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Summary of Section I
Present Status of Resources Development

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INTRODUCTION

The first two years after the 1970 United Nations geothermal symposium in Pisa, Italy, saw a slow but steady growth in geothermal development and exploration, mainly based on decisions made in the late 1960s. This period was highlighted by the increase of electrical capacity at The Geysers, California, USA, from 78 megawatts electrical (MWe) in 1970 to 237 MWe by the end of 1972 (Worthington, 1975). This period also saw the beginning of construction at Cerro Prieto, Mexico, and the continued development of space-heating and agricultural systems in Iceland, the USSR, and Hungary. Geothermal exploration increased steadily from 1970 to 1972, with substantial efforts in Italy, Japan, Iceland, USA, Indonesia, the Philippines, and Mexico. In addition, the continuing efforts of the United Nations supported exploration in Chile, El Salvador, Ethiopia, Kenya, Nicaragua, and Turkey. Also during these years, an increasing popular and governmental awareness developed of the nature and possible importance of geothermal energy.

The slow, steady increase in geothermal activity accelerated abruptly in 1973 when imported oil became difficult for many countries to obtain and petroleum prices rose sharply. This price rise, combined with a belated awakening to the fact that oil and gas resources are indeed limited, led private industry and governments to pay much more attention to alternate energy sources, particularly in those countries dependent on imported oil. This attention has been manifested in accelerated exploration, increased drilling, and marked expansion of geothermal research and development.

The status of geothermal electricity generation in 1975 is shown in Table 1. Geothermal exploration efforts are not listed in Table 1 but are outlined below. Also, Table 1 does not reflect the continuing growth in the use of geothermal energy for space-heating and agricultural purposes.

ITALY

The status of geothermal development in Italy is covered in admirable detail by Ceron, Di Mario, and Leardini (p. 59). As of March 1975, the total installed geothermal electrical capacity in Italy was 417.6 MWe, of which 380.6 was in the Larderello region, 15 at Travale, and 22 in the Monte Amiata region (Fig. 1). Net geothermal power production in 1974 amounted to 2.29×10^9 kWh, which represents an average utilization of 64% of total installed capacity.

Although 20 productive new wells were drilled in the Larderello region between December 1969 and March 1975, the production of old wells decreased notably, resulting in a net decrease of 9.1% in steam production. In part this decrease was offset by replacing atmospheric turbines with more efficient condensing turbines.

In the Monte Amiata region, steam production from December 1969 to March 1975 decreased 28%, in part due to rapid inflow of recharge water into the Bagnore field.

Extensive exploration in the Travale region since 1969 has extended the old field (Cataldi et al., 1970) northeast where five wells have been drilled and a sixth was in progress in May 1975 (Burgassi et al., p. 1571). Although all of the wells encountered high temperatures (up to 270°C), only three are productive (T22, R4, and probably C1). Dry steam from well T22 has been used since July 1973 to supply a 15-MWe power plant (Burgassi et al., p. 1571).

Extensive exploration is being carried out throughout the pre-Apennine belt by the Ente Nazionale per l'Energia Elettrica (ENEL) in cooperation with the Consiglio Nazionale Ricerche (CNR). In the Monte Sabatini region (Baldi et al., p. 871), a well drilled at Cesano in January 1975 discovered a geothermal reservoir that produced a brine of 356 000 ppm total dissolved solids, primarily $SO_4^{=}$, Na^+, and K^+ (Calamai et al., p. 305). Temperatures at depth are at least 210°C and may exceed 300°C. At Torre Alfina in the Monte Volsini region, a hot-water geothermal system at a production temperature of 120 to 140°C has been discovered (Ceron, Di Mario, and Leardini, p. 59; Cataldi and Rendina, 1973); and in the Monte Cimini region a hot-water system at 60 to 80°C reservoir temperature was discovered (Ceron, Di Mario, and Leardini, p. 59). Exploration is being carried out in the Naples region (Cameli et al., p. 315; Baldi, Ferrara, and Panichi, p. 687), near Siena (Fancelli, Nuti, and Noto, Abstract III-23)[1], and in the Roccastrada, Colli Albani, Roccamonfina, and Vulture areas (Ceron, Di Mario, and Leardini, p. 59). According to Barelli, Calamai, and Cataldi (Abstract I-3), the electrical energy potential of the pre-Apennine belt is 130 to 660 MW-centuries.

[1]The Abstract number refers to the numbering in the abstract volume for this symposium.

Table 1. World geothermal generating capacity in megawatts (electrical), 1975.

Country	Field	Operating	Under construction
United States	The Geysers	502	216
Italy	Larderello	380.6	
	Travale	15	
	Monte Amiata	22	
New Zealand	Wairakei	192	
	Kawerau	10	
Japan	Matsukawa	22	
	Otake	13	
	Onuma	10	
	Onikobe	25	
	Hatchobaru		50
	Takinoue		50
Mexico	Pathé	3.5	
	Cerro Prieto	75	
El Salvador	Ahuachapán		90
Iceland	Námafjall	2.5	
	Krafla		55
Philippines	Tiwi		100
Soviet Union	Pauzhetsk	5	
	Paratunka	0.7	
Turkey	Kızıldere	0.5	2.5
Total		1278.8	563.5

USA

The status of geothermal development in the USA is summarized by Koenig, Anderson, and Huttrer (p. 139). Geothermal electrical capacity at The Geysers, California, has increased rapidly from 78 MWe in 1970 to 502 MWe in 1975. Additions of approximately 100 MWe per year are planned through 1980, although it appears that the installation timetable will be delayed by protracted regulatory and environmental hearings.

Although no other geothermal areas in the USA are currently producing electricity, the past five years have seen greatly accelerated exploration by private industry, in great part stimulated by the increased costs of fossil fuel. In addition, the Geothermal Steam Act of 1970 finally was implemented in 1973, and the vast areas of geothermal potential on federal government land are gradually being made available for exploration by private industry. Significant geothermal discoveries have been made at the Valles Caldera, New Mexico; Roosevelt Hot Springs, Utah; Carson Desert of western Nevada; and the Heber, East Mesa, and Brawley areas of the Imperial Valley in southern California (Fig. 2). Step-out drilling has extended both The Geysers and the Salton Sea geothermal fields, and there has been continued exploratory drilling at Beowawe, Nevada, and Surprise Valley, California. Exploratory drilling, however, met with little success in California at Honey Lake, Sierra Valley, and Mono Lake; in Oregon at La Grande and Lakeview; in Nevada at Tipton; in Idaho at Mountain Home; in Utah at Brigham City; and in Arizona at Casa Grande and Chandler (Koenig, Anderson, and Huttrer, p. 139). With the exception of the Casa Grande area (Dellechaie, p. 339), virtually none of the data from these drilling ventures have been released by the private companies involved.

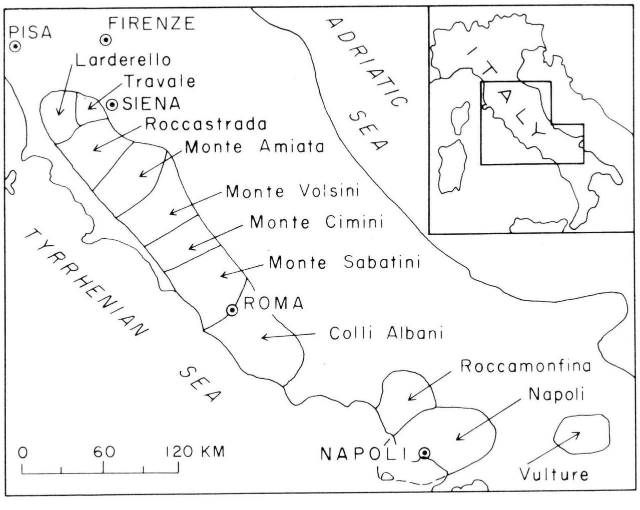

Figure 1. Map showing geothermal regions of Italy (after Ceron, Di Mario, and Leardini, p. 59).

The past five years have also seen an upsurge in geothermal research and development financed by the federal government. The Energy Research and Development Administration (ERDA), created in January 1975 from the old Atomic Energy Commission, is funding research and development in all aspects of the geothermal cycle. Major efforts include the development of technology to extract heat from hot dry rock (Smith et al., p. 1781), investigation of new conversion technologies (particularly binary cycles and impulse turbines), development of new drilling technologies (for example, Altseimer, p. 1453), and investigation of representative geothermal areas, including the Raft River area in Idaho, the area just west of the Valles Caldera in New Mexico (Smith et al., p. 1781), several sites in western Nevada (Beyer, Morrison, and Dey, p. 889), and the Coso Mountains of California. The National Science Foundation (NSF) also carried out a substantial geothermal program in 1973 and 1974, including site investigations at Marysville, Montana (Blackwell and Morgan, p. 895), at Kilauea Volcano, Hawaii (Zablocki et al., 1974; Furumoto, p. 993), and at Roosevelt Hot Springs, Utah (Ward, Rijo, and Petrick, Abstract III-90; Whelan, Nash, and Petersen, Abstract II-55). Since 1971 the U.S. Geological Survey (USGS) has had an extensive program of investigations aimed at the nature and distribution of geothermal resources, including major investigations at Long Valley (February 1976, Journal of Geophysical Research), The Geysers (McLaughlin and Stanley, p. 475; Hearn, Donnelly, and Goff, p. 423; Donnelly and Hearn, Abstract III-18; Isherwood, p. 1065), the Coso Mountains, California (Duffield, Abstract II-12; Duffield, 1975; Lanphere, Dalrymple, and Smith, 1975), southeastern Oregon (MacLeod, Walker, and McKee p. 465), Raft River, Idaho (Williams et al., p. 1273), and Yellowstone (White et al., 1975; Eaton et al., 1975; Fournier, White, and Truesdell, p. 731). In addition, the USGS recently produced a substantial report evaluating the geothermal resources of the United States (White and Williams, 1975). The Bureau of Reclamation has also carried out geothermal research, primarily aimed at self-desalination of geothermal fluids from the East Mesa area, southern California (Mathias, p. 1741; Fernelius, p. 2201; Swanberg, p. 1217).

The geopressured resources of the Gulf Coast are attracting increasing attention (Jones, p. 429; Wilson, Shepherd, and Kaufman, p. 1865). These deposits have a huge energy potential (Papadopulos et al., 1975) consisting both of thermal energy and dissolved methane.

Geothermal heat is being used directly for space heating on an increasing but still small scale in the United States,

Figure 2. Map showing locations of geothermal drilling in the United States and northern Mexico.

primarily at Klamath Falls, Oregon (Lund, Culver, and Svanevik, p. 2147), and at Boise, Idaho (Kunze et al., p. 2141). Geothermal waters are also used for greenhouse heating at scattered localities in the western United States.

Development of the extensive geothermal resources of the USA continues to be plagued by institutional problems (Koenig, Anderson, Huttrer, p. 139; Aidlin, p. 2353; Eisenstat, p. 2369; Finn, p. 2295; Schlaugh and Worcester, 1974; Olson and Dolan, 1975). These problems include ownership considerations (surface vs subsurface), leasing delays, uncertainties about tax status (with respect to depletion allowance and intangible drilling deductions), legal definition of geothermal resources (mineral, gas, water, or *sui generis*), overlapping and multiple regulatory bodies, and environmental litigation.

JAPAN

Geothermal exploration and development in Japan experienced rapid acceleration since 1970, primarily in response to the 1973 energy crisis. The dry-steam system at Matsukawa (Fig. 3) and the hot-water system at Otake continue to produce electricity at 22 MWe and 13 MWe respectively, and there are plans to expand Matsukawa to 90 MWe (Mori, p. 183). A 10-MWe installation has been operating at the Onuma hot-water system since 1973 (UN, Centre for Natural

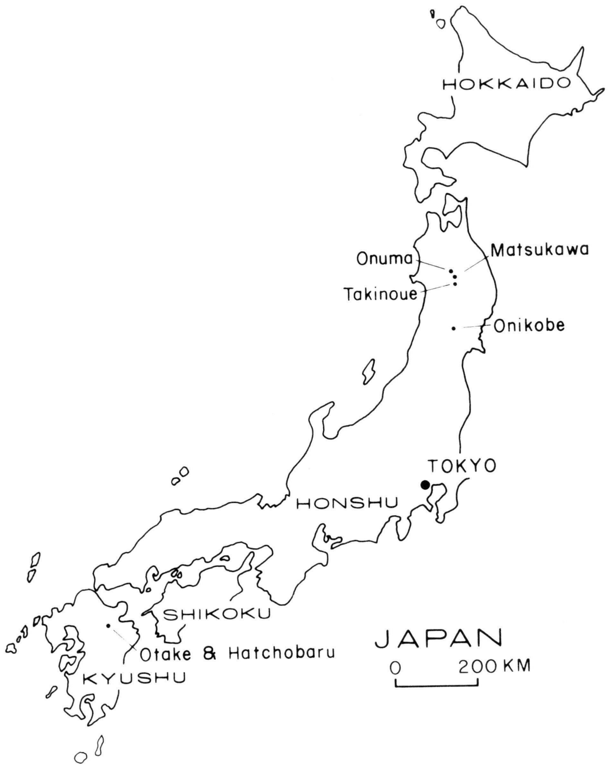

Figure 3. Map showing major geothermal areas of Japan.

Resources, Energy, & Transport, p. 3), and a 25-MWe installation has been put into service at the Onikobe caldera (Yamada, p. 665). Drilling is in progress at Takinoue (7 km southwest of Matsukawa) where a 50-MWe plant is to be completed by 1977 (Mori, p. 183). A geothermal power plant of 50-MWe capacity is also under construction at Hatchobaru (Yamasaki and Hayashi, p. 673; Aikawa and Soda, p. 1881). Intensive exploration is being carried out on northern Honshu and on Hokkaido (Mori, p. 183). If these exploration ventures are successful, the geothermal electrical capacity of Japan could well exceed 1000 MWe by 1982.

In addition to the exploration and development efforts described above, the government of Japan has instigated an aggressive program of geothermal investigations, aimed at establishing perhaps 50 000 MWe of geothermal generating capacity by the year 2000 (Mori, p. 183). This program is part of the "Sunshine Project" (Sakakura, p. 2431) and includes extensive regional evaluation by the Japanese Geological Survey (for example, Baba, p. 865; Sumi and Takashima, p. 625).

ICELAND

Geothermal development in Iceland during the past five years is highlighted by the development of the Krafla field (Fig. 4). Production wells have been drilled, and a 55-MWe power station is to be completed in 1976 (Pálmason, Ragnars, and Zoëga, p. 213). In addition, the Svartsengi area (235°C reservoir temperature) has been drilled to 1.7-km depth and will be used via a heat exchanger to provide 80 megawatts thermal (MWt; 1 MWt = 10^6 joule/sec) for house-heating in communities on the western part of the Reykjanes peninsula and at the Keflavík international airport (Arnórsson et al., p. 2077). The Krísuvík area has also been explored (Arnórsson et al., p. 853) and could supply perhaps 500 MWt for 100 years.

Geothermal energy in Iceland continues to be used primarily for space heating, but with some electrical generation and process use. Warm water from the Reykjavík and Reykir thermal areas supplies 340 MWt and meets nearly all the heating requirements of Reykjavík and neighboring towns (Tómasson, Fridleifsson, and Stefánsson, p. 643; Arnórsson et al., p. 853; Thorsteinsson, p. 2173). New district heating systems using water from which steam has been flashed were installed at Námafjall (2 MWt in 1971) and Hveragerdi (8 MWt in 1973; Thórhallsson et al, p. 1445). These geothermal systems are at temperatures of 200 and 215°C respectively, and the district heating systems are consequently plagued with silica-scaling problems. At Námafjall, the geothermal steam is used to dry diatomite and to generate 2.5 MWe of electricity. A plant for drying seaweed is being constructed at Reykhólar (Björnsson and Grönvold, Abstract II-3; Ludviksson, Abstract IX-7), and studies are being carried out with a view to producing NaCl and MgCl from the saline Reykjanes geothermal area (Lindal, p. 2223; Björnsson, Arnórsson, and Tómasson, 1972).

Owing to its ideal location on the mid-Atlantic Ridge, Iceland has a very large geothermal potential, both for electricity generation and for space heating. Bodvarsson (p. 33) estimates that the high-temperature areas of Iceland have a production potential of 3200 MWt for 50 years, and that the heat content of recoverable low-temperature resources may amount to the equivalent of 4 × 10^9 tons of petroleum.

MEXICO

Geothermal development in Mexico has been primarily at Cerro Prieto (Fig. 2) where electricity has been generated at 75-MWe capacity since November 1973 (Alonso, p. 17). The 15 wells that supply the power plant produce a water-steam mixture from depths of 900 to 1500 m (Isita S., Mooser H., and Soto P., Abstract I-17). Plans are being implemented to expand the generating capacity to 150 MWe (Guiza, p. 1973), and the potential of the field is estimated by Tolivia M. (p. 275) to be between 33 and 235 years at a production rate of 150 MWe. Alonso (p. 17) estimates a minimum

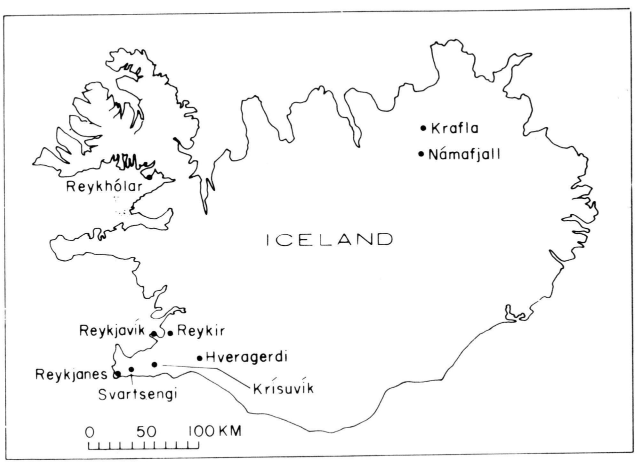

Figure 4. Map showing explored and developed geothermal areas of Iceland.

capacity of 450 to 500 MWe, and Mercado G. (p. 487) estimates a capacity on the order of 1000 MWe for several decades. Isita S., Mooser H., and Soto P. (Abstract I-17) note that a recent well (M-53) achieved a reservoir temperature of 344°C and produced separated steam at 117 tons per hour at 11 bars wellhead pressure, and suggest that there may be important extensions of the Cerro Prieto field east of the presently exploited area.

Geothermal exploration has taken place at many areas in Mexico (Alonso, p. 17), and extensive investigations including exploratory drilling have been carried out at Ixtlan de las Hervores and Los Negritos (Fig. 5). In addition, intensive geological surveys have been carried out at Los Azufres, La Primavera, and San Marcos. Alonso (p. 17) estimates the geothermal potential of Mexico to be roughly 4000 MWe.

CENTRAL AMERICA AND THE CARIBBEAN

The most noteworthy geothermal advance in Central America since 1970 has been the development of the Ahuachapán field in El Salvador (Fig. 5), where 16 production wells have been drilled (Romagnoli et al., p. 563). In 1975, 30 MWe were to be installed with 60 MWe additional by 1977 (Einarsson, p. 2363). A reservoir study carried out in 1971 estimated the geothermal reserve as at least 50 MWe-centuries (UN, Centre for Natural Resources, Energy, & Transport, p. 3). Ahuachapán is also notable for the apparently successful demonstration of reinjection into the reservoir as a means of effluent disposal (Einarsson, Vides R., and Cuéllar, p. 1349).

Geothermal development is also proceeding in Nicaragua, Costa Rica, and Guatemala, and geothermal energy could allow Central America to become independent of petroleum imports for power generation by 1980 (Einarsson, p. 2363). Investigations in Nicaragua from 1969 to 1971 under the auspices of the United States Agency for International Development revealed two promising areas, San Jacinto-Tisate and Momotombo, but development efforts were set back several years by the disastrous Managua earthquake of 23 December 1972. Temperatures of 209°C were recorded at 210 m at Momotombo (F. Morlock, oral commun., 1975). In Costa Rica, reconnaissance geothermal exploration has been carried out for several years by the Costa Rica Institute of Electricity. Current attention is focused on Guanacaste Province where geological and geophysical surveys beginning in July 1976 may lead to the siting of exploration wells later in the year (J. Kuwada, oral commun., 1976). The Guatemalan government expects to begin geothermal drilling at Moyuta in 1976.

Although little geothermal exploration has been carried out in Panama, Mérida (Abstract I-26) reports the recent discovery of a field having "great possibilities."

On Guadeloupe in the French West Indies, a drilling program carried out at Bouillante resulted in one well with high production of water and steam from a zone at 338 m and a temperature of 242°C (Demians d'Archimbaud and Munier-Jolain, p. 101). Three other wells, to depths of 800 m, 850 m, and 1200 m, did not achieve significant production. It appears that an extensive reservoir might exist at greater depth, and further drilling is proposed (Demians d'Archimbaud and Munier-Jolain, p. 101).

SOUTH AMERICA

Beginning in 1968, the United Nations Development Program and the Government of Chile conducted an intensive

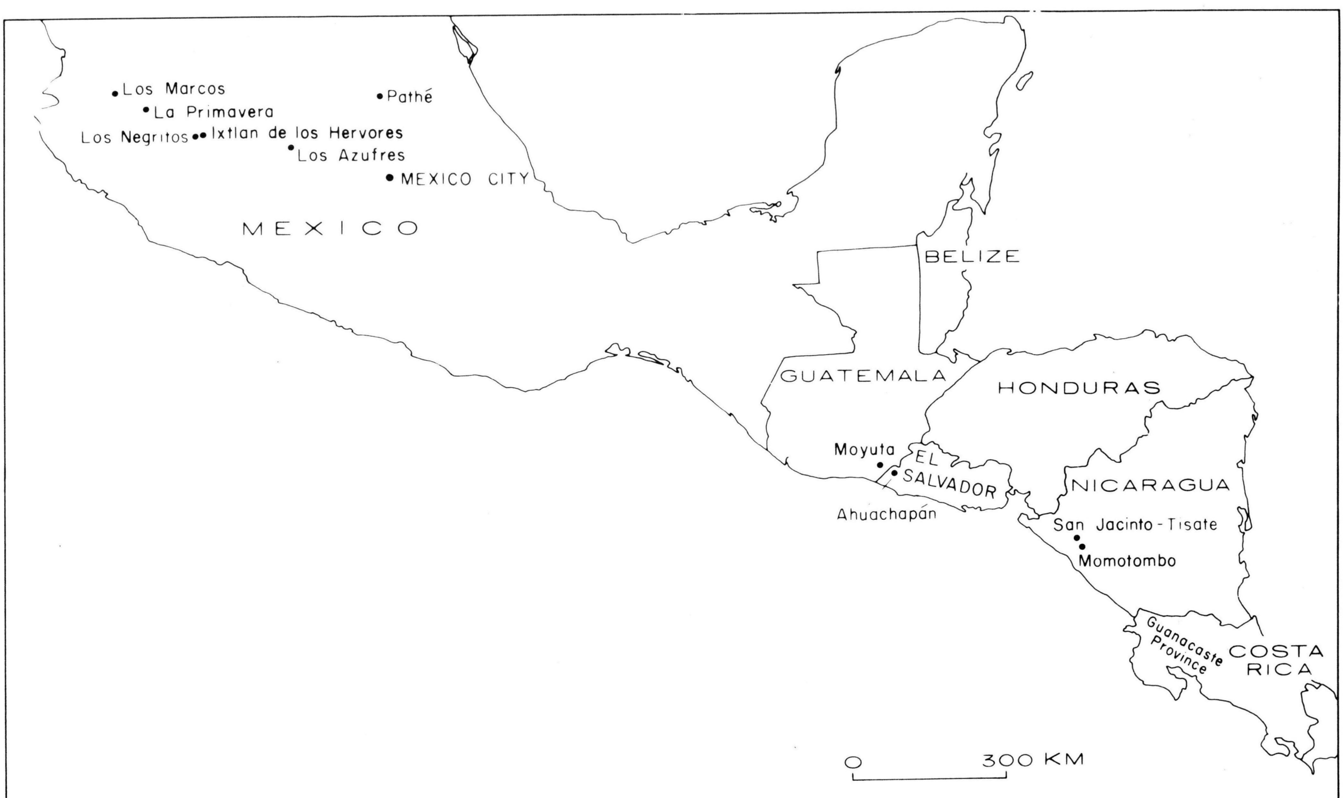

Figure 5. Map showing geothermal areas being explored or developed in Central America.

Figure 6. Map showing major geothermal areas of Chile, Peru, and Bolivia.

geothermal exploration program at El Tatio in northern Chile (Fig. 6). Geological, geochemical, and geophysical investigations, carried out in great part by New Zealand scientists, led to the drilling of six exploration wells (10-cm diameter) and in 1973-1974 to the drilling of seven production wells (20-cm diameter) to a maximum depth of 1.8 km (Lahsen and Trujillo, p. 157; UN, Centre for Natural Resources, Energy, & Transport, p. 3). The principal producing zone is at 800 to 900 m and has a temperature of 265°C (Lahsen and Trujillo, p. 157). The wells produce a mixture of steam and water, with the water containing appreciable lithium, arsenic, and cesium (Cusicanqui, Mahon, and Ellis, p. 703). Steam equivalent to 18 MWe is obtained from three wells at El Tatio, and a pilot desalination plant has been installed on one well.

In addition to the intensive work at El Tatio, geothermal exploration has been carried out elsewhere along the Andes Mountains of South America, most notably at Puchuldiza and Polloquere in northern Chile (UN, Centre for Natural Resources, Energy, & Transport, p. 3). In addition, the Andes in southern Peru and western Bolivia are likely to have similar geothermal potential; Parodi I. (p. 219) emphasizes the potential around the Ubinas volcano in Peru, and Carrasco C. (p. 43) describes areas of geothermal potential in the Cordillera Occidental and Altiplano of Bolivia.

TURKEY

During the past five years, the Mineral Research and Exploration Institute of Turkey (MTA) has carried out extensive geothermal exploration (Kurtman and Şâmilgil, p. 447), primarily in western Turkey (Fig. 7). Geothermal energy is likely to supply 10% of the Turkish electrical energy requirements in the year 2000, and geothermal exploration and development have a prominent place in the 1975 to 1979 five-year economic plan (Alpan, p. 25).

Development of the Kızıldere field (Tezcan, p. 1805) has proceeded slowly, owing in great part to serious $CaCO_3$ scaling problems. Six out of fourteen existing wells are considered productive (Alpan, p. 25), with a maximum subsurface temperature of 207.4°C. The MTA has built an 0.5-MWe pilot generating plant, and has plans for an 11.4-MWe facility (Alpan, p. 25). In addition, a pilot greenhouse is in operation.

Exploration and drilling are being carried out in the surroundings of Ankara and Afyon, primarily to supply hot water for space heating. At Afyon a well to 905 m recorded a bottom-hole temperature of 106°C and produced at 20 l/sec (Tan, p. 1523). Near Ankara, three geothermal areas are under exploration: the Kızılcahamam graben, the Murtet graben, and the Çubuk graben (Kurtman and Şâmilgil, p. 447; the Çubuk graben apparently is the same as the Meliksah area of Keskin et al., Abstract III-51). The Na:K ratio at Kızılcahamam suggests a reservoir temperature of greater than 195°C, and accordingly the area is being considered for the possible production of electricity as well as for space heating.

Exploration and shallow drilling in the Seferihisar and Tuzla regions of western Turkey have discovered areas promising for the production of electricity from hot-water geothermal systems. The Seferihisar area is characterized by many Quaternary rhyolite domes, and chemical geothermometers suggest a reservoir temperature greater than 200°C (Kurtman and Şâmilgil, p. 447); a temperature of 137°C was measured at 70 m in well G-2 (Eşder and Şimşek, p. 349). At Tuzla, post-lower Pliocene dacite domes are associated with sinter-depositing springs, and Na-K-Ca geothermometry suggests temperatures of approximately 215°C (Kurtman and Şâmilgil, p. 447). One shallow drillhole has produced a water-steam mixture, with a measured bottom-hole temperature of 145°C (Öngür, Abstract II-36).

NEW ZEALAND

Although approximately 8% of the electrical energy used in New Zealand comes from geothermal sources, Wairakei and Kawerau (Fig. 8) remain the only two producing areas. Installed capacity at Wairakei remains constant at 190 MWe, but modifications of the steam collection system to allow multiple flash resulted in a gain in electrical output equivalent to a 20-MWe increase in electrical capacity (Bolton, p. 39). At Kawerau, geothermal fluids continue to supply approximately 11% of the total energy required by the Tasman

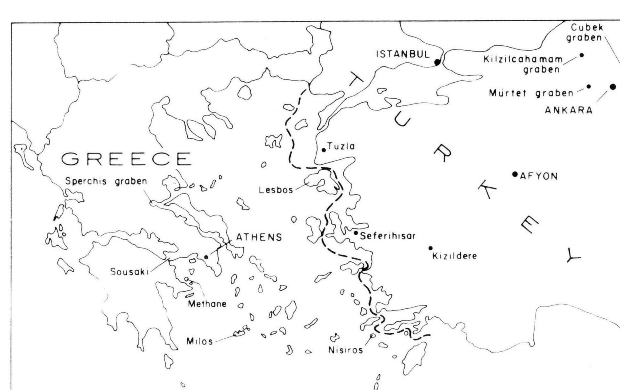

Figure 7. Map showing geothermal areas being explored in Turkey and Greece.

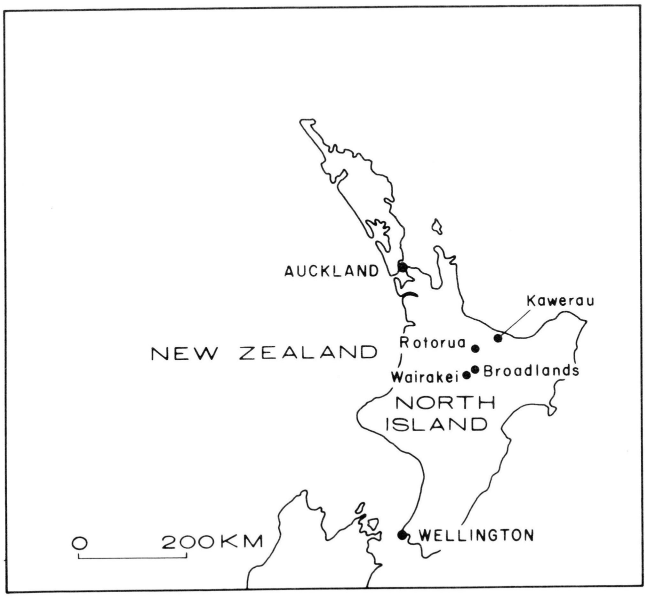

Figure 8. Map showing major developed geothermal areas of New Zealand.

Pulp and Paper Company mill (Bolton, p. 37). Geothermal fluids also are used extensively in Rotorua for heating homes (Burrows, 1970) and for the air conditioning of a hotel (Reynolds, 1970).

Geothermal drilling was suspended in New Zealand from 1971 to 1973, largely because of the expectation that substantial quantities of electricity would be generated from a large offshore natural gas field. In 1973 a program of four wells per year was reactivated at Broadlands, and in 1974 the worldwide energy crisis stimulated a similar drilling program to establish the full potential of the Kawerau field.

Twenty-eight wells have now been drilled in the Broadlands field, and seventeen of these wells produce fluid sufficient to sustain a 165-MWe plant. The New Zealand Power Planning Committee has recommended a 150-MWe station to be commissioned in 1981 (Bolton, p. 37).

Bolton (p. 37) estimates that the New Zealand geothermal fields could produce approximately 1.45×10^{10} kWh/yr, from an installed capacity approaching 2000 MWe. Hochstein (Abstract I-16) gives a similar estimate for proved and "semiproved" reserves. Bolton (p. 37) notes that only 15% of the estimated geothermal potential is proven, and accordingly it has been difficult to incorporate geothermal energy into national energy planning.

EAST AFRICA

Since 1970, the French government has carried out geothermal exploration in the French Territory of Afars and Issas, primarily in the Asal Rift (Fig. 9). This exploration has led to the conclusion that optimum sites for geothermal wells are not in the central part of the rift but on the margins where any geothermal systems will be sealed (Stieltjes, p. 613). Two wells were drilled in 1975. One of these wells had a temperature of 253°C at 1050 m and produced a brine of salinity greater than 190 000 mg/l (A. C. Gringarten and L. Stieltjes, data presented at the Workshop on Geothermal Reservoir Engineering, Standford University, Dec. 15–17, 1975).

Geothermal exploration in Ethiopia has been carried out since 1970 under the United Nations Technical Assistance program, and promising areas were identified in the Lakes District, the Awash Valley, and the northern Danakil Depression (Fig. 9; UN, Centre for Natural Resources, Energy, & Transport, p. 3). There are proposals for further work in the Lakes District, possibly leading to a 10-MWe power station.

Of the many hot-spring areas in the Rift Valley of Kenya, only Olkaria, Eburru, and Lake Hannington have been explored (Fig. 9). At Olkaria, two wells were drilled to 502 m and 942 m in 1957 to 1958 (Noble and Ojiambo, p. 189), but no further exploration took place until a joint program of the United Nations Development Program and the East African Power and Lighting Company began in 1970. In addition to bringing the deeper Olkaria hole into intermittent production, the program drilled four additional holes at Olkaria to depths of 1.3 km (Noble and Ojiambo, p. 189) and temperatures up to 287°C. Although the Olkaria field appears to be large, output of the wells drilled to date is restricted by the great depth to the water table and by low permeability. Deepening of the existing wells at Olkaria to 1.7 km is planned, along with further drilling in the Olkaria area and possibly the Lake Hannington and Eburru areas. In an area of high-power costs such as Kenya, even wells of only moderate output such as Olkaria 3 and 4 appear to be economically attractive (Noble and Ojiambo, p. 189).

Geothermal exploration in the western rift of Uganda was renewed in 1973 by the Uganda Geological Survey and Mines Department, with limited resistivity and microearthquake surveys conducted at Sempaya, Kitagata, and Lake Kitagata (Fig. 9). From chemical and resistivity data, Maasha (p. 1103) estimates a subsurface temperature of at least 160°C at Sempaya, the most promising of the three areas.

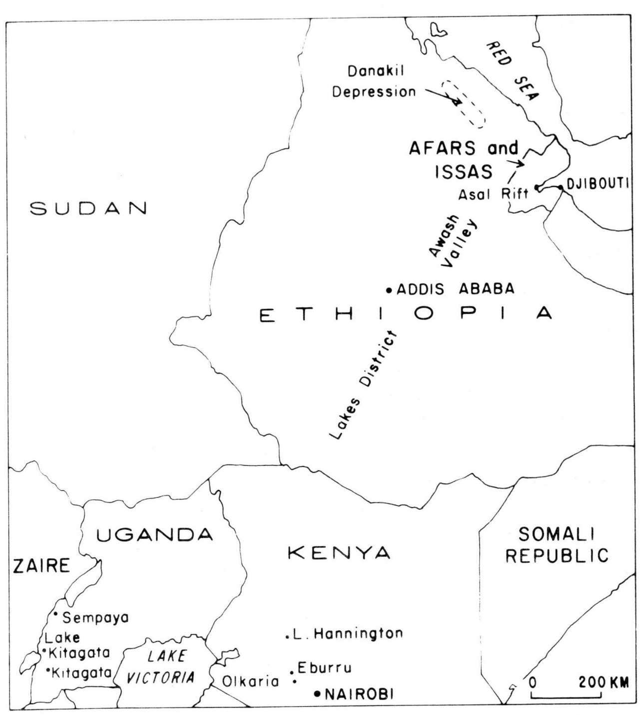

Figure 9. Map showing geothermal areas in East Africa.

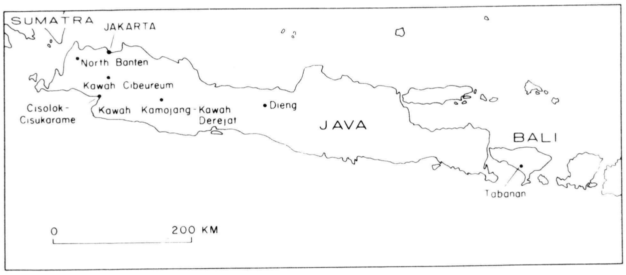

Figure 10. Map showing major geothermal areas under exploration in Java and Bali, Indonesia.

INDONESIA

Extensive geothermal exploration has been carried out in Indonesia during the past five years, primarily on the islands of Java and Bali (Fig. 10). This exploration is highlighted by the confirmation of the Kawah Kamojang area as a vapor-dominated geothermal system of large potential (Hochstein, p. 1049). As of May 1975, four holes had been drilled to depths of 500 to 800 m, and at least two of these wells produce dry steam (Hochstein, p. 1049; Kartokusumo, Mahon, and Seal, p. 757).

The Dieng area of central Java was investigated from 1970 to 1972 by the Indonesian Power Research Institute with initial assistance from the United States Government (Truesdell, 1971; Muffler, 1971). Five holes were drilled in 1972 to depths ranging from 84 to 183 m. Maximum temperature encountered was 173°C at 139 m (Radja, p. 233, as quoted from Danilchik, 1972). Unlike the Kawah Kamojang area, the Dieng geochemistry suggests the presence of a hot-water geothermal system at depth (Truesdell, 1971).

Exploration has also been carried out at Kawah Derajat, Kawah Cibeureum, Cisolok-Cisukarame, and Tambanan (Bali) jointly by the Geological Survey of Indonesia and Geothermal Energy of New Zealand, Ltd. (Akil, p. 11; Radja, p. 233). In addition, the North Banten area has been investigated by Pertamina (the Indonesian oil and natural gas company) and Kyushu University of Japan (Radja, p. 233). Reconnaissance evaluation of the Indonesian islands (Radja, p. 233) indicates substantial geothermal potential throughout the nation.

CANADA

The regional geothermal potential of Canada has been evaluated in an excellent study by Souther (p. 259). Significant geothermal potential in Canada appears to be concentrated near young, silicic volcanic centers in British Columbia, most prominently Mt. Edziza and Meager Mountain (Fig. 11). The latter has been studied in detail by the British Columbia Hydro and Power Authority, and a 347-m hole has found 69°C water (Nevin and Stauder, p. 1161). The chemistry of thermal waters in the area suggests a subjacent reservoir of over 185°C (Souther, p. 259).

INDIA

Geothermal reconnaissance has been carried out throughout India during the past five years, with emphasis on tectonic setting and the interpretation of hot-spring chemistry in terms of subsurface temperatures (Krishnaswamy, p. 143; Subramanian, p. 269; Gupta, Narain, and Gaur, p. 387). The region of most immediate potential appears to be the Himalayan arc in northwestern India (Fig. 12), but the Konkan area, and the Sanha, Cambay, Narbada-Tapti, and Godavari grabens may have significant potential.

Exploration efforts through 1975 have concentrated in the Puga, Chumathang, and Parbati Valley areas of northern India. In the Puga area, six wells at depths up to 80 m recorded temperatures up to 135°C and flowing steam and water; chemical geothermometers suggest a base temperature of 220 to 270°C (Shanker et al., p. 245). At Chumathang, 20 km north of Puga, a temperature of 109°C was recorded at 30 m, and geochemistry of fluids suggests a reservoir temperature of 145 to 184°C (Shanker et al., p. 245). In the Parbati Valley (which contains the Manikaran area), geochemistry of fluids suggests reservoir temperatures of over 200°C (Jangi et al., p. 1085; Gupta, Saxena, and Sukhija, p. 741; Chaturvedi and Raymahashay, p. 329). In all three areas, scaling by $CaCO_3$ appears to be a significant production problem (Subramanian, p. 269; Chaturvedi and Raymahashay, p. 329).

In the Cambay graben, high temperatures and pressures (up to 170°C and 100 kg/cm^2) have been found at depths of up to 3.4 km (Krishnaswamy, p. 143), suggesting the

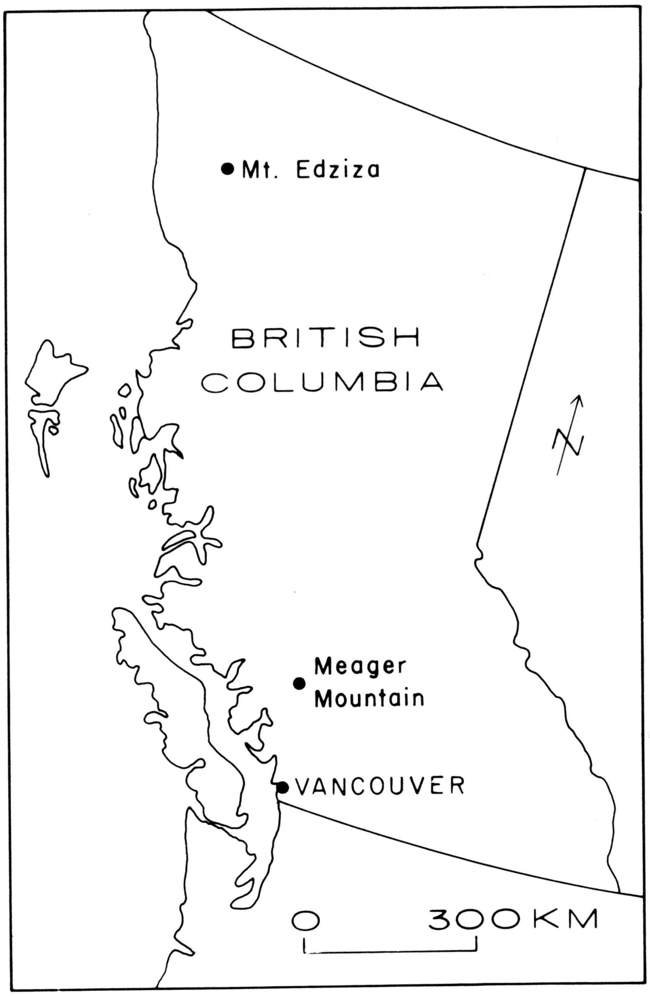

Figure 11. Map showing geothermal areas being explored in British Columbia, Canada.

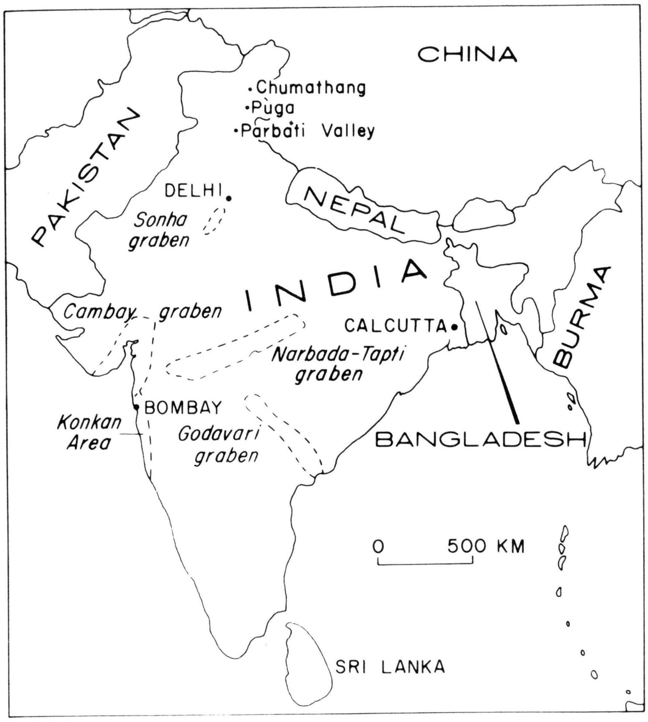

Figure 12. Map showing geothermal areas and regions of geothermal potential in India.

presence of a geopressured resource similar to that in the Gulf Coast of the United States.

Geothermal exploration in India is likely to progress rapidly in the next few years as a new cooperative program between the Ministry of Energy and the United Nations Development Program gets under way in the Parbati Valley and the West Coast (Krishnaswamy, p. 143; Subramanian, p. 269). In addition, further exploration is planned by the Geological Survey of India in the Puga, Chumathang, and Sohna areas (Krishnaswamy, p. 143).

FRANCE

Geothermal development in France has been highlighted since 1969 by the utilization of 70°C water from Jurassic rocks at a depth of 1.8 km in the Paris Basin to heat apartments at Melun (Maugis, 1971; BRGM, 1975; Fig. 13). A similar installation is now being constructed at Creil, 50 km north of Paris (P. Coulbois, oral commun., 1975). Aquifers of temperature greater than 50°C have also been identified in other sedimentary basins of France, in particular the Aquitanian Basin and Alsace (BRGM, 1975). Geochemical exploration for geothermal resources has also been carried out in the Massif Central (Fouillac et al., p. 721).

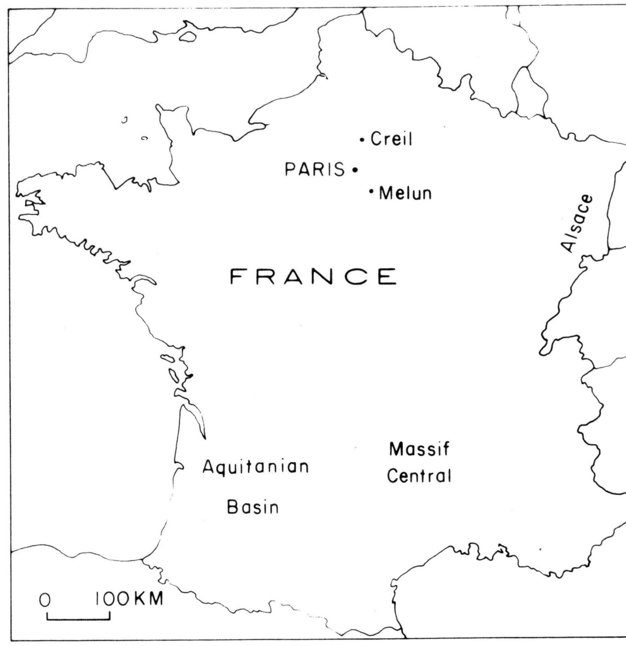

Figure 13. Map showing areas of geothermal development and exploration in France.

GREECE

Since 1970, reconnaissance geochemical exploration has been carried out in six areas of Greece (Dominco and Papastamatoki, p. 109): the Sperchis graben, Sousaki, Methane, Lesbos, Nisiros, and Milos (Fig. 7). The most promising area of the six appears to be the island of Milos, where a 70-m hole drilled in 1972 discharged steam and water and had a bottom-hole temperature of 138°C (Dominco and Papastamatoki, p. 109). A program of deep test drilling on Milos is planned. Greek thermal waters appear to be a mixture of sea water and meteoric water, with salinities as great as, and locally exceeding, that of sea water (Dominco and Papastamatoki, p. 109).

EASTERN EUROPE AND THE USSR

The temperature map given by Čermák, Lubimova, and Stegena (p. 47, Fig. 6) shows that temperatures greater than 40°C at 1 km exist over much of southeastern Europe. The Pannonian Basin of Hungary and the basins immediately

Figure 14. Map showing geothermal areas and regions of eastern Europe.

north and south of the Caucasus have temperatures greater than 50°C at 1 km, and geothermal resources have been developed for space-heating and agricultural purposes in all three areas.

In Hungary, thermal waters are produced from highly permeable upper Cenozoic sandstones at depths up to 2.5 km and temperatures up to 150°C (Boldizsár and Korim, p. 297). Most of the geothermal production is from southeastern Hungary, in a belt extending northeast from Szeged to Debrecen (Fig. 14), with some utilization in northwestern Hungary and at Budapest (Boldizsár and Korim, p. 297, Fig. 1; Balogh, p. 29). At the end of 1974, there were 433 wells in Hungary producing water at greater than 35°C wellhead temperature. These 433 wells produced 461 m^3/min, giving 1010 MWt (Boldizsár and Korim, p. 297). Balogh (p. 29) estimates that 5 to 30 × 10^{10} m^3 of thermal water can be recovered from depths of 1.5 to 2.5 km beneath Hungary. Boldizsár and Korim (p. 297) estimate the water recoverable from the main reservoir (the iower Pliocene sandstones) to be 28 × 10^{10} m^3, with a usable heat content of 5 × 10^{19} J.

Geothermal resources similar to those of Hungary also occur in the surrounding countries, but there has been little utilization to date. Figure 1 of Boldizsár and Korim (p. 297) shows clearly that the area of high geothermal gradients in southeast Hungary extends into Romania (see also C. Opran quoted in Geothermics, 1974, v. 3, p. 82), and that the area of high gradients in northwestern Hungary extends northeast into Czechoslovakia. Figure 6 of Čermák, Lubimova, and Stegena (p. 47) suggests that temperatures of greater than 50°C at 1 km occur in Austria and Yugoslavia.

Geothermal investigations have been carried out in the Slovakian Socialist Republic (Franko and Račický, p. 131) and are beginning in Bohemia (the Czech Socialist Republic; T. Pačes, oral commun., 1975). In Slovakia, the most promising region is the central depression of the Danube Basin, southeast of Bratislava, where water at 138°C has been found at 2.5 to 3 km (Franko and Račický, p. 131).

Although heat-flow and geothermal gradients are not as high in Poland as in the countries to the south, there still may be opportunities for geothermal utilization in southwestern Poland (Dowgiałło, p. 123). Water up to 60°C has been produced from drillholes into granite at depths of 660 and 750 m at Cieplice, and water up to 46°C has been produced in a drillhole into granite at a depth of 700 m at Ladek. The silica content of the Cieplice water suggests that temperatures at depth exceed 100°C. Thermal waters also have been found in drillholes into Mesozoic sediments beneath Silesia; one well has produced 19.4 1/sec of 59.5°C water (Dowgiałło, p. 123).

From all indications, the use of geothermal energy in the USSR continues to expand rapidly, although very few specific data were presented to the United Nations Symposium. Kharahashiyan and Khelkvist (Abstract I-18) state that 28 geothermal fields in the USSR are in industrial operation, mainly supplying heat to houses, industries, and agricultural operations, and that 200 000 m of exploratory geothermal wells have been drilled since 1966. According to Fomin et al. (p. 129), geothermal resources in the USSR could supply greater than 10^{18} J/yr. Mavritsky and Khelkvist (p. 179) estimate the "reserves" (potential yield?) of thermal waters with temperatures of 40 to 250°C in the USSR to be 22 × 10^6 m^3 per day. These "reserves" consist of "steam-water deposits" (>100°C reservoir temperature?) in Kamchatka and the Kuril Islands, and "thermal water deposits" in Kamchatka, the Caucasus, Middle Asia, Kazakhstan, and Siberia. Hydrothermal convection systems with temperatures up to 257°C in Kamchatka have a natural heat discharge of 3.8 × 10^9 J/sec, enough to support an electrical generating capacity of 350 to 500 MWe (Fedotov et al., p. 363).

PHILIPPINES AND TAIWAN

Extensive drilling has taken place in the Tiwi area of southeastern Luzon, the Philippines (Fig. 15), and a 100-MWe geothermal plant is to be completed by 1977, with an additional 100 MWe to follow soon thereafter (UN, Centre for Natural Resources, Energy, & Transport, p. 3). In addition, drilling indicates that the Los Banos area, also

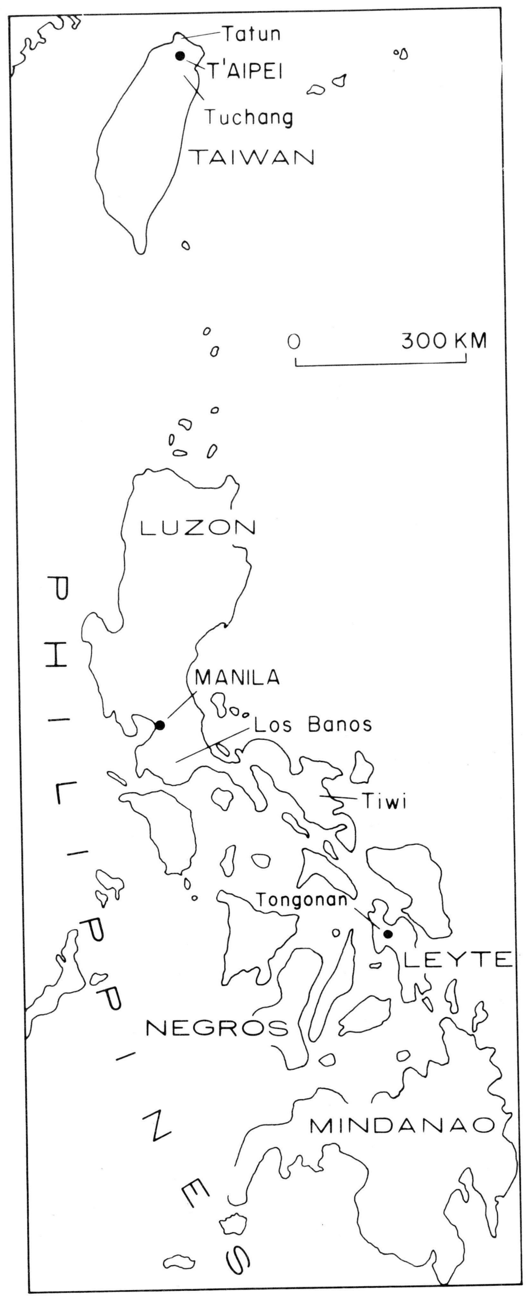

Figure 15. Map showing geothermal areas in Taiwan and the Philippines.

on Luzon, is of considerable promise. Exploration and some drilling have also been carried out at Tongonan on Leyte, and exploration has been proposed for several promising sites on Negros and Mindanao.

Although no information on Taiwan could be presented at the United Nations Symposium, two geothermal fields have been explored (Chen, 1975). The Tatun field (Fig. 15) has reservoir temperatures up to 293°C, but acidity of the water (pH 2) has precluded development to date. A well drilled to 240 m in the Tuchang field found temperatures of 173°C and a sodium bicarbonate fluid of pH 8.5.

AZORES (PORTUGAL)

Geothermal exploration has proceeded in the Azores, albeit somewhat inadvertently, since 1970. One hole was drilled to 981 m on the north flank of Agua de Pau volcano on the island of São Miguel by Dalhousie University (Halifax, Nova Scotia, Canada) as part of an investigation into the processes of formation of oceanic islands. Although the drill hole was not intended for geothermal exploration, temperatures of over 200°C were found at depths greater than 550 m (Meucke et al., 1974). Further exploration and development are planned for the area (V. Forjaz, 1975, oral presentation at the Workshop on Small Geothermal Power Plants, Furnas, the Azores, September 8-14, 1975).

CONCLUSION

The acceleration in geothermal development since 1973 has not yet had a major effect on the world's installed geothermal capacity (Table 1) owing to the lag of two to five years between discovery of a field and commercial utilization. Also, the electrical capacity figures do not reflect the continuing steady growth of direct utilization of geothermal heat. The upsurge in geothermal exploration and production drilling, the dramatic expansion of geothermal research and development, the continuing high petroleum prices, the dwindling supplies of petroleum and natural gas, and the increased awareness of the need for environmental protection are combining to bring geothermal energy from a minor curiosity to a significant source of electricity and heat throughout the world.

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REFERENCES CITED

BRGM, 1975, La geothermie en France: Bureau de Recherches Géologiques et Minières Bull., 2nd Ser., section 2, 24 p.

Björnsson, S., Arnórsson, S., and Tómasson, J., 1972, Economic evaluation of Reykjanes thermal brine area, Iceland: Am. Assoc. Petroleum Geologists Bull., v. 56, p. 2380-2391.

Burrows, W., 1970, Geothermal energy resources for heating and associated applications in Rotorua, New Zealand: UN Symposium on the Development and Utilization of Geothermal Resources, Pisa, Proceedings (Geothermics, Spec. Iss. 2), v. 2, pt. 2, p. 1169-1175.

Cataldi, R., and Rendina, M., 1973, Recent discovery of a new geothermal field in Italy: Alfina: Geothermics, v. 2, p. 106-116.

Cataldi, R., Rossi, A., Squarci, P., Stefani, G., and Taffi, L., 1970, Contribution to the knowledge of the Larderello geothermal region: Remarks on the Travale field: UN Symposium on the Development and Utilization of Geothermal Resources, Pisa, Proceedings (Geothermics, Spec. Iss. 2), v. 2, pt. 1, p. 587-602.

Chen, C., 1975, Thermal waters in Taiwan a preliminary study [abs]: International Union of Geodesy and Geophysics, XVI General Assembly, Grenoble, Aug. 25 to Sept. 6, 1975, Abstracts of papers presented at the Interdisciplinary Symposia, p. 268.

Danilchik, W., 1972, Dieng geothermal exploration drilling project, Indonesia, during 1972—interim report: U.S. Geol. Survey Project Report, Indonesian Investigations (IR) INd-28, 53 p.

Duffield, W. A., 1975, Late Cenozoic ring faulting and volcanism in the Coso Range area of California: Geology, v. 3, no. 6, p. 335-338.

Eaton, G. P., Christiansen, R. L., Iyer, H. M., Pitt, A. M., Mabey, D. R., Blank, R. H., Jr., Zietz, I., and Gettings, M. E., 1975, Magma beneath Yellowstone National Park: Science, v. 188, p. 787-796.

Lanphere, M. A., Dalrymple, G. B., and Smith, R. L., 1975, K-Ar ages of Pleistocene rhyolitic volcanism in the Coso Range, California: Geology, v. 3, no. 6, p. 339-341.

Maugis, P., 1971, Exploitation d'une nappe d'eau chaude souterraine pour le chauffage urbain dans la région Parisienne: Annales Mines, no. 5, p. 135-142.

Meucke, G. K., Ade-Hall, J. M., Aumento, F., MacDonald, A., Reynolds, P. H., Hyndman, R. D., Quintino, J., Opdyke, N., and Lowrie, W., 1974, Deep drilling in an active geothermal area in the Azores: Nature, v. 252, p. 281-285.

Mori, Y., 1970, Recent plans of geothermal exploitation: UN Symposium on the Development and Utilization of Geothermal Resources, Pisa, Proceedings (Geothermics, Spec. Iss. 2), v. 2, pt. 2, p. 1144-1149.

Muffler, L. J. P., 1971, Evaluation of initial investigations, Dieng geothermal area, central Java: U.S. Geol. Survey open-file rept. (IR) IND-10, 22 p.

Olson, H. J., and Dolan, W. M., 1975, Geothermal energy—an industry appraisal: American Mining Congress, San Francisco, Sept. 30, 1975.

Papadopulos, S. S., Wallace, R. H., Jr., Wesselman, J. B., and Taylor, R. E., 1975, Assessment of onshore geopressured-geothermal resources in the northern Gulf of Mexico basin, *in* White, D. E., and Williams, D. L., eds., Assessment of geothermal resources of the United States—1975: U.S. Geol. Survey Circular 726, p. 125-146.

Reynolds, G., 1970, Cooling with geothermal heat: UN Symposium on the Development and Utilization of Geothermal Resources, Pisa, Proceedings (Geothermics, Spec. Iss. 2), v. 2, pt. 2, p. 1158-1161.

Schlaugh, P. J., and Worcester, T. E., 1974, Geothermal resources: A primer for the practitioner: Land and Water Law Review, University of Wyoming College of Law, v. IX, no. 2, p. 327-367.

Truesdell, A. H., 1971, Geochemical evaluation of the Dieng Mountains, central Java, for the production of geothermal energy: U.S. Geol. Survey open-file rept. (IR) IND-8, 29 p.

White, D. E., Fournier, R. O., Muffler, L. J. P., and Truesdell, A. H., 1975, Physical results of research drilling in thermal areas of Yellowstone National Park, Wyoming: U.S. Geol. Survey Prof. Paper 892, 70 p.

White, D. E., and Williams, D. L., eds., 1975, Assessment of geothermal resources of the United States—1975: U.S. Geol. Survey Circular 726, 105 p.

Worthington, J. D., 1975, Geothermal development, *in* Status report—energy resources and technology: Report of The Ad Hoc Committee on Energy Resources and Technology, Atomic Industrial Form, Inc., 23 p.

Zablocki, C. J., Tilling, R. I., Peterson, D. W., Christiansen, R. L., Keller, G. V., and Murray, J. C., 1974, A deep research drill hole at the summit of an active volcano, Kilauea, Hawaii: Geophys. Research Letters, v. 1, p. 323-326.