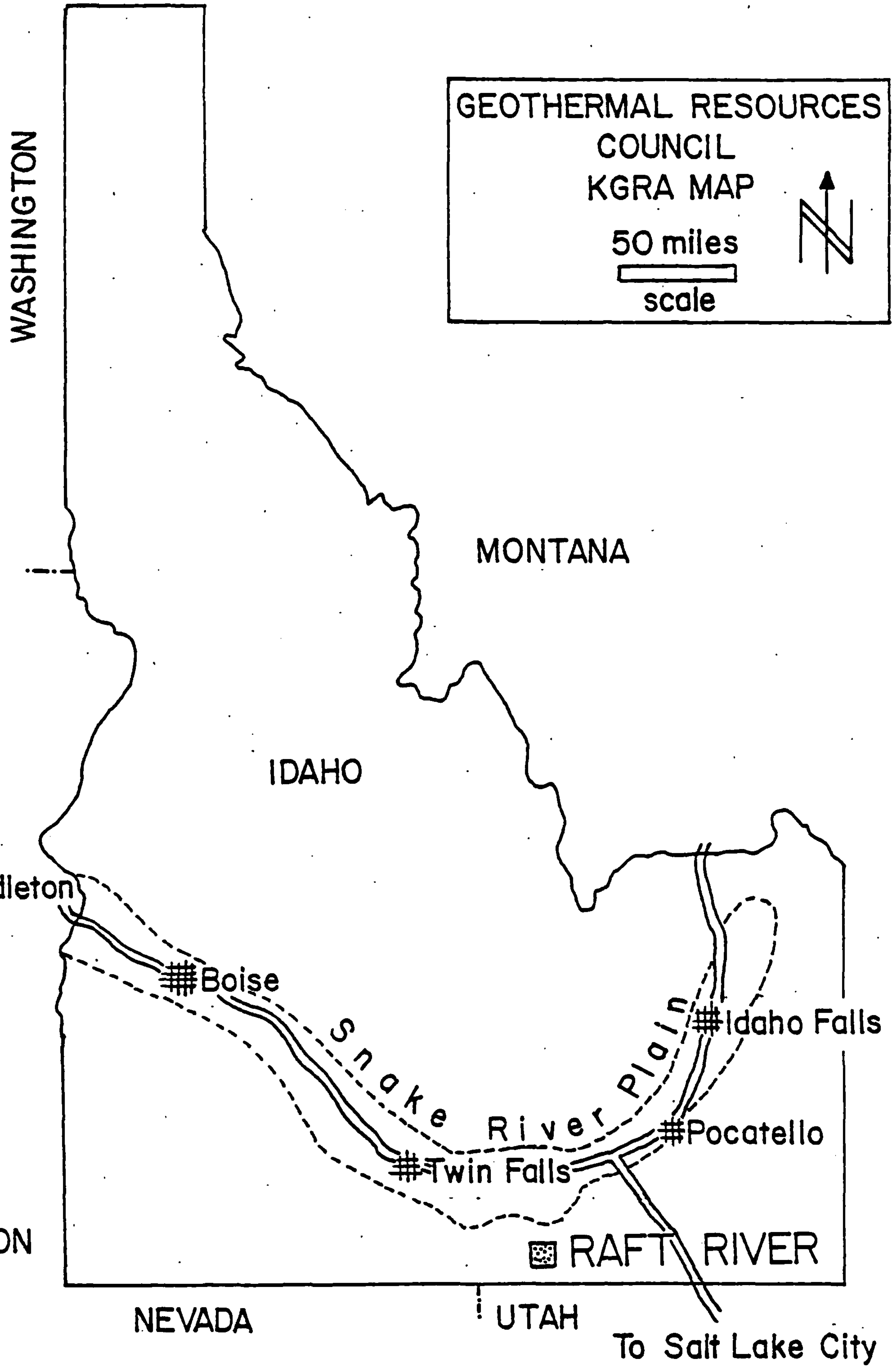
DISTANCE: 70 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Predominantly quaternary volcanics consisting of rhyolitic ash flows (tuff); subsequent caldera collapse followed by localized volcanic activity; hot springs and travertine deposits.

REMARKS

Union Geothermal Company of New Mexico and New Mexico Public Service Co. have entered into an agreement with the U.S. Department of Energy to construct and operate a 50 MW demonstration plant at the Baca location no. 1; the power plant is now being designed by the Bechtel Corporation; field development drilling will start in mid-1979. Operations are being delayed by environmental problems concerning Native Americans.


GEOTHERMAL RESOURCES
COUNCIL
KGRA MAP
50 miles
scale
N
WASHINGTON
MONTANA
IDAHO
To Pendleton
Boise
Snake River Plain
Idaho Falls
Pocatello
Twin Falls
OREGON
RAFT RIVER
NEVADA
UTAH
To Salt Lake City

KGRA RAFT RIVER AREA SOUTHERN IDAHO STATE IDAHO

KGRA

SIZE: 22,529 acres

LAND OWNERSHIP:

Federal: 17,430 acres (No federal land has been leased under the Geothermal Act of 1970. A 5,000 acre federal land withdrawal is pending)

State and private: 5,099 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1974

OPERATOR: EG&G Idaho, Inc.

DEEP WELLS: 7

INVOLVED UTILITY: Raft River Geothermal Cooperative

ESTIMATED POWER POTENTIAL: Unavailable

PRINCIPAL OPERATOR

NAME: U.S. Department of Interior through EG&G Idaho, Inc.

WELLS: 7

TESTS: Extensive production and injection tests

FIRST POWER PLANT (The power plants will probably be operated by a utility group)

TYPE CONSIDERED:	Binary	Binary
SIZE (NOMINAL):	60 KW	5 MW
STATUS:	Constructed	Under construction
SCHEDULED ON LINE:	Compl. 1977	1980

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 295°F *SALINITY:* 2,000-5,000 ppm

DEPTH (TOP OF RES.): 4,000-5,000 ft *MAXIMUM FLOW RATE:* 1,500 gpm

LOAD CENTERS

The power produced would probably be used within the Raft River Geothermal Cooperative service area for agricultural purposes.

GEOLOGY AND GEOTHERMAL PHENOMENA

The reservoir is basically fractured granitic rock overlain by the tuffaceous sediments of the Salt Lake formation which is also fractured at depth. The main reservoir at depth is leaking into a shallow reservoir that was discovered in the 1930's.

REMARKS

Area has been developed by EG&G Idaho, Inc. under the sponsorship of U.S. Department of Energy as a research site. Experiments have been conducted on aquaculture, agriculture, alcohol, potato waste, multiple direction drilling, injection, reservoir stimulation and power generation. The power generation facilities are research in nature and employ the binary cycle system. Note that the binary system is used because the reservoir temperature is below 390°F.

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Selected References

1. Assessment of Geothermal Resources of the United States, U.S. Geological Survey Circular 726, 1975.

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4. Geothermal Handbook, Geothermal Project, Office of Biological Services, U.S. Fish and Wildlife, 1976.

5. Geothermal-Overviews of the Western United States, David N. Anderson and L. Axtell, Geothermal Resources Council, 1972.

6. Site-Specific Analysis of Geothermal Development-Data File of Prospective Sites, F. Williams et al., prepared for Energy Research and Development Administration, Division of Geothermal Energy, by The Mitre Corporation, Oct. 1977.

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THE MOST PROMISING GEOTHERMAL FIELDS IN THE WESTERN UNITED STATES (EXCLUDING THE GEYSERS GEOTHERMAL FIELD)

BY
DAVID N. ANDERSON
EXECUTIVE DIRECTOR
GEOTHERMAL RESOURCES COUNCIL

Presented at the
Geothermal Resources Council
Special Short Course No. 9
San Francisco, California
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TABLE OF CONTENTS

ABSTRACT

This paper contains a brief summary of each of the most promising geothermal fields in the Western United States. The summaries contain data on size, ownership, discoveries, number of wells, involved utilities and operators, estimated power production potential, reservoirs, load centers, geology, geothermal phenomena and other important information concerning recent and on-going activities.

DISCUSSION OF TERMS

Numerous terms have been used on the summary sheets in this report that may not have meaning to a casual acquaintance of geothermal energy. Therefore, a list of the less obvious terms, with a brief explanation of each, follows:

1. KGRA - Known Geothermal Resource Area. This term was originated by the U.S. Geological Survey.

2. AREA - Area is used to define that part of the state in which a specific field is located.

3. SIZE AND LAND OWNERSHIP - Figures are always in acres.

4. DISCOVERY AND TOTAL WELL DATA - Year, refers to year of the discovery; Operator, to who made the discovery; and Deep Wells to the number of wells drilled into the reservoir. Note: Some of the wells in the count may have been abandoned or converted to injection service.

5. UTILITY AND POWER POTENTIAL - Involved Utility, refers to that company which is involved directly in the development of power generation facilities or as otherwise noted. Estimated MWe, means the amount of electrical power in MW's that could be produced for a 30 year period. A MW is equal to 1,000 kilowatts (KW). Note: All power estimates are from U.S.G.S. Circular 790.

6. PRINCIPAL OPERATORS - Names of the most active operators in the field. In some cases not all of the operators in a field have been listed. Wells refers to the number of wells drilled or controlled by the operator that penetrate the reservoir (some of the wells may have been abandoned or converted to injection). Tests refers to the kinds of tests made.

7. FIRST POWER PLANT - Type considered refers to the type of plant design e.g. double flash, single flash, binary, etc. Size refers to the size of the plant in MW's. Status means where the plant development presently sits in time. Scheduled on Line means the date when the plant is expected to start producing power.

8. RESERVOIR DATA - Type refers to what kind of reservoir is present - dry steam (vapor) or hot water (all of the reservoirs covered in this report are hot water types). Temp. refers to the reservoir temperature in degrees Fahrenheit. Depth refers to the distance from the surface to the top of the reservoir. Salinity depicts the amount of dissolved chemicals in parts per million. Max. Flow Rate is the maximum rate of

fluid that a well produced during a flow test. Flows from geothermal wells are usually measured in thousand pounds per hour.

9. RESERVOIR TEMPERATURE - All areas in this report have reservoir temperatures in excess of 300°F (149°C or nominal 150°C) except Raft River, Idaho which has a reservoir temperature of 295°F. Although the Raft River reservoir temperature is below 300°F (the generally agreed threshold for economic power production is 375°F) it has been included because of the construction of two research power plants, a 60 KW and a 5 MW unit.

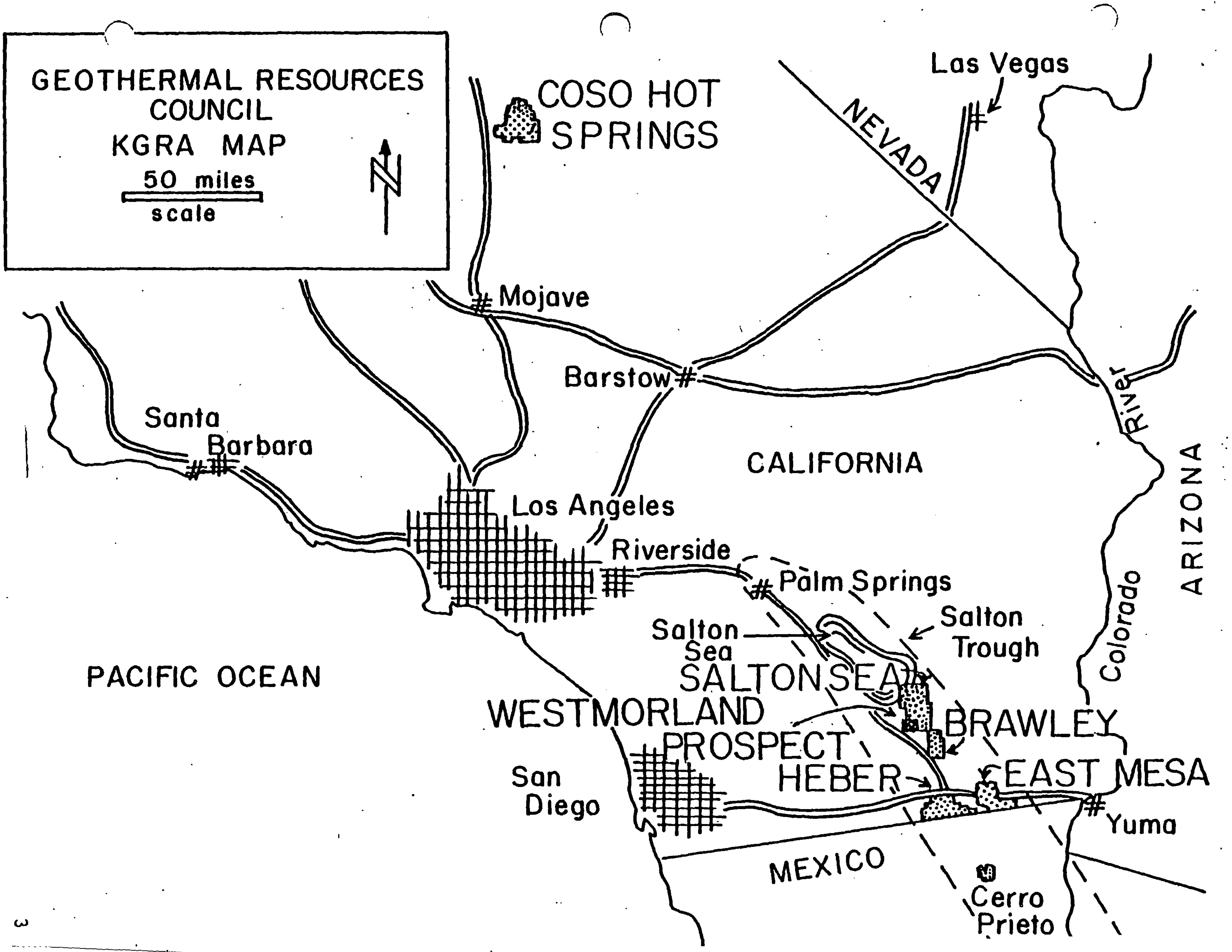
10. LOAD CENTERS - This listing shows the population and the power line distance from the field to the closest city or metropolitan area.

11. GEOLOGY AND GEOTHERMAL PHENOMENA - These terms are self explanatory.

It should be noted that The Geysers geothermal field has been omitted from the following summaries because it is now under production and its details have been widely published. However, this dry steam field is now producing 663 gross MW's of electricity and an additional 600 MW's are now being planned or are under construction.

PRODUCTION RECAP

The total estimated electrical potential of the 13 fields covered in the summaries is 12,684 MWe for 30 years. The estimates are taken from U.S. Geological Survey Circular 790 (1978). It should also be recognized that the fields covered are only a small percentage of the more than 57 Known Geothermal Resource Areas (KGRA's) that have convection systems with temperatures greater than 300°F (150°C) which have been identified by the U.S. Geological Survey.


GEOTHERMAL RESOURCES COUNCIL
KGRA MAP
50 miles
scale
COSO HOT SPRINGS
Las Vegas
NEVADA
Mojave
Barstow
Santa Barbara
CALIFORNIA
Los Angeles
Riverside
Palm Springs
Salton Sea
Salton Trough
River
Colorado
ARIZONA
PACIFIC OCEAN
SALTON SEA
WESTMORLAND
BRAWLEY
PROSPECT
San Diego
HEBER
EAST MESA
Yuma
MEXICO
Cerro Prieto

KGRA SALTON SEA AREA IMPERIAL VALLEY STATE CALIFORNIA

KGRA

SIZE: 95,824 acres

LAND OWNERSHIP:

Federal: 18,644 acres
State and Private: 77,180 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1958

OPERATOR: Kent Imperial Corp.

DEEP WELLS: 30

INVOLVED UTILITY: Southern California Edison and San Diego Gas & Electric Co.

ESTIMATED POWER POTENTIAL: 3,400 MW

PRINCIPAL OPERATORS

NAME: Magma Power Co.
WELLS: 11
TESTS: Production and injection

NAME: Union Oil Co.
WELLS: 6
TESTS: Production and injection

FIRST POWER PLANT

	SCE	Magma/SDG&E
TYPE CONSIDERED:	Flash	Double Flash
SIZE (NOMINAL):	10 MW	49 MW
STATUS:	Under design	Preliminary design
SCHEDULED ON LINE:	1982	--

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 640°F+ *SALINITY:* 250,000-330,000 ppm

DEPTH (TOP OF RES.): 3,000 ft *MAXIMUM FLOW RATE:* 500,000 lbs/hr

LOAD CENTERS

CITY: Los Angeles area
POPULATION: 9 million
DISTANCE: 185 miles

CITY: San Diego area
POPULATION: 1.5 million
DISTANCE: 130 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Tertiary and quaternary marine sands and shales, non marine fluvial and lacustrine sediments and interbedded evaporites; field is traversed by five rhyolite volcanoes trending NE-SW; numerous mud pots and mud volcanoes; minor CO_2 surface vents; major faults strike at high angle to trend of volcanic cones. Area underlain by an active spreading center (the east Pacific rise).

REMARKS

Presence of field known prior to 1925; CO_2 produced from shallow wells during the 1940's; major drilling effort (12 wells) in the early 1960's, which was accompanied by an attempt to reclaim potash from the produced brine; drilling activity renewed in early 1970's; SDG&E and ERDA funded and constructed a 10 MW equivalent (no turbine generator) pilot flash binary power plant in 1975 which is not included under first power plants; high salinity (20 to 30%) will hamper full development due to corrosion and scaling problems. Techniques are being developed to lessen the corrosion problems by a three party association: Union Oil Co., Mono Power Co. (a subsidiary of Southern California Edison), and Southern Pacific Land Company. In addition, Magma Power Co. is also active in corrosion and scaling research.

KGRA WESTMORLAND PROSPECT (Salton Sea) AREA IMPERIAL VALLEY STATE CALIFORN

KGRA

SIZE: approx. 20,000 acres

LAND OWNERSHIP:

Federal: 0
State: 0
Private: 20,000 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1976

OPERATOR: Republic Geothermal, Inc.

DEEP WELLS: 6

INVOLVED UTILITY: Imperial Irrigation District service area

ESTIMATED POWER POTENTIAL: 1710 MW

PRINCIPAL OPERATORS

NAME: Westmorland Geothermal Associates (Republic Geothermal, Inc. and MAPCO)

WELLS: 6

TESTS: Production and injection

FIRST POWER PLANT

TYPE CONSIDERED: Double Flash

SIZE (NOMINAL): 50 MW

STATUS: Under design

SCHEDULED ON LINE: 1983

RESERVOIR DATA

TYPE: Hot water

TEMPERATURE: 500°F

SALINITY: 20,000-70,000

DEPTH (TOP OF RES.): 4,000 ft

MAXIMUM FLOW RATE: 580,000 lbs/hr

LOAD CENTERS

CITY: Los Angeles area

POPULATION: 9 million

DISTANCE: 185 miles

CITY: San Diego area

POPULATION: 1.5 million

DISTANCE: 130 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Tertiary and quaternary marine sands and shales and lacustrine lake bed and deltaic sediments; no surface volcanic expression or geothermal indicators; vertical strike slip faulting controls distinct fault block salinities; distinct gravity and thermal anomalies. Area underlain by an active spreading center (the east Pacific rise).

REMARKS

Area is jointly leased and operated by Westmorland Geothermal Associates (Republic Geothermal, Inc. and MAPCO); a federal loan guarantee for reservoir evaluation and development drilling was obtained in 1979 and work on two additional wells is under way; area lies to the SW of the Salton Sea anomaly.

KGRA BRAWLEY AREA IMPERIAL VALLEY STATE CALIFORNIA

KGRA

SIZE: 28,885 ACRES

LAND OWNERSHIP:
Federal: 0
State: 0
Private: 28,885 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1975

OPERATOR: Union Oil Co.

DEEP WELLS: 10

INVOLVED UTILITY: Southern California Edison

ESTIMATED POWER POTENTIAL: 640 MW

PRINCIPAL OPERATORS

NAME: Union Oil Co.
WELLS: 8
TESTS: Production and injection

NAME: Chevron Resources Co.
WELLS: 2
TESTS: Short term production

FIRST POWER PLANT SCE

TYPE CONSIDERED: Single Flash
SIZE (NOMINAL): 10 MW
STATUS: Under construction
SCHEDULED ON LINE: 1980

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 500°F *SALINITY:* 100,000 ppm
DEPTH (TOP OF RES.): 3,000 ft *MAXIMUM FLOW RATE:* 70,000 lbs/hr

LOAD CENTERS

CITY: Los Angeles area
POPULATION: 9 million
DISTANCE: 200 miles

CITY: San Diego area
POPULATION: 1.5 million
DISTANCE: 115 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Tertiary and quaternary marine sands and shales and non marine fluvial and lacustrine sediments; no surface volcanic expression or geothermal indicators; field in close proximity to active Brawley fault. Area is underlain by an active spreading center (the east Pacific rise).

REMARKS

Field was identified by University of California at Riverside field studies in late 1960's and early 1970's; high salinity due to close proximity to lowest portions of northern landward extension of Salton Trough (evaporite sink); high salinity will cause problems in the design, construction and operation of power plants; the Union 10 MW power plant is approximately 85% complete.

KGRA HEBER AREA IMPERIAL VALLEY STATE CALIFORNIA

KGRA

SIZE: 58,568 acres

LAND OWNERSHIP:
Federal: 0
Private: 58,568 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1972

OPERATOR: Magma Power Company

DEEP WELLS: 17

INVOLVED UTILITY: Southern California Edison and San Diego Gas & Electric Co.

ESTIMATED POWER POTENTIAL: 650 MW

PRINCIPAL OPERATORS

NAME: Chevron Oil Company

WELLS: 8

TESTS: Extensive production and injection

NAME: Union Oil Company

WELLS: 7

TESTS: Short term, production

FIRST POWER PLANT

	SCE	SDG&E (see remarks)
TYPE CONSIDERED:	Double Flash	Flash Binary
SIZE (NOMINAL):	50 MW	65 MW
STATUS:	In final design	Design complete
SCHEDULED ON LINE:	Late 1982	1984

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 350-375°F *SALINITY:* 14,000 ppm

DEPTH (TOP OF RES.): 3,200 ft *MAXIMUM FLOW RATE:* 440,000 lbs/hr

LOAD CENTERS

CITY: Los Angeles area

POPULATION: 9 million

DISTANCE: 225 miles

CITY: San Diego area

POPULATION: 1.5 million

DISTANCE: 100 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Tertiary and quaternary marine sands and shales and non marine fluvial and lacustrine sediments, minor volcanic sills; no surface volcanic expression or geothermal indicators. Area is underlain by an active spreading center (the east Pacific rise).

REMARKS

In 1977-78 the field was considered by U.S. Department of Energy as a possible site for a 50 MW binary power plant (the plant was subsequently awarded to Union Oil Co. at their Baca location in northern New Mexico). In December of 1979 Chevron Resources Company (the major operator) signed a contract with Southern California Edison, who will construct a 50 MW power plant. The completion date is late 1982. San Diego Gas & Electric is contemplating the co-sponsoring of a 50 MW binary type demonstration power plant with the U.S. Department of Energy.

KGRA EAST MESA AREA IMPERIAL VALLEY STATE CALIFORNI

KGRA

SIZE: 38,365 ACRES

LAND OWNERSHIP:

Federal: 32,725
Federal leased: 11,770 acres
State and Private: 4,840 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1972

OPERATOR: U.S. Bureau of Reclamation

DEEP WELLS: 18

INVOLVED UTILITY: San Diego Gas and Electric Co.

ESTIMATED POWER POTENTIAL: 360 MW

PRINCIPAL OPERATORS

NAME: Republic Geothermal, Inc.
WELLS: 8
TESTS: Production and injection

NAME: Imperial Magma
WELLS: 5
TESTS: Production and injection

FIRST POWER PLANT	Republic	Magma
TYPE CONSIDERED:	Double Flash	Binary
SIZE (NOMINAL):	48 MW (net)	10 MW
STATUS:	Plant designed	Construction completed
SCHEDULED ON LINE:	Late 1982	Spring 1980

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 400°F *SALINITY:* 2,500 ppm

DEPTH (TOP OF RES.): 2,450 ft *MAXIMUM FLOW RATE:* 740,000 lbs/hr

LOAD CENTERS

CITY: Los Angeles area
POPULATION: 9 million
DISTANCE: 245 miles

CITY: San Diego area
POPULATION: 1.5 million
DISTANCE: 120 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Tertiary and quaternary marine sands and shales and non marine fluvial and lacustrine sediments; no surface volcanic expression or geothermal indicators; area is slightly westward sloping, sandy mesa with a minimum elevation a few feet above the valley floor; major faults trend NW-SE. Area is underlain by an active spreading center (the east Pacific rise)

REMARKS

In the early 1970's the U.S. Bureau of Reclamation drilled and tested 5 wells and constructed and tested multi-stage flash and vertical tube desalination units; a facility (operated by U.S. DOE) at the site is available for the testing of various prototype energy conversion machines; loan guarantee granted to Republic Geothermal, Inc. for reservoir development; a shallow, slightly brackish aquifer is present over most of the mesa. Magma's 10 MW binary power plant will be the first binary type plant in the United States and the first hot water plant in the United States.

KGRA COSO HOT SPRINGS AREA MOJAVE STATE CALIFORN

KGRA

SIZE: 51,760 acres

LAND OWNERSHIP:

Federal: 43,330 acres
(BLM: 16,690 acres)
(Navy: 26,640 acres)
State and private: 8,430 acres

DEVELOPMENT

Numerous shallow temperature wells have been drilled and a deep reservoir test was completed by U.S. Department of Energy in December 1977.

INVOLVED UTILITY: Mono Power Co. (a subsidiary of Southern California Edison)

ESTIMATED POWER POTENTIAL: 650 MW

PRINCIPAL OPERATORS (see remarks)

NAME:

WELLS:

TESTS:

NAME:

WELLS:

TESTS:

FIRST POWER PLANT

TYPE CONSIDERED: Decision pending confirmation of a reservoir

SIZE (NOMINAL):

STATUS:

SCHEDULED ON LINE:

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 390°F+ *SALINITY:* 6,000 ppm

DEPTH (TOP OF RES.): 2,000 ft *MAXIMUM FLOW RATE:* well was not tested

LOAD CENTERS (see remarks)

CITY: Los Angeles area
POPULATION: 9 million
DISTANCE: 160 miles

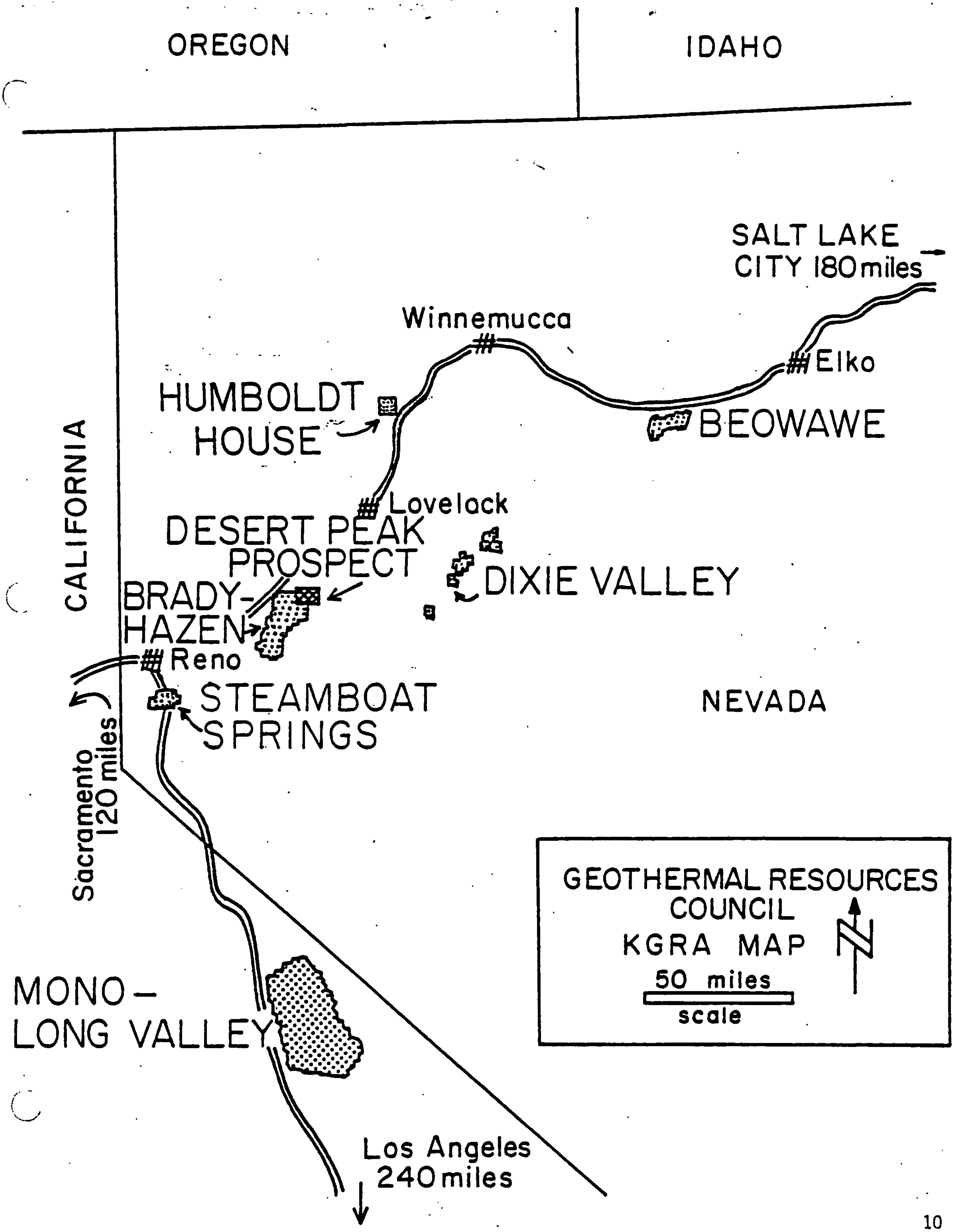
CITY: Bakersfield area
POPULATION: 86,000
DISTANCE: 60 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Granitic, metasedimentary and metavolcanic rocks extruded and overlaid by rhyolites and andesites in the form of cinder cones, pierlitic domes and flows. Volcanic flows and air falls are interbedded with lacustrine and fanglomerate deposits. Structurally the area appears to have been under tension throughout the late Cenozoic which caused a fault pattern to develop that served as volcanic conduits. Fumaroles and hot springs are common in some parts of the KGRA.

REMARKS

Major portion of KGRA land is controlled by the federal government and is partially overlain by instrumented bombing ranges operated by the U.S. Navy. This aspect, in the past, has caused a general reluctance by the Navy to lease or allow the land to be opened for leasing by the U.S. Bureau of Land Management. Recently the Navy has developed a program to contract directly for the development of several square miles of land owned in fee and to allow the U.S. BLM to commence leasing procedures on other lands. In late 1979 the U.S. Navy and California Energy Company (CEC) signed a contract to develop the Navy fee land. The contract calls for CEC to ultimately develop 75 MW's of electrical power. The power produced on the Navy fee land would go to power Navy installations in the


OREGON
IDAHO
SALT LAKE CITY 180 miles
Winnemucca
Elko
HUMBOLDT HOUSE
BEOWAWE
CALIFORNIA
Lovelock
DESERT PEAK PROSPECT
DIXIE VALLEY
BRADY-HAZEN
Reno
STEAMBOAT SPRINGS
NEVADA
Sacramento 120 miles
GEOTHERMAL RESOURCES COUNCIL
KGRA MAP
50 miles
scale
N
MONO-LONG VALLEY
Los Angeles 240 miles

KGRA STEAMBOAT SPRINGS AREA WESTERN NEVADA STATE NEVADA

KGRA

SIZE: 8,914 acres

LAND OWNERSHIP:

Federal: 4,457 acres
Private: 4,457 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: Unknown

OPERATOR: Unknown

DEEP WELLS: 1

INVOLVED UTILITY: Sierra Pacific Power Co. service area

ESTIMATED POWER POTENTIAL: 350 MW

PRINCIPAL OPERATORS

NAME: Phillips Petroleum Co.

WELLS: 1 deep, 20+ temp. grad. and four 800-2,000 ft observation wells

TESTS: None

NAME: Gulf Mineral Resources Co. (Gulf has extensive land interests in the area.)

WELLS: None

TESTS: None

FIRST POWER PLANT (see remarks)

TYPE CONSIDERED:

SIZE (NOMINAL):

STATUS:

SCHEDULED ON LINE:

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 400°F+ *SALINITY:* 3,000 ppm

DEPTH (TOP OF RES.): 2,000 ft+ *MAXIMUM FLOW RATE:* --

LOAD CENTERS

CITY: Reno

POPULATION: 150,000

DISTANCE: 12 miles

CITY:

POPULATION:

DISTANCE:

GEOLOGY AND GEOTHERMAL PHENOMENA

Sierra Nevada granitic rocks, highly fractured; fractures related to the eastern Sierra frontal fault system; hot springs and siliceous sinter terraces common.

REMARKS

Phillips Petroleum Co. drilled a deep test in mid 1979 and the test results looked promising. A follow-up exploration program which includes three 2,000 ft. temperature test holes is in progress.

A utility group consisting of Sierra Pacific Power Co. (the lead agency), Sacramento Municipal Utility District, Pacific Power and Light, Portland General Electric and the Eugene Water and Electric Board is considering the co-funding of a 50 MW plant at Desert Peak, Beowawe or Dixie Valley provided that a suitable reservoir can be developed and an agreement can be reached with the operator(s). In addition, the group is considering a 10 MW pilot plant at any one of five sites (the three mentioned above plus Steamboat Springs and Humboldt House).

KGRA DESERT PEAK PROSPECT (Brady-Hazen) AREA RENO STATE NEVADA

KGRA

SIZE: 98,508 acres

LAND OWNERSHIP:
- Federal: 59,358 acres
- Federal leased: 26,049 acres
- State and private: 39,150 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1976

OPERATOR: Phillips Petroleum Co.

DEEP WELLS: 4

INVOLVED UTILITY: Sierra Pacific Power Co. service area

ESTIMATED POWER POTENTIAL: 750 MW

PRINCIPAL OPERATORS

NAME: Phillips Petroleum Co.

WELLS: 4

TESTS: Production

NAME:

WELLS:

TESTS:

FIRST POWER PLANT (see remarks)

TYPE CONSIDERED:

SIZE (NOMINAL):

STATUS:

SCHEDULED ON LINE: unavailable

RESERVOIR DATA

TYPE: Hot water

TEMPERATURE: 400°F+

SALINITY: 6,000-8,000 ppm

DEPTH (TOP OF RES.): 2,000+ ft

MAXIMUM FLOW RATE: Test program under way

LOAD CENTERS

CITY: Reno

POPULATION: 150,000

DISTANCE: 55 miles

CITY:

POPULATION:

DISTANCE:

GEOLOGY AND GEOTHERMAL PHENOMENA

Faulted tertiary volcanics (basalts, rhyolites) overlying a metamorphosed basement complex; hot springs, sinter and travertine deposits.

REMARKS

Desert Peak area lies just north of the Brady-Hazen KGRA and will eventually be included. Preliminary meetings have taken place between the operator, utility and an engineering firm concerning the design and construction of a power plant. Additional exploration and development work is under way.

A utility group consisting of Sierra Pacific Power Co. (the lead agency), Sacramento Municipal Utility District, Pacific Power and Light, Portland General Electric and the Eugene Water and Electric Board is considering the co-funding of a 50 MW plant at Desert Peak, Beowawe or Dixie Valley provided that a suitable reservoir can be developed and an agreement can be reached with the operator(s). In addition the group is considering a 10 MW pilot plant at any one of five sites (the three mentioned above plus Steamboat Springs and Humboldt House).

KGRA DIXIE VALLEY AREA CENTRAL NEVADA STATE NEVADA

KGRA

SIZE: 38,989 approx. acres

LAND OWNERSHIP:

Federal: 38,989 approx. acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1978

OPERATOR: Sunoco Energy Devel. Co. (Sunedco)

DEEP WELLS: 4

INVOLVED UTILITY: Sierra Pacific Power Co. service area

ESTIMATED POWER POTENTIAL: --

PRINCIPAL OPERATORS

NAME: Sunedco

WELLS: 4

TESTS: Production

NAME: Natomas/Thermal Power Co. / Southland Royalty

WELLS: 2

TESTS: Preliminary testing

FIRST POWER PLANT (see remarks)

TYPE CONSIDERED:

SIZE (NOMINAL):

STATUS:

SCHEDULED ON LINE:

RESERVOIR DATA

TYPE: -- *TEMPERATURE:* -- *SALINITY:* --

DEPTH (TOP OF RES.): -- *MAXIMUM FLOW RATE:* --

LOAD CENTERS

CITY: Reno

POPULATION: 150,000

DISTANCE: 110 miles

CITY:

POPULATION:

DISTANCE:

GEOLOGY AND GEOTHERMAL PHENOMENA

Jurassic metasedimentary rocks overlain by tertiary sediments, which are overlain by volcanic deposits including basalt and andesitic rocks, rhyolitic flows and ash deposits, and younger alluvial fans. Early structural history consists of complexed folding and thrust faulting. Active structure consists of normal faults bounding a north-northeast trending graben with horst blocks. Numerous hot springs present.

REMARKS

In November 1978, Sunedco completed and production tested the first deep well in the area. Results from the test have been encouraging and have caused the drilling of two additional wells. In addition, a two company association (Natomas/Thermal Power Co. and Southland Royalty) have drilled two additional wells. Although the area was discovered over two years ago, none of the involved operators have made a formal press release concerning the potential.

A utility group consisting of Sierra Pacific Power Co. (the lead agency), Sacramento Municipal Utility District, Pacific Power and Light, Portland General Electric and the Eugene Water and Electric Board is considering the co-funding of a 50 MW plant at Desert Peak, Beowawe or Dixie Valley provided that a suitable reservoir can be developed and an agreement can be reached with the operator(s). In addition, the group is considering a 10 MW pilot plant at any one of five sites (the three men-

FIELD HUMBOLDT HOUSE AREA BATTLE MOUNTAIN STATE NEVADA

FIELD

SIZE: Unknown
LAND OWNERSHIP:

DISCOVERY AND TOTAL WELL DATA

YEAR: 1978
OPERATOR: Phillips Petroleum Co.
DEEP WELLS: 3

INVOLVED UTILITY: Sierra Pacific Power Co. service area.

ESTIMATED POWER POTENTIAL: 47 MW

PRINCIPAL OPERATORS

NAME: Phillips Petroleum Co.
WELLS: 2
TESTS: Production tests only

NAME: Union Oil Co.
WELLS: 1
TESTS: Preliminary

FIRST POWER PLANT (see remarks)

TYPE CONSIDERED:
SIZE (NOMINAL):
STATUS:
SCHEDULED ON LINE:

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 360°F+ *SALINITY:* 6,000 ppm
DEPTH (TOP OF RES.): 1,800 ft *MAXIMUM FLOW RATE:* Unavailable

LOAD CENTERS

CITY: Reno
POPULATION: 150,000
DISTANCE: 120 miles

CITY:
POPULATION:
DISTANCE:

GEOLOGY AND GEOTHERMAL PHENOMENA

Mesozoic metamorphosed volcanic and sedimentary rocks overlain by tertiary lake beds in the valleys; large hydrothermally altered areas, old tuffa mounds and other hot springs deposits; structure is high angle faults bounding basins and mountain ranges.

REMARKS

Phillips Petroleum Co. feels that they have only penetrated a shallow auxiliary reservoir and that the main reservoir exists at depth and will contain water at temperatures of approximately 430°F. The Humboldt House area is not an official KGRA, however, it is near the Rye Patch KGRA.

A utility group consisting of Sierra Pacific Power Co. (the lead agency), Sacramento Municipal Utility District, Pacific Power and Light, Portland General Electric and the Eugene Water and Electric Board is considering the co-funding of a 50 MW plant at Desert Peak, Beowawe or Dixie Valley provided that a suitable reservoir can be developed and an agreement can be reached with the operator(s). In addition, the group is considering a 10 MW pilot plant at any one of five sites (the three mentioned above plus Steamboat Springs and Humboldt House).

KGRA BEOWAWE AREA BATTLE MOUNTAIN STATE NEVADA

KGRA

SIZE: 33,225 acres

LAND OWNERSHIP:

Federal: approx. 16,000 acres
State and private: approx. 1,600 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1959

OPERATOR: Magma Power Co.

DEEP WELLS: 8

INVOLVED UTILITY: Sierra Pacific Power Co. service area

ESTIMATED POWER POTENTIAL: 127 MW

PRINCIPAL OPERATORS

NAME: Chevron Oil Co.
WELLS: 4
TESTS: Limited production

NAME: Getty Oil Co.
WELLS: none
TESTS: none

FIRST POWER PLANT (see remarks)

TYPE CONSIDERED:

SIZE (NOMINAL):

STATUS:

SCHEDULED ON LINE:

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 412°F *SALINITY:* 1,400 ppm

DEPTH (TOP OF RES.): 700 ft *MAXIMUM FLOW RATE:* 1,500,000 lbs/hr ±

LOAD CENTERS

CITY: Reno
POPULATION: 150,000
DISTANCE: 220 miles

CITY: Elko
POPULATION: 10,000
DISTANCE: 40 miles

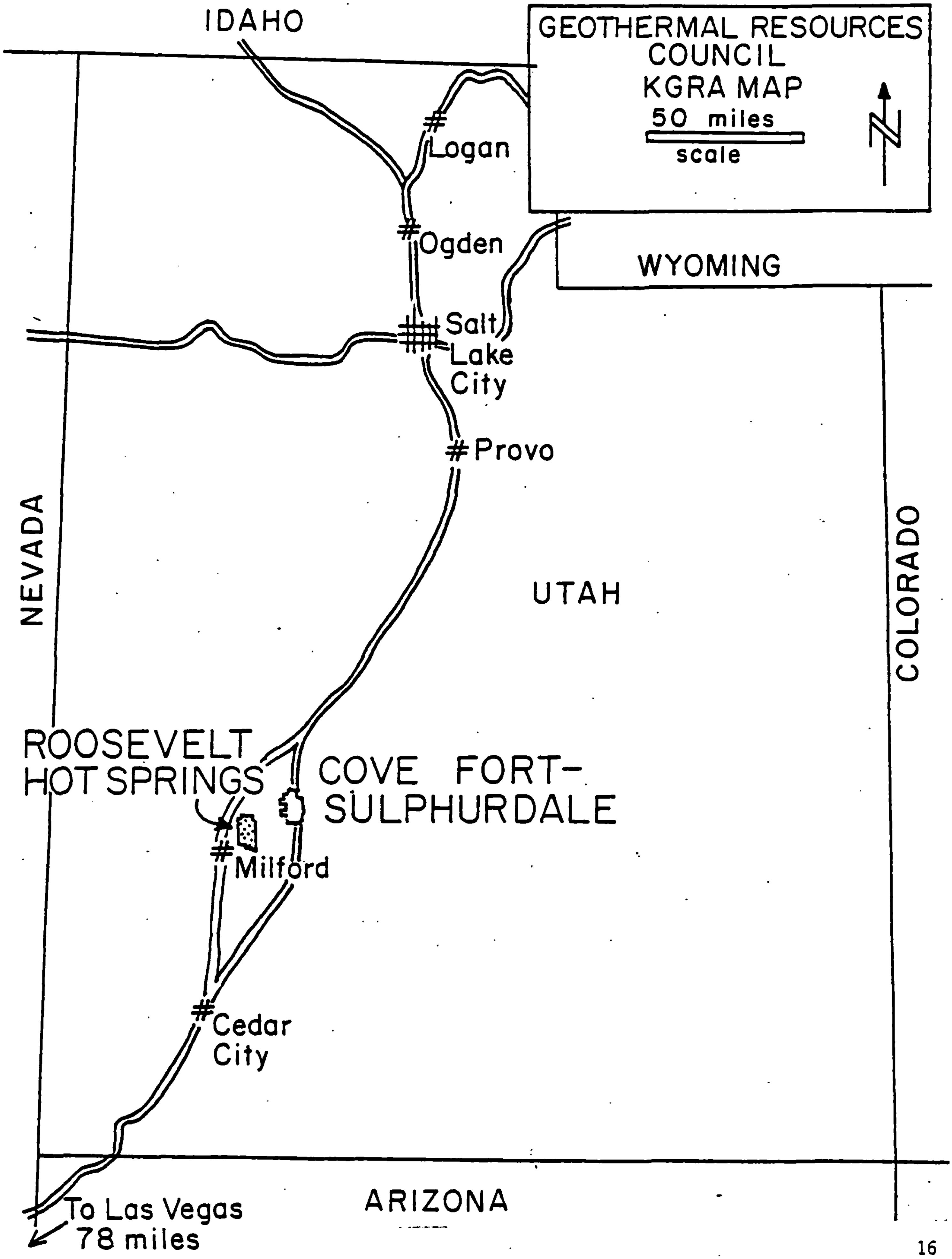
GEOLOGY AND GEOTHERMAL PHENOMENA

Paleozoic sediments overlaid by tertiary volcanics, principally basaltic flows; area centered along a major normal, NE-SW trending fault; numerous hot springs, geysers, fumaroles and sinter deposits.

REMARKS

Chevron Oil Co. has an extensive exploration program under way which includes the drilling of several wells. Getty Oil Co. has started a temperature gradient well program. The field area has been unitized (Chevron and Getty Oil Cos.)

A utility group consisting of Sierra Pacific Power Co. (the lead agency), Sacramento Municipal Utility District, Pacific Power and Light, Portland General Electric and the Eugene Water and Electric Board is considering the co-funding of a 50 MW plant at Desert Peak, Beowawe or Dixie Valley provided that a suitable reservoir can be developed and an agreement can be reached with the operator(s). In addition, the group is considering a 10 MW pilot plant at any one of five sites (the three mentioned above plus Steamboat Springs and Humboldt House).


GEOTHERMAL RESOURCES COUNCIL
KGRA MAP
50 miles
scale
IDAHO
Logan
Ogden
WYOMING
Salt Lake City
Provo
NEVADA
UTAH
COLORADO
ROOSEVELT HOT SPRINGS
COVE FORT-SULPHURDALE
Milford
Cedar City
ARIZONA
To Las Vegas 78 miles

KGRA ROOSEVELT HOT SPRINGS AREA MILFORD STATE UTAH

KGRA

SIZE: 29,791 acres

LAND OWNERSHIP:

Federal leased: 24,592 acres
State and private: 5,199 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1975

OPERATOR: Phillips Petroleum Co.

DEEP WELLS: 9

INVOLVED UTILITY: Utah Power and Light service area

ESTIMATED POWER POTENTIAL: 970 MW

PRINCIPAL OPERATORS

NAME: Phillips Petroleum Co.

WELLS: 7

TESTS: Extensive production and injection

NAME: Thermal Power Co.

WELLS: 2

TESTS: Production

FIRST POWER PLANT

TYPE CONSIDERED: Several power plant proposals are now being considered

SIZE (NOMINAL):

STATUS:

SCHEDULED ON LINE:

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 500°F *SALINITY:* 7,800 ppm

DEPTH (TOP OF RES.): 2,700 ft *MAXIMUM FLOW RATE:* 1,000,000 lbs/hr

LOAD CENTERS

CITY: Salt Lake City area

POPULATION: 820,000

DISTANCE: 200 miles

CITY: Las Vegas, Nevada

POPULATION: 160,000

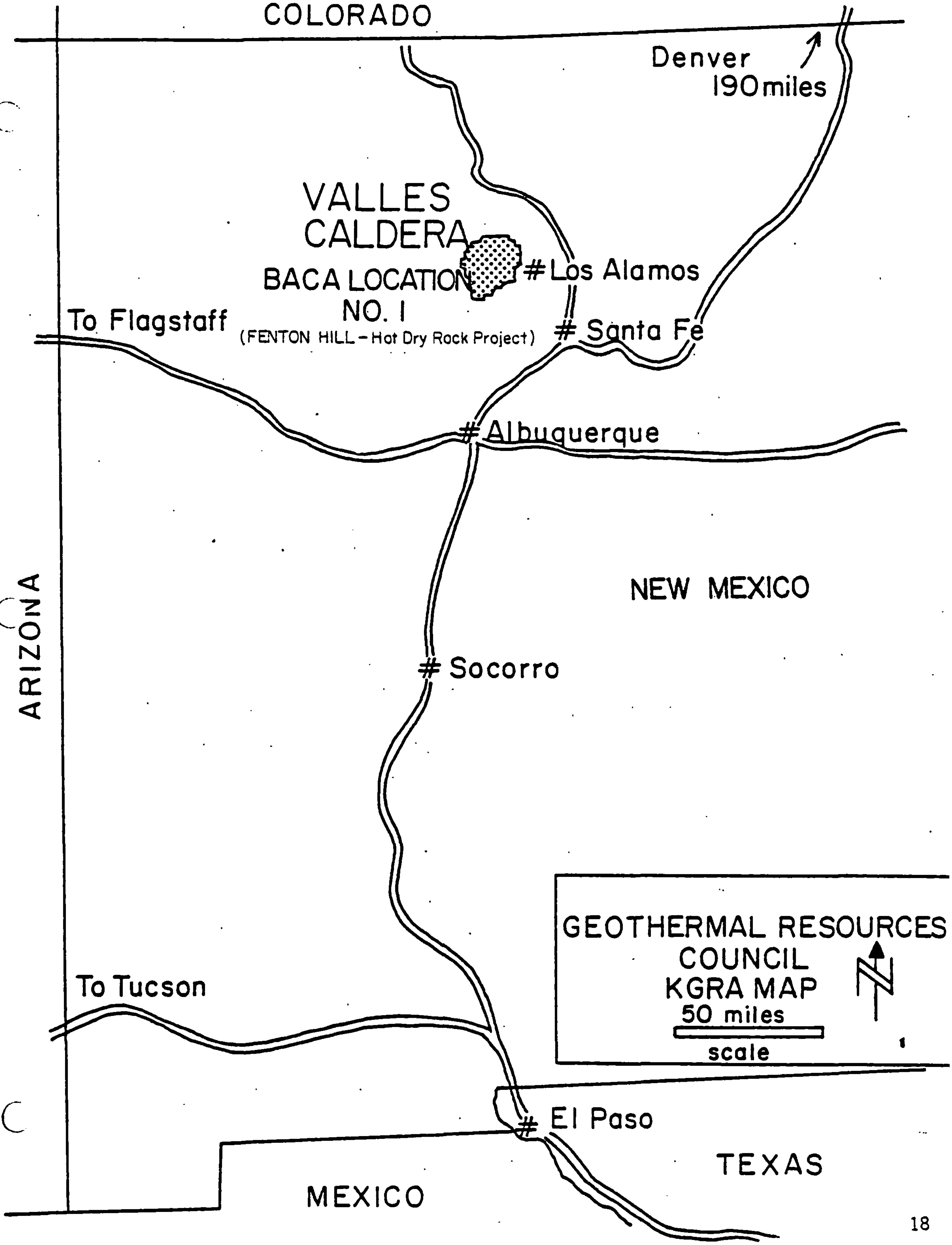
DISTANCE: 240 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Precambrian (?) metamorphics overlaid by unconsolidated tertiary and quaternary sediments; quaternary volcanics are present on the surface three miles east of the field; sinter deposits in KGRA area.

REMARKS

Large percentage of KGRA has been unitized; cooling water may be difficult to obtain.


COLORADO
Denver
190 miles
VALLES
CALDERA
BACA LOCATION
NO. 1
(FENTON HILL - Hot Dry Rock Project)
Los Alamos
Santa Fe
To Flagstaff
Albuquerque
ARIZONA
NEW MEXICO
Socorro
GEOTHERMAL RESOURCES
COUNCIL
KGRA MAP
50 miles
scale
To Tucson
El Paso
TEXAS
MEXICO

KGRA BACA LOCATION NO. 1 (Valles Caldera) AREA -- STATE NEW MEXI

KGRA

SIZE: 168,761 acres

LAND OWNERSHIP:

Federal: 30,000+ acres
Federal leased: 18,000 acres
State and private: 120,700+ acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1970

OPERATOR: Pat Dunigan

DEEP WELLS: 14

INVOLVED UTILITY: New Mexico Public Service Co.

ESTIMATED POWER POTENTIAL: 2,700 MW

PRINCIPAL OPERATORS

NAME: Union Geothermal Co. of New Mexico (a subsidiary of Union Oil Co.)

WELLS: 14

TESTS: Extensive production and injection

FIRST POWER PLANT

TYPE CONSIDERED: Double Flash

SIZE (NOMINAL): 50 MW

STATUS: Preliminary design under way by Bechtel National Corp.

SCHEDULED ON LINE: 1982

RESERVOIR DATA

TYPE: Hot water

TEMPERATURE: 530°F

SALINITY: 6,000 ppm

DEPTH (TOP OF RES.): 3,200 ft

MAXIMUM FLOW RATE: 50,000 lbs/hr

LOAD CENTERS

CITY: Santa Fe, New Mexico

POPULATION: 50,000

DISTANCE: 65 miles

CITY: Albuquerque, New Mexico

POPULATION: 409,000

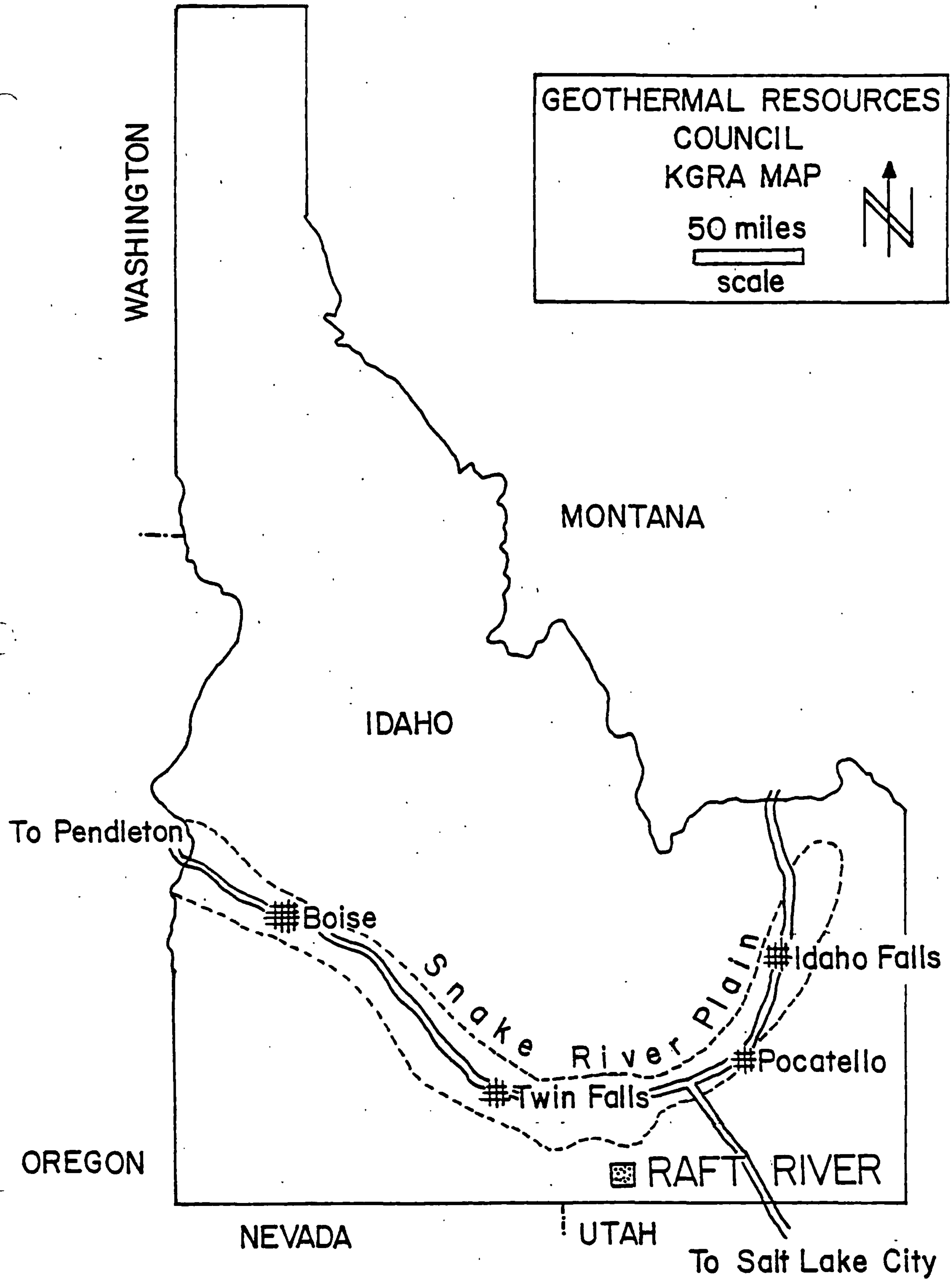
DISTANCE: 70 miles

GEOLOGY AND GEOTHERMAL PHENOMENA

Predominantly quaternary volcanics consisting of rhyolitic ash flows (tuff); subsequent caldera collapse followed by localized volcanic activity; hot springs and travertine deposits.

REMARKS

Union Geothermal Company of New Mexico and New Mexico Public Service Co. have entered into an agreement with the U.S. Department of Energy to construct and operate a 50 MW demonstration plant at the Baca location no. 1; the power plant is now being designed by the Bechtel Corporation; field development drilling will start in mid-1979. Operations are being delayed by environmental problems concerning Native Americans.


GEOTHERMAL RESOURCES COUNCIL
KGRA MAP
50 miles
scale
WASHINGTON
MONTANA
IDAHO
To Pendleton
Boise
Snake River Plain
Idaho Falls
Pocatello
Twin Falls
OREGON
RAFT RIVER
NEVADA
UTAH
To Salt Lake City

KGRA RAFT RIVER AREA SOUTHERN IDAHO STATE IDAHO

KGRA

SIZE: 22,529 acres

LAND OWNERSHIP:

Federal: 17,430 acres (No federal land has been leased under the Geothermal Act of 1970. A 5,000 acre federal land withdrawal is pending)

State and private: 5,099 acres

DISCOVERY AND TOTAL WELL DATA

YEAR: 1974

OPERATOR: EG&G Idaho, Inc.

DEEP WELLS: 7

INVOLVED UTILITY: Raft River Geothermal Cooperative

ESTIMATED POWER POTENTIAL: Unavailable

PRINCIPAL OPERATOR

NAME: U.S. Department of Interior through EG&G Idaho, Inc.

WELLS: 7

TESTS: Extensive production and injection tests

FIRST POWER PLANT (The power plants will probably be operated by a utility group)

TYPE CONSIDERED:	Binary	Binary
SIZE (NOMINAL):	60 KW	5 MW
STATUS:	Constructed	Under construction
SCHEDULED ON LINE:	Compl. 1977	1980

RESERVOIR DATA

TYPE: Hot water *TEMPERATURE:* 295°F *SALINITY:* 2,000-5,000 ppm

DEPTH (TOP OF RES.): 4,000-5,000 ft *MAXIMUM FLOW RATE:* 1,500 gpm

LOAD CENTERS

The power produced would probably be used within the Raft River Geothermal Cooperative service area for agricultural purposes.

GEOLOGY AND GEOTHERMAL PHENOMENA

The reservoir is basically fractured granitic rock overlain by the tuffaceous sediments of the Salt Lake formation which is also fractured at depth. The main reservoir at depth is leaking into a shallow reservoir that was discovered in the 1930's.

REMARKS

Area has been developed by EG&G Idaho, Inc. under the sponsorship of U.S. Department of Energy as a research site. Experiments have been conducted on aquaculture, agriculture, alcohol, potato waste, multiple direction drilling, injection, reservoir stimulation and power generation. The power generation facilities are research in nature and employ the binary cycle system. Note that the binary system is used because the reservoir temperature is below 390°F.

Selected References

1. Assessment of Geothermal Resources of the United States, U.S. Geological Survey Circular 726, 1975.

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3. Geothermal Energy Resources of the Western United States, a map. National Geophysical and Solar-Terrestrial Data Center, National Oceanic and Atmospheric Administration, Boulder, Colorado, 1977.

4. Geothermal Handbook, Geothermal Project, Office of Biological Services, U.S. Fish and Wildlife, 1976.

5. Geothermal-Overviews of the Western United States, David N. Anderson and L. Axtell, Geothermal Resources Council, 1972.

6. Site-Specific Analysis of Geothermal Development-Data File of Prospective Sites, F. Williams et al., prepared for Energy Research and Development Administration, Division of Geothermal Energy, by The Mitre Corporation, Oct. 1977.

APPLICATIONS OF MODERATE-TEMPERATURE GEOTHERMAL RESOURCES

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Idaho National Engineering Laboratory
Idaho Falls, ID

ABSTRACT

Moderate-temperature hydrothermal resources will, in time, be the "bread and butter" of the hydrothermal industry. Estimates indicate that thirty-seven states in the U.S. have geothermal resources that may be presently economically exploitable. The medium- and low-temperature (50 to 150°C) hydrothermal resource contains about five times as much recoverable energy as the high-temperature (above 150°C) resource. Direct use of the energy from the resource, in process and space heating, is viable today. Economic electrical production using fluids in the 150°C range is possible in the near-term future.

INTRODUCTION

The upper 10 kilometers of the earth's crust may contain more than 8×10^{24} calories of heat; however, the majority of this heat is too diffuse to be economically exploitable as an energy source. Estimates indicate that thirty-seven states in the U.S. have geothermal resources that may be presently economically exploitable. The medium- to low-temperature (50 to 150°C) hydrothermal resource contains about five times as much recoverable energy as the high-temperature (above 150°C) resource when extraction practices are limited to current or near-term technology (Figure 1). The direct application of geothermal energy is a viable technology that already is in worldwide use. Commercial and government cooperative projects are now underway which will expand the use of direct applications in the United States.

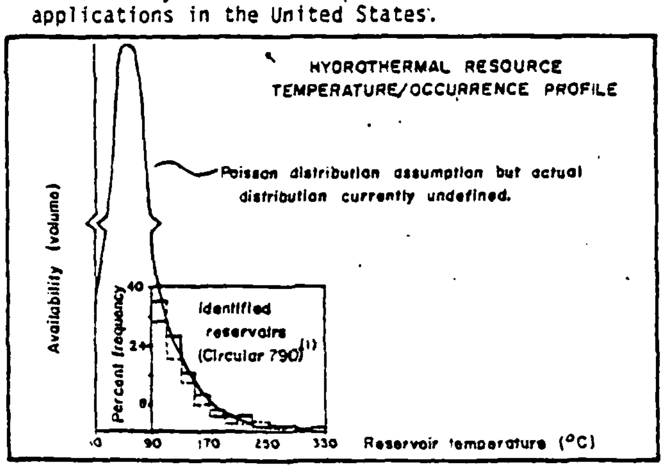


Figure 1

DIRECT APPLICATIONS

The practices employed in the direct use of geothermal energy encompass a wide spectrum. At one end is the age-old balneological use, while at the other is the use of geothermal energy for refrigeration. Applications range from melting snow to providing the thermal energy requirements for a modern food dehydration plant.

It is startling to realize that the commercial use of geothermal energy is older than the commercial use of natural gas. District space heating by the Artesian Hot and Cold Water Company of Boise, Idaho, was initiated in 1893. This system at one time serviced a peak of 400 customers. Currently, the space heating requirements of approximately 200 homes are met by the system. The largest known, and probably the most economical, district heating system is in Reykjavik, Icèland. It supplies a total population of about 90,000 with space and domestic water heating. The present capacity for the system is 350 MW (th). The average cost of heating is about 30% below oil heating costs.[2]

The earliest utilization of geothermal energy in modern industrial processing is not well documented, but appears to have been initiated in the early 1950's. The Italians used steam at Larderello in the early 1800's for evaporator heating. A compilation of the types of industrial processes and the country in which they are currently utilized is presented in Table 1.

Hydrothermal resources are now being employed for industrial processing in the United States. The first of these operations was the Medo-Bel Creamery in Klamath Falls, Oregon. Medo-Bel has been using this energy source since 1973 for milk pasteurization. Geothermal Food Processors have recently initiated onion and celery drying operations at Brady Hot Springs, Nevada. In addition, the DOE field demonstration (PON) program has stimulated industrial developments in potato processing, grain drying, aquaculture, agribusiness, and sugar processing.

Table 1

CURRENT INDUSTRIAL PROCESSES USING GEOTHERMAL ENERGY[3]

Application	Country	Description of Application
Wood & Paper Industry		
Pulp & Paper	New Zealand	Processing and a small amount of electrical power generation. Kraft process used.
Timber Drying	New Zealand	Kiln operation.
Washing & Drying of Wood	Iceland	Steam drying.
Mining		
Diatomaceous Earth Plant	Iceland	Production of dried diatomaceous earth recovered by wet-mining techniques.
Chemicals		
Salt Plant	Japan, Philippines	Production of salt from sea water.
Sulphur Mining	Japan	Sulfur extraction from the gases issuing from a volcano.
Boric Acid, Ammonium Bicarbonate, Ammonium Sulphate, Sulphur	Italy	Includes recovery of substances from the volatile components which accompany the geothermal steam.
Miscellaneous		
Confectionary Industry	Japan	
Grain Drying	Philippines	Geothermal steam heats rotary kiln dryer.
Brewing & Distillation	Japan	
Stock Fish Drying	Iceland	Fish drying in shelf dryers.
Curing Cement Building Slabs	Iceland	Curing of light aggregate cement building slabs.
Seaweed	Iceland	Drying seaweed for export.
Onion Drying	United States	Dehydration of onions.
Milk Pasteurization	United States	Milk processing using low-temperature resource.

Industrial use represents 40% of our national energy consumption, the single largest share, with residential space conditioning and water heating using 20%, commercial space conditioning and water heating using 15%, and transportation accounting for the remaining 25%.

The energy used by industry can be broken into the following categories:

Process Steam	40.6%
Electric Drive	19.2%
Electrolitic Process	2.8%
Direct Process Heat	27.8%
Feedstocks & Chemicals	8.8%
Other	0.8%

Process steam and direct process heat account for 68.4% of the total industrial use of energy, much of which can potentially be supplied by hydrothermal energy. Today, high-temperature processing is being practiced in many cases only because those are the temperatures naturally achieved when fossil fuel is consumed. A study by Intertechnology Corporation[4] reviewed in excess of 75 processes and defined the associated heat requirements. Typical processes which can be operated in the low to moderate range, together with the percentage of the process energy needs as a function of maximum temperature required, are given in Table II. It should be noted that the methodology of the study considered the process temperature required, not the temperature supplied. However, in many processes, time and temperature can be traded-off to permit the use of lower temperature energy sources. Thus, there are potentially many additional processes which can be adapted to low-temperature energy sources.

Although a national market analysis has not been completed, an analysis of ten Rocky Mountain states shows that space conditioning and industrial processing are prime market sectors for the direct applications of hydrothermal energy. Currently, greater than 75% of the energy requirements of these market sectors is met by fossil fuel consumption, with electricity claiming the majority of the remaining sales. Energy competition projections for the referenced states indicate a future higher dependence upon coal, which may encounter environmental or other growth constraints.

Table II

TYPICAL INDUSTRIAL PROCESS HEAT REQUIREMENTS

	40°C-60°C	60°C-80°C	80°C-100°C	100°C-120°C	120°C-140°C	140°C-160°C	160°C-180°C	180°C-200°C	200°C
Dehydrated Fruits & Vegetables	0	100%	→	→	→	→	→	→	→
Concrete Block - Low-Pressure	0	100%	→	→	→	→	→	→	→
Autoclave	0	0	0	0	0	0	0	100%	
Frozen Fruit & Vegetables	0	0	39%	100%	→	→	→	→	→
Poultry Dressing	100%	→	→	→	→	→	→	→	→
Meat Packing	0	99%	100%	→	→	→	→	→	→
Prepared Feeds - Pellets	0	0	100%	→	→	→	→	→	→
Alfalfa Drying	0	0	0	0	0	0	0	0	100%
Plastic Materials	0	0	0	0	0	0	0	0	100%
Dairy Industry - Cheese	23%	100%	→	→	→	→	→	→	→
Condensed Milk	0	63%	63%	93%	100%	→	→	→	→
Dried Milk	0	0	42%	66%	71%	71%	71%	100%	→
Fluid Milk	0	0	100%	→	→	→	→	→	→
Soft Drinks	61%	100%	→	→	→	→	→	→	→
Soap	0	0	0	1%	→	→	→	→	100%
Detergents	0	0	0	52%	→	→	→	→	100%

A cross matching of the hydrothermal resources, as known today and projected for the future, on a county-by-county basis with the potential user sectors, has defined the prime commercial sectors that could most effectively convert to hydrothermal energy. This analysis reveals that all ten states under study have significant resources which correlate with potential energy market areas, and that the majority of the industrial and population centers are co-located with hydrothermal resources. The current energy use, considering all potential uses of direct heat, is 362×10^{12} Btu/yr, with a growth potential, by the year 2020, of 3980×10^{12} Btu/yr.

The largest single user segment is space conditioning and water heating. The current energy use for this is 288×10^{12} Btu/yr, and this could grow to 2504×10^{12} Btu/yr by 2020.

Many of the major industrial energy consumers in the states studied can use low to moderate heat sources to meet a portion, if not all, of their energy needs. These industries include food and kindred products processing, wood and lumber products, mining and minerals, chemical processing, and the concrete industry. Table III lists the top prospect industries that are matched by counties with hydrothermal resources.

The energy requirements of the industrial sector are somewhat smaller than the energy needs for residential/commercial space conditioning, but the ten-state area growth potential is excellent. In addition, it appears that the market can be more readily penetrated in the industrial sector since industrial applications are energy intensive (therefore decreasing the delivered cost per Btu), require less public acceptance, and have favorable tax benefits for investors. Current industrial energy use in the low to moderate heat processing sector which can be served by hydrothermal energy is 74×10^{12} Btu/yr, with a growth potential to 1476×10^{12} Btu/yr by the year 2020.

Table III

TOP 20 INDUSTRIAL PROCESS HEAT APPLICATIONS DIRECTLY MATCHED(a) FOR GEOTHERMAL ENERGY REPLACEMENT IN THE RMB&R REGION ($\times 10^{12}$ BTU/HR)

Industry	Matched 1975 Energy Use(b)
Dehydrated Fruits & Vegetables	11.80
Concrete Block	7.10
Frozen Fruits & Vegetables	5.24
Poultry Dressing	4.82
Meat Packing	4.45
Prepared Feeds	3.65
Plastic Materials	3.63
Dairy Industry	3.24
Soft Drinks	2.91
Soaps	1.24
Inorganic Chemicals	1.06
Ready-Mix Concrete	.98
Gypsum	.97
Canned Fruits & Vegetables	.97
Beet Sugar	.82
Treated Minerals	.69
Cotton Seed Oil Mills	.34
Prepared Meats	.34
Pharmaceuticals	.25
Furniture	.21

(a) Industries matched by co-location with resources and compatible process temperatures in those counties having hydrothermal resources.

(b) Regional consumption of direct heat energy in 1975 replaceable by hydrothermal energy from co-located and temperature-matched resources.

Market growth projections for hydrothermal energy in the ten-state area analyzed present an attractive profile. From the data illustrated in Figure 2, it is evident that a substantial portion of the region's energy needs can be satisfied by hydrothermal energy. Competition from conventional energy sources, as well as other alternative energy types (solar, biomass, etc.) result in the choice of conservative market penetration rates, as shown by the estimated penetration (bottom) curve.

ENERGY CONSUMPTION PROJECTIONS FOR THE RMB & R REGION

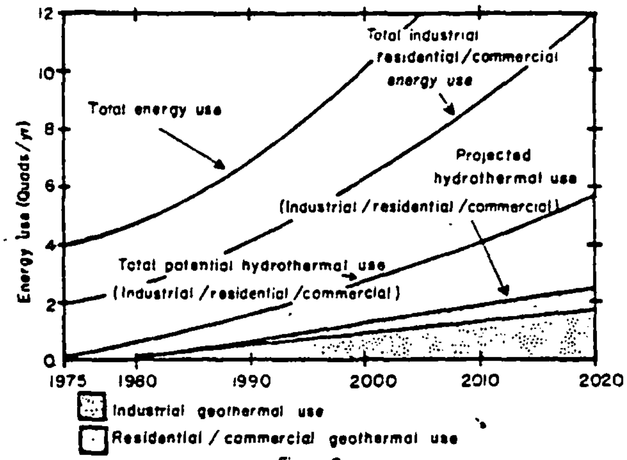


Figure 2

In the U.S., direct applications of hydrothermal energy are minimal, a result of our former abundant, inexpensive fossil fuel supply. However, with reduced fossil fuel supplies and increasing energy requirements, the nation can no longer delay implementing the significant contributions that the direct utilization of geothermal resources can make to meeting energy demands. Reducing resource uncertainties, assisting industry in developing confidence in the applications of hydrothermal fluid, removing unnecessary barriers, solving environmental issues, demonstrating uses, and providing incentives are necessary activities if the objective of widespread utilization of geothermal resources is to be attained. Many applications of geothermal heat are considered straightforward applications of existing technology, but there are applications, such as industrial drying with low- to medium-temperature geothermal fluids, where technical issues remain to be resolved by experiment, demonstration, or analysis. Small-scale and pilot testing are important incentives to demonstration and full-scale applications of industrial processes.

At the Raft River Geothermal Test Site in southcentral Idaho, a highly successful aquaculture experiment has demonstrated the desirability of raising aquatic species directly in geothermal fluids, a fluidized-bed geothermal dryer has converted potato wastes into high protein fish food, and an agriculture/irrigation experiment has explored the benefits and detriments of raising field crops with spent geothermal fluids. In addition, the first U.S. geothermal-powered air conditioner cools a Raft River office building; on-line building space heating is being examined, and new heat exchanger designs are being evaluated for highly corrosive and scaling water applications.

To further promote the development and early commercialization of direct applications, the Department of Energy has issued two Program Opportunity Notices for field experiments. Currently, eight projects are in progress and an additional fourteen are in the contract negotiation stage. The projects are listed in Table IV.

Table IV

GEOTHERMAL DIRECT USE FIELD EXPERIMENTS

Project	Location	Application
Utah Roses, Inc.	Salt Lake City, UT	greenhouse space heating
Utah Energy Office	Salt Lake City, UT	space & water heating
Montana Energy & MHD Research & Development Institute, Inc.	Butte, MT	space heating
Madison County Energy Commission	Rexburg, ID	district heating & industrial food processing
Chilton Engineering	Elko, NV	space & water heating
Town of Pagosa Springs	Pagosa Springs, CO	district heating
City of Boise	Boise, ID	district heating
Haakon School	Philip, SD	space & water heating
South Dakota School of Mines	Diamond Ring Ranch, SD	space heating & agribusiness
St. Mary's Hospital	Pierre, SD	space heating
Ore-Ida Foods, Inc.	Boise, ID	space heating & industrial food processing
Monroe City	Monroe, UT	district heating
City of Klamath Falls	Klamath Falls, OR	district heating
Torbett-Hutchings-Smith Memorial Hospital	Marlin, TX	space & water heating
Klamath County YMCA	Klamath Falls, OR	space & water heating
City of El Centro	El Centro, CA	space heating & cooling
TRW, Inc.	Redondo Beach, CA	industrial food processing
Navarro College	Corsicana, TX	space & water heating
City of Susanville	Susanville, CA	district heating
Geothermal Power Corp.	Novato, CA	space heating & agribusiness
Hydrothermal Energy Corp.	Reno, NV	space & water heating
Aquafarms International, Inc.	Mecca, CA	aquaculture

Each project, with minor variations, is organized to include the following major phases:

a) Environmental Report Preparation
b) Resource Assessment
c) Well Drilling
d) Well Evaluation
e) Corrosion Evaluation
f) Water Disposal Method Decision
g) System Design
h) System Construction
i) System Monitoring

The type and complexity of the current projects vary from space heating and grain drying (Diamond Ring Ranch) to food processing (Ore-Ida Foods, Inc.). While only existing technology is being employed to carry out the projects, they will provide an excellent baseline for future commercial development.

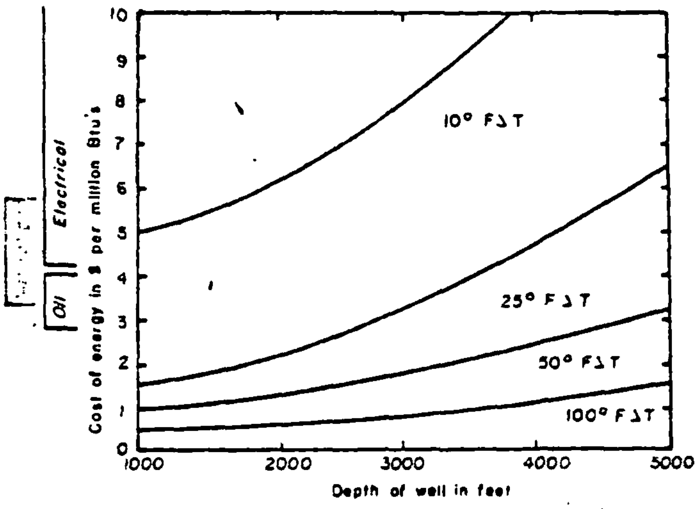
Valuable environmental, technical, operational and economic information will be generated as a result of these projects. In addition, institutional barriers will be tested, private firms and organizations will gain experience, and public awareness of hydrothermal energy will be increased.

Since it is difficult to discuss direct application economics except in a generic manner, these projects are especially important to the development of the hydrothermal market. Economics are extremely site and application dependent. Major factors which determine the economics are:

a) Depth of Resource
b) Geophysical Surveys Required
c) Utilization Factor
d) ΔT Available
e) Pumping Costs
f) Disposal Method Required
g) Fluid Transmission Distance
h) Water Quality
i) Heat Exchanger Surface Area Required
j) Cost of Investment Capital
k) Taxation Position of Developer/User

Figure 3 illustrates the importance of using as much of the energy as possible. If only a 10°F ΔT is available for use, the resource must be shallow and near its utilization point, whereas the project economics are greatly improved if ΔT's of 50 to 100°F can be obtained. Estimates from the field experiments program and actual cost data from several private developments yield energy cost rates from $.46/MBtu to $5.83/MBtu.

COSTS OF GEOTHERMAL



Plot assumes 500 gpm production and one mile of main distribution pipe

Figure 3

ELECTRIC APPLICATIONS

The lower temperature limit for economic electric power generation approaches 170 to 180°C. Since many of the presentations at this symposium will discuss power cycles, power economics, resource definition and reservoir engineering for electric power production, only a brief description of the research being performed to include the moderate-temperature resources into the "economic" power production range is discussed herein.

As one of the initial steps in the application of moderate-temperature hydrothermal resources to electrical power production, a prototype power plant, rated at 60 kW, was constructed in Idaho's Raft River Valley. This was the first time a binary cycle generated electricity from medium-temperature geothermal fluid and supplied power to a commercial grid. Isobutane is being used as the working fluid in this system. The primary function of this facility is to test advanced components and systems, and to gain actual operating experience.

Attempts to find less expensive devices to transfer heat are also continuing. Both fluidized-bed and direct-contact heat exchangers have been developed. Models of fluidized-bed exchangers, which use a bed of floating sand to scrub the scale from heat-exchanger tubing, were tested to analyze their flow-distribution characteristics. It now appears, however, that component development will center on direct-contact exchangers in which the secondary fluid mixes with the hot geothermal fluid.

A second prototype system, a 500 kW direct contact heat exchanger pilot plant, is being designed by Barber Nichols Company for the Lawrence Berkeley Laboratory. This system will be tested at Raft River in the fall of 1979. It will be the first test of a binary geothermal system with heat exchangers large enough to eliminate size effects.

As an outgrowth of this research and development work, a 5 MW(e) binary cycle pilot plant is being built at Raft River, Idaho. This plant will utilize state-of-the-art components, but will employ a dual boiling power cycle using isobutane as a working fluid. It is designed to take maximum advantage of the valley's low seasonal temperatures which are typical of the intermountain west. Design work was completed in January of 1978, and construction initiated in August, 1978. The facility should begin operation by mid-1980.

The 5 MW(e) plant will require about 2250 gallons per minute of 143°C geothermal fluid. The Raft River well field has four deep production wells. These wells will produce a flow of approximately 2850 gallons per minute, which is sufficient to operate both the power plant and auxiliary experiments. The production wells range in depth from 5000 to 6500 feet, and draw geothermal water from a zone of fractures 3750 to 6000 feet deep.

To protect the shallow groundwaters, and to prevent subsidence or ground settling, the expended hydrothermal fluid will be injected back into the ground. The Raft River well field contains three medium-depth injection wells. Tests are presently being conducted to determine their ability to accept long-term injection.

This research and development work, coupled with industry participation, will be instrumental in determining the economic and technical feasibility of the use of moderate-temperature resources for electric power production.

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(3) Howard, J.F., "Present Status and Future Prospects for Non-Electric Uses of Geothermal Resources," UCRL 51926, Lawrence Livermore Laboratory, October 15, 1976.

(4) Intertechnology Corporation, "Analysis of the Economic Potential of Solar Thermal Energy to Provide Industrial Process Heat," ERDA, Volume 1, February 7, 1977.

TAXATION OF GEOTHERMAL ENERGY

Sharon Wagner

INTRODUCTION

Whenever the issues of taxes, tax credits, tax incentives, depletion allowances, and/or intangible deductions are raised, it must be remembered that there are 51 tax systems in this country: one federal and 50 state. State corporate and personal income tax structures may or may not parallel the federal corporate and personal income tax structure. Generally the states have followed the federal government's lead in constructing their own tax systems. However, in the post-Proposition 13 mood of the electorate, it is not clear that states will adopt tax incentives for geothermal resources. Moreover, since the geothermal tax incentives adopted as part of the 1978 Energy Tax Act are so new, there will be some uncertainty as to their application until the IRS promulgates its Treasury Regulations for these new internal Revenue Code (IRC) sections. Until that time, it is safe to assume that the IRS will follow (with certain exceptions) the Treasury Regulations and court cases that are applied to the oil and gas industry. Most of the Treasury Regulations cited in the footnotes in the text below were written for the oil and gas industry but they are generally applicable to geothermal.

THE FEDERAL TAX SYSTEM

Prior to the passage of the Energy Tax Act of 1978,[1] the federal tax treatment of geothermal resources was based mainly on judicial decisions; not statutory authority. In 1969 the 9th Circuit Court of Appeals[2] held that the federal intangible drilling deduction[3] and the percentage depletion allowance[4] applied to the geothermal drilling at The Geysers. To reach this result the Court held that geothermal steam was "gas" within the meaning of §263(c) and §613(b) (1) of the IRC.

In 1975 the Code was revised to provide a 22% percentage depletion allowance for any geothermal deposit in the U.S., or a U.S. possession that was determined to be gas.[5] But the IRS refused to follow either the Court decisions or the new Code provision and contested both the intangible drilling deduction and depletion allowance on activities and income from The Geysers. Furthermore, because of the IRS intransigence the tax treatment of drilling a geothermal deposit that was hot water instead of the steam was even less clear.[6]

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[1]P.L. 95-618, §403(b), amending IRC, §613A(b).

[2]Arthur E. Reich, 52 T.C. 700 (1969), aff'd, 454 F. 2d 1157 (9th Cir. 1972) and George D. Rowan, 28 T.C.M. 797 (1969).

[3]IRC §263(c).

[4]IRC §613.

[5]P.L. 94-455.

[6]In Miller v. United States, 78-1 U.S.T.C. P9127 (D.C.C.D. Cal. 1977) the federal district court denied the intangible drilling deduction to investors who drilled geothermal wells in Nevada in an area of hot water, not steam, reservoirs.

The Energy Tax Act of 1978 has eliminated most of the uncertainties of tax treatment of geothermal exploration and development. The new tax provisions can be used to promote capital investment and to generate for the investor certain tax savings which reduce the risk of investment. Furthermore, the definition of geothermal deposits[7] is broad enough to include all the various forms of geothermal energy including dry steam, hot water or dry hot rocks. The act covers three basic subjects: intangible drilling costs, depletion allowance, and tax credits.

I. INTANGIBLE DRILLING COSTS

A. Option to Deduct Intangible Drilling Costs

§402 of the Energy Tax Act amends §263(c) of the IRC to allow a taxpayer the option to deduct as expenses intangible drilling costs (called "intangibles" or IDCs) [8] The costs of drilling and completing a geothermal well are divided for tax purposes into two classes: intangible drilling costs and equipment costs. The equipment costs must be capitalized and "recovered" through depreciation or depletion. Intangible drilling costs may be treated in two ways.[9]

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[7] "A geothermal reservoir consisting of natural heat which is stored in rocks or in an aqueous liquid or vapor (whether or not under pressure)."

[8] Intangible drilling costs are defined by Part 5A, Temporary Income Tax Regulations for the Energy Tax Act, 45 Fed. Reg. 6779 (1980) (to be codified in 26 CRF Part 1) as any cost incurred which in itself has no salvage value and which is "incident to and necessary for the drilling of wells and the preparation of wells for the production of geothermal steam or hot water." Such expenditures expressly include "labor, fuel, repairs, hauling, supplies etc." that are used (1) in the drilling, shooting and cleaning of wells; (2) in such clearing of ground, road making, surveying, and geological works as are necessary in preparation for the drilling of wells; and (3) in the construction of such derricks, tanks, pipelines, and other physical structures as are necessary for the drilling of wells and the preparation of wells for the production of geothermal steam or hot water.

[9] Since the geothermal provision for the option to expense intangibles is separate from oil and gas activities, a taxpayer may make one kind of election for his geothermal deposits and a different one for his oil and gas wells. For example, he could decide to expense intangibles for both geothermal and oil and gas properties or he could capitalize oil and gas and expense geothermal intangibles.

They may be deducted as expenses (in tax terminology they may be expensed) in the year in which they are incurred or they may be capitalized and deducted over a certain period of time as depreciation or depletion.[10] Allowing a taxpayer to expense (deduct) all the intangibles in the year in which they were incurred gives the taxpayer a kind of "accelerated depreciation."

The taxpayer must make his election to expense or to capitalize intangibles in his first taxable year in which he incurs such costs.[11] Once the election is made, the taxpayer must treat such expenditures on all geothermal properties in the same manner for all future years.[12] For example, if Taxpayer (T)[13] has spent $50,000 of intangible costs, T may claim as a deduction on his income tax return the $50,000 of intangible costs. But if T decides to capitalize intangible drilling costs T will not take $50,000 for 1978, but instead will deduct this amount over a given period of time as depreciation or depletion. However, if the taxpayer elects to capitalize his intangibles, he is granted a second election for dry or productive wells.[14]

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[10]Part 5A, Temp. Reg. supra note 8, states that intangibles, if capitalized, are to be separated and recovered as depreciation or depletion. Intangibles not represented by physical property (clearing ground, draining, road making, surveying geological work, excavating, grading, and the drilling, shooting, and cleaning of wells) are to be recovered through depletion. But intangible expenditures represented by physical properties (wages, fuel, repairs, hauling, supplies, etc.) are to be recovered through depreciation.

[11]A taxpayer must make a clear election either to expense or to capitalize. If he does not, the IRS will hold that he elected to capitalize intangibles. It is best that if a taxpayer desires to expense intangibles, he include with his income tax return an express statement of election to expense in accordance with the option.

[12]U.S. Treasury Regulation §1.611-4(e)

[14]But this second election need not have to be exercised until the first year in which a dry hole is drilled.

[13]The owner of the operating rights in a property who has the responsibility to develop the property is granted the option of expensing intangibles. But each taxpayer, regardless of his relationship to another taxpayer, is entitled to a separate election. Thus each partner in a partnership is entitled to a separate election. Trusts as separate taxpayers are entitled to an election regardless of the kind of election made by the beneficiaries.

The costs incurred in drilling a nonproductive well may be deducted by the taxpayer as an ordinary loss provided a proper election is made. But the taxpayer must make a clear statement of election to deduct as ordinary losses intangible drilling and development costs of nonproductive wells. If a clear statement is not made, such costs can be recovered only through depreciation and depletion.

But a noncorporate taxpayer, a Subchapter S corporation or a personal holding company that decides to expense intangibles instead of capitalizing them, may be subject to one of the following: the minimum tax (see "B"); a limitation on deductions to the amount "at risk" (see "C"); recapture of intangible deductions if the property is sold at a profit (see "D").

B. Preference Income-Minimum Tax

Some types of income are given preferential treatment by special provisions of the tax law. A minimum tax applies to a number of items that are considered to be of a tax preference nature. These types of income include capital gains, stock options, and income offset by depletion, amortization, and intangible drilling costs. The tax is computed by totaling all the items of tax preference, then reducing this amount by the greater of $10,000 or one-half a taxpayer's regular income tax after reduction by credits. A flat 15% rate is then applied against the balance.[15]

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[15]A taxpayer may be able to claim the unused part of certain credits against his minimum tax. Also if a taxpayer has a net operating loss that remains to be carried forward to a succeeding tax year, the minimum tax otherwise due may be deferred in an amount of up to 15% of the net operating loss to be carried forward to subsequent tax years when the loss is absorbed. In the years when the loss is absorbed, the taxpayer will be liable for the minimum tax deferred in an amount equal to 15% of the net operating loss absorbed in each year. See IRC §57(a)(11).

If taxpayer has "excess intangible drilling costs" that exceed net geothermal income, he will have preference income subject to the minimum tax. Intangible drilling costs are considered to be excessive when the intangible drilling and development costs of a geothermal well allowable for the tax year are greater than the sum of (1) the amount allowable if the costs had been capitalized and straight-line recovery of the intangibles had been used and (2) the net income for the tax year from the geothermal property.

Straight-line recovery means the rateable amortization of such intangibles over the 120 month period beginning with the month in which production from the well begins (or, if elected, any method which would be permitted for purposes of determining cost depletion). Net income from all such property reduced by any deductions allocable to the properties, except intangible drilling and development costs in excess of straight recovery.

This preference does not apply to taxpayers who elect to capitalize by straight-line recovery their intangibles. Nor does it apply to nonproductive wells.[16]

Special rules apply to corporations in computing their minimum tax[17]. And the IRS will publish rules under which items of tax preference of both individuals and corporations are to be properly adjusted where the tax treatment that gave rise to the preference does not result in a reduction of the taxpayer's income tax for any tax year.

In effect what this provision does is to lessen the benefit of the option to expense intangible drilling costs. Few taxpayers now have geothermal income and if they chose to expense intangibles, they will have preference income (that is, the amount they deduct by expensing intangibles will definitely be greater than the sum of intangibles capitalized and net geothermal income).

C. Losses Limited to Amount at Risk. [18]

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[16]Nonproductive wells are those which are plugged and abandoned without having produced steam or hot water in commercial quantities for any substantial period of time.

[17]See IRS Publication 542, Corporations and the Federal Income Tax.

[18]See IRC §465(c).

The 1976 Tax Reform Act limited the tax benefits available to persons engaging in oil and gas operations. These same limitations with some changes were extended to geothermal operations by the 1978 Energy Tax Act.

Before passage of the 1976 Act a taxpayer could take deductions up to the amount of this cost (or "basis") in a business or investment venture. But the basis of a taxpayer often included expenditures financed by nonrecourse loans for which the taxpayer had no personal liability (i.e., he had nothing "at risk" because of the way the loan was made to him or to an investment group). Such leveraged nonrecourse loans were often employed by investors to finance drilling and development costs of oil and gas activities. Since a taxpayer could elect to expense intangible drilling costs, he could take deductions far in excess of his own actual investment. This kind of investment was desirable for a high bracket taxpayer because the large deductions for intangibles could be used to offset income earned from other sources.

The 1976 law added §465 to the IRC and limited the amount of losses[19] deductible by a taxpayer engaged in exploring for and exploiting oil and gas. The taxpayer's deduction cannot exceed the total amount the taxpayer has <u>at risk</u> in the venture. Deductions taken for intangibles are considered losses for purposes of this section.

The Revenue Act of 1978 changed the "at risk" rules for years beginning after December 31, 1978. The most significant change is that previously allowed losses must be recaptured when the taxpayer's "at risk" amount is reduced below zero. But only the excess of the losses previously allowed in a particular "at risk" activity over any amounts previously recaptured will be recaptured under this provision. However, such recaptured losses may be deductible in a later year if at the "at risk" is later increased.

The practical effect of these "at risk" provisions is to eliminate the use of nonrecourse financing to increase available deductions.

D. Recapture of Intangible Costs Expenses As Ordinary Income on Disposition of Geothermal Property.

Probably the most far-reaching change of the 1976 Tax Reform Act affecting corporate and noncorporate taxpayers is the requirement that upon the disposition of oil and gas property taxpayers are required to recapture all or some part of the intangible costs incurred as ordinary income if the property is disposed of at a gain (a profit). These recapture provisions were extended by the Energy Tax Act of 1978 to intangible drilling costs incurred in connection with geothermal deposits.[20]

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[19]A loss is the excess of allowable deductions allocable to a particular activity over the income derived from the activity during the taxable year.

[20]P.L. 95-618, §402(c), amending IRC §1254(a).

This recapture provision applies only to intangibles which the taxpayer elects to expense in the year in which they were incurred and does not apply to intangibles which were capitalized. The amount of intangibles recaptured as ordinary income (instead of as capital gains) is the lesser of (1) the intangible costs incurred (reduced by an amount which would have been allowed as cost depletion had such intangibles been capitalized) or (2) the gain realized on the disposition. Or, in other words, the amount recaptured and taxed as ordinary income is the amount that the intangibles deducted exceed that which would have been allowed had the intangibles been capitalized and amortized on a straight-line basis (120 months) from the time the property went into production.[21]

II. PERCENTAGE DEPLETION

The IRC provides two methods of computing a depletion allowance: cost depletion and percentage depletion. Cost depletion provides for a deduction for the taxpayer's basis (cost) in the property in relation to the production and sale of minerals from the property. On the other hand, percentage depletion is a statutory concept that provides for a deduction of specified percentages of the gross income from the property. The deduction, however, cannot exceed 50% of the net income from the property. A taxpayer is required to compute depletion both ways and to claim the larger of the two amounts.

A depletion allowance reduces the taxpayer's basis in a property but the total amount taken as a depletion allowance is not restricted to the taxpayer's basis. Even though cost depletion will be zero after the taxpayer's initial basis has been recovered (for example, T deducts $5,000 per year for five years for a total of $25,000 - the amount of his original investment), the taxpayer may continue to claim a percentage depletion based on income from the property.[22]

§403 of the 1978 Energy Tax Act grants percentage depletion on income from geothermal deposits. The rate through 1980 is 22%. It decreases by 2% yearly until 1983 and thereafter the rate is 15%.

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[21] It should be noted that there are questions as to the proper method of calculating the reduction of recapturable intangibles under this section.

[22] A depletion allowance on the income derived from production and sale of the minerals from a property is available only to the owner of an economic interest in that property. An owner of an economic interest can be an owner of mineral interests, royalties, working interests, overriding royalties, net profits interests or certain kinds of production payments.

This percentage depletion allowance is much more favorable than the one allowed oil and gas. It is not limited in any way to a specified amount of production. It has no 65% of taxable income limitation nor is it restricted to independent producers. However, the percentage depletion cannot exceet 50% of the taxable income from the property and is subject to the minimum tax-preference income rules.[23]

There is some question about the availability of depletion on minerals which are consumed by the producer of such minerals. Many manufacturers are now exploring and developing their own sources of energy supplies, particularly natural gas reserves and in some areas geothermal. But the depletion allowance is dependent upon the sale of a mineral. Some courts have held that no depletion is allowable for minerals consumed in the operation of the producing energy property. It is not clear, however, if a depletion allowance is precluded with respect to gas used in manufacturing operations. For example, the IRS ruled in 1968 that the value of dry gas manufactured from wet gas and used as fuel for gasoline absorption plant is includible in determining "gross income from the property" for percentage depletion purposes, but the value of dry gas reinjected into the geological formation is not includible. One way for the corporate taxpayer to avoid the problem is to conduct its exploration and development activities through a wholly-owned subsidiary. The subsidiary could sell the gas to the parent at an arm's length price and create depletable gross income.

III. TAX CREDITS

A. Residential Energy Credit

§101 of the 1978 Energy Tax Act provides for a nonrefundable tax credit for certain expenditures incurred for equipment which uses geothermal energy in a taxpayer's principal residence in the United States. The equpment must be new and must meet certain performance and quality standards; it must reasonably be expected to remain in production for five years. The credit is as follows: (a) 30% of the expenditure up to $2000, (b) 20% of the expenditure from $2000 to $10,000. The maximum credit is is $2200. The credit may be carried over to future years for equipment purchased after April 20, 1977 and before January 1, 1986.

B. Additional Investment Tax Credit for Alternative Energy Property

A 10% investment tax credit in addition to the existing investment tax credit is available for geothermal equipment which qualifies as either "alternative energy property" or "specially defined energy property." Public utilities cannot benefit to the extent of "alternative energy property" but can use the credit for "specially defined energy property."

The business energy credit is limited to 100% of tax liability, except for solar or wind energy property on which the credit is refundable. Until the IRS issues its regulations on this new section it will not be completely clear what kind of equipment qualifies.

[23] The excess of the depletion deduction over the adjusted basis of the property at the end of the year (determined without regard to the depletion deduction for the year) is what would be preference income.

STATE TAX SYSTEMS[24]

Of the fifteen states with known geothermal resources Nevada, Texas, Washington and Wyoming have no state personal or corporate income tax. Alaska, Colorado, Hawaii, Idaho, Montana, and New Mexico apply their income tax levies to adjusted gross income as calculated for federal income tax. But five states have an independently determined income tax: Arizona, California, Louisiana, Oregon and Utah. Their differences from the federal law are largly due to the state provisions concerning percentage depletion for resources extraction industries.

Two states, California and Arizona, provide two examples of how complex the state tax picture can be. California has a franchise tax and a corporate income tax. The franchise is for the privilege of exercising a corporate franchise within the state. The tax rate is 9.6% for calendar or fiscal years ending in 1980. For subsequent years the rate is dependent on bank and corporation tax revenues. The following chart gives these rates.

1981

Revenues Collected in 1979-80	Corporation Tax Rate for 1981
Less than $2,950,000,000	9.6%
$2,950,000,000--$3,025,000,000	9.5%
$3,025,000,000--$3,100,000,000	9.45%
Greater than $3,100,000,000	9.40%

1982

Sum of Revenues Collected in 1979-80 and 1980-81	Corporation Tax Rate for 1982
Less than $6,000,000,000	9.6%
$6,000,000,000--$6,075,000,000	9.50%
$6,075,000,000--$6,150,000,000	9.45%
$6,150,000,000--$6,225,000,000	9.40%
Greater than $6,225,000,000	9.35%

1983

Sum of Revenues Collected in 1979-81, 1980-81 and 1981-82	Corporation Tax Rate for 1983
Less than $9,450,000,000	9.6%
$9,450,000,000--$9,525,000,000	9.50%
$9,525,000,000--$9,600,000,000	9.45%
$9,600,000,000--$9,675,000,000	9.40%
$9,675,000,000--$9,750,000,000	9.35%
Greater than $9,750,000,000	9.30%

24 For an extensive analysis of state tax systems see State Taxation of Geothermal Resources Compared with State Taxation of Other Energy Minerals, Sharon C. Wagner, published by the Geothermal Resources Council, Davis, CA.

Insofar as the franchise tax overlaps the corporate income tax, the amount due under the franchise tax is offset against the amount due under the income tax. The computation of income for both the franchise tax and the income tax follows generally the pattern of the federal income tax and interpretations of the federal law by the Treasury Department, with the exception of depletion provisions.

Prior to 1975 California provisions for depletion allowance for oil and gas and other minerals conformed basically to federal law. However, California did not follow the Federal Tax Reduction Act of 1975 which eliminated percentage depletion for oil and gas wells (with a few exceptions). California merely placed a limit on the total amount deductible by each individual taxpayer. These limitations apply only after the total accumulated depletion allowed or allowable exceeds the adjusted cost of the property.

A deduction of 22% of gross income, less rentals and royalties, for the taxable year is allowed for oil and gas properties. This deduction may not exceed 50% of taxable income computed without allowance for depletion. In addition, where the deduction exceeds $1.5 million and is greater than the adjusted cost of the taxpayer's interest in the property, the deduction is reduced. The reduction equals 125% of the amount in excess of $1.5 million.[25]

For example, suppose that the 22% depletion is $3.5 million and that this amount exceeds the cost of the taxpayer's interest in the property. The deduction in this case is reduced by 125% of $2 million ($3.5 million minus $1.5 million), which equals $2.5 million. The allowed deduction in this case is $3.5 million minus $2.5 million which equals $1 million. If, instead, the 22% depletion amounts to $7.5 million, then the reduction is 125% of $6 million, which is equivalent to the depletion allowance itself, and no deduction is allowed.[26]

In September 1979, Governor Brown signed a bill[27] that conforms selective provisions of the Bank and Corporation Tax Law and the Personal Income Tax Law to the 1978 federal Energy Tax Act. The major changes that affect geothermal development are:

1) The at risk loss restriction provision of present law, which applies to four specified activities (farming, oil and gas, motion pictures, and equipment leasing) is extended to apply to all activities except real estate carried on by individuals and partnerships. This applies to geothermal properties. See discussion of federal "at risk rules" above.

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[25] CAL. REV. & TAX CODE §17686.

[26] Bock, <u>1978 Guidebook to California Taxes</u>, p. 123.

[27] Chapter 1168, Laws 1979, effective January 1, 1979.

2) Under §24832 and §17686 both individuals and corporations are given a 22 percent depletion allowance for geothermal wells. The 22 percent is computed on the gross income from the property during the taxable year, excluding from such gross income the amount equal to any rents or royalties paid or incurred by the taxpayer in respect of the property. The allowance cannot exceed 50 percent of the taxable income of the taxpayer (computed without allowance for depletion) from the property. See discussion above under oil and gas deduction rules.

3) Excess intangible drilling costs are an item of tax preference for personal income tax only.

4) Owners of geothermal wells are specifically permitted to treat drilling costs as a current expense rather than being required to capitalize these costs. But "excess intangible drilling costs" are subject to recapture. See discussion above under the federal law.

Arizona has raised its corporate tax rates several times in recent years and another change for corporate and individual income tax rates was pending before the Legislature in December, 1979. The current rates are as follows:

1st	$1,000.	2.5%
2nd	1,000.	4
3rd	1,000.	5
4th	1,000.	6.5
5th	1,000.	8
6th	1,000.	9
Over	6,000.	10.5

In 1977 Arizona was the first state specifically to provide for a depletion allowance and depreciation deduction for geothermal wells in computing new income. The depletion allowance is 27 1/2% of gross income, excluding an amount equal to any rents or royalties paid in respect of the property. The allowance cannot exceed 50% of the taxable income of the taxpayer from the property, computed without subtraction for depletion. Also expenditures paid or incurred during the income tax year for the development of a geothermal resource well, if paid or incurred after 12/31/53, may be deducted from gross income or charged to the capital account. Amounts up to $75,000 paid or incurred for the purpose of ascertaining the existence, location, extent or quality of any deposit of geothermal resources are allowed as a deduction.

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ECONOMIC RISK OF GEOTHERMAL PROJECTS

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Management methods for evaluating business opportunities involving uncertainties have included the concept of risk analysis. Risk analysis can be a powerful tool to compare the economic attractiveness of the various investments available to the business community. Natural resource development groups utilize this technique to select their exploration targets and to appraise the anomalies found. Additional funds can be allocated to those providing the opportunity for greatest return per dollar risked.

What is the risk factor used in economic analysis? When the probability of occurrence of any given event has been established, the risk factor will be known. The mathematical concept of risk factor can be considered as: The probability that an event will occur in one of several ways is the sum of the probabilities of the occurrence of all the possible ways that event can occur.

For example, a review of exploration work on geothermal prospects determines that in basin fill areas containing water saturated rocks four electrical resistivity anomalies are due to low resistivity sediments and one is due to an unusual amount of heated pore water.

The chances for being successful in a temperature confirmation drilling program on these resistivity anomalies will be 1:5. The probability of being successful is not the same as risk. In this example, in five attempts at success in a series when the risk is 1:5, the probability of success is approximately 68 percent.

The summation of risks involved in geothermal development evolves to essentially the question: Can the energy compete with other sources of energy available to the customer and still provide a reasonable rate of return on the necessary investment? The competitive fuel in the area of major geothermal steam occurrences is fuel oil. Coal is a strong competitor for hot water flash systems. Coal prices will probably follow oil prices in the next two decades. At this time hot water systems at temperatures below 400^{o} F. cannot produce the energy for electricity generation inexpensive as coal fueled generating plants.

A look at the oil supply situation will provide a background for assessing the risk of oil prices increasing more rapidly than cost associated with geothermal development.

Saudi Arabia oil production is around 8.7 to 9 million barrels per day. Two years ago that country produced 10.2 million barrels a day. Present capacity is believed to be 11 million barrels per day. ARAMCO has added about three million barrels per day capacity during the past two years. The capability for producing much more exists. The willingness to produce in increased amount is another thing that poses a risk to the assumption they will. The Saudis are determined to maintain OPEC as an effective organization and will continue their production at around 8 to 9 million barrels per day. World oil demand should continue to increase 2 to 3 percent per year until the end of 1980.

OPEC production in 1978 was approximately 29 million barrels per day. This has gradually moved back to the 1977 high of 30 million barrels per day.

All free world net growth in oil demand (now 48 million barrels per day) during the next three years will be satisfied by non-OPEC sources: Mexico, North Slope and the North Sea.

Until 1985 world oil prices will be increasing, about the average rate of inflation. From 1985 on, world oil prices will be increasing at accelerating rates as OPEC countries maximize their return on a diminishing number of barrels.

Natural sources of heat above 450° F. in the western United States can produce electricity at prices competitive with low sulfur coals shipped from the Powder River Basin of Wyoming to the electricity generating centers supplying western Nevada and California. Water within the low energy 150° F. temperature range can provide processing heat, if the source is in a location where the energy can be used in the United States. It is expected that sulfur limits for fuel oil will be set similar to coal. To meet such standards, additional investment and costs will be required to prepare acceptable fuel. With such increases in cost, additional new uses for geothermal heat (energy) will become practical. As that happens, more people become interested in joining the exploration search to find and develop new deposits of heat for production of energy.

The development of a geothermal reservoir is capital-intensive, requires expert planning, and long times from initial expenditure until positive income is achieved. The utilization of a geothermal reserve requires extensive engineering, approximately two years in negotiation and planning with governmental agencies, and significant capital. (35 to 50 million dollars per 50 mw.)

The costs of maintaining and operating producing fields is about four to five times greater than the capital investment. An important portion of this cost is associated with the injection system that collects the cooled water and returns it to the sub-surface reservoirs after the heat is removed. Reducing these costs is an essential objective if geothermal energy is to remain competitive with other fuels.

Countries with high fuel costs and geothermal sites are now developing a wide variety of geothermal plants. Japan appears to be building the most efficient flash systems for use in hydrothermal areas with reservoir temperatures above 350° F.

Useful geothermal reserve assessment requires professional engineering analysis. The goal is to determine how much heat can be produced at a useful rate and temperature for at least 20 years from one area. This demands a thorough understanding of the manner in which heat is transported to areas of accumulation, how it accumulates, the methods and costs to find, produce and convert to a useable form of energy. With those studies in hand, a person can then determine what part of this resource can be sold in competition with other fuels and thereby establish the size of the reserve.

The supply of geothermal energy has been related to: all the heat present above an arbitrary temperature datum; the amount of heat between certain temperature levels, that heat contained in producing water, and; that heat contained in the rock framework transferred to the moving body of water.

The amount that could be produced in the United States if the government would provide incentives equal to other energy sources is now thought to be between 12,000 and 15,000 megowatts.

These incentives have included tax credits, deductions in tax calculations, investment tax credits, rapid depreciation, and depletion allowances. Other incentives include aid in exploration, aid in developing, engineering of generating plants, financing of generating plants, and reservoir engineering studies. Very little has been prepared showing the increased benefit to governmental programs, including tax revenue by demonstrating the increased flow of dollars from projects that would become profitable with this aid compared to project tax revenues that would be commercial without this aid. Dr. Robert Rex has calculated that for a 48 net mw plant paying 25 mils/KWH for the energy the government income would be more than 213 million dollars during the 30 year productive life. If this were on private land the government income would be 178 million dollars.

The actual potential of geothermal energy is affected by how the resource and reserves are calculated. These calculations must consider availability and application of governmental incentives, the price of other energy sources, versus the market price of geothermal energy, and the reliability of the production forecast. The size of required investment, the expected profit generated by those investments, plus the availability of lands to explore will be the motivating forces in developing the true potential of geothermal energy in the United States.

The most important factor in converting any resource into a reserve is how the individuals that are actively dedicated to discovery and development attack the problem. The key to successful reserve development is the quality of the people assigned to the task.

The critical economic factors affecting the risk of a geothermal project being successful can be considered in two categories. The first is that associated with the production of the geothermal energy. The second is in the conversion of the energy into a useful form for the production of electricity.

The energy producer, after finding the geothermal anomaly, must consider his risk of resource development concentrated into four major items. These are the reservoir life, the sales price for the energy, the plant design, and the pricing structure. Other opportunites for investment will affect the amount of money he may dedicate to the program.

The number of years of reservoir production at useful temperatures and volume of fluid that can be expected is of utmost importance. The reservoir economic life is affected by the rate of decline in temperature and production as this affects the drilling and equipment investment and the operating costs.

The risk the project succeeds depends upon the price of energy produced. The sales price defines the cash flow available for development and operating expense. This price establishes the limits of investment that can be made and the potential rate of return on this investment. The competitive stature of the resource will be prescribed by the price of the delivered energy. The final size of the economic reserve is thus determined by these factors. That size then determines the amount of risk the energy producer can assume at various stages of exploration and development.

The plant design affects the cost of designing the production mode as the delivered product must conform to the requirements of the plant. Single-phase fluid delivery (for other than dry steam) requires greater investment to maintain that phase from the reservoir into the plant than does a two-phase system. Injection disposal facilities are dependent upon the plant requirements. The rate of production from the reservoir is also dependent upon the plant design. The limits of fluid temperature useful in running the plant are established by the plant's design. The life of the producing facility is seriously affected by this factor.

The pricing structure can encourage efficiency in developing new reservoirs or negate the advantage of searching for deeper, though hotter, horizons. Provisions for reservoir failure can allow the taking of a greater risk in developing the reservoir to its maximum size. If the reservoir performance must be guaranteed by the producer, he can then only develop the amount of energy that has very little risk. Thus, the fuel producer and the utility have little chance for maximizing their return on the use of this impressive source of energy unless pricing structures recognize this effect.

Electricity producers are not prepared to undertake projects that have a risk of complete failure in the early stages. They are not oriented to taking risks of the magnitude considered acceptable by natural resource developers. For instance, developers know the risk of finding one million barrels of oil with a wildcat is about one in forty times being successful. So their organization has the ability to provide for the unsuccessful exploration ventures effect on their marketable supply of energy. The ability to evaluate and predict the reservoirs' capability for producing certain quantities of fluid is highly developed in oil companies because the few successful finds must be developed to their full capacity.

Utilities historically expect a certain amount of fuel to be delivered on schedule throughout the plant's lifetime. The utility organization has not developed the capability of being comfortable with reservoir engineering analysis. Geothermal energy does not provide the risk abatement feature of having another source of supply that can be brought in to augment a premature declining geothermal energy supply. This is the major risk the utility management recognizes in the economic viability of building a geothermal plant. The risk of having a favorable cost at the Busbar for the electricity produced can be determined after the design of the generating plant has established the production requirements for delivery of the geothermal energy. These requirements are strong factors in the producer of the energy identifying his costs of production and therefore a likely energy sales price.

The fixed costs affect the final price of produced electricity. Dry steam plants can be constructed for a lower investment than single-flash plants. The single-flash plants require a lower investment than the double-flash design.

The lower efficiency of the single-flash plant requires a much higher volume of fluid to be produced and handled to produce the same number of kilowatt hours. This effect of these design segments on the producer of energy and producer of electricity create the risk that each will have selected the optimum design for their components.

Knowing the size of the available fuel supply lowers the risk of underfinancing a development project. For rocks to be considered a reservoir, there must be sufficient horizontal and vertical permeability to allow the fluid to move easily. A 6,000-foot to 8,000-foot well must sustain flow rates of more than 100,000 pounds of steam per hour, or 500,000 pounds of water (at no less than 325 degrees Fahrenheit) per hour for 20 to 25 years to be considered commercial for electricity generation. Direct use of heat for industrial or space heating and cooling does not require such high heat output. The lower temperatures for such uses can be found in a greater number of anomalies. However, their usefulness is dependent upon low cost being achieved in development and production.

The geologic model that is generally accepted by geothermal explorers and developers has three basic requirements:

1. A heat source (presumed to be an intrusive body) that is about 2000^{o} F. and within 40,000 feet of the surface.

2. Meteoric waters circulating to depths of 10,000 feet where heat is transferred from the conducting impermeable rocks above the heat source.

3. Vertical permeability above the heat source connecting the conducting rocks with a porous permeable reservoir that has a low conductivity impermeable heat retaining member at its top.

Geological investigation is the necessary ingredient that makes all exploration techniques useful. Broad reconnaissance of the surface data integrated into subsurface data is used to find an area of general interest. The ingenuity of the prospect finder in using data available to all workers determines whether an exploration program moves into advanced stages of using the proper combinations of the acceptable methods.

Geologic interpretation of the data acquired may justify the money required for exploratory drilling. The results of the drilling must be integrated into the geologic investigation to determine if a promising prospect is present.

The investigation must establish that:

1. High heat flow or strong temperature gradients are present at depth.

2. The geology provides reasonable expectation that a reservoir sequence of rocks is present at moderate depths from 2000 to 6000 feet.

3. The sequence of rocks offers easy drilling with minimal hole problems.

4. A high base temperature and low salinity waters as indicated by geo-chemistry of water sources should be present. The surface alteration and occurrence of high heat flow should cover an area large enough to offer the chance for a field capacity of more than 200 megawatts.

Table I (adjusted for 1980 costs) from C. Heinzelman's presentation of October 15, 1977 illustrates exploration techniques and associated costs. The overall amount of money (per succesful prospect) required is 3 million to 4.75 million 1977 dollars. This provides for limited failure and followup costs, but does not include the other exploration failures and land costs.

Table I

Exploration Techniques and Approximate Costs

Objective	Technique	Approximate Cost ($)
Heat Source & Plumbing	Geology	$ 20,000
	Microseismicity	15,000
Temperature Regime	Gravity	20,000
	Resistivity	25,000
	Tellurics and magneto-tellurics	50,000
	Magnetics	15,000
	Geochemistry (hydrology)	12,000
	Land analysis and permitting	25,000
	Temperature gradient - 20 holes(500' or less)	100,000
	Stratigraphic holes -4	160,000 - 240,00[illegible]
Reservoir Characteristics	Exploratory and confirmation tests -3-	1,800,000 - 4,000,00[illegible]
	Reservoir testing	250,000

To establish a discovery approximately $2,500,000 - $5,000,000 will be required.

This is probably the minimum expenditure needed to change a portion of the resource base into an area of reserve with production potential.

Upon deciding that a significant geothermal anomaly exists, the rate of engineering expenditures must increase rapidly to determine whether the development can proceed into a commercial venture. Essentially, there are no set figures for what it costs to develop a geothermal field. The basic reason for this is that each depends upon engineering the development to be compatible with the geology of the accumulation, and the requirements of the electricity generating system. The electricity generating system must be designed within the constraints of available temperature, rate of production, and ambient conditions of the field site. The key variables affecting risk are:

1. Temperature of the fluids produced.
2. Composition of the reservoir fluids.
3. Composition of surface or near surface fluids.
4. Geology of the reservoir framework.
5. Flow rates that can be sustained by the reservoir.
6. Cost of drilling in the prospect area.
7. Well spacing and geometry of the producing and injection sites.
8. Turbine system to be used.
9. General operating costs in the area.

Test Wells - Thermal evaluation requires the drilling of test holes. Heat flow and temperature gradient evaluation requires drilling to intermediate depths. Confirmation drilling requires holes drilled to the actual reservoir for diagnostic evaluation.

Heat flow and temperature gradients measured in the upper 100 to 500 feet of depth are useful in describing the area where the heat transfer is most intense. These do give a qualitative analysis as to the location and shape of the hottest near surface heat accumulation. Linear projection of temperatures obtained near the surface cannot be used to predict the temperatures that will be encountered 2000 to 3000 feet below the surface, even if the section below has a uniform lithology and the geothermal gradient is a straight slope. The temperature for a fluid-saturated system cannot be projected to a maximum above that for boiling water at the pressure calculated for the depth of projection. At some point along the boiling point curve, the temperature of the system may become isothermal and the rocks and fluids will have the same temperature for many hundreds of feet deeper. The rock temperature may decrease as a hole is drilled deeper if the hole is on the descending edge of a plume of hot water or merely below the spreading top of a plume. Heat flows from a hot body to a cooler body. This is not a function of being above or below a reference point of depth.

To lower the risk that the performance of the geothermal cell can be predicted, deep tests must be drilled. These holes must be of sufficient size to adequately determine the ability of the reservoir to produce fluids above 365° F. at rates approaching 100,000 pounds of steam per hour, or 500,000 pounds of liquid per hour.

To determine if a commercial development is possible, three or four wells must test the reservoir to obtain the basic reservoir engineering data. Reservoir pressure drawdown and buildup analysis must be conducted to determine reservoir permeability and extent. Fluid characteristics and analysis of non-condensible gas present require extensive flow testing. Injectivity testing is required to develop plans for disposal and pressure maintenance systems. Rocks may produce fluids easily, but may not accept them on return to the reservoir. This must be established in the laboratory and confirmed in the field for a developer to consider risking the investment needed to develop a field. The utility customer needs the same assurance.

A summary of estimated development costs after exploration expenses for the field supply, power plant, and ancillary equipment for a 50-megawatt hot water flash unit is as follows:

Table II

Development wells - 12	$ 14,400,000
Injection wells - 6	6,000,000
Pipelines	2,800,000
Miscellaneous field expense (includes interest and working capital)	9,000,000
Power plant	35,000,000
	$ 67,200,000

Economic Considerations

To obtain an economic comparison of geothermal fuels with the more widely used fuels is quite difficult, because each geothermal area requires a plant design specifically useful for that local area. The California Geyser's steam price of 17.5 mills per kilowatt hour is as inexpensive as geothermal energy can be produced in the United States today. This is a dry steam fuel, and the operators have more than a decade of experience in drilling, completion, and production operations. Optimum techniques have been developed so that maximum steam production per dollar invested can be maintained. The high energy content of this fluid provides a competitive heat rate, easy to construct collection systems, and the most simple of plant and reinjection facilities. The actual cost of the wells is frequently as high as $1,500,000, but the operation and the high utility of the steam allows a minimal price for the energy.

The wide variation of estimates of fuel costs and electricity generating costs derives from treatment of fuel processing and storage expense, income taxes, ad valorem taxes, insurance, interest during construction, return on investment required, and specific requirements for plants in the area of operation for the estimating companies.

The utility usually expects to earn a minimum of 25 percent return on investment on its equity portion of the investment. The exploration and producing investors have learned that a minimum acceptable rate of return on investment for their portion of the projects is 25 percent return on investment. The average conventional energy venture (non-geothermal) usually obtains about twice this rate of return to compensate for the risks involved. The prime rate has risen so high today that low risk venture returns will provide a ROI that is nearly as attractive.

The return on investment for the developer is most sensitive to the price received for the energy. Next to reliability of supply, the utilities' desires to use geothermal energy in electricity generating systems is dependent upon its price being low enough to make its use worthwhile. Much like coal and uranium, geothermal fuel prices will be a negotiated price between the supplier and the user. Each field will have significant differences in design so a uniform price cannot be expected for construction of the production facilities, or construction of the utilities conversion plant.

The nature of the reservoir geometry and the ability of the reservoir to respond to changes in production, rates, and temperatures, will determine the final costs for producing electricity from each geothermal project.

The basic structure of price must provide an attractive rate of return to the prospector. To achieve this, the prospector's risk capital investment and time at risk before income must be minimized. Most important, the revenue should reflect the actual value of the energy sold.

Cost Comparisons

The cost comparisons between the various sources of energy that will be available and useable for electricity generation during the next decade will affect the rate of geothermal energy's growth. The economic desirability of the production or use of a fuel is sensitive to its price. Regulatory requirements have direct effect upon production and construction costs. The tax treatment for each fuel system is a dynamic one. This makes it very difficult to assess the resulting economics.

The amount of money needed to construct and operate plants to use each fuel is a strong component of how much the electricity producing customer will pay per unit of fuel. The average coal and oil burning plant uses 8,500 to 10,500 Btu/kwh. A nuclear plant uses about 14,000 Btu/kwh. Geothermal plants use between 21,000 to 33,000 Btu/kwh.

Oil

Electricity produced from oil fired plants is directly related to the cost of low sulfur fuel oil. An oil fired turbine generator plant costs between $400 - 500 per kilowatt. A combined cycle plant is about $360 per kilowatt. The difference in heat factor, operating cost, and available capital for these plants establish which will be used for meeting the increased demand and plant replacement schedule within a utilities service area. The estimated cost developed by Stanford Research Institute of fuel oil in mills per kilowatt hour is approximately 23 mills per kilowatt hour. Strong competition between suppliers results in a stabilizing effect upon the overall price of oil. Utility planners have estimated the range of price of oil to be 20.5 to 21 mills per kilowatt hour. These cost ranges combined with the new plant costs will produce electricity between 33 and 44 mills per kilowatt hour. This figure must be adjusted for the strong energy price increase during the last twelve months.

Coal

Coal prices are related to specific sources of supply and dedication of specific sources of coal to certain plants. Coal does not presently have the wide range of usefulness that oil enjoys today. This limits the substitution of one coal for another.

The price of steam coal and plant construction costs to meet environmental requirements result in an estimated price of 35 mills for electricity generated in new coal plants. Fuel suppliers currently estimate coal can be delivered within a 1,000-mile radius for 10 to 15 mills per kilowatt hour if surface mining methods are used.

Nuclear

Nuclear fuel plants appear to offer the least expensive electricity for a non-indigenous source of energy.

The utility industry estimates they will be paying 6 to 6.5 mills per kilowatt hour for nuclear fuels and plant costs in 1977 dollars will be $800 to $1,000 per kilowatt. The estimated cost of electricity from such plants will be between 32 to 34 mills per kilowatt hour.

Geothermal

Comparison of conventional electricity prices with geothermal steam prices are a matter of public record. This is the least expensive of all thermal systems employed in the United States. To obtain a comparison of hot water flash steam plants, it is necessary to use developments outside the United States for performance factors. Economics of hot water flash to steam projects continue to be impressive. Cerro Prieto's development is very encouraging as exploratory work confirms this development can exceed 500 mw. The improvement in heat recovery with double flash units would reduce the cost of electricity and increase the size of reserves significantly. Seventy-five megawatts have now been developed and work is underway on the next 75 megawatts. The first unit of 75 megawatts was developed for $264/kw and produced electricity for approximately $.008, tax free. Today, costs would be about twice that amount. The cost includes the well field operation as this is an integrated operation. It is estimated the second 75 megawatt plant will produce electricity for about 16 mills, tax free.

It is possible to use the development work at Momotombo Nicaragua to evaluate the costs of developing a hot water flash field today. DeGolyer McNaughton, the international consulting firm, and Herman Dykstra, a reservoir engineering consultant, have completed examination of all the field test data from Momotombo. Tests using bottom hole pressure devices in selected wells were combined with field flowing tests. The firm concluded that double flash turbines could produce 96 megawatts for more than 30 years using the portion of the reservoir developed. Subsequent completion tests have demonstrated more than 100 megawatt capacity.

Turbine specifications prepared provide for a plant turbine with 80 psig first stage and 20 psig second stage. The power plant for this 225° C. field may have two 35 megawatt units in operation by mid-1980. The estimated cost for the electricity generating plant installed will be $460 per kilowatt. A savings of $26 million in foreign exchange would result from this development.

Steam

Geyser's steam price is about as inexpensive as geothermal energy can be produced today. The 1979 price of 17.5 mills per kilowatt hour is well below the competitive value of this energy. Twenty-five mills per kilowatt hour would be a price more nearly reflecting its actual value in an area using oil or coal for electricity generation.

PG&E's plant #15 is expected to cost $320 per kilowatt with provisions for H_2S treatment. This is an increase of 250 percent over the average of the 1961-1974 period. In the same period, the cost of electricity generated averaged about 5.6 mills per net kilowatt hour. 1979 operating costs will have increased the busbar price to 25 to 30 mills per kilowatt hour.

Summarizing the preceding discussion on comparison of costs and resultant prices of electricity, we can tabulate oil, coal, nuclear versus geothermal as follows:

	Oil	Coal	Nuclear
Fuel mills per kilowatt hour	20-23	9-11	6-7
Plant $/kw	400-500	780-1000	1000-1200
Electricity Busbar mills/kwh	33-34	38-40	38-40

	Geothermal		
	Steam	Flash 450°F.	Binary
Fuel mills per kilowatt hour	17.5	18-22	26-30
Plant $/kw	320	450-475	500-1000
Electricity Busbar mills/kwh	25-30	27-32	40-48

Reserve Esitmates

With these competitive conditions and an idea of the required investments in plant and fields, we can estimate the potential reserves identified in relation to the proven reserve.

The proven reserves of the Geysers is now 1507 megawatts. The potential reserves are another 1200 megawatts. To infer that the hot water area surrounding the dry steam reservoir will produce waters that will be used in flash steam plants is reasonable. Inferred hot water flash reserve should be approximately 1,000 megawatts.

The proven reserves in the Imperial Valley are 400 megawatts. Potential reserves of Brawley, East Mesa, Heber, Niland, and Westmoreland total 1600 megawatts. Reserves have been inferred with anothe 1,000 megawatts in these and similar anamolies within the province. Considerable work must be done on conversion systems, and deep drilling in the California portion of the Imperial Valley if another 5,000 megawatts are to be moved from the resource category into the reserve category in the next 20 years.

In the western Utah area Roosevelt is the only area with proven reserves. It appears that sufficient testing and plant design work has been completed to assign 80 megawatts to that classification. 120 megawatt potential and 300 megawatt inferred reserves can be assigned to Roosevelt on information now available. The remainder of that general area including Cove Fort - Sulfurdale, Thermal-Black Mountain, should have 1,000 megawatts potential reserves and 500 megawatt inferred.

Dixie Valley should have 100 mw potential if continuity of productive zones can be established. Another 400 mw may be inferred on similar anomalies within the Valley. South Nevada from Tonopah to Ely should contain 500 mw of potential and inferred reserves. Testing of potential areas in Nevada has not progressed to the stage where proven reserves can be assigned. The potential reserves of Phillips' three areas, and Chevron's two areas in the norhtern half of the state, indicates 400 megawatt reserve. An additional 600 megawatt can be inferred on the basis of drilling data being extrapolated with geophysical surveys. With continued confirmation success in the Carson sink area, an additional 500 megawatts could be moved from resource to inferred reserves. New Mexico's Valles Caldera is considered as having 100 megawatt potential reserve. From the size of the anomaly and the temperature indicated by surface springs, an inferred reserve of another 300 megawatts should be assigned. This area has a total reserve of 400 megawatts.

Summary

Electricity Generation Reserves

	Proven (Measured) MW	Potential (Indicated) MW	Inferred (Geol-Geoph) MW
Geysers	1520	1240	1000
Imperial Valley	400	1600	1000
Coso-Lassen Long Valley Mammoth Randsburg			700
Dixie Valley		100	400
Roosevelt	80	120	300
Cove Fort Sulfurdale Black Mountain-Thermal		300	400

	Proven (Measured)	Potential (Indicated)	Inferred (Geol-Geoph)
N. Nevada - Fallon to Winnemucca		400	600
S.Nevada Tonopah to Ely		200	300
New Mexico		100	300
Alvord Area		100	100
Alvord to Vale			300
Subtotal	2050	4160	5400
Total	11,600 megawatts		

The direct use of geothermal heat in the United States is on a local project basis except in Klamath Falls, Oregon and Boise, Idaho. Local greenhouse operations, individual processing plants in industrial and agricultural projects, are found throughout the western United States, Alaska, Texas and the southeast Appalachians. It is estimated these present direct uses represent proven reserves of 35 megawatts. It is easy to estimate the direct use potential is two to three times the 11,600 mw indicated as electricity generation reserves. The geographic distribution of direct use reserves is the major constraint to such development.

Reserves cannot be assigned to geopressure-geothermal projects. It is hoped the government research work in progress can develop sufficient data to provide inferred reserves in 20 years. The resource is large but definition criteria are not established.

An oil accumulation to provide 164,000,000 barrels per year for 30 years would require 4.9 billion barrels to be available for production. Consider that less than 0.2 of 1 percent of all wildcats drilled in the United States during the last four years discovered producible reserves over the life of the field greater than 1 million barrels of oil.

To assess the impact of the development of this reserve now identified plus the stimulus such development will give to exploration requires an assumption that the governmental agencies believe indigenous sources of energy are necessary to the economy of the U.S.A.

Stanford Research Institute, The University of California, Riverside, and Science Application Ind. have each provided thoughtful studies on the effect of tax incentives for the development of geothermal resources. The effect of such tax treatment has been focused on the resulting price of electricity or upon how much income this would "shelter" for the producer. This focus should be changed. The size of increased resources resulting from incentives should be emphasized.

Each study has sidestepped critical questions of: How large a capacity can be economically developed from recognized prospects with the subject incentives? How many would be developed lacking such economic stimuli? What is the flow back to the government agencies in tax revenues if certain incentives are initiated? This demands careful analysis of the possibility of reduced tax flow from projects that are certain to be developed without the incentives versus the increased tax revenue from those projects that would not have been developed without the incentives.

Consideration of the dynamic effect of taxation regulations on an incipient industry will show a tremendous benefit to government agencies in increased tax revenues. Robert Rex prepared the following illustration demonstrates the flow of monies to federal, state and county agencies for a single 48 net megawatt project on federal lands.

ESTIMATED GOVERNMENT REVENUES
FROM FIELD DEVELOPMENT PROGRAM

EAST MESA 48 MW PROJECT

10 percent federal royalty payments	$ 70,200,000
federal income taxes	67,110,000
state income taxes	16,590,000
ad valorem taxes	59,700,000
	$213,600,000

ASSUMES 25 MILS/KWH - 30-YEAR PROJECT LIFE - 6 PERCENT ANNUAL INFLATION RATE

If the reserves now known on federal lands are developed, additional ones will be added in the process of development and by the increased exploration attracted to the area of successful development. Five thousand megawatts production on federal lands and two thousand megawatts on non-federal lands should return to the government $903 million in revenues each year over the first 30 years of the projects' lives. $7.02 billion would flow to the federal government as royalty, $9.4 billion as income tax. $2.3 billion would be allocated to the various states' income tax revenues and more than $8.4 billion to local county governments as ad valorem taxes.

Summary

In 1973 the geothermal reserves in the United States were 500 megawatts. reserves identified since 1970 total about 11,100 megawatts. This is enough energy to supply the total electrical needs for 11,000,000 people. To generate the same electricity using fuel oil, 164 million barrels per year would be needed. Five billion barrels of oil would need to be discovered to supply the equivalent energy for 30 years.

Geothermal energy can compete with the other types of energy now being used in the United States. To do so, the energy must be available from its reservoir at a temperature above 400° F. Below this temperature, operating costs rise significantly as the number of wells to produce and reinject the fluid increases.

Tax incentives must be provided to encourage significant investment in the mid-temperature hot water resources if this type energy is to be developed.

The cost of the plants rise rapidly as the temperature of the reservoir decreases. The volume of fluid required to move through the system increases rapidly to supply the required heat. There are economic limits established by temperataure that must be recognized. If the Btu content of a ton of coal drops, there is a point where it is not useable for power production. The same is true for oil and gas fluids as their associated water or inert gas ratio increases. Geothermal fluids quality and usefulness is also dependent upon its Btu content per unit volume produced. The building of power plants for mid-temperature projects is critical to the utilization of this large resource.

For this reason, it is difficult to present a specific cost of electricity produced by broad types of resource. The probable range of prices for electricity generated from steam and hot water reservoirs today is:

Steam 450 degrees F and above	24-30	mills/kwh
Hot water flash - below 400° F	36-50	
above " "	27-32	
Binary	40-48	

Research must continue on how to make fluids with temperatures below 400°F. useful. The technology is now mature. There are vast quantities of heat in this resource awaiting the solution to the economic problems of using this low grade heat.

Risk capital must be readily available in units of 10 to 15 million dollars at the beginning of exploration. Development to 400 megawatts may require up to $100 million investment before payout of the first 50 megawatt unit is obtained. The investors

with sufficient money to carry out a successful program will compare the return of invested capital offered by similar projects (utilizing similar technology and business know-how). The projects offering the best rate of return for similar risk and investment will usually be the ones selected for funding.

The biggest problem in obtaining risk capital is the uncertainity of the business. This includes the discrimination in tax treatment of hot water versus steam. This precludes being able to market the energy at competitive prices and obtain as favorable rate of return as other industries offer. Prospective investors should have assurance that government rules and regulations will encourage the discovery and use of this energy.

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FINANCING GEOTHERMAL DEVELOPMENT

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What has always interested me in the geothermal industry is that "Exploration and Development," as in the title of this Short Course, are always linked together. In practice, however, and espeially from the financial aspects of the business, there is a great difference in each of these. In discussing the various options available for the overall geothermal implementation process, I should like to stress the need for parallel development in the financing of both the exploration and the development phases. I must also stress the critical need for involving one's financial personnel and/or out-side financial advisors from the earliest planning stages. In addition, I must point out that the ability to finance a project to completion (through to the beginning of cash flow) is the net result of the successful completion of all of the previous phases of that project. A successful financing is the bottom-line criterion that bespeaks the project's ultimate feasibility. I say this because, in order to finance a project successfully, the prospective investors must understand all of the risks and mitigating measures involved prior to their supplying the required funding. Let me discuss the building blocks upon which our industry is based.

I. INTRODUCTION

The first of these is, of necessity, the exploration phase, the scope of which includes general reconnaissance, leasing, preliminary exploration, deep drilling, testing, and development drilling functions. A resource company must first decide that it is in the geothermal business and it must allocate funding to engage in preliminary reconnaissance activities. Leasing, and the attendant expenditure of funds, then takes place. Further monies are spent in site-specific exploration (geology, geophysics, gradient drilling, etc.) before a decision is made to commit the substantial funds necessary for deep production drilling. Based on a successful completion of the deep well, extensive testing must take place before deciding whether step-out drilling is warranted in order to bring the field to a desired production level.

This brief synopsis tells only half the story, however. Geothermal is a capital-intensive industry. The utilization of the resource requires the construction of a power plant, agribusiness or industrial facility in addition to the investment in drilling. Since these are site-specific utilization investments, the investor in this phase of development must be assured that the resource on which the facility is being built will last as long as it takes to recover his investment. As a result, the investor is sharing the risk of the reservoir's projected performance through time, in some cases as long as thirty years. There are few oil companies that know or care how to own and run a utility or a dehydration plant. The idea of having to invest significant funds or guarantees beyond the normal scope of their ongoing business is hardly appealing either. For example, if a resource company invests $20 million in the development of a resource but then has to spend an additional $50-60 million to develop it to the point of cash flow - that's a lot of dollars to bet on a single reservoir. And only the limited number of the largest of companies could participate in this game. It is clear that the utilization phase also requires the investment of risk capital, but it appears that the sources thereof will most likely be different.

Now that we've defined the different phases of geothermal development process through to cash flow, let us discuss for a moment the types of markets that geothermal resources are active in. Previous speakers have discussed these, so I will summarize the differences between geothermal for electric and for direct-use applications. It is most important to note that the electric market requires generally a higher temperature of geothermal resources (300° F plus) and results in an energy product, electricity, that can be transmitted over long distances. Non-electric or direct-use geothermal applications have generally focused on temperatures below 300°F (although higher temperatures can be used in industrial and agricultural applications) and the energy has to be consumed within a fairly close proximity to the site (five to ten miles). A further comparison demonstrates that electric projects may require minimum capital investments (resource and plant combined) of approximately $20 million, whereas investments for direct-use projects range from $250,000 to approximately $6 million. In addition, project time scales are very different. For electric projects, from wildcat to busbar may take eight to ten years; for non-electric, two or three years at most. Clearly, based on the capital magnitude differential as well as marketing approaches and time frames, there will be significant differences as to how to proceed with the financing of each type and each type of project.

II. ELECTRIC DEVELOPMENT PROJECTS

A. The Exploration Phase basically has the same dry hole risks in geothermal as exist for oil and gas. Although development techniques differ, the same financing options exist in geothermal as well. They are, among others, as follows:

(1) Resource company financing. Both minerals and oil and gas exploration companies have capital bases which permit the assumption of dry hole risk. The funds available for the exploration and drilling of geothermal production wells presumably would come from the cash flows generated either by high-risk, high-return successful oil and gas or mineral discoveries or high-risk, high-return previous geothermal drilling. In the latter category, only Magma Power, Thermal Power, Thermogenics and Union Oil Company so far share in this distinction in the United States. Phillips Petroleum, AMAX, and Sunedco are representative of the former. In the event a resource company wants to reduce its exposure associated in a given field, it might arrange participations (joint-ventures) with other companies in the well to be drilled. To obtain additional properties or particularly attractive ones, a resource company might farm-in and drill on the above-described basis to earn an interest. There are many varieties to implementing this kind of approach. They originate from the oil patch or minerals sector, but all basically revolve about the investment capabilities of a capital base able to withstand dry hole risk.

(2) Outside investor financing is generally expressed by means of drilling partnerships. The development of an economically attractive prospect might be undertaken by a less-affluent or participation-oriented company or by an operating company interested in acquiring a foothold in a resource which it might not otherwise be capable of developing by itself. Drilling funds have been successfully utilized by Republic Geothermal, Inc., McCulloch Oil Company and some others. This kind of approach to financing should receive added encouragement from the Energy Act of 1978.

(3) User advance payments. In order to secure rights to an energy resource, a utility or a public entity may desire to advance funds towards the development drilling of a given reservoir. It is unlikely, however, that such advances would be available prior to an initial successful discovery well. Apparently, a similar type of arrangement was negotiated at The Geysers between a prospective energy user and a potential developer.

(4) Other. There are numerous varieties to the above approaches, but one particularly interesting option revolves around the utilization of the Geothermal Loan Guarantee Program (GLGP) to fund field exploration and development work in combination with risk capital provided in scenarios 1-3. Other speakers have dealt with the GLGP, so I shall not dwell on this approach further.

B. The Utilization Phase picks up where the exploration phase leaves off. Once the capability to produce resource is demonstrated, the utilization facilities are necessary to provide a marketable product which, in this case, is a power plant. Several questions arise at this point, however. First, what initial size of plant should be the objective of the exploration phase? When should the construction of the power plant be timed for? At what point does the potential financial participant/investor become involved? Clearly, the time value of money being what it is (especially now in these inflationary times), the answer must be that both the exploration and development programs be integrated, at least as to planning, from as early a point as the conception of the project. I shall not dwell on this point in detail herein, but refer you to the article on power plant sizing and refinancing strategy the Geothermal Resources Council is making available in conjunction with this talk. I should like to discuss three general approaches to providing the required equity investment and loan capital sums necessary to implement a power plant financing package.

(1) Venture capital may be defined for the purposes of this paper as tax-oriented risk capital. The ability to accept resource utilization risk as well as the capability to utilize available tax benefits will enable the users of the resource to accelerate the construction of power generation facilities. Combining the use of such capital with portable (1-5 MW), semi-portable (10-20 MW) and fixed (site-specific 55 MW and up) units with bank financing or DOE -guaranteed funding is the most likely source of sizeable funding available for geothermal power plant construction. Both individual as well as corporate investors have the ability to participate under this kind of investment arrangement. Provided the project is structured in the appropriate fashion and that the financing is exempt from utility-type regulation, the vast amounts of "equity" or risk capital required for the expected growth of the geothermal industry can be raised in this manner.

(2) At-risk lending for geothermal power plant construction is a type of financing yet to be made available to the industry. In theory, reservoir evaluation techniques will eventually be judged by financial institutions to be sufficiently reliable to permit the advancing of funds, without recourse, against the risk of the project itself. If the reliability of a given reservoir could be proved to the satisfaction of a prospective lending institution, it would be willing to lend a certain percentage of the total project cost on an at-risk basis.

(3) Intermediary Risk-Assuming Companies (IRAC) represent a financing vehicle combining possibly both of the above mentioned approaches. One can best define an IRAC as a wholesaler of geothermal electric power. The "T formation," as I call it, includes, at left end, the resource company selling geothermal fluid at the well-head to the IRAC. The IRAC itself is the center, purchasing the fluid and converting it to electricity, which it sells to the right end, the utility, by means of a power sales agreement, usually on a take or pay basis. The IRAC produces the electricity by use of the power plant which it leases from the quarterback - the owner/lessor. This concept is spelled out in greater detail in the accompanying article. The basic point of this structure is that the utility accepts a loan planning risk, but avoids the reservoir risk in that it has no investment in the plant on the reservoir. The resource company can sell its product without having to build a power plant, delete its financial strength, and risk regulation as a public utility. As owners/lessors, the power plant owners qualify for full investment tax benefits in exchange for assuming reservoir risk. Used in conjunction with the DOE Loan Guarantee Program, the level of risk is reduced to acceptable levels for the investors in the owner/lessor. The IRAC also accepts the operating risk or farms it out. This overall program of risk and reward allocation places all of the incentives in the right places. This specialized form of project financing has only begun to demonstrate the viability of developing power generation on yet unutilized reservoirs. Current legislation may permit further streamlining of this approach by exempting IRAC's producing less than 80 MWe from regulation in which instance the IRAC would be the power plant owner as well.

C. Summary. Electric commercialization is most efficiently achieved when both the exploration and development phase are integrated financially and a construction program appropriate to the resource in question is developed. The financing of such projects can be streamlined and the net result, the cost of electricity, be achieved on the most cost-effective basis possible.

I. DIRECT-USE DEVELOPMENT PROJECTS

A. The Exploration Phase has similar risk characteristics as drilling for electric with one important difference. The depth of the resource, and therefore the cost of reaching it, is significantly smaller. This results in a lot of differences in the direct-use field as compared with the electric. Many more and smaller companies can be and are involved in direct-use projects, often for their own utilization. The variety of companies is much greater because BTU production can be used for any industry requiring process heat, be it agriculture, dehydration, space heating, etc. Many more non-electric prospects appear to have been identified, and once development is planned, a much shorter turnaround time to cash flow can be expected. This appears to be the result of the minimal environmental impacts of such projects as well as of the significantly smaller capital investment (and lead time) necessary to start-up the project. Shallower and less expensive production wells can be drilled more quickly. Depending on depth, temperature, and flow rates desired, completed non-electric production well cost could run from as low as a few thousand to as much as $250,000. In contrast, an average electric production or injection well to 7,000 feet could run from a million dollars to two million or more. Sources of funds for non-electric production well drilling are essentially the same as outlined in Section IIA, with one further addition. Given the significantly lower cost threshold of entry, an end-user such as a food processor or agricompany might be willing to invest in shallow production drilling themselves if the cost savings or back-up system potential appeared favorable enough.

B. The Utilization Phase for direct uses involves the same types of risks and has available to it all the same sources of funding as described in Section IIB above. A detailed paper will be coming out soon describing sources and types of funds available to direct-use projects. This information is contained in Section Seven on "Financing" of the Workshop on Direct Utilization of Geothermal Energy conducted by the GRC/OIT in Klamath Falls, Oregon in February 1979. I shall basically restrict my comments on this topic to the fact it is generally easier to finance a small project with a quick turn-around to cash flow as opposed to a large project with a long lead time to cash flow where delay and environmental hazards are inherently much greater. Since geothermal can furnish the energy for a wide variety of different businesses, evaluation and analysis of each of these different businesses should not concentrate primarily on the geothermal aspect alone. Overall management capability, economic viability, process and technological risks, marketing, and business structure - all have to be exhaustively reviewed. In this context, geothermal energy is but one component in a processed product and is but one additional variable - that of the fuel supply - to be assessed in a business with many variables. In non-electric, if the resource fails, the option may exist to retrofit to a conventional fuel source, in electric development, if the resource fails, the project fails.

In summary, based on the availability of recently enacted tax benefits, and based on the environmentally and economically desirable aspects of lower temperature geothermal resources, it appears that these projects offer desirable investment opportunities, although on a smaller scale. In fact, at-risk loan capital should become much more rapidly available to the commercialization of such direct-use quality geothermal resources than for electric, because options do exist for the use of the facilities on a commercial basis even with failure of the resource.

IV. CONCLUSIONS

In both the electric and direct-use sections of this paper, I have maintained a parallel structure in discussing the kinds of capital available to the exploration and development phases. Because the successful commercialization of a previously unutilized geothermal resource depends on obtaining different kinds of investment capital for each of the phases, I strongly recommend that one not be undertaken without planning for the other. Integration will save both time and significant amounts of money, thereby enhancing the project's potential for profitable implementation.

NATURE AND OCCURRENCE OF GEOTHERMAL RESOURCES

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INTRODUCTION

Geothermal energy is heat energy which orginates within the earth. Under suitable geologic circumstances, which we will examine in some detail in this paper, a small portion of this energy can be extracted and used by man. So active is the earth as a thermal engine that many of the geological processes that have helped to shape the earth's surface are powered by transport of internal thermal energy. Such seemingly diverse phenomena as motion of the earth's crustal plates, uplifting of mountain ranges, occurrence of earthquakes, eruption of volcanos and spouting of geysers all owe their origin to the redistribution of the earth's internal heat as it flows from inner regions of higher temperature to outer regions of lower temperature.

Temperature within the earth increases steadily with increasing depth. Figure 1 illustrates this increase of temperature with depth for the first few tens of kilometers in the earth. Plastic or semi-molten rock exists everywhere under the continents at depths ranging from 20 km to 40 km and under the oceans at shallower depths of 10 km. For reference, using present drilling technology, holes can be drilled to depths of about 10 km (6.2 miles) under good drilling conditions. Temperatures at these depths are believed to range between 200°C and 500°C, and to increase substantially with depth so that at the earth's center, nearly 4,000 miles deep, the temperature may be more than 4000°C (Figures 1, 2 and 3). Because the earth is hot inside, heat flows steadily outward to the surface where it is permanently lost by radiation into space at the prodigious rate of 35 million million watts (2.4 x 10^{20} calories/year). At present only a very small portion of this heat can be captured for man's benefit. Two ultimate sources for this heat appear to be most important among a number of contributing alteratives: 1) heat released throughout the earth's 4.5 billion year history by radioactive decay of certain isotopes of uranium, thorium, potassium, and other elements; and 2) heat released during subsequent mass redistribution when much of the heavier material sank to form the earth's mantle and core (Figure 2).

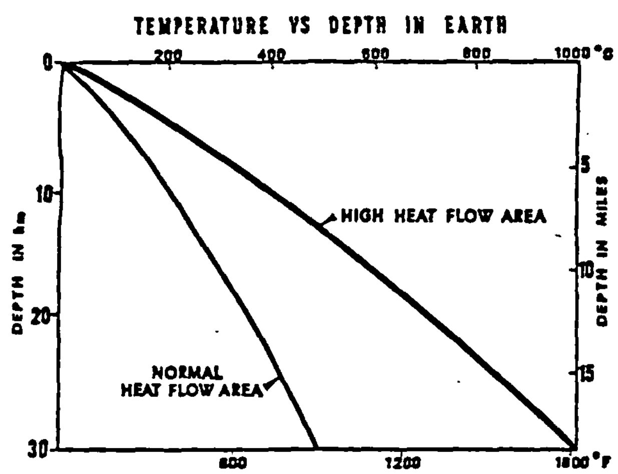


FIGURE 1

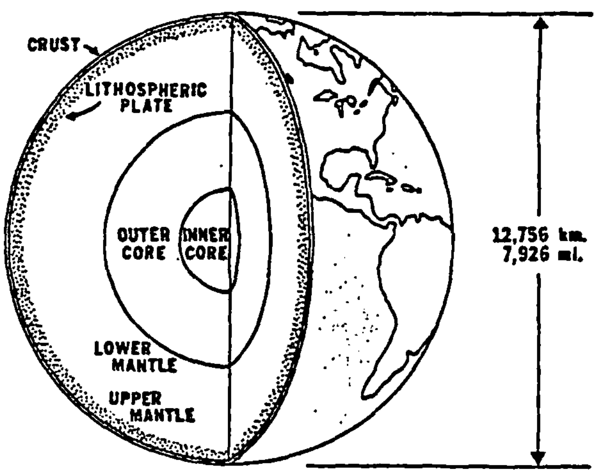


FIGURE 2

Geothermal resource areas, or "geothermal areas" for short, are those in which higher temperatures are found at shallower depths than is normal. This condition usually results from either 1) intrusion of molten rock to high levels in the earth's crust, 2) higher-than-average flow of heat to surface, often in broad areas where the earth's crust is thin, 3) heating of ground water due to deep circulation, or 4) anomalous heating of a shallow rock body by an unusually large content of radioactive elements. We will consider each of these aspects in more detail below. In many geothermal areas heat is brought to the surface or near surface by convective circulation of groundwater. If temperatures are high enough, steam may be produced, and geysers, fumaroles, and hot springs are common surface manifestations of underlying geothermal reservoirs.

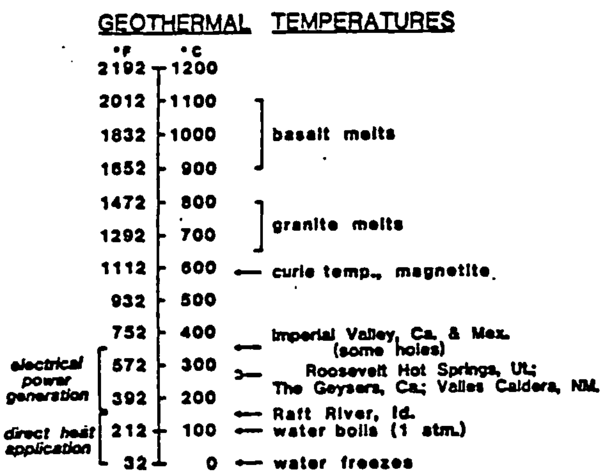


FIGURE 3

GEOLOGIC PROCESSES

The distribution of geothermal areas on the earth's surface is not random but rather is governed by global and local geologic processes. This fact helps to lend order to exploration for geothermal resources once the global and local geologic processes are understood. At present our understanding of these processes is rather sketchy, but with rapidly increasing need for use of geothermal resources our learning rate is high.

Figure 4 shows the principal areas of known geothermal occurrences on a world map. Also indicated are areas of young volcanic activity and a number of currently active fundamental geologic structures. It is readily seen that geothermal resource areas correspond to areas that now have or recently have had volcanic and other geological activity. It is interesting to look briefly at some of the reasons why this is true.

Outward flow of heat from the deep interior causes the earth's mantle to form convection cells in which deeper, hotter mantle material rises toward the surface, spreads out parallel to the surface as it cools and, upon cooling, descends again. The crust above these convection cells cracks and spreads apart along linear zones thousands of kilometers long (Figure 5).

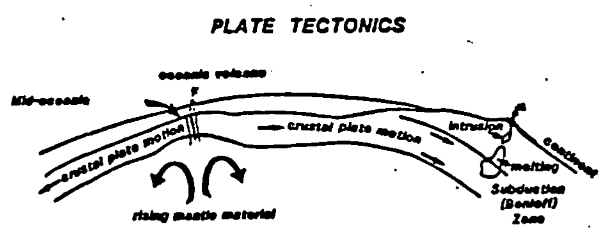


FIGURE 5

The crustal plates on each side of the crack or rift move apart at rates of a few centimeters per year. Molten mantle material rises in the crack and solidifies to form new crust. This process occurs at the mid-oceanic ridges (Figure 4). As the laterally moving oceanic crustal plates collide with certain of the continental land masses, they are thrust beneath the continental plates. At these subduction zones the oceanic plates descend to regions of warmer mantle material. These processes give rise to the diverse phenomenon that geologists call plate tectonics. The cooler, descending plate is warmed both by surrounding warmer material and by frictional heating as it is thrust downward. At the upper boundary of the descending plate, temperatures become high enough in places to cause melting. This gives rise to molten rock bodies (magmas) that ascend buoyantly through the crust (Figure 6). Ascending magmas may reach to within 1.5 to 5 km (5,000 to 15,000 feet) of the surface, and they may give rise to volcanos if part of the molten material escapes to the surface through faults and fractures in the upper crust. Referring to Figures 4 and 5, these processes of subduction and magma generation are currently operating along the west coast of Central and South America, in the Aleutian Islands, Japan and elsewhere. Hachure marks show the linear and

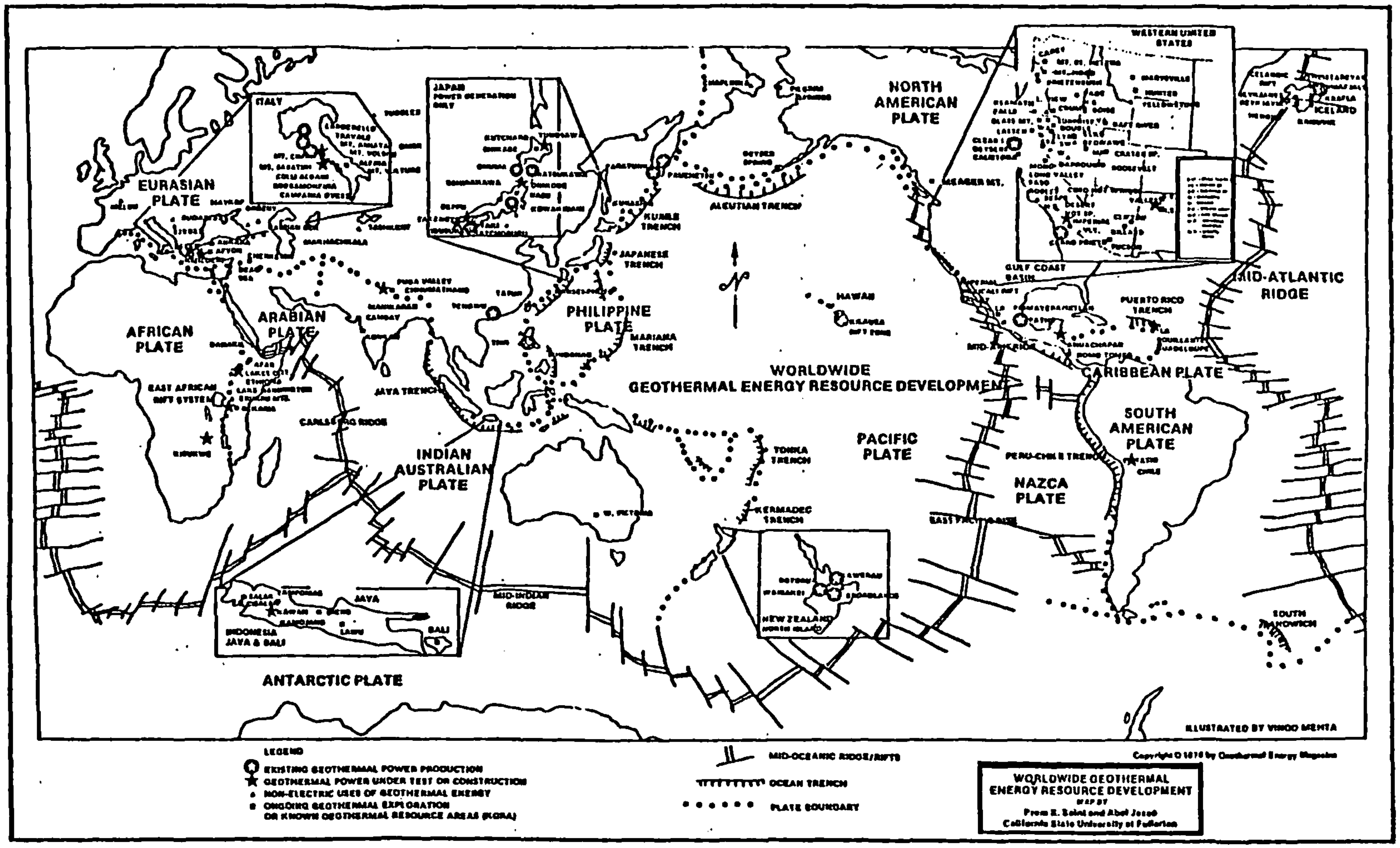

EURASIAN PLATE
NORTH AMERICAN PLATE
AFRICAN PLATE
ARABIAN PLATE
PHILIPPINE PLATE
WORLDWIDE GEOTHERMAL ENERGY RESOURCE DEVELOPMENT
INDIAN AUSTRALIAN PLATE
PACIFIC PLATE
NAZCA PLATE
SOUTH AMERICAN PLATE
CARIBBEAN PLATE
MID-ATLANTIC RIDGE
ANTARCTIC PLATE
ITALY
JAPAN
WESTERN UNITED STATES
INDONESIA JAVA & BALI
NEW ZEALAND
ALEUTIAN TRENCH
JAVA TRENCH
TONGA TRENCH
KERMADEC TRENCH
MID-INDIAN RIDGE
ILLUSTRATED BY VINOD MENTA
LEGEND
EXISTING GEOTHERMAL POWER PRODUCTION
GEOTHERMAL POWER UNDER TEST OR CONSTRUCTION
NON-ELECTRIC USES OF GEOTHERMAL ENERGY
ONGOING GEOTHERMAL EXPLORATION OR KNOWN GEOTHERMAL RESOURCE AREAS (KGRA)
MID-OCEANIC RIDGE/RIFTS
OCEAN TRENCH
PLATE BOUNDARY
WORLDWIDE GEOTHERMAL ENERGY RESOURCE DEVELOPMENT

FIGURE 4

arcuate zones, marked by deep ocean trenches, along which subduction of oceanic crust is currently taking place. The above geologic processes, which result in transport of large quantities of heat to shallow depths at mid-ocean ridges and in areas above subduction zones, give rise to some of today's "hot spots" and associated geothermal resources.

CRUSTAL INTRUSION

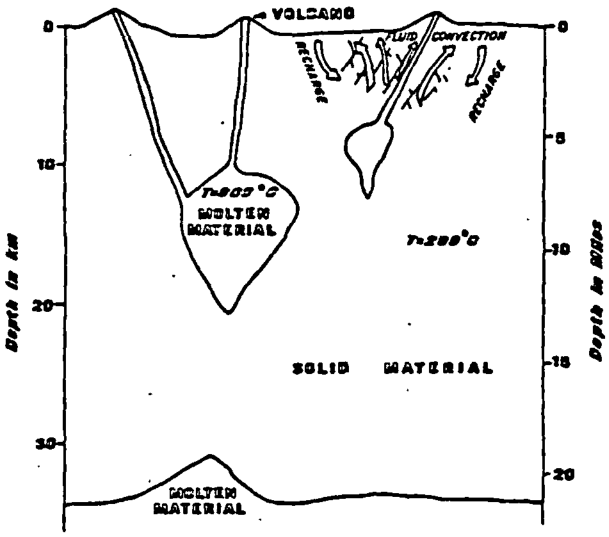


FIGURE 6

A second important geologic process is the "point source" of heat in the mantle (as opposed to the rather large convection cells) which causes surface volcanic eruptions as molten rock is transported to the near surface. As crustal plates move over local mantle hot spots, a linear or arcuate zone of volcanic rocks is seen with young volcanic rocks at one end and older ones at the other end. The Hawaiian Island chain is an excellent example of this process. Geologists speculate that Yellowstone, Wyoming, which is one of the largest geothermal areas in the world, sits over such a hot spot and that the older volcanic rocks of the eastern and western Snake River Plain in Idaho are the surface trace of this mantle hot spot in the geologic past.

Geothermal resources are not always due to near-surface intrusion of molten rock bodies. Certain areas have a higher-than-average rate of increase in temperature with depth (high geothermal gradient) without shallow magma being present. Much of the western United States is such an area of high heat flow. Here geophysical and geologic data indicate that the earth's crust is thinner than normal, and heat therefore flows upward from the mantle correspondingly faster.

Much of the western U. S. is geologically active, as manifested by earthquakes and volcanos. Earthquakes are caused by fracturing and sliding of rocks within the crust. Such processes keep fracture systems open and allow circulation of groundwater to depths of two to four miles. Here the water is heated and rises buoyantly along other fractures to form geothermal resources near surface. Many of the hot springs and wells in the West and elsewhere owe their orgin to such processes.

GEOTHERMAL RESOURCE TYPES

We have seen that the fundamental cause of geothermal resources lies in the transport of hot rock or hot fluids near to the surface through a number of geologic processes. We have also considered what the ultimate source of the heat is. Before considering the more detailed distribution of resources in the United States, let us turn to an examination of the various geothermal resource types.

The classification of geothermal resource types show in Table 1 is modeled after one given by White and Williams (1975) of the U. S. Geological Survey. Each resource type will be described briefly with emphasis on those types that are presently nearest to commercial use.

TABLE 1

GEOTHERMAL RESOURCE CLASSIFICATION
(After White and Williams, 1975)

Resource Type	Temperature Characteristics
1. Hydrothermal convection resources (heat carried upward from depth by convection of water or steam)	
a). Vapor dominated	about 240°C(464°F)
b). Hot-water dominated	
i) High Temperature	150° to 350°C+
ii) Intermediate Temperature	90°C to 150°C
iii) Low Temperature	less than 90°C
2. Hot rock resources (rock intruded in molten form from depth)	
a). Part still molten	higher than 650°C
b). Not molten ("hot dry rock")	90°C to 650°C
3. Other resources	
a). Sedimentary basins (Hot fluid in sedimentary rocks)	30°C to about 150°C
b). Geopressured (hot fluid under high pressure)	150°C to about 200°C
c). Radiogenic (heat generated by radioactive decay)	30°C to about 150°C

Hydrothermal Resources

Hydrothermal resources are geothermal resources in which the earth's heat is carried upward by the convective circulation of hot water or its gaseous phase, steam. Underlying the system is presumably a body of still molten or recently solidified rock that is very hot and that represents a crustal intrusion of molten material (Figure 6). Whether or not steam actually exists in the geothermal reservoir depends critically on temperature and pressure conditions at depth. Figure 7 (after White, et al., 1971) shows a hydrothermal system where steam is present, a so-called vapor-dominated hydrothermal system (1 a. of Table 1). The convection of deep water brings a large amount of heat from depth to a region where boiling takes place at a temperature of about 240°C under the prevailing pressure conditions. Boiling presumably takes place at a deep subsurface water table as well as in pore spaces within the reservoir. Vapor moves upward and is probably superheated further by the hot surrounding rock. A zone of cooler, near-surface rock may induce condensation, with some of the condensed water moving downward to be vaporized again. Within the entire vapor-filled part of the reservoir, temperature is nearly uniform due to fluid convection. Reservoir recharge probably takes place mainly by cool ground water moving downward and into the convection system from the margins. If an open fracture penetrates far enough, steam may vent at the surface. A well drilled into such a reservoir would produce superheated steam.

VAPOR DOMINATED GEOTHERMAL RESERVOIR

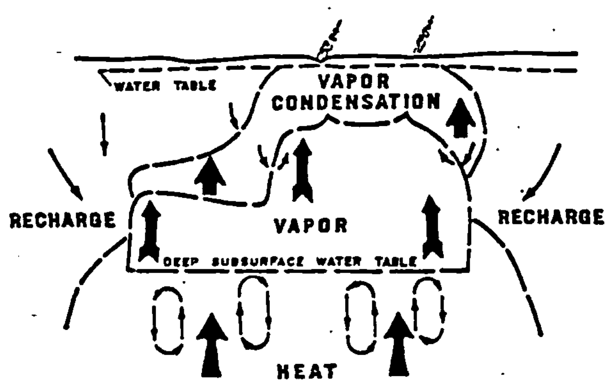


FIGURE 7

The Geysers geothermal area in California (Figure 14) is a vapor-dominated geothermal resource. Steam is produced from depths of 1.5 to 3 km (5,000 to 10,000 feet), and this steam is fed directly to turbine generators that produce electricity. The current generating capacity at The Geysers is 663 MWe (megawatts of electrical power, where 1 megawatt = 1 million watts) and about 860 MWe of additional generating capacity is scheduled to come on line by 1983. Other vapor-dominated resources occur at Lardarello and Monte Amiata, Italy, and at Matsukawa, Japan. Part of the resource at Yellowstone, Wyoming consists of a dry steam field. There are few known vapor-dominated resources because special geologic conditions are required for their formation. However, they are eagerly sought by industry because they are presumably easier and less expensive to develop.

HIGH TEMPERATURE GEOTHERMAL SYSTEM
FLOW CONTROLLED BY FRACTURES

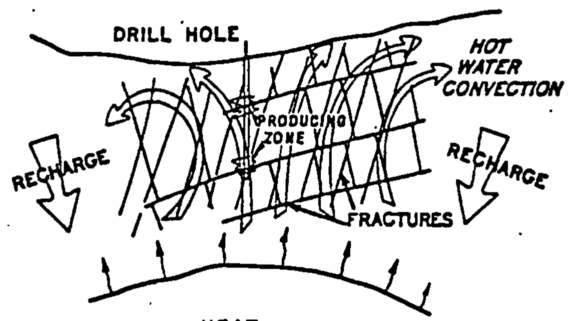


FIGURE 8

Figure 8 schematically illustrates a high temperature hot-water-dominated hydrothermal system (1 b.(i) of Table 1). The source of heat beneath such a system is probably molten rock or rock which has solidified only in the last few tens of thousands of years, lying at a depth of perhaps 3 to 10 km (10,000 to 35,000 feet). Normal ground water circulates in open fractures and removes heat from these deep, hot rocks by convection. Fluid temperatures are uniform over large volumes of the reservoir because convection is rapid. Recharge of cooler ground water takes place at the margins of the system through circulation down fractures. Escape of hot fluids at the surface is often minimized by a near-surface seal or cap-rock formed by precipitation from the geothermal fluids of minerals in fractures and pore spaces. Surface manifestations of such a geothermal system might include hot springs, fumaroles, geysers, spring deposits, altered rocks, or alternatively, no surface manifestation at all. If there are no surface manifestations, discovery is much more difficult. A well drilled into a water-dominated geothermal system would likely encounter tight, hot rocks with hot water inflow from the rock into the well bore mainly along open fractures. Areas where different fracture sets intersect may be especially favorable for production of large volumes of hot water. For generation of electrical power a portion of the hot water produced from the well is allowed to flash to steam within surface equipment as pressure is reduced, and the steam is used to drive a turbine generator.

Examples of this type of geothermal resource are abundant in the western U.S. and include Roosevelt Hot Springs, Utah, and the Valles Caldera area, New Mexico. A total of 53 such resource areas have been identified (Muffler and others, 1978) in the West, with Nevada having a disproportionately large share.

A second type of hot-water system is shown in Figure 9. Here the reservoir rocks are sedimentary rocks that have intergranular porosity. Geothermal fluids can sometimes be produced from such a reservoir without the need to intersect open fractures by a drill hole. Examples of this resource type occur in the Imperial Valley of California, in such areas as East Mesa, Heber, Brawley, the Salton Sea, and at Cerro Prieto, Mexico. In this region there is a crustal spreading center, as discussed above, known as that East Pacific Rise. Figure 4 shows that East Pacific Rise goes northward up the Gulf of California. Its location under the continent cannot be traced very far, but it is believed to occur under and be responsible for the Imperial Valley geothermal resources. The source of the heat is upwelling, very hot molten or plastic material from the earth's mantle. This hot rock heats overlying sedimentary rocks and their contained fluids. The location of specific resource areas appears to be controlled by faults that presumably allow deep fluid circulation to carry the heat upward to reservoir depths. In the Imperial Valley, the geothermal fluids are very saline in places; often dissolved-salt content is more than 30 percent.

IMPERIAL VALLEY, CALIFORNIA GEOTHERMAL RESOURCE

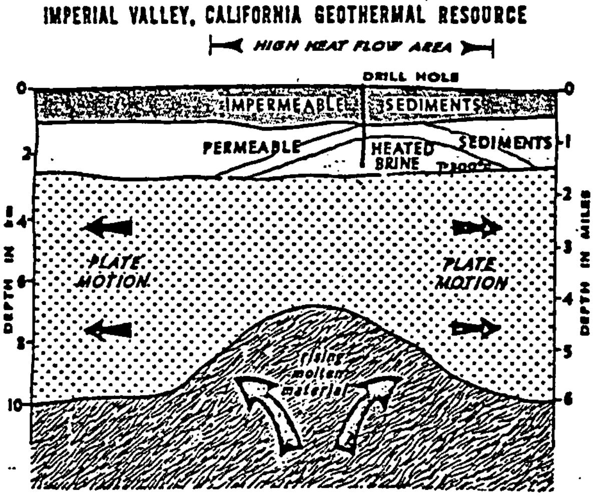


FIGURE 9

Virtually all of industry's geothermal exploration effort is presently directed at locating vapor- or water-dominated hydrothermal systems of the types described above having temperatures above 200°C (392°F). These resources are capable of commercial electrical power generation today. Exploration techniques are generally conceded to be inadequate for discovery of these resources at a fast enough pace to satisfy the reliance the Nation may ultimately put upon them for alternative energy sources. Development of better and more cost-effective exploration is badly needed.

The fringe areas of high-temperature vapor- and water-dominated hydrothermal systems often produce water of low and intermediate temperature (1 b. (ii) and 1 b. (iii) of Table 1). These lower temperature fluids are suitable for direct heat applications but not for electrical power production. In addition, low- and intermediate-temperature waters can result from deep water circulation in areas where heat conduction and the geothermal gradient are merely average, as previously discussed. Waters circulated to depths of two to four miles are warmed in the normal geothermal gradient and they return to the surface or near surface along open fractures because of their buoyancy. Warm springs occur where these waters reach the surface, but if the warm waters do not reach the surface, they are generally difficult to find. This type of warm water resource is especially prevalent in the western U.S. (Figure 14).

Sedimentary Basins

Some basins are filled to depths of 10 km (33,000 feet) or more with sedimentary rocks that have intergranular and open-space porosity. In some of these sedimentary units, circulation of ground water can be very deep. Water may be heated in the normal or enhanced geothermal gradient and may then either return to the near-surface environment or remain trapped at depth (3 a. of Table 1). The Madison group carbonate rock sequence of widespread occurrence in the Dakotas, Wyoming and Montana contains warm waters that are currently being tapped by drill holes in a few places for space heating and agricultural purposes (Figure 14). Substantial benefit is being realized in France from use of this resource type for space heating by tapping warm waters contained in the Paris basin. Many other areas of occurrence of this resource type are known worldwide.

Geopressured Resources

Geopressured resources (3 b. of Table 1) consist of deeply buried fluids contained in permeable sedimentary rocks which are warmed in the normal earth's geothermal gradient by their great burial depth. In addition, these fluids are tightly confined by surrounding impermeable rock and thus bear pressure that is much greater than hydrostatic, that is, the fluid pressure supports a portion of the weight of the overlying rock column as well as the weight of the water column. Figure 10 (from Figure 2 of Papadopulos, 1975) gives a few typical parameters for geopressured reservoirs and illustrates the origin of the above-normal fluid pressure. These geopressured waters, found mainly in the Gulf Coast (Figure 14), generally contain dissolved methane. Therefore three sources of energy are actually available from such resources: 1) heat, 2) mechanical energy due to the great pressure with which these waters exit the borehole, and 3) the available methane.

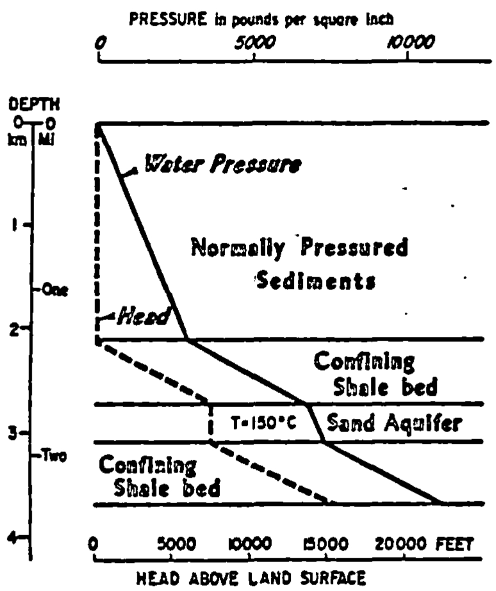


FIGURE 10

Industry has a great deal of interest in development of geopressured resources, although they are not yet economic. The Department of Energy (DOE), Division of Geothermal Energy, is currently sponsoring development of appropriate exploitation technology.

Radiogenic Resources

Research which could lead to development of radiogenic geothermal resources in the eastern U. S. (3 c. of Table 1) is currently underway following ideas developed at Virginia Polytechnic Institute and State University. The eastern states coastal plains are blanketed in many places by a layer of thermally insulating sediments. In places beneath this thermal blanket, rocks having enhanced heat production due to higher content of radioactive elements are believed to occur. These rocks represent old intrusions of once-molten material that have long since cooled and crystallized from the molten state. Geophysical and geological methods for locating such radiogenic rocks beneath the sedimentary cover are being developed, and drill testing of the entire geothermal target concept (Figure 11) is currently being completed under DOE funding. Success would most likely come in the form of low- to intermediate-temperature geothermal waters suitable for space heating and industrial processing. This could mean a great deal to the eastern U.S. where energy consumption is high and where no shallow, high-temperature hydrothermal convection systems are known. Geophysical and geologic data indicate that radiogenically heated rock bodies may be reasonably widespread in the East (Figure 14).

RADIOGENIC GEOTHERMAL RESOURCE

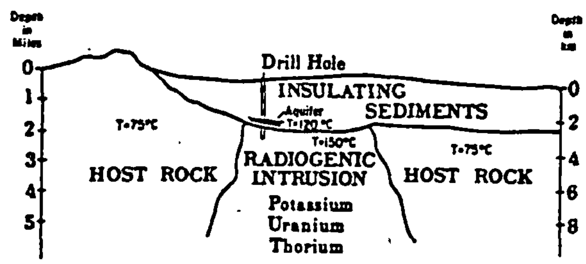
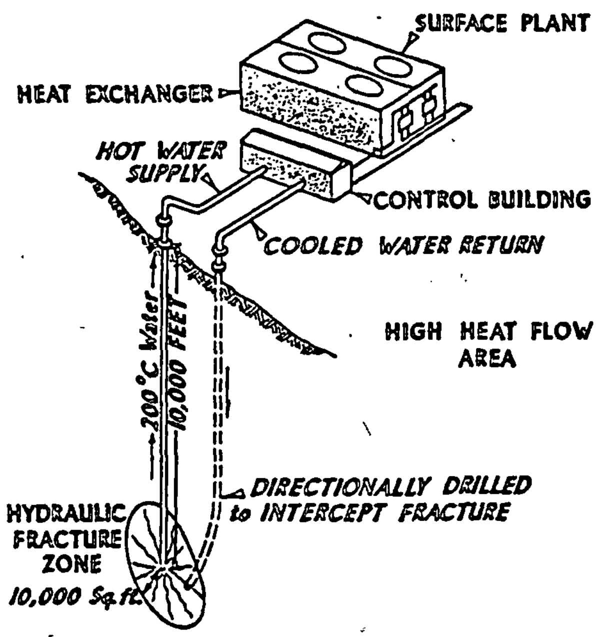


FIGURE 11

Hot Rock Resources

Hot dry rock (2 b. of Table 1) is defined as heat stored in rocks within about 10 km of the surface from which the energy can not be economically extracted by natural hot water or steam. These hot rocks have few pore spaces or fractures, therefore contain little water. The feasibility and economics of extraction of heat for electrical power generation and other uses from hot dry rocks is presently the subject of intensive research at the U. S. Department of Energy's Los Alamos Scientific Laboratory in New Mexico. Their work indicates that it is technologically feasible to induce an artificial fracture system in hot, tight rocks at depths of about 3 km (10,000 feet) through hydraulic fracturing from a deep well. Water is pumped into a borehole under high pressure and is allowed access to the surrounding rock through a packed-off interval near the bottom. When the water pressure is raised sufficiently, the rock cracks to form a fracture system that usually consists of one or more vertical, planar fractures. After the fracture system is formed, its orientation and extent are mapped using geophysical techniques. Then a second borehole is sited and drilled in such a way that it intersects the fracture system. Water can then be circulated down the deeper hole, through the fracture system where it is heated, and up the shallower hole (Figure 12). Fluids at temperatures of 150°C to 200°C have been produced in this way from boreholes at the Fenton Hill experimental site near the Valles Caldera, New Mexico. Much technology development remains to be done before this technique will be economically feasible.

Experiments are underway at the Department of Energy's Sandia Laboratory in Albuquerque, to learn how to extract heat energy directly from molten rock (2 a. of Table 1). These experiments have not indicated economic feasibility for this scheme in the near future. Techniques for drilling into molten rock and implanting heat exchangers or direct electrical converters remain to be developed.



HOT DRY ROCK GEOTHERMAL RESOURCE

FIGURE 12

HYDROTHERMAL FLUIDS

The process causing many of today's high-temperature geothermal resources consists of convection of aqueous solutions around a cooling intrusion. This same process has operated in the past to form many of today's base metal and precious metal ore bodies. The fluids involved in geothermal resources are thus quite complex chemically and often contain elements that cause scaling and corrosion of equipment and that can be environmentally damaging if released.

Geothermal fluids contain a wide variety and concentration of dissolved constituents. Simple chemical parameters often quoted to characterize geothermal fluids are total dissolved solids (tds) in parts per million (ppm) or milligrams per liter (mg/l) and pH. Values for tds range from a few hundred to more than 300,000 mg/l. Many resources in Utah, Nevada, and New Mexico contain about 6,000 mg/l tds, whereas a large portion of the Imperial Valley, California resources are toward the high end of the range. Typical pH values range from moderately alkaline (8.5) to moderately acid (5.5). A pH of 7.0 is neutral - neither acid nor aklaline. The dissolved solids are usually composed mainly of Na, Ca, SiO_2, Cl, SO_4, and HCO_3. Minor constituents include a wide range of elements with Hg, F, B and a few others of environmental concern. Dissolved gases usually include CO_2 and H_2S, the latter being a safety hazard. Effective means have been and are still being developed to handle the equipment and environmental problems caused by dissolved constituents in geothermal fluids. Some of these methods will be considered in later papers at this conference.

RESOURCES IN THE UNITED STATES

Figure 14 displays the distribution in the United States of the various resource types discussed above. Information for this figure was taken mainly from Muffler and others(1979) where a much more detailed discussion is given. Not shown are locations of hot dry rock resources because very little is known. In addition, it should be emphasized that the present state of knowledge of geothermal resources of all types is poor. Because of the very recent emergence of the geothermal industry, insufficient exploration has been done to define properly the resource base. Each year brings more resource data, so that Figure 14 will rapidly become outdated.

Figure 14 shows that most of the known geothermal resources are in the western half of the U. S. All of the presently known sites that are capable or believed to be capable of geothermal electric power generation from hydrothermal convection systems are in the West. In addition, the preponderance of thermal springs is in the West. Large areas underlain by warm waters in sedimentary rocks exist in Montana, the Dakotas, and Wyoming (the Madison Group of aquifers), but the extent and potential of these resources is poorly undersood. The geopressured resource areas of the Gulf Coast and surrounding states are also shown. Resource areas indicated in the eastern states are highly speculative because almost no drilling has been done to actually confirm their existence, which is only inferred at present.

Regarding the temperature distribution of geothermal resources, low- and intermediate-temperature resources are much more plentiful than are high-temperature resources. There are many, many thermal springs and wells that have water at a temperature only slightly above the mean annual air temperature (which is the temperature of most non-geothermal ground water). Resources having temperatures above 150°C are infrequent, but represent important occurrences worth the discovery costs. In U. S. Geological Survey Circular 790, Muffler and others (1979) show a statistical analysis of the temperature distribution of geothermal resources and conclude that the cumulative frequency of occurrence increases exponentially as reservoir temperature decreases (pg. 31), as is the case for many natural resources (Figure 13). For geothermal resources the relationship is based only on the data for known occurrences having temperatures 90°C or higher. It is firmly enough established, however, that we can have confidence in the existence of a very large low-temperature resource base, most of which is undiscovered. In fact Circular 790 postulates that there are nearly three times more accessible geothermal resources above 90°C in the western U.S. than the amount discovered to date. These figures do not include possible hot dry rock or other more speculative resources. Table 2 is a summary of the current estimate of the geothermal resource base as taken from Circular 790. Table 2 demonstrates our lack of resource knowledge through the ranges and relative amounts of undiscovered resources and through the many missing numbers.

ACKNOWLEDGEMENTS

Preparation of this paper resulted from work funded under Contract DE-AC07-78ET-28392 from the Department of Energy to the University of Utah. Typing was done by Cindy Schouten and the figures were drafted by Doris D. Cullen.

Thanks are extended to Geothermal World Corporation for permission to reproduce Figure 4.

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Muffler, L.J.P., and others, 1979, Assessment of geothermal resources of the United States-1978: U.S. Geol. Survey Circ. 790, 163 p.

White, D.E., Muffler, L.J.P., and Truesdell, A.H., 1971, Vapor-dominated hydrothermal systems compared with hot-water systems: Economic Geology, v. 66, no. 1, p. 75-97.

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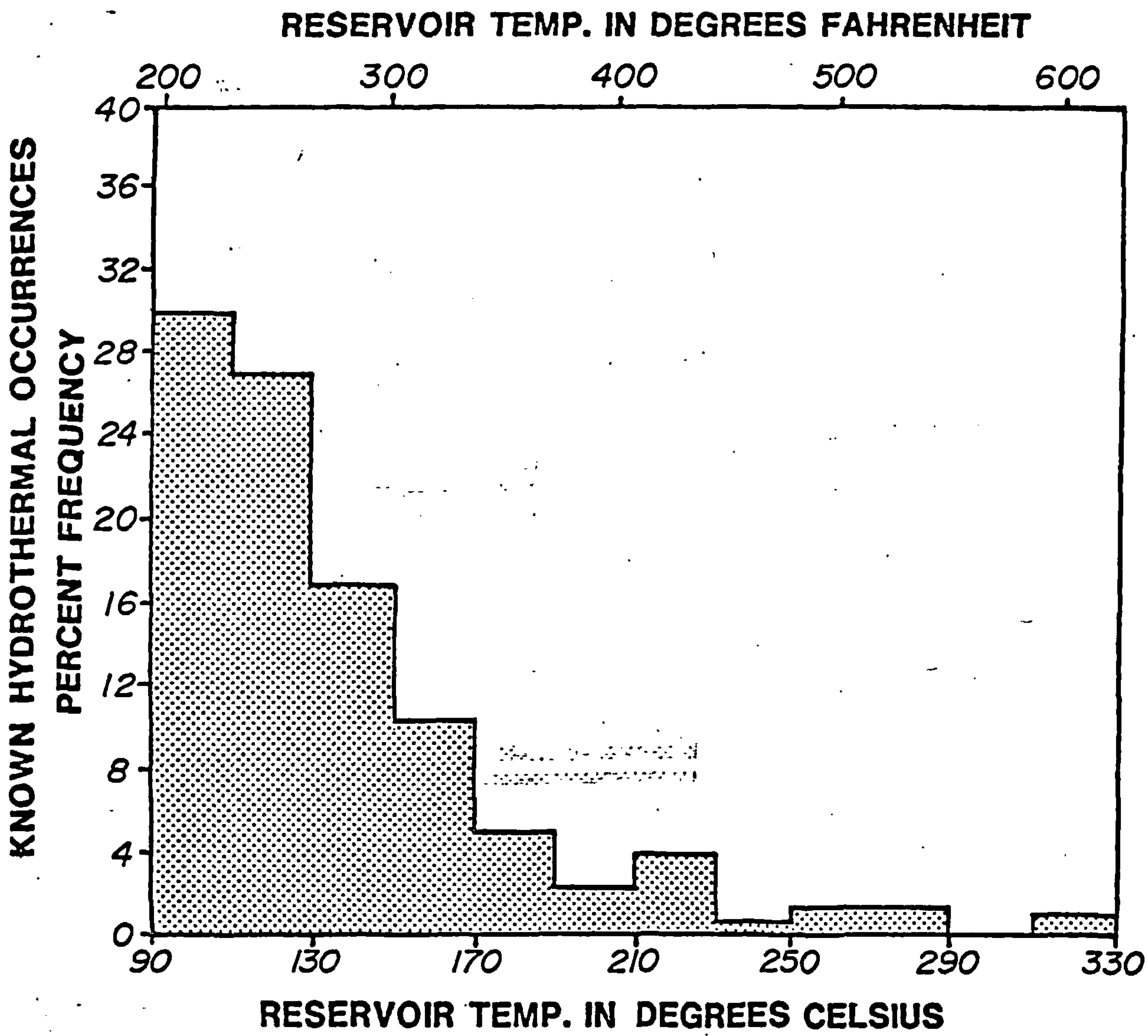
RESERVOIR TEMP. IN DEGREES FAHRENHEIT
200
300
400
500
600
40
36
32
28
24
20
16
12
8
4
0
KNOWN HYDROTHERMAL OCCURRENCES
PERCENT FREQUENCY
90
130
170
210
250
290
330
RESERVOIR TEMP. IN DEGREES CELSIUS

FIGURE 13

TABLE 2

Geothermal Energy of the United States
After Muffler and others (1979) Table 20

RESOURCE TYPE	ELECTRICITY (MWe for 30 yr)	BENEFICIAL HEAT (10^{18}joules)	RESOURCE (10^{18}joules)
Hydrothermal			
Identified	23,000	42	400
Undiscovered	72,000-127,000	184 - 310	2,000
Sedimentary Basins	?	?	?
Geopressured (N. Gulf of Mexico)			
Thermal			270 - 2800
Methane			160 - 1600
Radiogenic	?	?	?
Hot Rock	?	?	?

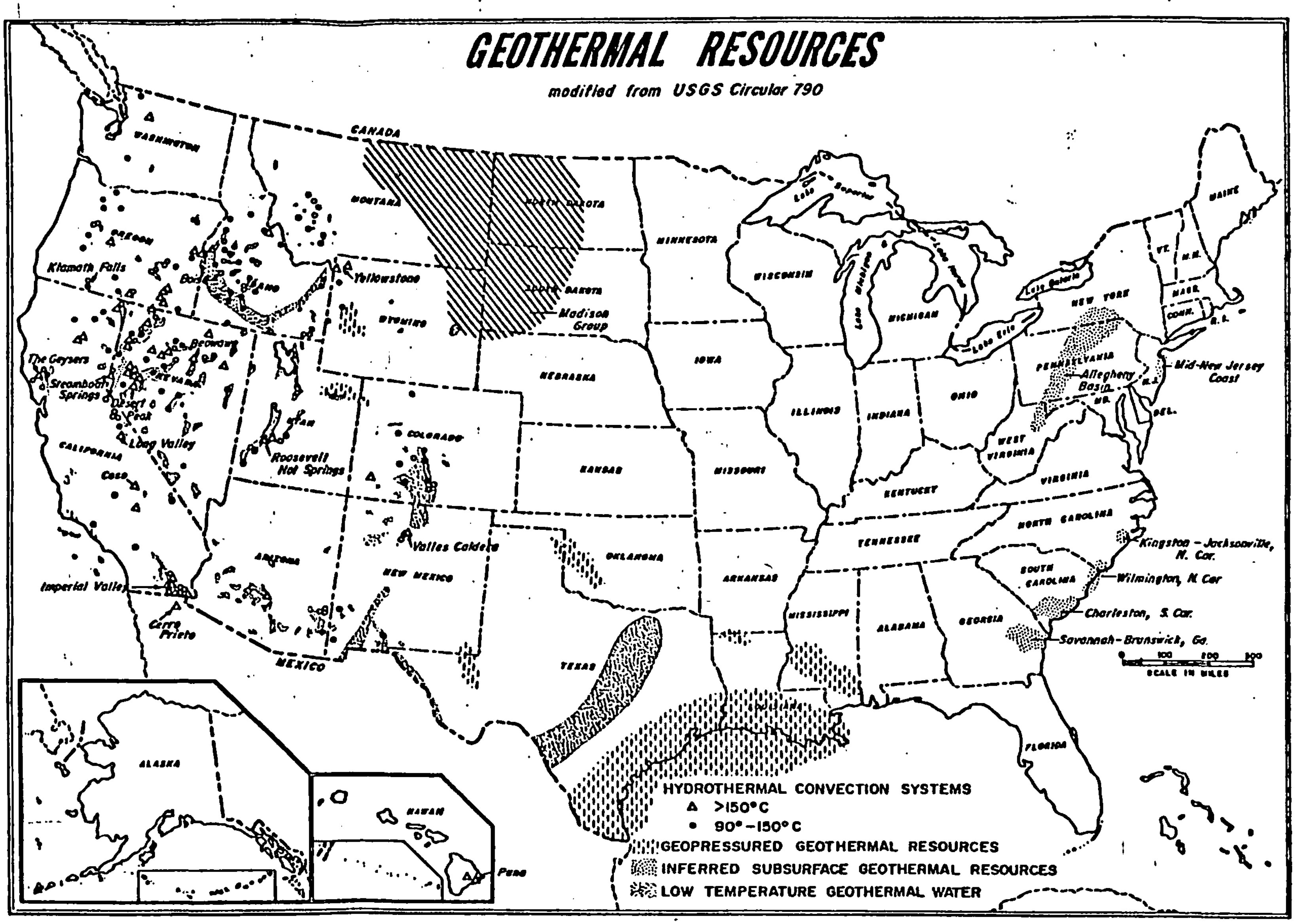
GEOTHERMAL RESOURCES
modified from USGS Circular 790
CANADA
MEXICO
Klamath Falls
Yellowstone
Madison Group
The Geysers
Steamboat Springs
Desert Peak
Long Valley
Roosevelt Hot Springs
Coso
Valles Caldera
Imperial Valley
Cerro Prieto
Allegheny Basin
Mid-New Jersey Coast
Kingston - Jacksonville, N. Car.
Wilmington, N. Car
Charleston, S. Car.
Savannah-Brunswick, Ga.
SCALE IN MILES
HYDROTHERMAL CONVECTION SYSTEMS
Δ >150°C
• 90°-150°C
GEOPRESSURED GEOTHERMAL RESOURCES
INFERRED SUBSURFACE GEOTHERMAL RESOURCES
LOW TEMPERATURE GEOTHERMAL WATER

FIGURE 14

SUBJ
GTHM
GRCA

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DEC 19 1980
WATER RIGHTS

12-04-80 DRAFT

(GEOTHERMAL RESOURCE CONSERVATION ACT)

1981

GENERAL SESSION

____ B. No. ____ By________________

AN ACT RELATING TO THE DEVELOPMENT OF GEOTHERMAL RESOURCES IN THE STATE; DECLARING THE PUBLIC INTEREST IN THIS DEVELOPMENT AND ASSIGNING REGULATORY AUTHORITY REGARDING THIS TO THE DIVISION OF WATER RIGHTS; DEFINING THE RESOURCE AND ITS RELATIONSHIP TO WATER; PROVIDING FOR THE PROTECTION OF CORRELATIVE RIGHTS AND THE PREVENTION OF WASTE; AUTHORIZING AND ESTABLISHING PROCEDURES FOR UNITIZING OF GEOTHERMAL AREAS; AND PROVIDING FOR PROCEDURES TO GOVERN REGULATION BY THIS DIVISION.

THIS ACT ENACTS THE UTAH GEOTHERMAL RESOURCE CONSERVATION ACT BY ENACTING SECTIONS 73-21-1 THROUGH 73-21-10, UTAH CODE ANNOTATED 1953; AND REPEALS SECTION 73-1-20, UTAH CODE ANNOTATED 1953, AS ENACTED BY CHAPTER 189, LAWS OF UTAH 1973.

Be it enacted by the Legislature of the State of Utah:

Section 1. Section 73-21-1, Utah Code Annotated 1953, is enacted to read:

73-21-1. This chapter shall be known and may be cited as the "Utah Geothermal Resource Conservation Act."

Section 2. Section 73-21-2, Utah Code Annotated 1953, is enacted to read:

73-21-2. It is declared to be in the public interest to foster, encourage, and promote the discovery, development, production, utilization, and disposal of geothermal resources

by law. When these lands are committed to a unit agreement

____ B. No. ____ 12-04-80 DRAFT

the unit shall have a first and prior lien for costs incurred pursuant to the plan of unitization upon each owner's geothermal rights and his share of unitized production to secure the payment of the owner's proportionate part of the cost of developing and operating the unit area. This lien may be established and enforced in the same manner as provided by sections 38-1-8 through 38-1-26. For these purposes any nonconsenting owner shall be deemed to have contracted with the unit operator for his proportionate part of the cost of developing and operating the unit area. A transfer or conversion of any owner's interest or any portion of it, however accomplished, after the effective date of the order creating the unit, shall not relieve the transferred interest of the operator's lien on the interest for the cost and expense of unit operations.

(f) A provision, if necessary, for carrying or otherwise financing any person who elects to be carried or otherwise financed, allowing a reasonable interest charge for this service payable out of that person's share of the production.

(g) A provision for the supervision and conduct of the unit operations, in respect to which each person shall have a vote with a value corresponding to the percentage of the costs of unit operations chargeable against the interest of that person.

(h) Such additional provisions that are found to be appropriate for carrying on the unit operations.

(5) No order of the division providing for unit operations shall become effective unless and until the plan for operations prescribed by the division has been approved in writing by those persons, who under the division's order, will be required to pay 66% of the costs of the unit operation, and also by the owners of 66% of the production or proceeds of same that are free of costs, such as royalties, overriding

royalties, and production payments; and the division has made a finding that the plan for unit operations has been so approved. If the persons owning the required percentage of interest in the unit area do not approve the plan within six months from the date on which the order is made, the order shall be ineffective and shall be revoked by the division unless for good cause shown the division extends this time.

(6) An order providing for unit operations may be amended by an order of the division in the same manner and subject to the same conditions as an original order for unit operations; but if this amendment affects only the rights and interests of the owners, the approval of the amendment by the owners of royalty, overriding royalty, production payments, and other interests which are free of costs shall not be required. Production allocation may be amended only according to subsection 73-21-7 (4) (c).

(7) All operations, including, but not limited to, the commencement, drilling, or operation of a well upon any portion of the unit area shall be deemed for all purposes the conduct of such operations upon each separately-owned tract in the unit by the several owners of tracts in the unit. The portions of the unit production allocated to a separately-owned tract in a unit area shall, when produced, be deemed for all purposes to have been actually produced from that tract by a well drilled on it. Good faith operations conducted pursuant to an order of the division providing for unit operations shall constitute a complete defense to any suit alleging breach of lease or of contractual obligations covering lands in the unit area to the extent that compliance with these obligations cannot be had because of the order of the division.

(8) The portion of the unit production allocated to any tract, and the proceeds from the sale of this production, shall be the property and income of the several persons to whom, or

to whose credit, the same are allocated or payable under the order providing for unit operations.

(9) Except to the extent that the parties affected so agree and as provided in subsection 73-21-7 (4) (e), no order providing for unit operations shall be construed to result in a transfer of all or any part of the title of any person to the geothermal resource rights in any tract in the unit area. All property, whether real or personal, that may be acquired in the conduct of unit operations shall be acquired for the account of the owners within the unit area and shall be the property of these owners in the proportion that the expenses of unit operations are charged.

(10) An order of the division for unit operations shall constitute a complete defense to any suit charging violation of any statute relating to trusts, monopolies, and combinations in restraint of trade on account of unit operations conducted pursuant to the order.

Section 8. Section 73-21-8, Utah Code Annotated 1953, is enacted to read:

73-21-8. (1) Geothermal fluids are deemed to be a special kind of underground water resource, related to and potentially affecting other water resources of the state. The utilization or distribution for their thermal content and subsurface injection or disposal of same shall constitute a beneficial use of the water resources of the state.

(2) (a) Geothermal owners shall, prior to the commencement of, or increase in, production from a well or group of wells to be operated in concert, file an application with the division to appropriate such geothermal fluids as will be extracted from the well or group of wells. Publication of applications shall be made as provided in section 73-3-6, and protests may be filed as provided in section 73-3-7. The division shall approve an application if it finds that the

applicant is a geothermal owner and that the proposed extraction of geothermal fluids will not impair existing rights to the waters of the state.

(b) The division may grant the quantity of an application on a provisional basis, to be finalized upon stabilization of well production. Flow testing of a discovery well shall not require an application to appropriate geothermal fluids.

(3) The date of an application to appropriate geothermal fluids, when approved by the division, shall be the priority date as between the geothermal owner and the owners of rights to water other than geothermal fluids. No priorities shall be created among geothermal owners by the approval of an application to appropriate geothermal fluids.

Section 9. Section 73-21-9, Utah Code Annotated 1953, is enacted to read:

73-21-9. Rights to geothermal resources and to geothermal fluids to be extracted in the course of production of geothermal resources acquired under section 73-21-8 shall be based on the principle of correlative rights.

Section 10. Section 73-21-10, Utah Code Annotated 1953, is enacted to read:

73-21-10. (1) Any person adversely affected by any rule, regulation, or order issued under this chapter may within 60 days after the effective date of the rule or regulation or entry of the order bring a civil suit against the division in the district court of Salt Lake County or in the district court of the county in which the complaining person resides to test the validity of the rule, regulation, or order, or to secure an injunction or to obtain other appropriate relief, including all rights of appeal.

(2) An action or appeal involving any provision of this chapter, or a rule, regulation, or order issued under it shall be determined as expeditiously as feasible. The trial court

shall determine the issues on both questions of law and fact and shall affirm or set aside the rule, regulation, or order, or remand the cause to the division for further proceedings. The court is authorized to enjoin permanently the enforcement by the division of this chapter, or any act done or threatened under it, if the plaintiff shall show that as to him the act or conduct complained of is unreasonable, unjust, arbitrary, or capricious, or violates any constitutional right of the plaintiff or if the plaintiff shows that the act complained of constitutes or results in waste or does not in a reasonable manner accomplish an end that is the purpose of this chapter.

(3) Any person who, for the purpose of evading this chapter or any rule, regulation, or order of the division issued under it, shall make or cause to be made any false entry in any report, record, account, or memorandum required by this chapter, or by any rule, regulation, or order issued under it, or shall omit or cause to be omitted from the report, record, account, or memorandum, full, true and correct entries as required by this chapter, or by the rule, regulation, or order, or shall remove from this state or destroy, mutilate, alter, or falsify the record, account, or memorandum, is guilty of a class A misdemeanor.

(4) No suit, action, or other proceeding based upon a violation of this chapter or any rule, regulation, or order of the division issued under it shall be commenced or maintained unless same shall have been commenced within two years from the date of the alleged violation.

Section 11. If any provision of this act, or the application of any provision to any person or circumstance, is held invalid, the remainder of this act shall not be affected thereby.

Section 12. Section 73-1-20, Utah Code Annotated 1953, as enacted by Chapter 189, Laws of Utah 1973, is repealed.

Jan. 15, 1980

U.S. GEOLOGICAL SURVEY GEOTHERMAL RESEARCH GRANTS AND CONTRACTS FUNDED IN FY 79

Extramural Geothermal Research, Project 9700-01537, Donald W. Klick, Project Manager, Reston

GRANT/CONTRACT NO. (Proposal No.)	GRANTEE/CONTRACTOR (P.I.)	RESEARCH TITLE	ORIGINAL START DATE	TOTAL DURATION	FY 79* AMOUNT	USGS SCI LIAISON	DOE/DGE LIAISON
Grant No. 14-08-0001-G-534 (Option)	UNIV. OF ARIZONA (Denis L. Norton)	Chemical Mass Transfer Between Circulating Fluids and Rocks in Modern Geothermal Systems	01 SEP 78	24 mos.	$56,897	Bob Fournier, MP	Gerry Brophy
	Previous Funding: FY 78-$36,735.						
Grant No. 14-08-0001-G-593 (GT-9-01)	ARIZONA STATE UNIV. (Peter R. Buseck)	Mercury and Other Trace Elements in Soils as Geochemical Tracers for Geothermal Activity	15 DEC 78	12 mos. (option for ad'l 12 mos.)	$63,923	Bob Fournier, MP	Bob Gray
Grant No. 14-08-0001-G-342 (Incremental)	BROWN UNIVERSITY (Joseph Kestin)	Thermophysical Properties of Water Substance and of Aqueous Solutions	01 AUG 76	48 mos.	$87,050	John Haas, R	Bob Gray
	Previous Funding: Current Grant: FY76-$84,878; FY77-$85,699; FY78-$84,432. Previous Grant No. 14-08-0001-G-242: FY75-$81,126.						
Grant No. 14-08-0001-G-626 (GT-9-12)	BROWN UNIVERSITY (E. M. Parmentier)	Studies of Hydrothermal Circulation	01 AUG 79	12 mos.	$34,011	Paul Delaney, MP	Gerry Brophy
Grant No. 14-08-0001-G-627 (GT-9-13)	BROWN UNIVERSITY (John F. Hermance)	Precision Magnetotelluric Measurements in the Geothermal Environment: Problems and Prospects	15 SEP 79	12 mos.	$53,239	Dal Stanley, D	Bob Gray
Grant No. 14-08-0001-G-297 (Letters)	UNIV. OF CALIFORNIA, SAN DIEGO (John M. Goodkind)	A Study of Gravity Variations as a Monitor of Water Levels at Geothermal Sites	15 JAN 76	48 mos.	$39,875 (10 mos)	Bob Jachens, MP	Gerry Brophy
	Previous Funding: FY76-$61,278; FY77-$46,910; FY78-$83,184.						
Grant No. 14-08-0001-G-361 (GT-9-02)	UNIV. OF CALIFORNIA, SAN DIEGO (Harmon Craig)	Isotopic and Chemical Studies of Geothermal Gases	01 SEP 76	37 mos.	$60,581	Jim O'Neil, MP	Gerry Brophy
	Previous Funding: FY76-$30,657; FY77-$1,913; FY78-$39,020.						
Grant No. 14-08-0001-G-628 (GT-9-18)	UNIV. OF COLORADO (David R. Kassoy)	Heat and Mass Transfer in Fault Zone Controlled, Liquid Dominated Geothermal Systems	28 SEP 79	12 mos.	$50,718	Al Moench, MP	Bob Gray
Grant No. 14-08-0001-G-477 (Letter)	COLORADO SCHOOL OF MINES (George V. Keller)	Evaluation of Methods for Deep Electrical Exploration of the Earth for Geothermal Resources	01 DEC 77	~~24~~ 30 mos.	$34,218	Dal Stanley, D	Bob Gray
	Previous Funding: FY78-$54,440.						
Grant No. 14-08-0001-G-624 (GT-9-51)	COLORADO SCHOOL OF MINES (L. T. Grose)	Volcanotectonics and Thermogeology of the Southastern Cascade Range, Northeastern California	01 MAY 79	12 mos.	$82,579	Pat Muffler, MP	Bob Gray
Grant No. 14-08-0001-G-576 (Option)	UNIV. OF HAWAII (Murli H. Manghnani)	Laboratory Investigations of the Seismic and Thermal Properties of Basalts to Melting Temperatures	01 SEP 78	24 mos.	$71,008	Gary Olhoeft, D + H. M. Iyer, MP	Bob Gray
	Previous Funding: FY78-$60,330.						

*For 12-month duration unless otherwise stated.

GRANT/CONTRACT NO. (Proposal No.)	GRANTEE/CONTRACTOR (P.I.)	RESEARCH TITLE	ORIGINAL START DATE	TOTAL DURATION	FY 79* AMOUNT	USGS SCI LIAISON	DOE/DGE LIAISON
Grant No. 14-08-0001-G-631 (GT-9-55)	UNIV. OF HAWAII (Michael P. Ryan)	Partial Melting, Three-Dimensional Melt Topology, and Electrical Conductivity in Granitic and Basaltic Rocks of Geothermal Environments	01 JUN 79	12 mos.	$69,268	Gary Olhoeft, D	Bob Gray
Contract No. 14-08-0001-17782 (L-9)	ICELANDIC MUSEUM OF NATURAL HISTORY (Sveinn P. Jakobsson, Head, Dept. of Geology)	A 200-meter Drill Hole on the Island of Surtsey, Iceland	01 JUN 79	12 mos.	$98,370	Jim Moore, MP	Gerry Brophy
Grant No. 14-08-0001-G-643 (GT-9-53)	MASSACHUSETTS INST. OF TECHNOLOGY (Theodore R. Madden)	Magnetotelluric Modeling for a Crustal Environment for Geothermal Exploration	01 SEP 79	12 mos.	$29,100	Doug Klein, D	Bob Gray
Grant No. 14-08-0001-G-630 (GT-9-33)	UNIV. OF NEW MEXICO (Wolfgang E. Elston)	Regional Assessment of Intermediate-Temperature Geothermal Resources of Southwestern New Mexico	01 SEP 79	12 mos.	$36,753	Ed Wolfe, Flagstaff	Gerry Brophy
Grant No. 14-08-0001-G-406 (GT-9-03)	NEW MEXICO STATE UNIVERSITY (Chandler Swanberg)	Correlation Among Water Chemistry Data, Regional Heat Flow, and the Geothermal Potential of Western United States	01 JAN 77	36 mos.	$61,395	Bob Mariner, MP & Bob Fournier, MP	Gerry Brophy
	Previous Funding: FY77-$81,764; FY78-$88,766.						
Grant No. 14-09-0001-G-623 (GT-9-40)	OREGON STATE UNIV. (Richard Couch)	Aeromagnetic Measurements in the Cascade Range and Modoc Plateau of Northern California	01 JUN 79	24 mos.	$143,338	Dave Williams, D	Bob Gray
			(incremental funding for second year in FY80-$56,994)				
Grant No. 14-08-0001-G-547 (Option)	SAN DIEGO STATE UNIVERSITY (Gordon Gastil)	Reconnaissance Study of Thermal Springs and Wells and the Deposits of Recently Extinct Thermal Springs in the Peninsular Ranges Province of Southern and Baja California	01 JUL 78	29 mos.	$26,204 (15 mos)	Bob Fournier, MP	Gerry Brophy
	Previous Funding: FY78-$18,244.						
Contract No. 14-08-0001-16379 (GT-9-23)	SIERRA GEOPHYSICS, INC. (David M. Hadley)	Statistical Separation of Random and Non-Random Components of the Spatio-Temporal Seismicity Distribution for Correlations with Geothermal Systems	01 AUG 79	12 mos.	$56,479	Craig Weaver, Seattle	Bob Gray
Grant No. 14-08-0001-G-425 (GT-9-46)	SOUTHERN METHODIST UNIVERSITY (David D. Blackwell)	Heat Flow Study and Geothermal Resource Analysis of the Snake River Plain and Margins, Idaho	01 JUN 77	36 mos.	$79,849 (11 mos)	John Sass, MP & Don Mabey, SLC	Gerry Brophy
	Previous Funding: FY77-$126,682; FY78-$114,353.						
Grant No. 14-08-0001-G-536 (GT-9-37)	SOUTHERN METHODIST UNIVERSITY (Wayne Peeples)	Simultaneous Inversion of Data from Disparate Geophysical Experiments in Geothermal Areas	15 JUL 78	24 mos.	$39,146	Don Mabey, SLC	Bob Gray
	Previous Funding: FY78-$38,675.						
Contract No. 14-08-0001-16321 (Option)	SYSTEMS, SCIENCE, & SOFTWARE, INC. (T. David Riney)	Integrated Model of the Shallow and Deep Hydrothermal Systems in the East Mesa Area, Imperial Valley, California	01 SEP 78	18 mos.	$58,900 (6 mos)	Manny Nathenson, MP	Bob Gray
	Previous Funding: FY78-$68,721.						

GRANT/CONTRACT NO. (Proposal No.)	GRANTEE/CONTRACTOR (P.I.)	RESEARCH TITLE	ORIGINAL START DATE	TOTAL DURATION	FY 79* AMOUNT	USGS SCI LIAISON	DOE/DGE LIAISON
Grant No. 14-08-0001-G-629 (GT-9-61)	UNIV. OF TEXAS, AUSTIN (Francis X. Bostick & H. W. Smith)	Magnetotelluric Interpretation Procedures for Three-Dimensional Earth Structures in Geothermal Areas	15 AUG 79	12 mos.	$40,947	Dal Stanley, D	Rob Gray
Grant No. 14-08-0001-G-426 (GT-9-58)	UNIV. OF TEXAS, DALLAS (Ronald W. Ward) Previous Funding: FY77-$39,993; FY78-$50,022.	Evaluation of Geothermal Systems Using Teleseisms	01 MAY 77	36 mos.	$71,926	H. M. Iyer, MP	Rob Gray
Grant No. 14-08-0001-G-544 (GT-9-56)	UNIV. OF UTAH (David S. Chapman) Previous Funding: FY78-$66,952.	Delineation of Heat Flow Provinces in Utah	01 SEP 78 (Incremental funding for third year in FY80-$89,291)	37 mos.	$59,158	John Sass, MP	Gerry Brophy
Grant No. 14-08-0001-G-600 (GT-9-15)	VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY (Lynn Glover, John Costain, and Krishna Sinha)	Basement Trends in Metamorphism, Plutonism, and Heat Flow Under the Atlantic Coastal Plain in North Carolina for Potential Geothermal Resources	15 MAR 79	12 mos.	$99,859	Dan Milton, R	Gerry Brophy
Grant No. 14-08-0001-G-625 (GT-9-22)	UNIV. OF WASHINGTON (John R. Booker)	Geomagnetic Sounding in the Cascade Mountains of Washington State as a Geothermal Exploration Technique	01 JUL 79	12 mos.	$25,921	Jim Towle, D	Rob Gray
		FY 79 PROPOSALS ALSO FUNDED IN EARLY FY 80			FY 80** Amount		
Contract No. 14-08-0001-16546 (GT-9-52)	UNIV. OF CALIFORNIA, BERKELEY (H. Frank Morrison) Previous Funding: FY77-$38,149; FY78-$60,353.	Interpretation of Self-Potential Data from Geothermal Areas	01 OCT 77	36 mos.	$73,494	Don Hoover, D	Rob Gray
Grant No. 14-08-0001-G-361 (GT-9-64)	UNIV. OF CALIFORNIA, SAN DIEGO (Harmon Craig) Previous Funding: FY76-$30,657; FY77-$1,913; FY78-$39,020; FY79-$60,581.	Isotopic and Chemical Studies of Geothermal Gases	01 SEP 76	46 mos.	$45,470 (9 mos)	Jim O'Neil, MP	Gerry Brophy
Grant No. 14-08-0001-G-674 (GT-9-57)	PURDUE UNIVERSITY (Lawrence Braile)	Evaluation of Detailed Seismic Refraction Profiling for Regional Geothermal Exploration with Application to Yellowstone and the Snake River Plain and Adjacent Areas	01 DEC 79	24 mos. (Incremental funding for second year in FY81-$41,747)	$163,941	Dave Hill, MP	Rob Gray
Grant No. 14-08-0001-G-541 (GT-9-63)	WOODS HOLE OCEANOGRAPHIC INSTITUTION (William J. Jenkins) Previous Funding: FY78-$47,659.	Mapping of Volcanic and Conducted Heat Flow Sources for Thermal Springs in the Western United States Using Helium Isotopes and Other Rare Gases	30 SEP 78	24 mos.	$56,716	Jim O'Neil, MP	Gerry Brophy
Contract No. 14-08-0001-16310 (GT-9-44)	WOODWARD-CLYDE CONSULTANTS (George E. Brogan) Previous Funding: FY78-$58,713.	Faults and Occurrences of Geothermal Anomalies	15 SEP 78	26 mos.	$84,090	Jim Robison, MP	Rob Gray

GEOTHERMAL RESOURCES OF THE GREEN RIVER BASIN, WYOMING, INCLUDING THERMAL DATA FOR THE WYOMING PORTION OF THE THRUST BELT

by

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CONVERSION FACTORS

Length	1 meter = 3.281 feet (ft) 1 foot = 0.3048 meter (m) 1 kilometer = 0.6214 mile (mi) 1 mile = 1.6093 kilometers (km)
Mass flow	1 gallon per minute = 3.785 liters per minute (lpm) 1 liter per minute = 0.2642 gallon per minute (gpm)
Pressure	1 pound per square inch = 0.07031 kilogram per square centimeter (kg/cm^2) = 0.06805 atmosphere (atm.) 1 kilogram per square centimeter = 14.22 pounds per square inch (psi) = 0.9678 atm.
Thermal gradient	1 degree Fahrenheit per thousand feet = = 1.823 degrees Celsius per kilometer (°C/km) 1 degree Celsius per kilometer = 0.5486° Fahrenheit per thousand feet (°F/1,000 ft)
Thermal conductivity	1 millicalorie per centimeter per second per degree Celsius (10^{-3} cal/cm sec°C) = = 241.8 British thermal units per foot per hour per degree Fahrenheit (Btu/ft hr°F) = 0.418 watt per meter per degree Kelvin (W/m°K)
Heat flow	1 microcalorie per square centimeter per second ($10^{-6}cal/cm^2sec$)= = 1 heat flow unit (HFU) = 0.013228 British thermal unit per square foot per hour (Btu/ft^2hr) = 41.8 milliwatts per square meter ($10^{-3}W/m^2$ or mW/m^2)
Temperature	1 degree Fahrenheit = 0.56 degree Celsius (°C) 1°Celsius = 1.8°Fahrenheit (°F) °F = 1.8°C + 32 °C = (°F − 32)/1.8

INTRODUCTION

This is the fifth in a series of reports describing the geothermal resources of Wyoming basins (see Figure 1). Each basin report contains a discussion of hydrology as it relates to the movement of heated water, a description and interpretation of the thermal regime, and four maps: a generalized geological map (Plate I), a thermal gradient contour map (Plate II), and a structure contour map and ground-water temperature map (Plates III and IV) for a key formation.

The format of the reports varies, as does the detail of interpretation. This is because the type of geothermal system, the quantity and reliability of thermal data, and the amount of available geologic information vary substantially between basins and between areas within basins.

This introduction contains (1) a general discussion of how geothermal resources occur, (2) a discussion of the temperatures, distribution, and possible applications of geothermal resources in Wyoming and a general description of the State's thermal setting, and (3) a discussion of the methods we used in assessing the geothermal resources. This introduction is followed by a description of the geothermal resources of the Green River Basin of southwestern Wyoming (Figure 1). Also included in this report is a discussion of thermal data available for the Wyoming portion of the Thrust Belt.

Funding for this project was provided by the U. S. Department of Energy to the Wyoming Geothermal Resource Assessment Group under Cooperative Agreement DE-F107-79ID12026 with the University of Wyoming Department of Geology and Geophysics. Compilations of oil-well bottom-hole temperatures can be examined at the office of the Geological Survey of Wyoming in Laramie.

The text uses primarily British units. As outlined in footnotes on the following page, heat flow and thermal conductivity data are generally presented in metric units. A table of conversion factors faces this page.

GEOTHERMAL SYSTEMS AND RESOURCES

By a geothermal resource, we mean heated water close enough to the earth's surface to be useful. Further definition or classification of geothermal resources is not attempted because such definition and classification are based upon changing technological and economic parameters. Rather, we have used geothermal data to describe the thermal regime in each basin. In these descriptions, thermal anomalies have been identified, but we do not try to determine to what degree a given anomaly is a geothermal resource.

Geothermal systems vary from the very-high-temperature, steam-dominated type 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 the complex of geologic and hydrologic conditions. Most places in 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 (Figure 2). The only 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/m2 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 3 and 4 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.

Because warm water is less dense than cold water, deep-heated water tends to rise, a process known as *free convection*. Free convection is relatively weak, and is significant only under conditions of extreme temperature difference or relatively unrestricted flow. Of more importance in Wyoming basins is *forced convection*, in which water moves in a confined aquifer from a high outcrop recharge area at a basin margin to a lower discharge area. Water is forced over folds or up faults, fractures, or wells by the artesian pressure developed within the confined aquifer.

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 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 (Heasler et al., 1983). Where a system like those described above (Figures 3 and 4) 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 gradient, 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 the basins are suited to relatively small-scale, direct-use projects located close by. 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 applications.) Below 100°F, uses are limited to such applications as soil and swimming pool warming, de-icing, 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 (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 much larger, unseen geothermal resource. For example, Hinckley (1984) 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 ambient temperature.

METHODS OF ASSESSMENT

The principal purpose of these reports is the documentation and prediction of temperatures in the subsurface. In sections above, we have established a qualitative framework in which higher than-expected thermal gradients occur where deep-heated water is brought to shallow depth. For quantification of temperatures and gradients, a variety of techniques was used.

Sources of subsurface temperature data 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), the Wyoming Geothermal Resource Assessment Group has obtained temperature measurements in over 380 holes across Wyoming (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 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 thermal conductivity were made.* This information was coupled with the measured gradients to calculate the local heat flow. Where stratigraphic relationships or multiple holes with similar heat flow allowed us to rule out hydrologic disturbance, we could determine a purely conductive heat flow. This heat flow was, in turn, applied to all sequences of strata for which thermal conductivities could be estimated to obtain gradient values in the absence of holes that could be logged. Particularly in the deeper portions of Wyoming sedimentary basins, this technique was used as a semiquantitative check on less reliable data.

(2) The most abundant subsurface temperature data are the bottom-hole temperatures (BHT's) reported with logs from oil and gas wells. We used BHT's, because of their abundance, to assess geothermal resources in this study. About 14,000 oil and gas well bottom-hole temperatures were collected for the study areas (Table 1). 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.

Mean annual air temperatures for Wyoming basins are between 40 and 48°F (Lowers, 1960). These values, assumed to approximate mean annual ground temperatures, were used in calculating gradients over fairly large areas under the assumption that variations due to elevation and micro-climatic effects are negligible compared with BHT inaccuracies. The files of the Geological Survey of Wyoming were the principal source of BHT data. (A slightly larger data base is available at the Wyoming Oil and Gas Conservation Commission Office in Casper, Wyoming.)

The use of oil field bottom-hole temperatures in geothermal gradient studies is the subject of some controversy among geothermal researchers. There 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. It has been suggested, for example, that in some areas BHT's may correlate with the ambient temperature during drilling and, specifically, that many of the thermometers used in the summer are reading their maximum temperature before they are lowered down the drill hole. Similarly, drilling fluids may transfer heat to the bottom of a drill hole, warming or cooling the rock depending on the drilling fluid temperature and the depth of the hole. The magnitude of a 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 these studies it was assumed that such factors as time of year, operator error, time since circulation, and drilling fluid characteristics are random disturbances which "average out" because of the large number of BHT's. However, circulation of drilling fluids was considered a systematic effect which depresses temperature more with increasing depth. With sufficient data at all depths, anomalous gradients may be identified despite the fact that they are depressed in value.

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

As explained above, temperature gradient values may be lower in deeper holes because of drilling effects. This was taken into account in identifying gradient anomalies by grouping all temperature and gradient data for a basin into 500-foot depth intervals and then calculating the mean value and the 50th, 66th, 80th, and 90th percentile for each interval. These calculations are tabulated in each basin report. The 80th percentile - the value below which 80 percent of the data fall - was chosen arbitrarily as a lower cutoff for the identification of geothermal anomalies.

We calculated a single *background thermal gradient* for each basin (Table 1), based on thermal logs, thermal conductivities of the basin's sedimentary sequence, and heat flow. Although BHT gradients are assumed to be depressed with depth, we do not feel that we can define as anomalous those gradients which are lower than the background thermal gradient. Therefore, thermal gradient values are identified as anomalous only if they fall above the 80th percentile for their depth range *and* above the background thermal gradient for the basin in which they occur. Thus, a gradient of 16°F/1,000 ft, which is considered anomalous at 8,000 feet because it is above both the background thermal gradient and the 80th percentile for the 7,500-8,000-foot depth range, is not considered anomalous at 3,000 feet if it falls below the 80th percentile for the 2,500-3,000-foot depth range.

In these basin studies, a lower BHT cut-off of 100°F was used. In our experience, a temperature gradient based on a temperature lower than 100°F is usually not reliable. Also, sub-100°F water will be of little economic value unless found at very shallow depth.

The final criterion for identification of an area of anomalous gradient is that a group of anomalous points (determined as outlined above) occur in the same area.

Particularly above and within zones of ground-water movement, gradients defined from bottom-hole temperatures may not completely reflect the character of a geothermal resource. For example, Figure 5 shows the effect of ground-water movement homogenizing temperatures in the lower portion of a hole at the top of the Thermopolis Anticline. A gradient calculated from a single BHT at 800 feet would miss the very high gradients and temperatures in the top part of the hole. Conversely, a gradient calculated from a BHT at 400 feet would give a seriously erroneous temperature at 600 feet. These effects illustrate the importance of thermal logging in areas of suspected hydrologic disturbance*. As a general check on the downward projection of thermal gradients, we know from heat flow and rock thermal conductivity considerations that gradients below levels of hydrologic disturbance are similar throughout Wyoming.

An additional constraint on the use of gradient data to evaluate geothermal resources is that ground water must be present to transport the heat. Therefore, we have identified for each basin a productive, basin-wide aquifer which is deep enough to contain water at useful temperatures and for which thermal and hydrologic data are available. A map of temperatures within that aquifer, on which BHT's of that formation are plotted and contoured, is included in each basin report. As with the temperature gradient maps, verification is provided by the much sparser thermal logging data. No attempt was made to correct BHT's for drilling effects, so a certain degree of underestimation of temperatures may be expected in the deeper zones, as described above. Although the deviation of BHT's from true formation temperatures is not known, a tempering effect is that a drill hole in an aquifer with active circulation should equilibrate to undisturbed temperatures relatively quickly.

(3) The third source of subsurface temperature data is measurements in springs and flowing wells. The amount that these waters cool before they reach the surface is generally unknown; therefore, they provide only a minimum temperature check on BHT data. 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. Selected locations where thermal water (greater than 70°F) discharges at the surface are indicated on the thermal gradient maps.

SUMMARY

The authors have investigated the geothermal resources of several Wyoming sedimentary basins. Oil-well bottom-hole temperatures, thermal logs of wells, and heat flow data have been interpreted within a framework of geologic and hydrologic constraints. Basic thermal data, which includes the background thermal gradient and the highest recorded temperature and corresponding depth for each basin, is tabulated in Table 1.

These investigations of the geothermal resources of Wyoming sedimentary basins have resulted in two main conclusions.

(1) Large areas in Wyoming are underlain by water at temperatures greater than 120°F (Figure 6). Although much of this water is too deep to be economically tapped solely for geothermal use, oil and gas wells presently provide access to this significant geothermal resource.

(2) Isolated areas with high temperature gradients exist within each basin. These areas -- many revealed by hot springs -- represent geothermal systems which might presently be developed economically.

GEOTHERMAL RESOURCES OF THE GREEN RIVER BASIN, WYOMING, INCLUDING THERMAL DATA FOR THE WYOMING PORTION OF THE THRUST BELT

Study Area

The Green River Basin is located in southwestern Wyoming (see Figure 1), and includes all of Sublette County and parts of Uinta, Lincoln, and Sweetwater Counties. It is approximately 180 miles long and 90 miles in width near the southern end. Major uplifts border the basin on all sides reaching elevations of over 13,000 feet in the Wind River Range. The basin floor ranges in elevation from 6000-7500 feet.

The climate in the area varies with altitude. Most of the basin receives less than eight inches of precipitation per year while the surrounding mountains often receive greater than 50 inches per year (Ahern et al., 1981). The mean annual surface air temperature for the Green River Basin is approximately 42°F (Lowers, 1960).

Stratigraphy

The sedimentary rocks in the Green River Basin range in age from Cambrian to Recent and unconformably overlie the Precambrian igneous-metamorphic basement. Figure 7 is a stratigraphic column indicating the general lithologies and thicknesses for the formations present in the basin. The greatest total sedimentary thickness (about 30,000 feet) occurs in the deep syncline which parallels the Wind River Mountains (Krueger, 1968). Surface outcrops in the basin are primarily Tertiary and Quarternary in age (see Plate I).

The Paleozoic rocks of the Green River Basin consist mainly of marine shelf deposits with maximum aggregate thickness of 4500 feet. The western edge of the basin bordering the Thrust Belt marks the eastern edge of the Rocky Mountain geosyncline where much thicker sections of Paleozoic and early Mesozoic rocks were deposited (Ralston et al., 1981). These rocks generally consist of calcareous crystalline limestones and dolomites which grade upward into interbedded mudstones, siltstones and shales.

The Mesozoic stratigraphic section is essentially composed of clastic material deposited in marine shelf and continental environments (Ahern, et al., 1981). The Triassic and Jurassic rocks are approximately 3000 feet thick while those of Cretaceous age have an aggregate thickness of up to 15,000 feet. The Mesaverde Group, a thick sequence of sandstones and shales with interbedded coals and conglomerates, is much thicker and more distinctive in the eastern portion of the basin, where it is divided into four members. It thins significantly to the west and is absent (due to nondeposition or erosion) on the Moxa Arch (Hale, 1955). The Lewis Shale and Lance Formation are also truncated in the western portion of the basin.

The lower Paleocene Fort Union Formation is similar to the underlying shales, sandstones and siltstones of the Mesaverde Group except that it contains more coal sequences. It is equivalent to the Hoback Formation in the northwest part of the basin which reaches a thickness of 16,000 feet (Dorr, et al., 1977).

The late Paleocene and Eocene deposits of the Green River Basin are composed of a complex intertongueing of fluvial and lacustrine sediments of the Wasatch, Green River and Bridger Formations. The aggregate thickness of the sediments is more than 12,000 feet in the south central basin but averages about 6000 feet over most of the area (Ahern et al., 1981).

Sediments of Miocene and Pliocene age are primarily conglomerates, claystones and sandstones with a maximum thickness of 4000 feet in the southeast portion of the basin (Ahern et al., 1981). Quaternary sediments consist of unconsolidated silt, sand, clay and gravel usually less than 100 feet in thickness.

Structure

The Green River Basin is a north-south elongated intermontane basin formed during the Laramide Orogeny. According to Berg (1971) tectonic activity has resulted in approximately 35,000 feet of structural relief in the syncline parallel to the Wind River Mountains (see Figure 8) where the top of the Precambrian is believed to be about 27,000 feet below sea level. In general, the basin is structurally simple, with a few major north to northeast trending folds occurring beneath the unconformable Eocene strata (Blackstone, 1955).

Figure 8 shows the major tectonic features surrounding and within the Green River Basin. To the north and northeast are the Gros Ventre and Wind River Mountains, respectively. The Gros Ventre Range has a small granitic core area flanked by Mesozoic and Paleozoic sediments which apparently have been thrust southwest (Krueger, 1968). The southwest flank of the northwest-southeast trending Wind River Mountains is overlapped by Eocene sediments which cover the structural details of the area. However, several small outcrops of steeply dipping Paleozoic rocks as well as seismic data indicate a major thrust fault at the base of the southwest flank of these mountains (Berg, 1971). According to Berg (1971) a Precambrian wedge of the Wind River Mountains has been thrust over the deep basin syncline resulting in a wedge underlain by Paleozoic sediments and overlain by Eocene rocks.

Further to the south the basin rises gradually to the Rock Springs uplift, a north-south trending asymmetric anticline which bounds the Green River Basin on the east. The core of the uplift is eroded into the Cretaceous Baxter Shale. A series of east-west trending faults occur along the stucture. The southern margin of the Green River Basin is the Uinta Mountain uplift which has been thrust northward into the basin

(Krueger, 1968). The northern flank of the Uintas has been partially covered by the Eocene lacustrine Green River Formation, the Bishop Conglomerate, and the Browns Park Formation.

The north-south trending Thrust Belt forms the western boundary of the Green River Basin (see Figure 8 and Plate I). The Thrust Belt consists of a very thick series of Paleozoic and Mesozoic miogeosynclinal sediments which have been thrust eastward onto a much thinner shelf sequence (Krueger, 1968). The Darby Thrust is the easternmost fault of the Wyoming Thrust Belt, forming the western boundary of the Green River Basin.

In the northwestern portion of the area is a small sub-basin known as the Hoback Basin (see Figure 8). Although the Hoback Basin is physiographically a continuation of the Green River Basin, the two basins are separated by a continuous topographic divide called The Rim. Surface drainage of the former is to the north. The Hoback Basin is overridden on the southwest and northeast by the Thrust Belt and Gros Ventre Range respectively (Dorr et al., 1977). The Hoback Basin contains at least 15,000 feet and possibly as much as 30,000 feet of lower Tertiary clastic sediments shed from the adjacent uplift (Ahern et al., 1981).

An east-west profile through the central part of the Green River Basin has the configuration of a broad, gentle syncline with the east flank rising at a very low angle to the Rock Springs uplift while the west flank is cut abruptly by the Thrust Belt. The Moxa Arch is a north-south trending feature which extends from the Bridger Lake area on the Wyoming-Utah border 120 miles north to the LaBarge platform where it swings to the northwest under the Darby-Prospect Fault (Wach, 1977). Although the arch is a very gentle anticline with a maximum relief of 2000 feet (Krueger, 1968), its geometry is slightly asymmetric, with the steep side to the east.

The east flank is reported to have high angle reverse faults displacing Paleozoic and Mesozoic rocks with Tertiary strata left undeformed. Numerous closures have been seismically located along the arch, giving rise to a number of oil and gas fields including Church Buttes, Opal, Moxa, and Emmigrant Springs.

A general structure contour map of the Green River Basin indicates the elevation of the top of the Dakota Sandstone (Plate II). Because most of the tectonic activity in the basin occurred in late Mesozoic and early Cenozoic time the structural configuration of sediments deposited prior to that activity is roughly similar. The Dakota Sandstone was chosen as a datum for contouring because it is known to be a regional aquifer and a large data base exists for it compared to other stratigraphic units.

Hydrology

Very few data are available for pre-Tertiary aquifers in the Green River Basin. Most of the material for the following discussion is taken from Ahern et al., 1981, the only comprehensive report attempting to deal with basinwide hydrology.

Due to the lack of available data, the water-bearing properties of the pre-Tertiary formations have in some cases been inferred from lithologic properties in outcrop and from hydrologic data obtained from other Wyoming basins (Ahern et al., 1981). However, water production and transmissivities in the central portion of the basin may be less than reported due to a possible reduction in permeabiltiy of 20-60% with the increase of overburden pressure (Fatt and Davis, 1952; Fatt, 1953; Wyble, 1958). A further restriction on pre-Tertiary formation groundwater in the Green River Basin is that thrusting along the margins of the basin severely inhibits recharge of these aquifers due to extensive fault displacement.

The stratigraphic column in Figure 7 includes the general water bearing properties for each formation. Ahern et al. (1981) have assigned eight division to the water-bearing rocks in the Green River Basin-Thrust Belt area:

(1) The Precambrian aquifer is highly fractured and weathered in outcrop near the Gros Ventre and Wind River Mountains producing zones of high permeability. A few wells and springs produce water from the aquifer along the flank of the Wind River Mountains although no flow data are available.

(2) The Flathead aquifer (composed of the Flathead Sandstone), is considered to be a good potential source of water because it is known to contain lenses of permeable sandstone, has a conglomeratic base, and good secondary permeability, (Lines and Glass, 1975). However, except on the LaBarge Platform it is buried too deeply to be within economic reach.

(3) The Paleozoic aquifer includes the Bighorn Dolomite, Darby Formation, Madison Limestone, Tensleep Sandstone and Phosphoria Formation. Because these formations are primarily carbonates the greatest permeability exists where solution openings and fractures occur. Although few data are available for the Madison Limestone in the Green River Basin due to lack of outcrop and great depth of burial, this aquifer exhibits excellent porosity and great yield throughout Wyoming.

(4) The Nugget aquifer includes the Thaynes Limestone, Nugget Sandstone, and Twin Creek Limestone. This aquifer yields 20-900 gpm in springs just west of the LaBarge Platform. However, there is a notable decrease in measured transmissivity and porosity values from the Thrust Belt to the Green River Basin, although there is no change in lithology. The difference may be due to increased

lithostatic pressure and decreased fracture occurrence in the Green River Basin (Ahern et al., 1981).

(5) The Upper Jurassic-Lower Cretaceous aquifer is comprised of a series of vertically and areally discontinuous aquifers. The low permeability and general absence of springs is probably due to the large amounts of shales, siltsones and mudstones present in these units (Ahern et. al., 1981).

(6) The Frontier aquifer, composed solely of the Frontier Formation, produces moderate amounts of water (Ahern et al. 1981). Permeability is highly dependent on cementation of the sandstone.

(7) The Mesaverde aquifer outcrops along the Rock Springs uplift, which provides a favorable recharge zone. Seven wells north of the uplift yield 15-200 gpm from the Rock Springs and Ericson Formations. Farther to the west this aquifer has been partially truncated by an erosional unconformity on the Moxa Arch.

(8) The Tertiary aquifer is by far the best understood and most productive in the Green River Basin (Ahern et al., 1981; Welder 1968). The Wasatch Formation, the Laney Member of the Green River Formation and the Bridger Formation are the major water producers in this aquifer. The Wasatch Formation is most productive along the basin flanks in the northern and central portion of the basin as well as in the southwest corner. Impermeable shales and marlstones of the Green River Formation intertongue with the Wasatch in the basin center creating a hydrologic barrier. Water-bearing sand lenses in the Laney Member of the Green River Formation are utilized along the eastern margin of the basin. The permeable sands of the Bridger Formation, overlying the Green River and Wasatch Formations

produce water in the south-cenral part of basin (Ahern et al., 1981).

In general, circulation in the Paleozoic and Mesozoic aquifers is highly restricted due to deep burial of the sediments as well as lack of recharge areas (Ahern et al., 1981). Due to the large stratigraphic displacement of the Pre-Tertiary sediments of the eastern margin of the Thrust Belt against the Baxter-Hilliard aquitard, any water entering the basin from the outcrop area must transfer down through this thick sequence of shales (Ahern et al., 1981). Flat potentiometric gradients and very saline water within these aquifers (Ahern et al., 1981) further indicate that the amount of flow in the basin is small and circulation is restricted.

Based on drill stem test data on the periphery of the basin, ground water flow in the Mesozoic and Paleozoic aquifers appears to come from recharge areas along the LaBarge Platform. Water then flows southeast towards the southern part of the basin. Additional flow may come from the Great Divide and Washakie Basins to the east (Collentine et al., 1981).

Groundwater movement in the post Baxter-Hilliard strata is better understood due to more data, little structural disturbance of the sediments and good stratigraphic control. Recharge for these aquifers is generally along the flanks of the uplifts but impermeable zones within the Green River Formation prevent downward movement of groundwater (Ahern, et al., 1981).

Circulation in the Tertiary strata is from foothill outcrops toward the center of the basin and then southward. In the southwest part of the basin recharge comes from the north flank of the Uinta Mountains and movement is from south to north (Ahern et al., 1981).

Groundwater quality in the Green River Basin ranges from very poor to excellent, showing a general tendency to become more mineralized with increasing depth (Welder, 1968). Total dissolved solids (TDS) concentrations frequently exceed 10,000 mg/l in the Precambrian to Upper Cretaceous aquifers. Total Dissolved Solids (TDS) in most Tertiary aquifers frequently falls in the 500 to 3000 mg/l range (Ahern et al., 1981). Table 2 is a compilation of pre-Tertiary water quality data in the Green River Basin along with select groundwater analyses from Tertiary aquifers.

Heat Flow and Thermal Modeling

The conductive thermal modeling of an area incorporates stratigraphic, structural, and hydrologic data. These are parameters which set limits on the thermal conductivity of rocks, thermal gradients, and depths to aquifers. Also a regional heat flow value must be determined. Published heat flow values in the Green River Basin range from 46 to 67 milliwatts per square meter (mW/m^2) (Sass et al., 1971, Heasler et al., 1982). These values indicate the most reliable value for a regional heat flow is 54 mW/m^2. This value and an upper value of 67 mW/m^2 were used in Table 3 for the modeling of temperatures. To model the temperature at a given depth the following equation is used:

$$T_A = T_0 + (Q/K_1)dx_1, + (Q/K_2)dx_2 + \ldots.$$

where T_A is the temperature in a certain aquifer, T_0 is the mean annual surface temperature, Q is the regional heat flow, K_1 and dx_1 are the thermal conductivity and thickness of the lithologic unit closest to the ground surface, K_2 and dx_2 are the thermal conductivity and thickness of the lithologic unit below unit 1, and so on until the desired depth is reached.

Thermal conductivity values used for formations in the Green River Basin were taken from a variety of sources. Values for the Green River Basin from Sass et al., (1971), Decker and Bucher (1979), and Heasler et al. (1982) were used in addition to thermal conductivities measured for other Wyoming basins (see Decker et al., 1980; Decker and Bucher, 1979; Heasler and Hinckley, 1985; and Heasler, 1978). Where no thermal conductivity measurements have been made on a formation, a value was estimated using the approximate lithologies for the formation.

There are two basic structural models which have been utilized in the thermal modeling of the Green River Basin. These models are: 1) a deep sedimentary basin, and 2) an anticline-syncline geothermal system (see Figure 3). Conductive thermal modeling techniques were used to estimate subsurface temperatures in each case.

As a whole, the Green River Basin is a deep sedimentary basin, and could be considered to contain a moderate (194°F-302°F) to high (>302°F) geothermal resource simply due to the earth's normal increase in temperature with depth. In the Green River Basin the average thermal gradient is approximately 13°F/1000 feet.

By using conductive thermal modeling techniques for the central portions of the basin (characterized by Pacific Creek in Table 3) it is evident that a depth of approximately 10,000 to 12,500 feet must be reached to attain a temperature of 200°F. The structure contour map (Plate II) shows that in more than half the basin the Dakota Sandstone lies beneath at least 13,000 feet of sediments. A maximum temperature at the base of the sedimentary section in that area would probably exceed 350°F at a depth of approximately 27,000 feet. Relative depths and temperatures can be estimated for other formations above and below the Dakota Sandstone using the thicknesses shown in Figure 7.

While such temperatures (greater than 200°F) theoretically seem promising as potential geothermal resources, the great depth and poor quality of the waters associated with such depths place a severe constraint on the practical use of the resource. An additional problem with this particular model is the lack of knowledge concerning quantities of water at these depths. However, many of the deeply buried aquifers are being drilled in search of oil and gas. These holes may provide feasible access to geothermal resources.

The second type of geothermal system evaluated by conductive thermal modeling was the syncline-anticline system near the Church Buttes oil field on the southern portion of the Moxa Arch. Available data indicates that a high gradient area, shown as a hachured enclosure on the gradient contour map (Plate III), exists on the anticline. However, there is little information for the synclinal axis located to the west of the Arch. Conductive thermal modeling was used to estimate temperatures in the syncline to determine if upward movement of water could cause the high temperatures. From Table 3 it can be seen that conductive thermal modeling predicts temperatures in the Dakota Sandstone of 250°F - 300°F (for 54 to 67 mW/m^2). Thermal modeling for the anticline portion of the system predicts temperatures of 219°F to 260°F. The actual measured temperatures in the anticline range from 228°F to 278°F. Thus the temperature anomaly may be the result of local hydrologic conditions, i.e. flowing water heated in the syncline moving up over the anticline.

In order for such a thermal model to be applicable in terms of geothermal resource development a number of conditions must be met: 1) the aquifer must bring heated water close to the surface (generally within 5,000 feet) for the resource to be considered economical, 2) the water in the aquifer must be flowing rapidly enough so that there is no significant heat loss. Generally, the anticlines in the Green River Basin do not meet these criteria. The few structures that exist in the basin are buried under a minimum of 9,000 feet of

Tertiary sediments except on the LaBarge platform. In addition, recharge to the deeper, potentially warmer aquifers is essentially unknown; their water flow rates cannot be estimated. As previously mentioned circulation is probably very poor in these aquifers.

Additional high gradient areas have been located on the Moxa Arch in the vicinity of the LaBarge Platform (see Plate III). Because the Darby - Prospect Thrust overides the Moxa Arch in this area, the syncline-anticline model cannot be applied. The structure contour map (Plate II) indicates that the arch has been broken by faults in this area and thus any groundwater flow has probably been severely disturbed.

Gradient Contours

Plate III shows thermal gradient contours for the Green River Basin. Most of the data used for the map were obtained from oil and gas well bottom hole temperatures (BHT's). There are approximately 1500 BHT's for this basin, most of which are concentrated along the Moxa Arch, the site of greatest known oil and gas potential. Thermal logs of drill holes, shown as +'s on the map and in Table 4; were also used in contouring.

Using BHT's and thermal logs, the average thermal gradient for the Green River Basin is approximately 13°F/1000 feet. This value has been substantiated by conductive modeling from the land surface to the base of the Morrison Formation (See Table 3). The conductive model yields a gradient of 12.9°F/1,000 feet.

Table 5 and 6 list the statistical distribution of the BHT's and BHT-derived gradients in 500 foot depth intervals with the mean BHT and gradient and the 50th, 66th, 80th and 90th percentile for each interval. From Table 6 it is evident that in general the shallow holes (<4,500 feet deep) have higher gradients, while those deeper than 4,500 feet tend to have lower gradients (see also Figure 9). Thus shallow gradients tend to be higher than the average gradient while gradients from deep holes may be slightly lower than the average.

The gradients obtained from thermally logged holes correspond closely with those of BHT's obtained from deeper holes. The statistical analyses in Table 5 and 6 may be used in addition with data from thermally logged holes to obtain reliable temperature information as discussed in the introduction.

The gradient contour (Plate III) map has been contoured on 2.5°F/1,000ft intervals. In many areas there has been generalization, e.g. the odd values in a specific area have not been contoured. (In such cases the gradient is listed beside the hole location on Plate III). In most areas of the Green River Basin except the Moxa Arch, BHT data are sparse. In these areas of little data the gradient contours are approximate and may not reflect high gradient areas if such areas exist. For example, from flowing well information, a high gradient area may be present in the southeast portion of the basin near Flaming Gorge but there is insufficient BHT data to substantiate this. The Moxa Arch has been explored and drilled extensively, thus creating a degree of bias regarding density of data in the area. As mentioned previously, a syncline-anticline system is one of the most likely places to find a geothermal resource. Thus, the present distribution of data should be sufficient for locating most of the larger anomalous areas.

The hachured areas on Plates II, III, and IV delineate groupings of anomalously high gradients. These high gradient areas were determined by the following characteristics: 1) gradients of at least 16°F/ 1,000 ft, 2) 80th percentile group for their depth range (see Table 3), 3) BHT of at least 100°F.

Horizontal hachures identify thermal gradient anomalies of less than 4,500 feet in depth while vertical hachures indicate anomalies at depths greater than 4,500 feet. A cutoff point of 4,500 feet was used because, as seen in Table 5, there appears to be a natural break between gradients at 4,000 and 4,500 foot depth ranges.

There are a few cases in which a potential geothermal resource may not show up as an anomalous gradient area. One such instance would be existing drill holes which have reached warm or hot water. Using the average basin gradient of 13°F/1,000 ft, a depth of 4,500 feet should produce water of 100°F. If such water is under great enough pressure to produce artesian flow, a viable geothermal resource may exist at that particular area even through it is not indicated as a high gradient area. Locations of three flowing thermal wells (temperatures greater than 70°F) are given in Table 7.

Warm springs are a second instance where a potential resource may not be indicated on the gradient map. Two springs flowing water warmer than 70°F (Steele Hot Springs and Kendall Warm Springs) have been located on the gradient contour map (Plate III). Locations, flows, and other pertinent information for these springs are given in Table 7.

The Steele Hot Springs issue from the corner of Fremont Butte on the southwest flank of the Wind River Mountains. According to Breckenridge and Hinckley (1978), basement faults in the area provide a conduit for convectively rising thermal waters from a source in the underlying granite. Kendall Warm Springs are located in the northernmost part of the Green River Basin, occurring on the western flank of the Wind River Mountains which is cut by many major thrust faults. This thrusting has moved the Precambrian crystalline rocks over the Paleozoic section causing numerous faults and tight folds to form parallel to the trend of the range (Breckenridge and Hinckley, 1978). The Kendall Warm Springs occur where the Phosphoria Formation crops out in the center of one such anticline. An adjacent syncline lies east of the springs with a minimum depth of approximately 4,200 feet. According to Breckenridge and Hinckley (1978) recharge occurs at nearly 9,000 feet in elevation on the flank of the mountains where the Phosphoria outcrops. Since the elevation of the springs is 7,800 feet, artesian flow can be expected in the system. In addition, the depth of the syncline should be more than sufficient to produce the 85°F temperature of the springs.

Temperature Contours

The temperature contour map (Plate IV) was compiled from oil and gas well BHT's from the Dakota Sandstone and Morrison Formation. These BHT's are depicted by a solid dot on Plate IV. Additional data were obtained from BHT's in the Frontier Formation which were extrapolated to the Dakota Sandstone using the average gradient of the hole. These values are shown as open circles on Plate IV and were used only as a means of further defining the Dakota temperature contours.

Temperature differences within a formation are a function of depth of burial, the regional heat flow, changes in thermal conductivity within the formation, convective (water flow) heat transfer, and BHT measurement inaccuracies.

Since the Paleozoic and Mesozoic strata have very similar structural configurations in the Green River Basin it is possible to estimate temperatures above and below the Dakota Sandstone from the temperature contour map. The thicknesses shown in Figure 7 can be used in conjunction with an average basin gradient of 13°F/1,000 ft to adjust mapped Dakota Sandstone temperatures to greater or lesser depths.

Because there is a minimum of 5,000 feet of strata below the Dakota Sandstone, the highest temperatures likely to be produced from any sediments in the basin are probably at least 65°F higher than those shown on Plate IV.

The deepest portions of the basin in the east and northeast have not been contoured due to the lack of data in those areas. No wells in the area have been drilled deep enough to reach the Dakota Sandstone. The highest Dakota temperature reported was in a well near Farson with a temperature of 288°F at a depth of 17,007 feet. Temperatures in the area can be estimated using the previously described method.

As stated earlier, deeply circulating water is an essential ingredient of low-temperature geothermal resources in other basins in Wyoming. Unfortunately, very few data are available on the deeply buried Paleozoic and Mesozoic aquifers in the Green River Basin, consequently, hypothesis concerning potential geothermal resources in these aquifers cannot address the imporant question of the amount of water available.

Virtually all available hydrologic data for the Green River Basin is from the Upper Cretaceous and Tertiary sediments. All available hydrologic sources indicate that these formations constitute the principle water resources for the basin (Ahern et al., 1981; Welder, 1968; Robinove and Cummings, 1963). Referring to the gradient contour map (Plate III), it is evident that some of the anomalously high gradient areas are located in shallow (less than 4,500 feet) depth ranges. In almost any area of the basin such a depth occurs within the relatively flat-lying Tertiary sediments. The BHT's for these shallow anomalous area are as high as 130°F for a depth of 4,500 feet making them areas of potential geothermal use. However, much additional research needs to be undertaken in order to delineate such areas.

Thermal Data for the Wyoming Portion of the Thrust Belt

The Thrust Belt of Wyoming is an area of complex geology with unknown geothermal potential. Thermal data were gathered for the region west of the Green River Basin and east of the Wyoming border in Lincoln and Uinta Counties. Scant thermal data exist in this region. No heat flow values nor thermal conductivity studies have been published. Oil well BHT's were available for only 51 wells in Wyoming. Temperature-depth and gradient-depth plots of this data are shown in Figures 10 and 11, respectively. Since so few oil well BHT's were available, no statistical analysis of the data set was attempted. Twelve oil and gas exploration holes in Idaho (Ralston, et al., 1981) and 51 in Wyoming have thermal gradients ranging from 19 to 86°C/km. Maximum reported temperatures for these wells are 210°C at 3,810 meters in Idaho and 132°C at 4,122 meters in Wyoming.

Table 8 lists data for 38 thermally measured wells in the general area of the Thrust Belt. Measured thermal gradients are variable, ranging from 9.2 to 39.1°C/km. Due to the lack of thermal data and complex geology, no thermal gradient maps nor temperature contour maps were constructed.

Thermal springs as hot as 140°F occur both in Idaho (Ralston, et al., 1981) and Wyoming portions of the Thrust Belt (Breckenridge and Hinckley, 1978). The spring systems are commonly associated with deep, high angle faults (Ralston, et al., 1981). The most productive deep aquifers are the Madison Limestone and Bighorn Dolomite, from which spring flows of up to 40,000 gpm are reported (Lines and Glass, 1975).

Two hot springs of interest exist in the northern Green River Basin - Thrust Belt area. Auburn Hot Springs are located in T.33N., R.119W., sec. 20 in northern Lincoln County. Several areas of travertine cones, terraces, warm pools, small springs, and seeps are located in the area. Surface discharge temperatures for the springs range from 61 to 144°F (Breckenridge and Hinckley, 1978). Geochemical thermometry indicates subsurface temperatures of 162 to 216°F (Muffler, 1979). The springs are located at the crest of a tightly folded anticline near the intersections of several faults. Faults and folds generally trend north-northwest, coincident with the alignment of travertine deposits that extend 13 miles north-northwest of the springs (Breckenridge and Hinckley, 1978). These hot springs may be the result of local deep circulation along major faults although the existence of an anomalous heat source can not be excluded due to the sparse thermal data.

The other springs of interest are Granite Hot Springs. These springs are located in T.39N., R.113W., sec. 6 in the southeastern corner of Teton County and flow 300 gpm at a temperature of 106°F (Breckenridge and Hinckley, 1978) They are in the Gros Ventre Mountains at the northern end of the Green River Basin adjacent to the Thrust Belt. Geochemical thermometry indicates the subsurface temperature of Granite Hot Springs may be as high as 199°F (Muffler, 1979). The springs are apparently the result of deep water circulation along a high angle, large displacement fault (Breckenridge and Hinckley, 1978) although existing data does not exclude the existence of an anomalous heat source.

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Table 1. Summary of geothermal data on Wyoming sedimentary basins.

Basin:	Bighorn	Great Divide and Washakie	Green River	Laramie, Hanna, and 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)

Table 2. Ground water chemistry data for the Green River Basin.

TERITARY AQUIFER SYSTEM

Location SEC	RNG	TNP	Ca	Mg	Na	K	HCO_3	SO_4	Cl	TDS	Reference
15	108	28		0.1	720	2.6	1,720	2.2	94	1,690	a
15	109	10	49.0	12.0	2,496	10	402	528	3,340	6,564	b
16	114	30	13.0	2	552	1	274	512	296	1,512	b
23	110	13	1.2	.4	292	.8	605	1.8	85	704	a
16	107	22	7	1	436	2	701	115	42	1,016	b
30	111	31	8	1	217	1	317	142	16	490	b
23	107	30	0.0	6.8	338	4.0	567	93	39	883	a
24	109	9	.0	.0	330	.8	519	.0	62	777	a
26	106	3	.0	.6	218	3.1	115	84.2	66	592	a
					Na + K						
13	111	26	174	79	7,321		305	3,325	9,200	20,249	c
27	113	25	18	17	119		317	95	12	418	c
28	112	19	7	8	2,471		1,732	5	2,766	6,191	c
26	112	9	23	12	2,803		1,354	0	3,600	7,143	c
27	113	2	20	13	2,662		1,598	8	3,140	6,753	c
28	112	29	6	20	2,709		4,209	60	1,660	6,661	c
25	110	7	186	42	4,346		378	47	6,900	11,707	c
31	108	29	290	35	4,369		610		7,000	11,994	c

TERTIARY AQUIFER (UNDIVDED)

SEC	RNG	TNP	Ca	Mg	Na	K	HCO_3	SO_4	Cl	TDS	Reference
18	116	6					885	26	323	1,470	a
26	114	1	46	16	1.2	0.4	197	19	.8	186	a
32	107	8	2.1	0	92	.9	0	11	83	300	f
38	110	22	215	52	4.0	2.7	120	650	3.2	1,000	a
39	111	22	68	6	11		165	80	0	246	a
13	120	25	83.8	23.9			352.2	24.0	10.0	326	b
17	120	6	33.9	37.8	24.3	4.6	257.4	42.0	31.0	315	b
24	115	32	65.8	15.9	54.3	1.7	275.4	75.8	31.0	397	b
19	105	33	120	87			424.8	929	40.0	1,740	b

Table 2 continued.

Location SEC	RNG	TNP	Ca	Mg	Na	K	HCO_3	SO_4	Cl	TDS	Reference
18	110	27	28	10	4,894		4,660	0	4,550	12,089	c
27	113	23	174	88	4,205		1,208	24	6,200	11,212	c
28	113	32	67	62	5,045		1,903	4	6,900	13,076	c
29	113	25	26	9	3,853		7,088	256	1,510	9,252	c
32	114	29	158	116	3,750		3,001	280	4,450	10,232	c
19	113	25	132	10	4,304		1,453		6,000	11,230	c
16	106	12	76	50	41,786						c
17	108	26	31	27	11,242		6,076	150	14,000	28,620	c
27	113	17	84	36	3,949		630		5,978	10,357	d
-9	116	18	518.8	179.8	126.9	14.0	259.6	20,985	140	3,340	b
FRONTIER AQUIFER SYSTEM											
16	118	25	119.8	64.0	155.2	19.0	431	470	55.1	1,110	b
17	118	13	120	47.0	54.3	19.0	2,812	340	450	776	b
18	117	13	130	63.9			336.6	420	55	939	b
18	116	6			592.5		870.3	26	323.4	1,467	b
23	115	6	60.8	11.0	42.6	2.9	275.3	58.9	13.0	341	b
23	112	2	124	29	5,359		1,147	48	8,000	14,258	c
26	113	17	50	5	2,364		2,001	7	2,580	5,992	c
27	114	4	37	28	2,853		1,793	142	3,400	7,343	c
28	113	30	202	27	4,913		490	40	7,700	13,123	c
30	113	32					500	1,506	5,000	10,859	e
29	114	19					1,525	716	2,520	6,522	e
28	115	14					1,793	309	4,320	9,119	e
28	113	13					573	39	7,000	11,903	e
28	113	30					490	40	7,700	13,123	e
27	113	4					2,070	0	4,040	8,439	e
27	114	12					1,501	40	5,600	10,578	e
27	114	24					1,305	127	1,360	3,550	e
27	113	3					4	220	560	1,108	e
27	113	3					110	8	900	1,579	e
27	113	10					317	15	544	1,184	e
27	113	15					805	190	3,830	7,528	e
27	113	19					365	5	1,560	2,878	e
26	113	14					927	136	33,000	55,095	e
26	113	17					2,001	7	2,580	5,992	e
26	112	26					1,070	53	4,280	8,041	e

Table 2. continued

Location SEC	RNG	TNP	Ca	Mg	Na	K	HCO_3	SO_4	Cl	TDS	Reference
UPPER JURASSIC-LOWER CRETACEOUS AQUIFER SYSTEM											
22	115	8	50.9	12.0	71.8	.7	309.6	56.0	16.0	9,383	b
25	115	14	67.8	12.0	16.5	2.3	216.3	56.9	8.4	283	b
25	115	14	1,196	22.2	3.2	2.7	277.2	169.9	16.0	505	b
					Na + K						
27	113	14	1,539	104	8,088		329	7	16,300	25,200	c
26	113	11	697	133	6,281		525	5	11,000	18,375	c
26	113	2					268	5	14,300	23,482	e
26	113	4					281	5	5,400	9,021	e
26	113	4					573	5	10,700	17,967	e
26	113	10					403	10	13,800	22,968	e
26	113	11					525	5	11,000	18,375	e
17	104	2					4,260	0	4,032	10,309	e
27	113	33					403	5	8,100	13,569	e
27	113	33					207		5,000	8,343	e
27	113	35					317		12,600	20,814	e
20	114	19					1,405	35	5,400	10,149	e
29	114	11					865	417	1,100	19,599	e
29	114	12					855	395	10,300	18,251	e
17	112	22					889	35	6,500	11,493	e
17	112	22					1,220		6,100	11,138	e
16	113	13					1,061	370	6,600	12,346	e
16	112	4					905		6,200	10,983	
					Na + K						
17	112	6	139	29	4,352		815	35	6,500	11,493	d
16	113	13	25	2	4,825		795	270	6,600	12,346	c
28	114	12	182	30	6,923		855	395	10,300	18,251	c
NUGGET AQUIFER SYSTEM											
16	112	17	1,475	139	28,670		990	216	46,500	77,487	c
26	115	26	63.8	5.9	3.7	0.9	226.2	4.9	2.7	209	b
26	115	15	50.8	11.0	4.2	.6	2,064	5.1	3.2	198	b

Table 2 continued.

Location SEC	RNG	TNP	Ca	Mg	Na	K	HCO_3	SO_4	Cl	TDS	Reference
					Na + K						
27	113	14	2,112	107	36,830		364	881	60,000	1,000,110	c
28	114	11	2,489	357	33,799		500	936	56,600	94,426	c
28	115	14	777	113	16,400		380	2,416	25,000	44,893	c
17	116	8	1,696	1,260	7,066		1,584	4,815	13,100	28,717	c
27	115	22	63.8	250	10.7	.8	1,839	190	1.9	390	b
PALEOZOIC AQUIFER SYSTEM											
38	110	2	2,146	520	3.9	2.7	118.0	649.4	3.2	1,000	b
16	117	33	820	568	4,740		3,540	4,021	5,400	17,297	c
18	113	19	247	110	7,282		1,806	13,341	1,100	22,969	c
26	114	1	503.8	16.0	1.2	.4	193.8	19.0	.8	185	b
26	113	7	45.9	25.0	5.8	.7	216.3	22.0	7.7	227	b
26	113	7	48.8	30.0	6.7	1.3	275.3	33.0	10.0	287	b

a Welder, 1968
b Ahern, et al., 1981
c Crawford, 1963?
d Biggs and Espach, 1960
e Crawford and Davis, 1962
f Breckenridge and Hinckley, 1978

Table 3. Conductive thermal models for the Green River Basin.

Formation	Conductivity (10^{-3} cal/cm sec°C)	Formation Gradient[1] 1.3 HFU	1.6 HFU	Depth Feet	Thickness feet (meters)	Temperature (°C) at base of formation[1,2] 1.3 HFU	1.6 HFU
CHURCH BUTTE							
Browns Park	5.5	23.6	29.1	1,300	1,300(396)	14.4	16.5
Bridger	5.5	23.6	29.1	3,200	1,900(674)	36.3	43.5
Green River	4.0	32.5	40.0	5,325	2,125(648)	50.3	60.7
Wasatch	6.0	21.7	26.7	8,675	3,350(1,021)	69.3	84.0
Fort Union	7.0	18.6	22.9				
Lance	4.5	28.9	35.6				
Lewis	6.0	21.7	26.7	9,475	800(244)	74.6	90.5
Mesaverde	6.0	21.8	26.7	12,325	2,850(869)	99.7	121.3
Baxter	4.5	28.9	35.6	12.425	100(31)	100.3	122.1
Frontier	6.5	20.0	24.6	12.750	325(99)	102.9	125.3
Mowry	5.0	26.0	32.0	13,000	250(76)	104.0	126.7
Dakota	8.7	14.9	18.4	13,650	650(198)	108.5	132.3
Morrison	5.7	22.8	28.1	13,900	250(76)	109.8	133.9
Stump	7.4	17.6	21.6	14,500	600(183)	112.8	137.6
Twin Creek	8.0	16.3	20.0	15,275	775(236)	117.0	142.7
Nugget	7.4	17.6	21.6				
Woodside / Thaynes / Ankareh	7.2	18.1	22.2	16,850	1,575(400)	125.7	153.4
Dinwoody	2.8	46.4	57.1	16,925	75(23)	126.8	154.7
Phosphoria	9.6	13.5	16.7	17,300	375(114)	128.3	156.6
Tensleep	10.4	12.5	15.4	17,825	525(160)	130.3	159.9
Amsden	8.0	16.3	20.0	18,275	450(137)	132.5	161.8
Madison	9.6	13.5	16.7				
Darby	8.2	15.9	19.5				
Bighorn	11.0	11.8	14.5				
Gallatin	7.4	17.6	21.6				
Gros Ventre	6.0	21.7	26.7				
Flathead	8.5	15.3	18.8				
Precambrian	7.0	18.6	22.9				
PACIFIC CREEK							
Wasatch	6.0	21.7	26.7	7,600	7,600(2,316)	56.1	66.8
Fort Union	7.0	18.6	22.9	7,600	1,725(526)	65.9	78.9
Lance	4.5	28.9	35.6	9,325	900(274)	73.8	88.6
Lewis	6.0	21.7	26.7	10,225	900(274)	79.7	96.0
Mesaverde	6.0	21.8	26.7	12,470	2,245(684)	94.5	114.2
Baxter	4.5	28.9	35.6	15,760	4,395(1,340	133.2	161.9
Frontier	6.5	20.0	24.6	20,155	612(187)	136.9	166.5
Mowry	5.0	26.0	32.0	20,767	393(120)	140.0	170.4
Dakota	8.7	14.9	18.4	21,160	329(100)	142.5	172.2
Morrison	5.7	22.8	28.1	21,489	361(110)	144.0	175.3
Stump	7.4	17.6	21.6	21,850	250(76)	145.4	176.9
Twin Creek	8.0	16.3	20.0	22,100	248(76)	146.6	178.5
Nugget	7.4	17.6	21.6	22,348	338(103)	148.4	180.7
Woodside / Thaynes / Ankareh	7.2	18.1	22.2	22,686	1,379(420)	156.0	190.0
Dinwoody	2.8	46.4	57.1	24,065	25(8)	156.4	190.5
Phosphoria	9.6	13.5	16.7	24,090	320(98)	157.7	192.1
Tensleep	10.4	12.5	15.4	24,410	665(203)	160.2	195.2
Amsden	8.0	16.3	20.0	25,075	345(105)	161.9	197.3
Madison	9.6	13.5	16.7	25,420	500(152)	164.0	199.9
Darby	8.2	15.9	19.5	25,920	350(107)	165.7	201.9
Bighorn	11.0	11.8	14.5	26,270	300(91)	166.8	203.3
Gallatin	7.4	17.6	21.6	26,570	100(30)	167.3	203.9
Gros Ventre	6.0	21.7	26.7	26,670	500(152)	170.6	208.0
Flathead	8.5	15.3	18.8	27,170	150(46)	171.3	208.8
Precambrian	7.0	18.6	22.9	27,320			

[1] Calculated for heat flow values of 1.3 HFU (54 mW/m^2) and 1.6 HFU (67 mW/m^2). One HFU = 10^{-6} cal/cm^2 sec.

[2] Assuming a 41°F (5°C) mean annual air temperature.

Table 4. Thermally measured wells in the Green River Basin.[1]

Hole	Location West Longitude	Location North Latitude	Depth Meters	Depth Feet	Bottom-Hole Temperature °C	Bottom-Hole Temperature °F	Gradient[2] °C/km	Gradient[2] °F/1,000 ft	Interval[3] (M)
LINCOLN COUNTY									
East LaBarge 37-4	110 09.6	42 15.7	650	2,133	24.9	76.8	23.0	12.6	280-650
Green River 79-12	110 12.6	42 15.2	1,770	5,807	60.4	140.8	28.6	15.7	160-1,770
Wilson Ranch 8	110 04.9	41 38.4	1,900	6,234	70.9	159.5	25.3	13.9	10-1,900
SUBLETTE COUNTY									
Wagon Wheel 1	109 44.7	42 36.0	748	2,454	28.0	82.4	27.7	15.2	240-690
Wagon Wheel 2	109 44.9	42 35.9	1,480	4,856	50.7	123.2	30.4	16.7	120-1,480
Belco C-217	110 19.7	42 35.4	1,229	4,032	42.7	108.8	29.1	16.0	10-1,220
Belco S33-28	110 18.8	42 33.4	991	3,252	33.0	91.4	25.6	14.1	20-980
Belco S32-33	110 18.1	42 32.4	931	3,055	33.7	92.7	26.3	14.5	20-931
SWEETWATER COUNTY									
BLM Dodge Pass 1	110 02.1	41 55.8	230	755	15.3	59.5	37.3	20.5	70-180
7 Mile Gulch #2	110 00.3	41 45.2	1,910	6,267	71.3	160.3	24.8	13.6	10-1.910
Little America	109 52.4	41 32.4	445	1,460	23.4	74.2	20.0	11.0	10-445
BLM Horn 1-A	109 49.5	41 58.0	497	1,630	22.4	72.3			

[1] Measured by University of Wyoming personnel following the method of Decker, 1973.

[2] Gradient represents a linear least square fit of the temperature-depth data over the most thermally stable portion of the hole.

[3] Interval refers to the depth range in meters over which the least squares gradient was calculated.

Table 5. Summary of bottom-hole temperature data and statistics, including the 50th, 66th, 80th, and 90th percentiles, from the Green River Basin. A temperature under a percentile is the temperature below which that percent of the BHT's fall. For a depth interval for which very few BHT's have been measured, the percentile temperatures have little meaning.

Depth interval (feet)	Number	Temperature (°F) high	low	mean	50%	66%	80%	90%
500 - 1,000	6	99	72	85.8	85	97	97	99
1,000 - 1,500	5	94	60	79.4	80	93	94	94
1,500 - 2,000	10	117	74	89.1	87	92	105	117
2,000 - 2,500	26	120	64	86.9	86	88	94	104
2,500 - 3,000	50	110	78	90.3	90	93	102	102
3,000 - 3,500	108	126	70	94.4	94	97	102	107
3,500 - 4,000	121	152	81	97.1	96	99	103	110
4,000 - 4,500	61	130	87	101.6	102	104	107	109
4,500 - 5,000	55	150	85	106.6	104	109	112	126
5,000 - 5,500	29	146	95	109.9	108	112	115	122
5,500 - 6,000	32	134	96	115.8	117	119	126	131
6,000 - 6,500	23	139	110	122.0	121	125	129	138
6,500 - 7,000	38	162	108	127.2	129	131	132	140
7,000 - 7,500	136	190	108	137.7	138	143	148	153
7,500 - 8,000	152	176	112	140.1	142	147	151	155
8,000 - 8,500	105	240	117	145.3	146	151	154	160
8,500 - 9,000	74	191	98	150.7	153	157	162	172
9,000 - 9,500	43	235	124	155.0	159	162	167	174
9,500 - 10,000	49	258	122	168.0	168	176	178	190
10,000 - 10,500	34	235	149	175.7	176	180	186	191
10,500 - 11,000	64	208	135	169.0	168	177	181	196
11,000 - 11,500	79	220	138	181.7	184	189	193	199
11,500 - 12,000	60	249	162	188.8	188	196	200	206
12,000 - 12,500	26	265	168	199.4	196	206	210	218
12,500 - 13,000	41	320	166	210.2	207	212	216	232
13,000 - 13,500	25	278	160	204.0	204	209	214	220
13,500 - 14,000	15	236	162	195.2	192	208	212	219
14,000 - 14,500	2	248	176	212.0	248	248	248	248
14,500 - 15,000	19	258	168	227.4	235	241	244	258
15,000 - 15,500	5	260	201	226.8	218	250	260	260
15,500 - 16,000	7	255	205	226.6	223	240	248	255
16,000 - 16,500	5	248	195	232.0	246	248	248	248
16,500 - 17,000	5	280	212	250.8	256	280	280	280
17,000 - 17,500	7	288	190	241.0	230	256	288	288
17,500 - 18,000	3	274	210	252.0	272	274	274	274
18,000 - 18,500	4	300	213	263.3	282	282	300	300
18,500 - 19,000	6	292	202	268.7	281	287	287	292
19,000 - 19,500	4	313	161	261.5	296	296	313	313
19,500 - 20,000	2	304	255	279.5	304	304	304	304
20,000 - 20,500	0	-	-	-	-	-	-	-
20,500 - 21,000	1	305	305	305.5	305	305	305	305
21,000 - 21,500	0	-	-	-	-	-	-	-

Total: 1,529 bottom-hole temperature measurements.

Table 6. Summary of gradient data and statistics, including the 50th, 66th, 80th, and 90th percentiles, derived from bottom-hole temperatures from the Green River Basin. A gradient under a percentile is the gradient below which that percent of the gradients fall. For a depth interval for which very few BHT's have been measured, the percentile gradients have little meaning.

Depth interval (feet)	Number	Gradient (°F/1,000ft)						
		high	low	mean	50%	66%	80%	90%
500 - 1,000	6	63	32	49.5	48	59	59	63
1,000 - 1,500	5	45	13	30.0	28	41	45	45
1,500 - 2,000	10	41	16	26.1	24	27	41	41
2,000 - 2,500	26	33	9	19.4	17	20	23	27
2,500 - 3,000	50	24	12	17.3	16	18	19	22
3,000 - 3,500	108	25	9	15.9	15	16	17	19
3,500 - 4,000	121	27	10	14.8	14	15	16	18
4,000 - 4,500	61	20	10	14.1	14	14	15	15
4,500 - 5,000	55	21	9	13.5	13	13	14	15
5,000 - 5,500	29	20	10	13.1	12	13	14	15
5,500 - 6,000	32	15	9	12.8	12	13	14	15
6,000 - 6,500	23	15	10	12.8	12	13	13	14
6,500 - 7,000	38	17	9	12.7	12	13	13	14
7,000 - 7,500	136	20	9	13.1	13	13	14	15
7,500 - 8,000	152	17	8	12.7	12	13	14	14
8,000 - 8,500	105	24	8	12.6	12	13	13	14
8,500 - 9,000	74	17	6	12.4	12	13	13	14
9,000 - 9,500	43	20	8	12.2	12	12	13	14
9,500 - 10,000	49	22	8	12.9	12	13	14	15
10,000 - 10,500	34	18	10	13.1	13	13	14	14
10,500 - 11,000	64	15	8	11.8	11	12	12	14
11,000 - 11,500	79	16	8	12.4	12	12	13	13
11,500 - 12,000	60	18	10	12.5	12	13	13	14
12,000 - 12,500	26	18	10	12.8	12	13	13	14
12,500 - 13,000	41	21	9	13.2	12	13	13	14
13,000 - 13,500	25	18	8	12.3	12	12	13	13
13,500 - 14,000	15	14	8	11.1	10	12	12	13
14,000 - 14,500	2	14	9	12.1	14	14	14	14
14,500 - 15,000	11	14	8	12.6	13	13	13	13
15,000 - 15,500	5	14	10	12.1	11	13	14	14
15,500 - 16,000	7	13	10	11.7	11	12	13	13
16,000 - 16,500	5	12	9	11.7	12	12	12	12
16,500 - 17,000	5	14	10	12.5	12	12	14	14
17,000 - 17,500	4	14	8	11.6	10	12	14	14
17,500 - 18,000	3	13	9	11.8	12	13	13	13
18,000 - 18,500	4	14	9	12.1	13	13	14	14
18,500 - 19,000	6	13	8	12.1	12	13	13	13
19,000 - 19,500	4	13	6	11.4	13	13	13	13
19,500 - 20,000	2	13	10	12.1	13	13	13	13
20,000 - 20,500	0	-	-	-	-	-	-	-
20,500 - 21,000	0	-	-	-	-	-	-	-
21,000 - 21,500	1	12	12	12.3	12	12	12	12

$$\text{Gradient} = \frac{\text{Bottom-hole temperature} - \text{Mean annual surface temperature}}{\text{Depth}} \times 1{,}000$$

Table 7. Green River Basin thermal wells and springs.

Flowing Thermal Wells (>70°F)

Plate 3 Reference Number	Location (TNP-RGE-SEC)	Formation	Depth(ft)	Yield	Temp	Reference
1	15-108-28	Wasatch	2218	42 gpm	79°F	a
2	15-109-10	Wasatch	2420	20 gpm	77°F	a
3	23-110-13	Wasatch	1725	420 gpm	71°F	a

Thermal Springs

	Name and Location	Formation	Yield	Temp.	Reference
4	Steele Hot Springs 32-107-16	Precambrian?	20 gpm	96°F	b
		Precambrian?	5 gpm	102°F	b
5	Kendall Warm Springs 38-110-2	Phosphoria?	3,600 gpm	85°F	b

[a]Welder, 1968
[b]Breckenridge and Hinckley, 1978

Table 8. Thermally measured wells in the Thrust Belt[1].

Location Latitude	Location Longitude	Depth (meters)	Bottom-Hole Temperature (°C)	Gradient[2] (°C/km)	Interval[3] (meters)
42 58.8	111 0.7	83.0	10.496	27.9	20-83
42 49.8	110 56.8	195.0	11.188	25.6	120-195
42 47.2	111 2.4	44.0	7.336	21.4	10-44
42 46.8	110 55.1	60.0	11.338	18.6	20-60
41 51.8	110 34.8	130.0	28.499		
41 51.5	110 35.9	262.0	33.366	30.1	40-260
41 50.7	110 36.0	161.0	21.312		
41 50.7	110 35.6	61.0	21.640		
41 50.7	110 31.0	42.0	18.104		
41 50.2	110 36.2	168.0	23.646	30.7	110-160
41 50.1	110 30.8	86.0	22.342		
41 49.7	110 36.7	96.0	32.160	39.1	50-96
41 49.4	110 36.1	61.0	31.115		
41 41.6	110 37.9	153.0	10.694	22.6	80-150
41 41.6	110 37.9	152.0	10.478	26.3	80-140
41 41.6	110 37.8	52.0	8.175		
41 41.4	110 37.7	125.0	10.123	37.9	90-120
41 41.3	110 37.9	125.0	9.979	23.2	50-120
41 41.3	220 37.8	102.0	8.553		
41 41.0	110 37.8	96.0	9.363	26.3	50-90
41 41.0	110 37.5	174.0	11.526	15.5	50-174
41 41.0	110 37.5	80.0	8.317		
41 40.9	110 36.9	60.0	8.472	12.2	40-60
41 40.8	110 37.7	174.0	11.050	20.2	9-130
41 40.8	110 37.7	142.0	9.582	13.4	70-140
41 40.8	110 37.7	176.0	12.604	18.5	60-176
41 40.8	110 37.7	176.0	10.232	19.1	90-140
41 40.8	110 37.7	86.0	8.684		
41 40.8	110 37.7	166.0	10.630	20.0	80-160
41 40.2	110 36.9	101.0	9.145	9.2	50-101
41 17.7	110 40.1	75.0	9.197	15.6	50-75
41 16.9	110 40.9	110.0	9.082	17.1	40-110
41 16.8	110 40.9	218.0	12.899	26.6	120-218
41 16.5	110 41.0	98.0	8.277	11.1	30-98
41 9.9	110 47.9	270.0	13.688	28.0	50-240

[1] Measured by University of Wyoming personnel following the method of Decker, 1973.

[2] Gradient represents a linear least squares fit of the temperature-depth data over the most thermally stable portion of the hole.

[3] Interval refers to the depth range in meters over which the least squares gradient was calculated.

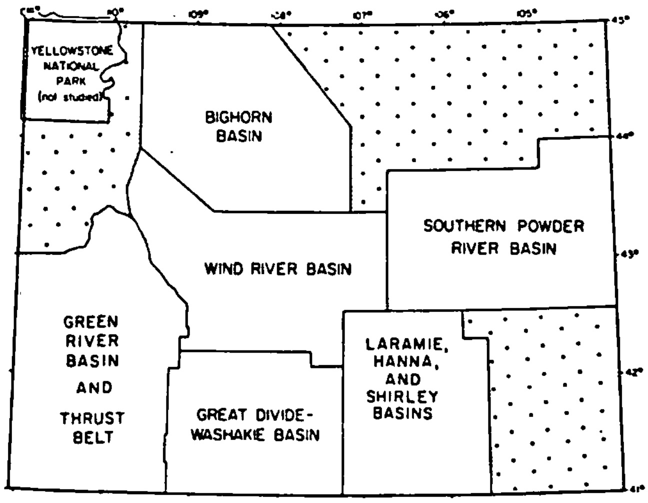


Figure 1. Study areas planned or completed in this series.

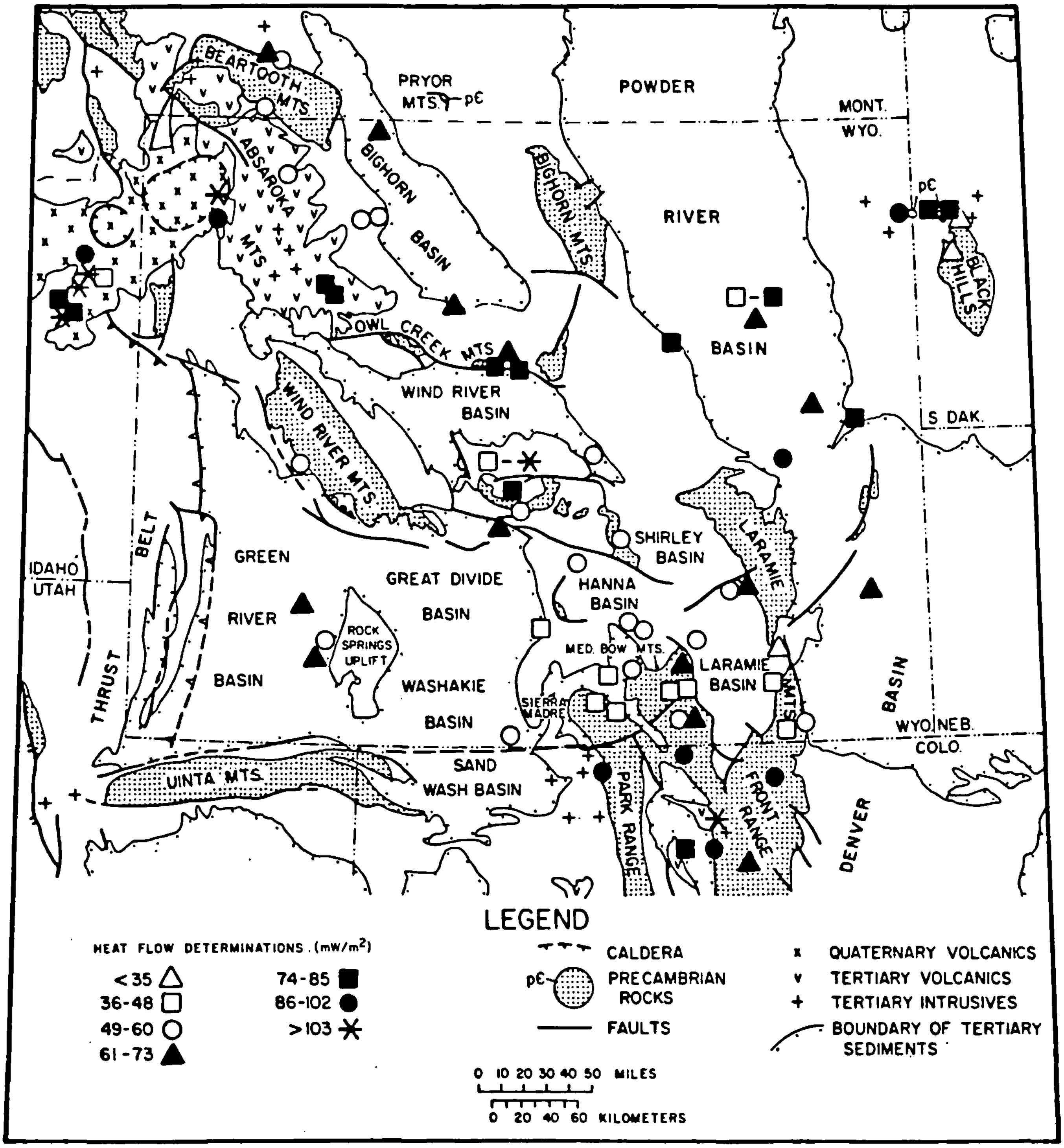


Figure 2. Generalized geology and generalized heat flow in Wyoming and adjacent areas. From Heasler et al., 1982.

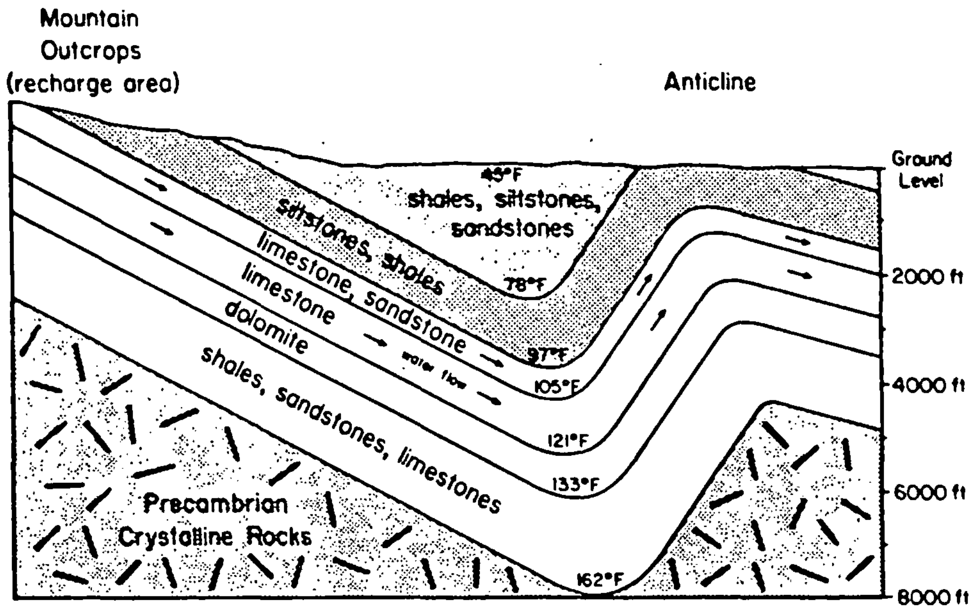


Figure 3. Simplified cross section of a typical Wyoming fold-controlled geothermal system.

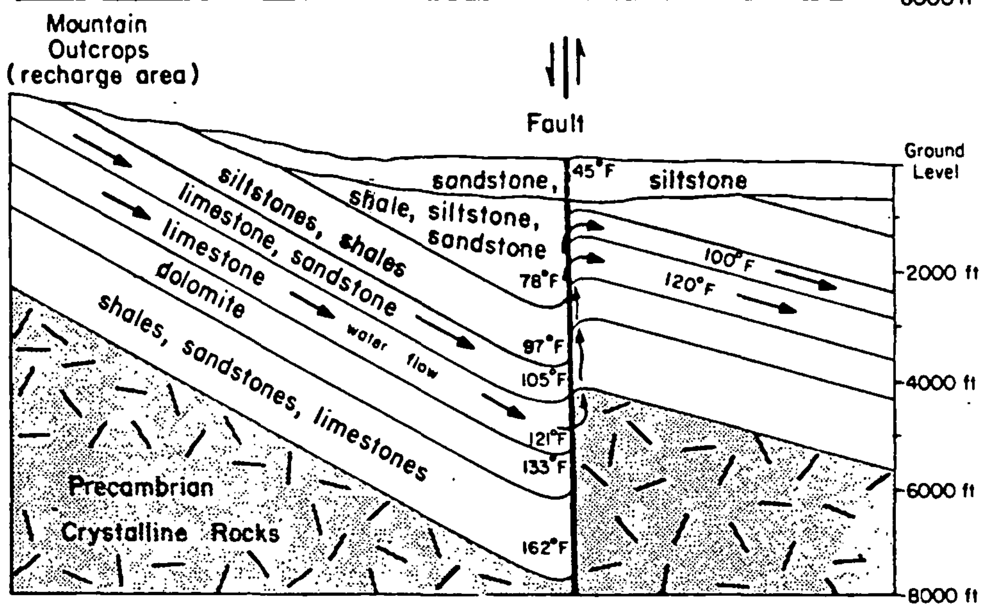


Figure 4. Simplified cross section of a typical Wyoming fault-controlled geothermal system.

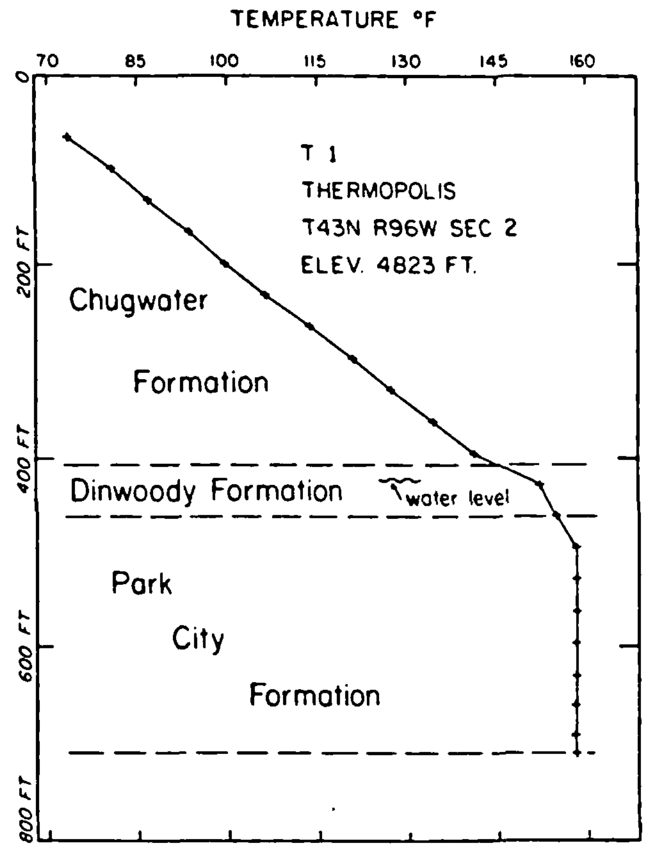


Figure 5. Temperature-depth plot, based on a thermal log of a well at Thermopolis, showing hydrologic disturbance. From Hinckley et al., 1982.

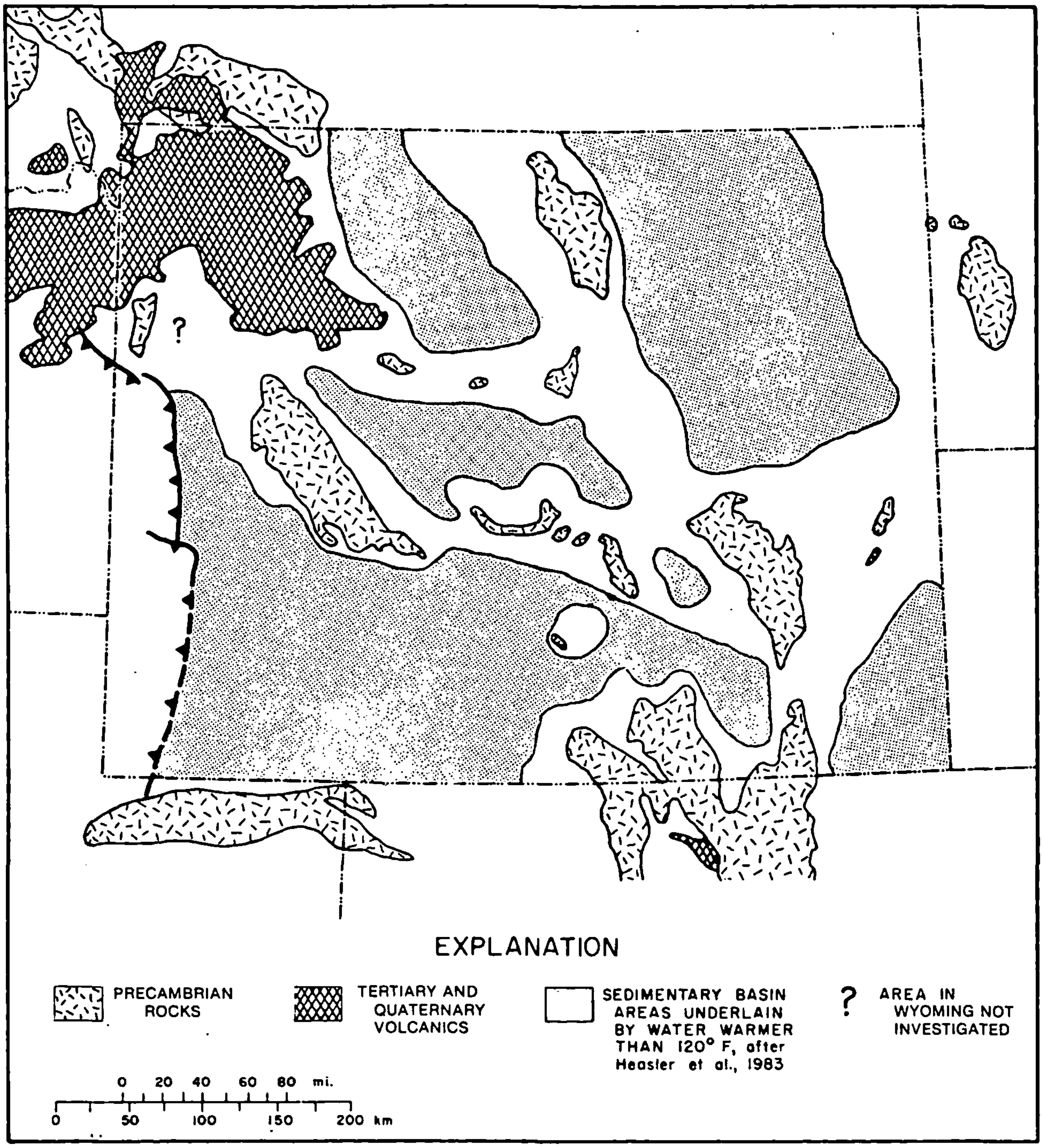
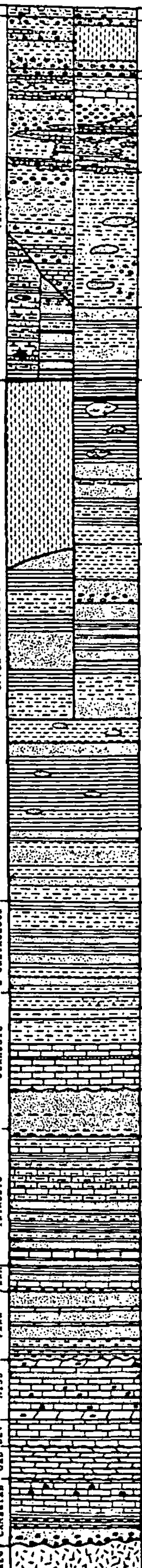


Figure 6. Simplified geologic map of Wyoming, showing sedimentary basin areas defined in this series of reports to be underlain by water warmer than 120°F. After Heasler et al., 1983.



Era	Period	Geologic Formation	Thickness (ft)[a]	Lithologic Description[b]	Water-Bearing Properties[b]
CENOZOIC	QUAT	QUATERNARY DEPOSITS	100	Unconsolidated sand, gravel, silt, and clay	Productive water-bearing deposits yielding 50-500 gpm ..
	TERTIARY	CAMP DAVIS FM SOUTH PARK FM BROWNS PARK FM	0-5200	Conglomerate, limestone, sandstone and tuffaceous mudstone	Major aquifer - well yields 10-120 gpm
		BISHOP CONGLOMERATE	0-200		
		BRIDGER FORMATION	0-2300	Tuffaceous lacustrine and flood plain deposits, becoming locally conglomeratic near the Uinta Mountains	Major aquifer in south - yields 2-100 gpm
		GREEN RIVER AND WASATCH FORMATIONS	0-2800	Green River Fm - lacustrine claystone, marlstone, oil shale and saline deposits with discontinuous lenses of fine-grained sandstone in the Laney and Tipton shale members; trona deposits in the Wilkins Peak Member Wasatch Fm - Newfork tongue (west) consists of mudstone, sandy with many lenses of fine-to course- grained sandstone; Cathedral Bluffs tongue consists of mudstone and sandstone	Major aquifer in east - sandstone lenses in Laney and Tipton yield 3-100 gpm to wells and springs, vertical permeability low due to heterogeneous lithology
		WASATCH FORMATION (MAIN BODY)	2500-7200	Silty to sandy claystone, lenticular beds of fine- to medium- grained sandstone becoming conglomeratic to the south and west	Major aquifer - well yields 1-1300 gpm in permeable sandstone and conglomeratic lenses
		(LEFT)HOBACK FM (NW) (RIGHT)FT UNION FM (SW) FT UNION FM	0-2500+	Hoback Formation - interbedded sandstone and calcareous shale with thick conglomeratic lenses (8000-16,000 feet thick) Ft. Union Formation - fine- to medium- grained silty sandstone, lignitic mudstone with coal; coarsens near mountains, major coal seams in lower portion	Minor aquifer - locally utilized
MESOZOIC	UPPER CRETACEOUS	LANCE FORMATION	0-4500	Very fine- to fine- grained, lenticular, clayey, calcareous, dark shale, coal and lignite	Minor aquifer probably capable of yielding small quantities of water from fine-grained sands and conglomeratic sandstones at base
		LEWIS SHALE	0-2700	Calcareous to non-calcareous shale with beds of siltstone and very fine-grained sandstone	Regional aquitard
		MESAVERDE FORMATION: ALMOND FM	0-1000	Sandstone, siltstone, shale and coal	Major aquifer; Ericson sandstone capable of large yields in 7 wells east of basin boundary ranging from 15-200 gpm
		MESAVERDE FORMATION: ERICSON FM	400-700	Sandstone, fine-grained to conglomeratic; middle siltstone and shale unit	
		MESAVERDE FORMATION: ROCK SPRINGS FM	900-1700	Sandstone, fine- to medium- grained with interbedded shale and coal	
		MESAVERDE FORMATION: BLAIR FORMATION	900-1800	Shale interbedded with siltstone and sandstone	
		BAXTER SHALE (CODY SHALE-NE)	2700-4500	Sandy shale with interbedded mudstone and shaley sandstone	Major regional confining unit
		FRONTIER FORMATION	50-2700	Lenticular sandstone, fine- to medium- grained; interbedded mudstone, claystone, siltstone, minor coal	Minor aquifer - irregular occurrence of high transmissivity due to variable cementation and lenticularity of beds; spring yields in west 1-100 gpm
	L CRETACEOUS	MOWRY SHALE	100-1000	Shale, hard, fissile with silty streaks, siliceous bentonite beds	Discontinuous aquifers - moderate water-bearing capabilities in Dakota and Muddy sandstones well yields 30-100 gpm in thrust belt
		DAKOTA SANDSTONE MORRISON FORMATION	400-600+	Sandstone with interbedded shale, clay and lignite	
	JURASSIC	STUMP SANDSTONE PREUSS REDBEDS (NW)	270-460	Interbedded sandstone, siltstone, mudstone, and limestone (Curtis Formation - Entrada Sandstone in southeast)	Aquitard
		TWIN CREEK LIMESTONE (NORTH, EAST)	150-725	Limestone, calcareous shale, gypsum and anhydrite (upper) Gypsum and anhydrite, red shale, siltstone, and dolomite (lower) (Gypsum Spring and Carmel Formations in southeast)	Minor aquifer -spring yields in west 75-300 gpm
		NUGGET SANDSTONE	400-700+	Sandstone, fine- to medium- grained, well sorted, minor amounts of cross-bedded clay and silt increasing with depth	Major Mesozoic aquifer - thrust belt springs yield up to 2000 gpm
	TRIASSIC	ANKAREH FORMATION	330-500+	Shale, interbedded siltstone, fine-grained sandstone, locally limestone in the middle portion	Minor regional aquifer -locally confining; spring in northwest yields 200 gpm
		THAYNES LIMESTONE	0-900+	Silty limestone with siltstone and shale in upper part	Major aquifer - most productive where solution openings and fractures exist
		WOODSIDE FORMATION	500-600	Anhydritic siltstone and mudstone with some fine-grained sandstone	Regional aquitard
		DINWOODY FORMATION	50-450	Siltstone, shale, dolomite; interbedded anhydrite in upper part	
PALEOZOIC	PERM	PHOSPHORIA FORMATION	200-400	Phosphatic carbonate, cherty shale, sandstone (northwest) Carbonate with sandstone (southeast)	Minor aquifer - locally confining
	PENN	TENSLEEP SANDSTONE (NORTH, EAST) WEBER SANDSTONE (SOUTH, WEST)	350-700	Fine-grained well-sorted sandstone with quartzite and thinly layered siliceous dolomitic limestone	Major aquifer - excellent secondary permeability where fractured; springs in thrust belt yield up to 2000 gpm
		AMSDEN FORMATION	300-600	Mudstone, siltstone, sandstone with cherty limestone	Minor aquifer - locally confining
	MISS	MADISON LIMESTONE	300-900	Limestone, thin-bedded to massive, brecciated and partly cherty; dolomite, thick-bedded to massive	Major regional aquifer - permeability dependent on degree of fracturing; spring in west yields 4000 gpm
	DEV	DARBY FORMATION	330-400	Limestone and dolomite, thin-bedded to massive, siltstone	
	ORD	BIGHORN DOLOMITE	150-500	Massive dolomite and dolomitic limestone	
	CAMBRIAN	GALLATIN LIMESTONE	0-200	Interbedded limestone, siltstone, and thin shale	Minor aquifer - potentially productive
		GROS VENTRE FORMATION	500-1000	Shale, with some sandstone and limestone beds	Regional aquitard
		FLATHEAD SANDSTONE	0-200 ?	Quartzite, fine-grained with coarse-grained sandstone lenses	Minor aquifer
PREC		PRECAMBRIAN UNDIVIDED	?	Gneissic granite with schist, granite and pegmatite	Locally utilized aquifer near outcrop areas; spring yields 2000 gpm in northwest

[a] Thicknesses from Ahern, et al., 1981; Welder, 1968; and Petroleum Information Cards

[b] Lithologic descriptions and water-bearing properties from Ahern, et al., 1981; Welder, 1968, Collentine et al., 1981

Figure 7. Stratigraphic column for the Green River Basin.

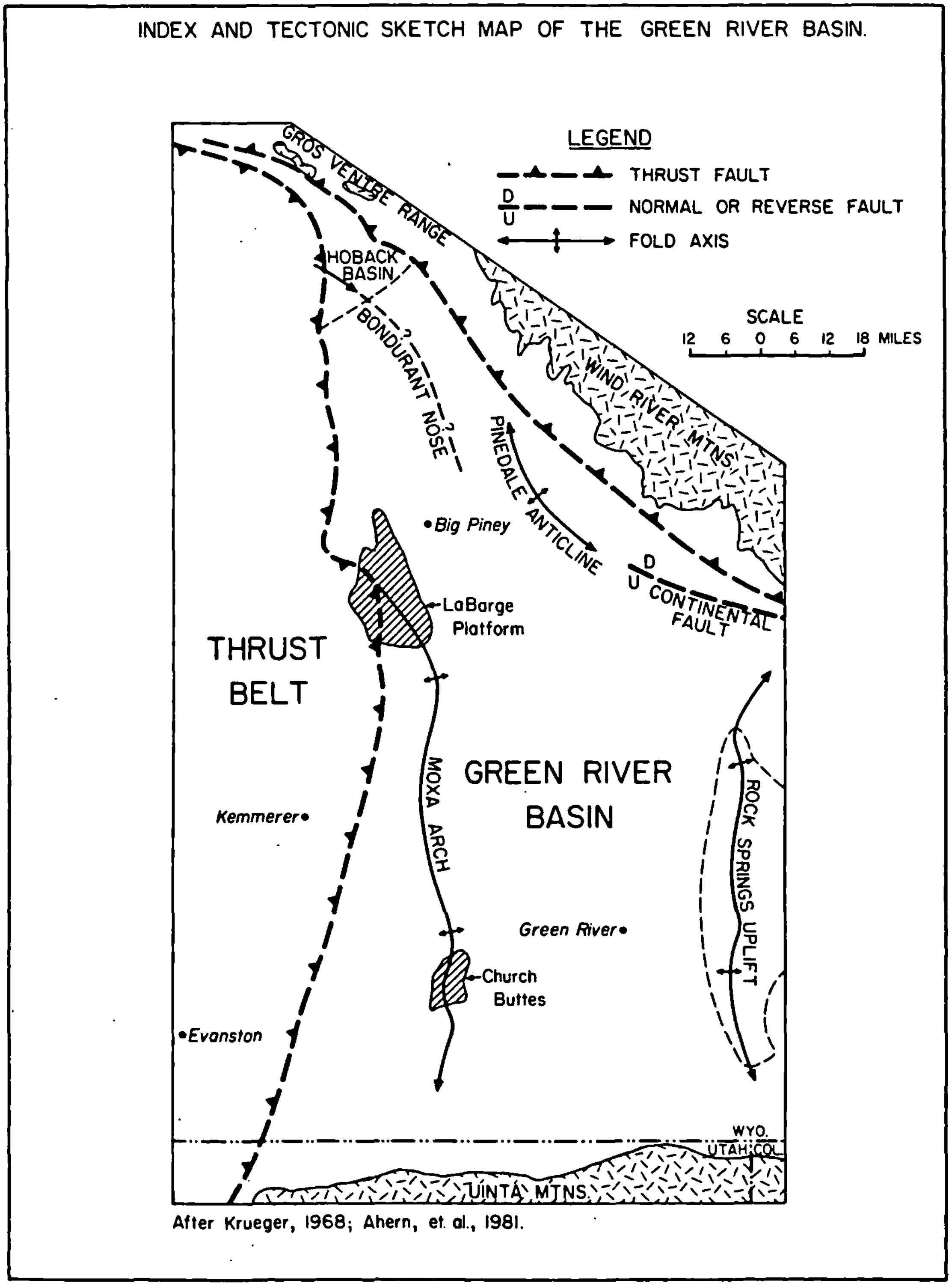


Figure 8. Index and tectonic sketch map of the Green River Basin.

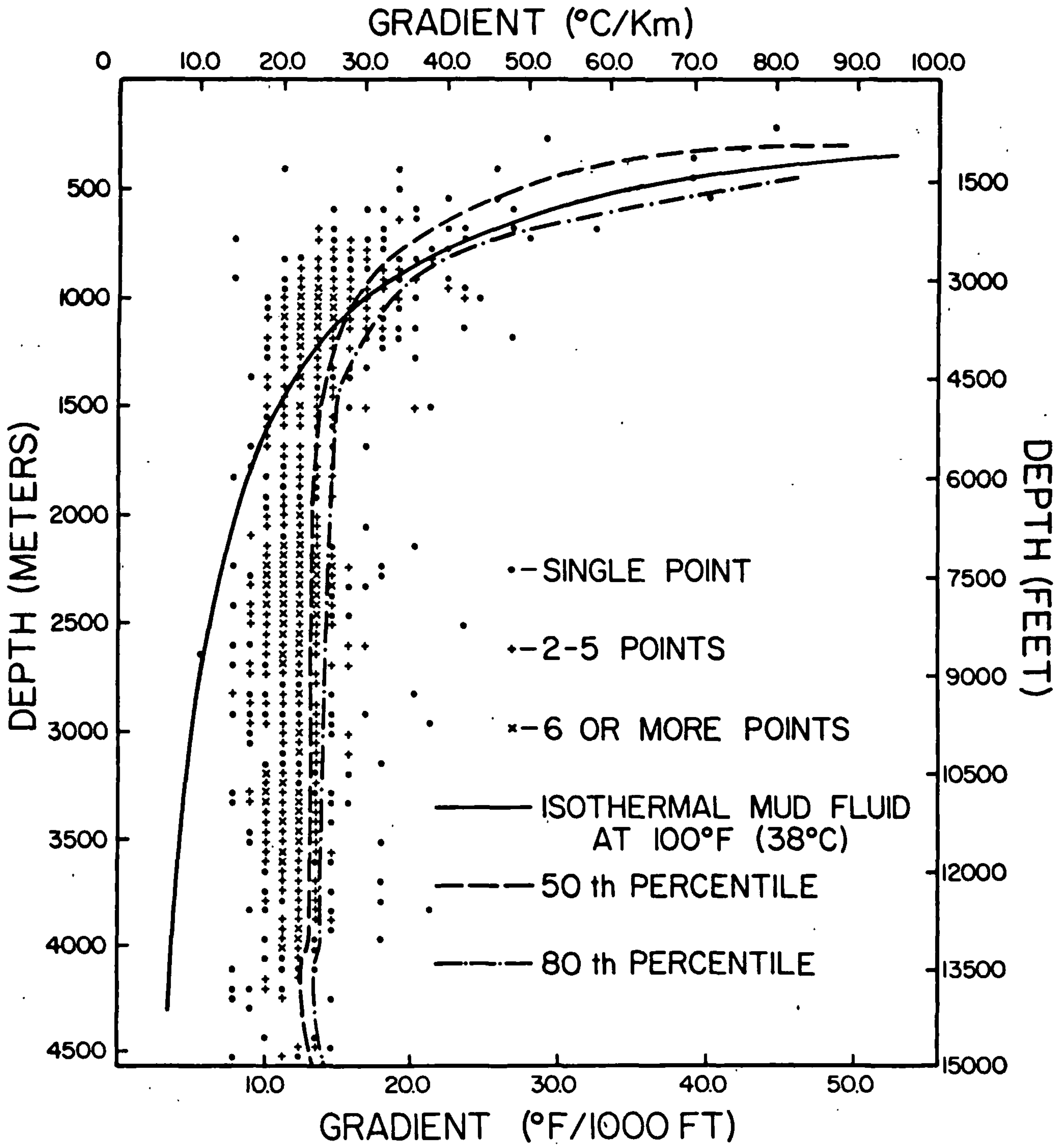


Figure 9. *GRADIENT-DEPTH PROFILE FOR GREEN RIVER BASIN, BASED ON 1529 BOTTOM-HOLE TEMPERATURES.*

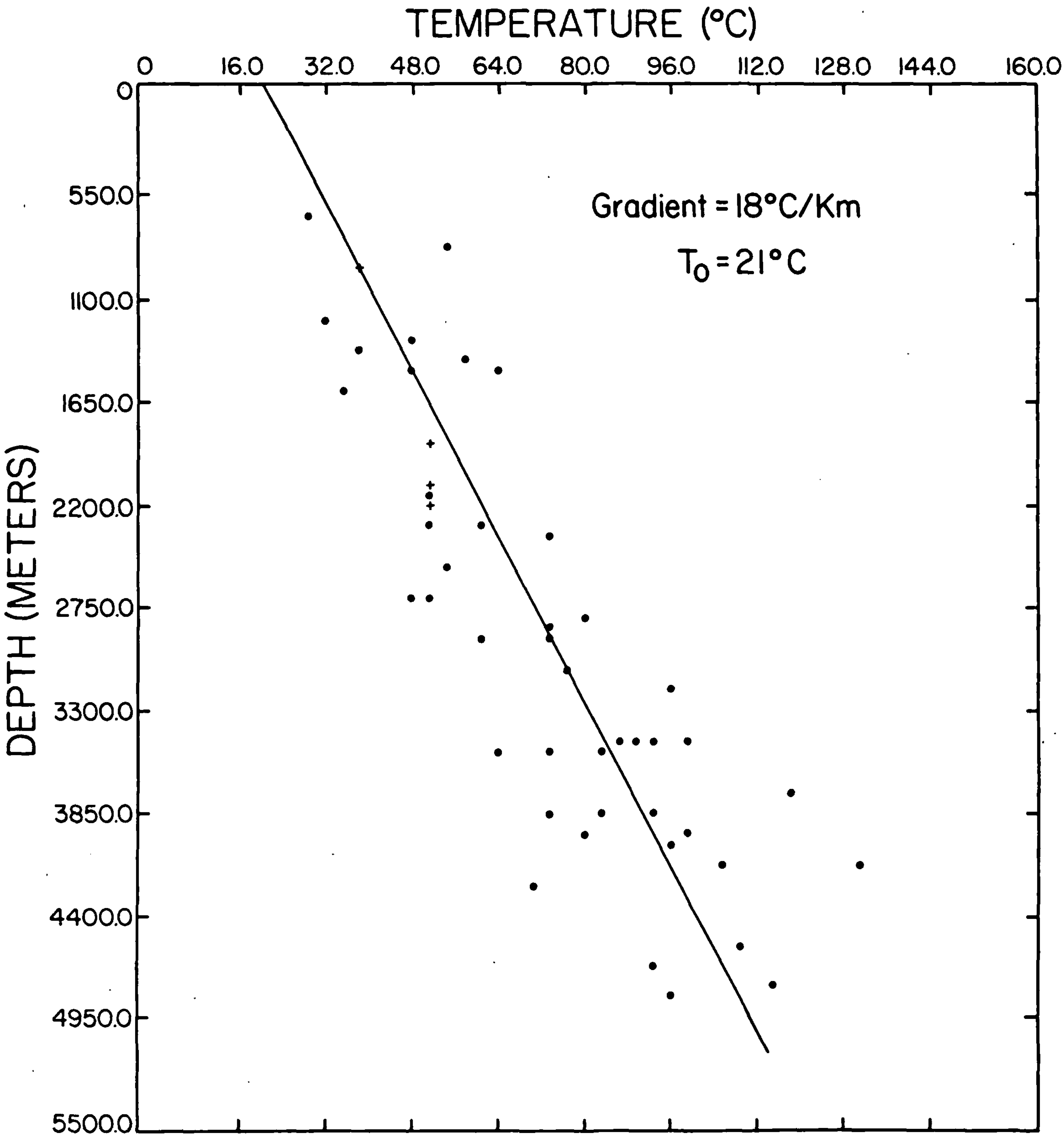


Figure 10. *TEMPERATURE - DEPTH PROFILE FOR THE THRUST BELT*
(based on 51 data values)

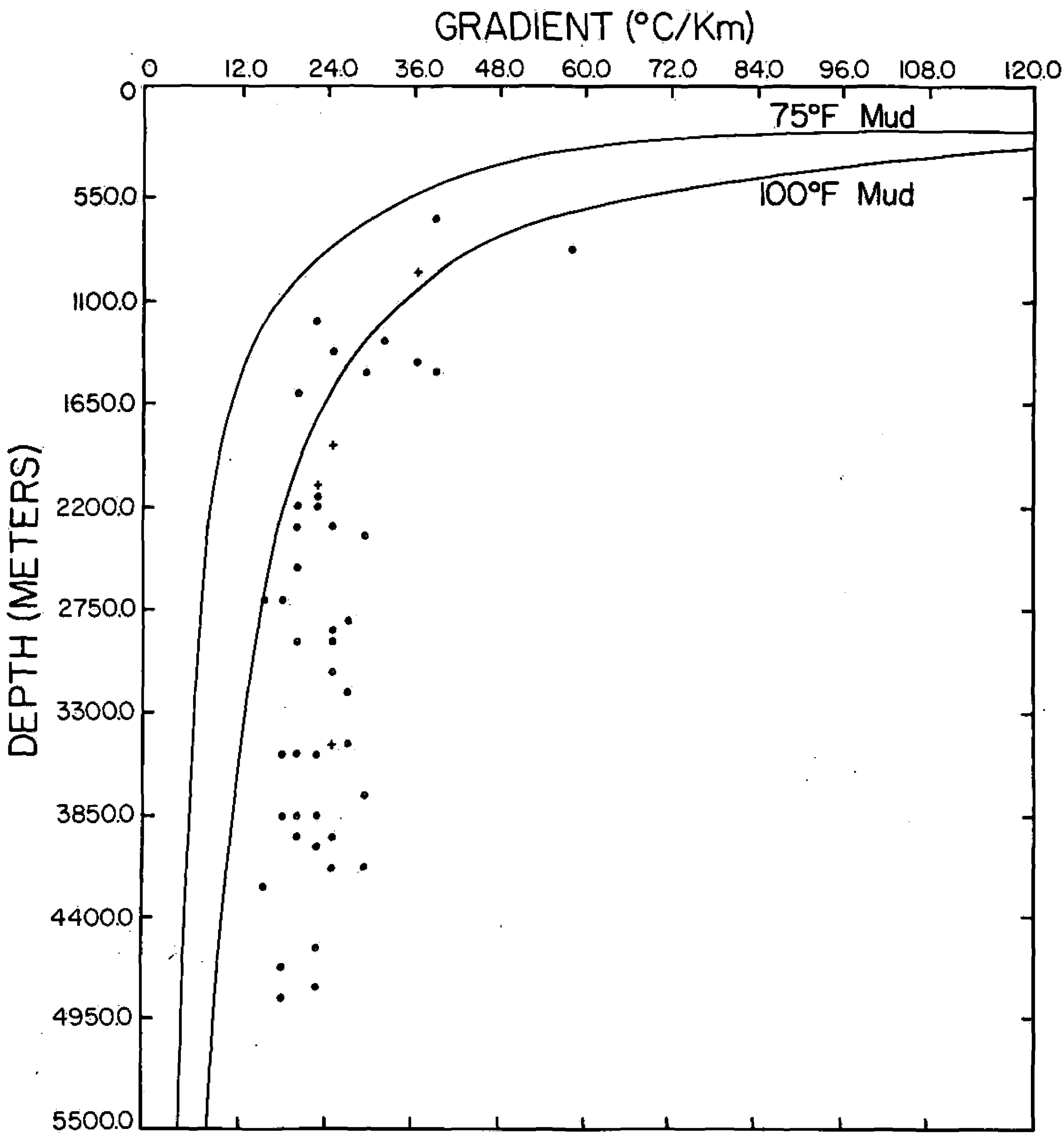


Figure 11. *GRADIENT-DEPTH PROFILE FOR THE THRUST BELT*

(based on 51 data values)

PLATE I

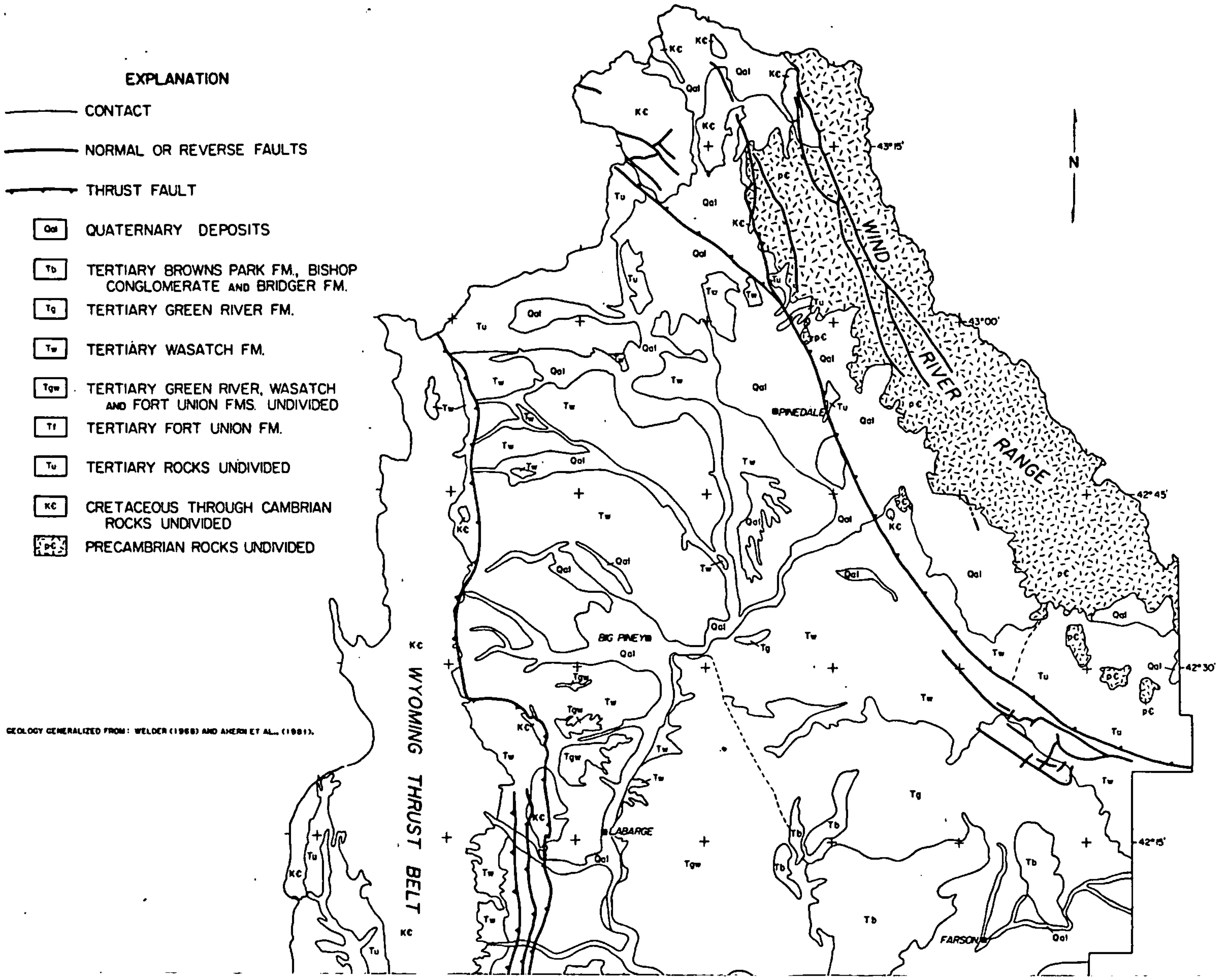

EXPLANATION
CONTACT
NORMAL OR REVERSE FAULTS
THRUST FAULT
Qal QUATERNARY DEPOSITS
Tb TERTIARY BROWNS PARK FM., BISHOP CONGLOMERATE AND BRIDGER FM.
Tg TERTIARY GREEN RIVER FM.
Tw TERTIARY WASATCH FM.
Tgw TERTIARY GREEN RIVER, WASATCH AND FORT UNION FMS. UNDIVIDED
Tf TERTIARY FORT UNION FM.
Tu TERTIARY ROCKS UNDIVIDED
Kc CRETACEOUS THROUGH CAMBRIAN ROCKS UNDIVIDED
pC PRECAMBRIAN ROCKS UNDIVIDED
GEOLOGY GENERALIZED FROM: WELDER (1968) AND AHERN ET AL., (1981).
N
WIND RIVER RANGE
WYOMING THRUST BELT
PINEDALE
BIG PINEY
LABARGE
FARSON
43°15'
43°00'
42°45'
42°30'
42°15'

PLATE II

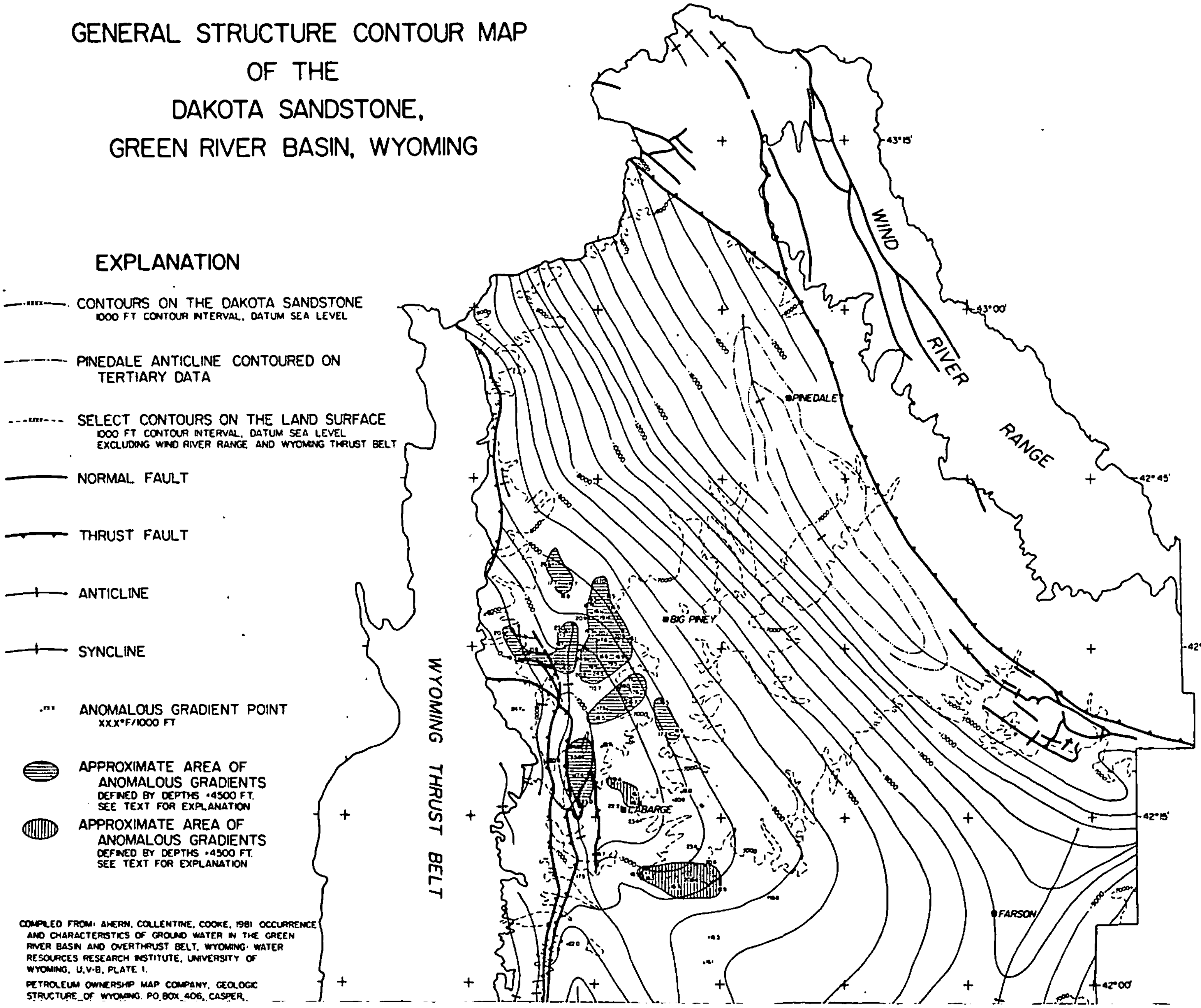
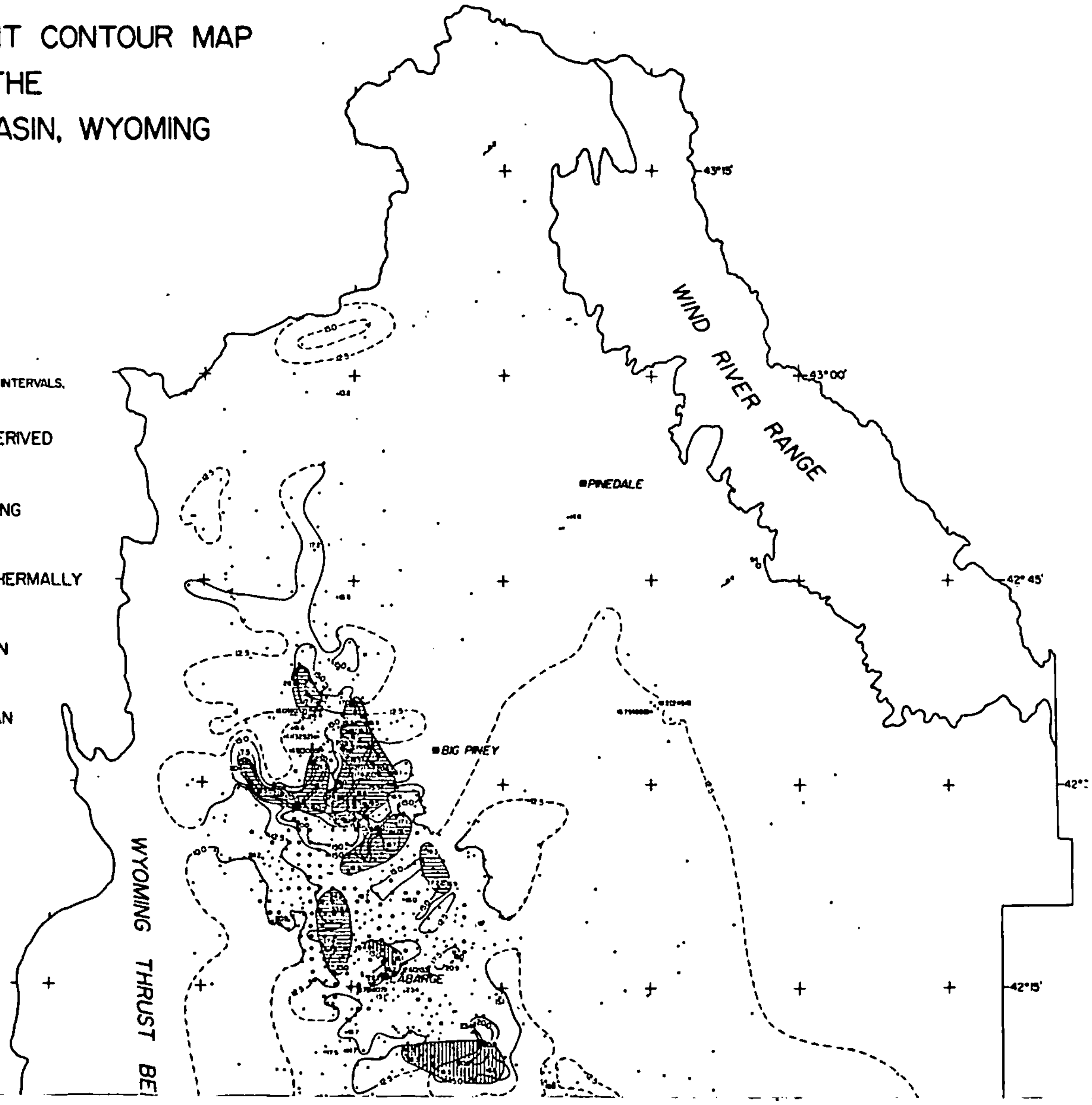

GENERAL STRUCTURE CONTOUR MAP
OF THE
DAKOTA SANDSTONE,
GREEN RIVER BASIN, WYOMING
EXPLANATION
CONTOURS ON THE DAKOTA SANDSTONE
1000 FT CONTOUR INTERVAL, DATUM SEA LEVEL
PINEDALE ANTICLINE CONTOURED ON
TERTIARY DATA
SELECT CONTOURS ON THE LAND SURFACE
1000 FT CONTOUR INTERVAL, DATUM SEA LEVEL
EXCLUDING WIND RIVER RANGE AND WYOMING THRUST BELT
NORMAL FAULT
THRUST FAULT
ANTICLINE
SYNCLINE
ANOMALOUS GRADIENT POINT
XXX°F/1000 FT
APPROXIMATE AREA OF
ANOMALOUS GRADIENTS
DEFINED BY DEPTHS <4500 FT.
SEE TEXT FOR EXPLANATION
APPROXIMATE AREA OF
ANOMALOUS GRADIENTS
DEFINED BY DEPTHS >4500 FT.
SEE TEXT FOR EXPLANATION
COMPILED FROM: AHERN, COLLENTINE, COOKE, 1981 OCCURRENCE AND CHARACTERISTICS OF GROUND WATER IN THE GREEN RIVER BASIN AND OVERTHRUST BELT, WYOMING: WATER RESOURCES RESEARCH INSTITUTE, UNIVERSITY OF WYOMING, U.V-B, PLATE 1.
PETROLEUM OWNERSHIP MAP COMPANY, GEOLOGIC STRUCTURE OF WYOMING. PO BOX 406, CASPER.
WIND RIVER RANGE
WYOMING THRUST BELT
PINEDALE
BIG PINEY
LABARGE
FARSON
43°15'
43°00'
42°45'
42°
42°15'
42°00'

PLATE III

THERMAL GRADIENT CONTOUR MAP OF THE GREEN RIVER BASIN, WYOMING



EXPLANATION

- THERMAL GRADIENT CONTOURS — XX.X°F/1000 FT, 2.5°F/1000 FT. CONTOUR INTERVALS, DASHED WHERE APPROXIMATE
- BOTTOM HOLE TEMPERATURE DERIVED GRADIENT DATA POINT
- THREE OR MORE GRADIENT DATA POINTS WITHIN A SECTION
- DATA POINTS OUTSIDE CONTOURING — XX.X°F/1000 FT.
- TEMPERATURE GRADIENT OF THERMALLY LOGGED HOLES — XX.X°F/1000 FT., (XXXX) FEET LOGGED
- WELLS FLOWING GREATER THAN 70°F WATER — X REFERS TO TABLE 7
- SPRINGS FLOWING GREATER THAN 70°F WATER — X REFERS TO TABLE 7
- HEAT FLOW DATA POINTS — XX mW/m²
- APPROXIMATE AREA OF ANOMALOUS GRADIENTS — DEFINED BY DEPTHS <4500 FT. SEE TEXT FOR EXPLANATION
- APPROXIMATE AREA OF ANOMALOUS GRADIENTS — DEFINED BY DEPTHS >4500 FT. SEE TEXT FOR EXPLANATION

TEMPERATURE CONTOUR MAP OF THE DAKOTA SANDSTONE, GREEN RIVER BASIN, WYOMING