AREA
World
Ht Flow

GL01426

In Earth and Planetary Science Letters, 28 (1975) 23–32

GLOBAL HEAT FLOW: A NEW LOOK

DAVID S. CHAPMAN* and HENRY N. POLLACK

Department of Geology and Mineralogy, The University of Michigan, Ann Arbor, Mich. (USA)

Received June 19, 1975
Revised version received August 11, 1975

A global heat flow map has been derived from existing observations supplemented in areas without data by an empirical predictor based on tectonic setting and age. In continental areas the predictor is based on the observed correlation of heat flow with age of last tectono-thermal event, and in oceanic regions on the observed relation of heat flow to age of ocean floor. The predictor was used to assign mean heat flow values to 5° × 5° grid areas on the globe, weighted according to the relative area of tectonic provinces represented. A spherical harmonic analysis to degree 12 of the heat flow field yields a mean value of 59 mW m^{-2}, a rms residual of 13 mW m^{-2}, and an amplitude spectrum which decreases gradually and almost monotonically from $n = 1$. The spherical harmonic representation of the heat flow field is free of the unreal distortions which have characterized earlier analyses based on a geographically sparse data set. Areas with residuals greater than 15 mW m^{-2} comprise less than 19% of the area of the globe, thus indicating that most heat flow provinces have characteristic dimensions adequately represented in a 12-degree analysis.

1. Introduction

The heat conducted to the surface of the earth from its interior averages about 60 mW m^{-2}, and most of the regional variation in the heat flux lies within a factor of three about the mean. Our present knowledge of the regional distribution of the heat flux, and its relationship to tectonic elements certainly must rank among the significant geophysical achievements of the past decade. The principal uses of the heat flow data are in estimating temperatures at shallow depths within the earth, and in serving as a boundary constraint on models of geodynamic processes.

It is convenient to have a functional representation of the surface heat flow, which for data distributed over the globe is most commonly in terms of surface spherical harmonic functions. Spherical harmonic analyses of global heat flow have been reported every few years in progressively greater detail as the data set has grown. In 1963, Lee and MacDonald [1] reported coefficients to degree 2 based on 813 observations; in 1965, Lee and Uyeda [2] calculated coefficients to degree 3 from 1162 values; and in 1969, Horai and Simmons [3] used 2812 existing observations to calculate coefficients to degree 7.

Unfortunately all these previous analyses of the existing measurements have been characterized by unreal distortions in the harmonic representation of the heat flow field, caused by lack of observations in several critical areas. A notable example of these distortions was the "African bubble", a broad heat flow high in excess of 120 mW m^{-2} extending over much of North Africa, which was a consequence of a few very high observations in the Red Sea, and lack of data to constrain the functions over much of Africa and the Middle East. Lesser but equally improbable features of these previous representations include: a broad high in excess of 100 mW m^{-2} in east Asia, unconstrained by lack of data between Lake Baikal and the Japan Sea; a high of 120 mW m^{-2} in the Precambrian of East Antarctica where no data exist; and zero or negative heat flow in the South Pacific near Antarctica, also where no data exist. These distortions arise from attempts to find a global expression for a geographically sparse data set. Even at

---

* Present address: Department of Natural Sciences, University of Michigan–Dearborn, Dearborn, Michigan, U.S.A.

the time of the Horai and Simmons [3] analysis, data were available for only 710 of the 2592 5° X 5° grid areas on the globe, and one third of these were represented by a single measurement. Furthermore, there was extremely poor coverage for most of Africa, South America, Antarctica, and the high-latitude oceans.

The problems associated with the spherical harmonic analysis of a sparse data set may be overcome in two ways: by improving the coverage with measurements in the unrepresented regions; or alternatively, by predicting heat flow in the unsampled regions, thereby creating a synthetic supplement to the existing observations. The former solution will certainly be slow, and in continental areas, an increasingly difficult task. However, a sufficiently adequate understanding of the underlying causes of regional variation in heat flow has now been achieved to make the second solution reasonable. In particular the recognition that continental heat flow is correlated with age of last tectono-thermal mobilization [4], and oceanic heat flow with the age of the ocean floor [5], makes it now possible to use prediction methods with existing tectonic and geologic maps to estimate with considerable confidence mean heat flows for all unsurveyed 5° X 5° regions.

In this paper we describe an empirical heat flow predictor which is used to supplement existing observations to create a full global heat flow data set, and the spherical harmonic analysis of the surface heat flow field thereby obtained.

2. Empirical heat flow predictor

The basis of our heat flow predictor is the correlation of heat flow with tectonic setting. For continents we follow the example of Polyak and Smirnov [4] who recognized that subsets of continental heat flow observations based on age of latest tectono-thermal event are normally distributed about the mean heat flow of that subset and that heat flow decreases from younger to older tectonic elements. Fig. 1 (top) shows the general decrease of continental heat flow with increasing age. We have constructed individual continental predictors from existing heat flow data [6] for North America, Europe west of the Scythian fault, Asia, and Australia. The parameters of these predictors are tabulated in Table 1. For Africa, Antarctica and South America there is insufficient observational data on which to base an individual continental predictor, and so the general parameters of Polyak and Smirnov (Table 1) are used. The discrepancies between tectonic province average heat flow for different continents and the Polyak-Smirnov values, most serious for the Paleozoic and Mesozoic, suggest that the Polyak and Smirnov analysis [4] requires updating. However, the use of predictor values based on their analysis will not lead to serious errors in Africa, Antarctica, or South America, all of which have large tracts of Precambrian terrane.

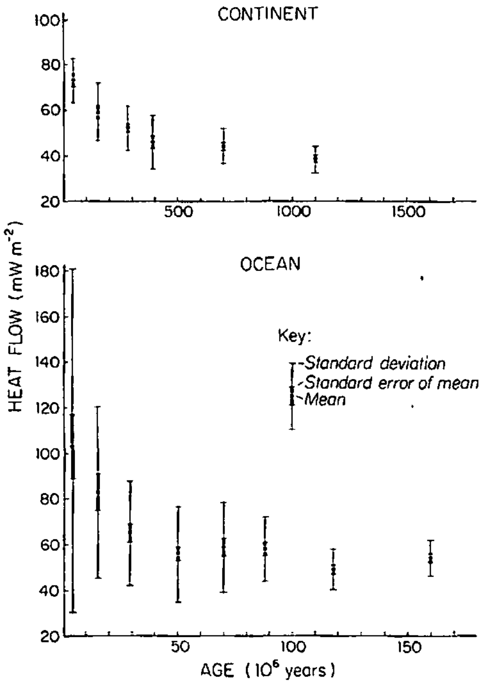


Fig. 1. Top: mean heat flow versus age of tectono-thermal province for continents, after Polyak and Smirnov [4]. Bottom: mean heat flow versus age of ocean floor for typical ocean. Length of bold bar gives magnitude of the standard error of the mean; thin bar gives standard deviation.

Predictors for oceanic regions were based on the general decrease of heat flow with age of ocean floor illustrated in Fig. 1 (bottom). Regional oceanic predictors were used for the North Pacific, South Atlantic, and Indian Oceans and a "typical ocean" predictor, based on mean values, used elsewhere. The parameters for each region are given in Table 2.

TABLE 1

Continental heat flow

Tectonic province	Heat flow (mW m^{-2})				
	N. America [6]	Australia [6]	Europe [6]	Asia [6]	Typical continent [4]
Archean shield	41	43		36	38
Proterozoic shield	55	73	38	45	
Precambrian platform	49				44
Phanerozoic non-orogenic	53	61	72	45	
Caledonian orogeny	48	85	65		46
Hercynian orogeny	62	58	67	56	52
Mesozoic orogeny	80			73	59
Cenozoic					
intermontane trough	75	80	78	63	41
folding					73
volcanism					92

For each 5° X 5° grid element on the globe, estimates were made of the fraction (to the nearest 5%) of the element represented by each tectono-thermal province, and/or oceanic age group present. The estimates were made visually from the maps and references listed in the Appendix. Mean heat flow values were then computed for each element using the appropriate predictor, weighted with respect to the area of each province present.

Three examples will serve to illustrate the application of our heat flow predictor methods. In the simplest case a single tectonic province is represented in a 5° X 5° area. The predicted heat flow is then the representative value for that tectonic province; and in general will be found to be in good agreement with the observational mean, providing the latter is well established. Such is the case for the element located at 50° to 55°N and 35° to 40°E which is comprised only of Russian platform, and for which the predicted heat flow and the mean of 14 observations are both 45 mW m^{-2}.

The second example is drawn from 5° X 5° elements comprised of more than one tectonic province, for which the distribution of observations is widespread. Fig. 2 shows such an example from eastern North America. We estimate the element to be com-

TABLE 2

Oceanic heat flow

Tectonic province	Age (Myr)	Heat flow (mW m^{-2})			
		N. Pacific [5]	S. Atlantic [5]	Indian [7]	Typical ocean
Jurassic	>136	54			
Early Cret.	100–136	49	48	53	49
Mid Cret.	76–100	58	59		58
Late Cret.	63– 76	60	59	55	59
Anom. 13-25	38– 63	60	53		56
Anom. 6-13	20– 38	67	29	64	65
Anom. 5- 6	10– 20	93	73		83
Anom. 0- 5	0– 10	118	90	100	103

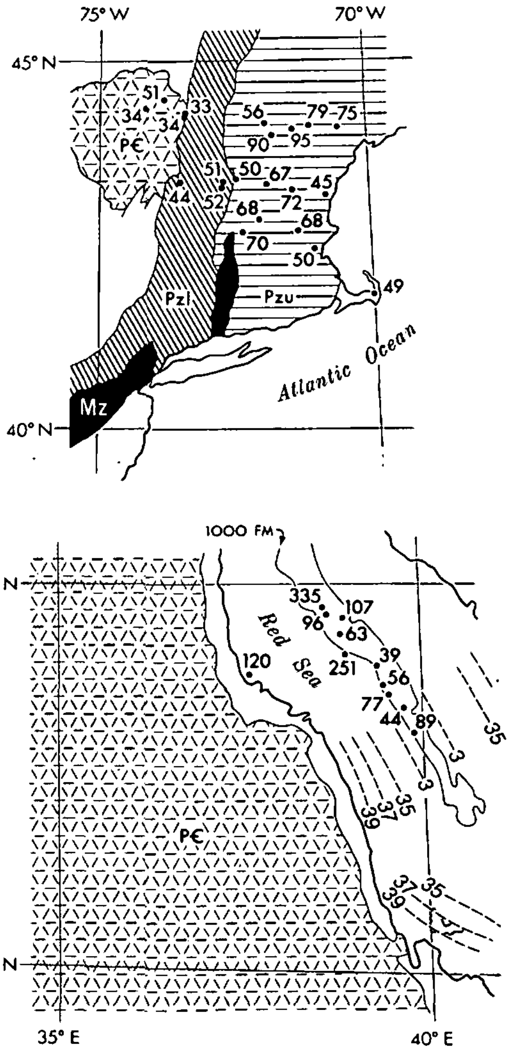


Fig. 2. Examples of 5° × 5° elements showing distribution of tectonic provinces and heat flow sites. Top: grid element from northeast United States for which heat flow sites are widely distributed within the element. Bottom: grid element from Red Sea where heat flow locations are unrepresentative of entire element. Ocean floor isochrons in 10^6 years from Girdler and Styles [8]. Heat flow in mW m^{-2}.

prised of the following provinces: Precambrian shield 10%; Phanerozoic non-orogenic (including foreland, coastal plain and shelf), 35%; Caledonian orogeny, 20%; Hercynian orogeny, 30% and Mesozoic orogeny, 5%. Using the North American values given in Table 2 for these provinces, the predicted heat flow for this grid element is 56 mW m^{-2}, in close agreement with the mean value of 59 mW m^{-2} for the 21 reported observations.

The final example is drawn from 5° × 5° elements which are again comprised of more than one tectonic province, but where the tectonic setting of the measurement sites are not generally representative of the grid element. An extreme case is the Red Sea region shown in Fig. 2. The grid element was divided into the following provinces by using the tectonic map of Africa (see Appendix) for the continental area, and Girdler and Styles' [8] spreading history for the Red Sea: Precambrian shield, 70%; oceanic crust, anomaly 13-25 (38–63 Myr), 10%; anomaly 6-13, (20–38 Myr), 10%; anomaly 0-5 (0–10 Myr), 10%. The predicted heat flow calculated from these fractions is 63 mW m^{-2}, in contrast to 117 mW m^{-2}, the mean of the 11 observations shown. This dis-

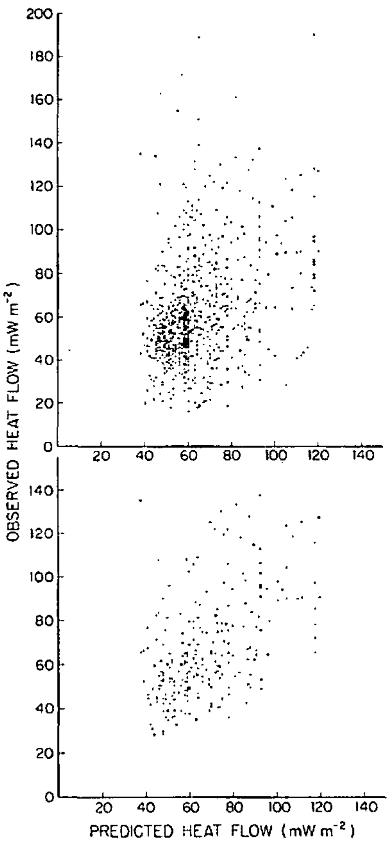


Fig. 3. Comparison of predicted heat flow with mean observed heat flow for 5° × 5° elements. Top: for the 829 elements where one or more observations exist. Bottom: for the 260 elements where 5 or more observations exist.

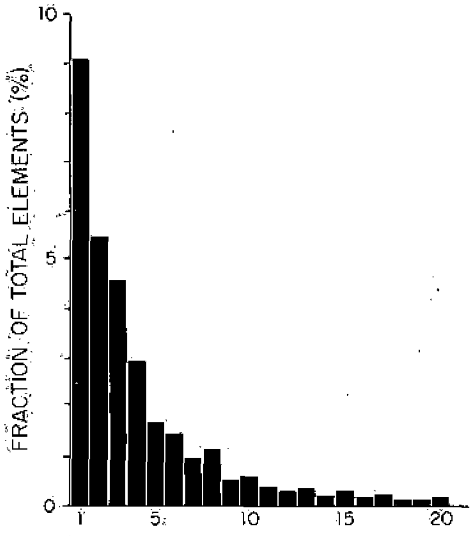


Fig. 4. Histogram of 5° × 5° heat flow measurement populations. 68% of total elements have no observations; 1% of total elements have more than 20 observations.

crepancy arises because the actual heat flow site distribution is clearly unrepresentative of the whole element; ten of the eleven sites lie within the anomaly 0-5 province, while this province represents only 10% of the grid element.

Predicted heat flow values have been computed for all 2592 5° × 5° elements and compared to 5° × 5° observational means wherever observations exist. The comparison is shown in Fig. 3 for the 829 elements with at least one measurement and for the 260 elements with 5 or more observations. Large differences between predicted and observed heat flow can be expected if there is only one or a small number of observations in the element (see magnitude of standard deviation for individual province heat flow, Fig. 1), or if the measurements are unrepresentative of the tectonic composition of the element. Fig. 4 is a histogram of density of observations per 5° × 5° element and illustrates the preponderance of poorly populated elements within the global heat flow data set. Regression correlations of predicted versus observed heat flow have been computed for several truncated data sets, with progressively higher minimum population cutoffs; agreement between prediction and observation improves consistently with increasing number of observations per element. In the next section we present the spherical harmonic analyses of the two heat flow data sets: the predicted heat flow alone; and the observed heat flow supplemented by predicted values in grid elements where no observations exist.

3. Spherical harmonic analysis

Each data set subjected to analysis comprises mean heat flow, observed or predicted, for all 5° × 5° elements on the surface of the globe. The spatial distribution of elements represented by observations, and which therefore contribute to the supplemented data set, is shown in Fig. 5. The 829 elements with at least one measurement, constitute 42% of the surface area of the globe, but are unevenly distributed. Both data sets have been represented by a spherical harmonic expansion of the form:

$$q(\theta,\phi) = \sum_{n=0}^{N} \sum_{m=0}^{n} [A_{nm} \cos(m\phi) + B_{nm} \sin(m\phi)]\, P_{nm}(\cos\theta) \qquad (1)$$

where q is the heat flow field, θ is colatitude, ϕ is longitude, A_{nm} and B_{nm} the coefficients of the expansion, and P_{nm} the associated Legendre functions, fully normalized so that:

$$\int_0^{2\pi} \int_0^{\pi} \left[P_{nm}(\cos\theta) \begin{matrix}\sin\\ \cos\end{matrix}(m\phi)\right]^2 \sin\theta \, d\theta \, d\phi = 4\pi \qquad (2)$$

The spherical harmonic coefficients A_{nm} and B_{nm} up to degree $n = 12$ were calculated by numerical integration from:

$$\begin{matrix}A_{nm}\\ B_{nm}\end{matrix} = \frac{1}{4\pi} \int_0^{2\pi} \int_0^{\pi} \overline{q}(\theta,\phi) \begin{matrix}\cos(m\phi)\\ \sin(m\phi)\end{matrix} \times P_{nm}(\cos\theta) \cdot \sin\theta \, d\theta \, d\phi \qquad (3)$$

and are given in Table 3. $\overline{q}$ in (3) is the 5° × 5° mean heat flow.

4. The new heat flow field

The degree 12 heat flow fields derived from analysis of the predicted data set and the observations plus predictor data sets are shown in Figs. 6 and 7 respectively. The most important characteristics of both

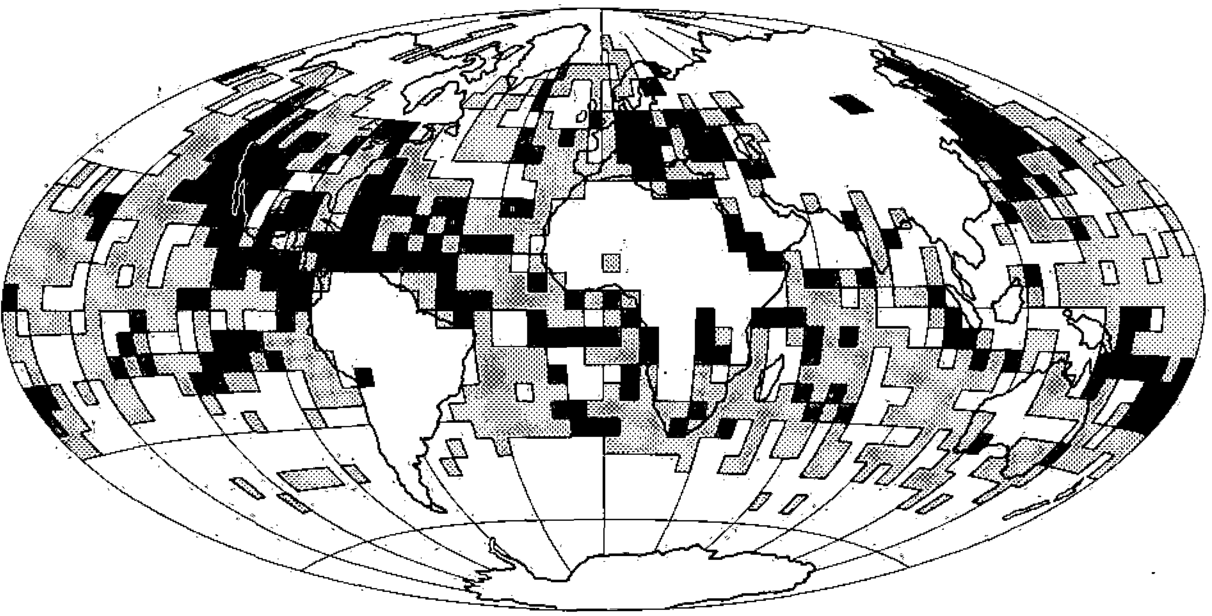


Fig. 5. Distribution of global heat flow data. Dot pattern indicates 1 to 4 observations in 5° × 5° element; solid pattern indicates 5 or more observations in 5° × 5° element. Aitoff-Hammer projection.

new representations are the excellent delineation of the features of the heat flow field already established from measurements, and the elimination of unrealistic distortions in regions where no observations exist.

All the major oceanic ridge systems are represented as heat flow highs, as are the marginal basins of the West Pacific, Alpine Europe, and the American Cordillera. The Galapagos spreading center and the Chile Rise appear as bulges on the East Pacific Rise pattern. Low heat flow regions include all the major shields and platforms, and the oldest oceanic regions. The West Australian low includes both the Yilgarn–Pilbara shield and part of the mid-Cretaceous Wharton basin.

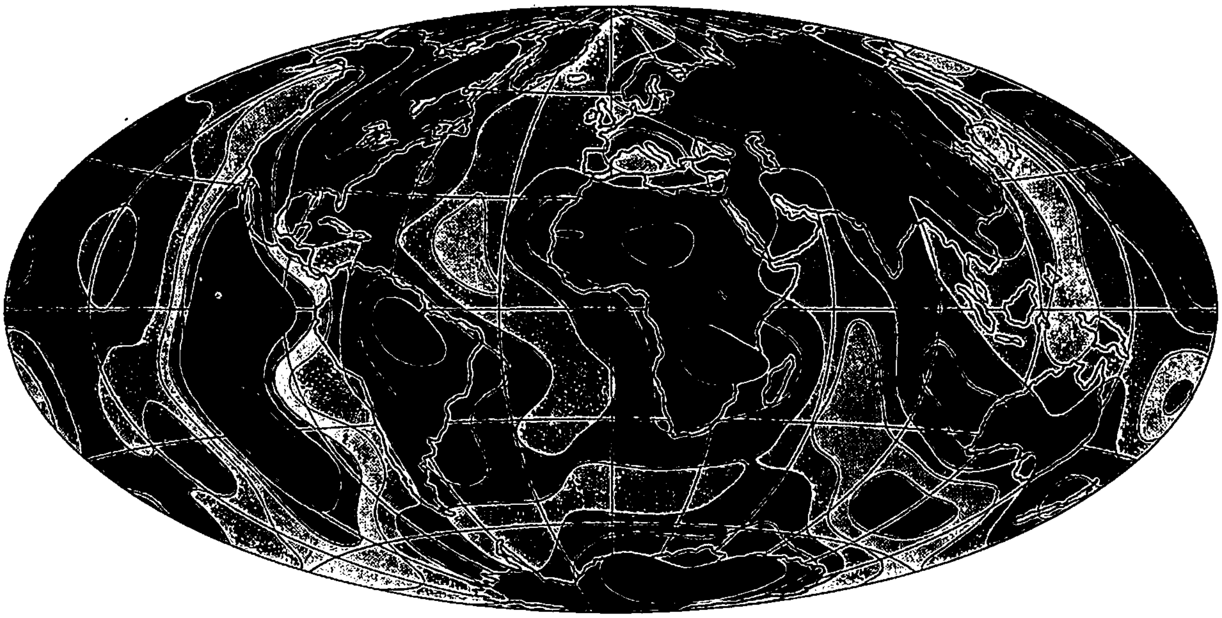
The difference between the reconstructed fields in Fig. 6 and 7 are slight. Heat flow observations in both the Red Sea–Gulf of Aden and Gulf of California regions are dominated by spatially restricted but abnormally high heat flow settings, and therefore appear in Fig. 7 as accentuated highs. The same provinces have much smaller effect when subjected to the predictor weighting procedure. In Fig. 7 the East Pacific Rise pattern is modified slightly. The southern Africa low is eliminated due to above normal heat flow observed in the central African shield [9].

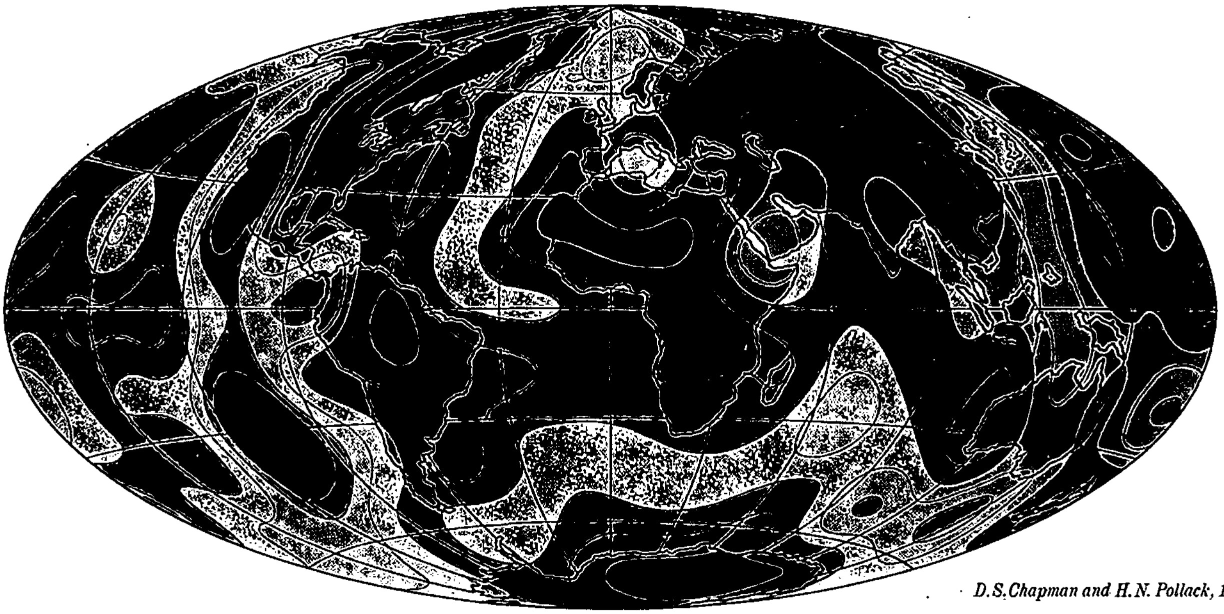
The mean values of 61 and 59 mW m^{-2} for the predicted and observed plus predicted heat flow fields respectively, are comparable to earlier estimates for the mean global heat flow [3,10]. The rms residual between the degree 12 reconstructions and the input data sets are 8 and 13 mW m^{-2} respectively. Areas with residuals greater than 15 mW m^{-2} comprise less than 19% of the area of the globe in both representations, thus indicating that most heat flow provinces have characteristic dimensions adequately represented in a degree 12 analysis. Those regions with larger residuals are recognized to be regions where strongly contrasting tectonic provinces lie in close proximity, such as the old ocean basin–island arc transitions in the western Pacific, and the ocean ridge–stable continent transitions in the vicinity of the Arabian Peninsula, Greenland, and western North America. Large residuals may also arise in regions where the general heat flow–age relationships do not apply, such as recent subduction zones [11] or areas of incipient rifting [9].

The mean value of the heat flow field represented by all harmonics of degree n, calculated from:

$$\left[\sum_{m=0}^{n} (A_{nm}^2 + B_{nm}^2)\right]^{1/2} \qquad (4)$$

GLOBAL HEAT FLOW





D.S. Chapman and H.N. Pollack, 1975

Fig. 6 (top). Degree 12 spherical harmonic representation of global heat flow from predictor method only.

Fig. 7 (bottom). Degree 12 spherical harmonic representation of global heat flow from observations supplemented by predictor.

ported by the U.S. National Science Foundation, Earth Science Section. One of us (D.S.C.) held a University of Michigan Rackham Predoctoral Fellowship during the preparation of this paper.

Appendix

Maps and references used in subdividing 5° X 5° elements into tectono-thermal and/or oceanic age group regions.

Continents

Africa: International Tectonic Map of Africa (1968), Association of African Geological Surveys and United Nations Educational Scientific and Cultural Organization, scale 1 : 5,000,000, coordinator G. Choubert.

Antarctica: Geological Map of Antarctica (1971), American Geographical Society, scale 1 : 5,000,000, compiled by C. Craddock.

Australia: Tectonic Map of Australia and New Guinea (1971), Geologic Society of Australia, scale 1 : 5,000,000, Sydney.

Europe and Asia: Tectonic Map of Eurasia (1966), Geological Institute of the Academy of Sciences of the U.S.S.R., scale 1 : 5,000,000, chief editor A.L. Yanshin.

North America: Tectonic Map of North America (1969), United States Geological Survey, scale 1 : 5,000,000, compiled by P.B. King.

South America: Geologic Map of South America (1964), Commission of the Geologic Map of the World, scale 1 : 5,000,000, general coordinator A.R. Lamego; Tectonic Map of Brazil (1971), Ministry of Mines and Energy, National Department of Mineral Production, Brazil, scale 1 : 5,000,000, coordinator E.O. Ferreira.

Oceans

General: Magnetic Lineations of the Oceans (1974), Geological Society of America, compiled by W.C. Pitman III, R.L. Larson, and E.M. Herron.

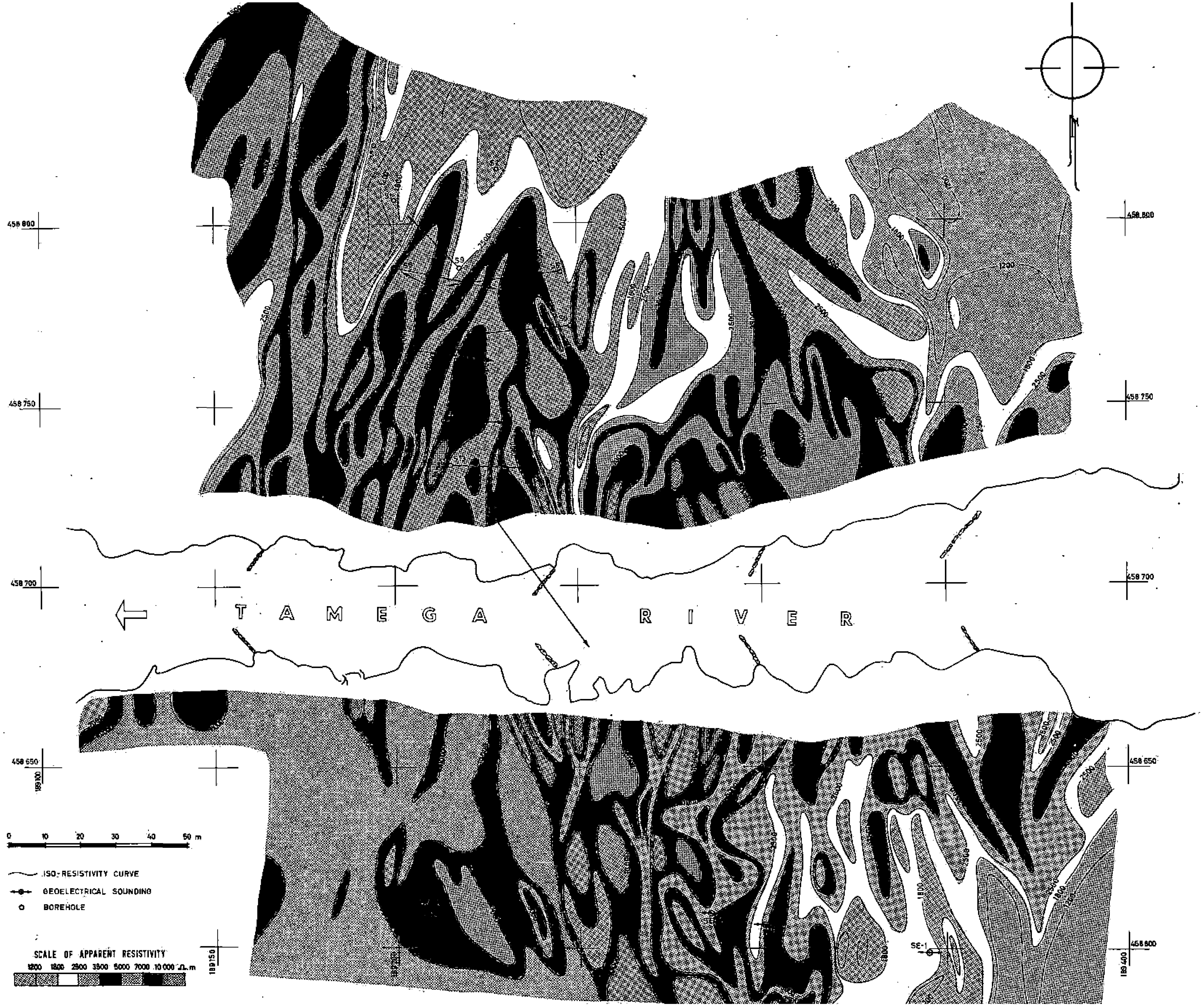
Arctic Ocean: E.M. Herron, J.F. Dewey, and W.C. Pitman III, Plate tectonics model for the evolution of the arctic, Geology 2 (1974) 377–380.

Indian Ocean: D. McKenzie and J.G. Sclater, The Evolution of the Indian Ocean since the Late Cretaceous, Geophys. J. R. Astron. Soc. 25 (1971) 437–528.

Marginal basins of the Western Pacific: J.G. Sclater, U.G. Ritter, and F.S. Dixon, Heat flow in the southwestern Pacific, J. Geophys. Res. 77 (1972) 5697–5704; J.G. Sclater, Heat flow and elevation of the marginal basins of the western Pacific, J. Geophys. Res. 77 (1972) 5705–5719.

References

1 W.H.K. Lee and G.J.F. MacDonald, The global variation of terrestrial heat flow, J. Geophys. Res. 68 (1963) 6481–6492.
2 W.H.K. Lee and S. Uyeda, Review of heat flow data, in Terrestrial Heat Flow, Geophysical Monograph Series No. 8 (American Geophysical Union, 1965) 87–190.
3 K. Horai and G. Simmons, Spherical harmonic analysis of terrestrial heat flow, Earth Planet. Sci. Lett. 6 (1969) 386–394.
4 B.G. Polyak and Ya.B. Smirnov, Relationship between terrestrial heat flow and the tectonics of continents, Geotectonics (1968) 205–213.
5 J.G. Sclater and J. Francheteau, The implications of terrestrial heat flow observations on current tectonic and geochemical models of the crust and upper mantle of the earth, Geophys. J. R. Astron. Soc. 20 (1970) 509–542.
6 A.M. Jessop, J.G. Sclater and M.A. Hobart, World heat flow data collection, Geothermal Series, Earth Physics Branch, Ottawa, in preparation.
7 D. McKenzie and J.G. Sclater, The evolution of the Indian Ocean since Late Cretaceous, Geophys. J. R. Astron. Soc. 25 (1971) 437–528.
8 R.W. Girdler and P. Styles, Two stage Red Sea floor spreading, Nature 247, 5435 (1974) 7–11.
9 D.S. Chapman and H.N. Pollack, Heat flow and incipient rifting in the central African plateau, Nature 256 (1975) 28–30.
10 W.H.K. Lee, On the global variations of terrestrial heat-flow, Phys. Earth Planet. Interiors 2 (1970) 332–341.
11 J.H. Sass, R.J. Monroe and T.H. Moses, Jr., Heat flow from Eastern Panama and Northwestern Columbia, Earth Planet. Sci. Lett. 21 (1974) 134–142.
12 E.M. Gaposchkin and K. Lambeck, 1969 Smithsonian Standard Earth (2), Spec. Rep. 315 (Smithsonian Astrophys. Observ., Cambridge, Mass., 1970) 93 pp.
13 D.D. Blackwell, The Thermal Structure of the Continental Crust, in: The Structure and Physical Properties of the Earth's Crust, Geophysical Monograph Series No. 14 (American Geophysical Union, Washington, 1971) 169–184.
14 R.F. Roy, D.D. Blackwell and E.R. Decker, Continental Heat Flow, in: The Nature of the Solid Earth, ed. E.C. Robertson (McGraw-Hill, New York, 1972) 506–543.

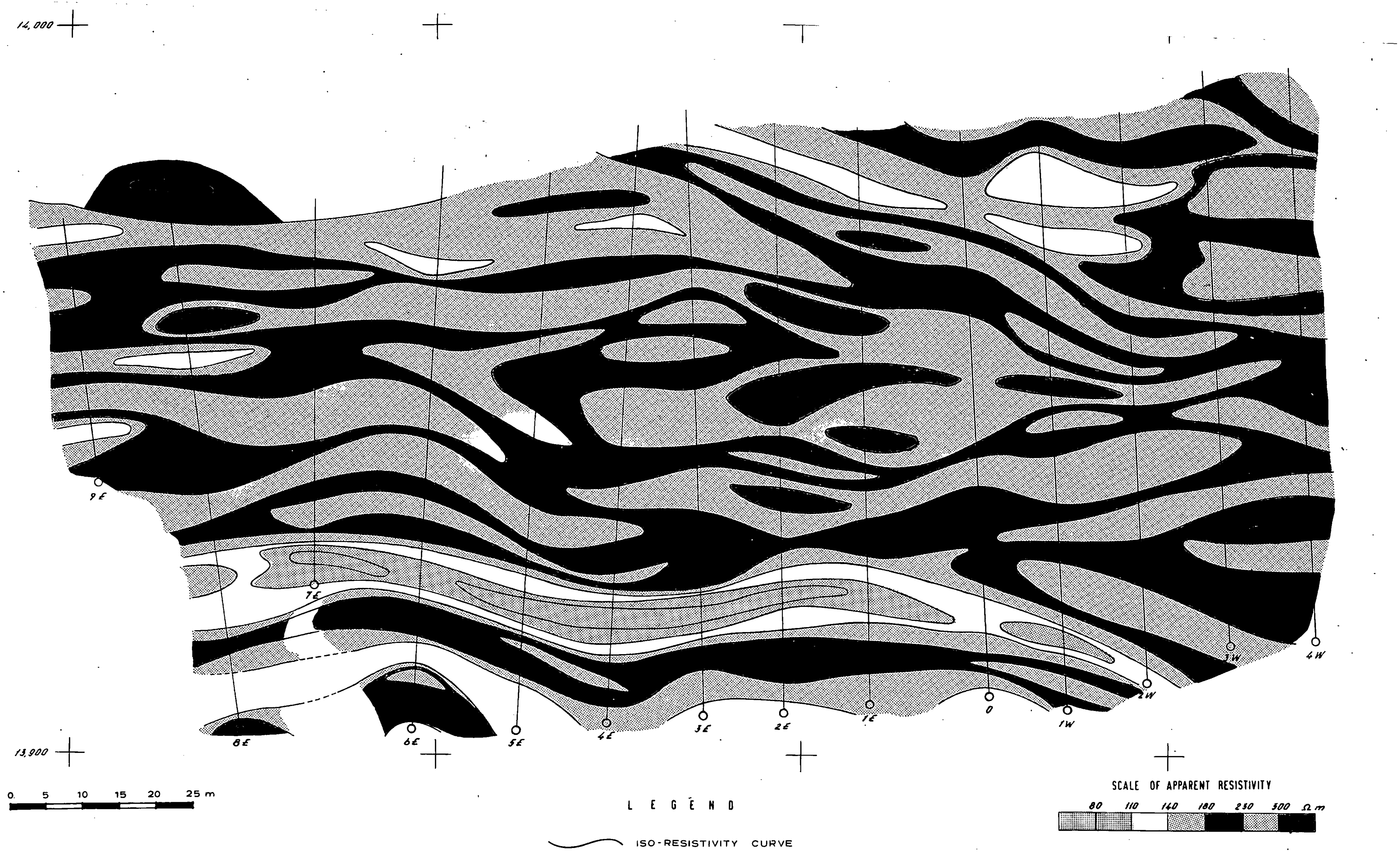

458 800
458 750
458 700
458 650
458 600
189 100
189 150
189 200
189 400
T A M E G A   R I V E R
S9
SE-1
1200
1800
2500
0 10 20 30 40 50 m
ISO-RESISTIVITY CURVE
GEOELECTRICAL SOUNDING
BOREHOLE
SCALE OF APPARENT RESISTIVITY
1200 1800 2500 3500 5000 7000 10 000 Ω.m

Congrès International

de Géologie de l'Ingénieur,

Paris, 1970

J. MOURA-ESTEVES ; thème n° 6.


14,000
13,900
9E
8E
7E
6E
5E
4E
3E
2E
1E
0
1W
2W
3W
4W
0. 5 10 15 20 25 m
LEGEND
ISO-RESISTIVITY CURVE
SCALE OF APPARENT RESISTIVITY
80 110 140 180 250 300 Ωm

Congrès International

de Géologie de l'Ingénieur,

Paris, 1970

J. MOURA-ESTEVES ; thème n° 6.

3/5

AREA
North Amer
Geothermics

GEOTHERMICS IN NORTH AMERICA: PRESENT AND FUTURE

W. K. SUMMERS,[1]

SYLVIA H. ROSS,[2]

ABSTRACT

Electrical power from natural steam has proven to be an economic source of energy in western North America. Power plants are now in operation in California and in Mexico, and development is continuing in these areas as well as in Central America. Most parts of western United States are being considered for exploration.

Techniques used in exploration include geologic mapping, fluid dynamics studies, and physical and chemical measurements in addition to test drilling. New suggestions for development include a heat-exchange process that uses super-heated water instead of steam and various types of nuclear stimulation. Passage of the federal Geothermal Steam Act of 1970 and increasing needs for electrical power should be the incentives that will make 1971 a major year for geothermal exploration.

INTRODUCTION

Geothermics is the utilization of naturally-occurring hot water and steam. Today, the primary interest in geothermics is for the generation of electrical power. However, there are other uses, such as the extraction of minerals contained in thermal water, or the use of hot water for heating, cleaning, or recreational purposes.

What is the allure of geothermal power? Businessmen generally don't turn to exotic, academically-interesting phenomena and spend cold cash for the sake of satisfying curiosity, so let's look at the reasons that have caused ultra-practical investors to be interested in geothermal power.

The major reason is that geothermal energy is a competitive power source. Electricity generated by natural steam sells for 3.0 to 7.9 mills at the bus bar. Thus, it can compete with power generated by more conventional sources. Hydroelectric plants, large nuclear power plants, and some coal facilities can sell power at prices ranging from 3 to 5 mills (fig. 1).

Geothermal development is attractive because it can be incremental. Capital expenditures can be made on an "as needed" basis, rather than committing large sums of capital before a market exists. For example, at the Geysers, in northern California, the first installation delivered a maximum of 12,500 kilowatts. Increments of power were added slowly until the present facility puts out about 82,000 kilowatts. The predicted maximum output of the area is more than a million kilowatts. In contrast, builders of a large dam cannot build a quarter of the dam and use it until the market grows large enough for half a dam.

A third advantage of geothermal energy is that it produces "pollution free" power. The plant causes no scares over nuclear contamination, emits no discharges to the atmosphere from the burning of fossil fuels, and can use recharge wells to return spent steam, in the form of water, to the energy reservoir.

Geothermal power can be utilized in conjunction with exploiting lowgrade mineral deposits or for developing industries that require large amounts of inexpensive electricity.

A final attraction is that geothermal power seems to be virtually inexhaustible. Even without reinjection of water, known steam fields do not seem to be depleting. Once a field has been defined, continued production is assured.

ACKNOWLEDGEMENTS

This paper is the product of conversations with persons active in geothermics, a survey of the published literature, and a search through unpublished field notes of tolerant cohorts.

Those who contributed to our understanding include: Hector Alonso, Comision Federal de Electricidad of Mexico; J. Q. Anderson, Geothermal Resources International, Inc.; John Banwell and G. R. T. Clacy, consultants to the Comision Federal de Electricidad de Mexico; Charles Boardman, Teledyne Geonuclear, Inc.; Charles Brietspecher, Signal Oil and Gas Company; Dalmu Costa, Nucleonics Corporation; R. F. Dondanville; R. L. Fenton, Washington State University; Bruce Hanshaw, U. S. Geological Survey; James Koenig, California Division of Mines and Geology; Paul Mann, University of Idaho; B. C. McCabe, Magma Power Company; James R. McNitt, United Nations; W. L. D'Olier, Occidental Petroleum Corporation; J. J. Raney, Stanford University; and R. W. Wolf, Yukon Geothermal Company, Ltd.

Some of the most significant publications pertaining to geothermal resources in North America include those by Austin (1966a, 1966B), Banwell (1957, 1963, 1964), Burnham and Stewart (1970), Facca and Associates (1962, 1964, 1965), Kaufman (1964), Meidas and Rex (1970), McNitt (1963), Rex (1968, 1970), Stewart and Burnham (1969), Waring (1965), White (1957, 1965), papers in the United Nations Conference on New Sources of Energy (1961), and California Geothermal Resources, Report to the 1968 Legislature.

Agencies of western states and Mexico have released preliminary reports on areas with geothermal potential. Specific information is available on Mexico (Alonso Espinosa, deAnda, & Mooser, 1964; Alonso Espinosa, 1966); California (McNitt, 1963; Keonig, 1967); New Mexico (Summers, 1965a, 1965b); Oregon (Groh, 1966; Peterson and Groh, 1967); Utah (Heylmun, 1966; Milligan, Marsell, and Bagley, 1966); Nevada (Horton, 1964); and Idaho (Ross, 1970).

---

[1] Ground-Water Geologist, New Mexico State Bureau of Mines and Mineral Resources.

[2] Ground-Water Geologist, Wyoming State Engineer's Office, Cheyenne, Wyoming

3/5

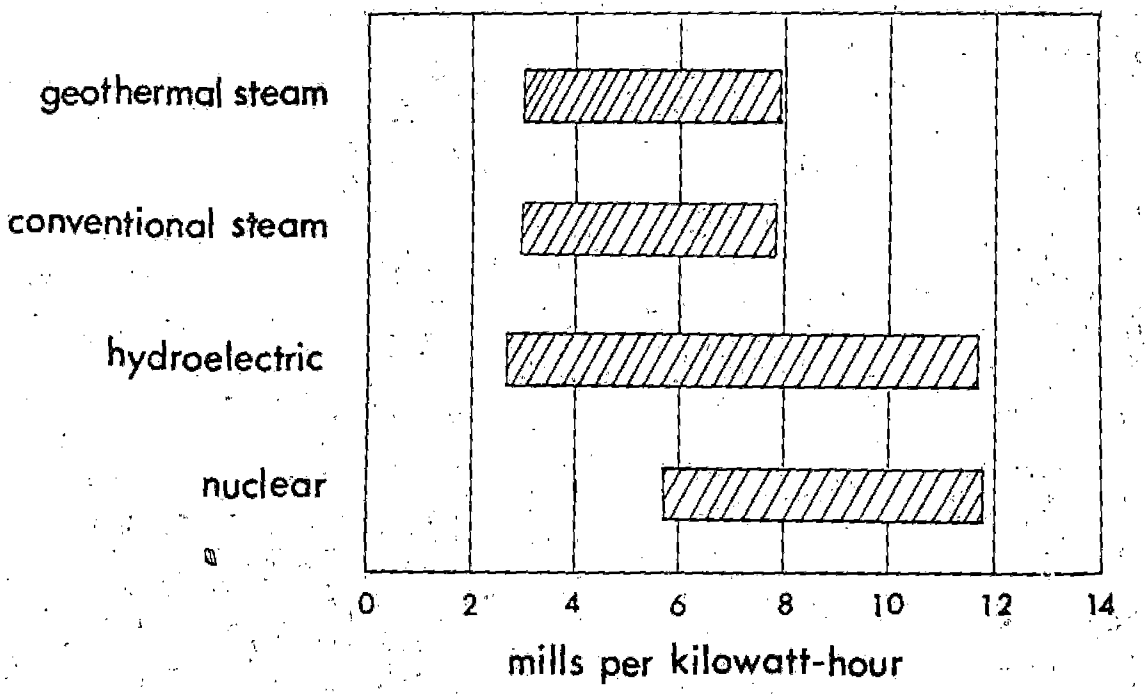
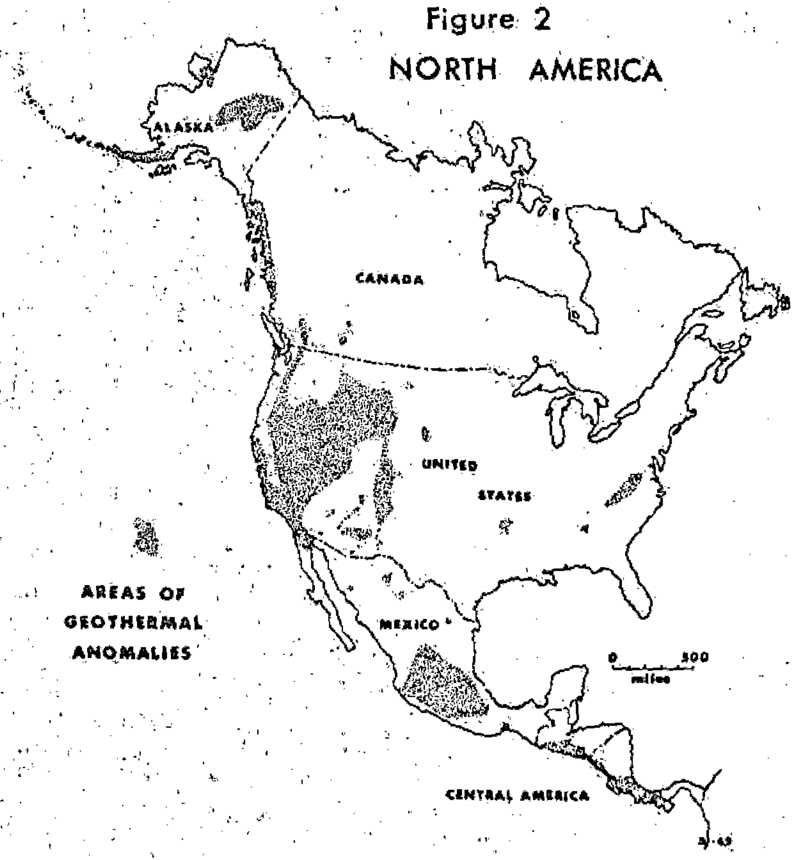


Figure 1. COST OF ELECTRICAL ENERGY PRODUCTION

Figure 2
NORTH AMERICA



3/5

Papers presented at the United Nations' symposium on the development and utilization of geothermal resources, held in Pisa, Italy, in September 1970, should be published in the near future. In addition, within the last two years numerous popularized articles on geothermal resources have appeared in various magazines.

HISTORY OF GEOTHERMAL DEVELOPMENT

Interest in geothermic power generation is not entirely new; power was first generated using natural steam at Lardarello, Italy, in 1904. The first attempt to develop geothermal power in the United States was during the 1920's at the Geysers, in California. This attempt failed for lack of a market for the power. The second successful attempt to generate electricity was during the 1950's in New Zealand; and the third, the installation of generating equipment at the Geysers.

Since 1956, Japan, Iceland, Russia, and Mexico have also begun to produce electricity from natural steam. Geothermal resources are being studied over the entire world; much of the work in underdeveloped countries has been under the auspices of the United Nations.

Geothermal potential in North America is confined almost exclusively to the region of the western cordillera (fig. 2). Today, in the United States, approximately 35 of the more than 1,000 known geothermal anomalies have been deliberately drilled for steam, and at least 10 geothermal fields in Central America also have been test drilled. However, only about 6 of these 45 fields are now in the development or production stages. Because of continuing development at producing areas, it is difficult to draw a sharp distinction between these two stages.

Although many of the anomalies seem to have little or no value for the production of electrical power, development of other areas has been abandoned or postponed because of technologic, economic, or legal problems.

DEVELOPED FIELDS IN NORTH AMERICA

The Geysers, California

The only major producing field in North America today is at the Geysers and Big Sulphur Creek thermal area. This field, about 90 miles north of San Francisco, is named for an area of surface thermal manifestations along Big Sulphur Creek in Sonoma County, California. The rocks in the immediate area are mainly graywackes, spilitic basalts, sandstones, and shales of the Franciscan and Knoxville Formations (fig. 3). These Upper Jurassic to Cretaceous rocks have been intruded by serpentine sills. Extrusive rocks of the Clear Lake volcanic series of Late Pliocene to Late Pleistocene age crop out several miles to the northeast.

This thermal field is significant for three reasons: It is the only "dry" steam field in North America, and is the only field actually producing commercial electric power. It is also the only operating plant in the world completely financed by private capital.

Drilling activity began in 1955 and the first power plant at the site was begun in 1958. The 12,500 kilowatt capacity plant, utilizing 250,000 pounds of steam per hour from 4 wells went into production in 1960. During the 1950's and 1960's, more than 40 producing wells were drilled over a total area of 300 acres. Wells range in depth from 1,500 to 5,000 feet and tap a fractured sandstone reservoir. Steam occurs at a maximum temperature of 473°F and at bottom-hole pressures of about 500 psi.

Wells drilled within the last few years have been deeper (5,000 to 7,000 feet), larger in diameter (9 to 12 inches), and generally more costly than wells drilled in the past. By the same token, these newer wells produce more steam and probably will have longer lives than the earlier ones. The character of the reservoir and the steam that it discharges have remained essentially unchanged.

In 1967, 16 wells produced enough steam to generate 54,000 kilowatts. Today, additional wells produce enough steam to generate 82,000 kilowatts. New construction should add 55,000 kilowatts by April 1, 1971; another 55,000 by October 1971; and an additional 220,000 by the end of 1972.

Otte and Dondanville (1968, p. 565), using what appear to be realistic estimates, believe that the energy production from the area for the next 30 years will amount to the equivalent of 150 million barrels of crude oil per square mile.

Pathe, Mexico

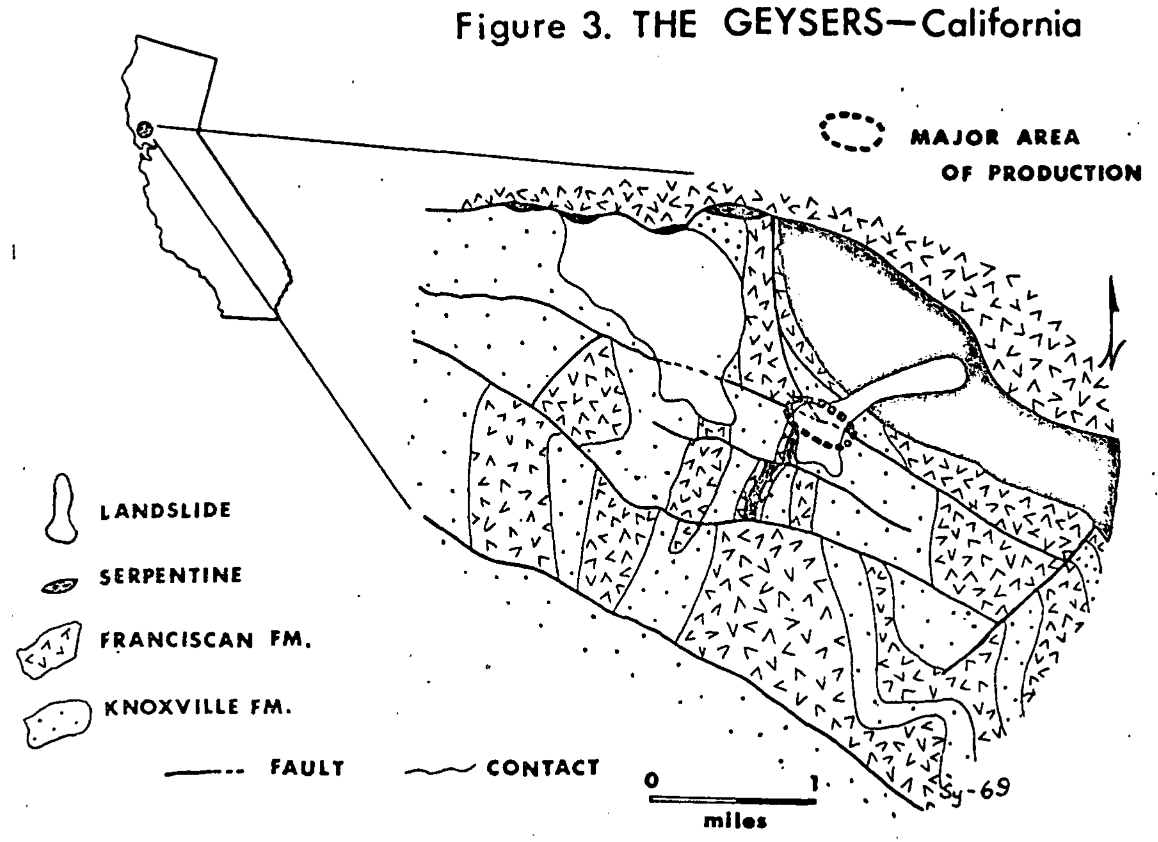
The Pathe geothermal field is in the central part of Mexico (fig. 4), about 125 miles northwest of Mexico City. Steam discharges from interbedded basaltic lavas, tuffs, rhyolites, and some lacustrine deposits which range in age from Pliocene to Holocene. These rocks, which are intensely fractured and extremely altered by hydrothermal activity overlie limestone of Lower Cretaceous age. Structurally, the field lies in a graben filled by the volcanics.

In January 1956, the first steam well began to produce at a depth of 808 feet with a bottom-hole temperature of 247°F. Since then, many holes have been drilled in the area, but only a few have successfully tapped steam or hot water. The highest gauge pressure is slightly more than 14 psi.

The results are disappointing, as the total amount of steam now discharged generates less than 500 kilowatts, although the non-condensing turbine through which the steam flows is rated at 3,500 kilowatts.

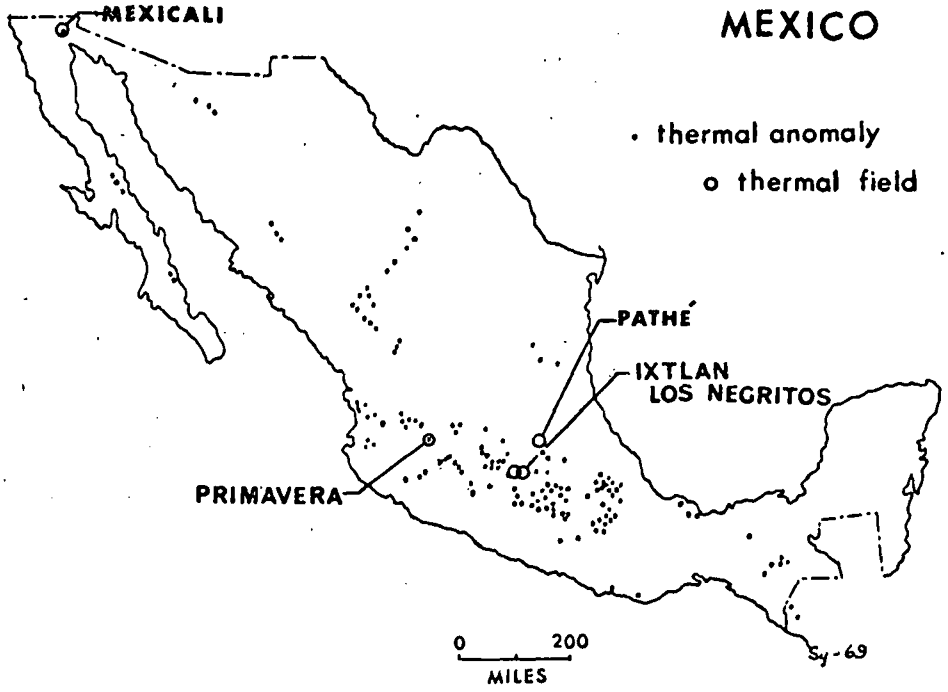
The low production of the field is presumed to be caused by the low permeability of the country rock. One of the major problems, as with many steam fields, is that the steam is "wet"; that is, it contains large amounts of water mixed with it. The Mexican government, in a continuing study of the area, has found that by discharging hot water and steam through a deep well, three other wells producing from a higher level discharge "drier" steam

Figure 3. THE GEYSERS—California



Modified from fig. 3, McNitt, in United Nations, 1964

Figure 4
MEXICO



Modified from fig. 12 of Waring, 1965

that can be fed directly into the pilot turbogenerator without the need of a steam-water separator.

Salton-Mexicali Province, California and Mexico

For practical purposes, the Salton-Mexicali geothermal province is coincident with the Imperial Valley of California and Mexico (fig. 5). The province is named for the two major steam fields currently being developed. One field is under development at the south end of the Salton Sea, California, and may underlie the sea in part (fig. 6). The field is referred to as the Salton Sea geothermal region, as the Niland field, or as the Buttes area.

The other field, in Mexico, is officially called the Mexicali geothermal field, but some recent literature refers to the area as the Cerro Prieto field (fig. 7). Cerro Prieto is a prominent, double-peaked basaltic volcano of Quaternary age near the field.

Structurally, the entire Imperial Valley is a graben that is a landward extension of the Gulf of California. In the vicinity of the Salton Sea, the structural trough is about 75 miles wide.

Clastic sediments filling the depression represent essentially continuous deposition since Miocene time. These sediments are primarily continental deposits of fanglomerate, conglomerate, and lacustrine sandstone and claystone. The Imperial Formation of Upper Miocene to Pliocene age, however, is a shallow marine claystone interbedded with oyster-shell reefs. The maximum thickness of the sequence is about 20,000 feet.

The upfaulted block on the west side of the graben consists primarily of granitic rocks of Cretaceous age; the upfaulted block on the east side is a complex of Precambrian igneous and metamorphic rocks capped by Tertiary volcanic rocks.

Igneous rocks associated with Quaternary volcanism have been penetrated in some of the steam exploration wells, and local volcanic features, such as Cerro Prieto and rhyolitic volcanic domes, suggest the possible existence of magma chambers at relatively shallow depths.

Natural steam is obtained at both the Salton Sea field and the Mexicali field from sandstones and shales overlain by a thick sequence of shale or clay and volcanic rocks. At the Salton Sea, the shale is 2,000 feet thick and grades into an arkosic sandstone at depths of 3,000 feet. The arkosic sandstone, 2,000 feet thick, is underlain by a silicified, metamorphic shale, lithologically similar to the shales higher in the sequence.

At Cerro Prieto, a typical well penetrated about 2,500 feet of clay and about 1,500 feet of alternating beds of sandstone and shale that form the geothermal reservoir. Various investigators have noted that where the clay or shale cover is thin or missing, the potential reservoir contains cold, or at best, only warm water.

Despite the similarity of geologic setting, the two fields are substantially different in several respects. The Salton Sea field is being developed for the mineral values contained in the hypersaline brines; the Mexicali field is being developed to generate electrical power.

Salton Sea Field

The Salton Sea field is underlain by two types of brine. The deeper brine is a very hot hypersaline one, containing up to 335,000 ppm dissolved mineral. Above it occurs a cooler, less saline brine. The maximum temperature of the hypersaline brine is about 700°F. The current plan is to market sodium chloride and calcium chloride, leaving the potassium chloride as a precipitate to be refined later when technologic advances should allow some of the contained metal values, including gold and copper, to be recovered as well.

Estimates of the values present in, but not necessarily recoverable from, the brine range from $20,000 to $40,000 per day per well. A 3,000 kilowatt power plant was operated for a time using the steam associated with the brine, but corrosion problems made it uneconomical.

The shallow, cooler brine at the Salton Sea contains only 10,000 to 30,000 ppm dissolved mineral, and is almost identical to the brine that is encountered in the Mexicali area.

Mexicali Field

The Mexicali field is perhaps unique in the history of geothermics as it is undoubtedly one of the largest of all known geothermal phenomena. Wells in the field discharge as much as 1.2 million pounds of wet steam per hour. Bottom-hole temperatures range from 400°F to 700°F; maximum gauge pressures reported are 800 psi.

The Comision Federal de Electricidad and the Comision de Energia Geotermica are developing the field to generate electrical power. As part of a study during development, the Mexican governmental agencies contracted with Washington State University for a joint study of the ground-water hydrology of the field using isotopic techniques.

The installation of two 27,500 kilowatt generators should be complete by June, 1972. The generators will use steam derived from 15 wells that have an average depth of 4,500 feet and discharge 120,000 pounds of separated steam per hour per well.

Studies of the province. Dr. Robert Rex of the University of California at Riverside is using a combination of gravity, temperature gradient, and electrical resistivity studies to determine potential high-thermal anomalies at depth in the Salton-Mexicali province. His basic premise is that natural steam is high in silica, which is deposited in the local rocks and tends to make them more dense than the same rocks away from the thermal area. By mapping the gravity and removing the known regional and structural anomalies, Rex prepares a map that shows the density contrast of the relatively shallow rocks.

Temperature-gradient studies identify areas of

3/5

FIGURE 5

SALTON-MEXICALI GEOTHERMAL PROVINCE

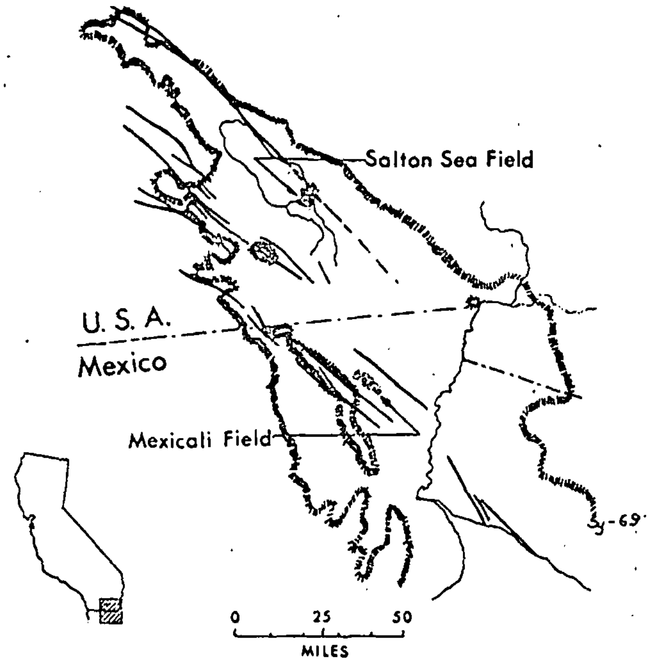
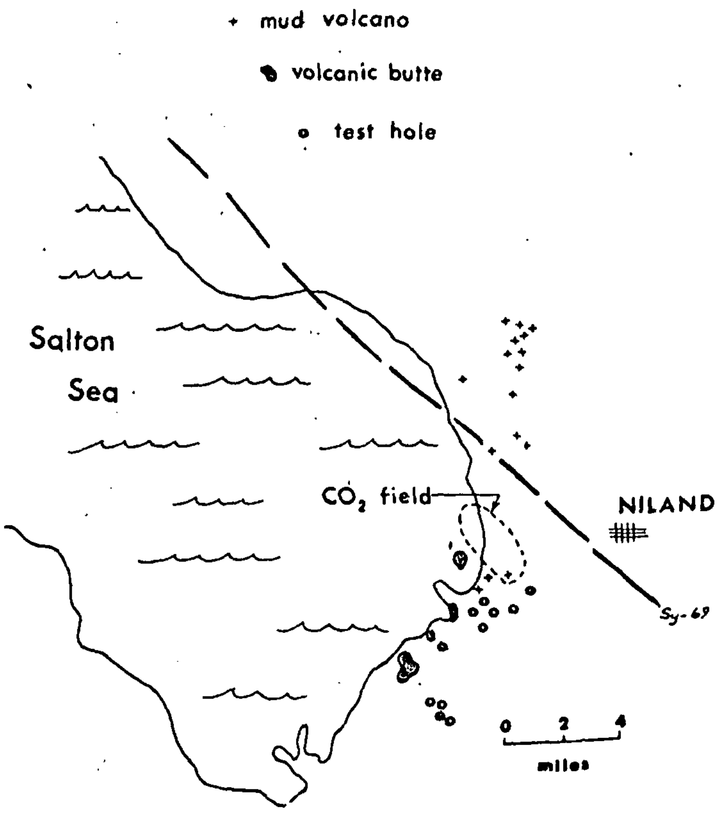


FIGURE 6

SALTON SEA GEOTHERMAL AREA



3/5

FIGURE 7

MEXICALI THERMAL AREA

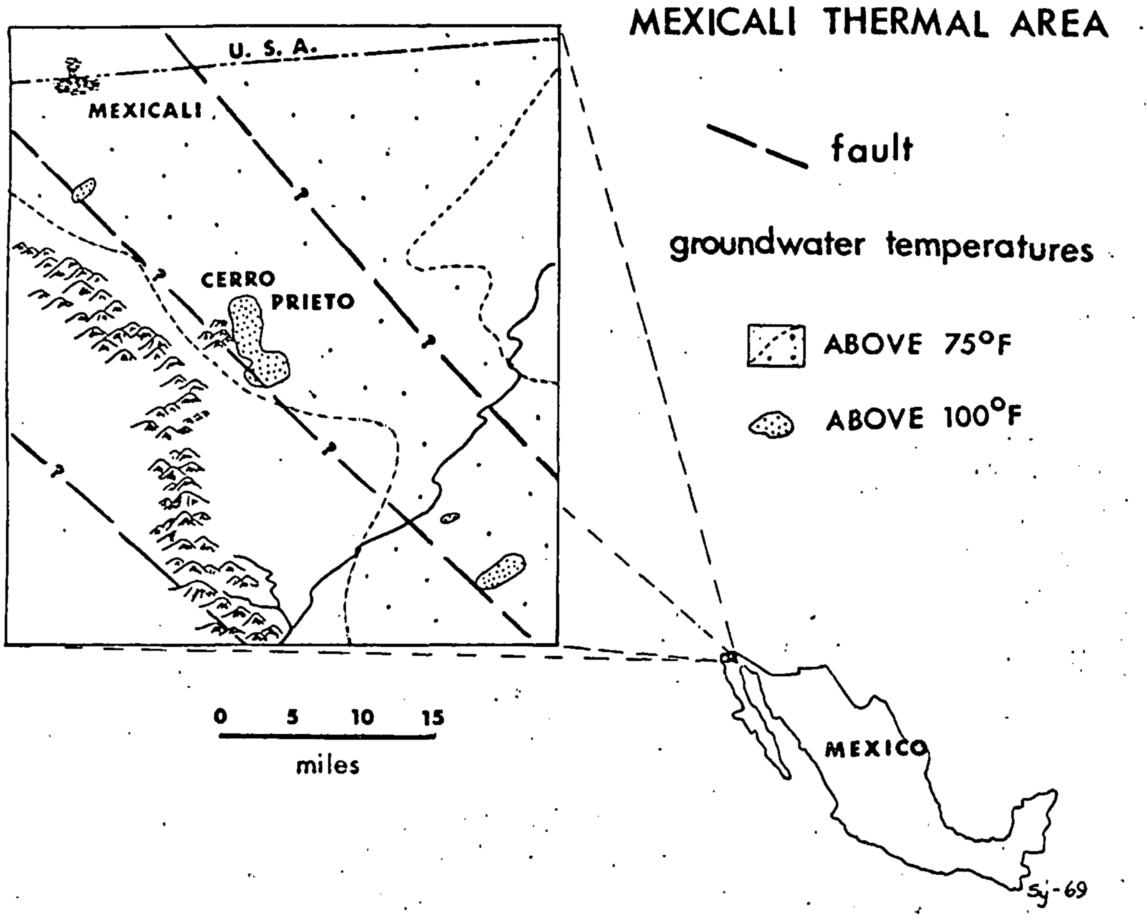
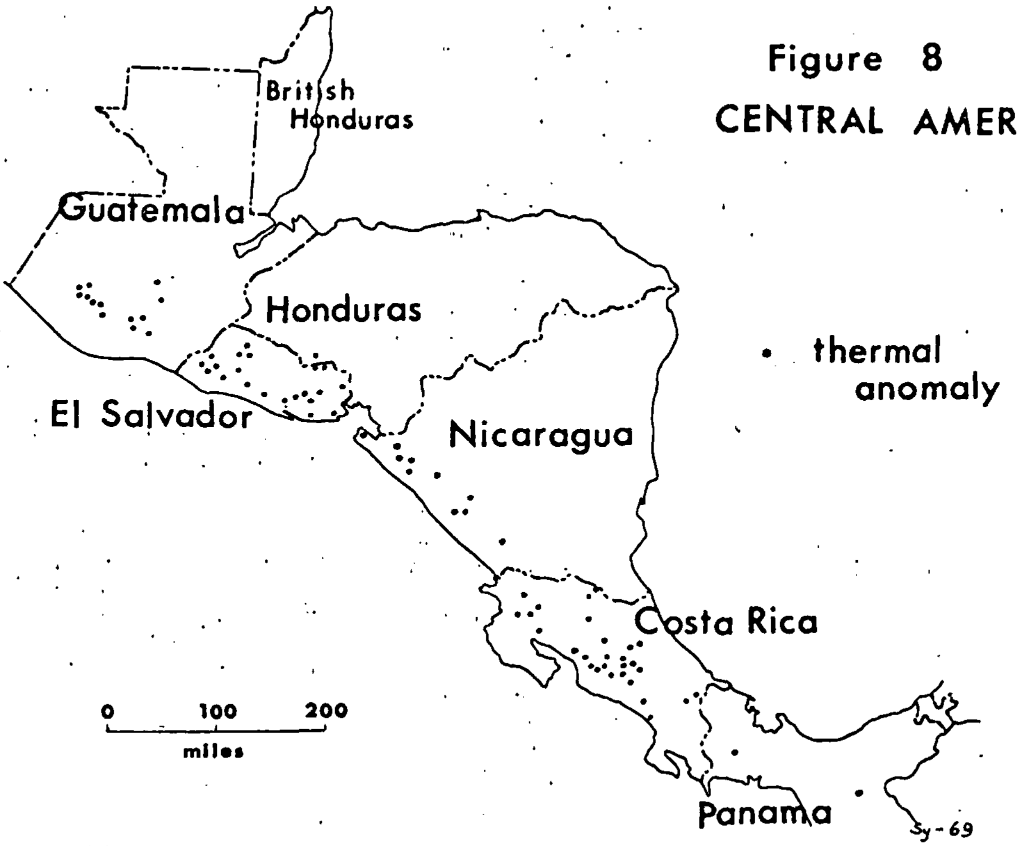


Figure 8

CENTRAL AMERICA



Modified from Fig 13, Waring, 1965

NILAND

Sy-69

high heat flow, and the resistivity profiles provide a vehicle for determining whether the water associated with a gravity high and a high heat flow of the Salton Sea type (high mineral content) or the Mexicali type (relatively low mineral content). To date, Rex, (1968, 1970) has defined nine individual thermal anomalies in the province.

REGIONAL SUMMARY OF GEOTHERMAL DEVELOPMENT

Although no other fields are being developed on a large scale at this time in North America, limited exploration is continuing. In addition, many areas have exploration potential. The following is a regional summary:

Central America

Reports of thermal phenomena -- volcanoes, solfataras, fumaroles, and hot springs -- from Costa Rica, Guatamala, Nicaragua, and Panama suggested that conditions might be favorable in Central America for the occurrence of natural steam.

From 1956 to 1958, the United Nations made a reconnaissance survey of the volcanic belt, which is also the area of thermal anomalies, from Guatamala through Costa Rica (fig. 8). This initial effort led to detailed exploration in El Salvador and Nicaragua.

El Salvador

From 1965 to early 1969, five test wells were drilled in three areas of El Salvador. In the Ahuachapan Mountain area, one well drilled in January, 1969, was shown to have a generating capacity of 7,000 kilowatts. The well discharged wet steam at a temperature of 430°F with a dissolved mineral content of about 16,000 ppm. Exploration in the other two areas was discontinued.

During 1969 and 1970, five more wells were drilled in the Ahuachapan Mountains, three of which produced steam. Preliminary estimates are that these wells can produce a total of 25 to 30 megawatts of power. A feasibility study is underway to determine the practicality of generating power.

The major technical problem is the disposal of the brine. Engineers believe that they probably can dispose of it by ponding and controlling discharge; efforts to develop an injection well to return the brine to the geothermal reservoir failed.

Nicaragua

In Nicaragua, the first study made for a country by a private contractor with the assistance of AID funds is in its final stages. Hot springs and other surficial thermal features were inventoried, and two potential areas, San Jacito - Taiste and Momotombo, were selected for detailed investigation.

In December 1970, a 2,000-foot test hole was drilled at Momotombo. It produced a "respectable flow" of dry steam at a temperature of more than 200°C, and preliminary estimates are that a 25 megawatt field can be established. Nicaragua is negotiating with AID for additional funds to develop the field.

Mexico

Mexico (fig. 4) has, in addition to the two fields already described, more than 100 other thermal areas, including nine active volcanoes, that might be explored with time. The output of the volcanic areas is difficult to judge, but it should be enormous. As an example, the fumaroles at Paricutín volcano discharge 1.4 million pounds of steam per hour.

The Comision Federal de Electricidad is exploring three new areas. The investigative procedure is similar in all the areas: The first stage is concurrent resistivity, gravity, and seismic surveys, geologic and geochemical surveys, and hydrogeologic studies. If these studies are promising, small diameter (nx) test holes are drilled to 1,800 feet. If the test holes are encouraging, large wells are drilled for tests to determine the practicality of final development of the field.

At Ixtlan, less than 50 miles from Paricutín, a graben filled with Quaternary volcanic rocks -- the classic requisite conditions for a thermal field -- shows promise. In 1959 and 1960, two shallow test holes produced flows of water having temperatures of 300°F. Subsequent exploration led to the drilling of eight small diameter test holes. Today three large diameter holes (one more than 3,000 feet deep) have been drilled to test the field's productive capability.

At Los Negritos, preliminary exploration has led to the drilling of six small diameter test holes. These tests were satisfactory and large diameter wells are planned. At Primavera, only the preliminary exploration is underway and no test holes have been drilled.

California

California is the location of most of the active geothermal exploration in the United States. The federal Geothermal Steam Act of 1970 (which became law on December 24, 1970) has opened to exploration large areas of California with geothermal potential. Previously, exploration has been limited to privately-owned land.

Interest in geothermics is high enough that the California Division of Oil and Gas is publishing for the Geothermal Resources Board a series of newsletters, Geothermal Hot Line. Primary purpose is to distribute information concerning geothermal development in California, its bordering states, and Mexico.

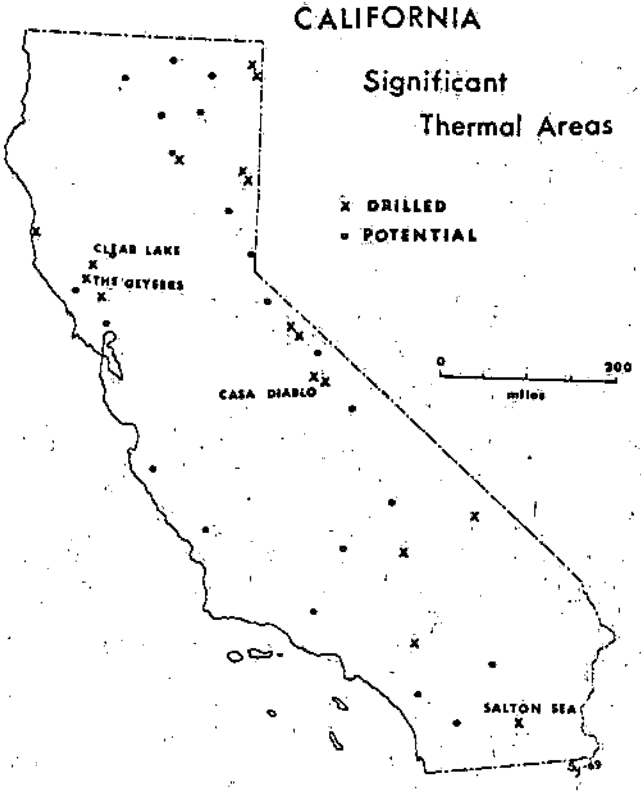
A report on geothermal steam within California to the 1967 State Legislature estimated that 38 thermal areas (fig. 9) have potential for power generation. The areas that are under development -- the Geysers and the Salton Sea area -- have been discussed previously. In addition, at least 17 other areas have been explored by drilling.

Two areas that have shown large potential are Clear Lake (Sulphúr Bank) and the Mono Lake - Casa Diablo area. On the basis of several wells drilled near Clear Lake, it is believed that the entire area, including the land beneath the lake itself, is a vast geothermic field. However, the disposal of reservoir

FIGURE 9

CALIFORNIA

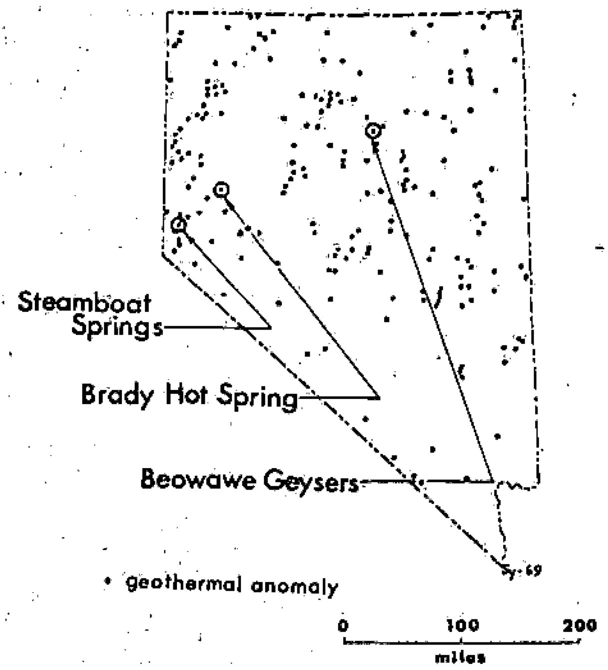
Significant Thermal Areas



Modified from California Geothermal Resources, 1967

FIGURE 10

NEVADA



Modified from Waring, 1965

FIGURE 11

IDAHO

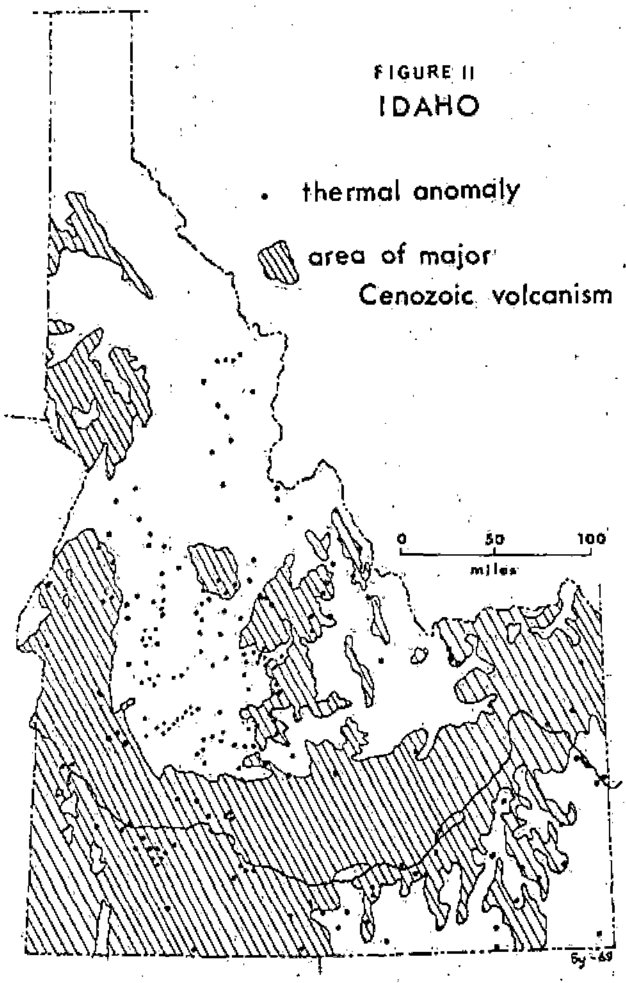
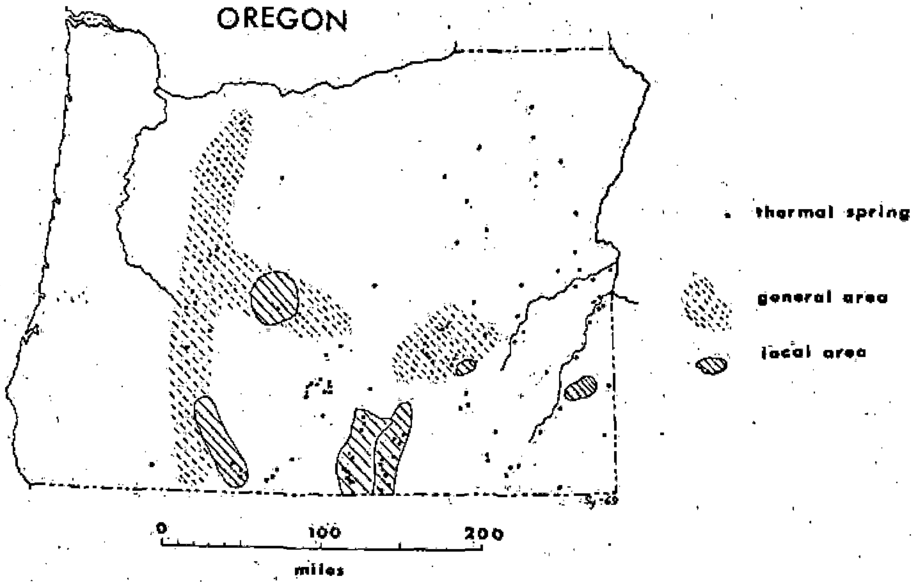


FIGURE 12

OREGON



PROSPECTIVE GEOTHERMAL AREAS

Modified from Groh, 1966

fluid containing boron in concentrations up to 500 ppm is still an unsolved problem.

The Mono Lake - Casa Diablo area, on the eastern side of the Sierra Nevada, also appears to have excellent geothermal potential. Between 1959 and 1962, nine wells were drilled; potential energy output by 1965 was 18,000 kilowatts. However, the thermal fluids contain boron, fluorine, and arsenic. Several companies are now interested in drilling on state and federal lands under and around Mono Lake itself. Exploration operations could begin within the next several months.

Other areas of interest are in the southeastern corner of Lassen National Park, near Randsburg, in the Coso Mountains, and in the Imperial Valley within the Salton - Mexicali geothermal province.

Arizona, New Mexico, Nevada, and Utah

Exploration for geothermal steam is just beginning in Arizona, New Mexico, Nevada, and Utah. Arizona has unknown potential for geothermal development. Locally, many of the 21 known thermal areas in the state are associated with Cenozoic volcanism and favorable structures.

Of the 57 known thermal areas in New Mexico, only the Jemez Caldera has been explored. Five wells have been drilled on the property; the most recent in 1970 to a depth of about 7,500 feet. This well is reported to have discharged dry steam before penetrating a wet steam zone. Until this well has been adequately tested and the results of the tests of the other wells have been made public, the capability of the field will not be known. Only 6 or 7 of the remaining 56 thermal areas show real promise under existing technology.

Six of Nevada's 185 thermal springs have been test drilled, and wells at Steamboat Springs, Brady Hot Springs, and the Beowawe Geysers (fig. 10) have all produced steam. Potential power capacity has been estimated conservatively at 40,000 kilowatts at Beowawe. However, most of the steam produced at these locations has been high in dissolved mineral content.

No attempt has been made in Utah to drill for high temperature steam. Although six regions contain thermal springs, areas in the western and central parts of the state seem to offer the most potential.

Rocky Mountain Region

With the exception of the Yellowstone National Park region, very little study has been made of the occurrence and distribution of natural thermal phenomena in Wyoming, Colorado, Montana, and South Dakota. Thermal springs occur in association with Cenezoic tectonic features, but other recent geothermal phenomena -- solfataras, fumaroles, and geysers -- seem to be lacking. Deep hole drilling, mainly for oil and gas exploration, also has not disclosed any exceptional anomalies. A comprehensive literature survey plus careful field inventories of thermal spring areas could reveal suitable prospects for exploration.

Idaho (fig. 11) has one of the largest of thermal anomalies in the western United States; more than 200 springs are on record and newly drilled wells have sometimes encountered thermal water in unexpected areas. Although no steam has been found, a few relatively-shallow wells obtain water at more than 200°F; thermal waters with temperatures of more than 150°F are common in both springs and wells. The areas with the most potential are those in the south-central and southwestern part of the state, along the borders of the Snake River plain.

The Pacific Northwest

About 40 percent of Oregon has been subjected to Late Cenozoic volcanism, and within this region are a number of tectonic structures favorable to geothermic exploration. Six areas, all in the south-central or southeastern portion of the state, seem to hold the most potential (fig. 12). Many wells in Oregon have encountered thermal waters; more than 350 have been drilled at Klamath Falls, mostly to obtain hot water for space heating. Although a few wells, mostly in the Warner Range, have been drilled specifically for steam, none has been successful.

Washington State has less geothermic potential than most of the other western states; most of the approximately one dozen thermal springs are confined to the Cascade Range. Only a few springs, such as those near the Quaternary volcanos Mt. Adams and Mt. St. Helens, produce water at more than 130°F.

Thermal activity in Canada is restricted almost entirely to western British Colombia and to a small area along the Kootenay River. A few additional thermal springs are along the Laird River west of Fort Nelson and at Banff, Alberta. Most of these springs have temperatures of less than 130°F; all issue from rocks of Cretaceous age or older.

Alaska and Hawaii

Alaska undoubtedly contains thermal areas that meet the requirements for geothermal power, but to date there has been no development of the resource to produce electricity. Steam has been used from Manly Hot Springs and from Circle Hot Springs for space heating. At this time, little, if any, market exists for geothermal power; but utilization of other natural resources could create the needed market. Additional problems would occur because most thermal areas are in remote volcanic regions, such as on islands in the Aleutian chain.

In the Hawaiian Islands, chances for developing natural steam under sufficient pressure for generating electrical energy appear slim, largely because of the generally porous nature of Hawaii's lavas. Lava lakes in some calderas remain molten at depth, but offer only local, limited potential for development. An exploratory drilling project, undertaken in 1961 in the Puna area of the Island of Hawaii, was discontinued in 1962 after several exploratory holes did not encounter steam under high pressure.

FUTURE DEVELOPMENT OF GEOTHERMAL RESOURCES

Now that we have reviewed the present status of geothermics in North America, let's turn to the

3/5

future and consider briefly some of the factors that will undoubtedly play a role in the development of geothermal resources. The discussion logically divides into three parts: exploration techniques, development techniques, and incentives and determents to continued exploration.

Exploration techniques

Known geothermal fields were discovered by drilling on obvious thermal anomalies, much as the first oil fields were discovered by drilling on oil seeps. A number of thermal anomalies have been drilled without apparent success; however, poor tests, even in areas later proved to be of value, are common. For example, the first attempts to find natural steam in the Salton Sea region were unsuccessful; three wells, the deepest 1,473 feet, were drilled in 1927. The pressure and volume of the obtained steam were deemed insufficient for commercial purposes, and efforts to develop a steam field were abandoned.

Thus, even though a prospect has been drilled, it has not necessarily been proven worthless. The major economic problems are how to choose a prospect and where to drill the first exploratory holes.

Geologic mapping. Needless to say, good geologic mapping is a must. In any exploration program, the first stage is reconnaissance field geology and geologic mapping. Structural geometry is of primary importance in determining the geothermal anomaly. Steeply-dipping, normal or strike-slip faults are common in thermal areas and probably aid in providing deep circulation of meteoric waters. Structural troughs are the most favorable large structures. Structures associated with calderas also are often prospective.

Regional lithologic studies are important in determining effective porosity and permeability at depth in a given system. Studies of geologic history, with special emphasis on tectonic and volcanic history, will perhaps aid in evaluating the total heat flow of a given anomaly. Almost all important thermal systems seem to be associated regionally with Cenozoic volcanism, although there may be no surface indication of volcanic rocks in the immediate vicinity of the surface anomaly.

Additional exploration techniques are being used increasingly to supplement basic mapping in geothermal prospecting.

Fluid dynamics studies. Geothermal studies have shown that water that discharges as natural steam or super-heated water is, for the most part, meteoric water. This is, it has its origin in the atmosphere and has reached its present position through some sequence of events that includes recharge and ground-water movement.

One step that is being added to searches for natural steam is the integration of relatively inexpensive studies of regional ground water hydrology with basic geology. More and more, the techniques of regional fluid dynamics, such as those of Tóth (1963) and Freeze and Witherspoon (1966) are being called upon to explain the occurrence, distribution, and chemistry of thermal waters.

These methods do nothing more than describe, quantitatively, the movement of ground water on a regional scale. The theory behind the methods presumes that all rocks have a finite permeability, that ground-water movement need not be confined to "permeable" zones, and that some components of ground-water flow reach great depths without passing through fault zones or other zones of high vertical permeability.

Regional fluid dynamics adds more information to the basic background required to determine where, and to what extent, physical or chemical observation should be made.

Physical techniques. The use of standard geophysical tools has been very effective in the search for natural steam. Future developments will most likely include refinements of old techniques and modification of classic theory to fit new data.

The work of Rex (1970) in using a combination of gravity, temperature gradient, and electrical resistivity to identify thermal anomalies has already been discussed. In addition, George Keller at the Colorado School of Mines, is using dipole resistivity and electromagnetic methods to locate natural steam; his techniques were applied successfully in the Nicaragua study.

A physical method that seemed to show promise was one that came out of New Zealand. The method uses a portable, slow-motion tape seismograph that measures seismic ground noise in the range of 1 to 20 cycles per second. The theory is that water contact with a heat source produces a seismic noise pattern that can be plotted to determine the extent of a favorable geothermal aquifer. The instrument is simply left at one station after another until an adequate number of stations have been occupied. The tape is analyzed electronically to determine (1) the overall noise amplitude, and (2) the dominant frequency and its amplitude. Preliminary indications are that a dominance of high noise and low frequency describe a good thermal aquifer. However, we know of no successful application of this technique.

One physical method that shows promise utilizes remote sensing techniques coupled with ground control. For example, Miller (1968), using infrared imagery, was able to map areas in Yellowstone National Park in which the ground surface temperature was as low as 2° to 4°F above normal. He estimates that in one area, 2,000 pounds of steam per hour are diffusing upward from the water table and are condensing a few tens of feet underground. Using the same tool, he further estimates that two steaming and warm ground areas are expanding at rates of as much as 15 feet per year.

Chemical studies. Potentially useful chemical observations can be divided into two principal types: Those that attempt to estimate the maximum temperature that the water has reached; and those that attempt to estimate the age of the water, or more precisely, the length of time that the water has been in the aquifer.

Efforts to estimate maximum temperatures fall into one of three categories: (1) The silica content of most thermal water is abnormally high. The temperature at which this amount of silica would be in equilibrium gives an indication of maximum temperatures to which the water has been recently heated. (2) Isotopic compositions of waters from thermal springs and wells are used to determine whether there has been enrichment or fractionization that can be related to temperatures at depth. (3) At the Mexicali field, sodium-potassium ratios seem to be related to temperatures, with high temperatures associated with the lower ratios. This observation seems applicable to other areas.

The period of time that the water has been in the system is being investigated by two basic isotopic-composition methods: (1) Certain isotopes tend to become enriched through reactions with rock or by mixing of meteoric water with water from other sources. (2) Other radio-isotopes, notably carbon 14 and tritium, can be used to determine the length of time the water has been removed from the atmosphere.

The value of these chemical observations is that they can provide insight into basic elements of a thermal system before an extensive test drilling program is undertaken. If sufficiently high temperatures are not indicated, exploration may not be fruitful. If the water is relatively old, it may indicate that the reservoir is recharged slowly and therefore would be subject to depletion if developed unwisely. As with many techniques, interpretation will depend in large measure on the validity of assumptions about the geology and fluid dynamics of the system. If such assumptions are close to reality, isotopic methods should prove extremely useful.

Exploration problems. One major exploration problem that remains to be solved is that of how we go about locating thermal steam reservoirs when they occur beneath thick, producing ground-water reservoirs, as they probably do in the Rio Grande Valley of New Mexico and along the borders of the Snake River plain in Idaho. These areas are geologically similar to areas of known capacity, yet the sweep of ground water through shallower aquifers is sufficiently great that it masks any surface manifestation of heat.

Development techniques

In most geothermal developments, no sharp line can be drawn between the end of the exploratory phase and the beginning of exploitation. Although most of the techniques described above are strictly exploratory, a few will be used during the development of a field to determine such factors as well spacing and productive well life.

It is in this exploitation phase that additional technology is particularly needed. Perhaps one of the most pressing problems is that of brine disposal. Depending on the area, one of two solutions seems to be the answer: economic removal of the mineral components or return of the thermal fluid to the reservoir. Three other interesting development techniques are also being considered.

Teledyne Geonuclear, Inc., on the assumption that natural steam moves vertically upward through high-angle fractures, is investigating the prospect of using low-yield nuclear explosions to increase vertical permeability of the steam reservoir around existing wells. The chimney thus created could have the effect of increasing effective well diameter from a matter of inches to as much as 70 feet, and could increase the yield of a single well from 10 to 20 fold.

A variation of the above technique has been suggested by workers at Pacific Northwest Laboratories of the Battelle Institute. They propose to recover energy from natural earth heat without relying on the discovery of natural steam. The rock crushing power of a nuclear device would be used to produce a large cavity filled with broken rock. Heat removal would be accomplished by drilling a second hole into the bottom of the cavity and adding water. The resultant high pressure, high temperature steam would be removed from the top of the cavity, used to power a turbine generator, condensed, and returned to the cavity.

Magma Energy Company has a completely different approach which is not only thermodynamically feasible, but seems to be economic. Magma proposes to use superheated water (rather than steam) having temperatures as low as 240°F in conjunction with heat exchangers. Thermal water will heat freon or propane, which will expand and discharge through a turbine generator. The used gas is condensed, reheated, and cycled back through the heat exchanger in a closed cycle. A field test of a small heat exchanger is being conducted at Brady Hot Spring in Nevada (fig. 11). A final decision on location of the first plant should be made in the near future.

If these heat-exchanging generators actually prove to be as economic as they seem to be, the whole approach to the development of natural thermal areas could change. The need to find reservoirs containing only a suitable type of steam will be gone, and we will be searching, instead, for copious quantities of very hot water. Magma expects to solve any brine disposal problems by returning the used water to the aquifer. This procedure should not only dispose of brine, it should also insure adequate water at good hydraulic heads in the aquifer.

Measurement problems

Problems that are common to both exploration and development phases are those of accurate measurements of borehole temperature and discharge. To date, measurements of temperature have been made with Amerada-type pressure and temperature bombs. These relatively costly measurements are not satisfactory for a variety of reasons: Bombs sometimes come loose and have to be recovered, or they fail by springing leaks under pressure. Occasionally they simply fail to record temperatures with sufficient accuracy to be meaningful.

Flow usually is measured with orifices, and these measurements are accurate if the density of the fluid is known. With dry steam no problem arises, but with wet steam the measurement is not so simple because the density of the water-steam mixture is not uniform. Nucleonics Corporation is attacking this problem by injecting phase radioactive tracers and scanning horizontal pipes vertically for gamma radiation distribution.

Incentives and Determents to Continued Exploration

Technologic problems can usually be solved, given time and enough interest. However, other factors, mainly political and economic, can be just as much, or more, of a problem than technology in the development of geothermal resources. On the other hand, favorable political and economic factors may accelerate geothermal exploration.

Until 1970, failure of the Federal government to provide adequately for the development of Federal geothermal lands has been the major deterent in the exploration and development of the resource in the western United States. On December 24, 1970, President Nixon signed the Geothermal Steam Act of 1970 (Public Law 91-581, 91st Congress, S.368). This law provides for the leasing of federal lands for the purpose of exploring for and developing geothermal steam and "geothermal resources," including any mineral values that might be extracted from thermal brines. Since the adoption of the law, a great number of companies have become actively interested in prospecting for and developing natural steam.

At the present time, at least four states -- California, New Mexico, Utah, and Idaho -- either have specific laws providing for the leasing of state land for geothermal development, or can operate effectively under prior statutes.

Economic deterents and incentives take on a variety of shapes and sizes. Discoveries of oil reserves on the North Slope of Alaska have caused some oil companies that might have been interested in geothermics to commit their capital to exploiting the more-familiar petroleum. However, some individuals believe that money not invested in geothermal exploration and development by oil companies will be more than replaced by investments from other sources. Some view geothermal power as "ecologically and environmentally safe," thus a good long-term investment.

One very practical consideration for the location of future exploration is the power market. Existing or planned power supply is more than adequate in western states such as Wyoming. However, in most other states the demand for power is growing, and may in fact be a limiting factor in the growth of specialized industries in these states. Here, geothermal power would not be competing with, but would be supplementing existing power sources.

Geothermics could provide in some areas a cheap source of electricity that could be used to exploit other local mineral commodities, such as phosphate or magnesium. Industries outside the mineral processing field (such as pulp and paper manufacture or the pumping of irrigation water) also require large amounts of relatively inexpensive power. Perhaps the ultimate in use is that proposed by Rex (Anon., 1969). He suggests that geothermal power produced from fields in the Salton - Mexicali province could be used to distill salt water, thus providing an ample, relatively-inexpensive water supply for the ever-thirsty southern California area.

315

REFERENCES CITED

Alonso Espinosa, H., 1966, La zona geotermica de Cerro Prieto, Baja California: Boletín de la Sociedad Geologia Mexicana, V. 29, p. 17-47.

Alonso Espinosa, H., L. F. deAnda, and F. Mooser, 1964, Focos termales en La Republica Mexicana: Boletin de la Associacion Mexicana de Geologos Petroleros, V. 16, p. 145-152.

Anon., 1969, Geothermal steam looks better: Science News, V. 95, p. 113-114.

Anon., 1970, Compendium of papers presented at the Imperial Valley - Salton Sea area geothermal hearing: Cal. Geothermal Resources Board and Cal. Legislative Joint Committee, Atomic Development, 35 presentations.

Austin, C. F., 1966a, Selection criteria for geothermal prospects in Papers presented at the AIME Pacific Southwest Mineral Industry Conference, Sparks, Nevada, May 5-7, 1965; Part C, Session on North American exploration and mine development: Nevada Bureau of Mines Report 13, p. 93-125.

___________, 1966b, Undersea geothermal deposits -- Their selection and potential use: NOTS TP 4122, China Lake California Naval Ordinance Test Station Research Department, 72 p.

Banwell, C. J., 1957, New Zealand thermal area and its development for power production: ASME Trans., V. 79, p. 255-268.

___________, 1963, Thermal energy from the earth's crust. Introduction and Part I: New Zealand Jour. of Geology and Geophysics, V. 6, p. 52-69.

___________, 1964, Thermal energy from the earth's crust. Part II - The efficient extraction of energy from heated rock: New Zealand Jour. of Geology and Geophysics, V. 7, p. 585-593.

Burnham, J. B., and Stewart, D. H., 1970, The economics of geothermal power: Pacific Northwest Laboratories, Battell Institute, Richland, Wash., 18 p.

California Geothermal Resources, 1967, Report to the 1967 Legislature by the Joint Legislative Committee on Tide Lands, 194 p., 75 p. bibliography.

Facca, G., and A. Ten Dam, 1965, Geothermal power economics: U. S. Congress. Senate Comm. on Interior and Insular Affairs, Subcomm. on Minerals, Materials, and Fuels. Hearing on S1674, July 22, 1965, p. 67-115.

Facca, Giancarlo, and Franco Tonani, 1962, Natural steam exploration in the U.S.A.: Bolletino di Geofisica Teorica ed Applicata, V. 4, p. 115-171.

_______________________, 1964, Theory and Technology of a geothermal field: Bull. of Volcanology, V. 7, 47 p.

Freeze, R. A., and P. A. Witherspoon, 1966, Theoretical analysis of regional ground-water flow: 1. Analytical and numerical solution to the mathematical model: Water Resources Research, V. 2, p. 641-656.

Groh, E. A., 1966, Geothermal energy potential in Oregon: The Ore Bin, Oregon Dept. of Geol. and Mineral Industries, V. 28, p. 125-135.

Heylmun, E. B., 1966, Geothermal power potential in Utah: Utah Geological and Mineralogical Survey Special Studies 14, 28 p.

Horton, R. C., 1964, Geothermal power in Mineral and Water Resources of Nevada, Nevada Bur. Mines Bull. 65, p. 267-269.

Kaufman, Alvin, 1964, Geothermal power -- an economic evaluation: U. S. Bur. Mines Inf. Cir. 8230.

Koenig, J. B., 1967, The Salton-Mexicali geothermal province: Calif. Div. Mines and Geol., Mineral Informatio Service, V. 20, p. 75-81.

McNitt, J. R., 1963, Exploration and development of geothermal power in California: Cal. Div. of Mines and Geol. Special Report 75.

Meidav, Tsvi, and Rex, R. W., 1970, Investigation of geothermal resources in the Imperial Valley and their potential value for desalination of water and electricity production: University of California, Inst. Geophys. Tech. Report 3, 54 p.

Miller, L. D., 1968, Steaming and warm ground in Yellowstone National Park: Its location, geophysics, vegetation, and mapping with arial multispectral imagery: Unpublished Ph.D. thesis, U. of Michigan.

Milligan, J. H., R. E. Marsell, and J. M. Bagley, 1966, Mineralized springs in Utah and their effect on manageable water supplies: Utah Water Research Laboratory, Utah State University Report WG23-6, 50 p.

Otte, Carel, and R. L. Dondanville, 1968, Geothermal development in the Geysers area, California [Abs.]: AAPG Bull., V. 52, p. 565.

Peterson, N. V., and E. A. Groh, 1967, Geothermal potential of the Klamath Falls area, Oregon-A preliminary study: The Ore Bin, Oregon Dept. of Geol. and Mineral Industries, V. 29, p. 209-231.

Rex, Robert W., 1968, Investigation of the geothermal potential of the Lower Colorado River basin: Phase I - The Imperial Valley Project: The Institute of Geophysics and Planetary Physics, University of California at Riverside.

____________, 1970, Investigation of geothermal resources in the Imperial Valley and their potential value for desalination of water and electricity production: Univ. of Cal., Inst. Geophysics, Planetary Physics, 14 p.

Rex, Robert W. and Randall, Walter, 1969, New thermal anomalies in the Imperial Valley of California: [abs.] Am. Geophys. Union Trans., V. 50, no. 4, p. 348.

Ross, Sylvia H., 1970, Geothermal potential of Idaho: Idaho Bureau of Mines and Geol. open-file report, 28 p.

Stewart, D. H., and Burnham, J. B., 1969, The application of plowshare to geothermal power: Pacific Northwest Laboratories, Battelle, Memorial Institute, Richland, Washington, 9 p.

Summers, W. K., 1965a, A preliminary report on New Mexico's geothermal energy resources: New Mexico Bur. Mines and Mineral Resources Circ. 80, 41 p.

____________, 1965b, Chemical characteristics of New Mexico,s thermal waters -- A critique: New Mexico Bur. Mines and Mineral Resources Circ. 83, 27 p.

Tóth, J., 1963, A theoretical analysis of ground-water flow in small drainage basins: Jour. Geophysical Research, V. 68, p. 4795-4812.

United Nations, 1964, United Nations conference on new sources of energy. Proceedings of the conference in Rome, Italy, Aug. 21-31, 1961. V. 2, Geothermal energy - I, 420 p.; V. 3, Geothermal energy - II, 516 p.

Waring, G., 1965, Thermal springs of the United States and other countries of the world -- A summary: U.S.G.S. Professional Paper 492, 383 p.

White, D. E., 1957, Thermal waters of volcanic origin: Geol. Soc. America Bull., V. 68, p. 1637-1658.

____________, 1965, Geothermal energy: U. S. Geol. Survey Circ. 519, 17 p.