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Geothermal energy: geology, exploration, and developments

PART 2

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ABSTRACT

Part 2 is a review of the geology and geothermal energy development in the following countries, which are currently commercially producing electric power from geothermal steam: United States, Iceland, Italy, Japan, Mexico, New Zealand, and Russia. Six other countries should have geothermal energy production in a few years, and at least 19 others are in the investigative stages. Current economics and governmental legislation in the United States are summarized. A select bibliography on the geology and exploration for geothermal energy in significant areas of the world is included.

AREAS OF GEOTHERMAL ENERGY PRODUCTION AND POTENTIAL DEVELOPMENTS

At the present time, seven countries derive electric power from geothermal steam, and several more are developing their geothermal resources for commercial exploitation (fig. 1, Part 1). Geothermal energy developments in the producing countries are summarized by country in the following order: United States, Iceland, Italy, Japan, Mexico, New Zealand, and Russia.

The United States

Geothermal energy is economically converted into electricity at one facility in the United States at the present time — The Geysers, California (fig. 3, Part 1). The Geysers geothermal steam field is significant for the following reasons:

(1) it was the first geothermal field in the Western Hemisphere to produce electric power successfully;

(2) to the present time, it is the only geothermal power facility on-stream in the United States;

(3) it is the only dry-steam field in North America;

(4) it is the site of the deepest steam well in the world;

(5) it is the only geothermal facility in the world completely financed by private capital; and

(6) it is projected to become the largest geothermal power complex in the world.

The productive Geysers area includes over 2 sq km along Big Sulphur Creek at about 600 to 1000 m elevation in the rugged Mayacmas Mountains (fig. 3, Part 1 and fig. 10, Part 2). The area is about 120 km north of San Francisco. The geology of the area is described in the following reports: Bailey (1946), Koenig (1963, 1969), McNitt (1963, 1968).

The area is underlain by a mixture of graywacke, shale, basalt, and serpentine of the Jurassic-Cretaceous eugeosynclinal Franciscan Group. These rocks were severely compressed and overthrust from the east by the Great Valley sequence along the Coast Range thrust during Late Mesozoic and Early Cenozoic time. Late Cenozoic normal faulting

FIGURE 10.—Sulphur Bank area, The Geysers, California. Two wells, center and left, testing to atmosphere. Steam at right is from flow line of hole being drilled. G. W. Berry photo.

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widely affected the area and produced a major northwest-trending, 40-km-long fault zone, along which occur The Geysers hydrothermal area and nine major mercury mines. A probable genetic relationship between vapor-dominated geothermal systems and mercury deposition with reference to The Geysers area is discussed by White and others (1971). Intersecting northwest- and northeast-trending normal faults localize the surface hot springs and areas of hydrothermal alteration in a northwest-trending graben.

Volcanic activity, dated from 3 million to about 50,000 years before present (Koenig, 1969), is evident on Cobb Mountain 5 km northeast of The Geysers and in the Clear Lake volcano-tectonic depression about 16 km northeast, where numerous hot springs occur. The volcanic rocks of the region include rhyodacite, dacite, andesite, and basalt in domes, flows, and pyroclastic accumulations. A close spatial and temporal relationship between volcanic activity, uplift, normal faulting, and geothermal activity suggests that the source of heat at The Geysers is a buried igneous mass of Pleistocene age, possibly associated at depth with the Cobb Mountain volcanic rocks.

The immediate thermal area of The Geysers is a hydrothermally altered zone 400 m long and 200 m wide. At least a dozen hot springs had a total estimated flow of 90 gpm at temperatures ranging from 50 to 100°C. Most of the springs are acidic (pH 2-3) and have chloride content similar to local rain water (2 ppm). The dry, slightly superheated steam is more than 99.9 percent pure water. Small, but possibly harmful amounts of boron in the steam condensate are returned to the subsurface via injection wells with no adverse effect on production from the steam wells.

Drilling, development, and general economics of The Geysers project are discussed by McNitt (1963), Koenig (1969, 1970), Barton (1970), McMillan (1970) and in a recent report to the California State Senate entitled "Economic Potential of Geothermal Resources in California" (1971). Modern drilling began in 1955, and to October 1969, 78 wells had been drilled of which only four were noncommercial. The status of drilling as of the end of September 1971 in The Geysers general area, which includes Sulphur Bank, Little Geysers, and Castle Rock Springs, is as follows (G. W. Berry, personal communication):

Wells completed	80
Producing wells abandoned	4
Holes drilled waiting	5
Dry holes (incl. 2 mechanical failures)	6
Holes drilling	2
Locations	2
Disposal wells	1
Wild well	1
Total	101

Recent wells have been drilled about 1200 to 2150 m deep and have averaged 100,000 lb of steam per hour (figs. 11, 12) which is derived from fractured and solution-fissured sandstones. The deepest steam well in the world, 2752 m deep, was drilled in August 1971 at The Geysers. This well is capable of producing 190,000 lb of steam per hour, or

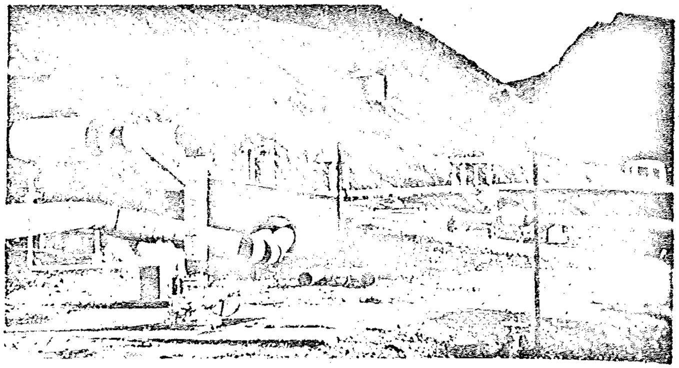

FIGURE 11.—Early producing well in foreground, with separator flow line to remove rock particles, The Geysers, California. Main lines with expansion loops go to Pacific Gas and Electric Co. Plant No. 1. Cordero Mining Co photo.

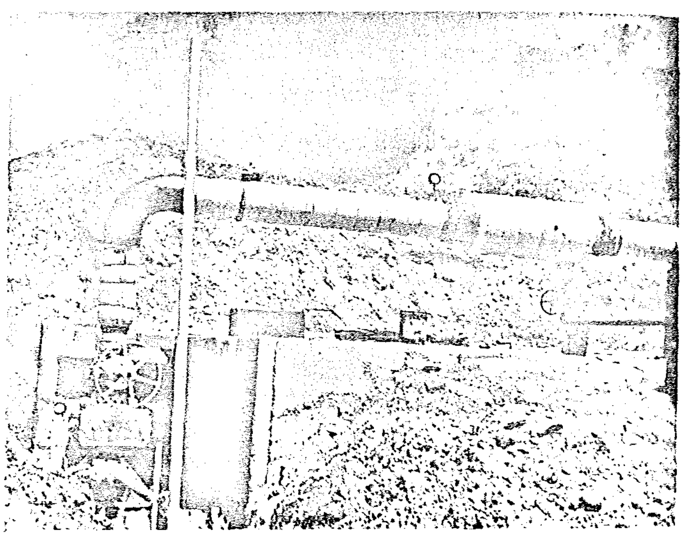

FIGURE 12.—Well head and separator assembly, The Geysers, California. D. A. McMillan photo.

about 10,000 kw. Reservoir temperatures range from 236 to 288°C, and shut-in pressures of the deeper wells range from 450 to 480 psig. More recent drilling is approximately on 40-acre spacing. A steam phase for much of the field is indicated by shut-in pressures independent of well depth. Apparently the reservoir character and discharging steam from the deeper wells have remained essentially the same during the 16-year life of the field. Boundaries of The Geysers steam field have not, as yet, been determined by drilling. The steam reservoir is known to include an area of at least 26 sq km, and it may be greater than 50 sq km.

Commercial geothermal power generation began in June 1960 with a 12,500-kw plant fed by 250,000 lb of steam per hour from four wells. Present production is 82,000 kw generated from four units. By the end of 1971, units 5 and 6 will be operational (fig. 13), bringing the capacity up to 192,000 kw. Annual increments added to the facility are expected to bring the on-line capacity up to 630,000 kw by 1975. Conservative estimates of total steam capacity based on yield of 150,000 lb of steam per hour per well are calculated to be about 1200 MW; liberal estimates range up to 4800 MW. A million people could be served by 1200 MW.

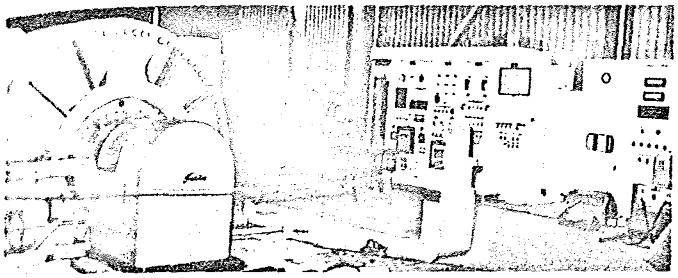

FIGURE 13.—Power Unit No. 5, 55 MW, Aug. 19, 1971, The Geysers, California. D. A. McMillan photo.

Three companies — Magma Power, Thermal Power, and Union Oil Company of California — are currently developing The Geysers field and selling steam to the Pacific Gas and Electric Company. Several other companies have leases in the region. Geothermal Resources International and Signal Oil Company have each drilled several wells with significant tested initial capacity. The total cost of geothermal energy at The Geysers, calculated on the actual price of the steam at $0.0026 per kwhr, is about $0.005 per kwhr produced (McMillan, 1970). This is more than hydro and less than fossil fuel power costs in California.

ICELAND

In Iceland the foremost use of low-temperature (80°C) thermal springs has been in space heating, rather than in power production. Over 250 thermal areas are known in Iceland. The geological, geophysical, and geochemical characteristics of many of these areas are presented by Bodvarsson (1964).

Geologic and seismic refraction studies indicate that Iceland is built up of typically inhomogeneous layers of Tertiary basalt reaching thicknesses of 3 km or more. These layers are overlain by Quaternary basalts mainly in the central and southern parts of the island. The mid-Atlantic Ridge passes through Iceland and effects measurable modern rifting, Recent volcanism, and markedly high heat flow. The Tertiary volcanic districts have minor Recent faulting and hot-water areas with temperatures below 150°C. The Quaternary districts occur along a major throughgoing northeast-southwest rift zone that bifurcates to the southwest. This rift contains spring areas with subsurface temperatures from 150 to 200°C and large areas of hot ground, natural steam vents, and thermal metamorphism. The highest temperature areas show a close association with centers of very recent silicic eruptions (Bodvarsson, 1970b). Individual surface thermal areas are controlled by intersections of contacts between permeable volcanic layers, dikes, and faults. Several thermo-artesian circulation systems are believed to come close to contact with magmatic intrusions, the ultimate heat sources for the high-temperature areas (Arnason and Tomasson, 1970; Bodvarsson, 1970).

Experience in drilling in many areas of Iceland shows that large amounts of high-temperature water can be produced from relatively shallow depth (less than 450 m). In some areas, deposition of silica and calcite contribute to a near-surface layer several hundred meters thick that acts as an impediment to hot water and steam circulation. High-production rates of individual bore holes are largely unrelated to natural surface heat discharge which implies large amounts of stored heat over large areas. Rate of use of this stored heat depends on availability of water.

Various geophysical and geochemical techniques involved in the assessment of geothermal areas have emerged from research in Iceland. Recent contributions include reservoir model studies by Bodvarsson (1970), and Thorsteinsson and Eliasson (1970), subsurface temperature measurements by Bodvarsson and Palmason (1964), infrared aerial surveys by Palmason and others (1970), microearthquake surveys by Ward and others (1969), trace elements in thermal waters by Arnórsson (1970b), and water-system differentiation by deuterium and chloride content by Arnason and Tomasson (1970).

Drilling for steam has been carried out mainly in two high-temperature areas: Namafjall and Hengill areas. A small 3000-kw plant has been operating at Namafjall since 1969, and plans call for a considerably larger natural steam plant at Hengill.

ITALY

Geothermal energy was used for the first time to generate electricity in 1904 at Larderello, Italy. By the late 1930s, capacity had increased to 100 MW, and at present the installed capacity of all Italian plants is 390,600 kw (fig. 14). A condensed review of the geothermal energy industry in Italy is provided in a booklet entitled "Larderello and Monte Amiata . . ." (1970).

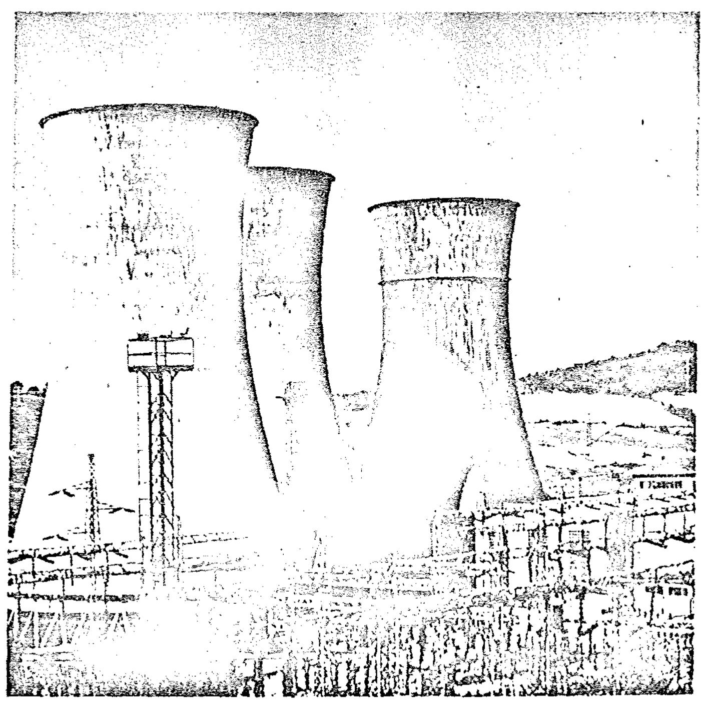

FIGURE 14.—Power plant, three cooling towers, and substation in Larderello, Italy. Total capacity 69,000 kw in four 14,500-kw units and one 11,000-kw unit. Cordero Mining Co. photo.

There are nine thermal fields along a 500-km zone on the western side of the Apennine Range in central Italy (fig. 15). Larderello and Monte Amiata are at the northwestern end, 200 km and 130 km northwest of Rome, respectively. Relatively few papers in English have appeared on the geology of the thermal areas of Italy. The two most important areas, Larderello and Monte Amiata, are described by Burgassi (1964) and Marinelli (1964). Most recently Calamai and others (1970) described the geology, geophysics, and geohydrology of the Monte Amiata fields which were discovered in an area of very little surface thermal activity.

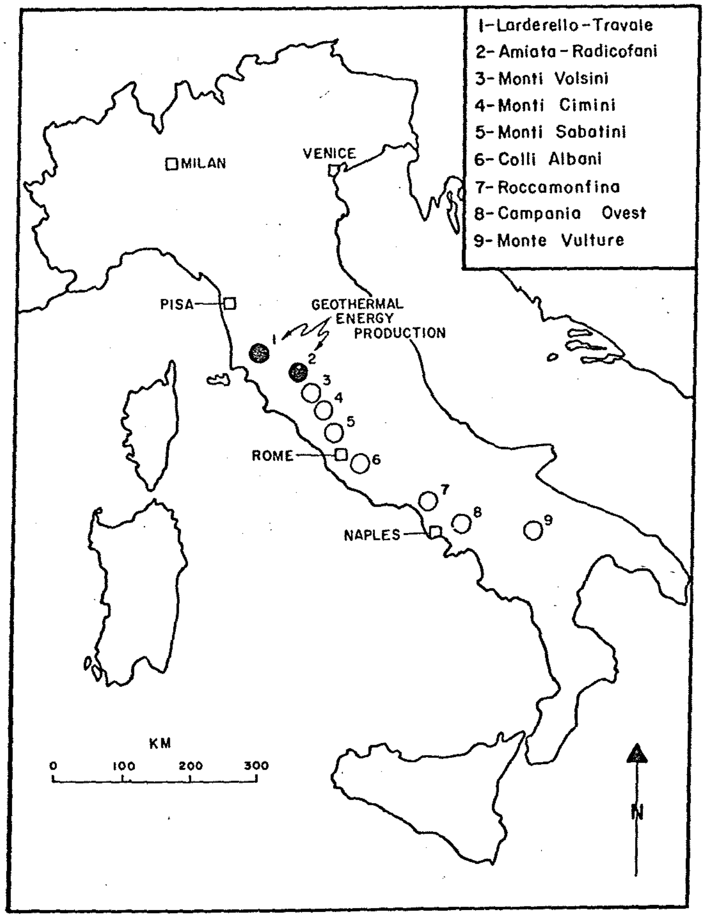

FIGURE 15.—Geothermal energy producing and developing areas in Italy.

At Larderello the rock sequence is sedimentary; igneous rocks are not directly evident in the area. Dry steam is produced from the Tuscan formation of Upper Triassic to Upper Jurassic age composed of highly pervious carbonate and anhydrite. The formation is underlain by a crystalline basement of phyllite and quartzite, and overlain by a chaotic thrust complex of clay, limestone, and ophiolite. Faulting in the basement allowed ascent of hydrothermal fluids into the porous anhydritic series, and the impermeable clays of the overlying thrust complex act as a cap rock by sealing in the fluids and heat of the geothermal system. The deeper faulting is pre-Quaternary and followed the Oligocene Apennine orogeny. The heat source is presumed to be a deep magmatic body of Miocene or younger age. Latest faulting of post-Pliocene age is tensional and associated with the post-orogenic collapse of the western margin of the Apennine Range. These latest faults form an intersecting network that localizes the recent hydrothermal activity. Natural outlets emitted largely steam and gas rather than hot water, although most have disappeared since exploitation of the Larderello steam. In the central producing area of Larderello, the geothermal gradient is 30°C per 100 m, or about 15 times normal.

The Monte Amiata area, 70 km southeast of Larderello, has a stratigraphic and structural regime generally similar to Larderello, except for the presence of ignimbrites and rhyolites of the post-Pliocene volcano, Monte Amiata. Volcano-tectonic collapse gave rise to a new fault system which controls feeble hot spring activity (including cold-gas outlets) on the flanks of 1500-m Monte Amiata. Within a 400-sq-km area around the Monte Amiata field, the geothermal gradient exceeds 10°C per 100 m, about five times normal.

In 1969 the greater Larderello area (Boraciferous Region) had a capacity of 365 MW. Dry steam was derived from 181 wells, with an average production per well of about 50,000 lb per hour at 150°C (fig. 16), (2500 kw), with shut-in pressure 5 atm and power station pressure 4.2 atm. Temperatures have increased during the time of exploitation, except in some local areas where recharging meteoric waters have effected cooling. The Travale and Monte Amiata regions together in 1969 had a capacity of 25 MW produced from 11 wells averaging 78,000 lb per hour. Planned expansion at Larderello should increase production there to about 415 MW. A comprehensive report on geothermal developments in Italy by Cataldi and others (1970) indicates that several thermal areas are being intensively explored and are in various stages of development. Substantial increase in geothermal power production in Italy must come from areas other than Larderello and Monte Amiata, since the limits of these fields apparently have been reached.

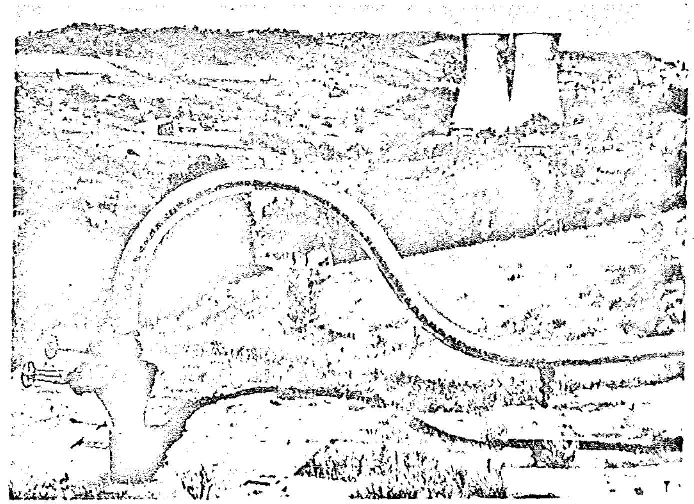

FIGURE 16.—View to north in Larderello geothermal area, Italy. Typical producing steam well and flow line in foreground. Cooling towers of Larderello No. 2 station at right. Town of Larderello in distance at right. Corder Mining Co. photo.

Japan

The Japanese have been engaged in intensive research and development of their geothermal resources because fuels — coal, oil, and uranium — must be imported from long distances overseas, and hydropower sites are limited. At present two fields, Matsukawa and Otake, are producing electric power, and four other areas are being developed for commercial production. About 200 Quaternary volcanoes and more than 90 areas of hot springs with water temperatures exceeding 90°C are known in Japan. Results of investigations and attending problems related to geothermal energy production are presented by Sato (1970).

The general geology of geothermal fields in Japan is covered by Saito (1964) and Ishikawa (1970). The Matsukawa field is described by Nakamura and others (1970), and the Otake field by Yamasaki and others (1970). Japan comprises part of the Circum-Pacific volcanic-tectonic belt, and hence has geothermal environments basically similar to those of Kamchatka and New Zealand. Most of the hot springs in Japan are closely associated with Quaternary volcanoes and domes of rhyolitic, dacitic, and andesitic composition, rather than basaltic composition. Many of the thermal fields are also found in highly faulted Tertiary volcanic and granitic areas that are seemingly unrelated to Quaternary volcanism. The heat sources of the geothermal fields are related to young volcanic centers as well as to deep intrusives of Tertiary and possibly Late Mesozoic age.

The Matsukawa area displays relatively little surface thermal manifestation, but has a wide area of hydrothermally altered rocks. Hot water and steam are trapped in Late Tertiary porous pyroclastics, brittle, fractured welded tuff, and marine black shale and sandstone. This sequence, up to 1700 m thick, was normal step-faulted during Late Tertiary and Quaternary time. Andesitic lavas from the Pleistocene volcano, Marumori, which is 1 to 2 km from the Matsukawa field, form a 160-m-thick cap over the older volcanic reservoir rocks. The geothermal system at Otake appears basically similar to Matsukawa, except apparently for more .urface flow of hot water and steam, and greater influence of intersecting faults on fluid migration. Thorough studies of hydrothermal alteration mineralogy and geochemistry of Japanese thermal areas appear in articles by Yamasaki and others (1970), Fujii and Akeno (1970), Koga (1970), Noguchi and others (1970), and Oki and Hirano (1970). Calculations on heat flow and energy reserves are presented by Hayakawa (1970) and Noguchi (1970).

The Matsukawa geothermal station in northeastern Honshu has a capacity of 20,000 kw, with a planned increase to 27,000 kw. The total potential of the greater Matsukawa area (including Takinokami 7 km distant) is estimated at 200 MW (Mori, 1970). The Otake plant in Kyushu has a capacity of 13,000 kw. According to calculations by Noguchi (1970), the total power potential of 124 magma chambers in Japan is 8400 MW for a few thousand years duration. The average generating capacity of all fields is about 70 MW. Many other uses of geothermal resources in Japan are reviewed by Komagata and others (1970). They include recreation and bathing resorts (150 million people annually visit hot spring sites), and agricultural, chemical, and secondary industries.

Mexico

Mexico is well endowed with potentially productive geothermal areas. More than 100 thermal areas and nine active volcanoes are known. Seven thermal areas in particular have been described (fig. 17). Pathé, the only currently producing area, generates 500 kw, although the turbine is rated at 3500 kw. Cerro Prieto is scheduled for a 75 MW operation in 1972.

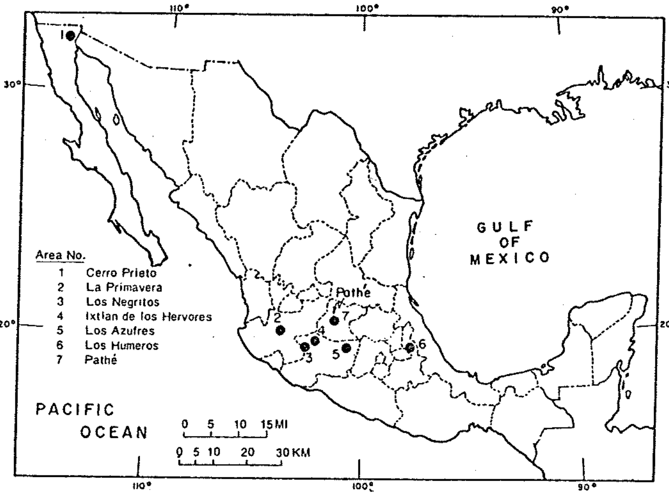

FIGURE 17.—Geothermal areas in Mexico (from Banwell and Gomez Valle, 1970).

The relatively recent developments in geothermal exploration in Mexico are presented by De Anda and others (1964), Alonso and others (1967), Alonso (1968), and Banwell and Gomez Valle (1970). There are six thermal areas in basically similar geologic environments within the trans-Mexican volcanic belt of Tertiary and Quaternary age. They are intimately associated with rhyolitic to andesitic flows, pyroclastics, and their sedimentary derivatives which accumulated in volcano-tectonic graben and caldera fault-block depressions. Surface phenomena, which are usually associated with Recent tensional faulting, consist of hot springs, steam vents, alteration zones, and hot ground. Surface temperatures range from 36 to 100°C (Banwell and Gomez Valle, 1970).

The Pathé field reservoir, which is a graben of intensely fractured and altered Tertiary andesites and basalts up to 1000 to 1500 m thick, overlies Cretaceous limestone formations and underlies Late Tertiary and Early Quaternary tuffs. Many wells have been drilled there, but only four wells have produced water and steam sufficient for power generation. The reason for the low productivity is believed to be lack of lateral permeability in the volcanic series. New drilling has been proposed to reach Cretaceous limestone where larger production may be expected (Mooser, 1965). More recently geological, geophysical, and geochemical investigations by the Federal Electricity Commission have been underway at the four other areas in southern Mexico. Preliminary data suggest that the Los Negritos field may have a potential comparable to the largest known geothermal fields of the world (Banwell and Gomez Valle, 1970).

The Cerro Prieto geothermal field (fig. 5, Part 1), in the Mexicali Valley about 30 km south of the USA-Mexico border, is part of the largest of all known geothermal systems in the world. Geologically it is an integral part of the enormous Salton-Imperial-Mexicali Valley geothermal system (Alonso Espinoza, 1966; Rex, 1970), which occurs in the sediment-filled graben associated with the northern part of the obliquely spreading Gulf of California and the East Pacific Rise system. The Cerro Prieto area is on the western side of the rift and on the general southern prolongation of the San Jacinto fault zone, where numerous normal and strike-slip faults step successive blocks down to the east. The basement of Cretaceous granitic rocks is overlain by about 2500 m of imperfectly compacted conglomerate, sandstone, and shale derived from erosion of block uplifts to the west and from deltaic sedimentation of the Colorado River to the east. These sedimentary rocks are locally intruded by Quaternary andesite and basalt manifest at the surface by the small Cerro Prieto crater 2 to 5 km west of the geothermal field. Boiling springs, mud volcanoes, and phreatic explosion vents are aligned in the area on a general north-south trend and extend into areas not fully explored.

Many wells have been drilled in the area to various depths up to nearly 2700 m. Usually, two steam and hot water producing zones of permeable sandstone interbedded with impermeable shale occur at depths of 600 to 900 m and 2400 to 2635 m. One well (M-20) drilled to 1385 m discharges a steam-water mixture at the rate of 1,500,000 lb per hour at a bottom hole temperature of 388°C. This is the greatest known natural steam-well discharge in the world (Mercado, 1969). Average well yields are about 500,000 lb per hour of moderately briney water (17,000 ppm total dissolved solids), with about 120,000 lb per hour flashing to steam. A geothermal plant with initial capacity of 75,000 kw is scheduled for completion in 1972. The power facility will tap steam from 15 wells drilled to average depth of 1375 m in an area of about 1 sq km. Residual brines will be drained initially into the Gulf of California, although the feasibility of an extractive chemical industry to process the brines rich in sodium, potassium, lithium, and calcium is being investigated. On the basis of geophysical data, the power potential of the Cerro Prieto field is well in excess of 1000 MW (Rex, 1971).

New Zealand

During the last 20 years, extensive development of geothermal resources has taken place in the Taupo volcano-tectonic depression in the North Island of New Zealand (fig. 18). A great deal of literature is available on many aspects of geothermal science and technology as developed by the New Zealanders in their classic areas. Basic geology, geophysics, and problems of energy extraction from heated rocks — data which are applicable to many thermal areas of the world — are provided by Banwell (1963, 1964) and Dawson (1964). Grindley (1965) in his paper on Wairakei presents one of the most extensive geologic studies of any to date on a productive geothermal field.

Many thermal areas are in the central 80-km-long portion of the 160-km-long Taupo volcanic zone (Healy, 1964).

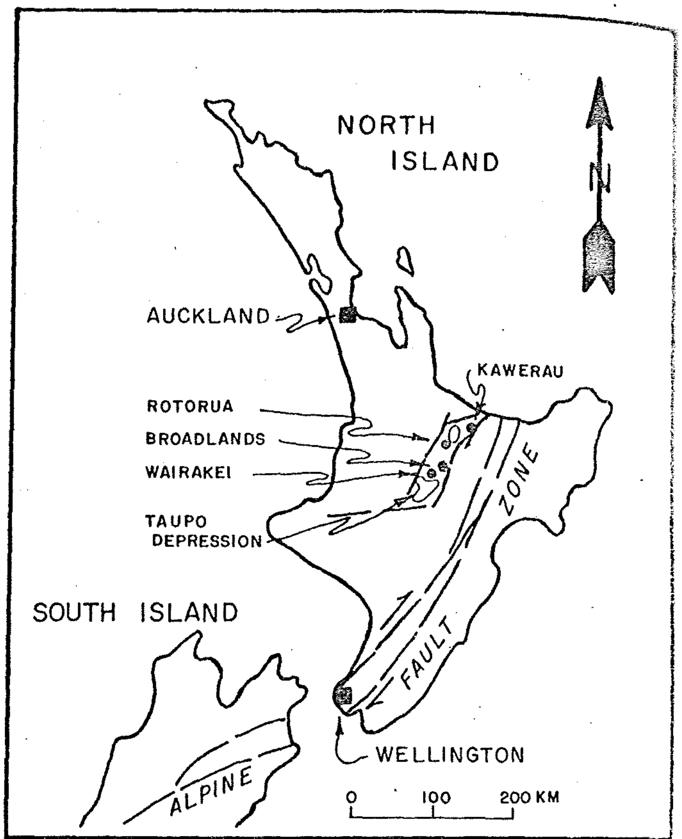

Figure 18.—Developed geothermal areas of New Zealand.

The Taupo volcano-tectonic depression occurs on strike with the Kermadec-Tonga submarine ridge and marginal to the regional Alpine fault. Numerous hot springs, fumaroles, and geysers occur in areas of abnormally high-temperature gradients. Features common to the hydrothermal fields on North Island (Grindley, 1965, 1966, 1970) include the following:

(1) reservoir rocks of nearly flat-lying Quaternary acidic volcanics up to a few thousand meters thick;

(2) a stepped aquifer system of several permeable pumiceous breccias and fractured flows interbedded with low-permeability mudstones, welded tuffs, and rhyolites.

(3) proximity to a rhyolitic eruptive center of Late Pleistocene age interpreted to overlie a granitic magma chamber;

(4) a northwest- and northeast-trending, conjugate, diagonal-slip fault system with fault intersections producing open fractures favorable for ascent of hydrothermal fluids and igneous intrusions; and

(5) direct association of areas of maximum heat flow with horsts and structural domes.

Many detailed geophysical investigations have been carried out in various thermal areas of New Zealand. Recent papers include direct and indirect methods of measuring heat flow (Dawson and Dickinson, 1970); seismic, gravity, and magnetic studies in the Broadlands field (Hochstein and Hunt, 1970); geothermal ground noise spectra (Clacy, 1968); electromagnetic induction methods for measuring resistivity (Keller, 1970); net mass loss from gravimetric measurements (Hunt, 1970); ground subsidence during exploitation (Hatton, 1970); absolute ground movement (Whiteford, 1970); d-c resistivity methods to 3 km deep (Risk and others, 1970); and near-surface (30 m deep) resistivity surveys (Lumb and MacDonald, 1970).

In the Wairakei area (figs. 19, 20), wells tap near neutral, weakly chloride waters at temperatures generally between 250 and 275°C. Steam discharge at wellhead is variable in different areas, and may range up to 50 percent. Only rarely is dry steam produced. The typical production well is 600 to 900 m deep. Average steam output of high-pressure wells (210 to 230 psi) is 52,000 lb per hour (4000 kw), and that of medium-pressure wells (75 to 85 psi) is 45,000 lb per hour (3000 kw). Average steam content at wellhead is 15 percent. Results of exploration drilling in recent years are described by McKenzie and Smith (1968).

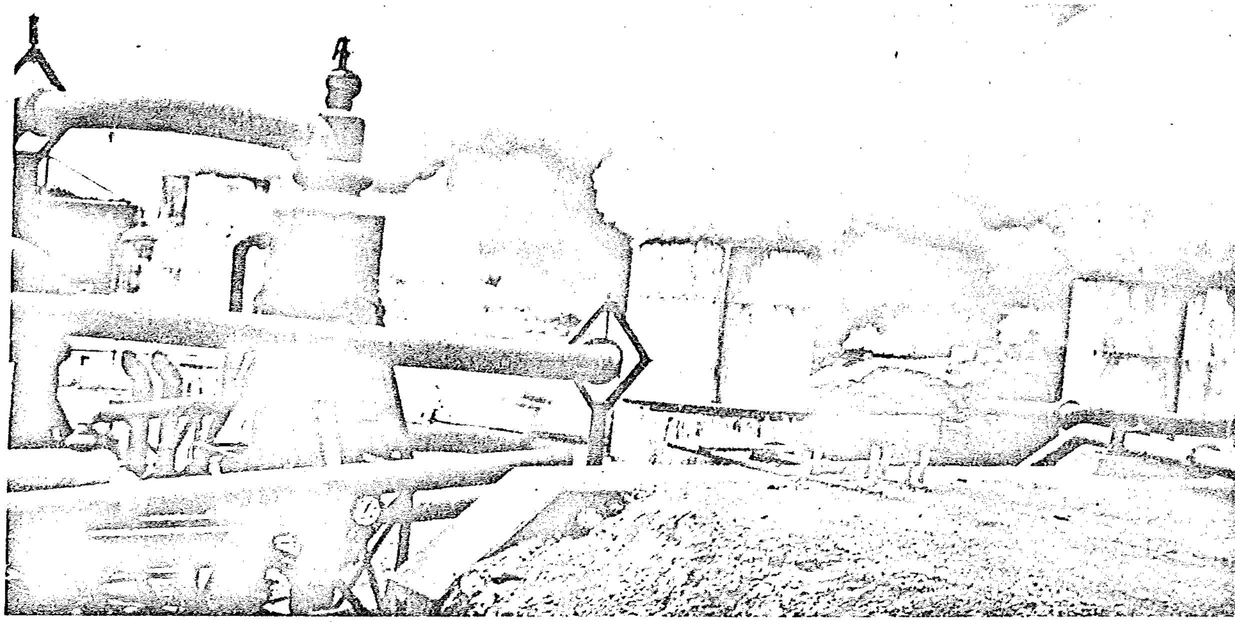

FIGURE 19.—Standard wellhead equipment in Wairakei, New Zealand. Average discharge is 15 percent steam which is recovered from cyclone separator (vertical cylinder at left). High-pressure dry steam goes directly to plant. Waste water goes to silencers (steaming center and right).

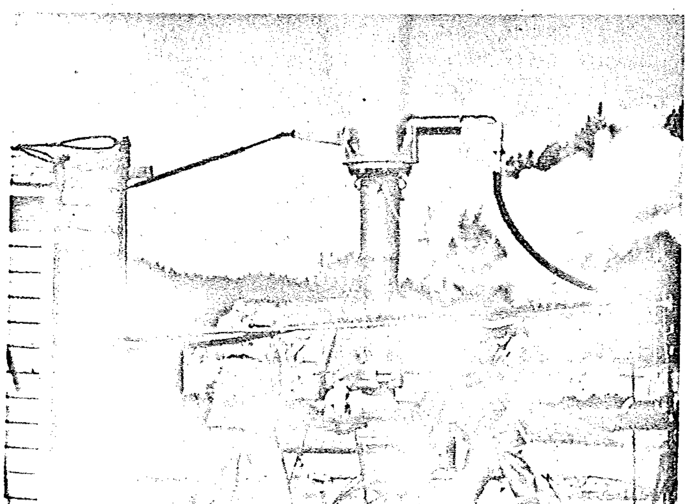

FIGURE 20.—Steam sampler measuring discharge of a high-pressure well in Wairekei, New Zealand. A sampling nozzle is drawn manually across the jet discharging vertically to atmosphere, with time in each position proportional to area of annular ring at radius being sampled. Sample is measured in small calorimeter in portable hut at left. G. W. Berry photo.

Geothermal developments in New Zealand to 1970 are summarized by Smith (1970). The electric power industry of New Zealand is entirely state owned and operated. About 20 percent of the electric power consumed in North Island is derived from geothermal sources. Greatest production comes from Wairakei, where present installed capacity is 192,000 kw, and expansion to 250,000 kw is being considered (fig. 21).

At Kawerau, steam is used for processing in a pulp and

FIGURE 21.—View in producing field, Wairakei, New Zealand. Steam is mostly from cylindrical silencers where hot water is flashing to atmosphere. G. W. Berry photo.

paper mill, and about 10,000 kw of power is also produced for the mill. Recent deeper drilling has enlarged the potential at Kawerau, but increasing deposition of calcite in the plumbing system poses a problem. Rotorua continues to use geothermal steam mainly for heating purposes (Burrows, 1970). Broadlands is a new and significant field discovered by regional resistivity surveys in an area of minimal natural thermal activity at the surface (Grindley, 1970; Facca, 1970). A generating capacity of 120 MW is tentatively scheduled for 1976.

Data on the behavior of geothermal systems in New Zealand during exploitation (Bolton, 1970) are revealing some pressure and temperature decline locally. However, the power output of the geothermal plants at the present level is expected to endure for many years, and significant increases in power generation are probable.

Russia

Steady and impressive progress in the science and engineering of geothermal resources utilization in many forms has been taking place in the Soviet Union along rather original lines compared to other countries during the last 30 years. Many papers given at the Pisa Symposium in 1970 cover Soviet developments to which the reader is referred for details far beyond the scope of this summary article.

At present, 11 geothermal projects are operating in the USSR. One geothermal power plant with capacity of 5000 kw is in operation at Pauzhetsk, in the southeastern part of Kamchatka. The geology of the hydrothermal systems in Kamchatka is described by Piip and others (1961), and Vakin and others (1970). The Pauzhetsk geothermal field is within the Circum-Pacific mobile belt of active volcanism, tectonism, and high heat flow, and is similar to the geothermal environments of New Zealand. Nearly flat-lying Quaternary pyroclastic formations with varying primary and fracture permeability are interbedded with impermeable layers that fill elongate and circular, normal faulted, volcano-tectonic depressions to thicknesses averaging 1500 m. Recent hydrothermal activity is localized at fault intersections of caldera collapse margins, which are superimposed on older graben-synclines, and is localized along fault margins of horst-anticlines within the large regional depressions. The thermal activity is closely associated with Middle to Late Pleistocene acid volcanism, rather than Pleistocene and Recent andesitic and basaltic volcanism.

Surface thermal phenomena consist of hot and boiling springs, geysers, steam jets, and patches of hot ground. Extensive studies of the hydrodynamics of geothermal systems in Kamchatka include relationships among temperature, viscosity, pressure, thermo-artesian head, and other factors. These studies are presented in several articles by Averiev (1967). Maximum temperature recorded to about 1220 m in depth is 200°C, and the temperature gradient may be as high as 70°C per 100 m.

The present facility at Pauzhetsk is being expanded to a planned total output of 29,000 kw. The geothermal resources of the Kamchatka region are believed to have a potential capacity of 500 MW from operation of several power stations (Vakin and others, 1970). Another area, Kunashiry in the Kurile Islands, is being considered for construction of a 6000-kw station (Tikhonov and Dvorov, 1970). The potential elsewhere in Russia for electric power generation from geothermal energy appears to be enormous (Makarenko and others, 1970; Tikhonov and Dvorov, 1970).

Geothermal resources in Russia are being used for many other purposes, such as space heating, agriculture, miscellaneous industries, and extraction of chemicals. Multiple uses are described for the Georgia region by Buachidze (1970), and the use of thermal waters obtained with oil and gas production in the Caucasus region is discussed by Sukharev and others (1970). General, lengthy summaries of scientific investigations and engineering of geothermal resources in Russia are provided by Makarenko and others (1970), and Tikhonov and Dvorov (1970).

Developing Areas in Other Countries

The aforementioned seven countries, which currently produce electricity from geothermal sources, will be followed within a very few years by several other countries (fig. 1, Part 1) that have geothermal power plants under construction or in the planning stages (Facca, 1970). *Chile* plans for a 20,000 kw plant at El Tatio (Koenig, 1971). The Ahuachapan area of western *El Salvador* has been explored and drilled (at least six wells) and estimates indicate a 25 to 30 MW power potential (Tonani, 1967; Sigvaldson and Cuellar, 1970; Summers and Ross, 1971). A recent article on microseismicity along a fault zone at Ahuachapan describes a relatively new method of locating thermal fluid-bearing zones in the subsurface (Ward and Jacob, 1971). The French have discovered a steam field with estimated capacity of 30,000 kw on *Guadaloupe* in the West Indies volcanic island chain (Cormy and others, 1970). In the Legaspi area of extreme southeastern Luzon, *Philippines*, a 10,000-kw power plant is planned (Koenig, 1971). Extensive geothermal investigations in the Tatun volcanic area at the northern tip of *Taiwan*, described fully by Chen (1970) and by Feng and Huang (1970), reveal a potential of 80 to 200 MW; a 10,000-kw plant is planned initially. The Menderes Massif geothermal province of Western Antatolia, *Turkey*, has been geologically and geophysically investigated along several Miocene-Pliocene grabens associated with hot springs and economic mercury mineralization; but no appreciable recent volcanism has occurred (Ten Dam and Khrebtov, 1970; Ten Dam and Erentoz, 1970). At Kizildere, the Turkish government is planning a 30,000-kw power station, and other areas as well hold promise for commercial exploitation.

Many other countries (fig. 1, Part 1) are in various stages of investigation of potential geothermal resources for development of electric power (Facca, 1970). These countries are as follows: Algeria (Cormy and d'Archimbaud, 1970); Bulgaria, Colombia (Arango and others, 1970); Czechoslovakia (Kremar and Milanovic, 1970); Ecuador (De Grys and others, 1970); Ethiopia, Fiji, Greece, Guatemala, Hungary (Boldizar, 1970); Indonesia (Muffler, 1971; Zen and Radja, 1970); Kenya, Morocco, Nicaragua, Poland (Dowgiallo, 1970); and Spain, Tunisia, Venezuela, and Yugoslavia (Kremar and Milanovic, 1970).

CURRENT STATUS AND OUTLOOK

Increase in interest in geothermal energy development in the Western United States is accelerating as a consequence of the following factors:

(1) demonstration of low-cost electric power production from geothermal steam relative to conventional and atomic sources,

(2) realization of the relatively minor pollution and environmental effects of geothermal power plants, and

(3) realization of the potential of the multipurpose or multiple-use approach to geothermal resource development involving the production of electricity, chemicals, and fresh water.

Energy exploration companies are investing many millions of dollars in research, exploration, and development. The government has passed legislation on leasing and operating regulations, taxation policies, total environment impact, etc., that should affect development on federal lands.

Assessments of costs involved in the various operations and facilities connected with exploration and development of geothermal energy are described in general by Facca and Ten Dam (1964), Bradbury (1970), and Kaufman (1970); and The Geysers geothermal field is described by McMillan (1970). Total cost per kwhr at The Geysers is 4.91 mills, at Larderello over 3.2 mills, and at Matsukawa 4.6 mills; all three are dry steam-producing fields. Costs at fields yielding a steam and hot water mixture are higher, however, but still competitive with conventional power sources. Cost analyses reported by Kaufman (1970) reveal that a base-load plant of 1500 MW capacity (assuming a privately financed plant and a 90 percent load factor during the life of the plant) will have a total cost of 2.96 mills per kwhr using geothermal energy, 3.45 mills per kwhr using hydropower, 4.82 mills per kwhr using natural gas, 4.87 mills per kwhr using oil, 5.22 mills per kwhr using coal, and 5.49 mills per kwhr using nuclear energy. Geothermal costs could be increased as much as 1.5 mills per kwhr to accommodate transportation costs, engineering and disposal problems, etc., and still remain relatively inexpensive.

In response to the Geothermal Steam Act of 1970, the U. S. Geological Survey has delineated lands classified as "known geothermal resource areas" (KGRA) where "the prospects for extraction of geothermal steam or associated geothermal resources are good enough to warrant expenditures of money for that purpose" (Godwin and others, 1971, p. 8). These areas are listed in the "Federal Register" between the dates of March 26 and April 23, 1971, and are on figures 22, 23, and 24. Leases on federal lands within a KGRA can be acquired only by competitive bidding. Classification factors, as determined by geological, geophysical, and geochemical data that are considered in the definition of KGRA's, are described by Godwin and others (1971). In further response to the Geothermal Steam Act, a notice of proposed rule-making on geothermal resources leasing and operations on public, acquired, and withdrawn lands is presented in the Federal Register, v. 36, no. 142, July 23, 1971. A general discussion of the implementation of the Geothermal Steam Act is presented by Stone (1971).

In an effort to keep interested people abreast of significant developments in the geothermal resources field, such as meetings, hearings, legislation, publications, prospect developments, activities and contributions of the Geothermal Resources Council, etc., a newsletter entitled *Geothermal Hot Line* was started and is published by the Geothermal Resources Board of California. This newsletter can be obtained from Geothermal Hot Line, Division of Oil and Gas, 1416 9th Street, Room 1316, Sacramento, California 95814.

CITED REFERENCES

Allen, E. T. and Day, A. L., 1935, Hot springs of the Yellowstone National Park: Carnegie Inst. Washington Pub. 466, 525 p.

Alonso, H., 1968, Geothermal energy in Mexico: Geol. Soc. America 1968 Ann. Mtg., Mexico City, Field Trip No. 6, Geology and utilization of geothermic energy at Pathe, State of Hidalgo, 15 p.

Alonso, H., Fernandez, G., and Guiza, J., 1967, Power generation in Mexico from geothermal energy: World Power Conf., 7th, Moscow.

Alonso Espinoza, H., 1966, La zona geotermica de Cerro Prieto, Baja, California: Soc. Geol. Mexico Bol., v. 29, p. 17-47.

Arango, E. E., Buitrago, J. A., Cataldi, R., Ferrara, G. C., Panachi, C., and Villegas, V. J., 1970, Preliminary study on the Ruiz geothermal project (Colombia): U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Arnason, B. and Tomasson, J., 1970, Deuterium and chloride in geothermal studies in Iceland: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Arnorsson, S., 1970a, Underground temperatures in hydrothermal areas in Iceland as deduced from the silica content of the thermal water: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

———— 1970b, The distribution of some trace elements in thermal waters in Iceland: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Austin, C. F., 1966, Selection criteria for geothermal prospects: Nevada Bur. Mines Rept. 13, pt. C., p. 93-125.

Averiev, V. V., 1967, Hydrothermal processes in volcanic areas and their relation to magmatic activity: Bull. volcanol., v. 30.

Bailey, E. H., 1946, Quicksilver deposits of the Western Mayacmas district, Sonoma County, California: California Jour. Mines and Geol., v. 42, p. 199-230.

Banwell, C. J., 1963, Thermal energy from the earth's crust. Introduction and Part I: New Zealand Jour. Geol. and Geophys, v. 6, p. 52-69.

———— 1964, Thermal energy from the earth's crust. Part II, The efficient extraction of energy from heated rocks: New Zealand Jour. Geol. and Geophys., v. 7, p. 585-593.

———— 1970, Geophysical techniques in geothermal exploration (Rapporteur's Report): U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Banwell, C. J. and Gomez Valle, R., 1970, Geothermal exploration in Mexico, 1968-1969: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Banwell, C. J. and MacDonald, W. J. P., 1965, Resistivity surveying in New Zealand thermal areas: Commonwealth Mining and Metallurgical Cong., 8th, Australia-New Zealand, New Zealand, Sec., 213, 1.

Barton, D. B., 1970, Current status of geothermal power plants at The Geysers, Sonoma County, California: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

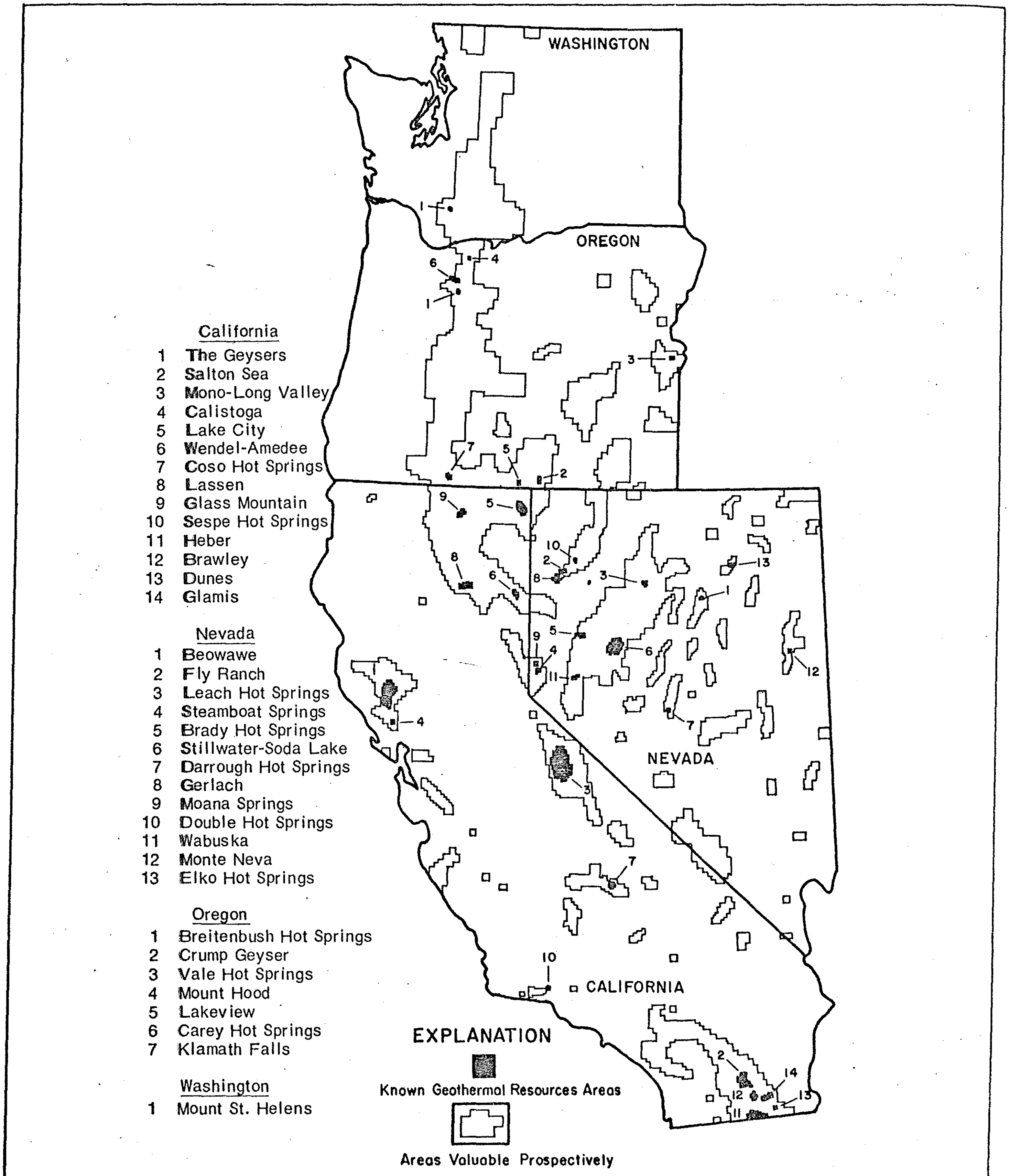

FIGURE 22.—Map of Western States showing lands classified for geothermal resources effective December 24, 1970 (from Godwin and others, 1971).

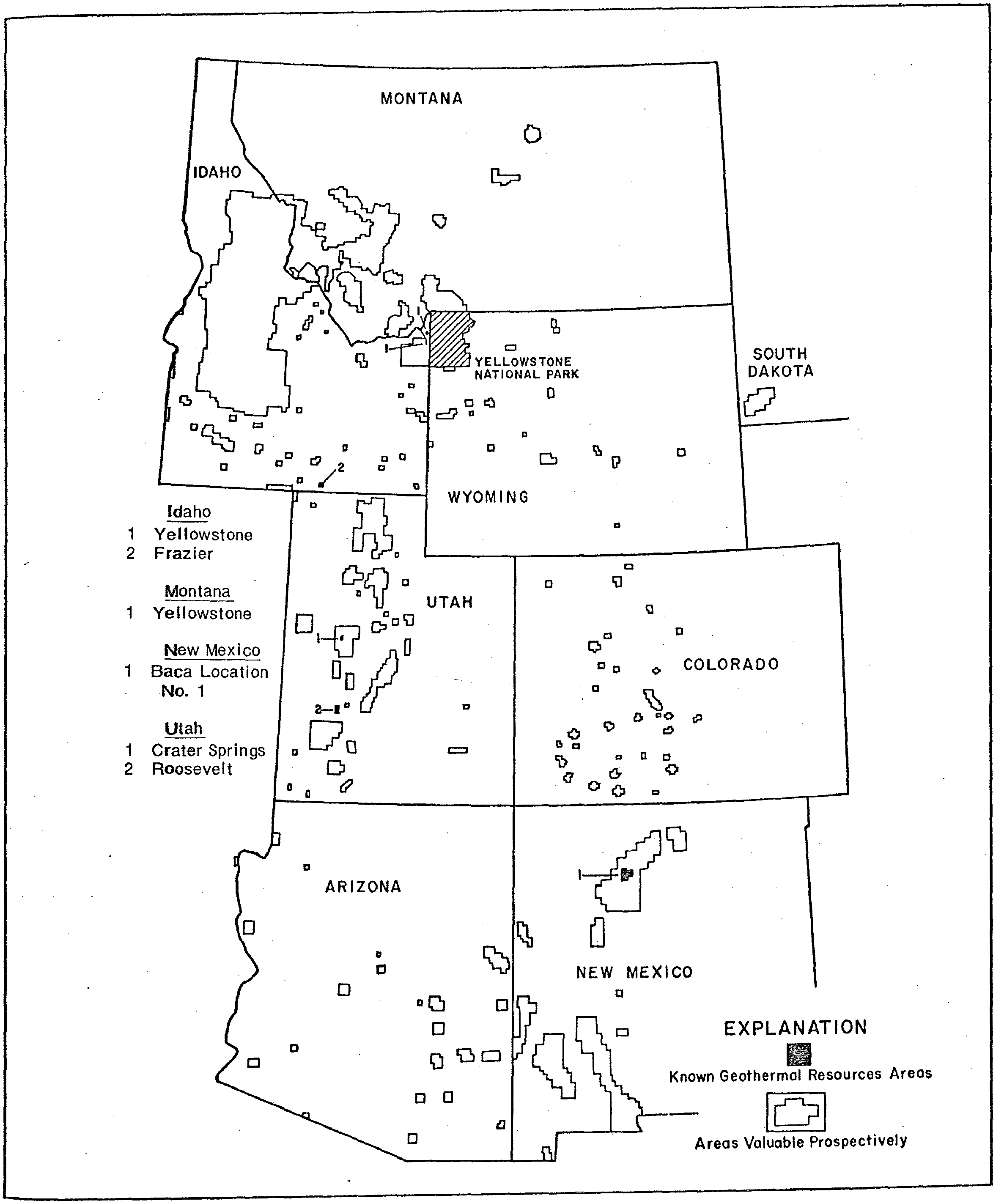

FIGURE 23.—Map of Western States showing lands classified for geothermal resources effective December 24, 1970 (from Godwin and others, 1971).

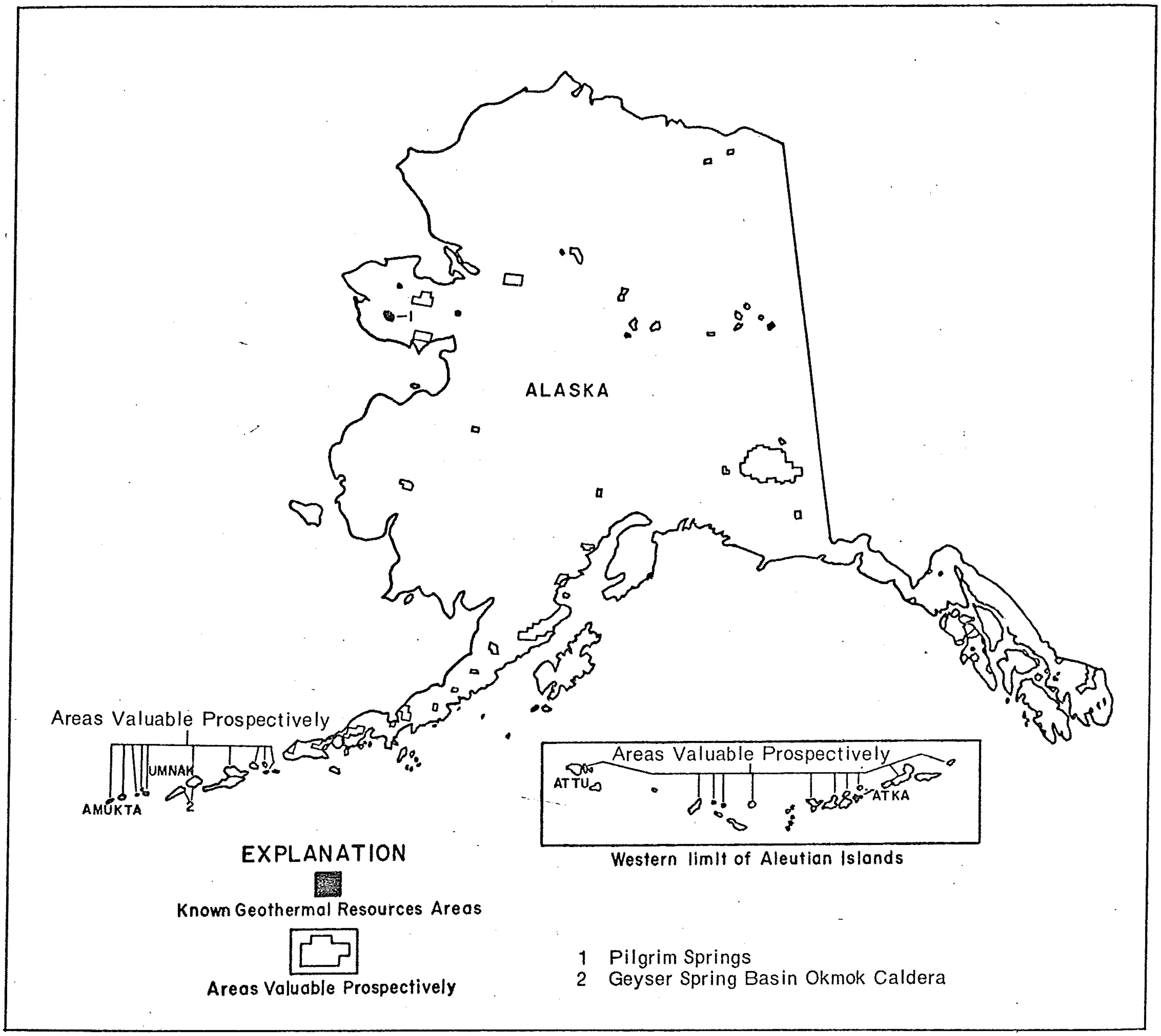

FIGURE 24.—Map of Alaska showing lands classified for geothermal resources effective December 24, 1970 (from Godwin and others, 1971).

Battini, F. and Menut, P., 1964, Etude structurale de la zone de Roccastrada en vue de la recherche de vapeur par les methodes geophysiques, gravimetriques et electriques: U. N. Conf. New Sources of Energy, Rome, 1961, Proc., v. 2, Geothermal Energy: I, p. 73-81.

Berry, F. A. F., 1966, Proposed origin of subsurface thermal brines, Imperial Valley, California (abs.): Am. Assoc. Petroleum Geologists Bull. v. 50, p. 644-645.

Biehler, S., Kovach, R. L., and Allen, C. R., 1964, Geophysical framework of the northern end of the Gulf of California structural province, *in* Marine geology of Gulf of California, a symposium: Am. Assoc. Petroleum Geologists Mem. 3, p. 126-143.

Biehler, S. and Rex, R. W., 1971, Structural geology and tectonics of the Salton trough, southern California, *in* Geol. Soc. America Cord. Mtg., Riverside, March, Field Trip Guidebook: Geol. Excur. in So. California, p. 30-42.

Birch, F., 1950, Flow of heat in the Front Range, Colorado: Geol. Soc. America Bull., v. 61, p. 567-630.

Blackwell, D. D., 1969, Heat flow determinations in the northwestern United States: Jour. Geophys. Research, v. 74, p. 992-1007.

——— 1971, Heat flow: EOS (Trans. Am. Geophys. Union), v. 52, no. 5, p. 135-139.

Bodvarsson, Gunnar, 1964, Physical characteristics of natural heat resources in Iceland: U. N. Conf. New Sources of Energy, Rome, 1961, Proc., v. 2, Geothermal Energy: I, p. 82-89.

——— 1970a, Evaluation of geothermal prospects and the objectives of geothermal exploration: Geoexploration, v. 8, p. 7-17.

——— 1970b, An estimate of the natural heat resources in a thermal area in Iceland: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Bodvarsson, G. and Palmason, G., 1964, Exploration of subsurface temperature in Iceland: U. N. Conf. New Sources of Energy, Rome, 1961, Proc., v. 2, Geothermal Energy: I, p. 91-98.

Boldizar, T., 1970, Geothermal energy production from porous sediments in Hungary: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Bolton, R. S., 1970, The behavior of the Wairakei geothermal field during exploitation: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy .

Bowen, R. G. and Peterson, N. V., 1970, Thermal springs and wells in Oregon: Oregon Dept. Geol. and Mineral Industries, Misc. Paper 14.

Bradbury, J. J. C., 1970, The economics of geothermal power (Rapporteur's Report): U. N. Symp. of Dev. and Util. of Geothermal Resources, Pisa, Italy.

Brune, J. N. and Allen, C. R., 1967, A microearthquake survey of the San Andreas fault system in southern California: Seis. Soc. America Bull., v. 57, p. 277-296.

Buachidse, I. M., Buachidse, G. I., and Shaorshadse, M. P., 1970, Thermal waters of Georgia: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Burgassi, R., 1964, Prospecting for geothermal fields and exploration necessary for their adequate exploitation, performed in various regions of Italy: U. N. Conf. New Sources of Energy, Rome, 1961, Proc., v. 2, Geothermal Energy: I, p. 117-133.

Burgassi, R., Battini, F., and Mouton, J., 1964, Prospection geothermique pour la recherche des forces endogenes: U. N. Conf. New Sources of Energy, Rome, 1961, Proc., v. 2, Geothermal Energy: I, p. 134-140.

Burgassi, P. D., Ceron, P., Ferrara, G. C., Sestini, G., and Toro, B., 1970, Geothermal gradient and heat flow in the Radicofani region (east of Monte Amiata, Italy): U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Burrows, W., 1970, Geothermal energy resources for heating and associated applications in Rotorua and surrounding areas: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Calamai, A., Cataldi, R., Squarci, P. and Taffi, L., 1970, Geology, geophysics, and hydrogeology of the Monte Amiata geothermal fields: Geothermics, Pisa, Italy, Instituto Internazionale per le Ricerche Geotermiche (CNR), v. 1 (Spec. issue).

Campbell, K. V. and others, 1970, A survey of thermal springs in Washington State: Northwest Science, v. 44, no. 1, p. 1-11.

Cataldi, R., Ceron, P., Di Mario, P., and Leardini, T., 1970, Progress report on geothermal development in Italy: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Chen, C. H., 1970, Geology and geothermal power potential of the Tatun volcanic region: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Cheng, W. T., 1970, Geophysical exploration in the Tatun volcanic region, Taiwan: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Clacy, G. R. T., 1968, Geothermal ground noise amplitude and frequency spectra in the New Zealand volcanic region: Jour. Geophys. Research, v. 73, p. 5377-5383.

Clayton, R. N., Muffler, L. J. P. and White, D. E., 1968, Oxygen isotope study of calcite and silicates of the River Ranch No. 1 well, Salton Sea geothermal field, California: Am. Jour. Sci., v. 266, p. 968-979.

Compendium of Papers, Imperial Valley — Salton Sea Area Geothermal Hearing, 1970, Geothermal Resources Board, California, Oct. 22 and 23.

Cormy, G., Demians d'Archimbaud, J., and Surcin, J., 1970, Prospection geothermique aux Antilles francaises Guadeloupe et Martinique: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Crosby, J. W., III, 1971, New developments in geothermal exploration: 1st Northwest Conf. on Geothermal Power, Dept. of Natural Resources, Olympia, Washington.

Dawson, G. B., 1964, The nature and assessment of heat flow from hydrothermal areas: New Zealand Jour. Geol. and Geophys., v. 7, p. 155-171.

Dawson, G. B. and Dickinson, D. J., 1970, Heat flow studies in thermal areas of the North Island of New Zealand: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

de Anda, L. F., Septien, J. I., and Elizondo, J. R., 1964, Geothermal energy in Mexico: U. N. Conf. New Sources of Energy, Rome, 1961, Proc., v. 2, Geothermal Energy: I, p. 149-164.

De Grys, A., Vera, J., and Goossens, P., 1970, A note on the hot springs of Ecuador: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Decius, L. C., 1964, Geological environment of hyperthermal areas in continental United States and suggested methods of propecting them for geothermal power: U. N. Conf. New Sources of Energy, Rome, 1961, Proc., v. 2, Geothermal Energy: I, p. 166-177.

Decker, E. R., 1969, Heat flow in Colorado and New Mexico: Jour. Geophys. Research, v. 74, p. 550-559.

Dibblee, T. W., Jr., 1954, Geology of the Imperial Valley region, California, *in* Geology of Southern California: California Div. Mines Bull. 170, Chap. 2, p. 21-28.

Dowgiallo, J., 1970, Occurrence and utilization of thermal waters of Poland: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Economic Potential of Geothermal Resources in California, 1971, Geothermal Resources Board, California, 35 p.

Ellis, A. J., 1970, Quantitative interpretation of chemical characteristics of hydrothermal systems: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Epis, R. C., ed., 1968, Cenozoic volcanism in the Southern Rocky Mountains: Colorado School Mines Quart., v. 63, no. 3, 287 p.

Facca, G., 1970, General report of the status of world geothermal development (Rapporteur's Report): U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Facca, G. and Ten Dam, A., 1964, Geothermal power economics, rev. ed.: Los Angeles, Worldwide Geothermal Exploration Co., 45 p.

Feng, T. T. and Huang, K. K., 1970, Exploration of geothermal resources in the Tatun volcanic region, Taiwan, Republic of China: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Fournier, R. O. and Rowe, J. J., 1966, Estimation of underground temperatures from the silica content of water from hot springs and wet-steam wells: Am. Jour. Sci., v. 264, p. 685-697.

Fournier, R. O. and Truesdell, A. H., 1970, Chemical indicators of subsurface temperature applied to hot spring waters of Yellowstone National Park, Wyoming, U. S. A.: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Frolov, N. M. and Vartanyan, G. S., 1970, Types of commercial deposits of thermal subterranean waters and some aspects relating to the assessment of their reserves: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Fujii, Y., and Akeno, T., 1970, Chemical prospecting of steam and hot water in the Matsukawa geothermal area: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Geological Society of America, Rocky Mountain Section, 1968, Igneous and hydrothermal geology of Yellowstone National Park: Geol. Soc. America Rocky Mtn. Sec., Bozeman, Mont., May 1968, Field Trip No. 6, 36 p.

George, R. D., Curtis, H. A., Lester, O. C., Crook, J. K., Yeo, J. B. and others, 1920, Mineral waters of Colorado: Colorado Geol. Survey Bull. 11, 474 p.

Geothermal Resources, 1967, 4th Prog. Rept. to the Legislature (California), Senate Permanent Factfinding Committee on Natural Resources, Sec. I, 66 p.

Gilbert, C. M., Christensen, M. N., Al-Rawi, Y., and Lajoie, K. L., 1968, Structural and volcanic history of Mono Basin, California-Nevada, *in* Coats, R. R., and others, eds., Studies in volcanology (Williams vol.): Geol. Soc. America Mem. 116, p. 275-329.

Godwin, L. H., Haigler, L. B., Rioux, R. L., White, D. E., Muffler, L. J. P., and Wayland, R. G., 1971, Classification of public lands valuable for geothermal steam and associated geothermal resources: U. S. Geol. Survey Circ. 647, 18 p.

Gomez Valle, R. G., Friedman, J. D., Gawarecki, S. J., and Banwell, C. J., 1970, Photogeologic and thermal infrared reconnaissance surveys of the Los Negritos — Ixtlan de los Hervores geothermal area, Michoacan, Mexico: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

rindley, G. W., 1964, Geology of the New Zealand geothermal steam fields: U. N. Conf. New Sources of Energy, Rome, 1961, Proc., v. 2, Geothermal Energy: I, p. 237-245.

——— 1965, The geology, structure, and exploitation of the Wairakei geothermal field, Taupo, New Zealand: New Zealand Geol. Survey Bull. n.s. 75, 131 p.

——— 1966, Geological structure of hydrothermal fields in the Taupo Volcanic Zone, New Zealand (abs.): Bull. volcanol., v. 29, p. 573-574.

——— 1970, Sub-surface structures and relation to steam production in the Broadlands geothermal fields, New Zealand: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

riscom, A. and Muffler, L. J. P., 1971, Aeromagnetic map and interpretation of the Salton Sea geothermal area, California: U. S. Geol. Survey, Geophys. Inv. Map GP-754.

roh, E. A., 1966, Geothermal energy potential in Oregon: Oregon Dept. Geol. and Mineral Industries, Ore Bin, v. 28, p. 125-135.

aigler, L. B., 1969, Mineral and water resources of Arizona: Arizona Bur. Mines Bull. 180.

amilton, W., 1960, Late Cenozoic tectonics and volcanism of the Yellowstone region, Wyoming, Montana, and Idaho, *in* Billings Geol. Soc. 11th Ann. Field Conf., West Yellowstone — Earthquake Area, 1960: p. 92-105.

atherton, T., MacDonald, W. J. P., and Thompson, G. E. K., 1966, Geophysical methods in geothermal prospecting in New Zealand: Bull. volcanol., ser. 2, v. 29, p. 487-498.

atton, J. W., 1970, Ground subsidence of a geothermal field during exploitation: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

ayakawa, M., 1970, The study of underground structure and geophysical state in geothermal areas by seismic exploration: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

ayakawa, M., Takaki, S., and Baba, K., 1967, Geophysical study of Matsukawa geothermal area, Northeast Japan: Japan Geol. Survey Bull. 18, 73.

ealy, J., 1964, Geology and geothermal energy in the Taupo Volcanic Zone, New Zealand: U. N. Conf. New Sources of Energy, Rome, 1961, Proc., v. 2, Geothermal Energy: I, p. 250-257.

——— 1970, Pre-investigation geological appraisal of geothermal fields: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

ielgeson, H. C., 1968, Geologic and thermodynamic characteristics of the Salton Sea geothermal system: Am. Jour. Sci., v. 266, p. 129-166.

ieylmun, E. B., 1966, Geothermal power potential in Utah: Utah Geol. and Mineralog. Survey Spec. Studies 14, 28 p.

iochstein, M. P. and Dickinson, D. J., 1970, Infrared remote sensing of thermal ground in the Taupo region, New Zealand: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

iochstein, M. P. and Hunt, M. T., 1970, Seismic, gravity, and magnetic studies, Broadlands geothermal field, New Zealand: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

iochstein, M. P., Innes, D. G., and Carrington, L., 1967, Seismic studies in the Broadlands geothermal area, p. 7-14, *in* Banwell and others, Broadlands geothermal area geophysical survey, New Zealand Dept. Sci. Indus. Res., Geophys. Div., unpubl. rept. 48.

odder, D. T., 1970, Application of remote sensing to geothermal prospecting: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

orton, R .C., 1964, Hot springs, sinter deposits, and volcanic cinder cones in Nevada: Nevada Bur. Mines Map 25.

unt, M. T., 1970, Net mass loss from the Wairakei geothermal field, New Zealand: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Ishikawa, T., 1970, Geothermal fields in Japan considered from the geological and petrological viewpoints: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

James, R., 1968, Wairakei and Larderello: geothermal power systems compared: New Zealand Jour. Sci. and Tech. v. 11, p. 706.

Kaufman, A., 1970, The economics of geothermal power in the United States: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Keller, G .V., 1970, Induction methods in prospecting for hot water: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Kiersch, G. A., 1964, Geothermal steam: origin, characteristics, occurrence and exploitation: U. S. Air Force Cambridge Research Labs. (AFCRL-64-898), Washington, D. C., U.S. Dept. of Commerce.

Koenig, J. B., 1963, Geologic map of California, Santa Rosa sheet: California Div. Mines and Geol.

——— 1967, The Salton-Mexicali geothermal province: Calif. Div. Mines and Geol. Mineral Inf. Service, v. 20, no. 7, p. 75-81.

——— 1969, The Geysers geothermal field: California Div. Mines and Geol., Mineral Inf. Service, v. 22, no. 8, p. 123-128.

——— 1970, Geothermal exploration in the Western United States: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

——— 1971, Geothermal development: Geotimes, v. 16, no. 3, p. 10-12.

Koga, A., 1970, Geochemistry of the waters discharged from drill hole at Otake and Hatchobaru areas (Japan): U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Komagata, S., Iga., H., Nakamura, H., and Minohara, Y., 1970, The status of geothermal utilization in Japan: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Kottlowski, F. E., Weber, R. H., and Willard, M. E., 1969, Tertiary intrusive-volcanic-mineralization episodes in the New Mexico region: Geol. Soc. America Ann Mtg., Atlantic City, N.J., (abs.), p. 278-280.

Kremar, B. and Milanovic, B., 1970, Geothermal exploration of hot water sources in Carpathians of Yugoslavia and Czechoslovakia: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Lange, A. L. and Westphal, W. H., 1969, Microearthquakes near The Geysers, Sonoma County, California: Jour. Geophys. Research, v. 74, no. 17, p. 4377-4378.

Larderello and Monte Amiata, 1970, Electric power by endogenous steam: Rome, Ente Nazionale per L'Eneggia Elettrica (ENEL), 44 p.

Lee, K., 1969, Infrared exploration for shoreline springs of Mono Lake, California test site: Stanford Univ. Remote Sensing Lab. Tech. rept. no. 69-7, 196 p.

Lee, W. H. K., ed., 1965, Terrestrial heat flow: Am. Geophys. Union Geophys. Mon. Ser. no. 8, 276 p.

Lee, W. H. K. and Uyeda, Seija, 1965, Review of heat flow data, *in* Lee, W. H. K., ed., Terrestrial heat flow: Am. Geophys. Union Geophys. Mon. Ser. no. 8, p. 87-190.

Lovering, T. S., 1965, Some problems in geothermal exploration: Soc. Mining Engr. Trans., v. 232, p. 274-281.

Lovering, T. S. and Goode, H. D., 1963, Measuring geothermal gradients in drill holes less than 60 feet deep, East Tintic district, Utah: U. S. Geol. Survey Bull. 1172, 48 p.

Lumb, J. T., and MacDonald, W. J. P., 1970, Near-surface resistivity surveys of geothermal areas using the electromagnetic method: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Lyon, R. J. P. and Lee, K., 1970, Remote sensing in exploration for mineral deposits: Econ. Geol., v. 65, p. 785-800.

Mahon, W. A. J., 1970, Chemistry in the exploration and exploitation of hydrothermal systems: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Makarenko, F. A., Mavritsky, B. F., Lokchine, B. A. ,and Kononov, V. I., 1970, Geothermal resources of the USSR and prospects for their practical use: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Marinelli, G., 1964, Les anomalies thermiques et les champs geothermiques dans le cadre des intrusions recentes en Toscane: U. N. Conf. New Sources of Energy, Rome, Italy, Proc., v. 2, Geothermal Energy: I, p. 288-291.

McEuen, R. B., 1970, Delineation of geothermal deposits by means of long-spacing resistivity and airborne magnetics: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

McKenzie, G. R., and Smith, J. H., 1968, Progress of geothermal energy development in New Zealand: Proc. 8th World Power Conf., Moscow.

McMillan, D. A., 1970, Economics of The Geysers geothermal field, California: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

McNitt, J. R., 1963, Exploration and development of geothermal power in California: California Div. Mines and Geology Spec. Rept. 75, 45 p.

——— 1964, Geology of The Geysers thermal area, California: U. N. Conf. New Sources of Energy, Rome, Proc., v. 2, Geothermal Energy: I, p. 292-302.

——— 1965, Review of geothermal resources, *in* Lee, W.H.K., ed., Terrestrial heat flow: Am. Geophys. Union Geophys. Mon. Ser. no. 8, p. 240-266.

——— 1968, Geology of the Kelseyville quadrangle, Sonoma, Lake, and Mendocino counties, California: California Div. Mines and Geol. Map Sheet 9.

——— 1970, The geological environment of geothermal fields as a guide to exploration (Rapporteur's Report): U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Meidav, T., 1970, Application of electrical resistivity and gravimetry in deep geothermal exploration: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Mercado, S., 1969, Chemical changes in geothermal well M-20, Cerro Prieto, Mexico: Geol. Soc. America Bull., v. 80, p. 2623-2630.

——— 1970, High-activity hydrothermal zones detected by Na/K, Cerro Prieto, Mexico: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Mooser, F., 1965, Progress report on recent developments of geothermal energy and volcanology in Mexico: Bull. volcanol., ser. 2, v. 28, p. 69-73.

Mori, Y., 1970, Exploitation of Matsukawa geothermal area: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Moxham, R. M., 1969, Aerial infrared surveys at The Geysers geothermal steam field, California: U. S. Geol. Survey Prof. Paper 650-C, p. C106-122.

Muffler, L. J. P., 1971, Evaluation of initial investigations, Dieng geothermal area, central Java, Indonesia: U. S. Geol. Survey, open file rept. 21 p.

Muffler, L. J. P. and White, D. E., 1969, Active metamorphism of Upper Cenozoic sediments in the Salton Sea geothermal field and the Salton trough, southeastern California: Geol. Soc. America Bull., v. 80, p. 157-182.

Mundorff, J. C., 1970, Major thermal springs of Utah: Utah Geol. and Minealog. Survey, Water Resources Bull. 13, 60 p.

Nakamura, H., Sumi, K., Katagiri, K., and Iwata, T., 1970, The geological environment of Matsukawa geothermal area, Japan: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Nicholls, H. R. and Rinehart, J. S., 1967, Geophysical study of geyser action in Yellowstone National Park: Jour. Geophys. Research, v. 72, no. 18, p. 4651-4663.

Noguchi, T., 1970, An attempted evaluation on geothermal energy in Japan: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Noguchi, K., Goto, T., Ueno, S., and Imahashi, M., 1970, Geochemical investigation of the strong acid water from the bored wells Hakone, Japan: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Nolan, T. B. and Anderson, G. H., 1934, The geysers area near Beowawe, Eureka County, Nevada: Am. Jour. Sci., v. 27, p. 215-229.

Oki, Y., and Hirano, T., 1970, Geothermal system of Hakone Volcano: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Oxburgh, E. R. and Turcotte, D. L., 1970, Thermal structure of island arcs: Geol. Soc. America Bull., v. 81, p. 1665-1688.

Pakiser, L. C., 1961, Gravity, volcanism, and crustal deformation in Long Valley, California: U. S. Geol. Survey Prof. Paper 424-B, p. 250-253.

Palmason, G., Friedman, J. D., Williams, R. S. Jr., Jonsson, J., and Saemundsson, K., 1970, Aerial infrared surveys of Reykjanes and Torfajokull thermal areas, Iceland, with a section on the cost of exploration surveys: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

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

Peterson, N. V., and McIntyre, J. R., 1970, The reconnaissance geology and mineral resources of eastern Klamath County and western Lake County, Oregon: Oregon Dept. Geol. and Mineral Industries Bull. 66, 70 p.

Phillips, K. N., 1941, Fumaroles of Mount St. Helens and Mount Adams: Mazama (Portland, Ore.), v. 23, no. 12, p. 37-42.

Piip, B. I., Ivanov, V. V., and Averiev, V. V., 1964, The hyperthermal water of Pauzhetsk, Kamchatka, as a source of geothermal energy: U. N. Conf. New Sources of Energy, Rome, 1961, Proc., v. 2, Geothermal Energy: I, p. 339-345.

Rex, R. W., 1966, Heat flow in the Imperial Valley of California (abs.): Am. Geophys. Union Trans., v. 47, p. 181.

——— 1970, Investigation of geothermal resources in the Imperial Valley and their potential value for desalination of water and electricity production: Riverside, California Univ. Inst. Geophys. and Planetary Phys., 14 p.

——— 1971, Geothermal energy — the neglected energy option: Bull. Atomic Scientists, v. 27, no. 8, p. 52-56.

Rinehart, C. D. and Ross, D. C., 1964, Geology and mineral deposits of the Mount Morrison Quadrangle, Sierra Nevada, California: U. S. Geol. Survey Prof. Paper 385, 106 p.

Rinehart, J. S., 1968a, Seismic signatures of some Icelandic geysers: Jour. Geophys. Research, v. 73, p. 4609.

——— 1968b, Geyser activity at Beowawe, Eureka County, Nevada: Jour. Geophys. Research, v. 73, p. 7703.

Risk, G. F., MacDonald, W. J. P., and Dawson, G. B., 1970, D.C. resistivity surveys of the Broadlands geothermal region, New Zealand: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Ross, S. H., 1970, Geothermal potential of Idaho: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Roy, R. F., Decker, E. R., Blackwell, D. D. and Birch, F., 1968, Heat flow in the United States: Jour. Geophys. Research, v. 73, p. 5207-5221.

Saito, M., 1964, Known geothermal fields in Japan: U. N. Conf. New Sources of Energy, Rome, 1961, Proc., v. 2, Geothermal Energy: I, p. 367-404.

Sass, J. H., Lachenbruch, A. H., Munroe, R. J., Greene, G. W., and Moses, T. H., Jr., 1971, Heat flow in the Western United States: Jour. Geophys. Research, v. 76, no. 26, p. 6376-6413.

Sato, H., 1970, The present state of geothermal development in Japan: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Sigvaldsson, G. E. and Cuellar, G., 1970, Geochemistry of the Ahuachapan thermal area, El Salvador, Central America: U.N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Smith, J. H., 1970, Geothermal development in New Zealand: U.N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Smith, R. L., Bailey, R. A., and Ross, C. S., 1961, Structural evolution of the Valles caldera, New Mexico, and its bearing on the emplacement of ring dikes: U. S. Geol. Survey Prof. Paper 424-D, p. D145-149.

———— 1970, Geologic map of the Jemez Mountains, New Mexico: U. S. Geol. Survey Misc. Geol. Inv. Map I-571.

Stone, R. T., 1971, Implementing the Federal Geothermal Steam Act of 1970: Northwest Conf. on Geothermal Power, 1st, Dept. of Natural Resources, Olympia, Washington.

Strangway, D. W., 1970, Geophysical exploration through geologic cover: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Studt, F. E., 1964, Geophysical prospecting in New Zealand's hydrothermal fields: U. N. Conf. New Sources of Energy, Rome, 1961, Proc., v. 2, Geothermal Energy: I, p. 380-384.

Studt, F. E. and Thompson, G. E. K., 1969, Geothermal heat flow in North Island of New Zealand: New Zealand Jour. Geol. and Geophys., v. 12, p. 673.

Sukharev, G. M., Vlasova, S., and Taranukha, Y. K., 1970, The utilization of thermal waters of the developed oil deposits of the Caucasus: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Summers, W. K., 1965a, A preliminary report of 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.

———— 1970a, Geothermal prospects of New Mexico: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

———— 1970b, New Mexico's thermal waters: New Mexico Bur. Mines and Mineral Resources microfilm.

———— 1971, Annotated and indexed bibliography of geothermal phenomena: New Mexico Bur. Mines and Mineral Resources.

Summers, W. K. and Ross, S. H., 1971, Geothermics in North America: present and future: Wyoming Geol. Assoc. Earth Sci. Bull., March, p. 7-22.

Tamrazyan, G. P., 1970, Continental drift and thermal fields: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Ten Dam, A. and Erentoz, C., 1970, Kizildere geothermal field, Western Anatolia: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Ten Dam, A. and Khrebtov, A. I., 1970, The Menderes Massif geothermal province: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Thompson, G. A. and White, D. E., 1964, Regional geology of the Steamboat Springs area, Washoe County, Nevada: U. S. Geol. Survey Prof. Paper 458-A, 52 p.

Thompson, G. A., Meister, L. J., Herring, A. T., Smith, T. E., Burke, D. B., Kovach, R. L., Burford, R. O., Salehi, I. A., and Wood, M. D., 1967, Geophysical study of Basin-Range structure, Dixie Valley region, Nevada: U. S. Air Force Cambridge Research Labs. (AFCRL-66-848), Washington, U. S. Dept. of Commerce.

Thompson, G. E. K., Banwell, C. J., Dawson, G. B., and Dickinson, D. J., 1964, Prospecting of hydrothermal areas by surface thermal surveys: U. N. Conf. New Sources of Energy, Rome, 1961, Proc., v. 2, Geothermal Energy: I, p. 386-400.

Thorsen, G. W., 1971, Prospects for geothermal energy in Washington: Northwest Conf. of Geothermal Power, 1st, Dept. of Natural Resources, Olympia, Washington.

Thorsteinsson, T. and Eliasson, J., 1970, Geohydrology of the Laugarnes hydrothermal system in Reykjavik, Iceland: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Tikhonov, A. N. and Dvorov, I. M., 1970, Development of research and utilization of geothermal resources in the USSR: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Tonani, F., 1967, Geothermal exploration in El Salvador: U. N. Rept., Central America.

———— 1970, Geochemical methods of exploration for geothermal energy: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Vakin, E. A., Polak, B. G., Sugrobov, V. M., Erlik, E. N., Belousov, V. I., and Pilipenko, G. F., 1970, Recent hydrothermal systems of Kamchatka: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Ward, P. L. and Jacob, K. H., 1971, Microearthquakes in the Ahuachapan geothermal field, El Salvador, Central America: Science, v. 173, p. 328-330.

Ward, P. L., Palmason, G., and Drake, C., 1969, Microearthquake survey and the mid-Atlantic ridge in Iceland: Jour. Geophys. Research, v. 74, no. 2, p. 665-684.

Waring, G. A., 1965, Thermal springs of the United States and other countries of the world — a summary: U. S. Geol. Survey Prof. Paper 492, 383 p.

White, D. E., 1955, Thermal springs and epithermal ore deposits, *in* Pt. I of Econ. Geol., 50th Anniversary vol., 1905-55, p. 99-154.

———— 1964, Preliminary evaluation of geothermal areas by geochemistry, geology, and shallow drilling: U. N. Conf. New Sources of Energy, Rome, 1961, Proc., v. 2, Geothermal Energy: I, p. 402-408.

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

———— 1967, Some principles of geyser activity, mainly from Steamboat Springs, Nevada: Am. Jour. Sci., v. 265, p. 641-684.

———— 1968a, Hydrology, activity, and heat flow of the Steamboat Springs thermal system, Washoe County, Nevada: U. S. Geol. Survey Prof. Paper 458-C, 109 p.

———— 1968b, Environments of generation of some base-metal ore deposits: Econ. Geol., v. 63, p. 301-335.

———— 1969a, Rapid heat-flow surveying of geothermal areas utilizing individual snowfalls as calorimeters: Jour. Geophys. Research, v. 74, p. 5191-5201.

———— 1969b, Thermal and mineral waters of the United States —a brief review of possible origins: Internat. Geol. Cong., 23rd, Prague 1969, v. 19, p. 269-286.

———— 1970, Geochemistry applied to the discovery, evaluation, and exploitation of geothermal energy resources (Rapporteur's Report): U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

White, D. E., Muffler, L. J. P., and Truesdell, A. H., 1971, Vapor-dominated hydrothermal systems compared with hot-water systems: Econ. Geol., v. 66, p. 75-97.

White, D. E., Muffler, L. J. P., Truesdell, A. H., and Fournier, R. O., 1968, Preliminary results of research drilling in Yellowstone thermal areas: Geol. Soc. America; Rocky Mtn. Sec. Program (abs.), p. 84.

White, D. E. and Roberson, C. E., 1962, Sulphur Bank, California, a major hot-spring quicksilver deposit, *in* Petrologic Studies (Buddington vol.): Geol. Soc. America, N. Y., p. 397-428.

White, D. E., Thompson, G. A., and Sandberg, C. H., 1964, Rocks, structure, and geologic history of Steamboat Springs thermal area, Washoe County, Nevada: U. S. Geol. Survey Prof. Paper 458-B, 63 p.

Whiteford, P. C., 1970, Ground movement in the Waiotapu geothermal region, New Zealand: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Wilson, S. H., 1970, Statistical interpretation of chemical results from drillholes as an aid to geothermal prospecting and exploitation: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Yamasaki, T., Matsumoto, Y., and Hayashi, M., 1970, The geology and hydrothermal alterations at Otake geothermal area, Kujya Volcano Group, Kyushu, Japan: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.

Zen, M. T. and Radja, V. T., 1970, Result of the preliminary geological investigation of natural steam fields in Indonesia: U. N. Symp. on Dev. and Util. of Geothermal Resources, Pisa, Italy.