GL01386

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
CONSERVATION DIVISION

GEOTHERMAL RESOURCES OPERATIONAL ORDER NO. 4

Effective August 1, 1975

GENERAL ENVIRONMENTAL PROTECTION REQUIREMENTS

This Order is established pursuant to the authority prescribed in 30 CFR 270.11 and in accordance with 30 CFR 270.2, 270.34(k), 270.37, 270.41, 270.42, 270.43, 270.44, and 270.76. Lessees shall comply with the provisions of this Order. All variances from the requirements specified in this Order shall be subject to approval pursuant to 30 CFR 270.48. References in this Order to approvals, determinations, or requirements are to those given or made by the Area Geothermal Supervisor (Supervisor) or his delegated representative.

All data submitted under this Order shall be available for inspection in accordance with the Freedom of Information Act of 1966 (P.L. 89-487), as amended in 1974 (P.L. 93-502), except information such as geological, geophysical, reservoir, trade secrets, and financial data and interpretations of such data, maps, and related files for which a lessee requests proprietary status; provided that such status is determined by the Supervisor to be warranted and is approved by appropriate officials of the Department of the Interior.

Protection of the environment includes the lessee's responsibility to: conduct exploration and development operations in a manner that provides maximum protection of the environment; rehabilitate disturbed lands; take all necessary precautions to protect the public health and safety; and conduct operations in accordance with the spirit and objectives of all applicable Federal environmental legislation and supporting executive orders.

Adverse environmental impacts from geothermal-related activity shall be prevented or mitigated through enforcement of applicable Federal, State, and local standards, and the application of existing technology. Inability to meet these environmental standards or continued violation of environmental standards due to operations of the lessee, after notification, may be construed as grounds for the Supervisor to order a suspension of operations.

The lessee shall be responsible for the monitoring of readily identifiable localized environmental impacts associated with specific activities that are under the control of the lessee. Monitoring of environmental impacts may be conducted by the use of aerial surveys, inspections, periodic samplings, continuous recordings, or by such other means or methods as required by the Supervisor. Due to the differing natural environmental conditions among geothermal areas, the extent and frequency of such monitoring activities will be determined by the Supervisor on an individual basis. In the event the Supervisor determines that the degree and adequacy of existing environmental protection regulations in certain areas are insufficient, the Supervisor may establish additional and more stringent requirements by the issuance of field orders or by modifying existing orders.

Lessees shall provide for acquisition of environmental baseline data as required in accordance with 30 CFR 270.34(k) for a period of one year prior to submission of a plan for production. Techniques and standards to be used by the lessee for meeting these requirements shall receive prior approval by the Supervisor.

1. Aesthetics. The lessee shall reduce visual impact, where feasible, by the careful selection of sites for operations and facilities on leased lands. The design and construction of facilities shall be conducted in a manner such that the facilities will blend into the natural environmental setting of the area by the appropriate use of landscaping, vegetation, compatible color schemes, and minimum profiles. Native plants or other compatible vegetation shall be used, where possible, for landscaping and revegetation.

2. Land Use and Reclamation. Operating plans shall be designed so that operations will result in the least disturbance of land, water, and vegetation. Existing roads shall be used where suitable. Entry upon certain environmentally fragile land areas, as designated by the surface management agency, may be either seasonally restricted or restricted to special vehicles or transportation methods which will minimize disturbance to the surface or other resources as specified by the Supervisor and surface management agency.

Operating plans shall provide for the reclamation and revegetation of all disturbed lands in a manner approved by the Supervisor and the appropriate surface management agency. Land reclamation may include preparation and seeding with prescribed wildlife food and plant cover or improved and acceptable substitutes thereof which will equal or enhance the food values for indigenous wildlife species and domesticated animals. Temporary fencing for such reclaimed areas may be required to facilitate restoration thereof.

The lessee shall at all times maintain the leased lands in a safe and orderly condition and shall perform the operations in a workmanlike manner. The lessee shall remove or store all supplies, equipment, and scrap in a timely and orderly fashion.

Operations under a geothermal lease shall not unreasonably interfere with or endanger operations under any other lease, license, claim, permit, or other authorized use on the same lands.

3. Public Access. The public shall have free and unrestricted access to geothermal leased lands, excepting however, where restrictions are necessary to protect public health and safety or where such public access would unduly interfere with the lessee's operations or the security thereof. The lessee shall provide warning signs, fencing, flagmen, barricades, or other safety measures deemed necessary by the Supervisor to protect the public, wildlife, and livestock from hazardous geothermal or related activities.

4. Recreation. Recreational values shall be adequately protected through planning and designing of site development to minimize the aesthetic degradation of the particular recreation area. The lessee shall generally be restricted from surface locations for drilling and other lease operations within 61 metres (200 feet) of established recreation sites and access routes thereto. However, the lessee may relocate a recreational site and/or access routes thereto when approved by the Supervisor with the concurrence of the land management agency.

5. Slope Stability and Erosion Control. Operations shall be conducted in such a manner so as to minimize erosion and disturbance to natural drainage. The lessee shall provide adequate erosion and drainage control to prevent sediments from disturbed sites from entering water courses for soil and natural resource conservation protection.

Mitigating measures to lessen environmental damage may include reseeding of disturbed soils, chemical stabilization, and dust and erosion control on well sites, roads, and construction areas.

All operating plans shall give proper consideration to the potential hazards of slope instability. Where potentially unstable ground conditions exist, design of proposed roads, drill sites, and surface facilities shall be approved by and constructed under the supervision of a qualified engineer or engineering geologist satisfactory to the Supervisor.

6. Biota. The lessee shall conduct all operations in such a manner as to afford reasonable protection of fish, wildlife, and natural habitat. The lessee shall take such measures as are necessary for the conservation of endangered and threatened species of flora and fauna as set forth in applicable executive orders, regulations, and State or Federal legislation such as the Endangered Species Act of 1973 and the Fish and Wildlife Coordination Act. When such species would be adversely affected by the lessee's operations on the leased lands, the lessee shall implement those measures necessary to minimize or eliminate such adverse effects and to protect the flora and fauna as specified by the Supervisor in accordance with recommendations by appropriate Federal and State agencies. Such measures may be in addition to provisions set forth in the lease or accompanying stipulations.

The Supervisor may receive information from recognized experts that a delicate balance of flora and/or fauna exists in the area of operations or proposed operations. Upon receiving such notice, the Supervisor will request timely advice and assistance from appropriate Federal and State agencies regarding: (1) an assessment of the status of flora and fauna in the area which may be adversely affected by operations, and (2) advice as to reasonable mitigating measures appropriate to minimizing or preventing adverse trends in populations, growth, vegetative recovery, or repopulations in potentially affected flora and/or fauna. Based on timely receipt of advice from appropriate agencies, the Supervisor will direct the lessee to take appropriate measures to minimize significant adverse trends in flora and fauna. Such measures may include, but not be limited to, revegetation with grasses, shrubs, or other vegetation of high forage values desirable for habitat, replacement of fauna where lost, replacement of water supply, or sources where destroyed.

Where the lessee's operations have destroyed significant flora and/or fauna or their natural habitat and replacement by natural processes will not take place in a normal growth cycle, the lessee shall take reasonable measures to replace those species or their habitat with the same or other acceptable species or habitat as directed by the Supervisor. The Supervisor's requirements shall be based on recommendations and advice received from appropriate Federal and State agencies.

7. Cultural Resources Preservation. The lessee shall exercise due diligence in the conduct of his operations to protect and preserve significant archaeological, historical, cultural, paleontological, and unique geologic sites. The lessee shall not disturb any known cemetery or burial ground of any group or culture.

Previously unknown sites uncovered by the lessee shall be immediately reported to the Supervisor, and operations on the particular site shall cease until said site can be assessed for its archaeological value and preservation. Necessary controls and remedial actions for the protection and preservation of cultural resources shall be issued on an individual site basis by the Supervisor as warranted.

The preservation, restoration, maintenance, and nomination of all resources for purposes of the National Register of Historic Places shall be in accordance with the provisions of Executive Order 11593 (36 FR 8921) entitled, "Protection and Enhancement of the Cultural Environment," or any amendments thereto.

8. Subsidence and Seismicity. Surveying of the land surface prior to and during geothermal resources production will be required for determining any changes in elevation of the leased lands. Lessees shall make such resurveys as required by the Supervisor to ascertain if subsidence is occurring. Production data, pressures, reinjection rates, and volumes shall be accurately recorded and filed monthly with the Supervisor as provided in 30 CFR 270.37. In the event subsidence activity results from the production of geothermal resources, as determined by surveys by the lessee or a governmental body, the lessee shall take such mitigating actions as are required by the lease terms and by the Supervisor.

If subsidence is determined by the Supervisor to present a significant hazard to operations or adjoining land use, then the Supervisor may require remedial action including, but not limited to, reduced production rates, increased injection of waste or other fluids, or a suspension of production.

A. Surveys. All required surveys shall be second order or better and shall be conducted under the direct supervision of a registered civil engineer or licensed land surveyor using equipment acceptable by the National Ocean Survey for second order surveys. All such work shall be coordinated with the county surveyor of the county in which the surveys and bench marks are to be established. Level lines and networks shall be tied to available regional networks.

Adjusted survey data shall be filed with the Supervisor within 60 days after leveling is completed. Any lessee having a commercially productive geothermal well or wells shall participate in cooperative County/State subsidence detection programs. All survey data filed with the Supervisor shall be available to the public.

B. Bench Marks. One or more wellsite bench marks shall be required at each completed well prior to prolonged production and said bench marks shall be located in a manner such that there is a minimal probability of destruction or damage to said bench marks. Wellsite bench marks shall be tied to existing regional networks. Additional bench marks between the wellsites and the regional network shall be at 0.8-km (one-half mile) intervals or as otherwise specified by the Supervisor. These bench marks shall be resurveyed during well production operations on a periodic basis as determined by the Supervisor.

Acceptable bench marks include, but are not limited to, a brass rod driven to refusal or 9 metres (about 30 feet) and fitted with an acceptable brass plate or a permanent structure with an installed acceptable brass plate.

C. Reservoir Data. Initial reservoir pressure and temperature shall be reported to the Supervisor in duplicate on Well Completion or Recompletion Report (Form 9-330C) for all completed wells within 30 days after the completion of measurements or tests conducted for the purpose of obtaining such data. Initial production test data including steamwater ratio, surface pressure and temperature, quality, and quantity of well effluent shall also be filed with the Supervisor on Form 9-330C within 30 days after a well is completed.

D. Seismicity. The installation of seismographs or other like instruments in producing geothermal areas for the purpose of detecting potential seismic activity may be initiated from time to time by appropriate public agencies. Lessees shall cooperate with the appropriate public agencies in this regard. The lessee and the appropriate public agency should take care not to unreasonably interfere with or endanger each other's respective operations. The Supervisor shall coordinate such detection programs between the appropriate public agency conducting the program and the lessee.

Where induced seismicity caused by the production of geothermal fluids is determined to exist by the Supervisor, then the Supervisor may require the lessee to install such monitoring devices as necessary to adequately quantify the effects thereof. If induced seismicity is determined to represent a significant hazard, the Supervisor may require remedial actions including, but not limited to, reduced production rates, increased injection of waste or other fluids, or suspension of production.

9. Pollution, Waste Disposal, and Fire Prevention. The lessee shall comply with all applicable Federal and State standards with respect to the control of all forms of air, land, water, and noise pollution, including the control of erosion and the disposal of liquid, solid, and gaseous wastes. The Supervisor may, at his discretion, establish additional and more stringent standards. Plans for disposal of well effluents must be approved by the Supervisor before any implementation action is undertaken. Immediate corrective action shall be taken in all cases where pollution has occurred.

The lessee shall timely remove or dispose of all waste including human waste, trash, refuse, and extraction and processing waste generated in connection with the lessee's operations in a manner acceptable to the Supervisor.

The lessee shall provide safeguards to minimize potential accidental fires and shall instruct field personnel in fire-prevention methods. The lessee shall maintain fire-fighting equipment in working order at strategic locations on the leased lands.

A. Pollution Prevention. In the conduct of all geothermal operations, the lessee shall not contaminate any natural waters and shall minimize adverse effects on the environment.

(1) Liquid Disposal. Liquid well effluent or the liquid residue thereof containing substances, including heat, which may be harmful or injurious and cannot otherwise be disposed of in conformance with Federal, State, and regional standards, shall be injected into the geothermal resources zone or such other formation as is approved by the Supervisor.

Toxic drilling fluids shall be disposed of in a manner approved by the Supervisor and in conformance with applicable Federal, State, and regional standards.

(2) Solid Waste Disposal. Drill cuttings, sand, precipitates, and other solids shall be disposed of as directed by the Supervisor either on location or at other approved disposal sites. Containers for mud additives for chemicals and other solid waste materials shall be disposed of in a manner and place approved by the Supervisor.

(3) Air Quality. Noncondensible gases such as carbon dioxide, ammonia, and hydrogen sulfide may be vented or ejected into the atmosphere, provided, however, that the volume and the measured concentration of such vented gas or gases shall not exceed applicable Federal, State, or regional air pollution standards. Copies of each permit issued by the appropriate air pollution control agency and the reports required thereunder shall be submitted to the Supervisor.

(4) Pits and Sumps. Pits and sumps shall be lined with impervious material and purged of environmentally harmful chemicals and precipitates before backfilling. In no event shall the contents of a pit or sump be allowed to contaminate streams, lakes, and ground waters. Pits and sumps shall be constructed in a manner and in such locations so as to minimize damage to the natural environment and aesthetic values of the lease or adjacent property. When no longer used or useful, pits and sumps shall be backfilled and the premises restored to as near a natural state as reasonably possible. Temporary fencing of unattended pits and sumps to protect wildlife, livestock, and the public may be required by the Supervisor and the surface management agency.

(5) Production Facilities Maintenance. Production facilities shall be operated and maintained at all times in a manner necessary to prevent pollution. The lessee's field personnel shall be instructed in the proper maintenance and operations of production facilities for the prevention of pollution.

B. Inspection and Reports. Lessees shall comply with the following pollution inspection and reporting requirements.

(1) Pollution Inspections. Drilling and production facilities shall be inspected daily by the lessee. Appropriate preventative maintenance shall be performed as necessary to prevent failures and malfunctions which could lead to pollution. Wells and areas not under production shall be inspected by the lessee at intervals prescribed by the Supervisor. Necessary repairs or maintenance shall be made as required.

(2) Pollution Reports. All pollution incidents shall be reported orally within 18 hours to the appropriate Geothermal District Supervisor and shall be followed within 30 days thereof by a written report stating the cause and corrective action taken.

C. Injection. The use of any subsurface formation, including the geothermal resources zone for the disposal of well effluent, the residue thereof, or the injection of fluids for other purposes such as subsidence prevention shall not be permitted until the lessee has submitted a plan of injection covering the proposed injection project and has subsequently received the Supervisor's written approval thereof.

(1) Plan of Injection. The plan of injection shall include the quantity, quality, and source of the proposed injection fluid; the means and method by which the fluid is to be injected; a structure map contoured on the intended injection zone; and cross-sections showing producing well locations and the proposed injection well location(s).

(2) Injection Report. The lessee shall file in duplicate with the Supervisor a Monthly Water Injection Report in a form approved by the Supervisor. The subject report shall be filed on or before the last day of the month following the month in which the injection took place.

(3) Inspection. Injection wells and facilities shall be inspected by the lessee at intervals as prescribed by the Supervisor to ascertain that all injected fluids are confined to the approved injection zone. A spinner survey, a radioactive tracer survey, and a cement bond log may be required on each injection well within 30 days after injection begins. The lessee shall furnish to the Supervisor two legible exact copies of any and all such surveys and logs. In the event of a casing failure, inadequate annular cement, or other mechanical failure, the lessee shall without unreasonable delay repair, suspend, or abandon the well. Where failure occurs in a zone which may damage surface or fresh water aquifers, injection shall immediately cease.

(4) New Wells. The drilling of new injection wells in accordance with an approved plan of injection shall be in conformance with the provisions of GRO Order No. 2. An Application for Permit to Drill, Form 9-331C, shall be filed in triplicate and approved for each injection well.

(5) Conversions. The conversion of an existing well to an injection well in accordance with or modification of an approved plan of injection shall be in conformance with the requirements of GRO Order No. 2. The lessee shall demonstrate to the satisfaction of the Supervisor by appropriate testing and logging that the well is mechanically sound and suitable for injection purposes. A Sundry Notice, Form 9-331, shall be filed in triplicate and approved for each conversion.

10. Water Quality. The primary responsibility for water quality and pollution control has been delegated to the States where such States have standards approved by the Environmental

Protection Agency. Such State standards must meet basic Federal requirements prohibiting the deterioration of waters whose existing quality is higher than established water quality standards. The lessee shall comply with the State water quality control organization's standards in such States as have federally-approved standards. The Supervisor, at his discretion, may establish additional and more stringent standards.

The lessee shall file, in duplicate, a detailed water analysis report for all completed geothermal wells within 30 days after completion and annually thereafter or as otherwise specified by the Supervisor. Unless otherwise prescribed by the Supervisor, such analyses shall include a determination of arsenic, boron, radioactive content, and radioactivity of the produced fluids. In the event that a health hazard exists, the Supervisor shall require appropriate health and safety precautions, periodic monitoring, or the suspension of production.

11. <u>Noise Abatement</u>. The lessee shall minimize noise during exploration, development, and production activities. The method and degree of noise abatement shall be as approved by the Supervisor.

The lessee shall conduct noise level measurements during exploration, development, and production operations to determine the potential objectionability to nearby residents as well as the potential health and safety danger due to noise emissions.

Noise level measurements and accompanying data shall be filed with the Supervisor. Such data shall provide the basis for operational and noise control decisions by the Supervisor and shall be based on an assessment of the noise relative to Federal or State criteria including adjustments for the area involved, meteorological conditions, and the time of day of the noise occurence.

The lessee shall comply with Federal occupational noise exposure levels applicable to geothermal activity under the Occupational Safety and Health Act of 1970 as set forth in 29 CFR 1910.95, which are incorporated herein by reference, or with State standards for protection of personnel where such State standards are more restrictive than Federal standards.

A. <u>Measurement Condition</u>. Outdoor noise measurements shall be made at least 3 metres (10 feet) from structures, facilities, or other sound reflecting sources and approximately 1 metre (3 feet) above ground level. Extreme weather conditions, electrical interference, and unusual background noise levels shall be avoided or given due consideration when measuring sound levels.

B. Measurements. The lessee shall monitor and measure noise levels using an octave band noise analyzer with an A-weighted frequency response or a standard sound level meter that conforms to the requirements set forth in USA Standard Specifications for General Purpose Sound Level Meters USASI S1.4-1961 or the latest approved revision thereof. Bandpass filters shall conform to the requirements of USASI S1.11-1966. The lessee shall measure noise level frequency distribution as required by the Supervisor. Sound levels shall be measured in conformance with the USA Standard-Method for the Physical Measurement of Sound USASI S1.2-1962.

C. Criteria. In the absence of more restrictive criteria as may be established in this paragraph, the lessee shall not exceed a noise level of 65 dB(A) for all geothermal-related activity including but not limited to, exploration, development, or production operations as measured at the lease boundary line or 0.8 km (one-half mile) from the source, whichever is greater, using the A-weighted network of a standard Sound Level Meter. However, the permissible noise level of 65 dB(A) may be exceeded under emergency conditions or with the Supervisor's approval if written permission is first obtained by the lessee from all residents within 0.8 km (one-half mile).

D. Assessment. The lessee shall be responsible for taking such noise level measurements as are deemed necessary by the Supervisor. The background noise level shall serve as the criterion for the rating and assessment, by the Supervisor, of the objectionableness of noise emission from a particular source. The background or ambient noise is defined hereby as the minimum sound level at the relevant place and time in the absence of the source noise and shall include consideration for the type of land use, the season, atmospheric conditions, and the time of day.

E. Attenuation. To attenuate objectionable noise, the lessee shall utilize properly designed muffling devices as required by the Supervisor.

F. Relationships. Reference levels and relationships for noise measurements shall be as follows:

(1) Reference sound pressure for airborne sounds shall be 20 MN/m (20 micronewtons per square metre).

(2) Reference power shall be 10-12 watts.

(3) Sound levels shall be measured using a standard Sound Level Meter with an "A" frequency response characteristic (weighting network).

(4) Sound level meter controls shall be set for as uniform a frequency response as possible when measuring sound pressure levels.

(5) Octave band noise levels shall be reported in equivalent A-weighted levels.

G. Record of Sound Measurements. The Supervisor may require sound level measurements during drilling, testing, and producing operations. Such measurements shall be filed in duplicate with the Supervisor and shall include the following data:

(1) Date, time, and location.

(2) Name of observer.

(3) Description of primary noise source emitter under test.

(4) Kind of operation and operating conditions.

(5) Description of secondary noise sources including location, type, and kind of operation.

(6) Type and serial numbers on all microphones, sound level meters, and octave band analyzers used. Length and type of microphone cables.

(7) Position of observer.

(8) Direction of arrival of sound with respect to microphone orientation.

(9) Approximate temperature of microphone.

(10) Results of maintenance and calibration tests.

(11) Weighting network and meter speed used.

(12) Measured overall response and band levels at each microphone position and extent of meter fluctuation.

(13) Background overall response and band levels at each microphone position with primary noise source not operating.

(14) Cable and microphone corrections.

(15) Any other pertinent data such as personnel

exposed directly and indirectly, time pattern of the exposure, atmospheric conditions, attempts at noise control, and personnel protection.

Reid Stone

Reid T. Stone
Area Geothermal Supervisor

APPROVED:

Russell G. Wayland

Russell G. Wayland
Chief, Conservation Division

July 86

Quarterly Progress Report

May 1, 1985 to June 30, 1986

Geophysical Research on Geothermal Resources in Montana

Grant No. DE-FG07-84ID12525

Montana College of Mineral Science and Technology

P. I. C. J. Wideman
W. R. Sill

To: Dr. Sill, Dr. Wideman

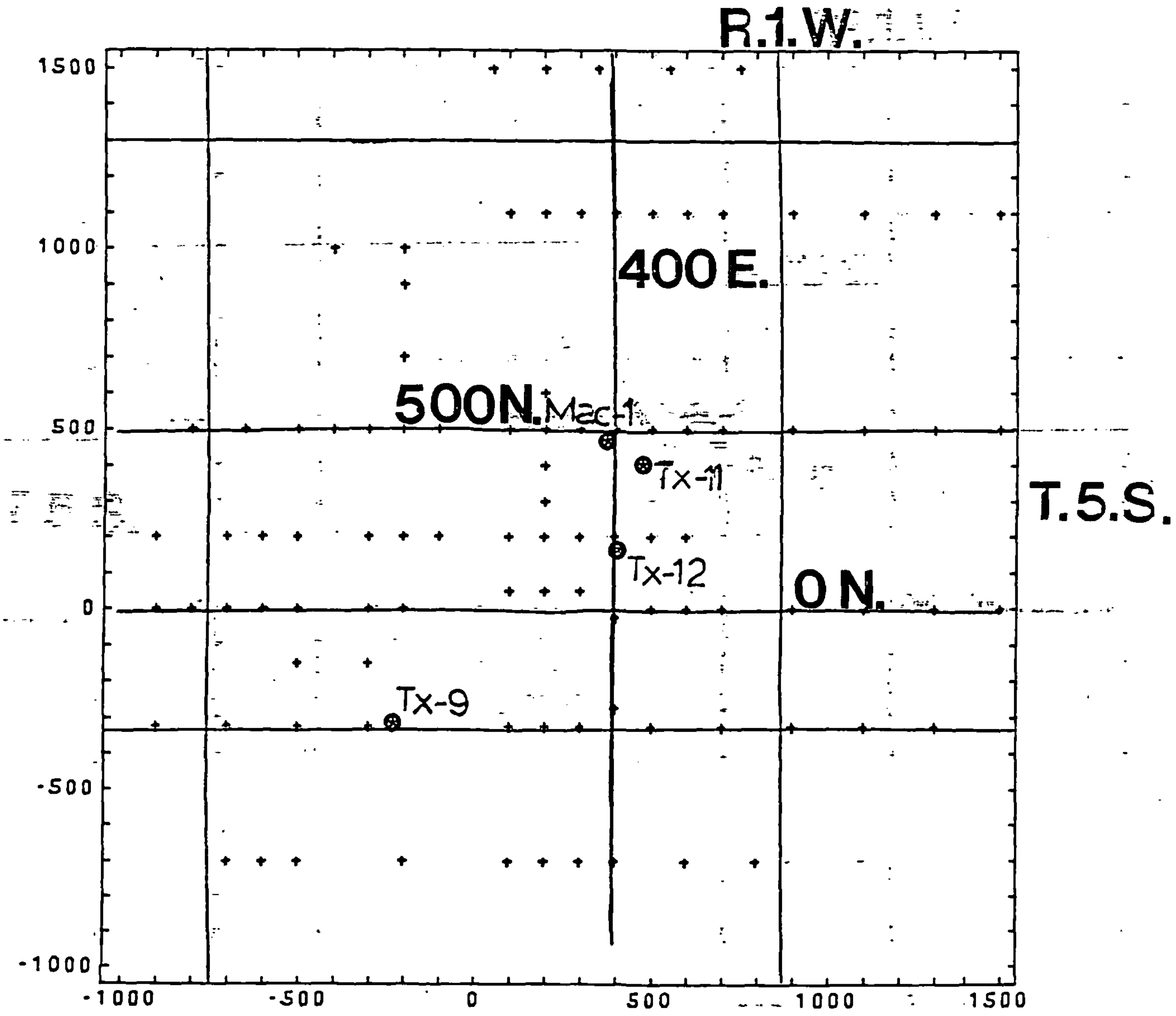
From: G. Emilsson

Re: Modeling of Ennis CSAMT data

Modeling of three lines of Ennis CSAMT field data was accomplished using PW2D, a two-dimensional finite element MT forward modeling program written by Wannamaker, Stodt, and Rijo of the University of Utah. Figure 1. shows the location of the lines in the Ennis CSAMT survey area. Figure 2. is the electrical model of the earth for the 0 N. line that was input into the program. Vertical exaggeration for all models is 5. Figure 3. is the resulting pseudosection. Compare to the 0 N. line field data pseudosection in Figure 4. Figures 5., 6., and 7. are the model, model pseudosection, and observed pseudosection respectively for 500 N. line. A north-south profile was developed using stations located at 400 E. Figures 8., 9., and 10. are the model, model pseudosection, and observed pseudosection respectively for this line. A complete discussion of these models will be presented in the thesis.

(7)

Ennis CSAMT stations



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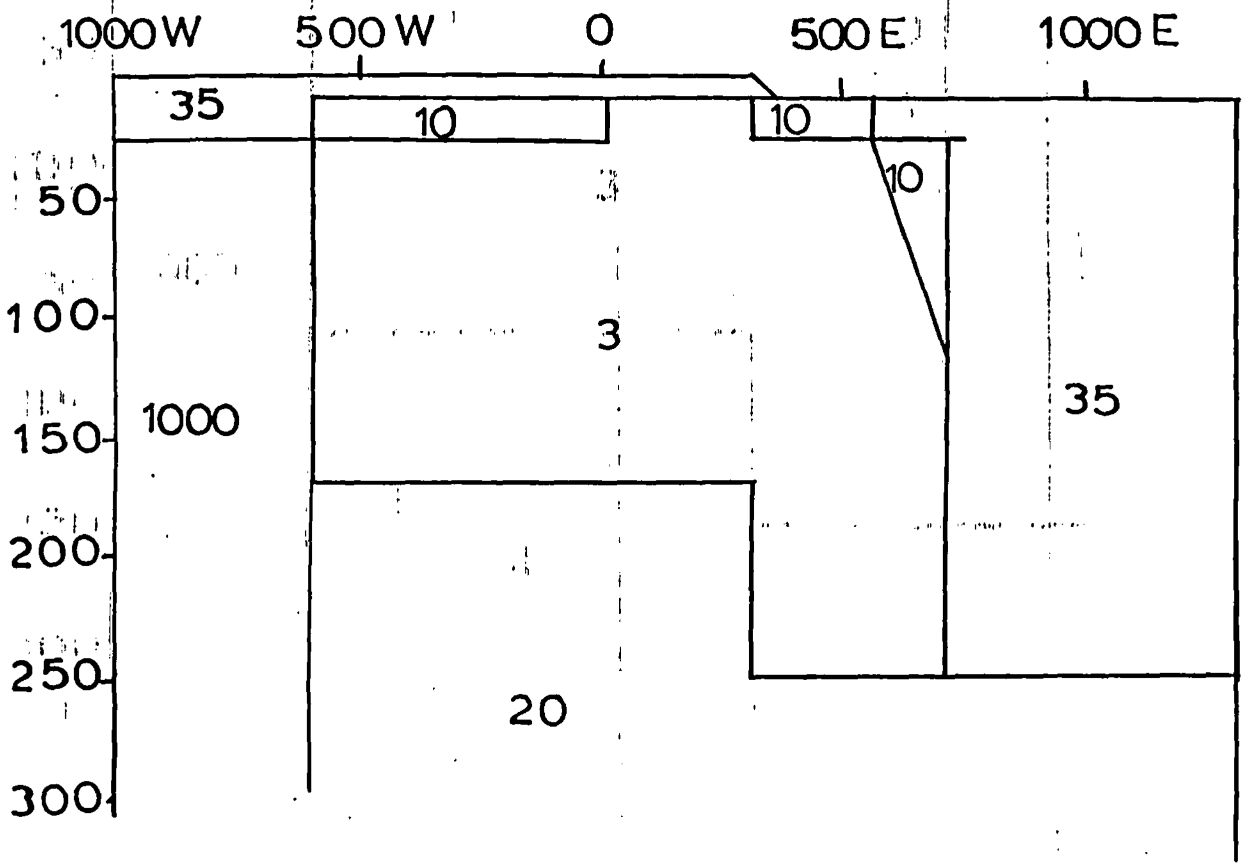

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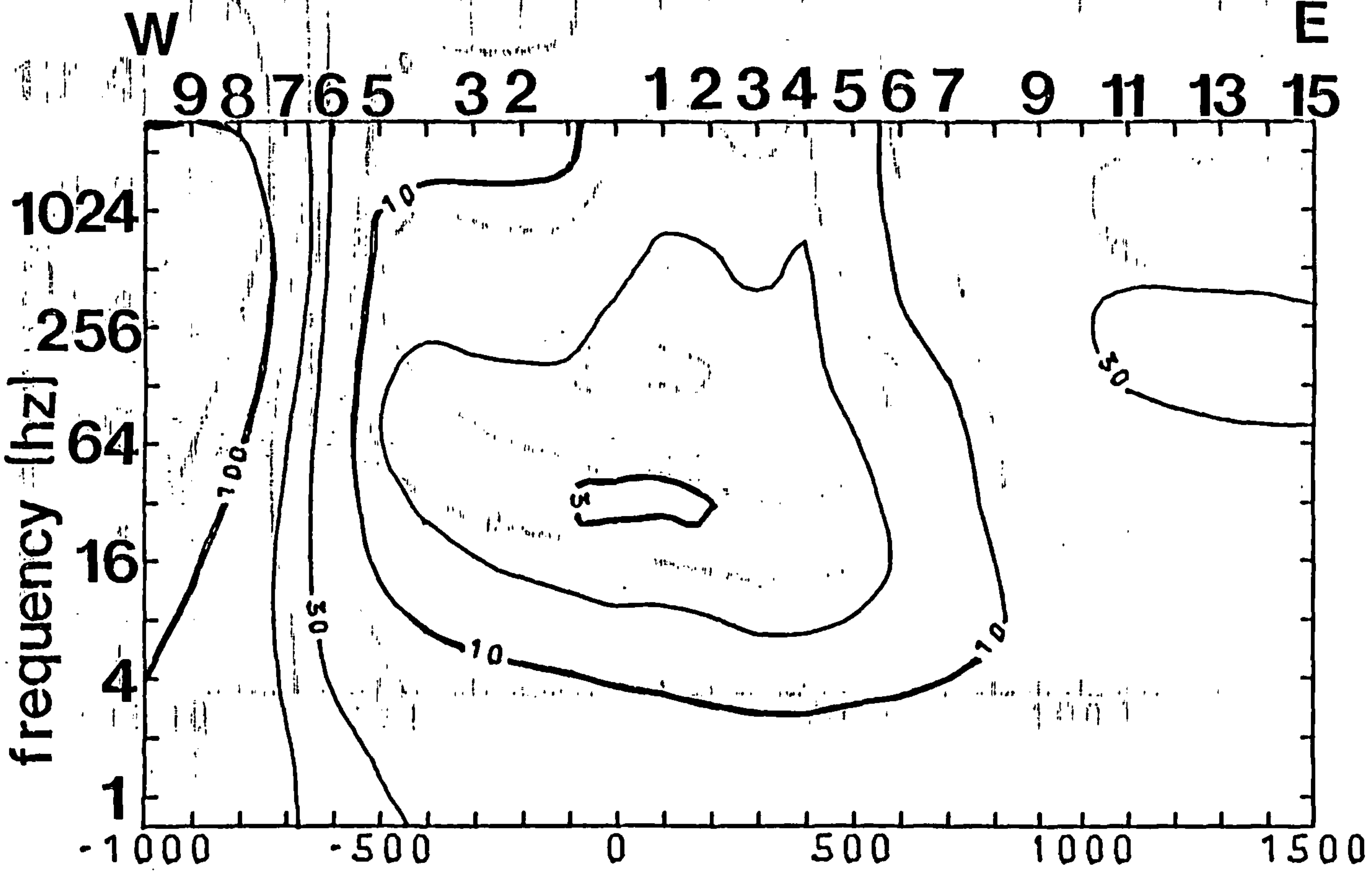
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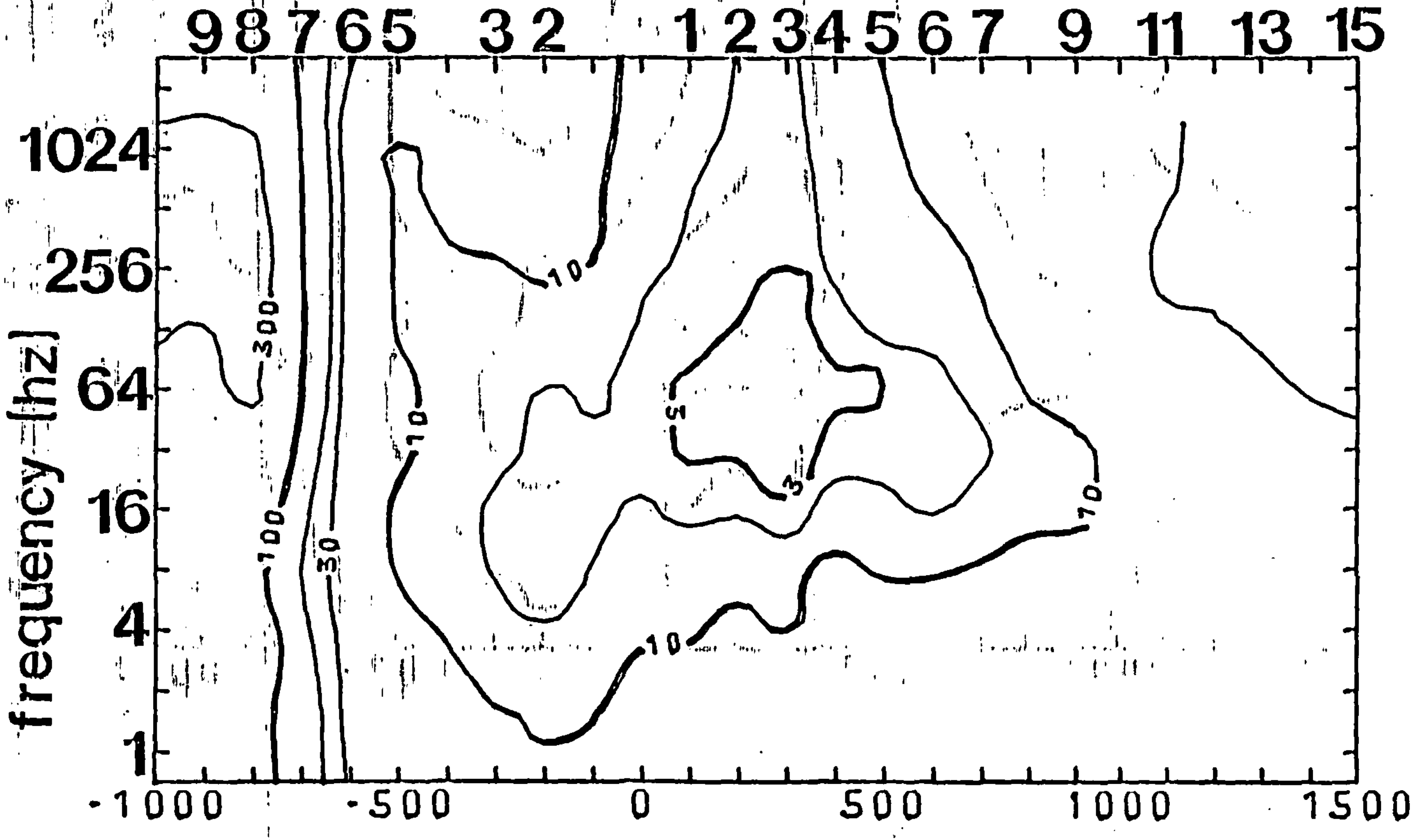

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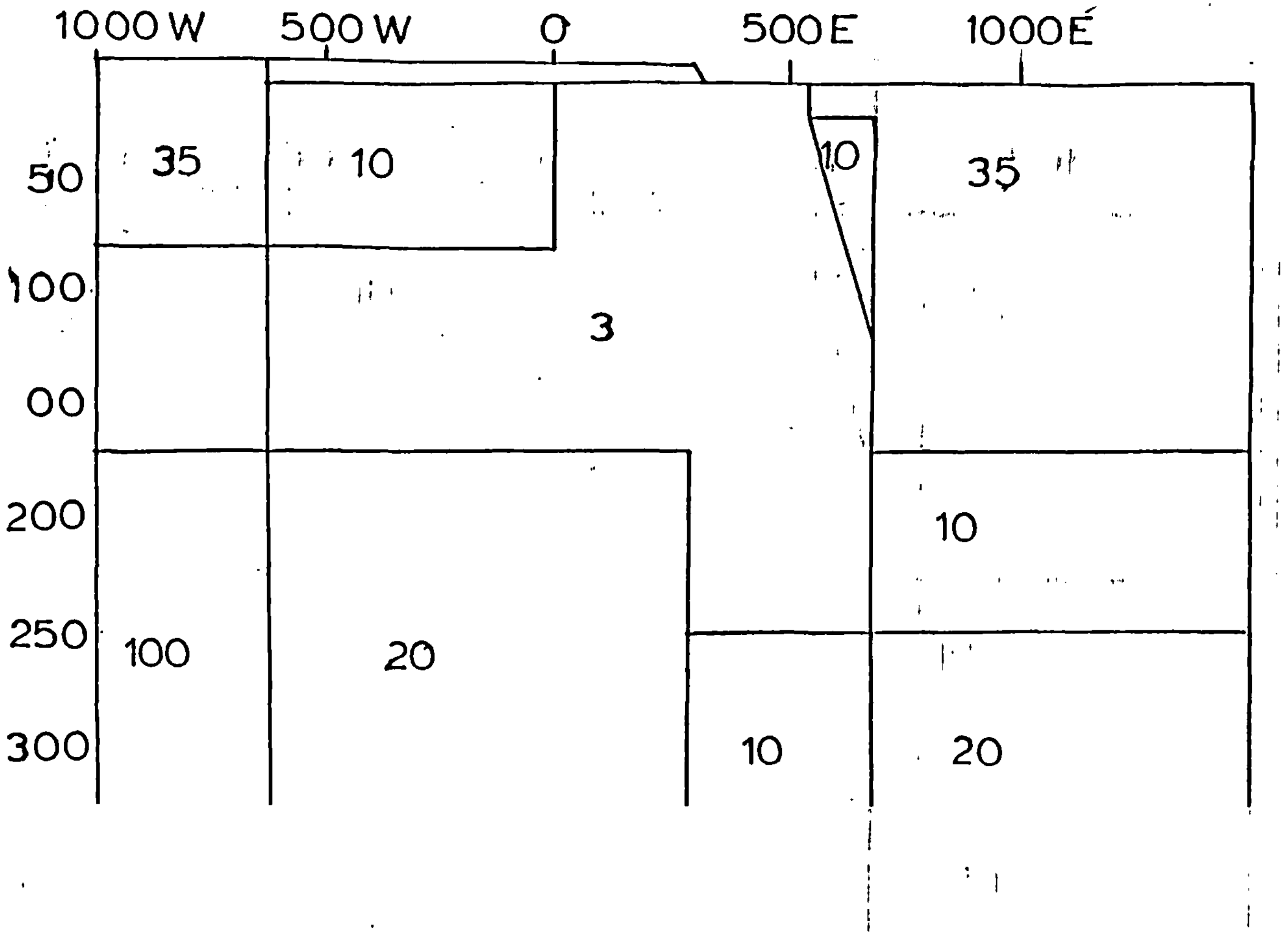
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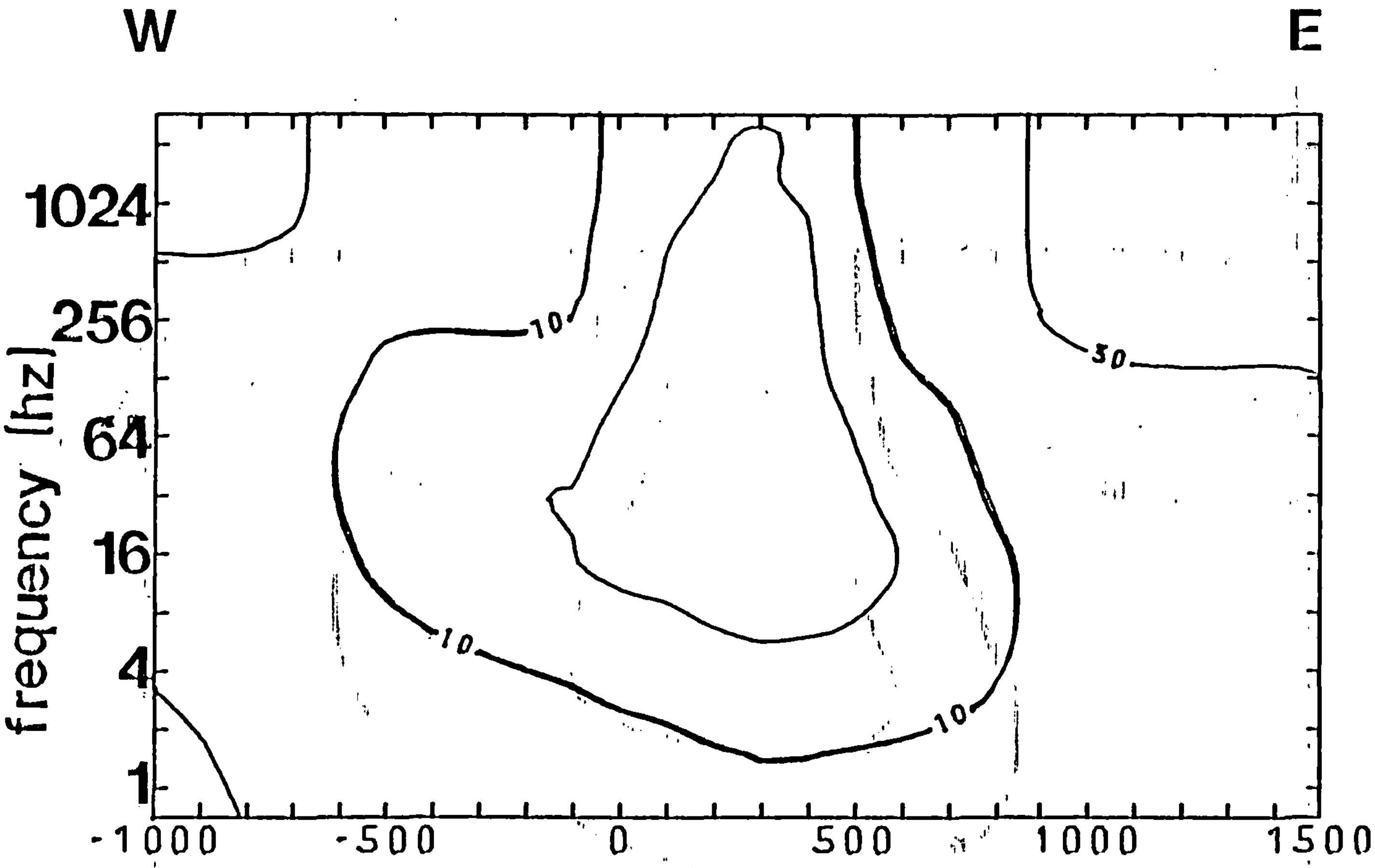
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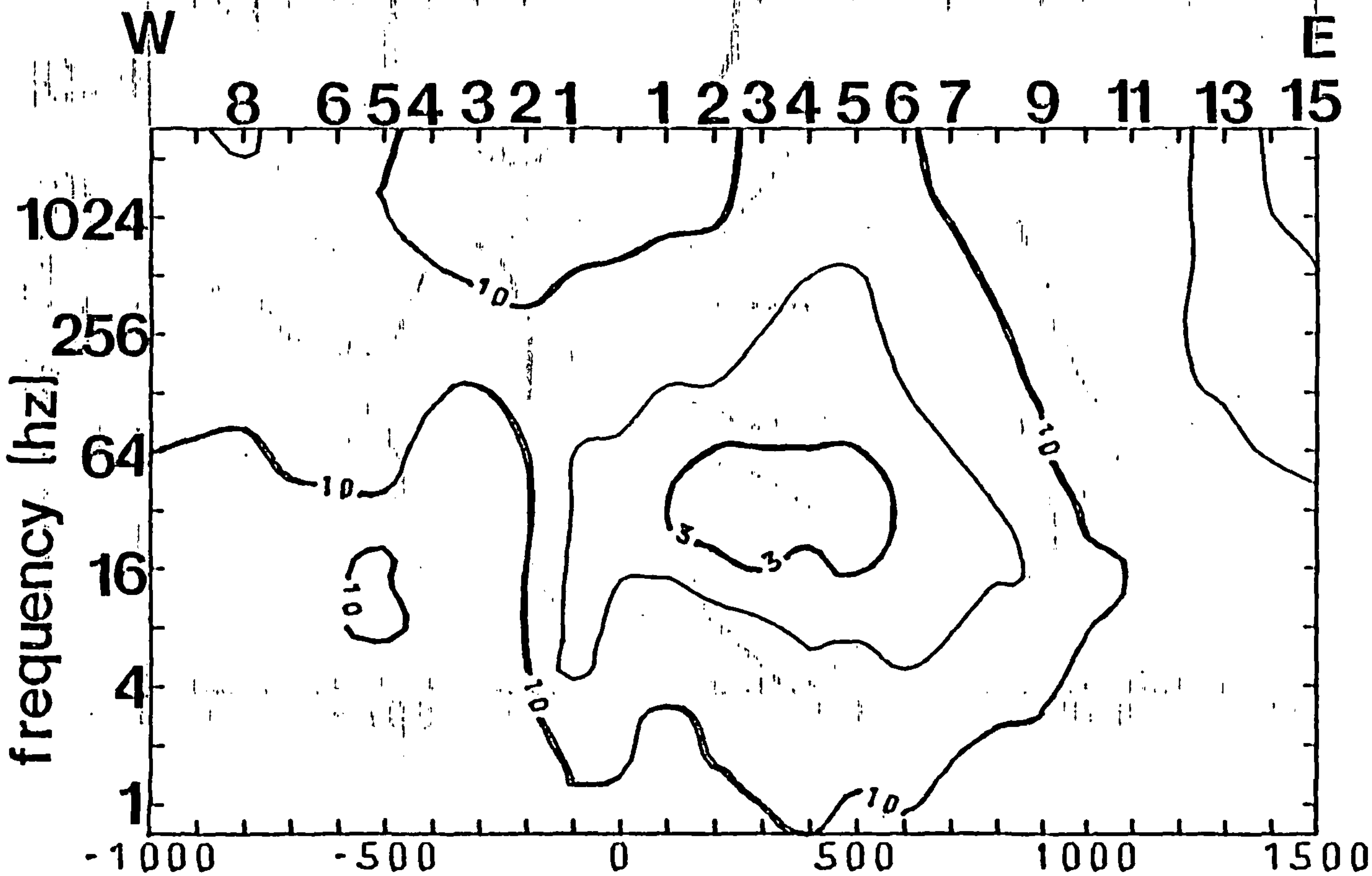
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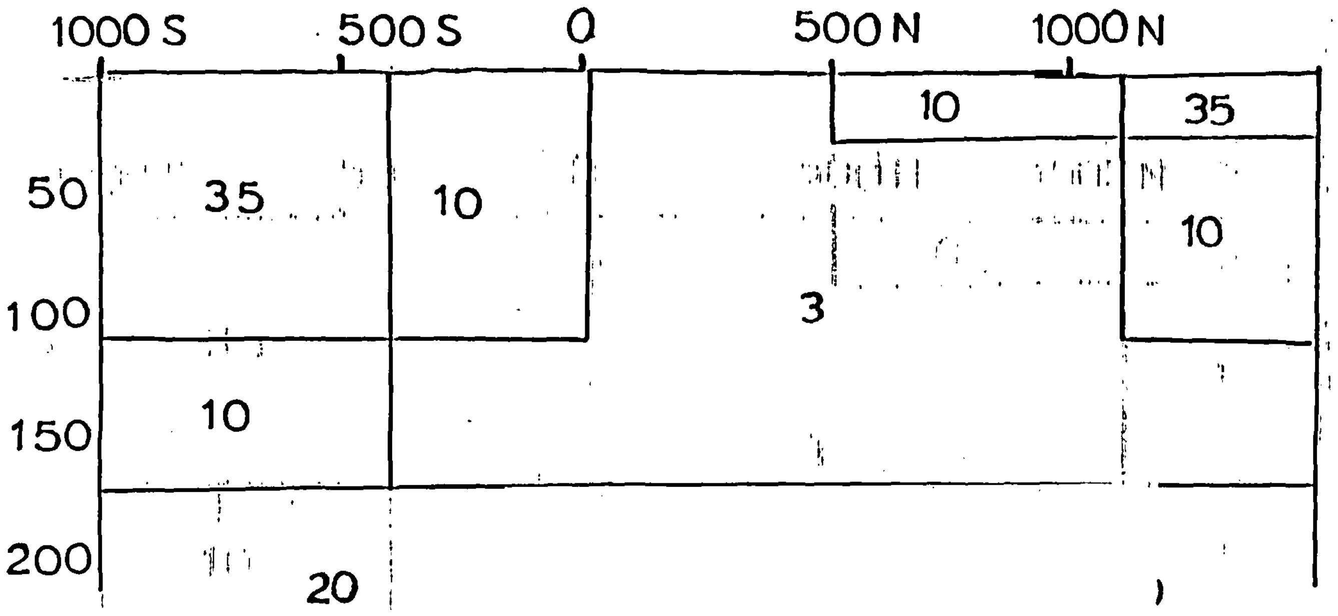
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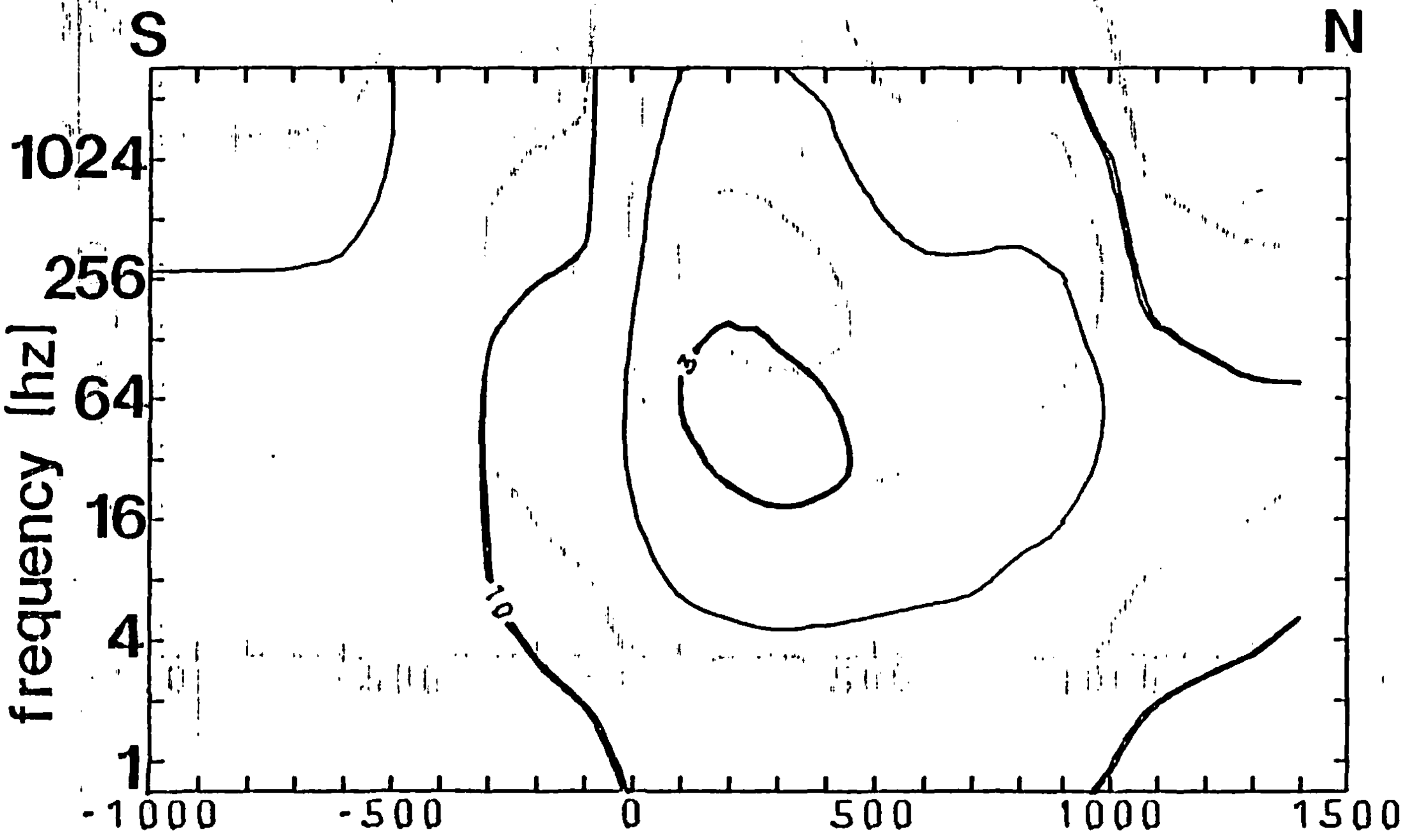
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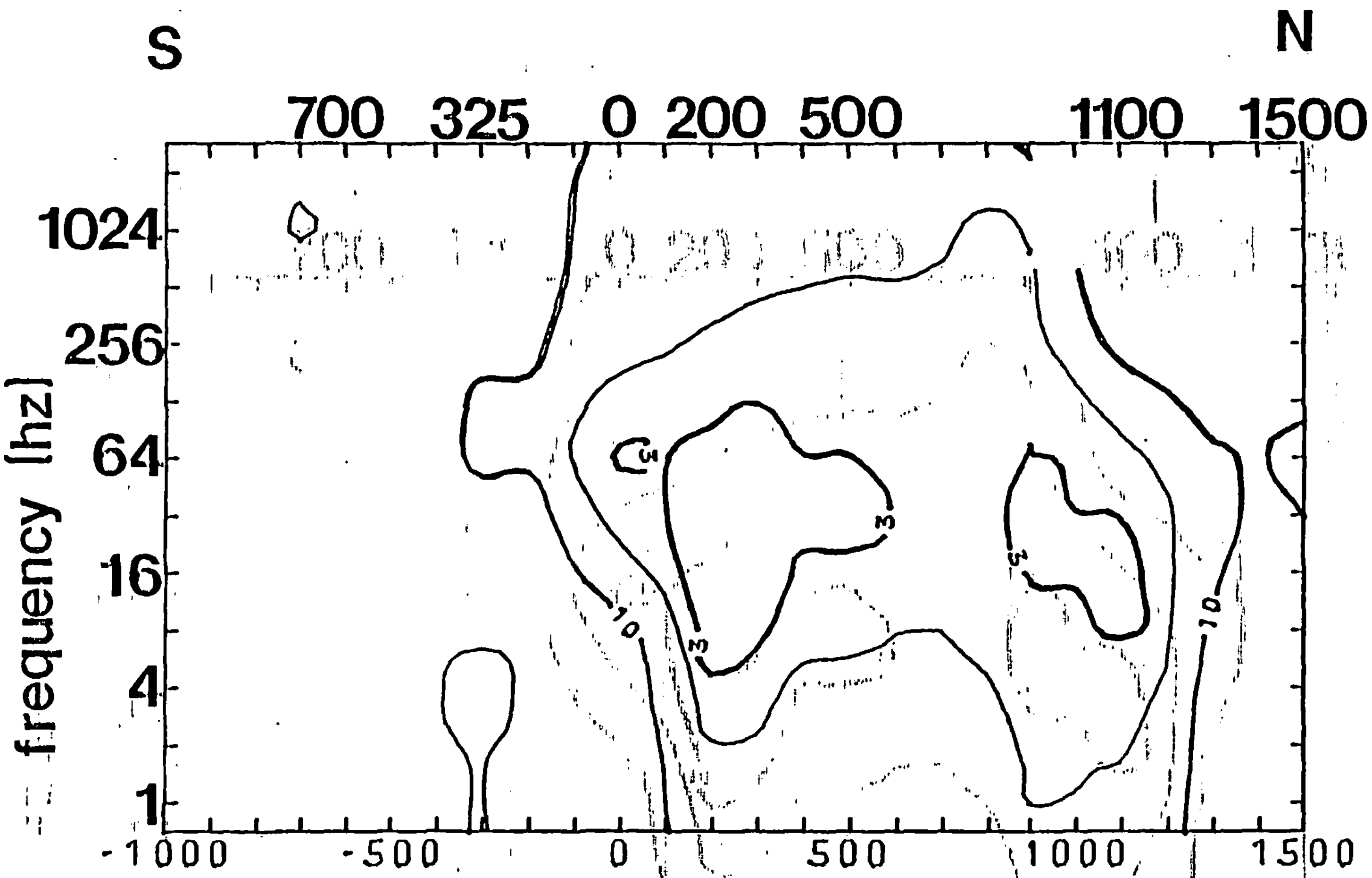
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During the months of May and June, 1986, forward and inverse 3-D gravity modeling programs have been written by Dave Semmens of Montana Tech. These programs model the earth using up to 250 blocks or bricks, and the programs along with examples of input and output are at the end of each section.

Forward 3-D Gravity Modeling

Program Gravbl is a 3-D, forward gravity modeling program. This program is derived from the following formula:

$$g_z(0,0,0) = \int_{y_1}^{y_2} \int_{z_1}^{z_2} \int_{x_1}^{x_2} \frac{G\rho\, z'\, dx'\, dy'\, dz'}{[(x')^2 + (y')^2 + (z')^2]^{3/2}}$$

where:

$g_z(0,0,0)$ = vertical gravity evaluated at the origin
G = universal gravity constant
ρ = density
x', y', z' = define the source location (see Figure 1)

x_1, x_2 - x limits of block
y_1, y_2 - y limits of block
z_1, z_2 - z limits of block

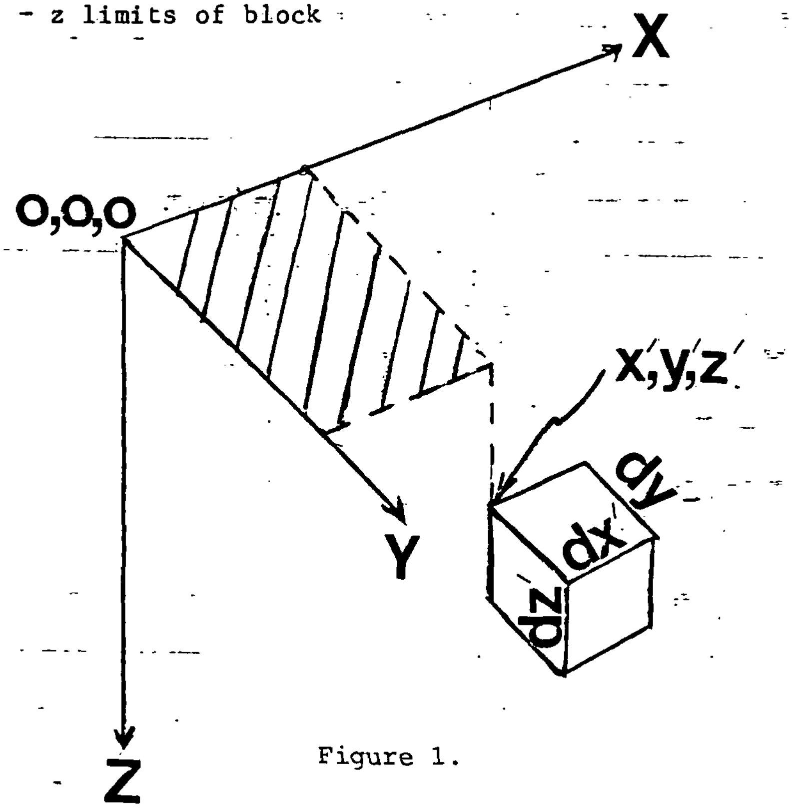

Figure 1.

The integration of this formula is relatively easy if the exact integration is carried out in 2 directions (say the x and z), and the integration in the final direction is approximated. In this program integration was carried out in the x and z directions, and the integration in the y direction was approximated. The resulting formula after integration is;

$$g_z(0,0,0) = G\rho\int_{y_1}^{y_2}\Big\{ Ln\left(x_1 + \sqrt{(x_1)^2 + (z_2)^2 + (y')^2}\right)$$

$$- Ln\left(x_2 + \sqrt{(x_2)^2 + (z_2)^2 + (y')^2}\right)$$

$$+ Ln\left(x_2 + \sqrt{(x_2)^2 + (z_1)^2 + (y')^2}\right)$$

$$- Ln\left(x_1 + \sqrt{(x_1)^2 + (z_1)^2 + (y')^2}\right)\Big\}\, dy' \qquad (2)$$

Where (2) represents the gravitational attraction of a single block as observed at the origin.

This is an integral of the form

$$g_z(0,0,0) = G\rho\int_{y_1}^{y_2} A(y)dy'$$

where:

A(y) are varying constants (mgals/meter).

And this integration was approximated using a quadrature formula (i.e. Talwani and Ewing, Geophysics, Vol. 25, No. 1, page 209). In effect what is being done with the quadrature formula is that a gravity anomaly from a 3-D body is being approximated by summing a number of anomalies from thin rectangular laminae defined by x_1, x_2, z_1, z_2, and a thickness Δy or

$$g_z(0,0,0) = G\rho \sum_{i=1}^{N} Ai \, \Delta Yi \qquad N\text{=number of laminae} \qquad (3)$$

In order for formula (3) to be accurate, enough y-values must be chosen to keep each ΔYi "small." In Gravbl the number of y-values (or the number of rectangular laminae described by x_1, x_2, z_1, z_2, and Yi) is determined by inserting laminae until the change in the gravitational attraction of adjacent laminae a distance Δy apart is within an input percentage. For example, if the input percentage is 5, enough laminae will be inserted (up to a maximum of 500), so that the change in gravity values between adjacent laminae is under .5 percent. By this approach the program user has control over the accuracy the of formula (3), and y-values for each laminae position are calculated rather than input.

Input

Gravbl reads input out of a data file named Gravbl.dat. The input data in Gravbl. dat must be ordered as follows:

Line	Input
1	Number of blocks in model (max. = 250)
2	XL(1), XR(1), ZU(1), ZD(1)

where:

XL(1) = Left edge of block 1
XR(1) = Right edge of block 1
ZU(1) = Upper edge of block 1 (Z pos. down)
ZD(1) = Lower edge of block 1

3	YMIN(1), YMAX(1)

where:

YMIN(1) = minimum Y-value in block 1
YMAX(1) = maximum Y-value in block 1

4 Density of block 1 (grams/cubic centimeter)
5 Maximum number of laminae for block 1 (to a maximum of 500)

Repeat lines 2, 3, 4, 5 for the number of blocks indicated in line 1.

Last 2 lines

- Percentage value which controls number of y-values used in each block (see text for explanation).
- XSIZE, YSIZE, NCOLS, NROWS (described in output section)

Output

The output of Gravbl is written to a data file named GBL.DAT where GBL.DAT will contain a varying number of values representing grid points located on a horizontal plane at the surface of the earth (z=0). The size of the grid; and therefore, the number of output values is determined by the following parameters placed in the last line of the input file Gravbl.dat:

XSIZE = size of the grid in the x-direction (meters)
YSIZE = size of the grid in the y-direction (meters)
NCOLS = number of columns in the grid
NROWS = number of rows in the grid

Therefore, the number of points output in file GBL.DAT will be (NCOLS x NROWS) in the following format:

XPOS, YPOS, gravity value (mgals)

where

XPOS = x position on the grid
YPOS = y position on the grid.

Program Gravbl

```
$ TY GRAVBL.FOR
C
C... GRAVBL IS A FORWARD GRAVITY PROGRAM THAT MODELS THE EARTH
C... BY USING BLOCKS (UP TO 500) OF VARIABLE DENSITY.
C
        COMMON /GRAV/XL(500),XR(500),ZD(500),ZU(500),DEN(500),
     &Y(500,500),LAMNUM(500),U(500),ANOM(500,500),NBLKS,XSIZE,YSIZE,
     &COLS,ROWS,XPOS,YPOS,TANOM(500),M1,MAXLAM(500),MAXPER,YMAX(500)
C
        REAL*8 ANOM
C
C...     MODEL INPUT
C
        OPEN(22,FILE='GRAVBL.DAT',STATUS='OLD')
        OPEN(23,FILE='GBL.DAT',STATUS='NEW')
C
        READ(22,*)NBLKS
        DO J=1,NBLKS
        READ(22,*)XL(J),XR(J),ZU(J),ZD(J)
        READ(22,*)Y(1,J),Y(2,J)
        YMAX(J)=Y(2,J)
        READ(22,*)DEN(J)
        READ(22,*)MAXLAM(J)
        END DO
        READ(22,*)XSIZE,YSIZE,COLS,ROWS
        READ(22,*)MAXPER
C
        DO I=1,NBLKS
        CALL REORDER(I)
C
C...     MAKE SURE LAMNUM(I) IS AN ODD NUMBER SO THAT QUADRITURE
C...     FORMULA WILL WORK
C
        L1=LAMNUM(I)/2
        T1=(LAMNUM(I)/2.)-L1
        IF(LAMNUM(I).GT.2)THEN
                IF(T1.EQ.0.0)THEN
                Y(LAMNUM(I)+1,I)=Y(LAMNUM(I),I)
                Y(LAMNUM(I),I)=Y(LAMNUM(I),I)-1.
                CALL FORWARD(LAMNUM(I),I)
                LAMNUM(I)=LAMNUM(I)+1
                END IF
        END IF
        END DO
C
        M1=0
        M=1
        CHECK=0.0
        XDELTA=XSIZE/(COLS-1)
        YDELTA=YSIZE/(ROWS-1)
C
10      IF(M.EQ.1)THEN
                XPOS=0.0
                YPOS=0.0
                TANOM(I)=0.0
```

```
               END DO
               WRITE(23,'(E12.4,2X,E12.4,2X,E12.4)')XPOS,YPOS
     &,TANOM(NBLKS+1)
               M=M+1
               GO TO 10
         ELSE
               DO I=1,COLS*ROWS-1
                       CALL GRID(I,CHECK,XDELTA,YDELTA)
                       DO J=2,NBLKS+1
                       DO K=2,LAMNUM(J-1)+1
                               CALL FORWARD(K-1,J-1)
                       END DO
                       CALL QUAD(J-1)
                       TANOM(J)=TANOM(J-1)+V(((LAMNUM(J-1)-1)/2)+1)
                       END DO
               WRITE(23,'(E12.4,2X,E12.4,2X,E12.4)')XPOS,YPOS
     &,TANOM(NBLKS+1)
               END DO
         END IF
C
         CLOSE(22)
         CLOSE(23)
C
         CALL EXIT
         END
C
C
C...  SUBROUTINES
C
C
         SUBROUTINE REORDER(I)
C
         COMMON /GRAV/XL(500),XR(500),ZD(500),ZU(500),DEN(500),
     &Y(500,500),LAMNUM(500),V(500),ANOM(500,500),NBLKS,XSIZE,YSIZE,
     &COLS,ROWS,XPOS,YPOS,TANOM(500),M1,MAXLAM(500),MAXPER,YMAX(500)
C
         REAL*8 ANOM
         KOUNT=1
         CALL FORWARD(KOUNT,I)
         KOUNT=2
         CALL FORWARD(KOUNT,I)
C
         M3=1
         J=1
10       PER=DABS((ANOM(KOUNT,I)-ANOM(KOUNT-1,I))/(DMAX1
     &(ANOM(KOUNT-1,I),ANOM(KOUNT,I))))*100.
C
         IF((M3.EQ.1).AND.(PER.LE.MAXPER))THEN
         PRINT *,'
         PRINT *,'MODEL GEOMETRY HAS NOT ALLOWED PROGRAM TO WORK!'
         PRINT *,'-------------------------------------------------------------'
         PRINT *,'EITHER CHANGE INITIAL Y VALUES AND/OR DECREASE THE'
         PRINT *,'ALLOWABLE DISCRETIZING PERCENTAGE FOR BLOCK',I,'.'
         PRINT *,'
         END IF
C
         IF(PER.GT.MAXPER)THEN
               DO L=J,1,-1
               ANOM(KOUNT+L,I)=ANOM(KOUNT+L-1,I)
               Y(KOUNT+L,I)=Y(KOUNT+L-1,I)
               END DO
               NEXTPX=KOUNT+J
               [illegible]
```

```
                J=M3-1
                GO TO 10
        END IF
                LAMNUM(I)=KEPTRK
C
                IF(M3.EQ.1)THEN
                LAMNUM(I)=2
                GO TO 20
                END IF
C
                IF(J.EQ.1)GO TO 20
C
        IF(YMAX(I)-Y(KEPTRK-1,I).LE.5.)GO TO 20
C
                IF(LAMNUM(I).GE.MAXLAM(I))THEN
                PRINT *,' MAXIMUM NUMBER OF LAMINA (',MAXLAM(I),') FOR
     & BLOCK ',I,' EXCEEDED.'
                GO TO 20
                END IF
C
                J=J-1
                KOUNT=KOUNT+1
                GO TO 10
20      RETURN
        END
C
C
C... SUBROUTINE FORWARD CALCULATES THE GRAVITY ANOMALY/UNIT WIDTH FOR
C... EACH LAMINAE
C
        SUBROUTINE FORWARD(I,J)
C

        COMMON /GRAV/XL(500),XR(500),ZD(500),ZU(500),DEN(500),
     &Y(500,500),LAMNUM(500),V(500),ANOM(500,500),NBLKS,XSIZE,YSIZE,
     &COLS,ROWS,XPOS,YPOS,TANOM(500),M1,MAXLAM(500),MAXPER,YMAX(500)
C
        REAL*8 A,B,A1,B1,A2,B2,ANOM
C
        G0=0.0000000667
C
C... START CALCULATIN'
C
C... PREVENT DIVIDE BY ZERO
C
        IF(XR(J).EQ.0.0)XR(J)=1E-10
        IF(XL(J).EQ.0.0)XL(J)=1E-10
C
        A0=ZD(J)*ZD(J)+Y(I,J)*Y(I,J)
        B=ZU(J)*ZU(J)+Y(I,J)*Y(I,J)
        A1=XL(J)+SQRT(XL(J)*XL(J)+B)
        A2=XR(J)+SQRT(XR(J)*XR(J)+B)
        B1=XR(J)+SQRT(XR(J)*XR(J)+A0)
        B2=XL(J)+SQRT(XL(J)*XL(J)+A0)
        IF((A1.EQ.0.0).OR.(A2.EQ.0.0).OR.(B1.EQ.0.0)
     &.OR.(B2.EQ.0.0))M1=M1+1
C
C... PREVENT TAKING LOG OF 0.0
C
        IF(A1.EQ.0.0)A1=.001
        IF(A2.EQ.0.0)A2=.001
        IF(B1.EQ.0.0)B1=.001
        IF(B2.EQ.0.0)B2=.001
```

```
      [illegible]
C
      RETURN
      END
C
C
C...  SUBROUTINE GRID GIVES X,Y GRID POSITIONS
C
C
      SUBROUTINE GRID(KOUNT,CHECK,XDELTA,YDELTA)
C
      COMMON /GRAV/XL(500),XR(500),ZD(500),ZU(500),DEN(500),
     &Y(500,500),LAMNUM(500),V(500),ANOM(500,500),NBLKS,XSIZE,YSIZE,
     2COLS,ROWS,XPOS,YPOS,TANOM(500),M1,MAXLAM(500),MAXPER,YMAX(500)
C
      REAL*8 ANOM
      NI=KOUNT/COLS
      XPOS=KOUNT*XDELTA-(NI*XSIZE+XDELTA*NI)
      IF(ABS(XPOS).LE.1.0E-01)XPOS=0.00E+00
      YPOS=NI*YDELTA
      IF(XSIZE.GT.CHECK)THEN
              CHECK=CHECK+XDELTA
              DO J=1,NBLKS
              XL(J)=XL(J)-XDELTA
              XR(J)=XR(J)-XDELTA
              END DO
      ELSE
              CHECK=0.0
              DO J=1,NBLKS
C
              XL(J)=XL(J)+XDELTA*(COLS-1)
              XR(J)=XR(J)+XDELTA*(COLS-1)
C
              DO I=1,LAMNUM(J)
              Y(I,J)=Y(I,J)-YDELTA
              END DO
              END DO
      END IF
      RETURN
      END
C
C
C...  SUBROUTINE QUAD CALCULATES THE ANOMALY ASSOCIATED WITH EACH BLOCK
C...  BY DOING THE INTEGRATION IN THE Y-DIRECTION USING TALWNI'S
C...  QUADRITURE FORMULA
C
C
      SUBROUTINE QUAD(K)
C
      COMMON /GRAV/XL(500),XR(500),ZD(500),ZU(500),DEN(500),
     &Y(500,500),LAMNUM(500),V(500),ANOM(500,500),NBLKS,XSIZE,YSIZE,
     1COLS,ROWS,XPOS,YPOS,TANOM(500),M1,MAXLAM(500),MAXPER,YMAX(500
C
      DIMENSION TEMP(500)
      REAL*8 ANOM
C
C...  FIND THE ANOMALY
C
      IF(LAMNUM(K)-1.GT.1)THEN
              I=1
              V(1)=0.0
      DO J=2,((LAMNUM(K)-1)/2)+1
C
        [illegible]
```

```
      B=ANOM(I+1,K)*[illegible]
     3Y(I+2,K))*(Y(I+1,K)-Y(I,K))
C
      C=ANOM(I+2,K)*((Y(I,K)-Y(I+2,K))/(Y(I+2,K)-Y(I+1,K)))
     2*(3.0*Y(I+1,K)-Y(I,K)-2.*Y(I+2,K))
C
      TEMP(J-1)=(A0+B+C)/6.0
C
      V(J)=V(J-1)+TEMP(J-1)
      I=I+2
      END DO
C
      ELSE
C
C...  TRAPEZOIDAL RULE FOR ONE AREA
C
      V(((LAMNUM(K)-1)/2)+1)=(Y(2,K)-Y(1,K))*.5*(ANOM(1,K)+ANOM(2,K))
      END IF
C
      RETURN
      END
#
```

Input for Gravbl

```
$ TY GRAVBL.DAT
3
0.,100.,10.,30.
0.,1000.
1.
500
100.,300.,10.,30.
0.,1000.
1.
500
300.,1000.,10.,30.
0.,1000.
1.
300
1000.,1000.,11,11
3
$
$
$
$ RUN GRAVBL
$
$
$
$
$
$ TY GBL.DAT
```

Output

```
 0.0000E+00    0.0000E+00   -0.3055E+00
 0.1000E+03    0.0000E+00   -0.3845E+00
 0.2000E+03    0.0000E+00   -0.3913E+00
 0.3000E+03    0.0000E+00   -0.3967E+00
 0.4000E+03    0.0000E+00   -0.3983E+00
 0.5000E+03    0.0000E+00   -0.4112E+00
 0.6000E+03    0.0000E+00   -0.4436E+00
 0.7000E+03    0.0000E+00   -0.4418E+00
 0.8000E+03    0.0000E+00   -0.4379E+00
 0.9000E+03    0.0000E+00   -0.4253E+00
 0.1000E+04    0.0000E+00   -0.2241E+00
 0.0000E+00    0.1000E+03   -0.3887E+00
 0.1000E+03    0.1000E+03   -0.7642E+00
 0.2000E+03    0.1000E+03   -0.7663E+00
 0.3000E+03    0.1000E+03   -0.7698E+00
 0.4000E+03    0.1000E+03   -0.7718E+00
 0.5000E+03    0.1000E+03   -0.6445E+00
 0.6000E+03    0.1000E+03   -0.5161E+00
 0.7000E+03    0.1000E+03   -0.5140E+00
 0.8000E+03    0.1000E+03   -0.5035E+00
 0.9000E+03    0.1000E+03   -0.4884E+00
 0.1000E+04    0.1000E+03   -0.3603E+00
 0.0000E+00    0.2000E+03   -0.4013E+00
 0.1000E+03    0.2000E+03   -0.7643E+00
 0.2000E+03    0.2000E+03   -0.7873E+00
 0.3000E+03    0.2000E+03   -0.7938E+00
 0.4000E+03    0.2000E+03   -0.7913E+00
 0.5000E+03    0.2000E+03   -0.7633E+00
 0.6000E+03    0.2000E+03   -0.7249E+00
 0.7000E+03    0.2000E+03   -0.7274E+00
```

```
[illegible]   [illegible]   [illegible]
0.1000E+03    0.3000E+03    -0.7692E+00
0.2000E+03    0.3000E+03    -0.7935E+00
0.3000E+03    0.3000E+03    -0.8006E+00
0.4000E+03    0.3000E+03    -0.8063E+00
0.5000E+03    0.3000E+03    -0.8124E+00
0.6000E+03    0.3000E+03    -0.8201E+00
0.7000E+03    0.3000E+03    -0.8174E+00
0.8000E+03    0.3000E+03    -0.8103E+00
0.9000E+03    0.3000E+03    -0.7862E+00
0.1000E+04    0.3000E+03    -0.4134E+00
0.0000E+00    0.4000E+03    -0.4067E+00
0.1000E+03    0.4000E+03    -0.7714E+00
0.2000E+03    0.4000E+03    -0.7953E+00
0.3000E+03    0.4000E+03    -0.8026E+00
0.4000E+03    0.4000E+03    -0.8055E+00
0.5000E+03    0.4000E+03    -0.8024E+00
0.6000E+03    0.4000E+03    -0.7979E+00
0.7000E+03    0.4000E+03    -0.7951E+00
0.8000E+03    0.4000E+03    -0.7879E+00
0.9000E+03    0.4000E+03    -0.7633E+00
0.1000E+04    0.4000E+03    -0.4024E+00
0.0000E+00    0.5000E+03    -0.4078E+00
0.1000E+03    0.5000E+03    -0.7737E+00
0.2000E+03    0.5000E+03    -0.7983E+00
0.3000E+03    0.5000E+03    -0.8056E+00
0.4000E+03    0.5000E+03    -0.8085E+00
0.5000E+03    0.5000E+03    -0.8013E+00
0.6000E+03    0.5000E+03    -0.7926E+00
0.7000E+03    0.5000E+03    -0.7898E+00
0.8000E+03    0.5000E+03    -0.7824E+00
0.9000E+03    0.5000E+03    -0.7575E+00
0.1000E+04    0.5000E+03    -0.3999E+00
0.0000E+00    0.6000E+03    -0.4062E+00
0.1000E+03    0.6000E+03    -0.7709E+00
0.2000E+03    0.6000E+03    -0.7953E+00
0.3000E+03    0.6000E+03    -0.8026E+00
0.4000E+03    0.6000E+03    -0.8053E+00
0.5000E+03    0.6000E+03    -0.8024E+00
0.6000E+03    0.6000E+03    -0.7979E+00
0.7000E+03    0.6000E+03    -0.7951E+00
0.8000E+03    0.6000E+03    -0.7877E+00
0.9000E+03    0.6000E+03    -0.7633E+00
0.1000E+04    0.6000E+03    -0.4024E+00
0.0000E+00    0.7000E+03    -0.4053E+00
0.1000E+03    0.7000E+03    -0.7701E+00
0.2000E+03    0.7000E+03    -0.7942E+00
0.3000E+03    0.7000E+03    -0.8013E+00
0.4000E+03    0.7000E+03    -0.8040E+00
0.5000E+03    0.7000E+03    -0.8123E+00
0.6000E+03    0.7000E+03    -0.8195E+00
0.7000E+03    0.7000E+03    -0.8168E+00
0.8000E+03    0.7000E+03    -0.8097E+00
0.9000E+03    0.7000E+03    -0.7857E+00
0.1000E+04    0.7000E+03    -0.4131E+00
0.0000E+00    0.8000E+03    -0.4014E+00
0.1000E+03    0.8000E+03    -0.7645E+00
0.2000E+03    0.8000E+03    -0.7874E+00
0.3000E+03    0.8000E+03    -0.7939E+00
0.4000E+03    0.8000E+03    -0.7964E+00
0.5000E+03    0.8000E+03    -0.8070E+00
0.6000E+03    0.8000E+03    -0.8122E+00
0.7000E+03    0.8000E+03    -0.8097E+00
[illegible]   [illegible]   [illegible]
```

```
0.0000E+00     0.9000E+03     -0.38[illegible]E+00
0.1000E+03     0.9000E+03     -0.7450E+00
0.2000E+03     0.9000E+03     -0.7670E+00
0.3000E+03     0.9000E+03     -0.7723E+00
0.4000E+03     0.9000E+03     -0.7745E+00
0.5000E+03     0.9000E+03     -0.7699E+00
0.6000E+03     0.9000E+03     -0.7633E+00
0.7000E+03     0.9000E+03     -0.7613E+00
0.8000E+03     0.9000E+03     -0.7557E+00
0.9000E+03     0.9000E+03     -0.7354E+00
0.1000E+04     0.9000E+03     -0.3844E+00
0.0000E+00     0.1000E+04     -0.2058E+00
0.1000E+03     0.1000E+04     -0.3936E+00
0.2000E+03     0.1000E+04     -0.4110E+00
0.3000E+03     0.1000E+04     -0.4149E+00
0.4000E+03     0.1000E+04     -0.4164E+00
0.5000E+03     0.1000E+04     -0.4084E+00
0.6000E+03     0.1000E+04     -0.3994E+00
0.7000E+03     0.1000E+04     -0.3979E+00
0.8000E+03     0.1000E+04     -0.3940E+00
0.9000E+03     0.1000E+04     -0.3814E+00
0.1000E+04     0.1000E+04     -0.2021E+00
#
$
```

Inverse 3-D Gravity Modeling

Program Grinv is an inverse program that uses the forward modeling of program Gravbl to predict (using observed gravity data) densities of each of the block in the forward model. This is accomplished by finding a best "first guess" forward model that approximates the observed gravity data. This first guess model is then used as a starting point from which predicted data is calculated and compared with the observed data. The error between the observed and the predicted data is then calculated and new densities are determined by Grinv to minimize this error. Once the error between the observed and predicted (theoretical) gravity data is below a reasonable input value (based on the error of the observed data set), final densities are calculated and output. Assuming that the geometry of the blocks used in the first guess model are accurate, these final densities should be those that give a best fit to the observed gravity data.

Because Grinv was written to accompany software available at Montana Tech, it will not be easily adaptable for use elsewhere. For example, matrix calculations were all done using IMSL library software. Also, observed gravity data is read from a data file output from the SURFACE II contouring graphics package.

Input

Grinv reads input data from a data file named G.dat. Input data in file G.dat must be ordered as follows:

Line	Input
1	Name of saved Surface II observed data file (20 characters maximum)
2	Number for weighting option: 0 = no weighting of data 1 = data weighted by one over the variance of the data point from the mean value of the data. 2 = data weighted by one over the square root of the difference between the maximum data value and the individual data point.
3	Number of blocks in the model (250 maximum)
4	XL(1), XR(1), ZU(1) ZD(1)
5	YMIN(1), YMAX(1)
6	Density(1)
7	Maximum number of laminae in block 1

Repeat lines 4, 5, 6, 7 for the number of blocks indiated in line 3.

Last 3 lines

- Percentage value which determines the number of y-values used for the quadriture formula approximation.
- Assumed standard deviation of the error in the observed data
- Maximum number of iterations toward solution of the density values

Output

Output to Grinv will be written either on the computer screen or a line printer, depending on the device being used. The output is self-explanatory and will consist of the calculated density values plus statistical information (i.e. Model and Data resolution, covarience, and correlation matrices) along with the original (first guess) model.

Program Grinv

```
$ TYPE GRINV.FOR
C
C... PROGRAM GRINV IS AN INVERSE GRAVITY MODELING PROGRAM
C... THAT PREDICTS DENSITIES THAT WILL GIVE A BEST FIT
C... TO OBSERVED GRAVITY DATA BASED ON FORWARD MODELING THAT
C... USES UP TO 250 RECTANGULAR BLOCKS OF EARTH. RIDGE REGRESSION,
C... WEIGHTING AND SCALING ARE USED
C
      COMMON /GRAV/XL(100),XR(100),ZD(100),ZU(100),
     &DEN(100,100),Y(500,500),NBLKS,XSIZE,YSIZE,NCOLS,
     &NROWS,YMAX(500),YMIN(500),MAXLAM(500),MAXPER,LAMNUM(500),
     &XPOS,YPOS,ANOM(500,500),V(500)
C
      COMMON /CBGINV/NDAT,NPARMS,KEPTRK,IA,IB,IC
C
      CHARACTER CHAR*1
C
      DIMENSION A(500,500),DPRED(500,500)
C
      DIMENSION W(250,250),DELT(400,1),DOBS(400),SQE(20,1),
     &WS(250,250),WKAREA(500),C(250,250),GINV(250,250),DELTM(250,1),
     &DELTN(250,1),SQEN(20,1),ERR(20,1),COVM(250,250),SIGMAM(250)
     &,CA(250,250),D(250,250),WSS(250,250),BMAX(150)
C
      CHARACTER*20 FILENAME
      OPEN(23,FILE='GBL.DAT',STATUS='NEW')
C*****************************************************************
C                  INPUT-OBSERVED GRAVITY DATA
C                   FROM SAVED SURFII GRIDFILE
C
C
C... ENTER FILENAME OF SAVED SURFII DATA FILE IN FILE G.DAT
C
      OPEN(26,FILE='G.DAT',STATUS='OLD')
      READ(26,'(A20)')FILENAME
C
C... READ NUMBER FOR WEIGHTING FROM FILE G.DAT
C...       0 = NO WEIGHTING
C...       1 = WEIGHT BY DATA VARIENCE FROM MEAN DATA VALUE
C...       2 = WEIGHT BY SQRT(DATA DIFFERENCE FROM MAX. DATA VALUE
C
      READ(26,*)NUMB
C
      OPEN(27,FILE=FILENAME,STATUS='OLD',FORM='UNFORMATTED'
     &,ACCESS='SEQUENTIAL')
C
C
C... READ IN FIRST RECORD
C
      READ(27)NCOLS,NROWS,IZERO
C
C... READ IN SECOND RECORD
C
      READ(27)IROWS,JCOLS,DIFY,DIFX,XMN,XMX,YMN,YMX,DUMMY
C
C... READ IN OBS DATA
C
      [illegible]
```

```
      [illegible]
      END DO
C
      XSIZE=ABS(XMX-XMN)
      YSIZE=ABS(YMX-YMN)
C
      CLOSE(27)
C*********************************************************************
C
C                 INPUT MODEL DATA FOR FORWARD PROGRAM
C                   DATA IN COMAND FILE G.DAT
C
      READ(26,*)NBLKS
      DO J=1,NBLKS
      READ(26,*)XL(J),XR(J),ZU(J),ZD(J)
      READ(26,*)Y(1,J),Y(2,J)
      YMIN(J)=Y(1,J)
      YMAX(J)=Y(2,J)
      READ(26,*)DEN(J,1)
      READ(26,*)MAXLAM(J)
      END DO
      READ(26,*)MAXPER
C
C                 INPUT DATA FOR INVERSION
C
      READ(26,*)STDDEV
      READ(26,*)ITMAX
C*********************************************************************
      NDAT=NCOLS*NROWS
      NPARMS=NBLKS
C
      IF(NUMB.EQ.1)THEN
              DO I=2,NDAT+1
              C(I,1)=C(I-1,1)+DOBS(I-1)
              END DO
              DMEAN=C(NDAT+1,1)/NDAT
              DO I=1,NDAT
              DO J=1,NDAT
              IF(I.EQ.J)THEN
              W(I,J)=1./(((DOBS(I)-DMEAN)**2)/(NDAT-NPARMS))
              ELSE
              W(I,J)=0.0
              END IF
              END DO
              END DO
      ELSE IF(NUMB.EQ.0)THEN
              DO I=1,NDAT
              DO J=1,NDAT
              IF(I.EQ.J)THEN
              W(I,J)=1.0
              ELSE
              W(I,J)=0.0
              END IF
              END DO
              END DO
      ELSE IF(NUMB.EQ.2)THEN
              BMAX(1)=0.0
              J=2
              I=2
E             BMAX(J)=AMAX1(ABS(DOBS(I-1)),ABS(DOBS(I)),ABS(DOBS(I+1)))
              IF(BMAX(J).LE.BMAX(J-1))BMAX(J)=BMAX(J-1)
C
              IF(I+1.EQ.NDAT)GO TO [illegible]
              [illegible]
```

```
                END IF
                IF(I+3.EQ.NDAT)THEN
                        IF(ABS(DOBS(I+2)).GE.BMAX(J))BMAX(J)=ABS(DOBS(I+2))
                        IF(ABS(DOBS(I+3)).GE.BMAX(J))BMAX(J)=ABS(DOBS(I+3))
                GO TO 9
                END IF
                I=I+2
                J=J+1
                GO TO 5
9               GMAX=BMAX(J)
                DO I=1,NDAT
                DO J=1,NDAT
                IF(I.EQ.J)THEN
                        IF(GMAX.EQ.ABS(DOBS(I)))THEN
                        W(I,J)=1.0
                        ELSE
                        W(I,J)=1./(SQRT(GMAX-ABS(DOBS(I))))
                        END IF
                ELSE
                        W(I,J)=0.0
                END IF
                END DO
                END DO
        END IF
C
        PRINT *,'                              '
        PRINT *,'************************************************************
     &******************'
        PRINT *,'                              '
        PRINT *,'                                INPUT MODEL'
        PRINT *,'                              '
        PRINT *,'------------------------------------------------------------
     &------------------'
        PRINT *,'  BLOCK #.       XL                   XR
     &ZU                ZB                DENSITY'
        DO J=1,NPARMS
        WRITE(*,'(3X,I3,2X,E12.4,2X,E12.4,2X,E12.4,2X,E12.4,2X,E12.4)')
     &J,XL(J),XR(J),ZU(J),ZB(J),DEN(J,1)
        END DO
        PRINT *,'************************************************************
     &******************'
        PRINT *,'                              '
C
        CLOSE(26)
C
        IA=250
        IB=250
        IC=250
        DAMP=.001
        KEPTRK=1
        KOUNT=0
C
        CALL FWRD(A,DPRED)
C
15      KOUNT=KOUNT+1
        IF(KOUNT.GT.ITMAX)THEN
        PRINT *,'MAXIMUM NUMBER OF ITERATIONS EXCEEDED -
     & CONVERGENCE NOT OBTAINED'
        GO TO 20
        END IF
C
C...  CALL SUBROUTS
C
        [illegible]
```

```
C... SCALE THE ATRANSPOSE WA [illegible] FOR ONES IN THE DIAGONAL
C
      DO I=1,NPARMS
      DO J=1,NPARMS
            IF(I.EQ.J)THEN
            D(I,J)=1./(SQRT(WS(I,I)))
            ELSE
            D(I,J)=0.0
            END IF
      END DO
      END DO
      CALL VMULFF(D,WS,NPARMS,NP4RMS,NPARMS,IA,IB,CA,IC,IER)
      CALL VMULFF(CA,D,NPARMS,NPARMS,NPARMS,IA,IB,WSS,IC,IER)
C
      DO I=1,NDAT
      DELT(I,1)=DOBS(I)-DPRED(I,KEPTRK)
      END DO
C
C... FIND ERROR
C
      CALL VMULFM(DELT,DELT,NDAT,1,1,400,400,SQE,20,IER)
C
C********** RIDGE REGRESSION *******************************
C
10    IF(DAMP.GE.100000)THEN
      PRINT *,'DAMPING FACTOR HAS REACHED 100000 - WILL NOT CONVERGE
     1TO PRESENT INPUT DATA STD. DEV.'
      GO TO 50
      END IF
      DO I=1,NPARMS
      DO J=1,NPARMS
      IF(I.EQ.J)WSS(I,J)=WSS(I,J)+DAMP
      END DO
      END DO
C
C... FIND INVERSE OF WS
C
      CALL LINV2F(WSS,NPARMS,IA,C,1,WKAREA,IER)
C
C...  FIND GENERALIZED INVERSE GINV
C
      CALL VMULFF(D,C,NPARMS,NP4RMS,NPARMS,IA,IB,CA,IC,IER)
      CALL VMULFF(CA,D,NPARMS,NPARMS,NPARMS,IA,IB,C,IC,IER)
      CALL VMULFF(C,A,NPARMS,NPARMS,NDAT,IA,500,CA,IC,IER)
      CALL VMULFF(CA,W,NPARMS,NDAT,NDAT,IA,IB,GINV,IC,IER)
C
C... DELTM IS THE JUMP HOPEFULLY TOWARD A SOLUTION
C
      CALL VMULFF(GINV,DELT,NPARMS,NDAT,1,IA,400,DELTM,250,IER)
C
      DO I=1,NPARMS
      DEN(I,KEPTRK+1)=DELTM(I,1)+DEN(I,KEPTRK)
      END DO
C
C... NOW HAVE NEW PARAMS.
C
      KEPTRK=KEPTRK+1
      CALL FWRD(A,DPRED)
C
      DO I=1,NDAT
      DELTN(I,1)=DOBS(I)-DPRED(I,KEPTRK)
      END DO
C
[illegible]
```

```
      IF(SQEN(1,1).GE.SQE(1,1)) THEN
              IF(SQRT(SQEN(1,1)/(NPARMS*NDAT)).LE.STDDEV)GO TO 12
      DO I=1,NPARMS
      DEN(I,KEPTRK)=DEN(I,KEPTRK-1)
      END DO
      DAMP=10.*DAMP
      IF(K.EQ.0.0)GO TO 20
      GO TO 10
      ELSE
12    SQE(1,1)=SQEN(1,1)
      DAMP=DAMP/10.
      DO I=1,NDAT
      DELT(I,1)=DELTN(I,1)
      END DO
      END IF
C
C... CHECK TO SEE IF SOLN. IS WITHIN STD. DEV. OF DATA
C
      CALL VMULFM(DELT,DELT,NDAT,1,1,400,400,ERR,20,IER)
      CHIERR=(1./(NDAT-NPARMS))*ERR(1,1)
C
C
      IF(DAMP.EQ.0.0)GO TO 20
C
      IF(SQRT(CHIERR).LE.STDDEV)DAMP=0.0
      GO TO 5
C
C********* OUTPUT ************************************************
C
20    PRINT *,'                         '
      PRINT *,'************************************************************'
      PRINT *,'                         '
      PRINT *,'                       OUTPUT'
      PRINT *,'                         '
      CALL VMULFF(GINV,GINV,NPARMS,NDAT,NPARMS,IA,IB,C,IC,IER)
      DO I=1,NPARMS
      DO J=1,NPARMS
      COVM(I,J)=CHIERR*C(I,J)
      END DO
      END DO
C
      DO I=1,NPARMS
      SIGMAM(I)=SQRT(COVM(I,I))
      END DO
C
      PRINT *,'------------------------------------------------------------'
      PRINT *,'                                                            '
      PRINT *,'I    DENSITY(I) +/- STD.DEV.'
      PRINT *,'------------------------------------------------------------'
      DO I=1,NPARMS
      WRITE(*,'(I2,3X,E10.3,2X,E10.3)')
     &I,DEN(I,KEPTRK),SIGMAM(I)
      END DO
      PRINT *,'------------------------------------------------------------'
C
      PRINT *,'------------------------------------------------------------'
      PRINT *,'INPUT STD. DEV. = ',STDDEV
      PRINT *,'CALC. DATA STD. DEV. =',SQRT(CHIERR)
      PRINT *,'NUMBER OF ITERATIONS FOR SOLUTION =',KOUNT-1
      PRINT *,'------------------------------------------------------------'
C
      PRINT *,'------------------------------------------------------------'
      PRINT *,'MODEL RESOLUTION MATRIX'
      CALL VMULFF([illegible],NPARMS,NDAT,[illegible],IA,IB,[illegible],IER)
```

```
      [illegible]
41    FORMAT(1X,A1,<NPARMS>F8.3,2X,A1)
      END DO
      PRINT *,'------------------------------------------------------------------'
      PRINT *,'------------------------------------------------------------------'
      PRINT *,'DATA RESOLUTION MATRIX'
      PRINT *,'
      CALL VMULFF(A,GINV,NDAT,NPARMS,NDAT,500,IB,C,IC,IER)
      DO I=1,NDAT
      PRINT 42,'|',(C(I,J),J=1,NDAT),'|'
42    FORMAT(1X,A1,<NDAT>E9.1,2X,A1)
      END DO
      PRINT *,'------------------------------------------------------------------'
C
      PRINT *,'------------------------------------------------------------------'
      PRINT *,'COVARIANCE MATRIX'
      PRINT *,'
      DO I=1,NPARMS
      PRINT 43,'|',(COVM(I,J),J=1,NPARMS),'|'
43    FORMAT(1X,A1,<NPARMS>E12.3,2X,A1)
      END DO
      PRINT *,'------------------------------------------------------------------'
C
      PRINT *,'------------------------------------------------------------------'
      PRINT *,'CORRELATION MATRIX'
      PRINT *,'
      DO I=1,NPARMS
      DO J=1,NPARMS
      C(I,J)=COVM(I,J)/(SQRT(COVM(I,I)*SQRT(COVM(J,J)))
      END DO
      END DO
      DO I=1,NPARMS
      PRINT 44,'|',(C(I,J),J=1,NPARMS),'|'
44    FORMAT(1X,A1,<NPARMS>E12.3,2X,A1)
      END DO
      PRINT *,'******************************************************************'
50    CALL EXIT
      END
C
C*************************************************************************
C     SUBROUTINES
C
C... SUBROUTINE FWRD IS A FORWARD GRAVITY PROGRAM THAT MODELS THE EARTH
C... BY USING BLOCKS (UP TO 500) OF VARIABLE DENSITY.
C
      SUBROUTINE FWRD(A,DPRED)
C
      COMMON /GRAV/XL(100),XR(100),ZB(100),ZU(100),
     2DEN(100,100),Y(500,500),NBLKS,XSIZE,YSIZE,NCOLS,
     2NROWS,YMAX(500),YMIN(500),MAXLAM(500),MAXPER,LAMNUM(500),
     2XPOS,YPOS,ANOM(500,500),V(500)
C
      COMMON /GGBINV/NDAT,NPARMS,KERTRX,IA,IB,IC
      DIMENSION A(500,500),DPRED(500,500),B(250,1)
C
      M1=0.
      M=1
      CHECK=0.0
      XDELTA=XSIZE/(NCOLS-1)
      YDELTA=YSIZE/(NROWS-1)
C
      IF(KERTRX.EQ.1)THEN
      DO I=1,NBLKS
      [illegible]
```

```
C.... FORMULA WILL WORK
C
      L1=LAMNUM(I)/2
      T1=(LAMNUM(I)/2.)-L1
      IF(LAMNUM(I).GT.2)THEN
           IF(T1.EQ.0.0)THEN
           Y(LAMNUM(I)+1,I)=Y(LAMNUM(I),I)
           Y(LAMNUM(I),I)=Y(LAMNUM(I),I)-1.
           CALL FORWARD(LAMNUM(I),I)
           LAMNUM(I)=LAMNUM(I)+1
           END IF
      END IF
      END DO
C
10    IF(M.EQ.1)THEN
      XPOS=0.0
      YPOS=0.0
C
      DO J=2,NBLKS+1
           CALL QUAD(J-1)
                Y(1,J-1)=V((LAMNUM(J-1)-1./2)+1)
           END DO
           M=2
           GO TO 10
      ELSE
30         DO I=1,NCOLSANROWS-1
                CALL GRID(I,CHECK,XDELTA,YDELTA)
                DO J=2,NBLKS+1
                DO K=2,LAMNUM(J-1)+1
                     CALL FORWARD(K-1,J-1)
                END DO
                CALL QUAD(J-1)
                A(I+1,J-1)=V(((LAMNUM(J-1)-1)/2)+1)
                END DO
           END DO
C
      DO I=1,NPARMS
      B(I,1)=DEN(I,KEPTRK)
      END DO
C
      CALL VMULFF(A,B,NDAT,NPARMS,1,500,IB,DPRED,500,IER)
C
      DO I=1,NDAT
      DPRED(I,KEPTRK)=DPRED(I,1)
      END DO
C
      IF(KEPTRK.EQ.1)THEN
      OPEN(29,FILE='A.DAT',STATUS='NEW')
      DO I=1,NDAT
      DO J=1,NPARMS
      WRITE(29,'(E12.4)')A(I,J)
      END DO
      END DO
      CLOSE(29)
      GO TO 40
      END IF
      IF(KK.EQ.2)GO TO 40
      END IF
C
      ELSE
C
      KK=1
20    IF(KK.EQ.1)THEN
```

```
        [illegible]
                CALL FORWARD(K-1,J-1)
        END DO
        CALL QUAD(J-1)
        A(1,J-1)=V(((LAMNUM(J-1)-1)/2)+1)
        END DO
        KK=2
        GO TO 20
        ELSE
        GO TO 30
        END IF
        END IF
C
40      DO J=1,NBLKS
        XL(J)=XL(J)+XSIZE
        XR(J)=XR(J)+XSIZE
        DO K=1,LAMNUM(J)
        Y(K,J)=Y(K,J)+YSIZE
        END DO
        END DO
C
        RETURN
        END
C
C
C...   SUBROUTINES
C
C
        SUBROUTINE REORDER(I)
C
        COMMON /GRAV/XL(100),XR(100),ZD(100),ZU(100),
     &DEN(100,100),Y(500,500),NBLKS,XSIZE,YSIZE,NCOLS,
     2NROWS,YMAX(500),YMIN(500),MAXLAM(500),MAXPER,LAMNUM(500),
     3XPOS,YPOS,ANOM(500,500),V(500)
C
        COMMON /CSGINV/NDAT,NPARMS,KEPTRK,IA,IB,IC
        KT=1
        CALL FORWARD(KT,I)
        KT=2
        CALL FORWARD(KT,I)
C
        MS=1
        J=1
10      PER=ABS((ANOM(KT,I)-ANOM(KT-1,I))/(AMAX1
     &(ANOM(KT-1,I),ANOM(KT,I))))*100.
C
        IF((MS.EQ.1).AND.(PER.LE.MAXPER))THEN
        PRINT *,'                                        '
        PRINT *,'MODEL GEOMETRY HAS NOT ALLOWED PROGRAM TO WORK!'
        PRINT *,'-----------------------------------------------------------'
        PRINT *,'EITHER CHANGE INITIAL Y VALUES AND/OR DECREASE THE'
        PRINT *,'ALLOWABLE DISCRETIZING PERCENTAGE FOR BLOCK',I,'.'
        PRINT *,'                                                  '
        CALL EXIT
        END IF
C
        IF(PER.GT.MAXPER)THEN
                DO L=J,1,-1
                ANOM(KT+L,I)=ANOM(KT+L-1,I)
                Y(KT+L,I)=Y(KT+L-1,I)
                END DO
                KPT=KT+J
                Y(KT,I)=(Y(KT-1,I)-Y(KT+1,I))/2.
                CALL [illegible]
```

```
                GO TO 10
        END IF
                LAMNUM(I)=KPT
C
                IF(M2,EQ,1)THEN
                LAMNUM(I)=1
                GO TO 20
                END IF
C
                IF(J,EQ,1)GO TO 20
C
        IF(YMAX(I,-((KPT-1;I),LE,5,)GO TO 20
C
                IF(LAMNUM(I).GE,MAXLAM(I))THEN
                PRINT *,' MAXIMUM NUMBER OF LAMINA (',MAXLAM(I),') FOR
     & BLOCK ',I,' EXCEEDED.'
                GO TO 20
                END IF
C
                J=J-1
                KT=KT+1
                GO TO 10
20      RETURN
        END
C
C
C... SUBROUTINE FORWARD CALCULATES THE GRAVITY ANOMALY/UNIT WIDTH FOR
C... EACH LAMINAE
C
        SUBROUTINE FORWARD(I,J)
C
        COMMON /GRAV/XL(100),XR(100),ZD(100),ZU(100),
     &DEN(100,100),Y(500,500),NBLKS,XSIZE,YSIZE,NCOLS,
     &NROWS,YMAX(500),YMIN(500),MAXLAM(500),MAXPER,LAMNUM(500),
     &XPOS,YPOS,ANOM(500,500),V(500)
C
        COMMON /DPGINV/NDAT,NPARMS,KEPTRK,IA,IB,IC
C
        G0=0.0000000667
C
C... START CALCULATIN'
C
C... PREVENT DIVIDE BY ZERO
C
        IF(XR(J),EQ,0,0)XR(J)=1E-10
        IF(XL(J),EQ,0,0)XL(J)=1E-10
C
        A0=ZD(J)*ZD(J)+Y(I,J)*Y(I,J)
        B=ZU(J)*ZU(J)+Y(I,J)*Y(I,J)
        A1=XL(J)+SQRT(XL(J)*XL(J)+B)
        A2=XR(J)+SQRT(XR(J)*XP(J)+B)
        B1=XR(J)+SQRT(XR(J)*XR(J)+A0)
        B2=XL(J)+SQRT(XL(J)*XL(J)+A0)
        IF((A1,EQ,0,0),OR,(A2.EQ,0,0),OR,(B1.EQ,0,0)
     &.OR,(B2.EQ.0.0))M1=M1-1
C
C... PREVENT TAKING LOG OF 0.0
C
        IF(A1,EQ,0,0)A1=,001
        IF(A2.EQ,0,0)A2=,001
        IF(B1,EQ,0,0,B1=,001
        IF(B2.EQ.0,0)B2=,001
C
```

```
     [illegible](2.5)-ALOG(2))-ALOG(2)).
C
      RETURN
      END
C
C
C...  SUBROUTINE GRID GIVES X,Y GRID POSITIONS
C
C
      SUBROUTINE GRID(KNT,CHECK,XDELTA,YDELTA)
C
      COMMON /GRAV/XL(100),XR(100),ZD(100),ZU(100),
     1DEN(100,100),Y(500,500),NBLKS,XSIZE,YSIZE,NCOLS,
     2NROWS,YMAX(500),YMIN(500),MAXLAM(500),MAXPER,LAMNUM(500),
     3XPOS,YPOS,ANOM(500,500),U(500)
C
      COMMON /CBGINV/NDAT,NPARMS,KEPTRK,IA,IB,IC
C
      NI=KNT/NCOLS
      XPOS=KNT*XDELTA-(NI*XSIZE+XDELTA*NI)
      IF(ABS(XPOS).LE.1.0E-01)XPOS=0.00E+00
      YPOS=NI*YDELTA
      IF(XSIZE.GT.CHECK)THEN
                CHECK=CHECK+XDELTA
                DO J=1,NBLKS
                XL(J)=XL(J)-XDELTA
                XR(J)=XR(J)-XDELTA
                END DO
      ELSE
                CHECK=0.0
                DO J=1,NBLKS
C
                XL(J)=XL(J)+XDELTA*(NCOLS-1)
                XR(J)=XR(J)+XDELTA*(NCOLS-1)
C
                DO I=1,LAMNUM(J)
                Y(I,J)=Y(I,J)-YDELTA
                END DO
                END DO
      END IF
      RETURN
      END
C
C
C...  SUBROUTINE QUAD CALCULATES THE ANOMALY ASSOCIATED WITH EACH BLOCK
C...  BY DOING THE INTEGRATION IN THE Y-DIRECTION USING TALWNI'S
C...  QUADRITURE FORMULA
C
C
      SUBROUTINE QUAD(K)
C
      COMMON /GRAV/XL(100),XR(100),ZD(100),ZU(100),
     1DEN(100,100),Y(500,500),NBLKS,XSIZE,YSIZE,NCOLS,
     2NROWS,YMAX(500),YMIN(500),MAXLAM(500),MAXPER,LAMNUM(500),
     3XPOS,YPOS,ANOM(500,500),U(500)
C
      COMMON /CBGINV/NDAT,NPARMS,KEPTRK,IA,IB,IC
C
      DIMENSION TEMP(500)
C
C...  FIND THE ANOMALY
C
      IF(LAMNUM(K)-1.GT.1)THEN
```

```
[illegible]
[illegible]

        B=ANOM(I+1,K)*((Y(I,K)-Y(I+2,K))**3)/((Y(I+1,K)-
     &Y(I+2,K))*(Y(I+1,K)-Y(I,K)))
C
        C=ANOM(I+2,K)*((Y(I,K)-Y(I+2,K))/(Y(I+2,K)-Y(I+1,K)))
     &*(3.0*Y(I+1,K)-Y(I,K)-2.*Y(I+2,K))
C
        TEMP(J-1)=(A1+B+C)/6.0
C
        V(J)=V(J-1)+TEMP(J-1)
        I=I+2
        END DO
C
        ELSE
C
C...  TRAPEZOIDAL RULE FOR ONE AREA
C
        V(((LAMNUM(K)-1)/2)+1)=(Y(2,K)-Y(1,K))*.5*(ANOM(1,K)+ANOM(2,K))
        END IF
C
        RETURN
        END
$
```

Input for Grinv

```
$ TY 2.DAT
FOR014.DAT
2
3
0.,10.,10.,30.
0.,40.
2.
500
10.,40.,10.,30.
0.,40.
2.
300
40.,60.,10.,30.
0.,40.
2.
500
5
.1
15
$
$
$
$ SET TERM/WIDTH=132
$
$ RUN GRINV

***************************************************************************

                  INPUT MODEL

---------------------------------------------------------------------------
  BLOCK #      XL              XR             ZU             ZD            DENSITY
    1     0.0000E+00     0.1000E+02     0.1000E+02     0.3000E+02     0.2000E+01
    2     0.1000E+02     0.4000E+02     0.1000E+02     0.3000E+02     0.2000E-01
    3     0.4000E+02     0.6000E+02     0.1000E+02     0.3000E+02     0.2000E-01
****************************************************************************


***********************************************************

                 OUTPUT

----------------------------------------------------------

I   DENSITY(I) +/- STD.DEV.
----------------------------------------------------------
1     0.130E+01   0.147E-02
2     0.260E+01   0.229E-03
3     0.300E+01   0.142E-02
----------------------------------------------------------
----------------------------------------------------------
INPUT STD. DEV. =    0.1000000
CALC. DATA STD. DEV. =  1.6230591E-04
NUMBER OF ITERATIONS FOR SOLUTION =           1
----------------------------------------------------------
----------------------------------------------------------
MODEL RESOLUTION MATRIX
```

```
------------------------------------------------------------------------------------------
------------------------------------------------------------------------------------------
DATA RESOLUTION MATRIX

!  0.1  0.1  0.0  0.0  0.2  0.1 -0.1  0.0  0.2  0.1 -0.1  0.0  0.1  0.1  0.0  0.0
!  0.0  0.1  0.0  0.0  0.1  0.1  0.1  0.0  0.1  0.1  0.1  0.0  0.1  0.1  0.0  0.0
!  0.0  0.0  0.0  0.0  0.0  0.0  0.2  0.1  0.0  0.0  0.2  0.0  0.0  0.0  0.1  0.0
!  0.0  0.0  0.0  0.1  0.0  0.0  0.0  0.5  0.0  0.0  0.0  0.1  0.0  0.0  0.0  0.1
!  0.1  0.1  0.0  0.0  0.2  0.2 -0.1  0.1  0.2  0.2 -0.2  0.0  0.1  0.1  0.0  0.0
!  0.1  0.1  0.0  0.0  0.1  0.2  0.1 -0.1  0.1  0.2  0.2  0.0  0.1  0.1  0.0  0.0
!  0.0  0.0  0.1  0.0  0.0  0.1  0.4  0.0  0.0  0.1  0.4  0.0  0.0  0.0  0.1  0.1
!  0.0  0.0  0.0  0.1  0.0  0.0  0.0  0.8  0.0  0.0  0.0  0.1  0.0  0.0  0.0  0.1
!  0.1  0.1  0.0  0.0  0.2  0.2 -0.2  0.1  0.2  0.2 -0.2  0.0  0.1  0.1  0.0  0.0
!  0.1  0.1  0.0  0.0  0.1  0.2  0.1 -0.1  0.1  0.2  0.2  0.0  0.1  0.1  0.0  0.0
!  0.0  0.0  0.1  0.0  0.0  0.1  0.4  0.0  0.0  0.1  0.4  0.0  0.0  0.0  0.1  0.0
!  0.0  0.0  0.0  0.1  0.0  0.0  0.0  0.8  0.0  0.0  0.0  0.1  0.0  0.0  0.0  0.1
!  0.1  0.1  0.0  0.0  0.2  0.1 -0.1  0.0  0.2  0.1 -0.1  0.0  0.1  0.1  0.0  0.0
!  0.1  0.1  0.0  0.0  0.1  0.1  0.1  0.0  0.1  0.1  0.1  0.0  0.1  0.1  0.0  0.0
!  0.0  0.0  0.1  0.0  0.0  0.0  0.2  0.1  0.0  0.1  0.3  0.0  0.0  0.0  0.1  0.0
!  0.0  0.0  0.0  0.1  0.0  0.0  0.0  0.5  0.0  0.0  0.0  0.1  0.0  0.0  0.0  0.1
------------------------------------------------------------------------------------------
------------------------------------------------------------------------------------------
COVARIANCE MATRIX

!   0.215E-05  -0.991E-06   0.129E-05  !
!  -0.991E-06   0.686E-06  -0.112E-05  !
!   0.129E-05  -0.112E-05   0.234E-05  !
------------------------------------------------------------------------------------------
------------------------------------------------------------------------------------------
CORRELATION MATRIX

!   0.100E+01  -0.816E+00   0.542E+00  !
!  -0.816E+00   0.100E+01  -0.835E+00  !
!   0.542E+00  -0.835E+00   0.100E+01  !
******************************************************************************************
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$
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GEOTHERMAL RESOURCES OF THE WIND RIVER BASIN, WYOMING

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^{2}sec)= = 1 heat flow unit (HFU) = 0.013228 British thermal unit per square foot per hour (Btu/ft^{2}hr) = 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 sixth 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 three maps: a generalized geological map (Plate I), a thermal gradient contour map (Plate III), and a structure contour map (Plate II).

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 Wind River Basin of centeral Wyoming (Figure 1).

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, and by the Wyoming Water Research Center. 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/m^2 would not suggest a significant geothermal resource.

In Wyoming basins, the primary mechanism for the translation of moderate heat flow into above-normal temperature gradients is ground-water flow through geologic structures. Figures 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 manmade 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 ±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 groundwater 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 WIND RIVER BASIN, WYOMING

The Wind River Basin covers approximately 8,000 square miles in central Wyoming (see Figure 1 for location). Most of Fremont County and the eastern one-third of Natrona County are in the Wind River Basin. The basin is bounded by major mountain uplifts on the north (Owl Creek Mountains), west (Wind River Mountains), and south (Granite Mountains). This uplifts are complexly folded and faulted areas for which most or all of the sedimentary rocks have been eroded. Thus, they form distinct hydrologic as well as structural and topographic boundaries. On the east the Wind River Basin is bounded by a gentle uplift, the Casper Arch. Along this broad fold the oldest exposed rocks are of Juarssic and Lower Cretaceous age.

Like other Wyoming basins, the Wind River Basin includes many fold and fault structures superimposed on the overall downwarp of the basin. The background heat flow and ground water circulation patterns control geothermal resource distribution.

The geothermal setting of the Wind River Basin will first be described in the context of heat flow values. Then the relevant stratigraphy will be presented, followed by discussion of the major folds and faults in the basin. The distribution of geothermal gradients will then be analyzed through discussion of areas of anomalously high gradients. A brief discussion of the thermal springs in the basin follows. The major conclusions of the report are then summarized.

HEAT FLOW

Heat flow determinations have been made at five sites in the Wind River Basin (Table 2). These values were derived through precision thermal logging and conductivity determinations of holes into Precambrian basement rocks. They are believed to be free of hydrologic disturbances and representative of regional patters. The heat flow values come from two general localities: the Granite Mountains along the southern margin of the basin, and the Owl Creek Mountains along the northern margin. Values from the Granite Mountains area in the southern part of the Basin vary from 50-70 milliwats per square meter (mW/m^2). Values from the eastern Owl Creek Mountains indicate a a heat flow in the 70-80 mW/m^2 range. The northern values are higher than the moderate heat flows of the southern basin and correspond with a broad zone of moderate to high heat flows across central Wyoming tentatively identified by Muffler (1979) and Decker et al., (1980). The origin of this zone of higher heat flow is not known, and the boundaries are based on rough contouring of the sparse data available. In consideration of the gross structural fabric of the basin, heat flow values are assumed to be most uniform along east-west or northwest-southeast trends. The distribution of the north to south decrease in heat flow cannot be defined without intermediate data points. Analysis of gradient anomalies within the Wind River Basin (see thermal gradient section below) suggests the higher heat flow of the Owl Creek Mountains may extend at least part way into the basin.

Breckenridge and Hinckley (1978) suggest warm springs in the northwestern Wind River Basin may be due to high heat flow associated with the Absaroka volcanic complex. No heat flow determinations have been made for this part of the basin. However, Hinckley et al., (1982) suggests that the Absaroka igneous activity to too old to affect significant modification of present regional heat flow patterns. The effect on the study area of Late Cenozoic volcanism in the Yellowstone-Teton National Parks area immediately northwest of the Wind River Basin is not clearly understood, but this activity is of an age to create local, present-day heat flow anomalies.

Heat flow determinations in the Wind River Basin indicate geothermal conditions similar to the other Wyoming Basins. In a sequence of normal sedimentary rocks, purely conductive thermal gradients generally fall in the 12 to 15°F/1,000ft range; perhaps slightly higher in the northern basin due to somewhat higher heat flow. Such gradients are not usually considered sufficient to provide a useful geothermal resource by themselves, but will lead to the development of high temperatures at depth. Thus, where deeply circulating ground water is brought close to the surface by circulation over folds or up fault systems, highly elevated gradients and attractive energy resources may result.

STRATIGRAPHY - HYDROLOGY

In the Wind River Basin the mass transfer of heat by moving water creates areas of high geothermal gradients. Therefore, it is important to identify those strata with favorable water-bearing characteristics. In addition, the confining strata above and below there aquifers must be considered in terms of their effectiveness in restricting ground water flow patterns.

The stratigraphic chart for the Wind River Basin (Table 3) lists formation thicknesses, lithologies, and general water-bearing characteristics. Much of these data are drawn from Richter (1981) to whom the reader is referred for a thorough discussion of Wind River Basin hydrogeology. Plate I presents the surface distribution of the various strata to be discussed. As a first cut, strata are identified as major confining unit, aquifer, or major aquifer. It should be understood that these division are very general and that in local areas of relatively higher permeability and/or small water demand, any formation listed may constitute a useful "Aquifer".

The youngest deposits in the Wind River Basin are the sands, silts, and gravels deposited along stream channels. Because of their good accessibility, obviously good recharge, and generally high permeabilities, these quaternary deposits form one of the most important aquifers in the bnsin. Ground water temperature in this aquifer will generally approximate the mean annual air temperature, 43°F for most of the Wind River Basin (Lowers, 1960). Such waters have geothermal potential primarily through the use of ground water heat pumps. These devices can extract heat from any above-freezing waters and are therefore constrained more by general ground water availability than by the distribution of geothermal anomalies.

The Moonstone, Arikarree, and White River Formations are only present locally in the basin. Simiarly to the quaternary deposits, they are unconfined aquifers. This lack of confinement precludes significant ground water circulation upwards from deep zones of these aquifers. They are therefore unlikely to provide waters of elevated temperature. The Wagon Bed, Tepee Trail, and Aycross Formations are poor water producers, are present only in the extreme northwest and southeast parts of the basin, and are therefore of little geothermal interest.

The Wind River Formation constitutes most of the surface of the Wind River Basin. This highly productive aquifer alone accounts for approximately 50 percent of all private domestic wells in the basin. (An additional 30 percent are developed in quaternary deposits (Richter, 1981)). Although the Wind River Formation is mostly unconfined, interbedded low-permeability shale and mudstone layers create artesian conditions locally (Richter, 1981). As with the Quaternary deposits, the Wind River Formation is most geothermally attractive for ground water heat pump applications. It is considerably thicker than the quaternary deposits, however, may be overlain by several thousand feet or younger sediments. Thus, relatively high temperatures may be available in deep wells.

Beneath the Wind River Formation, strata begin to develop significant geothermal potential. With grater depth of burial, higher temperatures will occur under normal gradients. The Fort Union - Lance aquifer, for example, is over 10,000 feet deep in the central basin and has reported temperatures in excess of 200°F. With the incident of major confining units, artesian conditions may be imposed on underlying aquifers and the stage is set for the type of forced convection depicted in Figure 3. Since the geothermal potential of these Mesozoic and Paleozoic-age strata is dependent on local structures, generalization beyond overall aquifer productivity and water quality cannot be made. Aquifers in the lower Cenozoic and Mesozoic sections are generally dependent on sandstone layers for their productivity. Well yields up to several hundred gallons per minute (gpm) are reported from various of these strata though most yields fall in the 10-50 gpm range. Water quality from these units is quite variable, but is generally poor. Chloride and sulphate are the most common anions; sodium is the dominant cation (Richter, 1981).

As the stratigraphic chart indicates (Table 3), there are several major aquifers in the Paleozoic section. Most important of these is the Tensleep Sandstone, which is under significant artesian pressure beneath much of the Wind River Basin. Dana (1962) reports a Tensleep-Madison well near Lander flowing 3,000 gpm and Richter (1981) reports that Tensleep well yields "typically range up to several thousand galls per minute". Richter (1981) reports well yields of up to several hundred gpm for the Park City and Amsden Formations and the Madison Limestone. Richter proposes that these formations, along with the Darby Formation and the Bighorn Dolomite, be grouped with the Tensleep Sandstone as a single "Tensleep aquifer system". This system has generally good quality water except in the deep, interior basin. Cations are mixed, with calcium and magnesium generally greater than sodium. Bicarbonate and sulphate are dominant anions.

At the base of the sedimentary section is the Flathead Sandstone. This unit has been developed as a highly productive aquifer in parts of the Bighorn Basin. It is known to produce moderate quantities of good quality water in the Wind River Basin, but has not been developed to any significant extent.

STRUCTURE

At sufficient depth, high temperature water could be developed from any of the aquifers discussed above. This is due to the simple increase in temperature with depth which occurs in the earth. In the structurally lowest part of the Wind River Basin, for example, the Flathead Sandstone should contain water in excess of 450°F. Even so, water temperatures reflecting only normal, background gradients are not generally considered valuable enough to justify well-drilling costs. Only where these deep heated waters are transfered closer to the surface will a significant geothermal resource exist. That transfer can be accomplished artificially via a drill hole, e.g. one drilled for oil and gas exploration and development, or naturally, structurally as in the schematic fold or fault of Figure 3.

Plate II is a contour map of the top of the Lower-Cretaceous age Cloverly Formation. It is essentially a simplification of maps by Barlow and Haun, 1978) and Keefer (1970). In a general, basin-wide sense, all the sedimentary formations older than Upper-Cretaceous in the Wind River Basin accumulated as a horizontally layered stack. This stack was deformed during the latest Cretaceous and Early Cenozoic to produce the structural relief seen in the Cloverly Formation. Thus this surface in general represents the structural relief of higher and lower strata in the basin. It is representative of other pre-deformation strata in all but the absolute elevations.

During and following this period of deformation, sedimentary material was continually eroded from the uplifts and deposited in the forming basin. This created broad, thickening basinward wedges of the Tertiary sediments. Thus, such aquifers as the Fort Union and Wind River Formations are progressively less deformed than underlying strata and less likely to contain geothermally useful fold and fault systems.

Mesozoic and Paleozoic aquifers receive precipitation and runoff recharge where they are exposed at the surface along the basin-bounding uplifts (see Plate I). Waters then move basinward, escaping upwards where faults or erosion have eliminated confinement. A general circulation for the Cloverly Formation has been proposed by Richter (1981) and is indicated by the arrows on Plate II. Given the similar geometry and recharge patters of most Mesozoic and Paleozoic strata, flow patterns are assumed to be similar.

THERMAL GRADIENTS

Information on thermal gradients in the Wind River Basin comes from two sources: oil and gas well bottom-hole temperatures (BHT's), and precision thermal logging. Tables 4 and 5 present summaries of the 1,733 bottom-hole temperatures and calculated gradients collected for the Wind River Basin. Temperatures range from 65 to 370°F, yielding gradients from 2.6 to 144.4°F/1,000 ft. Shallower than approximately 2,500 feet, all reported temperatures are less than 100°F and, along with their calculated gradients, are therefore subject to considerable error as discussed earlier. Nonetheless, the table lists many gradients in excess of 20°F/1,000 ft which are confidently based on deep holes with high temperatures. Table 6 lists data from the precision thermal logging of wells in the Wind River Basin (data from Heasler et al., 1983). These data are plotted on Plate III.

An alternative view of the BHT data is presented in Figure 7. Figure 7 shows the effect of drilling mud in creating unrealistically high gradients at shallow depths. The divergence of the 100°F mud curve from a significant portion of the data (e.g. the 80th percentile curve) indicates that only below 2,000 to 3,000 feet will bottom-hole temperatures be consistently free of drilling fluid induced increases. Points to the right of the 80th percentile line on this plot are those considered to represent possibly significant geothermal anomalies.

The areal distribution of gradients is presented on Plate III. All available bottom-hole temperature data, thermal logging, thermal spring, thermal well, and heat flow data are plotted on this map and approximate gradient contours are proposed. Where gradients identified as anomalous (based on Table 5 and Figure 7) occur in the same vicinity, an area of anomalous gradient is mapped. Due to the uncertainty of individual gradient points, contours and anomalous areas are generally based on consideration of a group of values for a given area.

Table 7 provides summary information on each of the areas of anomalous gradient identified on Plate III. Even in these areas, however, gradients are not extreme. Nowhere, for example, are there confirmed gradients as high as those for the Thermopolis and Cody areas of the Bighorn Basin (Hinckley et al., 1982; Heasler, 1982). The "approximate depths", "temperatures", and "principle formations" of Table 7 are simply those from which the available gradient data derive. While there is no implication that the anomaly is confined to these brackets, extrapolation to much shallower or much deeper zones must be done cautiously.

Since the basic heat flow into the Wind River Basin is insufficient to create high conductive gradients, geothermal anomalies are primarily a function of convective redistribution of heat. The complex interaction of ground water and geologic structure is the principle geothermal agent. The following pages will discuss what is known or can be deduced about that interaction in the Wind River Basin. General principles will be developed along with individual system specifics through analysis of each of the mapped anomalous areas. Included is consideration of temperatures, depths and general character of the potential geothermal resource, and possible, unverified extensions to the anomalous areas. The discussion begins with Area 2, where there are abundant data and a relatively straightforward geothermal system.

The high gradients of area 2 are perhaps the most well established of any in the Wind River Basin. In addition to abundant oil and gas well bottom-hole temperature data is a confirming thermally logged hole and a major hot spring (see Plate III). Plate II shows the coincidence of the area with a major fault system paralleling nearly the entire length of the Wind River Mountains. In addition, at Area 2 there is a significant fold immediately northeast of the fault system. The indicated ground water flow direction is northeastward and eastward off the flank of the mountains, descending into the Wind River Basin. Subtracting the structure contour elevations (0-1,000 feet) from the approximate surface elevation (6,000 feet) shows the top of the Cloverly to be around 6,000 feet deep adjacent to the fault. Addition of the 2,500 feet of intervening strata (see Table 3) places the Park City (Phosphoria) Formation at 8,500 feet with the Madison Limestone at 9,500 feet. A gradient of only 12°/1,000ft would thus lead to formation and contained ground water temperatures of about 150°F. Displacements across the fault system range from 3,000 to 6,000 feet. In the vicinity of Area 2, strata are uplifted approximately 4,000 feet on the northeast side of the fault. Folding has deformed the strata up an additional 3,000 feet (see Plate II) which means the Cloverly Formation was brought above the present land surface and eroded away at the crest of the fold. Waters in the Paleozoic aquifers remain confined beneath relatively impermeable strata, moving up and over the fault/fold system and delivering deep heated waters to the near surface.

The resource potential of Area 2 can be addressed based on this model. The presence of the generally productive Paleozoic aquifers at relatively shallow depths is advantageous where water quantity and quality are considerations. The depth/gradient aspects of this system indicate around 140°F as the maximum temperature likely to be encountered. This is in reasonable agreement with the 100 to 130°F bottom-hole temperatures reported when allowances are made for moving ground water failing to reach full equilibrium temperatures in the deep portion of the system, and for some cooling as waters ascend to shallower zones.

The major complication in the flow system of Areas 2 and 3 is faulting. Where strata are simply deformed into folds, stratigraphic continuity and ground water flow patterns are generally maintained (although the fracturing attending folding of competent rock layers may greatly enhance permeabilities along steep flexures). The effect of faulting, however, is quite variable. Faulting may create ground water pathways up through normally confining beds. Such zones as these may allow deep heated waters to rise to the near-surface, creating geothermal anomalies in the absence of folding. On the other hand, faulting may produce tight, impermeable zones which seriously restrict ground water movement. Also, the juxtaposition of permeable and impermeable strata across a fault may reduce or eliminate hydraulic continuity. Faults will change in configuration and effect on hydrology at different places, and thus produce effects which may be quite difficult to anticipate. In addition large, deep faults presented on Plate II are somewhat conjectural, based on interpretation of subsurface data, in some cases with little or no surface expression.

At present the effect of large-scale faulting on geothermal systems can best be analyzed emperically. The existence of geothermal anomalies strongly suggests that water is moving up and across the fault system in the vicinity of Areas 2 and 3. Elsewhere along the fault the effect is different. North of Area 2, for example, there are many bottom-hole temperature points, yet no gradient anomaly is indicated. Given the deep syncline just west of the fault along with the 5,000 foot fault displacement, the setting for a major geothermal system is created. Presumably, then, the fault in this area does not permit the free passage of ground water. Such a restriction is also indicated by the ground water flow parallel to the fault system in this area proposed by Richter (1981) (see Plate II).

Between Areas 2 and 3 are few data points to confirm or deny a gradient anomaly. If the general ground water flow directions of Richter (1981) are correct, the explanations of Areas 2 and 3 suggest the anomaly may extend all along the length of the fault (although adjacent folding is most developed in and around Areas 2 and 3). The thermal well southeast of Lander is also on this fault system. It flows 99°F water from a depth of 1,884 feet for a gradient of 30°F/1,000ft. Bottom-hole temperature values between this and Area 3 no not indicate high gradients, but data are sparse. Thus, it is not known whether the well marks an isolated area of anomalous gradient or a continuation of the Area 3 anomaly along the fault.

Area 1 essentially coincides with the Dubois Oil Field. The structure is complicated and not well understood in this area. The thick mantle of volcanic rocks in the area further confuses outcrop/recharge relationships. The depths and temperatures used to define the area are large enough to be reasonably secure. Hydrologic control is assumed to some combination of folding and faulting of undetermined extent.

Area 4 is established by only 2 data points, from approximately 3,000 feet. The area occupies the crest of a major fold, however, and is located so as to receive a component of ground water flow from deep areas to the southwest. Closer examination of the area including thermal logging would be necessary to verify the anomaly.

Area 5 is established by 3 data points. These points range over 6,500 feet of depth. A maximum temperature of 230°F is reported and is considered relatively reliable. The area is located near the top of a fold, the southeast limb of which is faulted as it dips very steeply into the adjacent syncline. Confined ground water arriving at area 5 from the east and southeast rises around

7,000 feet in the last four miles. For the Cloverly Formation this is sufficient to produce a gradient anomaly of 25°F/1,000 ft and temperatures of over 200°F (at a background gradient of 12°F/1,000 ft). For the Tensleep Sandstone, approximately 2,500 feet deeper, around 30°F can be added. Ground water flow from the southwest could produce only normal gradients at Area 5 and is therefore not indicated. Also, it can be inferred that the fault just west of Area 5 does not seriously restrict ground water movement.

Area 6 is in essentially the same configuration as Area 5, except that Area 6 exists on both sides of the fault. This is additional evidence that the fault is not a ground water barrier and that it may actually create a fractured zone of locally increased permeability. Gradients are somewhat lower in Area 6, reflecting the shallower nature of the adjacent syncline. This anomaly may extend all along the fault/fold system between areas 6 and 5. Numerous data northwest of Area 5, however, are consistent in marking a generally normal gradient in that area.

Area 7 coincides with the faulted portion of the Conant Creek anticline. Thermal springs issue from the Park City Formation in this area, where erosion has cut through the confining beds of the Chugwater Formation. Although the Springs flow only 61°F, within a third of a mile is a well (presumably with more direct subsurface access) flowing 70°F (Breckenridge and Hinckley, 1978). The Park City and Tensleep aquifers plunge northward from the spring site, and bottom-hole temperatures are as high as 140°F. Breckenridge and Hinckley (1978) discuss this geothermal system in reference to the springs and present the model of northeastward ground water flow heated in the depths of the syncline between Area 7 and Area 8. Any flow from the west or southwest would be adequate to produce the observed temperatures in the Paleozoic formations beneath Area 7. Richter's (1981) proposal of flow from the southeast would almost certainly be inadequate, and is therefore not indicated. Were it not for the thermal springs and flowing well, the sparse bottom-hole temperature data would probably not be considered sufficient to verify an anomaly in contradiction of the previously proposed flow direction.

Area 8 is defined by numerous and consistent bottom-hole temperatures from deep zones with high temperatures. Although there are no surface flows from this system, thermal logging confirms the bottom-hole temperature derived gradients. Most of the temperature values are from the Tensleep Sandstone which range from 150 to 180°F. The highest temperature reported for this area is 234°F from the Park City Formation at a depth of 5,443 feet. Like most of the anomalous areas discussed so far, Area 8 occupies the top of the fold, adjacent to a large displacement (2,000-3,000 feet) fault and a deep syncline. The Tensleep Sandstone is approximately 12,000 feet deep just west of Area 8, and is around 10,000 feet deep even in the shallower part of the syncline south of the anomaly. This is sufficient to produce temperatures of 180°F even at a 12°F/ 1,000 ft gradient. Ground water flow from the structural depression just northwest of Area 8 could be 230°F at this gradient. Thus, the gradient anomaly is consistent with ground water flow northward and eastward off the flanks of the Wind River Mountains.

As in previous cases, the anomaly at Area 8 requires that the fault not seriously impede ground water movement in that vicinity. Bottom-hole temperatures north and south of Area 8 along the same structural trend are not generally anomalous. A change in the hydrologic effect of the fault is a possible explanation of this distribution.

Area 9, 10, and 11 are weak anomalies. Gradients of 15-20°F/1,000ft are well established by deep wells into a variety of upper Mesozoic and Lower Cenozoic strata. The highest reported temperature in these areas is 348°F, from a depth of 20,853 feet in Area 9. These areas occupy one of the structurally lowest portions of the Wind River Basin, just south of a major and complex fault zone. The north side of this fault system has been uplifted to form the Precambrian cored Owl Creek Mountains. Displacements in excess of 20,000 feet are common; stratigraphic and hydrologic disruption is total. Due to the great depths involved and the very thick Tertiary section in this area, Pre-Cenozoic structure is not well known. As discussed earlier, Plate II is compiled for the Cloverly Formation but corresponds in general geometry to all strata deposited prior to the folding and faulting of the Cloverly Formation. The ages of the formations containing the data which define Areas 9-11 span the time of these deformational events, which further complicates the structural environment of any geothermal system.

Area 9 roughly conforms to the crest of a broad anticline in the Cloverly Formation. Structural mapping by Barlow and Haun, (1978) indicates this fold involves strata as young as the Waltman Shale Member of the Fort Union Formation. Ground water flow regimes are not known for the area, so maximum temperatures and anomaly extent cannot be predicted. Due to the great thickness of overlying Wind River Formation, and the moderate gradients involved, this anomaly probably only represents a useful resource where existing drilling provides access.

The origin of areas 10 and 11 is even less clear, for there does not appear to be the general structural control of folding as at Area 9. Whether there are unrecognized faults and folds controlling the flow of heated ground water in these deep systems is not known. Given the total thickness of sedimentary rocks in these areas, temperatures in excess of 400°F may be generated in the Paleozoic aquifers under normal gradients. If the ground water in these units accessed higher strata, anomalies would be grater than those already discussed.

An alternative explanation for the indicated anomalies in Areas 9-11 is higher heat flow. Measured heat flows just to the north in the Owl Creek Mountains are sufficient to create purely conductive gradients in the range of those observed (depending on formation thermal conductivities). In this case the apparent absence of structural/hydrologic control is no longer a problem for the moderately high gradients could be caused simply by the higher heat flow. Further study of the hydrology and thermal conductivities of the strata in this area may serve to define the geothermal potential and to refine understanding of regional heat flow as well.

Area 12 is on the margin of the Wind River Basin, in a configuration similar to that of Areas 6-8. Major faults dominate the structure, though the area roughly corresponds to the crest of a north-trending anticline. Based on Plate II, ground water circulation in confined aquifers is probably not deep enough to create this anomaly. Thus, vertical migration of ground water along the faults is a more likely mechanism. The thermal gradients of three data points identifying Area 12 are not high, however, and further exploration is needed to verify these gradients.

Area 13 is in a complexly faulted region which is an extension of the basin-bounding fault system of Area 9. In this environment it is highly unlikely that continuous, confined aquifers exist. It is much more difficult to assess the geothermal effects of fault-created zones of vertical permeability than to analyze simple fold systems. With detailed, deep thermal logging and geochemical studies it might be possible to delineate the mechanisms creating anomalies such as this. At the present, we can only infer that waters heated in deeper strata are rising along fault zones to create the gradient anomalies observed in overlying units. In such a case, the anomaly can be expected to decrease with depth.

Area 14 appears to be fold controlled. Waters confined to the Tensleep aquifer and moving into the area from the south and southeast will have passed through depths sufficient to produce the observed temperatures under normal geothermal gradients. Waters in deeper aquifers may be 20-30°F warmer, so the maximum temperature likely to be developed for this area is less than 200°F. In absence of faults and fractures to increase permeability and allow vertical migration of water between aquifers, the observed gradients are probably as high as this system can produce.

THERMAL SPRINGS

Breckenridge and Hinckley (1978) identify 7 thermal spring localities in the Wind River Basin. (see that bulletin for detailed discussion including water temperatures, flows, chemistry, and flora.) Fort Washakie Hot Springs and Conant Creek Springs have been discussed in connection with anomalous gradient Areas 2 and 7 respectively. Although the remaining five localities are definitely geothermally anomalous, they have not been included in the previous discussion due to a lack of subsurface thermal information. All seven thermal spring localitites are shown on Plate III.

In the southeast corner of the basin is 75°F Horse Creek Springs (T.32N., R.86W., sec. 35). According to

Breckenridge and Hinckley (1978) the springs flow from alluvium along the east-west trending north Granite Mountains fault system; both cooling Eocene age Igneous rocks in the area and deep circulation along the fault system are offered as possible heating mechanisms. As discussed above, igneous activity of this are is probably too old to still contribute significant heat. Thus, the fault system becomes the most plausible mechanism for the thermal springs. This suggests a thermal anomaly may extend for some distance east and west from the springs.

Sweetwater Station Springs (T.29N., R.95W., sec. 15), west of Jeffrey City, are also fault controlled (Breckenridge and Hinckley, 1978). That nearby bottom-hole temperatures reflect normal gradients indicates the localized nature of the spring system. This also raises the question of how many more small, fault-controlled geothermal systems exist in the Wind River Basin which have neither surface expression in springs nor the oil producing potential to attract discovery through drilling.

The most enigmatic geothermal phenomena in the basin are the thermal springs near Dubois. From north to south these three spring localities are: Warm Spring Creek Springs (T.42N., R.107W., sec. 32), Little Warm Spring (T.41N., R.107W., sec. 14), and Jakeys Fork Spring (T.41N., R.106W., sec. 29), and flow a total of 700 gpm at an average temperature of 78°F (Breckenridge and Hinckley, 1978). As can be seen on Plate III, these springs define a line parallel to the northeast flank of the Wind River Mountains. All three localities are along the contact of the Park City Formation and the overlying Chugwater Formation. Reflecting this same strong stratigraphic control are extensive travertine deposits running southeast from the springs over 30 miles (Breckenridge and Hinckley, 1978). Gilliland (1959) reports a total sub-

Chugwater sedimentary thickness of 3,000 feet. Mapping by both Gilliland (1959) and Keefer (1970) indicate no significant disruption of the gentle basinward dip of the strata in this area, and nearby bottom-hole temperatures indicate gradients no higher than 15°F/1,000 ft. Thus, circulation of ground water to the lowest strata in the section is necessary to produce the observed temperatures at the indicated granite, yet there is no sign that such a circulation system exists. The possibilities of such mechanisms as previously unrecognized fault systems or local heat flow anomalies cannot be addressed without further study.

SUMMARY AND CONCLUSIONS

Background heat flow in the Wind River Basin is generally insufficient to produce high conductive gradients. Only where hydrologic systems re-distribute heat through mass movement of water will high temperatures occur at shallow depths. Aquifers which may have the confinement and structural characteristics necessary to create such geothermal systems are the Lance/Fort Union, Mesa Verde, Frontier, Muddy, Cloverly, Sundance, Nugget, Park City, Tensleep, Amsden, Madison, Bighorn, and Flathead Formations. Of these, the Tensleep Sandstone and Madison Limestone are the most attractive in terms of both productivity and water quality.

Structural control on hydrology (and hence geothermal systems) occurs through folding and faulting. Where folding is important, oil and gas exploration holes have generally provides sufficient temperature data to evaluate geothermal gradients. Where faulting alone provides the flow patterns necessary to generate a geothermal anomaly, high gradients may be localized and the data used in this report may be insufficient to delineate such an anomaly. Fault systems tentatively identified as anomalous by bottom-hole temperatures and/or the occurrence of thermal springs present useful directions for further study.

Most of the identified geothermal anomalies in the Wind River Basin occur along complex structures in the southwest and south. Large, weakly anomalous areas in the north-central basin area are unexplained and may simply reflect the overall increase in heat flow believed to occur from south to north across the basin. The most attractive geothermal prospects identified are anomalous Areas 2 and 3 north of Lander, Sweetwater Station Springs west of Jeffrey City, and the thermal springs southwest of Dubois, Even in these areas, it is unlikely temperatures in excess of 130 - 150°F can be developed. Geothermal resources elsewhere in the study area are probably best pursued in conjunction with oil and gas production or water development projects. Particularly in the case of the Paleozoic aquifers, the coincidence of oil and gas deposits and useful thermal waters is very likely. This may allow exploitation of more valuable petroleum resource to pay drilling and development costs, with thermal waters being produced as a valuable by-product.

There is also potential in the Wind River Basin for normal temperature geothermal applications such as ground water heat pumps and surface de-icing operations. The extensive surface occurrence of the highly productive Wind River Formation is very favorable in this respect, for small supplies of 40-50°F ground water should be readily available over a large portion of the basin.

Areas in which the geothermal potential could most usefully be studied further are the fault systems previously mentioned and the thermal springs system in the vicinity of Dubois. Not only would such studies help to define potentially significant energy resources, but they may also provide useful data on overall basin hydrology.

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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. Wind River Basin heat flow values[1].

Location (T-R-Sec)	Heat Flow (mW/m^2)	Thermal Conductivity (W/m^oK)
29-90-6	63	3.70
29-90-6	60	3.67
28-92-27	60	2.93
28-92-27	58	2.93
28-92-27	68	2.76
28-92-27	74	2.76
28-92-27	77	2.93
28-89-28	54	2.93
28-92-27	71	2.93
28-92-27	66	2.93
28-92-27	64	2.93
40-92-22	71	3.30
40-92-22	79	3.30
30-90-18	59	2.34
30-90-7	50	2.34

[1] Measurements made by University of Wyoming personnel as described by Decker, 1973. Values primarily from Decker et al., 1980

Table 3. Stratigraphic column for the Wind River Basin[1].

Age	Formation	Thickness (ft.)	Physical Description	Water Bearing Characteristics	Water Quality[2]
Cenozoic					
Quaternary					
Tertiary					
Pliocene	Moonstone Fm.	0-1400	poorly consolidated shale, sandstone, mudstone, tuff, limestone, and conclomgerate	Major Aquifer: yields up to 500 gpm	TDS 100-1000 mg/l
Miocene	Arikaree Fm.	0-900	sandstone with interbedded tuff, limestone, and conglomerate; basal conglomerate	Aquifer: yeilds ≤ 100 gpm Major Aquifer: yields generally up to 300 gpm, 100 gpm not uncommon	TDS <600 mg/l; Ca, Na, HCO_3, SO_4
Oligocene	White River Fm.	0-1000	fine sandstone with interbedded tuff and bentonite	Aquifer: yields 1-300 gpm, max. 850 gpm	
Eocene	Wagon Bed Fm.	0-700	bentonitic sandstone	Confining Unit: yields < 10 gpm	TDS 1500-2500 mg/l
Eocene	Tepec Trail Fm.	0-2000	tuffaceous siltstone, sandstone	Confining Unit: yields < 10 gpm	
Eocene	Aycross Fm.	0-1000	shale, mudstone, conglomerate, volcanics, sandstone	Confining Unit:	
Eocene	Wind River Fm.	250-1000	siltstone, shale, mudstone, and sandstone	Major Aquifer: yeilds up to 1500 gpm, 200 gpm flowing wells	TDS 100-5000 mg/l; HCO_3, SO_4
Eocene	Indian Meadows Fm.	0-700	mudstone, sandstone, limestone	Confining Unit:	
Paleocene	Fort Union Fm.	0-8000	conglomerate, sandstone, shale, siltstone	Aquifer: yields up to 100 gpm, 10 gpm flowing wells. Basal section is a Confining Unit	
Mesozoic					
Cretaceous	Lance Fm.	0-6000	sandstone, shale, pebble conglomerate	Aquifer: yeilds up to 100 gpm	TDS >1000 mg/l; Na, SO_4, Cl, HCO_3
Cretaceous	Meeteetse Fm.	0-1300	sandstone, shale, siltstone, mudstone	Confining Unit	poor
Cretaceous	Mesaverde Fm.	600-2000	upper unit of sandstones; middle unit of shale, siltstone, and sandstone; basal sandstone	Aquifer: yeilds up to 500 gpm, locally artesian	TDS >1500 mg/l; Na, SO_4, HCO_3
Cretaceous	Cody Shale	3000-5500	shale with interbedded thin sandstones	Major Confining Unit	poor
Cretaceous	Frontier Fm.	500-1000	alternating sandstone and shale	Aquifer: yeilds up to 150 gpm, 10-25 gpm flowing wells	TDS <500-3000 mg/l; Na, SO_4, HCO_3, Cl
Cretaceous	Mowry Sh.	400-600	interbedded shale and bentonite	Major Confining Unit	
Cretaceous	Muddy Sst.	20-150	fine to medium sandstone	Aquifer: 10-50 gpm flowing wells	TDS >500 mg/l; Cl, HCO
Cretaceous	Thermopolis Sh.	120-250	shale and mudstone, sandstone lenses	Major Confining Unit	
Cretaceous	Cloverly Fm. and	300 to 600	sandstone, middle shale unit	Aquifer: yields generally <50 gpm, up to 300 gpm, 1025 gpm flowing wells	TDS <1500 mg/l; Na, HCO_3, SO_4
Jurassic	Morrison Fm.		mudstone and shale, sandstone lenses	Confining Unit: yeilds <5 gpm	
Jurassic	Sundance Fm.	150-600	sandstone and stilstone, carbonates at base	Aquifer: 250-50 gpm flowing wells from Sundance-Nugget aquifer	TDS <500-2000 mg/l; Na, Cl, SO_4
Jurassic	Gypsum Spring Fm.	0-230	alternating siltstone, shale, limestone, and gypsum	Confining Unit	poor

Table 3 continued

Age	Formation	Thickness (ft.)	Physical Description	Water Bearing Characteristics	Water Quality[2]
Jurassic	Nugget Sst.	0-400	fine to medium sandstone, siltstone at base	Aquifer: artesian conditions common	generally >1000 mg/l; Na, Cl, SO_4
Triassic	Chugwater Fm.	1000-1300	interbedded siltstone, sandstone, and shale	Major Confining Unit: Sandstone layers locally yield <20 gpm	generally poor, sandstone layers may have TDS <1000 mg/l
Traissic	Dinwoody Fm.	0-250	interbedded siltstone, sandstone, and limestone	Confining Unit	
Paleozoic					
Permian	Park City Fm.	150-300	interbedded limestone, dolomite, siltstone, sandstone increasing shale content eastward.	Aquifer: yields up to 100 gpm	TDS <100 mg/l; Mg, Ca, Na, HCO_3, SO_4
Pennsylvanian	Tensleep Sst.	200-600	massive, fine sandstone	Major Aquifer: up to 3000 gpm flowing wells	TDS <500 mg/l near outcrops; TDS >2000 mg/l in basin interior Mg, Ca, Na, HCO_3 SO_4
Pennsylvanian	Amsden Fm.	0-400	shale, limestone, dolomite; basal sandstone		
Mississippian	Madison Lms.	200-700	limestone, dolomite; cavernous near top	Aquifer: yields 1-300 gpm	TDS <500 mg/l
Devonian	Darby Fm.	0-300	dolomite, siltstone, shale	Confining Unit: yields springs where fractured	
Ordovician	Bighorn Dol.	0-300	dolomite; basal sandstone	Aquifer	
Cambrian	Gallatin Lms.	0-450	limestone, shale, thin sandstone beds	Confining Unit: yeilds <5 gpm	
Cambrian	Gross Ventre Fm.	0-750	limestone and shale	Confining Unit	
Cambrian	Flathead Sst.	50-500	sandstone, basal conglomerate	Aquifer: yields 1-25 gpm	TDS <500 mg/l; Ca, Na, SO_4, HCO_3, good qualit
Precambrian			granite, gniess and schist	small yields where fractured	

[1] Data condensed from Richter (1981) with modifications from Whitcomb and Lowry (1968)

[2] The quality of water in any water-bearing strata may significantly deteriorate as the water migrates basin ward.

Table 4. Summary of bottom-hole temperature data and statistics, including the 50th, 66th, 80th, and 90th percentiles, from the Wind 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%
0 - 500	10	84	65	72.4	72	75	82	84
500 - 1,000	18	100	60	79.2	80	86	94	95
1,000 - 1,500	76	152	50	83.2	81	90	93	98
1,500 - 2,000	103	117	62	88.8	89	95	99	103
2,000 - 2,500	57	123	62	90.7	90	95	97	113
2,500 - 3,000	82	146	69	96.6	96	102	107	113
3,000 - 3,500	164	172	72	107.9	109	117	121	126
3,500 - 4,000	142	164	79	107.8	105	115	121	126
4,000 - 4,500	83	156	78	107.1	108	111	117	122
4,500 - 5,000	105	171	78	110.2	109	113	120	129
5,000 - 5,500	92	234	61	117.2	116	121	128	131
5,500 - 6,000	63	160	89	122.1	120	126	138	143
6,000 - 6,500	75	163	97	126.9	126	134	143	149
6,500 - 7,000	79	185	95	131.3	129	135	146	152
7,000 - 7,500	75	198	109	142.2	138	152	160	180
7,500 - 8,000	64	212	64	148.9	150	159	164	174
8,000 - 8,500	39	182	122	152.4	156	162	168	175
8,500 - 9,000	46	190	112	150.7	151	160	166	181
9,000 - 9,500	27	195	120	153.2	151	165	171	184
9,500 - 10,000	34	230	68	158.3	160	169	180	205
10,000 - 10,500	34	250	125	175.0	181	189	204	215
10,500 - 11,000	31	214	124	163.8	163	173	184	198
11,000 - 11,500	45	240	134	187.4	192	199	205	211
11,500 - 12,000	43	250	142	196.9	195	202	208	214
12,000 - 12,500	22	260	135	197.0	208	214	217	225
12,500 - 13,000	14	306	170	217.9	212	226	242	265
13,000 - 13,500	12	245	159	207.2	216	238	238	240
13,500 - 14,000	17	267	172	221.2	230	240	255	264
14,000 - 14,500	9	268	218	245.7	256	262	262	268
14,500 - 15,000	6	290	174	246.8	268	281	281	290
15,000 - 15,500	7	284	200	241.4	250	252	265	284
15,500 - 16,000	7	292	216	248.3	252	254	270	292
16,000 - 16,500	11	316	245	294.0	305	309	314	316
16,500 - 17,000	2	278	258	268.0	278	278	278	278
17,000 - 17,500	4	340	317	331.3	338	338	340	340
17,500 - 18,000	8	345	268	315.3	338	340	345	345
18,000 - 18,500	9	345	308	331.2	337	338	344	345
18,500 - 19,000	2	351	338	344.5	351	351	351	351
19,000 - 19,500	5	356	318	331.4	325	340	356	356
19,500 - 20,000	4	343	318	327.3	343	343	343	343
20,000 - 20,500	1	310	310	310.0	310	310	310	310
20,500 - 21,000	3	348	323	338.0	343	348	348	348
21,000 - 21,500	-	-	-	-	-	-	-	-
21,500 - 22,000	2	370	309	339.5	370	370	370	370
22,000 - 22,500	-	-	-	-	-	-	-	-
22,500 - 23,000	1	370	370	370.0	370	370	370	370

Total: 1,733 bottom-hole temperature measurements.

Table 5. Summary of gradient data and statistics, including the 50th, 66th, 80th, and 90th percentiles, derived from bottom-hole temperatures from the Wind 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%
0 - 500	10	144	48	79.0	67	72	104	144
500 - 1,000	18	81	20	45.9	45	50	55	65
1,000 - 1,500	76	77	5	30.9	30	34	39	43
1,500 - 2,000	103	43	11	26.4	25	28	31	34
2,000 - 2,500	57	37	9	21.4	21	23	24	29
2,500 - 3,000	82	39	8	19.5	19	21	22	24
3,000 - 3,500	164	38	8	19.6	19	21	23	24
3,500 - 4,000	142	30	9	17.5	16	19	21	22
4,000 - 4,500	83	26	8	15.2	14	15	17	18
4,500 - 5,000	105	26	7	14.1	13	14	16	18
5,000 - 5,500	92	35	3	14.1	13	14	15	17
5,500 - 6,000	63	20	7	13.8	13	14	16	17
6,000 - 6,500	75	18	8	13.4	13	14	15	16
6,500 - 7,000	79	20	7	13.0	12	13	15	16
7,000 - 7,500	75	21	9	13.7	12	15	16	18
7,500 - 8,000	64	21	2	13.6	13	14	15	17
8,000 - 8,500	39	17	9	13.3	13	14	15	15
8,500 - 9,000	46	16	7	12.3	12	13	13	15
9,000 - 9,500	27	16	8	11.9	11	13	13	15
9,500 - 10,000	34	19	2	11.8	11	12	13	16
10,000 - 10,500	35	20	7	12.9	12	14	15	16
10,500 - 11,000	31	16	7	11.3	11	12	12	14
11,000 - 11,500	46	17	8	12.8	13	13	14	14
11,500 - 12,000	43	17	8	13.1	12	13	14	14
12,000 - 12,500	24	17	7	12.7	13	13	14	14
12,500 - 13,000	13	17	9	13.2	13	13	14	15
13,000 - 13,500	12	15	8	12.3	12	13	14	14
13,500 - 14,000	19	16	9	12.8	12	14	14	15
14,000 - 14,500	9	15	12	14.3	15	15	15	15
14,500 - 15,000	6	16	8	13.8	15	16	16	16
15,000 - 15,500	6	15	10	13	13	14	14	15
15,500 - 16,000	7	15	10	13.1	13	13	14	15
16,000 - 16,500	12	16	10	15.0	16	16	16	16
16,500 - 17,000	2	14	12	13.5	14	14	14	14
17,000 - 17,500	4	17	15	16.7	17	17	17	17
17,500 - 18,000	9	17	12	15.3	16	16	16	17
18,000 - 18,500	9	16	14	15.8	15	16	16	16
18,500 - 19,000	2	16	15	16.2	16	16	16	16
19,000 - 19,500	5	16	14	15.0	14	15	16	16
19,500 - 20,000	4	15	13	14.3	14	14	15	15
20,000 - 20,500	1	13	13	13.1	13	13	13	13
20,500 - 21,000	3	14	13	14.3	14	14	14	14
21,000 - 21,500	-	-	-	-	-	-	-	-
21,500 - 22,000	2	15	12	13.7	15	15	15	15
22,000 - 22,500	-	-	-	-	-	-	-	-
22,500 - 23,000	1	14	14	14.5	14	14	14	14

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

Table 6. Thermally measured wells in the Wind River Basin^1.

Location		Depth (meters)	Bottom-hole Tempreature (C°)	Gradient^2 (°C/km)	Interval^3 (meters)
Latitude	Longitude				
		FREMONT COUNTY			
43 38.5	109 42.1	67.9	6.606	10.0	40-67
43 37.2	109 38.5	630.0	25.660	31.1	90210
43 31.4	109 2.3	274.0	16.000	29.3	20-274
43 31.3	109 2.2	284.5	18.100	25.8	170-240
43 31.1	109 2.4	208.5	13.802	25.4	100-208
43 24.7	107 54.5	193.5	13.646	23.5	20-193
43 24.6	107 54.8	193.0	13.398	21.3	100-193
43 24.5	107 54.5	197.5	13.426	23.0	110-190
43 24.5	107 52.6	172.2	12.526		
43 24.4	107 55.0	140.7	11.892	20.2	100-140
43 24.4	107 55.0	141.0	11.892	20.2	100-140
43 24.4	107 54.8	190.7	13.739	19.7	80-190
43 24.4	107 53.5	133.2	10.706	4.2	9-133
43 24.4	107 52.9	152.0	13.340	34.4	10-150
43 24.4	107 51.7	99.5	11.030	24.3	50-99
43 24.3	107 52.5	164.3	12.621	5.3	29-164
43 24.2	107 53.4	118.7	11.613	6.8	30-118
43 24.1	107 53.7	84.3	12.177	6.3	9-84
43 20.7	107 51.2	40.0	13.074		
43 20.6	107 51.4	75.0	12.646		
43 20.6	107 51.4	89.0	11.411	20.0	60-89
43 20.3	107 52.0	173.0	15.330		
43 16.3	108 54.2	1,610.0	53.460	30.2	200-1,610
43 7.0	108 53.6	165.0	16.964	60.1	80-163
43 7.0	108 53.4	1,080.0	53.292	36.3	340-1,080
42 54.7	107 35.5	38.0	9.468		
42 54.6	107 32.9	38.0	7.232		
42 54.6	107 32.7	66.0	9.500		
42 54.6	107 32.3	58.0	9.497		
42 54.6	107 31.1	63.0	9.869		
42 54.4	107 33.2	52.0	9.448		
42 52.7	108 7.0	89.0	11.411	20.0	60-89
42 52.2	108 19.4	215.0	14.644	19.2	20-215
42 52.2	108 17.3	120.0	12.900	17.8	30-120
42 50.5	108 17.6	180.6	14.120	19.6	50-180
42 50.5	108 17.3	290.0	15.922	18.1	40-120
42 50.2	108 51.5	60.0	9.512	30.6	10-50
42 50.1	108 52.8	291.0	9.788		
42 46.2	108 9.5	220.0	14.304	25.9	80-220
42 45.4	107 10.4	1,410.0	62.101	39.0	100-1,410
42 45.4	107 40.7	41.0	8.740	11.8	20-41
42 45.4	107 40.7	29.0	8.268		
42 45.4	108 40.7	38.0	8.829		
42 44.6	107 10.7	1,900.0	71.884	33.4	10-1,900
42 44.6	107 35.4	339.0	14.611	27.8	150-210
42 44.5	107 35.3	340.0	14.631	21.5	150-340
42 44.0	107 35.2	232.0	14.918	38.7	20-150
42 41.9	107 48.4	127.0	10.144	20.2	50-127
42 41.8	107 48.5	60.0	9.044	20.8	20-60
42 41.8	107 48.3	96.0	9.976	15.1	40-90
42 40.7	107 46.1	87.0	10.883		
42 40.4	107 48.0	65.0	10.829	45.2	20-65
42 40.4	107 44.3	137.0	11.673	35.1	60-130
42 40.4	107 42.9	126.0	10.269	25.6	50-120
42 40.4	107 42.0	177.0	12.025	31.6	30-170
42 40.4	107 40.5	127.0	10.032	22.4	50-127
42 39.4	107 42.9	203.0	11.980	26.1	40-203
42 39.4	107 41.9	180.0	14.402	54.2	40-130
42 39.4	107 40.6	185.0	13.040	20.4	50-160
42 38.5	107 40.6	216.0	13.653	40.3	90-190
42 35.1	107 40.6	255.0	12.503	26.4	70-190
42 35.0	107 40.0	195.0	12.222	17.5	90-160
42 35.0	107 40.0	180.0	12.212	20.9	80-180
42 35.0	107 40.0	57.0	9.828	13.5	20-57
42 34.3	107 39.5	310.0	13.322	18.4	90-250
42 25.3	107 56.2	1,310.0	59.601	38.7	40-1,310
42 23.4	107 56.4	1,530.0	52.665	28.0	100-1,100

NATRONA COUNTY

42 51.4	106 46.4	670.0	33.435	26.6	200-740
42 51.4	106 4604	380.0	24.356	33.3	20-280

[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.

Table 7. Geothermal gradient anomalies in the Wind River Basin, Wyoming.

Area	Location (TWN-RNG)	Thermal Gradients (°F/1000 ft.)	Approximate Depths feet	Approximate Temperatures (°F)	Principal Formation(s)	Structural Control
1	42,43N-107W	15-30	3000-4000	110-160	Tensleep, Phosphoria	?
2	1,2N-1W,1E	20-40	2000-3500	100-130	Phosphoria, Tenslep Madison	fault/fold
3	25-2E 33N-99W	20-30	≤2000	90-110	Phosphoria	fault/fold
4	1S-5E	24-25	3000	110-120	Ft. Union	fold
5	1S-6E	16-20	2500-9000	170-230	Morrison, Tensleep	fold(?)
6	33,34N-94,95W	15-18	5000-8000	130-170	Shell Cr., Madison, Tensleep, Sundance	fault
7	33N-93,94W	20-25	4000-5000	130-140	Tensleep	fault/fold
8	32N-94,95W	15-19	6000-8000	120-180	Tensleep	fault/fold
9	38,39N-89,90,91W	15-17	7000-19000	140-330	Wind River, Ft. Union, Lance, Shannon, Cody Frontier	fold/fault
10	37N-90-91W	15-20	9000-15000	190-250	Ft. Union, Lance, Meeteetsee	?
11	37,38N-89W	15-17	5000-15000	190-270	Ft. Union, Lance	fold(?)
12	33N-90W	18-28	3000-6000	100-154	Tensleep	fault
13	37N-85, 86W	20-35	2000-4000	100-140	Cody, Frontier, Mowry	fault
14	37,38N-83W	19-22	3500-5000	110-170	Tensleep (?)	fold

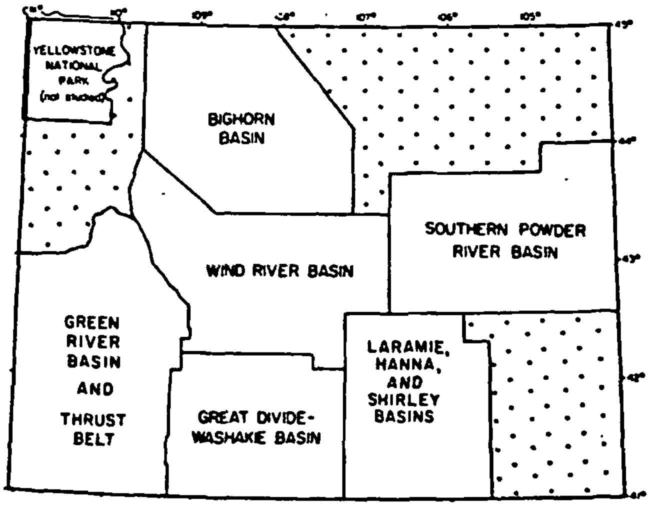


Figure 1. Study areas planned or completed in this series.

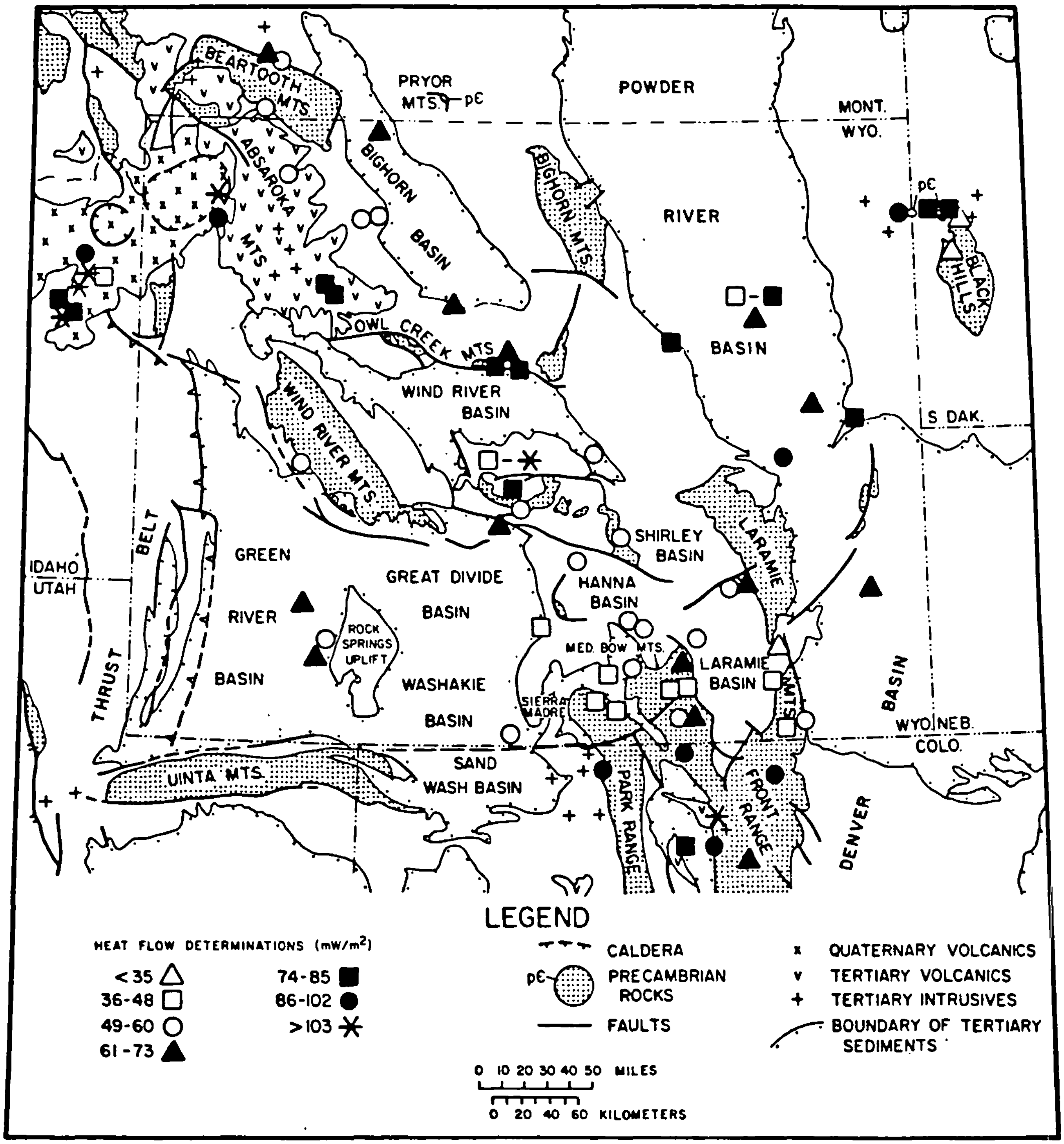


Figure 2. Generalized geology and generalized heat flow in Wyoming and adjacent areas. From Heasler et al., 1982.

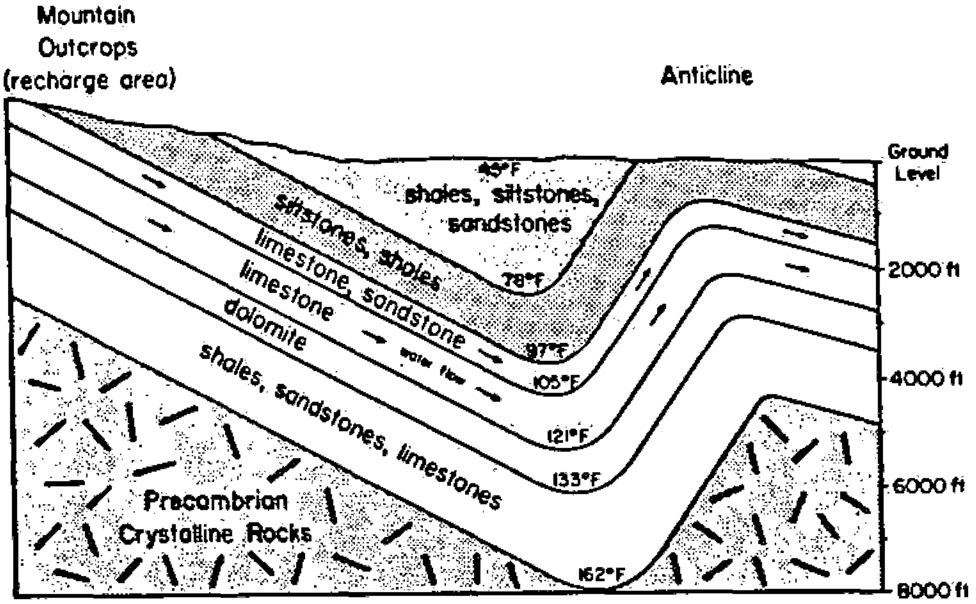


Figure 3. Simplified cross section of a typical Wyoming fold-controlled geothermal system.

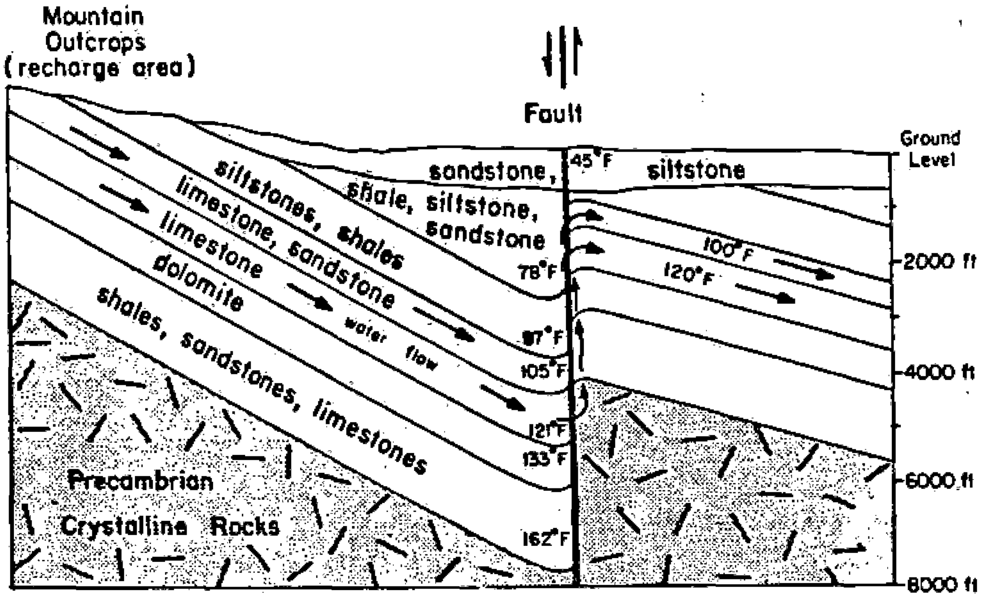


Figure 4. Simplified cross section of a typical Wyoming fault-controlled geothermal system.

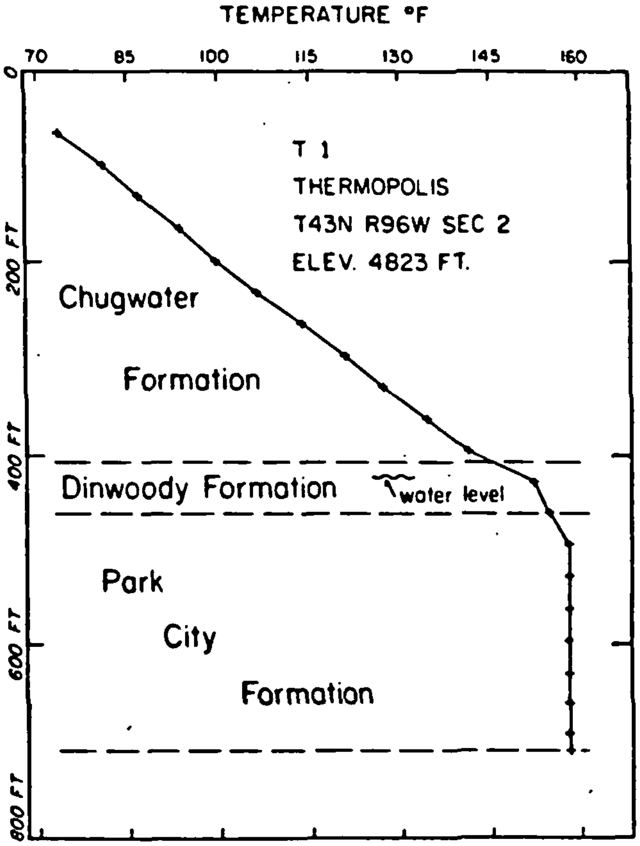


Figure 5. Temperature-depth plot, based on a thermal log of a well at Thermopolis, showing hydrologic disturbance. From Hinckley et al., 1982.

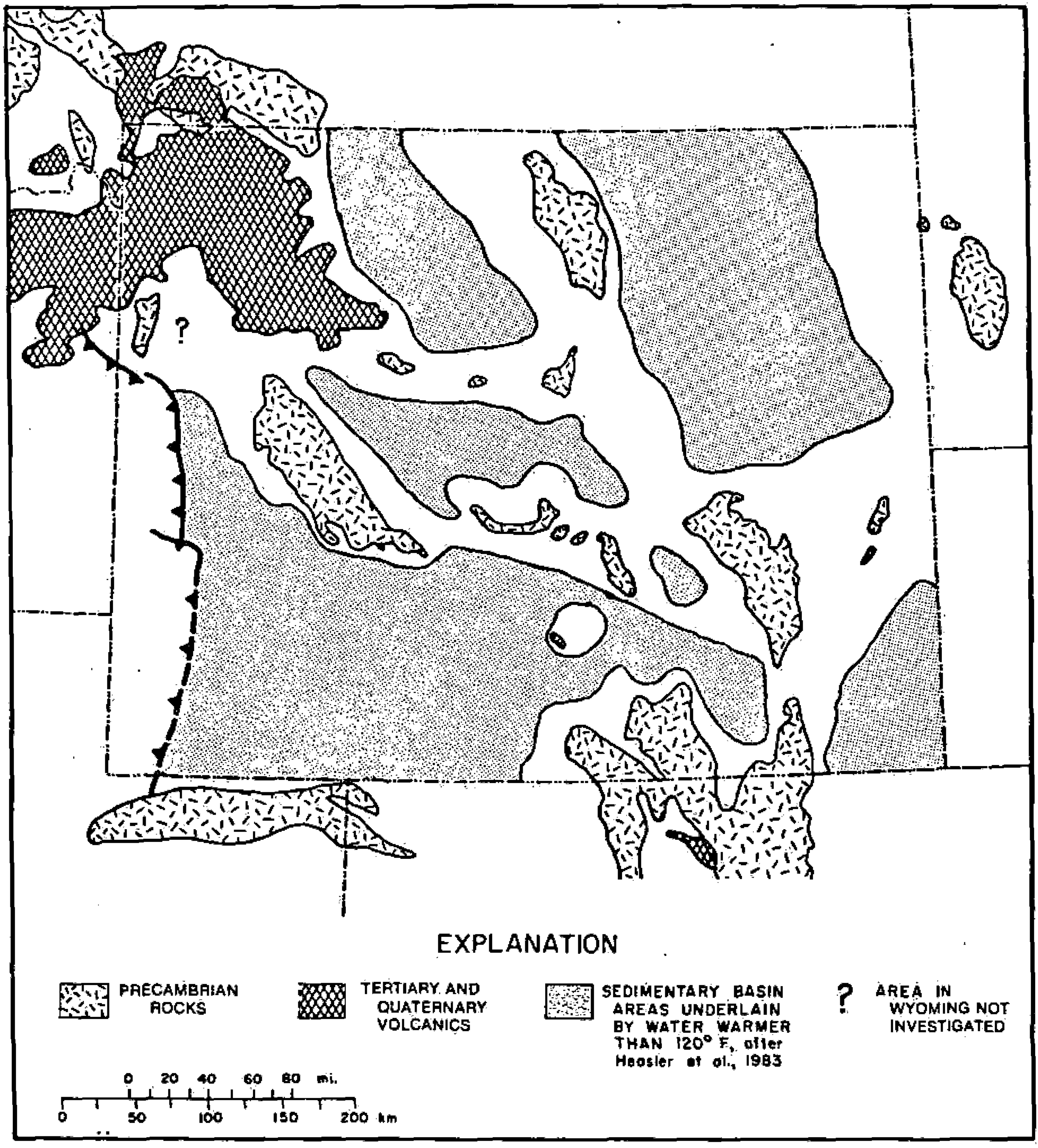


Figure 6. Simplified geologic map of Wyoming, showing sedimentary basin areas defined in this series of reports to be underlain by water warmer than 120°F. After Heasler et al., 1983.

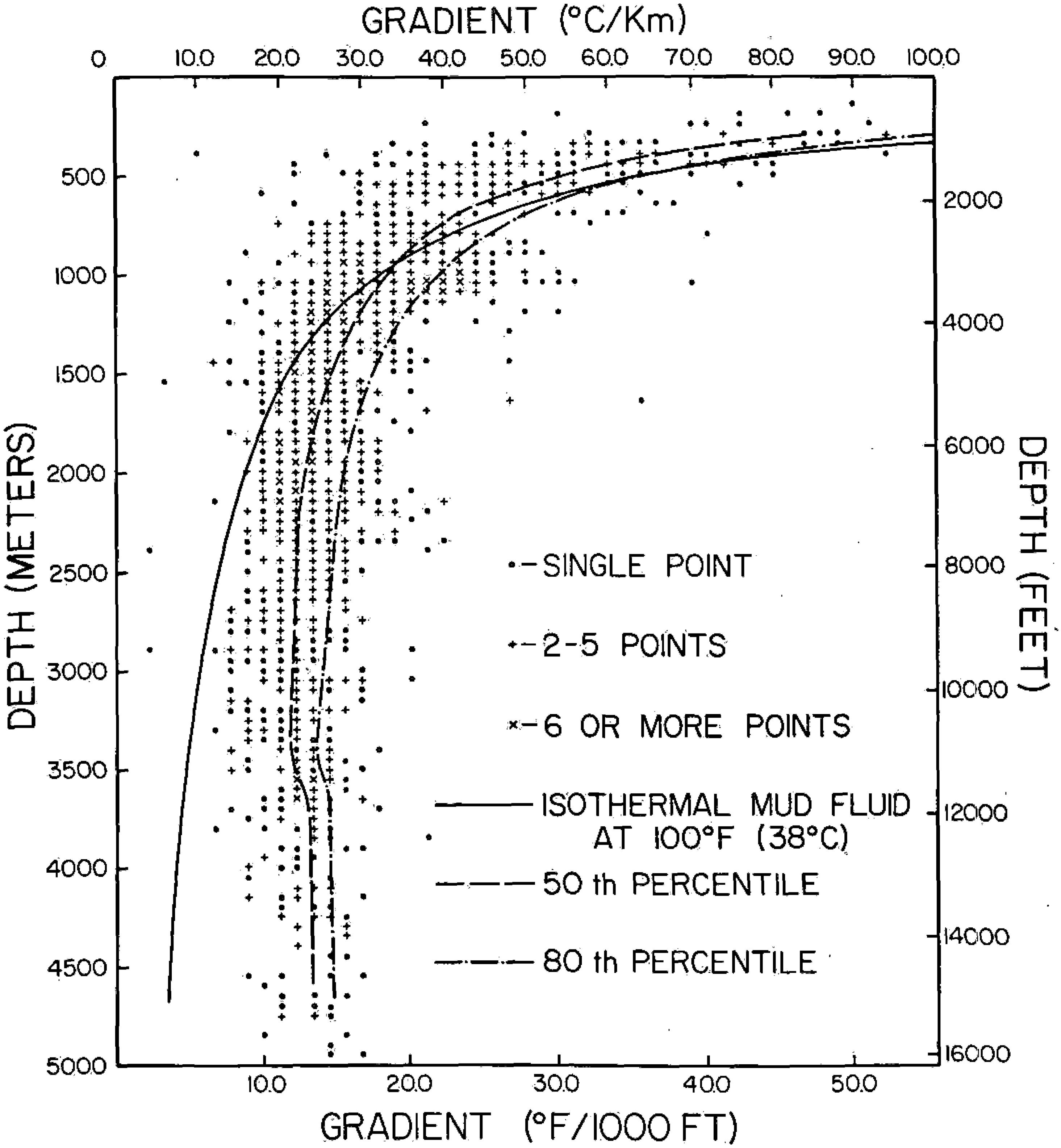
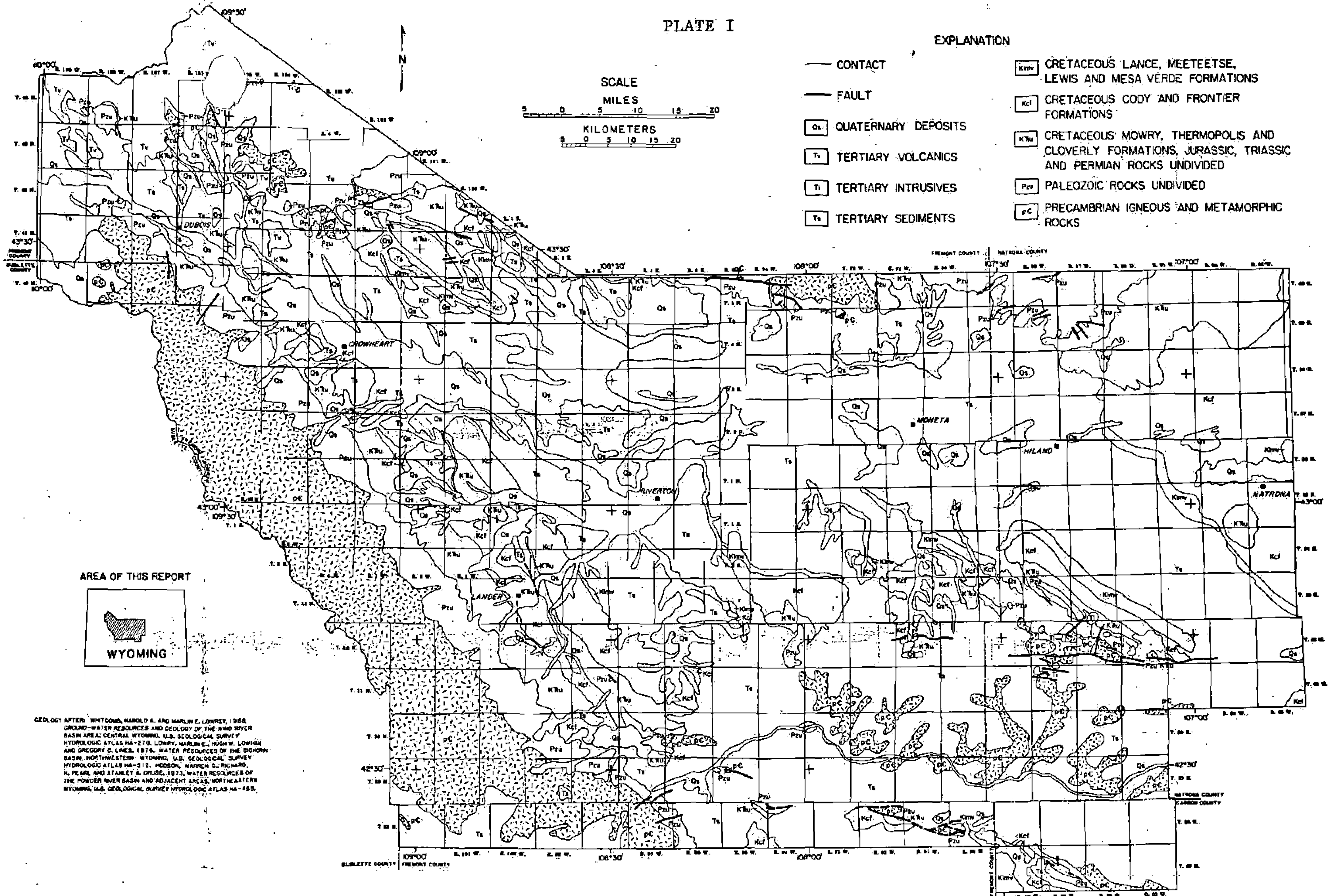


Figure 7. *GRADIENT-DEPTH PROFILE FOR WIND RIVER BASIN, BASED ON 1733 BOTTOM-HOLE TEMPERATURES.*

PLATE I

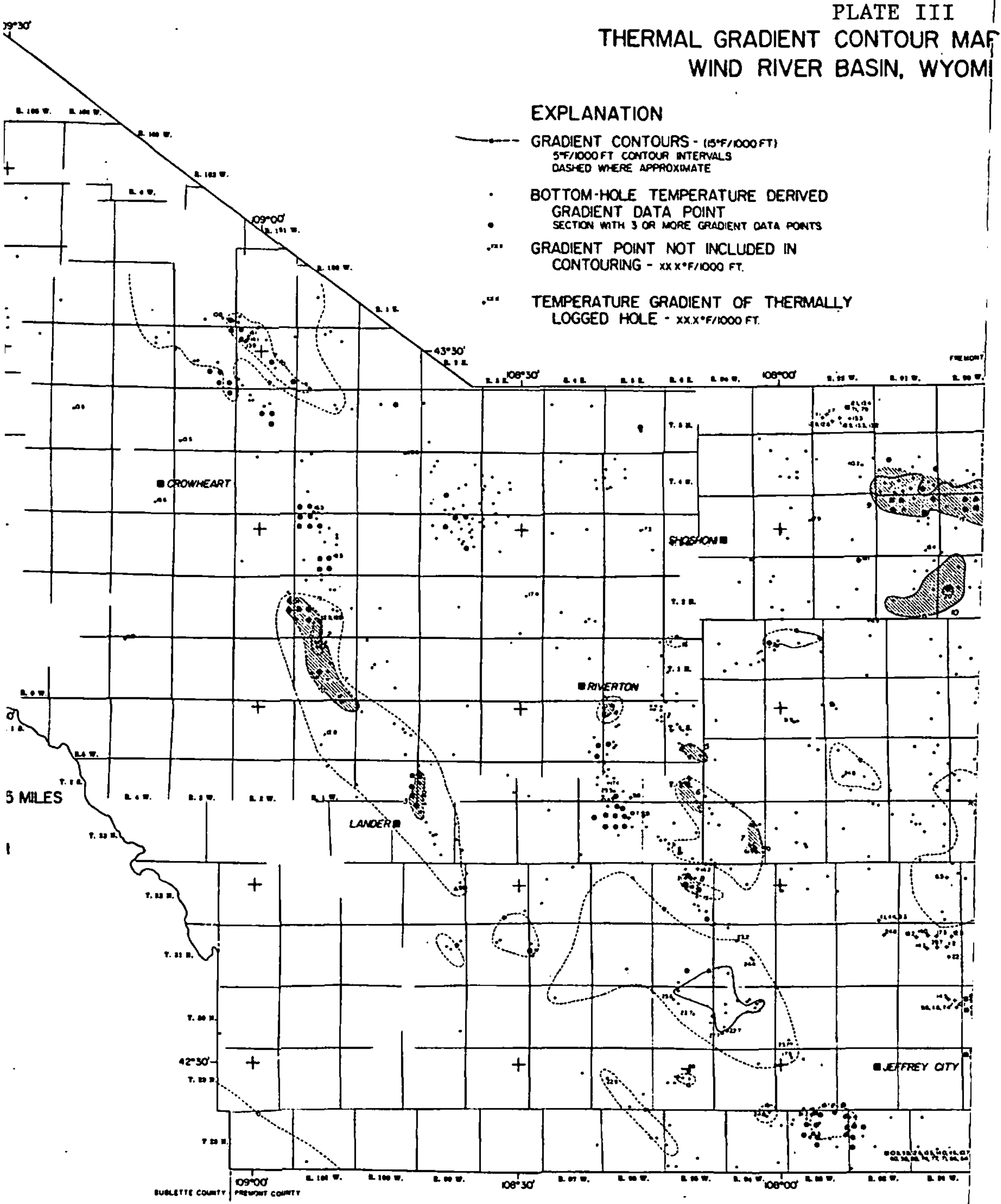


GEOLOGY AFTER: WHITCOMB, HAROLD A. AND MARLIN E. LOWRY, 1968, GROUND-WATER RESOURCES AND GEOLOGY OF THE WIND RIVER BASIN AREA, CENTRAL WYOMING, U.S. GEOLOGICAL SURVEY HYDROLOGIC ATLAS HA-270. LOWRY, MARLIN E., HUGH W. LOWHAM AND GREGORY C. LINES, 1976, WATER RESOURCES OF THE BIGHORN BASIN, NORTHWESTERN WYOMING, U.S. GEOLOGICAL SURVEY HYDROLOGIC ATLAS HA-512. HODSON, WARREN G., RICHARD H. PEARL AND STANLEY A. DRUSE, 1973, WATER RESOURCES OF THE POWDER RIVER BASIN AND ADJACENT AREAS, NORTHEASTERN WYOMING, U.S. GEOLOGICAL SURVEY HYDROLOGIC ATLAS HA-465.

GENERALIZED GEOLOGIC MAP OF THE WIND RIVER BASIN, WYOMING

PLATE III

THERMAL GRADIENT CONTOUR MAP
WIND RIVER BASIN, WYOMI



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Geth Res., LBL, 1973

Geothermal Steam Condensate Reinjection

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ABSTRACT

The simplest and most economical way to dispose of steam condensate and other geothermal fluids after power extraction is by reinjection into the geothermal reservoir. This process also offers opportunities for extraction of additional energy from the reservoir. Injection wells can be retired production wells. However, communication between the injection wells and currently producing wells must be avoided. Also, the injectivity of individual wells may decline with time unless preventive steps are taken. Brief case histories are given here of successful reinjection projects in three geothermal areas: The Geysers and Imperial Valley, California; and Valles Caldera, New Mexico.

INTRODUCTION

The native fluids produced from most geothermal systems recover only a fraction of the total energy within the system. The most apparent method of recovering additional heat from the system is to inject cold water back into the reservoir [illegible] extract heat from the reservoir rock. Also, geothermal electric generating plants which use condensing turbines generate an excess of condensed steam which must be disposed of. So even vapor-dominated or dry-steam fields will have large volumes of excess steam condensate, and fluid-dominated or hot-water fields will have even larger volumes to dispose of.

The simplest and most economical method of disposing [illegible] this water and condensed steam is to reinject it into [illegible] geothermal reservoir. The alternatives to this course [illegible] action are either surface disposal or underground disposal zones other than the geothermal reservoir. To purify [illegible] water adequately for surface disposal is often very expensive, and disposal zones other than a geothermal reservoir are often not available in many areas of the country.

Union Oil Company has operated geothermal condensate injection projects at The Geysers and Imperial Valley, California, and at the Valles Caldera, New Mexico. The purpose of this paper is to provide a case history for each [illegible] these projects.

THE GEYSERS

[illegible] The Geysers, California, a vapor-dominated reservoir, injection of steam condensate back into the reservoir began [illegible] 1969, and 4 149 000 000 gal of condensate have been injected since that time. Currently, 4 700 000 gal per day from 522 MW of installed capacity are being injected into six wells.

The condensed steam is essentially fresh water, although there is a small volume (about 1%) of other gases in the steam, some of which is soluble in the steam condensate. These contaminants, principally ammonia and boron, are present in concentrations in excess of the limits set by the Regional Water Quality Control Board for discharge directly to the watershed.

The condensed steam is received from the cooling tower basins of the electric generating plants and piped to settling basins. These settling basins are approximately 50 × 50 ft and 8 ft deep, constructed of concrete with wooden baffles, and are designed to remove any settleable solids from the effluent. Level control valves are installed on the outlet of these basins to insure that no air is allowed to enter the discharge pipe that leads to the injection wells. From the settling basin, the water either flows by gravity or is pumped through plastic-coated welded steel pipelines to the injection wells. Deaerating vessels are installed on the lines as an additional precaution against air being injected into the wells and causing corrosion problems. A continuously recording orifice meter is also installed in the pipeline to record the volume of water injected into each well.

All of the five injection wells were originally drilled as steam production wells and then converted to injection service. The wells are drilled with water-based drilling fluid down to the top of the steam reservoir, where a string of 9 5/8-in. casing is set. The producing interval is drilled using air as the circulating medium to the total depth of the well. Producing wells are left in this condition, but conversion to injection requires that a slotted liner be placed through the injection interval to prevent the formation from sloughing into the well bore on contact with water (Fig. 1).

The Geysers steam reservoir is a fractured graywacke with steam production occurring from a few hundred feet to over 9000 ft in depth. The initial reservoir pressure is about 500 psi. Since the injection wells have depths ranging from 2364 ft to 8045 ft, this low reservoir pressure causes a large pressure differential toward the formation, and the wells will inject large volumes of water without requiring pumping. The high permeability-thickness products (from 20 000 to 150 000 millidarcy feet) encountered in the wells are also a factor in the high injection rates (1200 gal/min) with no back-pressure at the wellhead.

The locations of the injection wells are chosen so that they are as far as possible from existing producing wells, and the injection interval is deeper than the producing

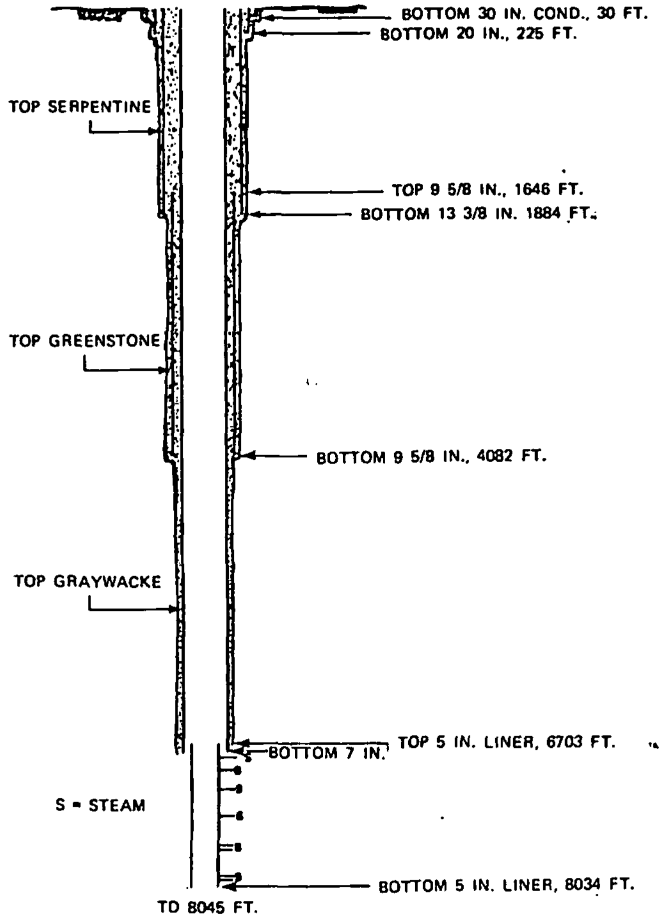

Figure 1. Typical injection well.

interval in the adjacent producing wells. This precaution has so far been sufficient to prevent communication of the injection water to the producing wells. The importance of injection depth was illustrated early in the life of the injection project when communication from the first injection well to a nearby producing well was established. A spinner survey run in the injection well showed that due to a bridge in the well bore, the water was being injected at a shallower depth than anticipated. The injection well was then cleaned out to total depth and a slotted liner run. The well was returned to injection and has been on injection for five years with no further evidence of communication.

There have been some problems with the injectivity of individual wells declining with time. The cause of this has been attributed to plugging of the fracture system with elemental sulfur in the steam condensate. This problem is easily overcome by shutting the well in and letting it heat up. Since the melting point of sulfur is 238°F and the reservoir temperature is 475°F, the sulfur is easily melted and can be pushed away from the well bore and back into the formation.

The Division of Oil and Gas is the state agency responsible for regulation of geothermal reinjection projects. Before approving the project, they examine the geologic and engineering data, including reservoir conditions, injection fluid volumes and analyses, geologic maps, and cross sections. They also must approve the drilling or conversion of each individual injection well. A report on the injection volumes is sent to the Division of Oil and Gas on a monthly basis. The water quality of the adjacent watershed is also monitored monthly.

The USGS is monitoring both seismically and by methods of triangulation any land movements that might occur as a result of our injection program. The data indicate that there is no noticeable change in the seismic activity within the area.

VALLES CALDERA, NEW MEXICO

Union Oil's reinjection experience at the Valles Caldera is a result of production testing two geothermal wells in that area during 1973 and 1974. The reservoir is a liquid-dominated reservoir, and the fluid flashes to a mixture of steam and water when the wells are produced. The wells were flowed through a steam-water separator and the water was flowed into holding ponds and then pumped to the injection well. The test has been under way for a little over a year, and during this time almost 100 000 000 gal of water were reinjected. There have been no evidences of injectivity impairment during that time.

IMPERIAL VALLEY

Union Oil's reinjection experience in the Niland area of the Imperial Valley is again the byproduct of a production test. This test was of one year's duration during 1964 and 1965. The reservoir is liquid-dominated, and static wells have a wellhead pressure of 200 psig. After initially overcoming this pressure, the heavier column weight of the cold injection water allowed the injection well to take water at a vacuum. During the one-year test, approximately 126 000 000 gal of water were reinjected. The injection rate into the well was approximately 600 gal/min. Again, there was no loss of injectivity during the test and there was no reservoir response.

A. J. Ellis

Geothermal Systems and Power Development

Natural hot water and steam fields are a valuable source of useful energy in several countries, and in many others they are being developed rapidly

For most people, geothermal fields probably call to mind visions of hot-spring areas like those of Yellowstone National Park, Iceland, or New Zealand, with geysers like Old Faithful or the Great Geysir, and fumaroles like Karapiti blowhole at Wairakei (see Fig. 1). But natural hot waters are now being used in many countries for space heating, bathing, and agricultural purposes, and the power stations in Italy, the United States, and New Zealand that produce electricity from geothermal steam have received considerable publicity. Plans to utilize geothermal energy are being made worldwide, and, although the technology is still at an early stage of development comparable to that of the petroleum industry at the turn of the century, rapid development may be expected as a result of the current energy crisis.

This article provides a brief outline of the nature of geothermal fields, geothermal power projects, and some development problems. The topic was covered thoroughly in a series of papers presented in a United Nations Symposium on the Development and Utilization of Geothermal Resources at Pisa, Italy, in late 1970 (*Geothermics* 1970) and again at a similar symposium held in San Francisco in May 1975.

Hot springs are found throughout the world, but systems with water temperatures above about 100°C within 1–2 kilometers of the surface are limited to regions with heat flows several times greater than the crustal average. Frequently these regions are in zones of current or recent crustal plate divergence, with associated basaltic volcanism (as along the Mid-Atlantic Ridge or the African rift valleys), or in subduction zones where plates meet and crustal material is forced down to depths where it melts to produce andesitic volcanism, such as is common around the margins of the Pacific and in the Caribbean. A belt of high-temperature hydrothermal systems stretching from Italy to Greece and Turkey, through the Caucasus, and to southwest China is associated with major tectonic activity and mountain building (Ellis, in press). Water temperatures may reach 120–150°C at depths of 3–4 km in coastal areas of the Gulf of Mexico basin (Jones 1970) and in western Siberia, in thick sedimentary beds filling a wide rift zone created by the separation of Siberian and European platforms (Tamrazyan 1970). Figure 2 shows the distribution of major hydrothermal systems throughout the world.

The geothermal fields now being investigated or used for power production are found in a wide variety of geological environments and rock types. The western Pacific fields are predominantly within recent andesitic or rhyolitic volcanic areas, whereas the Larderello steam field in Italy and the Kizildere area in Turkey are in regions of limestone, dolomite, marble, and shales. The Geysers steam field in northern California is situated in fractured graywacke, and, in the Salton Sea area of southern California, water at high temperatures is contained in deltaic river sediments.

All geothermal fields have individual peculiarities, but they also have features in common. In some sedimentary basins, or in areas of current metamorphism, heated waters or brines of moderate temperature (up to 150–200°C) may be accessible for geothermal exploitation. For the most part, however, with exceptions like Larderello and Kizildere, the known high-temperature (200–350°C) geothermal fields are found in, or are associated with, nearby Quaternary or Recent volcanic rocks. Extensive faulting, tilting, and graben and caldera formation are common in the volcanic hydrothermal areas, creating conditions of high permeability. Isotopic analysis of hydrogen and oxygen (Craig 1963) has shown that the hot water or steam discharged at the surface is derived from local cold surface water that penetrated the rocks from above. The circulation of water through the systems is thought to be extremely slow (at least 10^4 years). Geothermal systems are long-lived geological features, several having indicated lifetimes of the order of 10^6 years (White 1974), but fluid output during this period may be discontin-

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Figure 1. The fumarole, one of many in the Karapiti area to the south of the Wairakei Geothermal Field in New Zealand, is typical of the naturally occurring hot water–steam vents found in hot spring areas throughout the world. The steam emerges from the center of a minor hydrothermal explosion crater. (Photo by R. B. Glover.)

uous, due to the tendency of systems to seal themselves off through mineral deposition (Facca and Tonani 1967; Ellis 1970).

A model system

In a typical high-temperature geothermal system (Fig. 3), cold surface water penetrates to levels many kilometers deep through fractured or porous formations, becoming heated and chemically altered as it flows slowly through the rocks. The lower density of the heated water creates a convection cycle, and the upflowing hot water selectively follows routes of highest permeability. In porous horizons, the water can spread laterally for distances up to several kilometers. Impermeable formations such as igneous rocks or fine-grained sediments act as barriers between aquifers, but faults or igneous intrusions offer a passage through these strata. Various kinds of cap rocks, sometimes supplemented by the deposition of silica or calcium carbonate from the water, prevent rapid dissipation of both water and heat.

In areas where surface outflows are restricted, the geothermal system often contains a liquid throughout, with boiling water emerging at the surface under a "thermo-artesian" pressure. Where the surface outflows of water are of similar magnitude to the limited upflows permitted by faults in deep impermeable formations, a subsurface hot water–steam interface may form and persist. Steam leakage at high surface levels supplies fumaroles; water seepage at lower levels forms hot springs.

Wells in the field tap hot water, steam, or a mixture of the two, depending on their depth and site. They may force the hot-water level to recede deeper into the system, locally or over the whole area, creating or extending a steam phase. The pressures in the hot-water phase are equal to the overlying hydrostatic head of the water plus the pressure of the saturated steam phase above it (the steam pressure is temperature-dependent). The water output from wells in the field gradually decreases until the total output equals the input to the aquifer under the prevailing pressure gradients. A new inflow–outflow steady state is thereby reached, with new hot-water levels, temperatures, and saturated steam pressures.

In a system where subsurface permeabilities (see Fig. 3) are high compared to deep permeabilities, the liquid water levels may be depressed to great depths during pro-

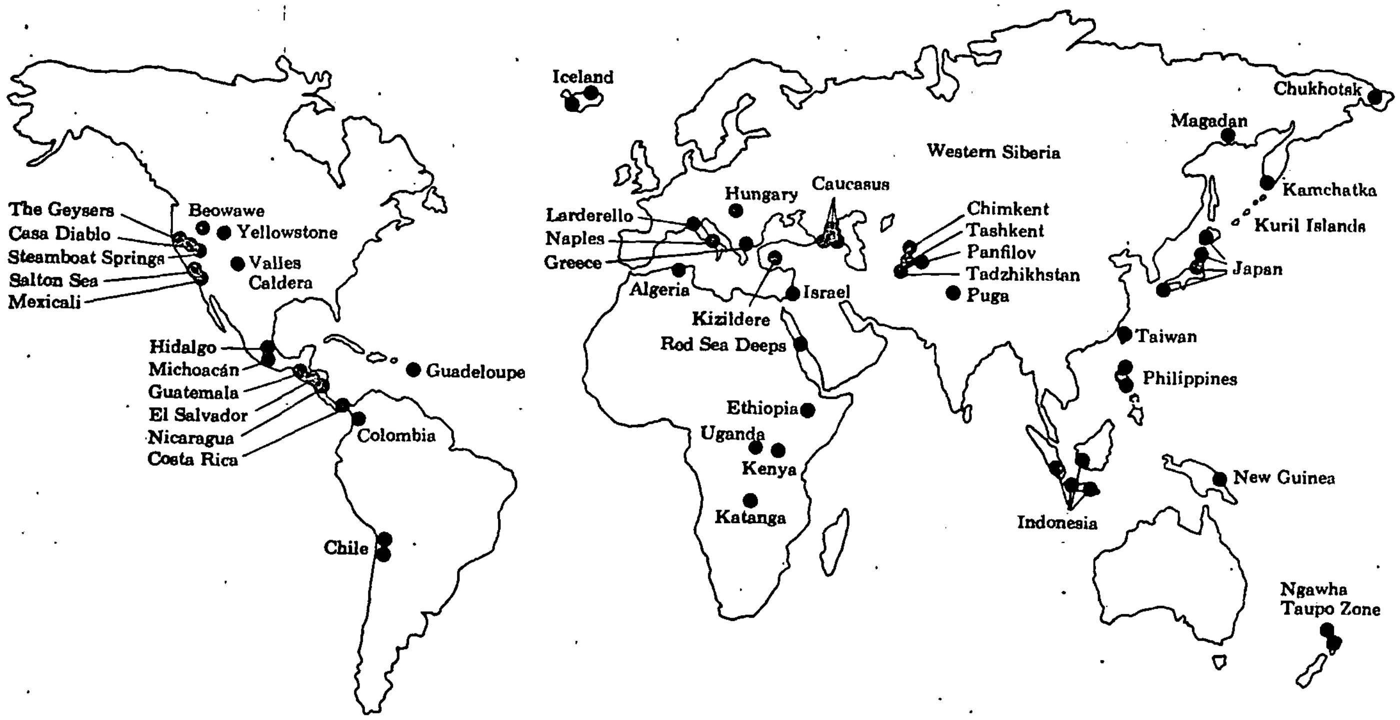

Figure 2. Colored dots indicate the major high-temperature hydrothermal areas of the world. Most are located in regions of current or recent volcanism or tectonic activity.

duction. The overlying country rock may contain saturated steam at temperatures in the vicinity of 235°, the temperature of maximum enthalpy for saturated steam (James 1968a). Steam condenses at the cooler top of the permeable formations, and the condensate falls back to recycle within the top section of the system. The characteristics of this type of "vapor-dominated" system are described in greater detail by White, Muffler, and Truesdell (1971). A well tapping a vapor-dominated system first discharges saturated steam (or steam plus water), but gradually the steam discharged becomes superheated as pressures are lowered. (There is little change in temperature because most of the heat in the system is stored in the rock.) This behavior is typical of wells at Larderello and The Geysers.

In drilling into a hot-water system, temperatures increase with depth, at first in an erratic manner, as steam flows or near-surface steam-heated groundwaters are encountered. In general, temperatures then increase with depth in accord with the boiling point–depth relationship: each point in the column of water is at a temperature at which the saturated steam pressure (plus gas pressure) equals the confining hydrostatic pressure. In the central part of the field a base temperature is reached at some depth (about 500 meters for a 250° system; 1,000 meters for a 300° system), and, in a system of good permeability, there is little further change in temperature with increasing depth.

Studies of convective heat transfer in porous media (e.g. Elder 1965) suggest that the high heat flows found in many hot-water geothermal areas are maintained by a rapidly rising central column of hot fluid trending into lateral and convecting flows near the surface, which creates a mushroom-shaped distribution of isotherms. Measured temperatures in the Wairakei field at various depths support this flow model (Banwell 1961). Because of the mushroom-shaped profile, at some positions it is possible to drill through a hot-water zone into colder country rock at deeper levels. In the vapor-dominated section of a system, temperatures are rather homogeneous due to rapid recirculation and convection, but, again, near-surface temperatures may be erratic, because of the uneven distribution of shallow steam-heated water or accumulations of condensate.

Assessing field characteristics

The surface manifestations of underground hot water or steam are highly variable. Some geothermal fields, such as Wairakei or Otake–Hatchobaru, Japan, are sites of active hot springs and fumaroles, but other major systems, as at The Geysers or near the Salton Sea, have unimpressive surface steam or water flows. In some areas the surface rocks are extensively altered by the hot fluids, as at The Geysers, and in others there are major surface silica deposits, as in many of the New Zealand fields, but the extent of surface alteration has no simple relationship to the size of the underground system.

To assess the power potential of a geothermal field, we must measure the size of the hot-fluid system, its temperature, and the probable permeability of the rocks. Careful geological, geophysical, and geochemical work by experienced personnel should precede any sizable investment in drilling; the costs are minor compared to those for drilling operations. In making their recommendations, the scientists should have a sense of reality as well as scientific curiosity. Some drilling has been recommended and carried out in unlikely territory. The basic scientific investigations in a geothermal field are straightforward, but the conclusions seldom narrow down to the exact answer "Drill here."

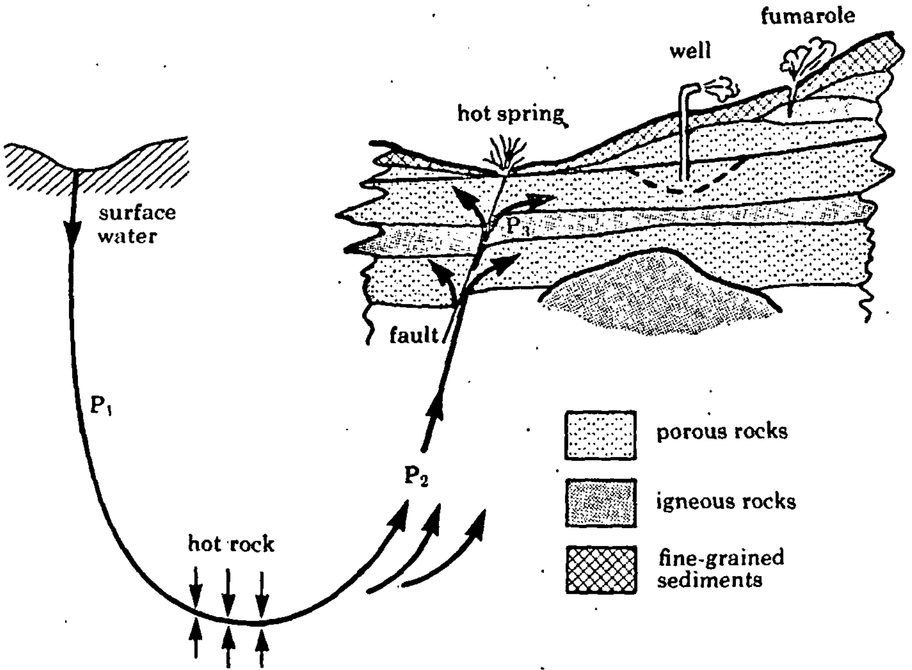

Figure 3. In a typical high-temperature geothermal system, cold surface waters slowly penetrate to depths many kilometers beneath the earth's surface, where they are heated and chemically altered by contact with hot rocks. The hot water, redirected upward in a convection cycle, follows routes of highest permeability. When it encounters impermeable formations, such as compact igneous rocks or fine-grained sediments, it flows upward along fracture zones created by faults or igneous intrusions. Light-colored rock strata are saturated with hot fluid. Steam leaks out as fumaroles at high surface levels, and water leaks out in hot springs at low surface levels. Wells may initially tap both hot water and steam for power generation; discharge of fluid often forces the hot-water level (*colored line*) deeper into the system, at least in the vicinity of the well. P_1, P_2, and P_3 indicate zones of limiting recharge permeability, deep permeability, and subsurface permeability, respectively.

A preliminary step in assessing a field is aerial photography, including infrared scanning, of the area under examination. Aerial photographs are useful in the preparation of a geological map representing the tentative structure and thermal anomalies of a region. Present and past areas of hydrothermal alteration are revealed and fault systems can be outlined. Gradations in vegetation types and growth offer a rough idea of near-surface temperature anomalies.

Next, a chemical study of the steam and water flows from springs, fumaroles, and local streams can provide much useful survey information at low cost (White 1970) (Fig. 4). Underground temperatures can be estimated by interpreting the analytical data in terms of calibrated chemical and isotopic reaction equilibria (Ellis 1970). For example, the concentration of silica and the relative proportions of ions such as sodium, potassium, calcium, and magnesium in spring waters are good geothermometers because they are controlled by various solubility and ion-exchange reactions (e.g. Fournier and Truesdell 1973). The concentrations of calcium and bicarbonate, together with the deep water temperature, enable us to measure the carbon dioxide concentrations in deep hot water. This is desirable because waters with high carbon dioxide concentrations tend to produce troublesome calcite scales in pipelines. In steam flows, the relative concentrations of carbon dioxide, hydrogen, methane, and water and the distribution of carbon or hydrogen isotopes among these molecular species enable us to estimate deep temperatures, assuming that the chemical equilibrium reaction is "frozen" during flow to the surface.

The ratios of relatively unreactive solutes such as chloride, bromide, boron, and cesium in water can be used to check the homogeneity of the underground system (whether a single body or several isolated aquifers), and the probable origins of the water can be traced by analysis of its characteristic hydrogen and oxygen isotopic makeup. In arid areas the water source may be important in defining the long-term output of the system.

Geochemical analysis can suggest whether the surface activity results from a vapor-dominated or a hot-water system. In general, springs arising from hot-water systems have chloride concentrations in excess of 50 ppm, and the proportions of other involatile ions are reconcilable with equilibrium in a high-temperature liquid. High concentrations of volatiles such as carbon dioxide (or bicarbonate), boron, and ammonia in spring waters suggest steam heating. However, these factors are indicative only and must be considered in context with other survey results. For example, there is an association between known steam-producing areas and mercury mineralization in local country rock.

Measurements of thermal gradients and of electrical resistivities in the field are probably the most profitable geophysical survey techniques (Banwell 1973). Thermal gradients should be measured over depths of at least several tens of meters in order to avoid surface anomalies due to water movement, vegetation, and ground contours. Many geothermal systems have been outlined successfully by this technique, and it is used extensively in steam-producing areas. In hot-water areas, convection and lateral near-surface spreading of the water may present a deceptive picture of the system's configuration, and in these areas thermal gradient measurements should be interpreted in conjunction with the results yielded by other techniques.

Electrical resistivity surveys have also been successful in determining the underground extent of geothermal areas. Usually dc techniques are used, with Schlumberger, Wenner, or dipole electrode arrays. One survey method is to traverse the area, measuring resistivity at a specific depth; another is to probe at a

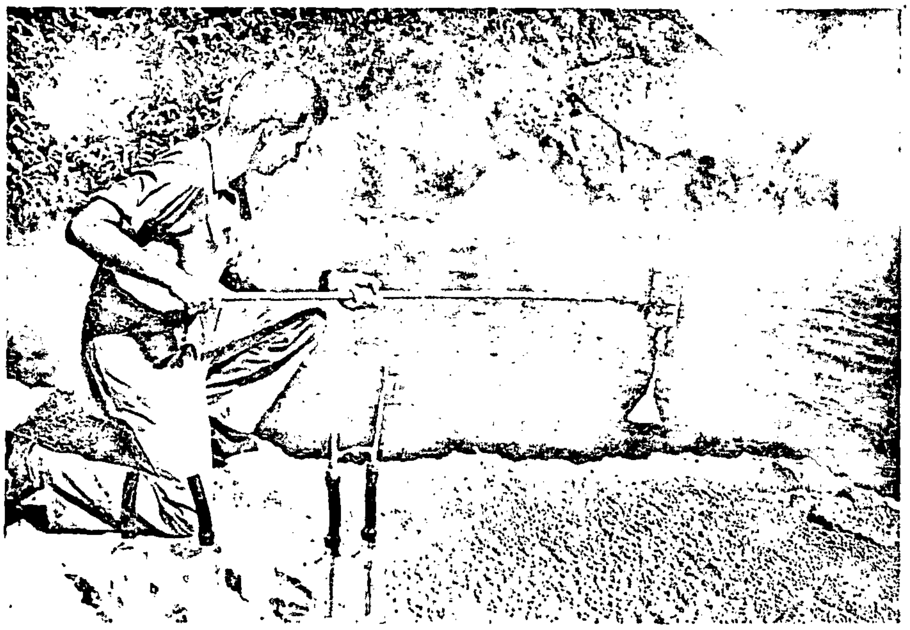

Figure 4. Geochemical analysis of the water and steam discharged by hot springs can help to determine whether a region is suitable for development as a source of geothermal power. In the photo a geochemist samples the gases rising up through the boiling water of the Champagne Cauldron in Geyser Valley, Wairakei. (Photo by A. L. Tilbury.)

single point to determine variations in resistivity with depth (Combs and Muffler 1973). The main variables controlling resistivity are water salinity, temperature, and rock porosity; low resistivity indicates an anomaly in one or more of these properties. The resistivity of hot saline water is very low, frequently of the order of a few ohm-meters, which may be compared with resistivities of many tens or hundreds of ohm-meters in the surrounding cold or impermeable country rock. Figure 5 is an example of a resistivity survey map, showing part of the Taupo Volcanic Zone of the North Island of New Zealand (Hatherton, Macdonald, and Thompson 1966). Broadlands and Wairakei appear to be fields of comparable size, but the natural heat outflow of Broadlands was less than one-seventh that of Wairakei (20,000 versus 150,000 kcal/sec).

Other features may also be measured, but for the most part they are less significant—for example, the amounts of heat, mass, and ground noise that leak from the underground system. Or else—like gravity and magnetic anomalies—these characteristics are difficult to interpret at an early stage of prospecting. Test drilling provides the only real check on the production capabilities of the field, which should not be oversold on the basis of scientific surveys alone. Although it may be of considerable underground extent and have high temperatures, the field may fail to produce useful quantities of hot fluid because of an unfavorable sequence of rock permeabilities or mineral deposition problems.

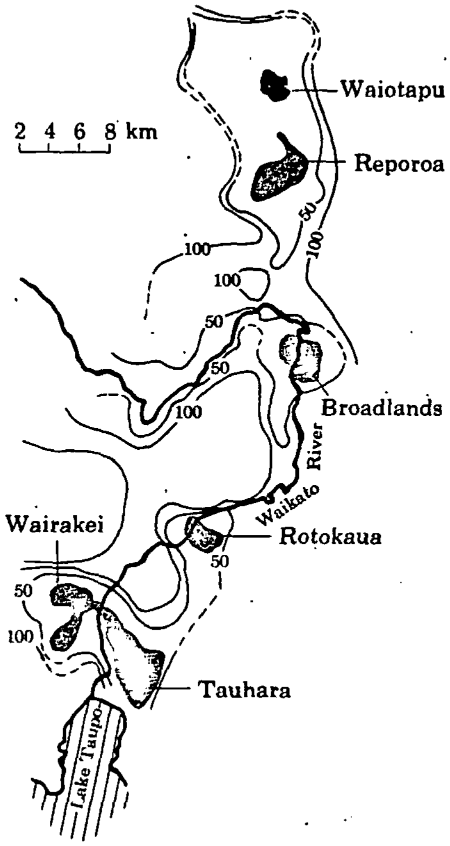

Figure 5. The survey map shows electrical resistivity contours, in ohm-meters, of part of the Taupo Volcanic Zone of the North Island of New Zealand. Resistivities were determined with a Wenner electrode spacing of 550 meters. Colored areas have apparent resistivities less than 5 ohm-meters. Although the Broadlands and Wairakei fields are comparable in size on the map, the natural heat outflow of Wairakei was much greater. (Adapted from Hatherton, Macdonald, and Thompson 1966).

Characteristics of developed fields

The temperatures, surrounding rocks, and fluid types encountered in the developed geothermal areas are outlined in Table 1. Whereas the steam fields of Larderello, The Geysers, and Matsukawa have temperatures consistently in the range 230–250°, hot-water fields have temperatures covering a wide range, up to a maximum of 370° measured at Cerro Prieto, Mexico (Mercado 1970). The compositions of water discharged from wells in several fields are given in Table 2. The analyses represent concentrations in water at atmospheric pressure after 20–40% steam loss (depending on the original water temperature); pH values are 1–2 units higher than in underground water, because the acidic gases CO_2 and H_2S are lost into the steam (Ellis 1970).

At depths below the surface where there is no oxidation, and if boiling has not occurred, high-temperature geothermal waters are usually alkali-chloride solutions with a near-neutral or slightly alkaline pH. The salinity of the water varies widely from field to field, as do the relative concentrations of particular solutes. The most concentrated solutions found so far are in the Imperial Valley of California, where a near-saturated sodium–calcium–potassium-chloride brine reaches temperatures above 300° in the Salton Sea area. High-temperature brine was also found on the Reykjanes Peninsula of southwest Iceland in a geothermal system based on seawater. In areas of recent volcanic activity geothermal waters are frequently

Table 1. Geothermal power installations in operation or at an advanced stage of development

	Geological situation	*Average (max.) drillhole depth (m)*	*Average (max.) temperature (°C)*	*Discharge type (S = steam; W = water)*	*Total dissolved solids in water (g/kg)*	*Total generating capacity (MW)*	
						Installed	*Planned addition*
Chile							
El Tatio	Quaternary and Tertiary rhyolite, andesite; Mesozoic sediments	650 (900)	230 (260)	S + W	15	—	15
El Salvador							
Ahuachapan	Quaternary andesite	1,000 (1,400)	230 (250)	S + W	20	30	50
Iceland							
Namafjall	Quaternary basalt	1,000 (1,400)	250 (280)	S + W	1.0	2.5	—
Italy							
Larderello region	Triassic–Jurassic sediments	600 (1,600)	200 (260)	S	—	406	—
Mount Amiata	Triassic–Jurassic sediments; Quaternary volcanics	750 (1,500)	170 (190)	S(+W)	—	25	—
Japan							
Matsukawa, N. Honshu	Quaternary andesites; Miocene sandstones	1,000 (1,500)	220 (270)	S	—	20	—
Otake, Kyushu	Quaternary andesites	500 (1,500)	230 (250)	S + W	2.5	11	—
N. Hachimantai	Quaternary andesites, dacites	800 (1,700)	— (>200)	S + W	—	10	—
Hatchobaru, Kyushu	Quaternary andesites	1,000 —	250 (300)	S + W	5.5	—	50
Onikobe, Honshu	Quaternary andesites, dacites, granite	300 (1,350)	— (288)	S(shallow) + W (deep)	1.5	—	20
Mexico							
Cerro Prieto	Sandstone, shales, granite	800 (2,600)	300 (370)	S + W	17	75	75
New Zealand							
Wairakei	Quaternary rhyolite, andesite	800 (2,300)	230 (260)	S + W	4.5	192	—
Kawerau	Quaternary rhyolite, andesite	800 (1,100)	250 (285)	S + W	3.5	10	—
Broadlands	Quaternary rhyolite, andesite	1,100 (2,420)	255 (300)	S + W	4	—	100
Philippines							
Tiwi, S. Luzon	Quaternary andesites	920 (2,300)	—	S + W	—	—	10.5
Turkey							
Kizildere	Pliocene–Miocene sandstones limestones; Palaeozoic schists	700 (1,000)	190 (220)	S + W	5	—	10
U.S.A.							
The Geysers	Jurassic–Cretaceous graywackes and shales, basalt	1,500 (2,900)	250 (285)	S	—	600	300
U.S.S.R.							
Pauzhetsk	Quaternary andesite, dacite, rhyolite	— (800)	185 (200)	S + W	3	5	7

Table 2. Composition of waters from geothermal wells

	Depth (m)	Source temp. (°C)	pH (20°C)	Solutes separated from discharge at atmospheric pressure (ppm)										
				Li	Na	K	Rb	Cs	Mg	Ca	F	Cl	Br	SO_4*
Well 44 Wairakei, N. Z.	695	255	8.4	14.2	1,320	225	2.8	2.5	0.03	17	8.3	2,260	6.3	36
Well 7 El Tatio, Chile	878	255	7.3	47.5	5,000	840	8.6	17.9	0.09	203	2.5	9,100	—	29
Well E-205 Matsao, Taiwan	1,500	245	2.4	26.0	5,490	900	12.0	9.6	131	1,470	7.0	13,400	—	350
Well IID-1 Salton Sea, Cal.	1,600	~340	~5.5	320	54,000	23,800	100	20	100	40,000	—	184,000	700	10
Well 8 Mexicali, Mexico	1,310	355	—	31	11,200	3,420	—	—	11	720	—	21,600	26	0
Well 1A Kizildere, Turkey	415	200	9.0	4.5	1,280	135	0.0	0.33	0.11	3.0	23.7	117	1.2	770

SOURCE: Ellis, in press.
* Total of molecular and ionized acid/base species.

dilute alkali-chloride solutions (0.5–1.5% total dissolved solids) with temperatures in the range 200–300°.

The solutes in geothermal waters can be divided roughly into two categories: "soluble" elements (of which there are very few) and elements with concentrations controlled by mineral equilibria. Chloride, bromide, iodide, boron, cesium, lithium, and ammonia fall in the first category under high-temperature, deep-water conditions, whereas most of the other elements are present at concentrations controlled by temperature- and pressure-dependent chemical equilibria. For example, the concentration of silica in the water of known systems above about 150° is controlled precisely by the solubility of quartz (Mahon 1966), while the ratio of sodium to potassium is controlled by feldspar equilibria reactions (Fournier and Truesdell 1973).

Concentrations of sulfate and fluoride are limited by the low solubilities of the minerals anhydrite and fluorite, respectively, while Ca^{2+}, CO_2, and HCO_3^- concentrations are related to the solubility of calcite, with which geothermal systems are usually nearly saturated. Deep waters high in CO_2 are particularly prone to deposit calcite in discharge pipes, in some cases presenting a serious problem to development.

The common rock-forming elements aluminum, iron, magnesium, and manganese are held at low levels by alumino-silicate–water equilibria (e.g. in high-temperature dilute geothermal waters Mg^{2+} concentrations are controlled at the level of parts per billion (10^9) and in equilibrium with chlorite and montmorillonite). At constant temperature the maximum concentrations of many divalent metal ions appear to vary in proportion to the square of salinity (m^2_{Na}). High-temperature brines may contain appreciable (ppm) concentrations of iron, manganese, copper, zinc, and lead (e.g. at Salton Sea), while in dilute water systems (as in New Zealand) these metals form a very much lower proportion of total dissolved solutes (ppb) (Ellis 1969).

Geothermal waters often contain unusually high concentrations of lithium, rubidium, cesium, boron, arsenic, and ammonia, in proportions reflecting the composition and types of rocks in the locality. The rare alkalis are especially abundant in rhyolitic or andesitic areas, while waters of sedimentary rock systems often contain exceptionally large concentrations of boron and ammonia. The hydrothermal recrystallization of minerals results in the concentration of many highly soluble species into the water phase (Ellis and Mahon 1964), including elements such as lead, zinc, and copper if the waters are highly saline.

There is little evidence in the fields so far investigated that the water or the chemicals in the water originate from a deep magmatic source. Some chemicals are dissolved from the containing rocks, but supply waters, evaporite beds, and connate waters all contribute to the composition of discharged fluid.

Unusually acidic hot water is found in rock systems containing sulfur, as in the Tatun Volcanic Zone of Taiwan (see Table 2). Hydrolysis of sulfur by water at high temperatures produces a strongly acid, sulfate, sulfide solution (Ellis and Giggenbach 1972) which is too corrosive to be used for power generation. High-temperature brines are also highly corrosive, because their pH is lower than that of dilute water systems at the same temperature. The pH differences are due to rock mineral equilibria acting as a buffer, controlling ratios such as a_{Na}/a_H, a_K/a_H at a particular value.

The steam produced by wells at The Geysers and Larderello con-

*As**	*SiO_2**	*B**	*NH_3**	*CO_2**	*H_2S**
4.8	690	28.9	0.15	19	1.0
48	810	210	3.1	32	—
3.6	639	106	36	2	—
—	—	498	500	—	—
2.0	1,420	37.0	—	1,180	—
38.	263	26.2	2.5	1,350	—

tains approximately 1% and 2% by volume, respectively, of total gases—predominantly CO_2—with minor amounts (1–2%) of H_2S, CH_4, H_2, N_2, and NH_3. In the hot-water areas the composition of the steam separated from the steam–water discharge at the surface contains gas of a similar composition, and up to the same total concentration (but frequently less and sometimes as low as 0.01%). In active volcanic areas H_2S may be present as a high proportion (10–15%) of total gases.

In hot-water fields in rocks of good permeability and at temperatures above about 200°, the original rocks are usually recrystallized into secondary equilibrium mineral assemblages. Typical assemblages found in quartz feldspathic rock systems are: at Broadlands from glassy rhyolitic rocks (260° water, 0.12*m* CO_2), the minerals quartz, K-feldspar, K-mica, albite, calcite, chlorite, and pyrite; at Salton Sea from deltaic sandstones (300° water, 0.01*m* CO_2), quartz, K-feldspar, K-mica, albite, chlorite, epidote, and pyrite; and in the Otake area from andesitic volcanics (250° water, 0.01*m* CO_2), the minerals quartz, albite, K-feldspar, montmorillonite-sericite, epidote, chlorite, pyrite, and anhydrite. In cooler, near-surface levels, calcium zeolites such as laumontite or mordenite may replace epidote or wairakite as the predominant calcium minerals, and at the depth of first boiling of the rising hot water there may be abundant deposits of calcite, silica, and K-feldspar (Browne 1970; Ellis, in press). High-temperature acidic waters produce alteration minerals such as kaolin, dickite, alunite, pyrophyllite, quartz, and montmorillonite.

Power generation

Some geothermal wells have a considerable energy output, and The Geysers, Larderello, Broadlands, and Mexicali fields all have wells with a steam discharge sufficient to generate at least 15 megawatts. In the last two fields the steam is accompanied by water having a similar energy output. A steam well at Travale, near Larderello, initially produced at the rate of 450 metric tons (tonnes) per hour (equivalent to about 45 MW).

In hot-water fields, steam is separated by cyclones from the mixed steam–water discharges at the wellhead and transmitted to the power station. The cover photograph of the Wairakei field shows several wellhead installations. In the foreground may be seen the steam–water separator, the twin-tower silencer, in which water expands to atmospheric pressure by steam flashing, and steam lines leading to the power station. Wellhead separation pressures range from approximately 50–200 pounds per square inch gauge (psig), and separation in two stages to supply steam to different turbine inlets makes the process both more economical and more flexible. Separated water, still at temperatures hotter than 100°, is usually rejected into a drainage system after passing through the silencer (Smith 1958). It now appears that, instead of separating water and steam at the wellhead, two-phase steam–water flows from wells could be piped to a large central separation plant without creating dangerous flow characteristics (James 1968b). This would enhance the possibility of using the residual heat of the separated water. For steam or hot-water transmission, conventional low-strength carbon steel pipes perform satisfactorily, as they are protected by the growth of an internal sulfide-oxide coating.

In the early stages of development in a field, generators using noncondensing turbines that vent their exhaust into the atmosphere are sometimes used temporarily to obtain immediate power production from individual wells. In permanent stations, condensing turbine generator sets, venting their exhaust to a vacuum, operate directly on geothermal steam at pressures up to 180 psig, but more usually in the range 50–100 psig. The largest generating unit, producing 106 MW, is in a recently established station at The Geysers. The direct use of steam containing H_2S and CO_2 has limited the choice of turbine blade materials to low-stress alloys, and, consequently, blade speeds are low (Marshall and Braithwaite 1973). No major erosion or corrosion problems have arisen in operating turbines. Turbine manufacturers are now taking an interest in designing special geothermal steam turbines, utilizing new alloys.

Direct-contact condensers use either local river water (as at Wairakei) or condensate recycled from cooling towers. With turbines taking in fresh steam continuously, geothermal stations are unique in not requiring the recycling of pure condensate as boiler "make-up" water. Due to the presence of noncondensable gases at 0.2–2% by volume in the steam, major gas-extraction plant is required, usually steam jet ejectors. In the condensing and gas-removal plant the oxidation of sulfide creates conditions of high acidity, and corrosion reaches a maximum.

At present there are only a few large power stations, and these are mainly in geothermal fields with temperatures in excess of about 220° (see Table 1). Although hot-water fields are encountered much more frequently than steam fields, the steam fields around Larderello and The Geysers currently produce more electricity than all of the hot-water fields together. The Larderello field comprises several production zones in an area covering approximately 250 km^2. Power development in its present form dates from post-1945 reconstruction, although some power was produced as far back as 1913. The Wairakei power station has been operating since 1958, with wells in two locations in an area of about 5 km^2. At The Geysers, power production commenced in 1960 with a 12.5 MW unit, but in recent years production capacity has increased dramatically, and now 100 MW per year is being added as new wells are drilled and new units installed. The field covers some 40 km^2, with wells and production units in several localities. The Japanese stations at Otake and Matsukawa both began to produce power in the 1960s, as did the stations at Pauzhetsk in Kamchatka, U.S.S.R., and at Namafjall, Iceland. Production at Cerro Prieto commenced in 1973, and the most recent station to come on-stream is at Hachimantai, which produces 10 MW.

Developments in several other areas are progressing rapidly and may lead to the establishment of power stations over the next few years. Especially promising high-temperature areas are found in Ethiopia at Dallol and in the Tendaho graben; in Greece on the island of Milos, 150 km southwest of Athens; on Guadeloupe; in Iceland at Krafla in the north and at Reykjanes, Krysuvik, and Hengill in the southwest; in Indonesia at Kawah Kamodjang, 40 km southeast of Bandung; in Italy at Monti Volsini, 80 km northwest of Rome; in Japan at Takinoue, North Honshu; in Kenya at Olkaria; in the Philippines at Tiwi, South Luzon; at Tongonan, North Leyte; and in the United States in the southern part of the Imperial Valley.

The production cost of geothermal power is variously quoted from about 0.3 to 0.8 U.S. cents per kWh (e.g. Armstead 1973), and installation costs range from $200–400 per kW. There is not a major difference between the cost of power from a small (20 MW) station and that from a large station (200 MW)—a factor with important implications for developing countries, where small needs may be met by inexpensive power.

The use of water at moderate temperatures (150–200°) is being investigated by pilot projects in several places, but at these temperatures conventional steam separation from two-phase flows is inefficient, and the water also commonly contains calcium carbonate concentrations at a level that causes rapid scaling in the pipes. Downhole pumps have been proposed to raise the water to the surface under pressure as a single-phase flow; at the surface, the heat is transferred to a secondary working fluid with a lower boiling point, such as isobutane or Freon. Projects focusing on the development of these binary-cycle systems are still in the experimental stage. For example, a 0.7-MW pilot power plant based on 81° water and Freon as a secondary fluid was opened at Paratunsk in southeastern Kamchatka in 1967 (Moskvicheva and Popov 1970).

Projects underway in New Mexico are aimed at utilizing the heat in hot dry-rock systems by artificial fracturing of granitic rocks at deep levels by high-pressure water and the creation of hydrothermal heat exchange systems (Smith 1973). Many practical problems have yet to be solved before this type of earth heat can be economically exploited, but the approach should offer new insight into the physical and chemical processes at work in geothermal systems.

Other uses

Geothermal power stations are inefficient in converting thermal energy to electric energy. The limiting thermodynamic efficiency is approximately 30% because of the low average steam temperatures, but the actual efficiencies of conversion are approximately one half this figure in steam-producing fields and about one quarter in water-producing fields. There is an obvious incentive to make more efficient use of the energy from high-temperature geothermal fields but, unfortunately, many of the fields are located in isolated areas with minor requirements for heating by waste hot water.

Two notably efficient projects using geothermal steam are at Kawerau, New Zealand, and Namafjall, Iceland. At Kawerau, a major paper and timber mill utilizes 200 tonnes/hr of steam produced from wells tapping water at temperatures up to 285°. Part of the steam is used in heat exchangers to produce clean process steam and part directly for timber drying and for the evaporation of black liquor. Surplus steam drives a noncondensing turbine to produce 10 MW of electricity for the industry (Smith 1970). At Namafjall, some 240 tonnes/hr of steam from four wells is used to dry diatomite from a nearby lake bed and to generate 2.5 MW of electricity, while the separated hot water supplies community space heating (Ragnars et al. 1970). The combination of electricity produced by steam and space heating by separated hot water is highly efficient, and plans are underway to utilize the fields of Reykjanes, Krysuvik, and Hengill to provide steam for power generation and industry and hot water for heating the populated areas around Reykjavik.

Space heating is usually not the primary objective of geothermal fields producing water at temperatures well in excess of 100°, but there are some exceptions. Reykjavik uses well water at up to 128°C to supply most of the city's heating needs. In the nearby Hengill field, water at up to 180–200° heats houses and greenhouses. In Rotorua, New Zealand, many wells produce water (up to about 200°) to heat houses and public buildings. A major hotel uses a geothermal well to produce air conditioning by means of a lithium-bromide absorption unit.

Geothermal wells can also be harnessed to serve other purposes. Production of heavy water with geothermal steam as an energy source has been proposed in New Zealand, Japan, and Iceland, but so far there are no practical developments. At Rotokaua, New Zealand, high-pressure steam derived from high-temperature geothermal water is used in a modified Frasch process to melt and raise to the surface sulfur contained in sediments at shallow depths.

The uses of geothermal water at lower temperatures are too diverse to review here. Lindal (1973) describes projects ranging from salt recovery and mining to animal husbandry, horticulture, and fisheries.

Problems of utilization

Vast quantities of fluid are expelled from geothermal production wells. For example, the rate of fluid production from the Larderello area is approximately 3 × 10^7 tonnes per

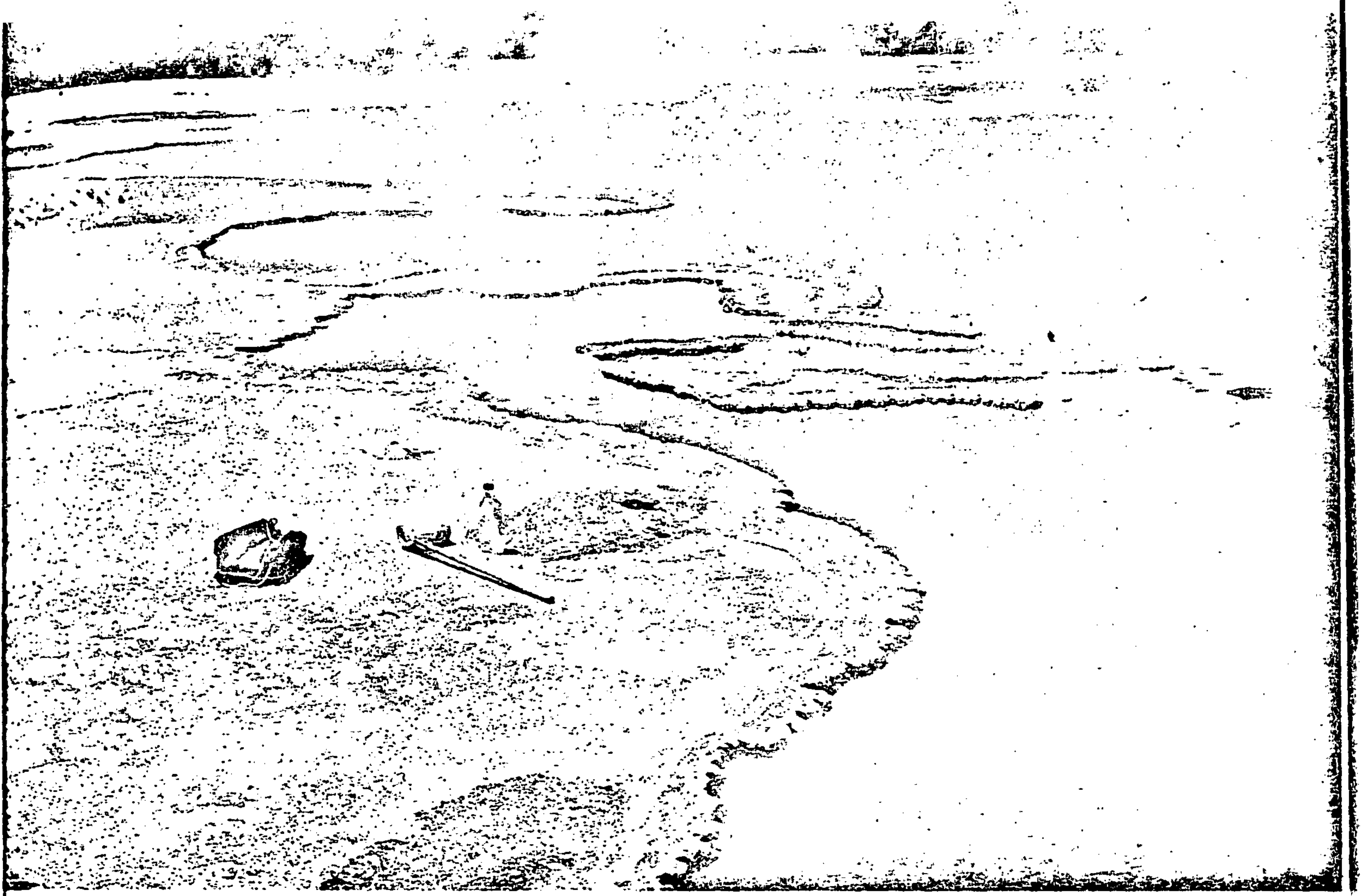

Figure 6. Ohaki pool, a large, deep, boiling spring of slightly alkaline chloride water, was the largest spring in the Ohaki-Broadlands area. Surrounding the pool is an extensive white silica sinter terrace with an intricate crenated edge. When wells were drilled and discharged in preparation for the production of electrical power, water levels in the pool dropped below sight. (Photo by R. B. Glover.)

year, and for Wairakei it is about 5 × 10^7 tonnes per year. During the years of operation at Wairakei, a total of almost 1 km^3 of water has been removed from the system. The extraction of this much fluid sometimes leads to local changes in the level of the field, depending partly on the strength of the near-surface rocks, and subsidence can produce local earth tremors. In the Wairakei area of low-strength ash and breccia formations, the ground level has generally fallen, exceeding 0.3 meters per year in the center of the field and tapering off to zero at the perimeter. Even so, the volume of the ground subsidence is only a small percentage of the total volume of water removed, and gravity surveys show that most of the water now being produced is being replaced by deep inflow (Hunt 1970).

In wells in rocks of low permeability, hot water tends to be replaced by steam. The artificially stimulated production of large volumes of water from a hot-spring area is likely to cause a general lowering of subsurface water levels, and steam created to fill the voids in the hot aquifer sometimes finds its way to the surface through lines of weakness to form new fumaroles or cause hydrothermal blowouts. Several large explosion craters have been formed in this way on the periphery of the Wairakei field. The water output from hot springs is likely to decrease and eventually cease. After major well production, the hot springs of Wairakei Geyser Valley and Broadlands no longer discharge, and what were once tourist attractions are now gray holes in the ground (see Fig. 6). A good example of how deep aquifer pressures and water levels decline to a new equilibrium level was presented by Bolton (1970) for ten years of operation of the Wairakei field. Most of the changes were due to varying water levels in the aquifer and consequent temperature–steam pressure adjustment to the new conditions.

In highly permeable fields, wells may produce water of almost constant composition for many years. At Wairakei, during fifteen years of operation the salinity as measured by chloride content did not change by more than 1–2%. In systems of lower permeability, however, although the general character of the water may not change markedly, concentrations are variable because of the effects of boiling and evaporation on rock surfaces (e.g. at Broadlands; see Mahon and Finlayson 1972).

In steam fields the concentration of

gas in the steam tends to decrease with time after the well is tapped, as would be expected if the steam were produced by deep-level boiling of water. At Larderello the steam temperatures have increased over the years of production, while pressures have generally stabilized after an initial period of decrease (Banwell 1974).

Deposition of silica or calcium carbonate sinters at the surface is characteristic of many hot-spring areas but, unfortunately, in some fields, minerals are also deposited along both natural and artificial flow channels, including fissures, pipes, and surface equipment. Calcium carbonate, the major scale-forming mineral in pipelines, is largely deposited when the water first boils, losing carbon dioxide and increasing in pH. The deposition of calcite in pipelines is particularly troublesome in fields with deep waters containing dissolved carbon dioxide at high concentrations (above $0.1m$). It has not caused trouble at Wairakei ($m_{CO_2} = 0.01$), but some deposition occurs in the Broadlands and Kawerau fields ($m_{CO_2} \approx 0.1$). Rapid rates of deposition have been recorded in other countries, and wells have become blocked in a matter of days or hours in severe situations. In some areas—Kizildere for example—calcite formation in pipes threatens to limit the development of the geothermal field.

Silica is deposited by high-temperature geothermal waters only when they become supersaturated with amorphous silica during cooling and concentration. The kinetics of silica polymerization and precipitation are highly complex (Rothbaum and Wilson, in press): the rate of polymerization depends on the degree of supersaturation, which in turn depends on the original water temperature and the amount of steam removed. Consequently, waters with original temperatures up to about 270–280° usually emerge into surface outflow drains before much silica is deposited. But in systems where water reaches very high temperatures—for example, Salton Sea and Cerro Prieto—some silica may be deposited in the outflow pipes. This problem was particularly troublesome at the Salton Sea wells (Skinner et al. 1967), where the casings became coated with a hard, black siliceous scale that contained high concentrations of iron, copper, and silver sulfides precipitated from the metal-rich brines.

Environmental impact

Geothermal power has been promoted in some quarters as "pollution-free." This is a fallacy: the problems are not major, but as with any other scheme to produce electric power, environmental problems must be considered (Axtmann 1975). A 100-MW power station in a dry-steam field requires fluid production from wells of about 10^7 tonnes per year, while in a hot-water field the required fluid production is greater by a factor ranging from about 3–10, depending on the water temperature. In the latter situation, rejection of separated water at temperatures of about 100° into local waterways could cause greater thermal pollution than would conventional power stations of equivalent capacity.

The magnitudes of annual chemical output from a 100-MW station for the representative hot-water fields of Wairakei and Cerro Prieto would be (in tonnes per year): alkali chlorides, 10^5; SO_4, NH_4, B, and F, each 10^2–10^3; SiO_2, 10^4; CO_2, 10^4–10^5; and H_2S, 10^3–10^4. In the steam fields of Larderello and The Geysers such a power station would produce comparable quantities of NH_4, B, CO_2, and H_2S. The major air pollutant from geothermal stations is hydrogen sulfide, but 30–50% of the total output of this gas may be dissolved in the cooling water.

In addition to simple thermal or salinity effects of geothermal effluents in local waterways, elements in the water such as boron, fluoride, and heavy metals may have their own harmful effects. In areas of intensive agriculture, like the Imperial Valley or Ahuachapan, El Salvador, disposal of effluents is a major development problem. At Ahuachapan, where local disposal of geothermal water is impossible because of its effect on nearby coffee plantations (coffee is a crop with low tolerance for boron), a long channel is being constructed to carry the waste water to the sea. And at El Tatio, Chile, the water contains 30–40 ppm arsenic, which could contaminate the limited local water supplies.

Some geothermal waters form metal-rich sulfide precipitates consisting mainly of antimony or arsenic sulfides but also containing high concentrations of metals such as mercury, thallium, gold, and silver. The precipitates may accumulate in local riverbeds, causing methyl mercury production, which can lead to unacceptably high mercury levels in fish (Weissberg and Zobel 1973).

An alternative to surface disposal is to reinject geothermal effluents into the field. Reinjection of condensate into the peripheral parts of The Geysers steam field is current practice and easily accomplished (Budd 1973) because of the relatively small volumes involved. Hot-water fields face a more serious water disposal problem, because every tonne of steam used requires the disposal of 3–10 tonnes of saline water. Reinjection of water through wells has been tried experimentally in several fields (e.g. Ahuachapan and Hachimantai), but the problem of scale formation in pipes and reservoir rocks may be a serious long-term limitation. The extraction of geothermal heat by the use of heat exchangers, either downhole or under pressure at the surface, should alleviate the problem of scale formation by avoiding the concentration of solutes and loss of carbon dioxide caused by steam flashing.

Chemical treatment of geothermal waters to remove scale-forming silica has been successfully attempted in a pilot project in New Zealand (Rothbaum and Anderton, in press). The result is a low density calcium silicate material suitable for use as an industrial filler or insulant, and an effluent which will not subsequently lay down silica scale. The treatment also removes arsenic—an important factor if water is to be released into local waterways. Desalination to produce a potable water and a concentrated brine of lower disposal volume is an alternative procedure in arid areas.

The next ten years

In the next decade geothermal fields will become an important source of electric power in many developing countries, particularly around the Pacific basin and in Latin America, but in developed countries they will rarely contribute more than a minor, though very economical, fraction of the total power production. In this period new geothermal power stations are likely to be established in field situations not very different from those being utilized at present. The number of producing fields will increase considerably, however, and new and improved technology, especially new turbine designs and deep-well pumps coupled with heat exchangers at the surface, will lead to much greater operational efficiency. Waste hot water from geothermal power stations will be used increasingly for community space heating, following the example of stations at Larderello, which are already supplying waste hot water for this purpose by pipeline for distances up to 105 km from the field (Haseler 1975). Water from geothermal fields having lower underground temperatures (80–150°C) is more likely to be used for space heating than for the production of electricity.

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