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CURRENT STATUS (1987) OF GEOTHERMAL EXPLORATION IN ETHIOPIA

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Abstract—The Government of Ethiopia realized 18 years ago that the Ethiopian rift valley and the Afar depression were regions of high geothermal potential suitable to be exploited for electric power generation. Systematic geothermal investigations on a regional scale started in 1969 and since then continuous investigations have been conducted and several geothermal prospect areas identified. Eight deep exploration wells have been drilled in the Aluto–Langano volcanic complex and sufficient geothermal steam to fuel an economically viable power plant has been discovered.

INTRODUCTION

Ethiopia has significant geothermal resources in the main Ethiopian rift valley and the Afar depression; both are part of the great East African rift system.

Geothermal exploration in Ethiopia dates back to 1969, when the first Ethiopian–United Nations Development Programme (UNDP) geothermal reconnaissance investigations started (Ethiopia–United Nations Development Programme, 1973). This work, consisting of geological, geochemical and hydrogeological surveys, as well as remote sensing (infrared imagery), covering the whole of the Ethiopian rift and Afar depression, resulted in the selection of potential areas for further detailed studies: Dallol in the Danakil depression, Tendaho in the northern Afar depression, and the Lakes district in the main Ethiopian rift. The Lakes district and Tendaho areas were subjected to more detailed studies.

Between 1979 and 1980 geothermal exploration was completed in the Tendaho area and drilling of three deep exploratory wells is planned to start in 1988.

In the Aluto–North Langano volcanic complex, eight deep exploration wells were drilled between 1981 and 1985 and a two-phase geothermal reservoir has been discovered. Well testing and feasibility studies have been completed. The project was financed by the Government of Socialist Ethiopia, the European Economic Community (EEC) and the United Nations Development Programme (UNDP).

Towards the end of 1985 geothermal investigations began on eight selected prospect areas in the southern Afar regions, with the financial aid of the World Bank and the Government of Ethiopia.

During the initial period of geothermal exploration and deep geothermal drilling, the Ethiopian Institute of Geological Surveys (EIGS) relied extensively on international experts. In order to become more self-sufficient the EIGS has made great efforts to train nationals in all fields of geothermal sciences and engineering as well as in deep geothermal drilling. Nowadays, the Institute has a strong geothermal unit capable of carrying out geothermal exploration, including drilling, with minimum consultancy of foreign experts.

RECONNAISSANCE SURVEY OF THE ETHIOPIAN RIFT VALLEY

Most of the geothermal manifestations are located in the Ethiopian rift system, which has high regional heat flow due to an underlying basic upper mantle intrusion beneath the thinned crust.

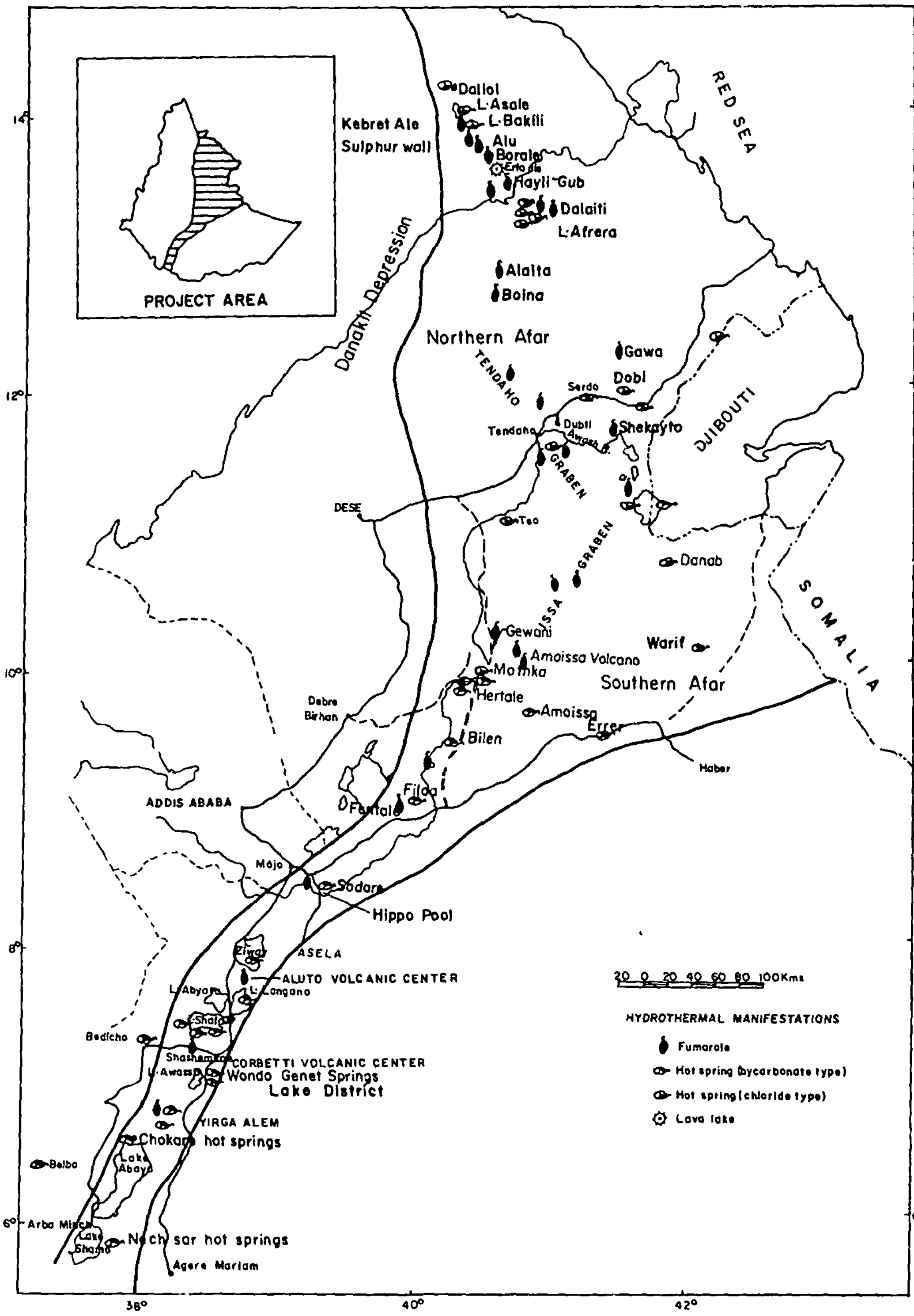

Fig. 1. Map of Ethiopia showing geothermal project area and main hydrothermal manifestations.

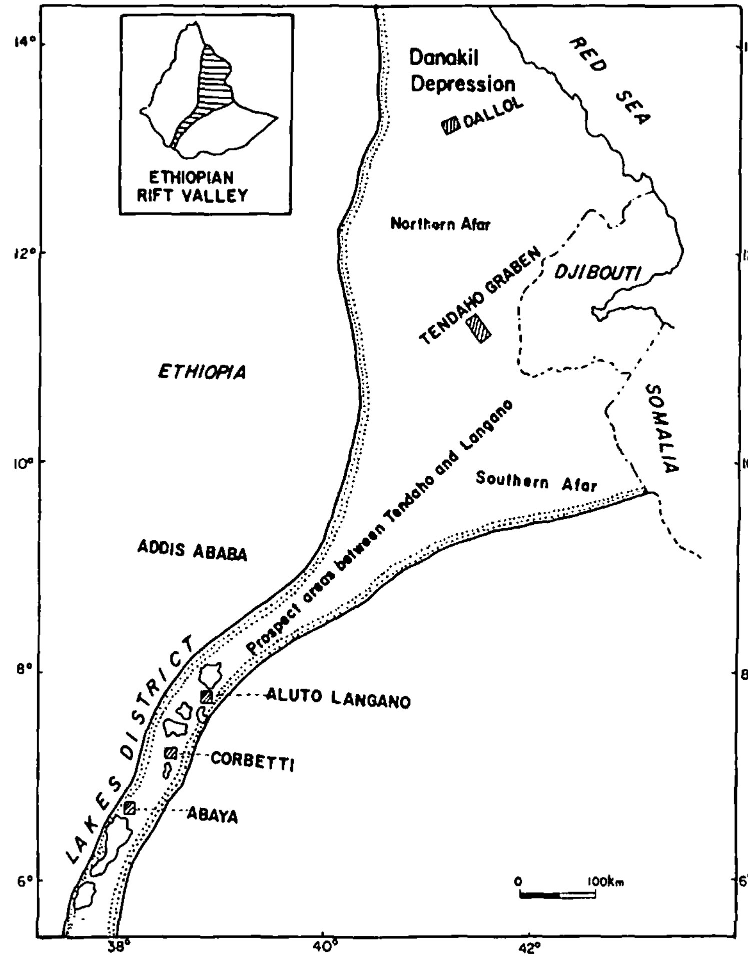

Fig. 2. Location of known geothermal resources in Ethiopia.

The objective of the geothermal project was to investigate all the thermal manifestations within an area of 150,000 km^2 of the Ethiopian rift valley and the Afar depression in order to identify geothermal resources (Fig. 1). The project included mapping of the geothermal features, and chemical analysis of gas and water samples (Table 1). Several areas of major interest were then selected, including Dallol in the Danakil depression, Tendaho in the North Afar and the Lakes district (Fig. 2). The Survey recommended further detailed studies in these areas.

TENDAHO GEOTHERMAL AREA

Tendaho geothermal area is located 600 km north-east of Addis Ababa on the main highway connecting the port of Assab to Addis Ababa. A series of studies have been conducted with the financial assistance of the Government of Italy. The area with important geothermal manifestations covers approximately 2500 km^2. All previous studies carried out in this area gave encouraging indications for the exploitation of geothermal resources to generate electricity and for non-electric uses. According to the technical and economical studies by Aquater (1982), a 20

Table 1. Water chemistry of selected hot springs in geothermal areas in the Ethiopian rift valley

Locality	Spring No.	Temperature (°C)	pH	Ca	Mg	Na	K	Li	HCO_3	Cl	SO_4	F	HBO_2	SiO_2
Dallol	1	51.5	7.5	3720	680	13.135	600	0.3	29	28.200	1167	1.0	26.0	99
Lake Afrera	26	51	7.4	1820	8	3208	250	0.8	37	7952	776	1.0	7.8	92
Tendaho	17	95	7.0	24	0.006	506	3.9	0.35	32.94	710	25.95	0.8	9.6	157
Teo	50	73	7.6	30	0.25	600	30	0.55	140	746	211	1.2	0.78	372
Danah	70	93	7.75	30	1.50	520	35	1.1	137	699	116	1.9	1.32	175
Waruf	2	50	7.3	32.06	6.84	219	11.2	—	231.7	178	200	0.52	—	73
Hertale	84	49	7.35	8	5	238	16	0.03	403	118	78	1.8	0.15	101
Bilen	92	40	6.90	25	10	200	18	0.02	537	64	37	3.3	0.15	107
Filweha	40	43	7.85	2	2	450	85	0.01	824	197	76	7	1.48	86
Sodore	4	46	7.6	14	8	675	44	—	1496	175	137	9.2	5	146
Lake Langano	10	95	9.0	1.5	0.2	750	40	0.46	841	497	244	16.1	3	163
Lake Shalla	30	94	9.0	1.3	0.3	2.425	25	0.52	3042	1649	29	73	5.8	96
Wondo Genet	4	85	8.2	100	3.4	390	30	0.36	900	0.82	85	11.8	0.1	161
Lake Abaya	6	96	10	1.0	0.5	1315	200	1.38	1821	765	102	43.3	301	428

MW plant seemed initially the most appropriate; according to power demand it could be extended to 100 MW. The supply of geothermal energy at competitive prices could make a significant contribution to the socio-economic development of the area. Based on the results of previous studies by Aquater, deep drilling is planned to commence in 1988 with the financial assistance of the government of Italy.

LAKES DISTRICT GEOTHERMAL AREA

Based on the recommendations and results of the reconnaissance survey of the 1969–1973 Ethiopian–UNDP Geothermal Project, detailed geologic, geochemical and geophysical surveys were carried out in most of the Lakes district, particularly Aluto–Langano, Shalla, Corbetti and Abaya areas. The studies have indicated the existence of heat sources in the northern, central and southern areas of the Lakes district that are associated with a shallow magma chamber beneath the Aluto, Corbetti and Hobecha volcanic centres. Deep exploration was also recommended in the above areas.

ALUTO–LANGANO GEOTHERMAL AREA

The Aluto–Langano geothermal area is located on the floor of the Ethiopian rift valley about 200 km south-east of Addis Ababa. In 1980 a Technical Review Committee, with the participation of United Nations experts, was convened to review and assess the available data on the Lakes district areas and to make recommendations on further activity, such as selection of priority areas for initial drilling and well siting. As a result, Aluto–North Langano area was recommended as first priority. Corbetti and Lake Abaya geothermal areas were recommended as second and third priorities.

Subsequent detailed investigations, including geophysics, were mainly concentrated in the Aluto area. The priority given to this area was partly influenced by its proximity to the existing National Electric Grid.

In 1978 the Ethiopian Government reached an agreement with the European Economic Community (EEC) and the United Nations Development Programme (UNDP) to jointly finance a deep geothermal exploration drilling programme. The objective of the project was to verify by drilling the existence of sufficient quantities of geothermal steam to fuel an economically viable power plant in the area (Bodvarsson, 1986; Hole, 1986; Mahon *et al.*, 1984; Molla Belaineh, 1986, 1987).

DEEP EXPLORATION WELLS

From 1981 to 1985 eight exploration wells were drilled in Aluto–Langano geothermal area. Two of the wells, LA-1 and LA-2, were drilled outside the Aluto volcanic complex, while the other six wells, LA-3 to LA-8, were drilled within the Aluto complex (Fig. 3).

The first well (LA-1) was drilled on the southern flank of the Aluto volcanic complex, on the northern extension of the East Basuma fault. Subsurface conditions encountered were characterized by poor permeability and low temperature.

Well LA-2 was located on the western flank of the Aluto volcanic complex and on the northern extension of the West Langano Wonji fault. Subsurface conditions were similar to those encountered in LA-1.

Six wells were drilled in the south-eastern part of the Aluto complex, LA-3 and LA-6 being located on the NNE–SSW trending fault zone, LA-4 and LA-5 east of the fault zone, and LA-7 and LA-8 to the west (Fig. 4).

Table 2. Water and gas composition in the deep exploratory wells of Aluto–Langano geothermal field

			Down-hole water composition (ppm)													Gas composition in discharging wells (mmol (100 mol)$^{-1}$ steam)			
Wells	Depth (m)	Maximum temperature (°C)	pH	Na	K	Ca	Mg	Co_3	HCO_3	Cl	SO_4	F	HBO_2	SiO_2	TDS	Enthalpy (kJ kg^{-1})	Sampling pressure (bars-gauge)	CO_2	H_2S
LA-1	1317	88	9.6	563	39	1	0.1	162	744	230	19	24	5	84	1871.1	—	—	—	—
LA-2	1602	117	9.2	85	20	1	0.1	18	177	206	20	2	0.5	29	366.6	—	—	—	—
LA-3	2144	315	9.3	675	157	1	0.1	163	830	310	282	38	14	556	3026.1	1650	3.0	2052	20
LA-4	2062	231	9.5	758	230	5	0.5	199	375	479	473	37	53	558	3167.5	1000	4.2	5432	2.4
LA-5	1867	208	9.0	1060	148	6	0.5	157	1300	720	168	28	27	317	3931.5	—	—	—	—
LA-6	2200.8	335	9.0	934	150	6	0.2	175	1442	454	204	46	30	418	3859.2	1650	5.4	2500	28
LA-7	2448.5	225	8.8	684	81	8	0.9	99	1489	325	135	23	23	210	3257.9	970	1.2	2163	2.6
LA-8	2500	271	9.1	670	53	6	0.4	107	536	550	73	22	31	186	2234.4	1150	2.0	2376	5.5

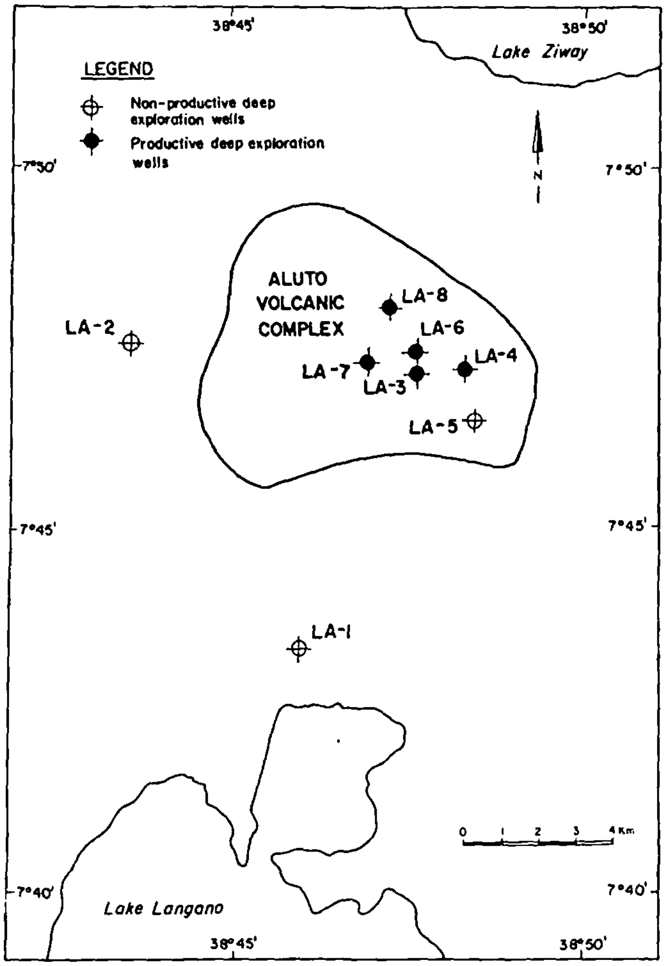

Fig. 3. Aluto–North Langano geothermal field and location of exploration wells.

The temperatures recorded in the Aluto wells were high (180°C in LA-5–335°C in LA-6); very low permeability was found in LA-5 and moderate permeability in the other wells (Table 2).

Wells LA-1 and LA-2 drilled outside the Aluto volcanic complex are non-productive. The wells drilled within the Aluto volcanic complex are productive with the exception of well LA-5. Each of the productive wells produce steam equivalent to approximately 2 MW_e.

According to the feasibility study by ELC–Electroconsult (1985, 1986) and ELC–Electroconsult and Geotermica Italiana (1986), the Aluto geothermal field is related to a hydrothermal system controlled by a recent fault (Wonji fault) that acts as an upflow area for the hot geothermal fluids. The lateral flow occurs through the Bofa basalt and crystalline ignimbrite, which acts as the geothermal reservoir.

The wells located along the upflow area (LA-3 and LA-6) produce fluids of high enthalpy (1500–1800 kJ kg^{-1}), while the lateral wells (LA-4 and LA-8) produce fluids with a low enthalpy (1000–1100 kJ kg^{-1}) and a high content of non-condensable gases. Permeability in the reservoir is rather low, ranging from 3 to 5 millidarcy (Table 3).

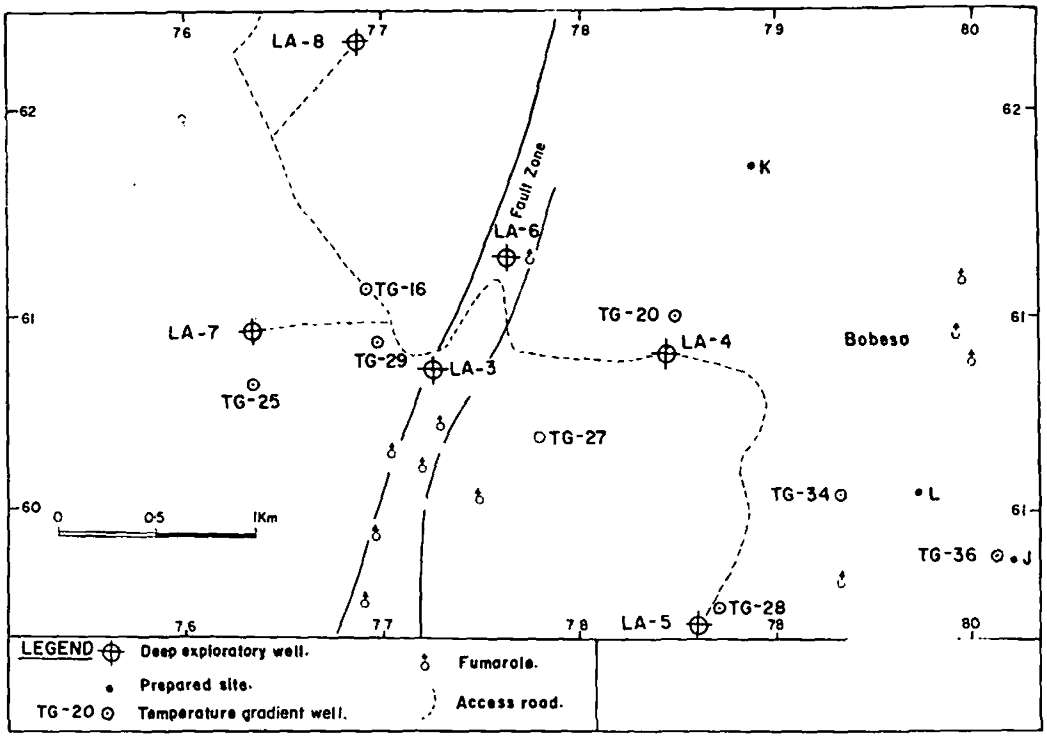

Fig. 4. Deep exploratory wells and geothermal manifestations in Aluto–North Langano geothermal field.

Simulations of field performance indicate that, at a fluid extraction rate sufficient to feed a 30 MW_e unit, the reservoir could produce for more than 30 yr.

EXPLOITATION OF RESOURCES

Aluto–Langano geothermal resources can be utilized to supply electricity and/or heat for various purposes. According to the feasibility study, the development of Aluto geothermal resources for electricity generation should be conducted in three consecutive phases to reach a full capacity of 30 MW.

Phase 1. Early installation of a 3.5 MW_e back-pressure unit utilizing the existing productive wells.

Table 3. Well characteristics in Aluto–Langano geothermal field (ELC–Electroconsult, 1986)

Well	Maximum temperature (°C)	Total depth (m)	Total flow-rate ($kg\,s^{-1}$)	Water flow-rate ($kg\,s^{-1}$)	Steam flow-rate ($kg\,s^{-1}$)	Enthalpy ($kJ\,kg^{-1}$)	Wellhead pressure (bar abs.)
LA-3	315	2143	10.4	6.2	4.2	1600	7
LA-4	230	2062	25.6	22.5	3.1	980	7
LA-6	335	2200	12.8	7.1	5.7	1650	7
LA-8	271	2500	14.8	11.6	3.2	1140	7
LA-7	225	2448	21.6	19.0	2.6	850	3

Phase 2. Installation of a 15 MW_e condensing unit to be ready by the end of 1997. Seven additional production wells will have to be drilled.

Phase 3. Installation of a second 15 MW_e condensing unit after a few years operation of unit one. Nine additional wells will have to be drilled.

Apart from electricity generation, the most convenient utilization of Aluto geothermal steam is its direct use in the commercial extraction of soda ash from Lakes Abiyata and Shalla.

CORBETTI GEOTHERMAL AREA

The Corbetti Caldera appears to be one of the most promising geothermal areas within the Ethiopian rift, as indicated by the large quantity of data collected in this area since 1969.

The area is located on the rift floor about 250 km south of Addis Ababa between Lake Shalla to the north and Lake Awasa to the south. The Caldera is 12 km in diameter. Judging from its well-preserved morphology, the Caldera must be considered very recent. The Caldera collapse is likely to have been the result of a huge eruption of pantelleritic pyroclastics and ignimbrites, which are found both along the inner Caldera walls and in the area around it. A large number of fumaroles and steam vents can be found within the Caldera.

Six gradient wells were drilled to depths of 93–178 m within the Caldera (Fig. 5). Some of the wells reached the water-table and found temperatures above 90°C (Table 4). Drilling of temperature gradient wells will continue until the end of June 1987.

Table 4. Well characteristics in Corbetti geothermal area

	Wells					
	CTG-1	CTG-2	CTG-3	CTG-4	CTG-5	CTG-6
Total depth (m)	148	178	152	93	96	162
Water-level (m)	—	162.7	134.2	—	91	—
Bottom hole temperature (°C)	80.4	90.2	92.3	92.8	25.6	94.1
Depth (m)	Temperature (°C)					
5	31.8	31.1	90.6	27.7	24.2	93.8
10	36.7	40.8	90.7	32.0	24.2	93.8
20	43.0	84.1	90.8	39.5	24.1	93.8
30	50.3	93.5	90.8	50.2	24.0	93.8
40	55.9	93.7	90.9	68.0	24.0	93.9
50	60.2	93.9	91.0	77.8	24.1	93.9
60	62.7	93.9	91.0	83.7	24.2	93.9
70	64.4	93.9	91.0	85.9	24.4	93.9
80	67.3	94.0	91.1	86.1	24.6	94.0
90	69.3	94.0	91.1		24.7	94.0
100	72.3	94.0	91.1			94.0
110	74.3	94.1	91.1			94.0
120	76.4	94.1	91.2			94.0
130	77.8	94.2	91.1			94.1
140	79.0	94.2	91.2			94.1
150		94.2				94.1
160		93.5				
170		92.1				
Ambient temperature (°C)	24.5	24.5	28.2	24.5	22	25.2

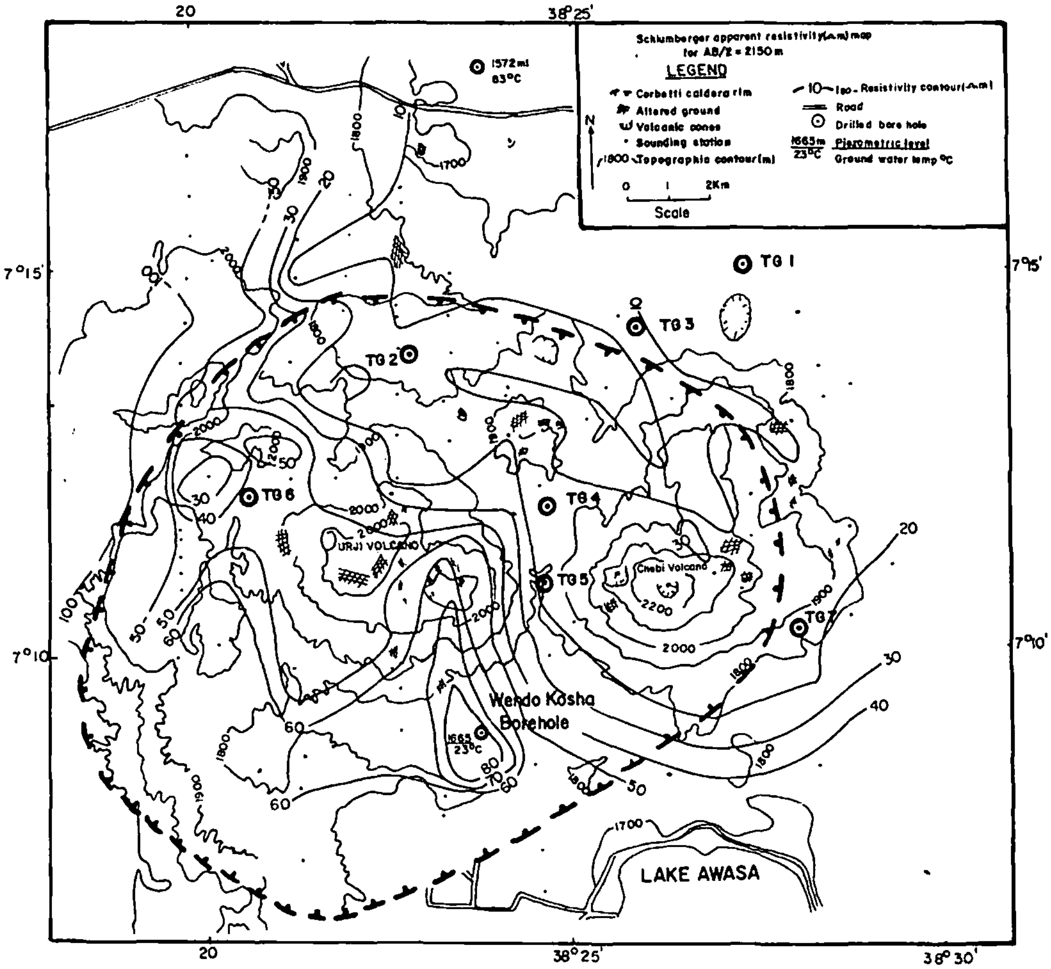

Fig. 5. Corbetti caldera.

SOUTH AFAR GEOTHERMAL AREA

There are many geothermal areas in the southern Afar between Tendaho to the north and Aluto–Langano to the south (Fig. 6).

On the basis of available information, the areas of Lake Abe, Teo, Danab, Meteka, Dofan, Fantale, Tulu-Moye and Gedemsa have been selected for reconnaissance and semi-detailed studies. Since 1985 geothermal studies have been conducted by ELC–Electroconsult of Milan under a contract from the Ethiopian Institute of Geological Surveys. The project is financed by the Ethiopian Government and the World Bank.

The exploration work was conducted in two phases. In the first phase geological, volcanological and fluid geochemical surveys were carried out. Based on these results, four priority areas, Dofan, Gedemsa, Fantale and Tulu-Moye, were selected for further geophysical and geochemical studies. The latter have already been carried out during the second stage of the project.

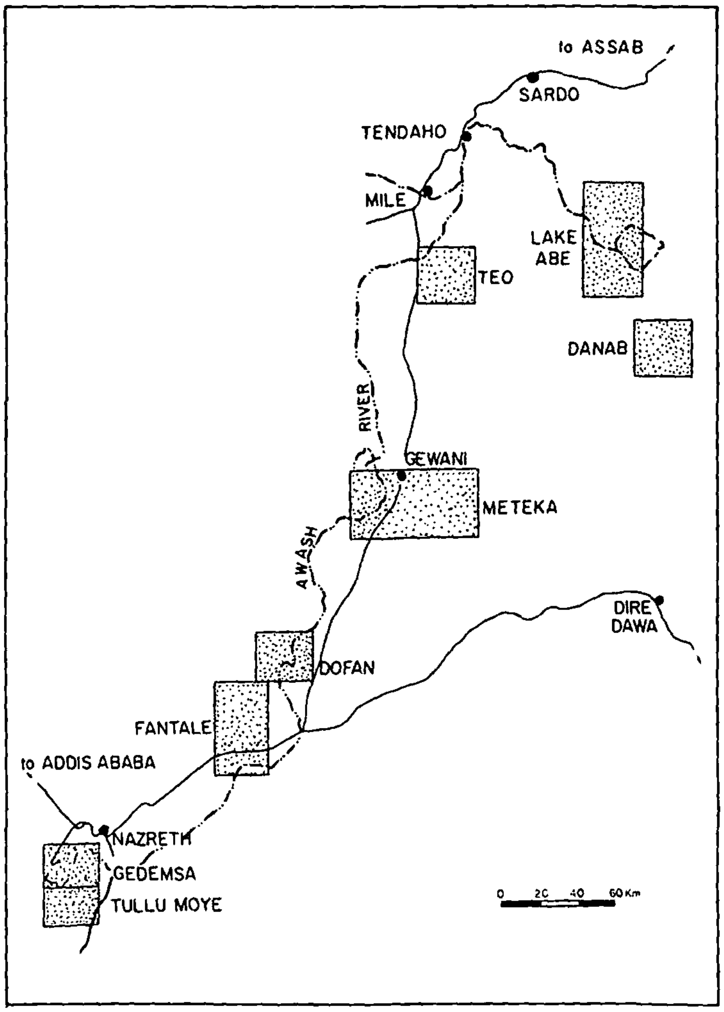

Fig. 6. Location of geothermal areas between Tendaho and Langano, in the southern Afar.

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PREFACE

The *Focus on* Series is prepared to give the U.S. Geothermal Industry a quick profile of several foreign countries. The countries depicted were chosen for both their promising geothermal resources and for their various stages of geothermal development, which can translate into opportunities for the U.S. geothermal industry. The series presents condensed statistics and information regarding each country's population, economic growth and energy balance with special emphasis on the country's geothermal resources, stage of geothermal development and most recent activities or key players in geothermal development. The series also offers an extensive list of references and key contacts, both in the U.S. and in the target country, which can be used to obtain detailed information.

The series is available for the following countries:
Argentina, Azores (Portugal), China, Costa Rica, Ecuador, El Salvador, Ethiopia, Guatemala, Honduras, Indonesia, Jordan, Mexico, St. Lucia, Thailand.

Additional countries might be available in the future.

The series is to be used in conjunction with four other publications specifically designed to assist the U.S. geothermal industry in identifying and taking advantage of geothermal activities and opportunities abroad, namely:

- The *"Review of International Geothermal Activities and Assessment of U.S. Industry Opportunities."* Final Report, August 1987. Prepared for Los Alamos National Laboratory.

- The *"Summary Report"* of the above publication.

- *"Equipment and Services for Worldwide Applications,"* U.S. Department of Energy.

- The *"Listing of U.S. Companies that Supply Goods and Services for Geothermal Explorers, Developers and Producers Internationally,"* August 1987, prepared by GRC.

Copies of these publications can be obtained from the Geothermal Technology Division of the U.S. Department of Energy. Correspondence should be addressed to:

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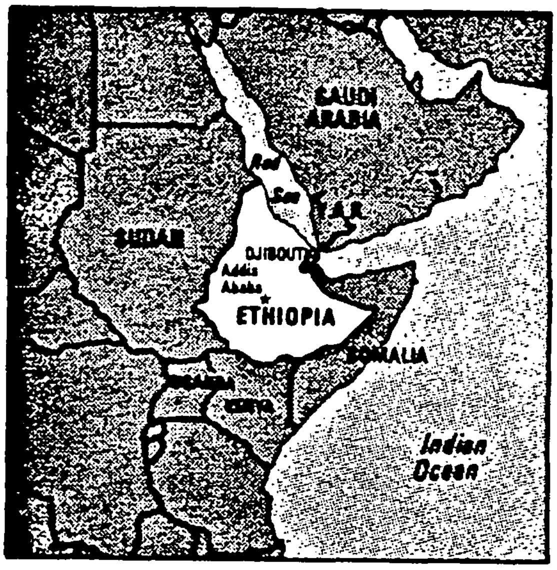
CONTENTS PAGE

FOCUS ON

ETHIOPIA



Official Name: Socialist Ethiopia

Area: 1.2 million sq. km (472,000 sq. mi.)

Capital: Addis Ababa

Population (1985): 42.3 million

Population Growth Rate: 2.9%

Languages: Amharic (official), Tigrinya, Orominga, Arabic, English

Economic Indicators:

Real GDP (1985): $4,230 million
GDP Avg. Annual Growth Rate (1980-85): 0.3%
Per Capita Income (1985): $110
Avg. Annual Inflation Rate (1985): 2.6%

Trade and Balance of Payments:

(1985) Exports: $338 million; Major Markets: U.S., FRG, Japan
(1985) Imports: $989 million; Major Suppliers: USSR, Japan, FRG, Italy

(1985) Official Exchange Rate: 2.07 Ethiopian Birr = US $1

Energy Profile: (Based on 1982 data unless otherwise indicated)

- Commercial Fuel Energy Consumption:

  Total: .781 million ton of oil equivalent (mtoe)
  1-Yr. Growth: 4.1%

- Commercial Fuel Breakdown:

  Liquid Fuels Pct: 80%
  Solid Fuel Pct: *
  Natural Gas Pct: *
  Electric Pct: 20%
  Commercial Fuel Consumption Growth Rate (1970-1980): -1.0%

* Negligible

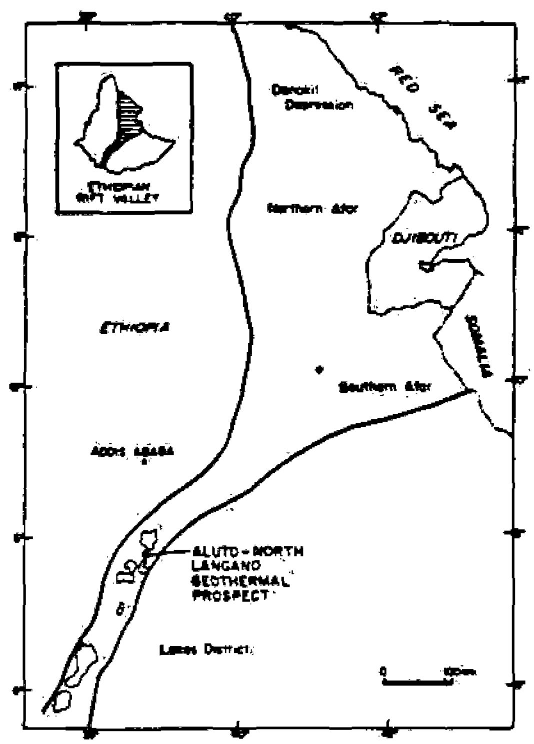
GEOTHERMAL RESOURCES

The Ethiopian Rift of the East African Rift Zone nearly bisects the country of Ethiopia from the northeast to the southwest. Regional uplifts and volcanism during the Tertiary period eventually gave way to rifting in the Pleistocene period. The Ethiopian Rift, which is widest (65 km) in the Lake District, now separates the Ethiopian Plateau from the Somalian Plateau. The Ethiopian Rift System comprises several units, the most important of which are Lake Rudolph Rift, Lake Stefanie Rift, the Main Ethiopian Rift and Afar.

In Ethiopia geothermal energy exploration and development comes under the jurisdiction of the Ministry of Mines and Energy. The Ethiopian Institute of Geological Surveys (EIGS), one of the organizations under the Ministry, is the executing agency.

Ethiopia probably has the largest geothermal potential of African countries and is one of the few lesser-developed countries to make progress in geothermal exploration. Its geothermal potential has been estimated by the World Bank to be 4,000 MWe. To date, there is not yet any utilization of the geothermal potential of the country either in electricity or direct heat except in the traditional baths and in religious health care centers.

A comprehensive assessment of the nation's geothermal resources was conducted, with UN assistance, in the early 1970's. Nine hydrothermal areas have been identified so far, including 3 in the Lake District. The Lake District, which lies approximately 200 km south of Addis Ababa is an area containing many hot springs with surface temperatures as high as 96°C and measured subsurface temperatures of 163°C. The two most likely prospects located in this area are Lake Abaya and Lake Langano-Aluto. Initial exploratory drilling was performed under the direction of GENZL (New Zealand), during the period of 1981-82.



REFERENCES

AND

KEY CONTACTS

B. Geothermal-Related Sources of Information

The following reports and documents are suggested for further information regarding geothermal energy and export opportunties overseas:

Los Alamos National Laboratory:

- Review of International Geothermal Activities and Assessment of U.S. Industry Opportunities

U.S. Department of Energy

- Equipment and Services for Worldwide Applications
- Guide to the International Development and Funding Institutions for the U.S. Renewable Energy Industry
- Federal Export Assistance Programs Applicable to the U.S. Renewable Energy Industry
- International Data Base for the U.S. Renewable Energy Industry
- Committee on Renewable Energy Commerce and Trade: CORECT's Second Year - October 1985-November 1986

California Energy Commission (CEC)

- Foreign Geothermal Energy Market Analysis
- Small Scale Electric Systems Using Geothermal Energy: A Guide to Development

U.S. Department of Commerce - International Trade Administration

- A Competitive Assessment of the U.S. Renewable Energy Equipment Industry

U.S. Export Council for Renewable Energy

- International Renewable Energy Industry Trade Policy

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POSSIBLE USES OF GEOTHERMAL FLUIDS IN KENYA

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Abstract—Small geothermal resources were studied using the chemical characteristics of the waters to determine reservoir temperatures. Those with reservoir temperatures in the range 100–160°C were recommended for small unit electricity generation, while those with lower temperatures were recommended for non-electric uses. If the resources are utilised the country could cut down on the importation of oil, coal and electricity and the use of wood as fuel. However, the principal use of geothermal energy on a large scale will be for the generation of electricity which can be easily distributed to both distant and diverse users.

PRESENT STATUS OF UTILIZATION OF GEOTHERMAL FLUIDS

Though there are many low and high enthalpy geothermal areas in Kenya, the major use of geothermal fluids is in the generation of electricity. Sixteen percent of the country's electrical energy requirement is generated from the fluids at Olkaria Geothermal Power Plant. Exploration to the north and west of the production field is under way with the aim of increasing the present power output. The country has an assessed geothermal power potential of 500–1000 MW. A non-electrical use of the fluids is practised on a very small scale (1 MW) in Eburru where steam is used in the drying of pyrethrum flowers.

GEOTHERMAL ENERGY EXPLORATION

There are many geothermal resources in Kenya, most of them in the rift zone where high subsurface temperatures exist due to the young volcanic activity. Outside the rift only a limited number of thermal centres exist. The Jombo Hill springs (79°C) in the Coast region is the most promising. Olkaria, Eburru, Menengai–Bogoria and Longonot–Suswa are the most promising thermal areas in the rift and this is where exploration and exploitation of geothermal energy have been concentrated.

Olkaria field has been under exploration for the last 30 years. It has been under exploitation since 1981 and is currently producing 45 MW. Since 1984 investigations to the north and west of the production field by the Kenya Power Company have been promising and an addition of 45 MW to the present production capacity might be realised in the near future. Eburru geothermal prospect has been under investigation since 1970 by various research organizations: UNDP, 1970–1972; JICA and Ministry of Energy, 1980–1985 and the Kenya Power Company (KPC) in 1986.

The KPC carried out some additional work after a review of the available data and eventually sited five exploratory wells for drilling to start in the first half of 1987. Menengai–Bogoria and Longonot–Suswa areas are at present under exploration under the UNDP–Geothermal Resources Exploration Project, 1984–1985 (UNDP, 1986).

Sampling of springs within and outside the rift zone for chemical water analyses has been conducted by various organizations: Tole (1986), Burgess *et al.* (1986) and Kamondo and Muiruri (1986). Some of the analytical results used in this report are from the above publications.

Table 1. Installed capacity and generation of electricity in Kenya (1980–1985)

Year	Hydro	Thermal oil	Geothermal	Total
Installed capacity (MW)				
1980	313.5	171.6	—	485.1
1981	353.5	171.6	15.0	540.1
1982	353.5	171.7	30.0	555.1
1983	353.5	160.2	30.0	543.7
1985	353.5	160.2	45.0	558.7
Generation (GWh)				
1980	1060	430	—	1490
1981	1381	334	39.0	1754
1982	1397	311	96	1804
1983	1478	164	262	1904
1984	1491	225	233	1949
1985	1680	139	236	2155

ENERGY SOURCES AND UTILIZATION

Indigenous energy resources (wood, hydro, geothermal) supply 78% of the country's energy requirements, while the remaining 22% comes from imported crude and refined oil, coal and electricity (Tables 1 and 2). Wood and charcoal meet the energy requirements of the "traditional sector" of the country and account for 72% of the total energy demand and supply in the Kenyan economy. Industries located primarily in rural areas depend upon wood as their main energy source. This industrial sub-sector uses firewood in agricultural processes such as the drying and curing of tea, tobacco and sugar or in other rural activities such as wood processing and pottery and brick-baking facilities. This is an important area in this study since it represents a significant sector, in which energy requirements could be met with small geothermal resources. The "modern sector" makes use of petroleum products, electricity and coal which account for the remaining 28% (Table 3). This area is also important in this study because it is the government's policy to reduce imported fuel and to encourage utilisation of indigenous energy sources (Table 4).

Figure 1 shows the population distribution; the energy uses and demand follow the same pattern of high population density, high energy demand and vice versa.

Table 2. Energy resources of Kenya

	Quantity (thousand OET)	Percentage (%)
Indigenous		
Wood	5488	71.8
Hydro	403	5.2
Geothermal	81	1.1
Total	5972	78.1
Imports		
Crude oil	1512	19.8
Refined oil	54	0.7
Coal	59	0.8
Electricity	51	0.6
Total		21.9
Net total	7648	100.0

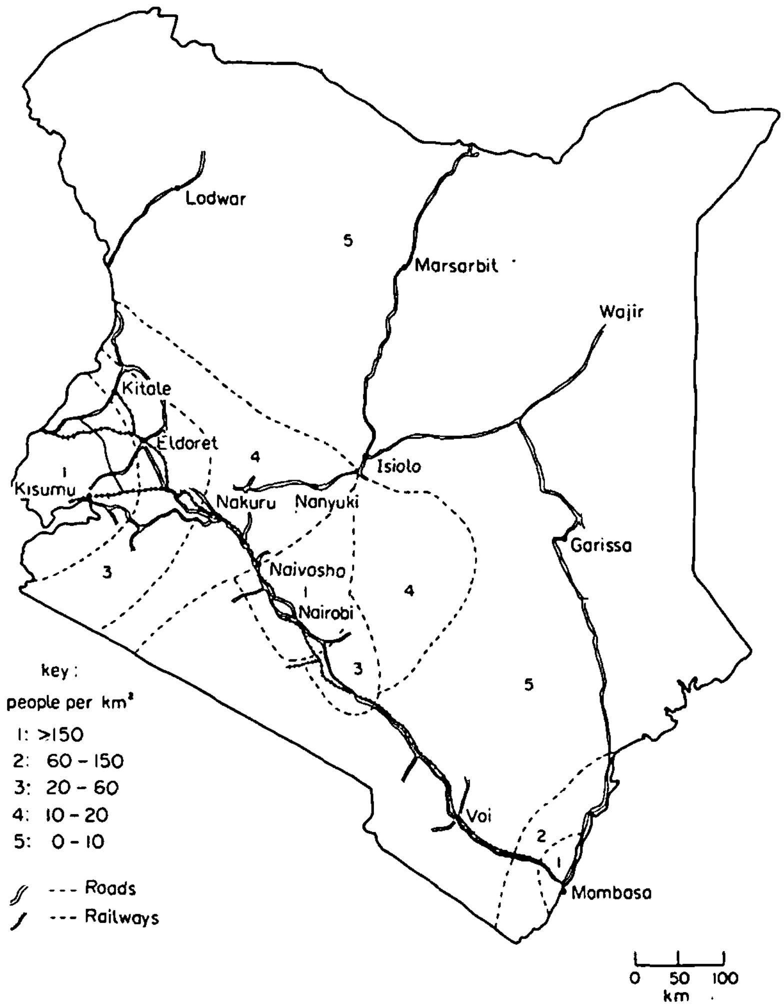

Fig. 1. Population distribution in Kenya.

Table 3. Estimated total energy consumption in 1980 and 1985 (thousand tons of oil equivalent)

	1980	1985	Percent distribution 1980	Percent distribution 1985	Growth rate (% p.a.)
Modern sector					
Petroleum	1665	1566	25.8	20.5	1.3
Coal	12	59	0.2	0.8	78.3
Electricity	433	535	6.7	7.0	4.7
Traditional sector					
Wood	2840	3455	44.1	45.2	4.3
Charcoal	1496	2033	23.2	26.5	7.2
Total	6446	7648	100.0	100.0	3.7

Table 4. Projected energy requirements (thousands of OET) to the year 2000

Source	1980	1985	1990	1995	2000
Total wood	7943	10,285	12,601	15,976	19,364
For firewood	4993	6104	7216	8661	10,115
For charcoal	2651	3775	4874	6622	8375
For industry	299	406	511	693	874
Total oil	3269	3876	4499	5975	7427
Refined oil	222	318	623	2099	3551
Imported crude	3047	3558	3876	3876	3876
Hydro	96	169	227	272	320
Geothermal	0	12	26	41	57
Electricity imports	29	21	21	21	21
Coal	33	52	72	112	153
Biomass	222	267	310	363	418
Solar	0	0	0	0	0
Total sources	11,592	14,682	17,756	22,760	27,760

LOCATION OF GEOTHERMAL RESOURCES AND THEIR CHEMICAL CHARACTERISTICS

The location of the geothermal resources and young volcanoes are shown in Fig. 2. The chemical characteristics of the thermal spring waters are given in Table 5.

Jombo Hills thermal springs

Jombo springs lie 60 km SE of Mombasa. They occur in four points spread over an area of 20 km^2 close to the Jombo Hill alkaline intrusion. The springs are sodium-chloride–bicarbonate waters. They are of near neutral pH and of moderate salinity. Silica and Na–K–Ca geothermometers indicate similar reservoir temperatures of 152 and 153°C respectively.

Homa Mountain thermal springs

The springs occur in three centres around the Homa Mountain carbonatitic intrusion. The springs with the highest discharge are to the south of the mountain while the other two centres about 10 km to the north record the highest discharge temperature of 84°C. The springs are mineralised sodium-bicarbonate–chloride waters with bicarbonate the dominant anion. The silica and Na–K–Ca geothermometers indicate a similar reservoir temperature in the range of 147–155°C (Muiruri and Kamondo, 1986).

Magadi thermal springs

The hot springs occur around the margin of Lake Magadi. They are of alkaline $NaHCO_3$ type with chloride a subordinate anion and a salinity in the range of 30,000 mg l^{-1}–45,000 mg l^{-1}. Estimates of heat discharge made by Burgess *et al.* (1986) in the vicinity of Lake Magadi are 250 MW for spring discharge above 30°C. The hottest discharge recorded was 85°C. Burgess *et al.* (1986) isotopic data suggest the Magadi spring water to be of meteoric origin from the local rainfall, streams draining the rift scarps and shallow ground water. A reservoir temperature above 170°C is indicated using the silica geothermometer.

Narosura thermal springs

The highest surface discharge temperature is 31°C. The waters are of near-neutral pH and low salinity. A reservoir temperature of 60°C is inferred using silica concentration.

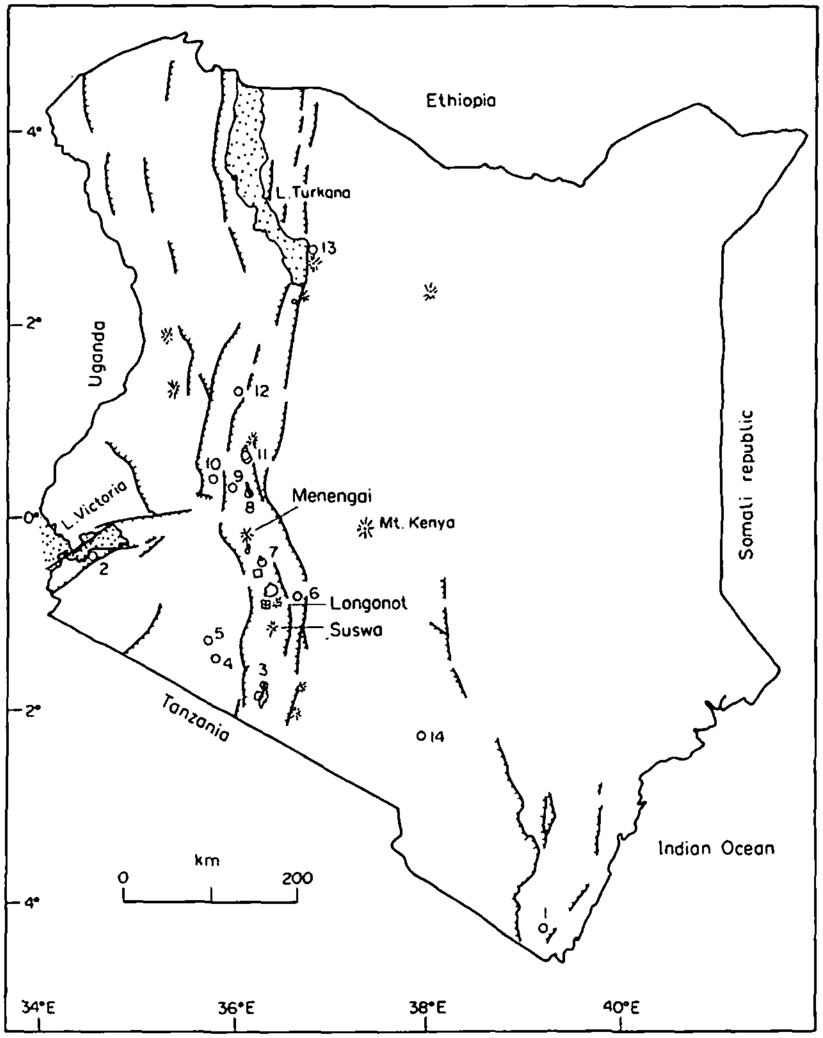

Fig. 2. Location of geothermal areas and young volcanoes in Kenya.

1 Jombo Hill thermal springs
2 Homa Mountain thermal springs
3 Magadi thermal springs
4 Narosura thermal springs
5 Maji Moto thermal springs
6 Kijabe thermal springs
7 Lake Elementaita and Kariaandusi thermal springs
8 Lake Bogaria thermal springs
9 Arus thermal springs
10 Kureswa thermal springs
11 Olkokwe thermal springs
12 Silale thermal springs
13 Loyangalani thermal springs
14 River Muooni thermal springs
□ Eburu field
⊞ Olkaria geothermal field

Kijabe and Maji ya Moto thermal springs

The rift margin springs are Kijabe on the eastern flanks of the rift and Maji ya Moto springs on the western flanks. The chemical analyses for the two areas display similar characteristics. They are dilute Na–HCO_3 waters of low salinity. Highest surface discharge temperature for Maji ya Moto is 57°C and 43.3°C for Kijabe.

The silica concentration from a borehole in Kijabe gives a reservoir temperature a little over 100°C. The Na–K–Ca geothermometer for Maji ya Moto springs gives a reservoir temperature of 101°C. The springs are interpreted as isolated occurrences of meteoric recharge reaching only moderate depths along fault channels. They are common features where regional faults separate terrains of different altitude.

Table 5. Chemical analyses of hot spring waters in Kenya

Spring number	Temp. (°C)	pH Field	pH Lab. (22°C)	Na (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Li (ppm)	Cl (ppm)
Jombo Hill									
1	79.0	6.89	7.36	1576	37.0	8.85	4.64	—	1896.00
2	66.6	6.32	7.73	1550	48.0	9.70	5.04	—	1942.00
3	65.0	6.82	7.30	1555	42.0	24.15	8.30	—	1962.00
4	59.6	7.76	7.64	1945	65.0	36.25	9.30	—	2592.00
5	52.4	7.20	7.55	1967	60.0	35.25	9.30	—	2609.00
6	49.4	6.34	7.06	1293	36.0	24.83	11.90	—	1673.00
7	28.8	6.28	6.30	45	2.0	12.93	7.45	—	21.26
Homa Mountain									
8	36.7	7.42	7.79	5550	77.0	—	2.33	—	1638.00
9	32.5	7.97	7.90	6210	71.0	3.61	1.48	—	1797.00
10	71.8	7.61	8.05	6260	105.0	1.45	0.62	—	1742.00
11	72.0	7.58	8.16	5070	133.0	1.85	0.59	—	1845.00
12	75.5	7.61	8.09	6190	84.0	0.98	0.63	—	1871.00
13	82.0	8.24	8.54	6710	97.0	1.45	0.85	—	1397.00
14	84.0	8.40	8.40	6610	80.0	0.78	1.00	—	1397.00
15	61.4	7.10	8.17	5900	75.0	1.21	0.53	—	1216.00
Lake Simbi									
	—	10.42	10.35	4.31	67.0	6.70	1.66	—	966.0
Lake Victoria									
	—	9.40	7.70	—	1.8	6.50	3.10	—	35.00
Magadi									
16	84.6	8.85	—	10,000	186.0	1.00	<0.4	1.17	5250.00
17	85.3	—	—	10,900	185.0	1.00	<0.4	1.13	5550.00
18	81.3	9.47	—	11,400	195.0	1.00	<0.4	1.18	5950.00
19	82.0	9.18	—	10,300	158.0	1.00	<0.4	0.84	5300.00
20	82.6	9.13	—	10,500	165.0	0.00	<0.4	0.91	5350.00
21	45.0	8.82	—	9640	112.0	1.00	<0.4	0.45	4900.00
22	66.6	8.96	—	11,100	157.0	1.00	<0.4	0.78	5850.00
23	38.5	9.56	—	12,000	97.0	1.00	<0.4	0.16	6550.00
24	40.5	9.65	—	12,600	109.0	1.00	<0.4	0.17	6850.00
25	45.3	9.57	—	12,300	115.0	1.00	<0.4	0.16	6450.00
Narosura									
26	31.0	7.00	7.56	16	7.2	12.00	28.00	—	0.60
27	31.0	7.00	7.64	16	7.5	12.00	28.00	—	0.40
28	22.0	5.00	7.78	15	8.3	13.00	28.00	—	0.40
Maji Moto									
29	52.0	7.00	8.15	37	15.0	20.00	12.00	—	15.00
30	52.0	7.00	7.82	39	15.0	19.00	12.00	—	14.00
31	57.0	7.00	7.88	37	14.0	19.00	11.00	—	16.00

Bogoria thermal springs

The Bogoria hot springs are on the southern side of the Lake. The highest surface discharge temperature recorded is 98°C. The spring waters are saline and alkaline of Na–HCO_3 type. The springs discharge a mixture of thermal water, groundwater and lake water. The springs discharge a total flow of 859 l s^{-1}. A reservoir temperature of 170–190°C is indicated by the chemical geothermometers.

Arus thermal springs

The spring waters are of low salinity and neutral pH. They have a Na–HCO_3–SO_4 to Na–SO_4–HCO_3 composition. The highest surface discharge temperature for the steam-heated springs is 94°C and the gas geothermometer indicates a reservoir temperature of 200–215°C.

HCO_3 (ppm)	SiO_2 (ppm)	SO_4 (ppm)	B (ppm)	NH_3 (ppm)	Si (ppm)	H_2S (ppm)	F (ppm)	TDS (ppm)
1051.00	132.40	0.16		90.00	—	0.00	0.58	3388.00
967.00	129.30	0.65	—	92.00	—	0.00	0.52	3822.00
995.00	127.40	0.70	—	90.00	—	0.00	0.49	3818.00
1121.00	98.00	0.00	—	48.00	—	0.00	0.42	4572.00
1022.00	106.70	0.00	—	94.00	—	0.00	0.48	4522.00
877.00	106.20	1.08	—	26.40	—	0.00	0.23	3132.00
—	67.80	22.22	—	—	—	—	0.00	160.00
11,059.00	98.10	1765.00	—	0.32	—	0.00	3.11	13,163.00
12,756.00	103.60	2078.00	—	—	—	0.00	3.31	15,006.00
13,152.00	90.50	1209.00	—	0.38	—	0.00	5.61	14,464.00
12,649.00	—	1170.00	—	0.32	—	0.00	5.75	15,676.00
12,743.00	117.30	2163.00	—	0.46	—	0.00	6.20	14,166.00
15,502.00	135.20	1209.00	—	1.98	—	0.00	8.10	14,162.00
15,776.00	143.90	1477.00	—	0.50	—	0.00	8.00	15,490.00
13,182.00	157.50	1333.00	—	0.34	—	0.00	7.90	—
—	—	—	—	—	—	—	2.70	
—	—	—	—	—	—	—	—	—
18,910.00	79.80	163.00	7.71	—	—	—	—	34,510.00
20,400.00	84.30	160.00	8.04	—	—	—	—	37,200.00
21,900.00	86.00	159.00	8.67	—	—	—	—	39,610.00
19,900.00	88.10	153.00	7.60	—	—	—	—	35,820.00
23,000.00	88.00	141.00	7.77	—	—	—	—	39,160.00
16,700.00	105.20	204.00	7.70	—	—	—	—	31,560.00
20,900.00	83.40	134.00	7.83	—	—	—	—	38,150.00
22,900.00	48.30	157.00	6.96	—	—	—	—	41,710.00
—	53.50	169.00	7.22	—	—	—	—	—
23,400.00	68.40	189.00	7.44	—	—	—	—	42,460.00
48.00	17.00	10.00	—	—	—	<0.1	<0.1	—
53.00	22.00	182.00	—	—	—	<0.1	<0.1	—
53.00	24.00	27.00	—	—	—	<0.1	<0.1	—
106.00	36.00	18.00	—	—	—	<0.07	<0.1	—
110.00	34.00	19.00	—	—	—	<0.07	<0.1	—
106.00	41.00	19.00	—	—	—	<0.07	<0.1	—

continued

Table 5. *Continued*

Spring number	Temp. (°C)	pH		Na (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Li (ppm)	Cl (ppm)
		Field	Lab. (22°C)						
RVA Spring									
32	—	—	—	100	7.1	1.00	0.20	—	5.00
33	43.3	—	—	83	1.4	0.00	<0.2	—	5.00
Lake Elementaita									
34	45.0	9.30	9.10	1050	35.0	0.46	<0.1	0.21	490.00
Kariandusi									
35	40.0	6.80	8.10	48	12.0	11.00	1.70	0.04	5.00
Lake Bogoria									
36	94.0	8.10	—	1265	26.0	1.26	0.37	0.56	220.00
37	96.0	8.70	—	1403	28.0	1.24	0.41	0.59	245.00
38	98.0	8.90	—	1633	34.0	0.58	0.15	0.49	323.00
39	91.0	8.50	—	1449	34.0	1.06	0.25	0.52	291.00
40	95.0	9.50	—	7360	162.0	0.80	0.02	0.38	1737.00
41	97.0	9.50	—	6900	149.0	0.46	0.01	0.45	1489.00
42	97.0	9.30	—	4600	141.0	0.44	0.01	0.38	1205.00
43	96.0	9.80	—	5980	117.0	0.30	0.02	0.45	1383.00
45	96.0	9.80	—	5980	113.0	0.34	0.02	0.36	1347.00
Arus									
46	93.0	7.00	—	10	16.0	2.20	0.68	0.01	0.57
47	94.0	6.90	—	4	9.0	0.52	0.24	0.01	1.77
Kureswa									
48	63.0	7.00	8.96	302	6.7	3.60	0.37	—	43.00
49	62.0	7.00	8.32	295	6.7	6.40	0.69	—	213.00
Olkokwe									
50	93.7	7.00	9.10	832	36.0	0.54	<0.7	0.56	260.00
Silale									
51	77.0	7.80	8.90	2180	57.0	3.00	0.20	0.98	290.00
52	81.0	7.70	9.00	2150	57.0	2.95	0.20	0.96	295.00
53	75.5	7.50	9.00	2100	53.0	2.53	0.20	0.95	295.00
54	75.0	8.00	9.00	2100	55.0	2.58	0.20	0.94	295.00
55	50.0	8.30	8.60	988	22.0	1.58	0.60	0.06	215.00
56	50.0	8.10	9.00	1000	22.0	1.55	0.50	0.05	205.00
57	27.0	8.10	9.00	1100	23.0	2.82	0.90	0.05	210.00
58	50.0	8.10	9.20	994	23.0	2.48	0.60	0.06	210.00
Loyangalani									
59	39.8	7.50	7.86	90	8.7	16.00	26.00	—	46.00
60	36.0	8.00	8.94	820	9.3	1.00	1.40	—	184.00
61	29.0	9.50	9.62	984	22.0	4.20	3.10	—	521.00
River Muooni									
62	43.0	7.00	7.77	486	21.0	253.00	51.00	—	277.00
63	42.0	7.00	7.77	486	18.0	242.00	48.00	—	269.00
64	43.0	7.00	7.77	478	19.0	245.00	49.00	—	273.00

Kureswa thermal springs

The hot springs are discharged from five adjacent areas. The highest surface temperature recorded is 63°C. The waters are near neutral with low salinity. A reservoir temperature of 126°C is deduced using the Na–K–Ca geothermometer.

Olkokwe thermal springs, Baringo

The Olkokwe hot springs are on Olkokwe island in Lake Baringo. The chemical data indicate evolved alkaline sodium-bicarbonate–chloride waters. Isotope data indicate a meteoric origin for the spring waters. The Na–K and silica geothermometer indicate a reservoir temperature of 155 and 164°C respectively.

HCO_3 (ppm)	SiO_2 (ppm)	SO_4 (ppm)	B (ppm)	NH_3 (ppm)	Si (ppm)	H_2S (ppm)	F (ppm)	TDS (ppm)
251.00	77.40	2.00	—	—	—	—	—	—
240.00	40.60	2.00	—	—	—	—		—
1450.00	—	82.00	0.92	—	58.30	—	—	—
147.00	—	8.20	0.02	—	36.50	—	—	—
2868.00	108.00	62.00	0.43	0.28	—	—	59.00	—
3051.00	114.00	62.00	0.46	0.17	—	—	65.00	—
3539.00	126.00	58.00	0.68	0.59	—	—	72.00	—
3234.00	126.00	58.00	0.62	0.45	—	—	65.00	—
15,864.00	216.00	86.00	2.70	3.74	—	—	285.00	—
15,250.00	192.00	72.00	2.30	6.63	—	—	266.00	—
9760.00	222.00	72.00	2.70	3.57	—	—	190.00	—
12,810.00	180.00	67.00	2.27	4.42	—	—	209.00	—
12,810.00	180.00	67.00	2.16	5.10	—	—	209.00	—
56.00	138.00	25.00	0.00	8.20	—	—	0.44	—
18.00	78.00	23.00	0.00	7.50	—	—	0.04	—
116.00	75.00	0.50	—	—	—	1.00	3.90	—
99.00	75.00	2.00	—	—	—	1.00	3.50	—
1960.00	—	40.00	1.04	—	87.00	—	—	—
4830.00	—	199.00	0.88	—	36.50	—	—	—
4710.00	—	197.00	0.87	—	35.70	—	—	—
4440.00	—	195.00	0.87	—	35.50	—	—	—
4840.00	—	196.00	0.87	—	35.50	—	—	—
2000.00	—	86.00	0.87	—	35.60	—	—	—
1930.00	—	79.00	0.87	—	35.20	—	—	—
2230.00	—	80.00	0.90	—	31.80	—	—	—
1940.00	—	81.00	0.89	—	36.80	—	—	—
220.00	24.00	—	—	—	—	0.26	0.03	—
1048.00	37.00	—	—	—	—	0.17	0.53	—
950.00	30.00	—	—	—	—	0.09	1.30	—
97.00	25.00	—	—	—	—	0.14	0.13	—
97.00	14.00	—	—	—	—	0.12	0.13	—
97.00	11.00	—	—	—	—	0.14	0.14	—

Lake Elementaita and Kariandusi thermal springs

The springs are to the north of Eburru geothermal prospect. The Elementaita springs are alkaline chloride–sodium-bicarbonate type. The Na–K geothermometer indicates a reservoir temperature of 150°C. The lake springs are more evolved than the Kariandusi springs in that they have higher Na–Ca, Na–K ratios and silica content. It is assumed that the lake springs are an outflow from Eburru geothermal system. The Kariandusi water, which has chemical characteristics different from the surrounding cool groundwaters, is considered a minor feature.

Silali thermal springs

Two areas of hot springs occur in Silali area. Lorusio springs are alkaline sodium-bicarbonate–

chloride waters with a discharge temperature of 75–81°C. The Na–K and silica geothermometers indicate a reservoir temperature of 115 and 124°C respectively. Kapendo springs are alkaline sodium-bicarbonate waters with a discharge temperature in the range of 27–50°C. The Na–K and silica geothermometers suggest similar temperatures to Lorusio of 115 and 120°C respectively.

Loyangalani thermal springs

These are located on the south-eastern shore of the alkaline Lake Turkana. The springs are the major water supply to the inhabitants of Loyangalani. The highest recorded surface temperature is 39.8°C with a total flow rate of 12.5 $l\,s^{-1}$ for the whole area. The spring waters are alkaline sodium-bicarbonate–chloride waters. A reservoir temperature of 71°C is estimated using silica concentration.

River Muooni thermal springs, west Tsavo

The highest surface discharge temperature is 43°C. The waters have a neutral pH and low salinity. The flow rate is high. A reservoir temperature of 72°C is inferred using the silica geothermometer.

POSSIBLE USES OF GEOTHERMAL FLUIDS

Table 6 gives the inferred reservoir temperature of the thermal areas and an indication of their possible uses.

Jombo hills thermal area

The hot springs occur over an area of about 20 km^2, which indicates the field might be extensive. A reservoir temperature of 153°C is suitable for small unit generation of electricity through medium–low temperature geothermal waters. This area is suitable for vegetable and fruit farming and is very close to the sugar plantations that feed the Associated Sugar Factory, 22 km away. The thermal energy could be used in the sugar factory for sugar refining or production of alcohol as well as canning vegetables and fruit juice production.

Homa Mountain thermal area

The thermal area occurs near Lake Victoria where there is a large fish industry. Cotton, millet and sugarcane are grown on a moderate scale. A reservoir temperature of 147–155°C is indicated. A small binary cycle unit generation of electricity is suitable for these temperatures. The energy could be used in the sugar industry. Geothermal energy in fisheries can be used in the following ways.

(a) Intensive aquaculture of high protein algae and crustacea both as human and animal feed and fish breeding.

(b) Preservation of products by ice freezing or drying and fish meal production.

Magadi hot springs

The springs occur on the shores of Lake Magadi. The springs are believed to be the source of the crystalline trona that covers the lake. The trona is dredged by the Magadi soda company and treated before being calcined in large kilns to produce soda ash. Energy requirements are fulfilled by fuel oil transported from Nairobi. The Magadi field has a reservoir temperature of 170°C. Thermal waters could be used to run a small power station for salt treatment.

Narosura, Maji Moto and Muooni thermal springs

A number of thermal centres are located in Game Reserves and National Parks. Muooni

Table 6. Inferred reservoir temperatures of the geothermal areas and possible applications

Location	Reservoir temperature inferred from chem. geoth. meters (°C)	Large unit electr. generation (>180)	Small unit electr. generation (100–180)	Pyrethrum drying and proc. (85–100)	Sisal drying (40–70)	Tourism thermal spa resorts (30–40)	Hydro-therapy treatment (40)	Lucerne drying and pelletising (120)	Sugar mill (60–70)	Alcohol production (35–150)	Fisheries and aquaculture (20–90)	Mining (>70)	Fruit juice production (80–120)	Canned vegetables (40–80)
		Required temperature (°C)												
Olkaria–Naivasha	245–250	···						···			···		···	···
Eburru–Elementaita	>200	···		···										
Menegai–Nakuru	—	···		···	···						···			
Suswa and Longonot	—	···												
Jombo Hill	153		···						···	···	···		···	···
Homa Mountain	147–155		···						···	···	···	···		
Narosura	60					···								
Maji Moto	100					···								
Kijabe	100						···							
Lake Bogoria	170–190		···			···								
Arus	200–215		···											
Kureswa	126		···											
Lake Baringo (Olkokwe)	155–164		···			···					···			
Silale (Kap./Lorusio)	115–125		···				···							
Loyangalani	70										···			
Muooni	72					···								
Magadi	>170		···								···	···		

thermal springs lie west of Tsavo National Park, Narosura in Maasai Mara game reserve and Maji Moto very close to Maasai Mara. The reservoir temperatures for these centres are low (Muooni, 72°C; Maji Moto, 100°C; Narosura, 60°C) and therefore unsuitable for electricity generation. Development of hot spring areas for recreation and tourism (spas, swimming pools, saunas etc.) would be a further tourist attraction in these areas. The hot water could be used for the climatization of hotels and lodges.

Kijabe and Kapendo thermal springs

Kijabe hospital lies close to the warm springs while Kapendo hospital in Silali area uses Kapendo thermal waters (43°C) for domestic needs. The two hospitals can use the thermal waters directly in thermal baths at 40°C for the treatment of patients suffering from rheumatic diseases.

Kureswa thermal springs

These occur in a sparsely populated area where small-scale ranching and crop-farming is practised. The Fluorspar mining company lies 20 km NW of the thermal springs. A reservoir temperature of 126°C is deduced. A small binary cycle unit could use the medium-low temperature (90–160°C) geothermal waters of this area. The power generated can then be used by the Fluorspar mining company.

Bogoria and Arus thermal springs

The reservoir temperatures for Arus (200–215°C) and Bogoria (170–190°C) are suitable for large scale electricity generation. However, small-scale electricity generation would ideally meet the local needs of this area, which is isolated from the national electricity network. Lake Bogoria is a well-known tourist resort, with geysers, boiling pools and a large family of flamingoes.

The geothermal waters could be used in the climatization of hotels. Arus thermal springs occur in an area of extensive cattle-rearing. The thermal energy could therefore be used in animal husbandry and to pasteurize milk.

Olkokwe thermal springs in Baringo

The hot springs are on Olkokwe island, a tourist resort in Lake Baringo. A reservoir temperature of 155–164°C is inferred. Thermal energy could be used in small units for local demand and to improve the fishing industry i.e. in drying facilities, fish meal production and refrigeration. The thermal waters could also be used directly to create recreational facilities (spas, saunas, etc.) for tourism.

Loyangalani thermal springs—Lake Turkana

The springs occur in an area of extensive livestock raising and fishing. The reservoir temperatures fall below electrical power production level. The thermal waters could be used directly in fish-ponds to repopulate the lake, in fish drying and in animal husbandry. A small electricity unit could probably be more effectively served by the geothermal field at the southern end of Lake Turkana in the Suguta Valley.

Eburru–Elementaita thermal area

The Eburru prefeasibility studies suggest a high geothermal potential. Deep drilling is to start in the first half of 1987 for electricity generation. Steam from shallow wells is used for the production of water by condensation and for heating in pyrethrum driers.

Menengai, Longonot and Suswa thermal areas

The three volcanoes have abundant fumerolic manifestations and are at present under exploration for large scale electricity generation. There is a vast cultivation of sisal and other small agricultural activities in Menengai. Nakuru is in Menengai geothermal zone and is the centre of the national pyrethrum processing plant. The above-mentioned activities all require process heat which could easily be supplied by geothermal resources.

Olkaria geothermal field—Naivasha area

Olkaria field has been under exploitation since 1981 and has large quantities of waste hot water. The field lies in Naivasha, a suitable area for fishing, vegetable, fruit and dairy farming. Energy from the hot waters could be used in vegetable and juice processing, the fish industry, lucerne drying and pelletising and milk pasteurization.

CONCLUSION

Though direct use of geothermal resources will help to meet the rural energy requirements and also reduce deforestation, there are many industries which cannot use this resource due to their location. Electricity has the advantage that it can be easily distributed to distant and diverse users. In general, therefore, the principal use of geothermal energy on a large scale will be in the generation of electricity.

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(12-84)

United States Government **Department of Energy**

memorandum

DATE: OCT 28 1988

REPLY TO
ATTN OF: IE-10

SUBJECT: Preliminary Report of Geothermal Definitional Trade and Investment Mission to Kenya, June 11-29, 1988

TO: Robert H. Annan
Executive Secretary
Committee on Renewable Energy Commerce
and Trade

This memorandum contains the findings and recommendations of a joint industry-government definitional trade and investment mission to Kenya in the area of geothermal energy development. A companion report containing more detailed technical observations is being drafted by the private sector members of the team for publication by the National Geothermal Association. It should be ready for dissemination to the U.S. geothermal industry by the end of December 1988.

I. BACKGROUND

A Trade and Development Program-sponsored geothermal definitional trade and investment mission visited Kenya June 11-29, 1988. Principal objectives of the mission were to: convey strong U.S. interest in participating in the development of Kenya's geothermal resources; brief Kenyan government officials, as well as potential local joint venture partners, on available U.S. geothermal technology and experience; gather detailed information on Kenyan plans to develop and additional 280MWe in geothermal generating capacity by the year 2005; and review potential U.S. Government bilateral and multilateral funding sources, as well as explore privatized financing options that may be available to assist Kenya in furthering its geothermal resources development goals.

U.S. Participants

Members of the Joint industry-government team included:

- Mr. Kendrick W. Wentzel - Director for International Energy Projects and Technical Assessments, Office of International Affairs, U.S. Department of Energy (DOE);

- Dr. Gerald T. West - Vice President for Development, Overseas Private Investment Corporation (OPIC);

- Dr. Chandler Swanberg, Vice President for Earth Sciences, Geothermal Resources International (GEO);
- Mr. Benjamin Holt, Chairman and Chief Executive Officer, The Ben Holt Company;
- Mr. Thomas H. Smith, International Sales Manager, Loffland Brothers Company; and
- Mr. Robert G. Streilein, Senior Sales Engineer, IMO Delaval Incorporated.

Meetings and Site Visits

Extremely fruitful discussions were held with senior officials of the following governmental organizations: Ministry of Energy, Ministry of Finance, and Kenya Power and Lighting Company (KPLC), as well as the Resident Representative of the World Bank and the Government's in-house geothermal consultant, GENZL of New Zealand.

The team also sought the views of Nairobi-based U.S. firms and potential local joint venture partners including: Amoco Kenya Petroleum Company, Halliburton Limited Kenya, Equator Bank, and H.Z. Construction Company. In addition, the team participated in an informal technical seminar at the existing 45MWe Olkaria Geothermal Power Plant, and conducted field visits to several potential geothermal development sites including: Olkaria Northeast, Olkaria West, Eburru, Menengai, Bogaria and Baringo.

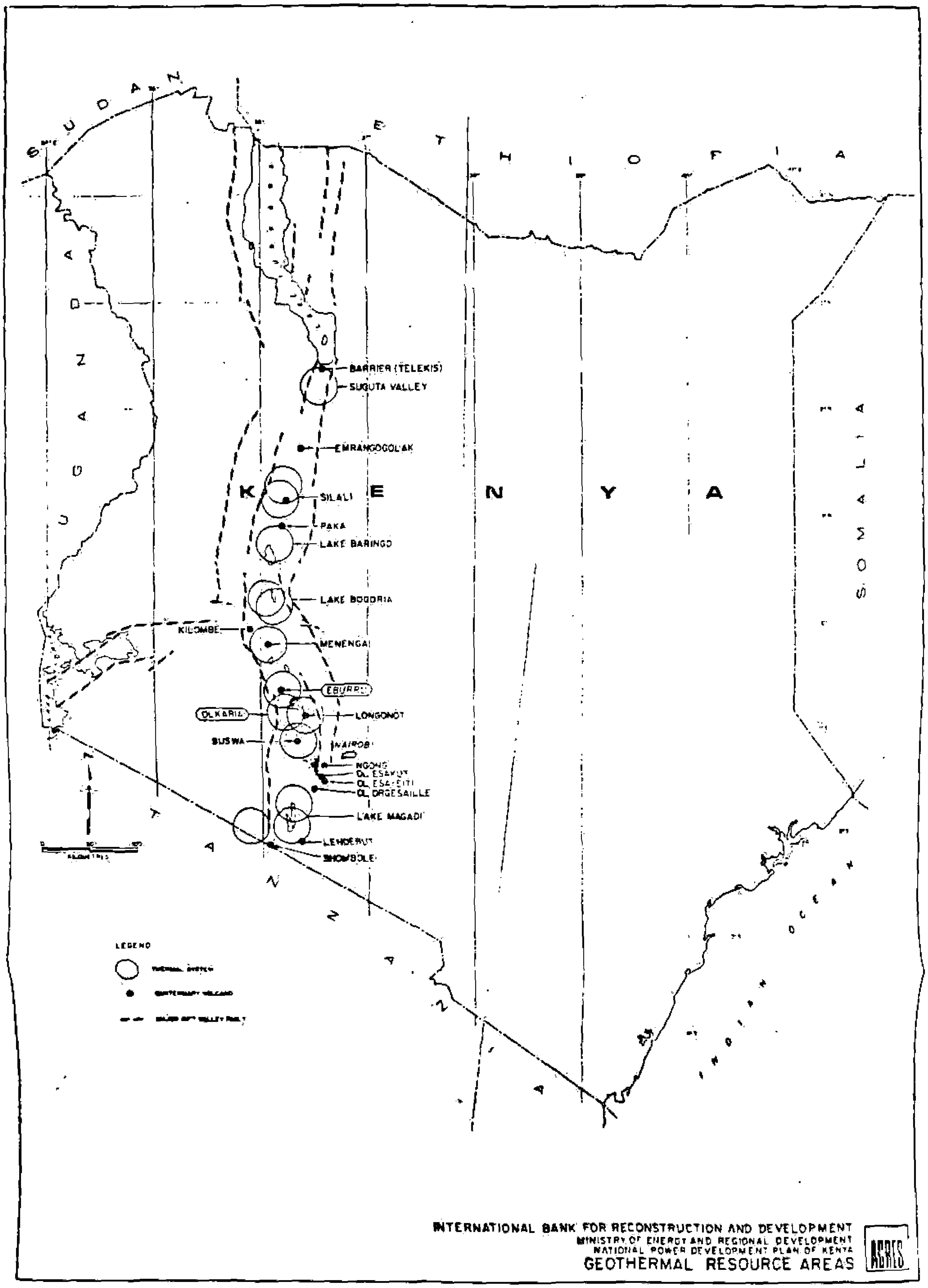
II. GEOTHERMAL RESOURCE BASE

Geothermal resources are located throughout the Rift Valley in central Kenya with substantial possible reserves measured in the thousands of megawatts electrical. The Rift Valley is a zone of crustal thinning which is characterized by near-surface magma with relatively high upper-crust temperatures. On the basis of surface thermal manifestations, 20 prospective geothermal resource areas have been identified for further exploration and prospective development. The location of these areas is illustrated in Figure 1.

Most Promising Fields

Of these potential areas, the Olkaria-Eburru region approximately 120 kilometers northwest of Nairobi is considered to hold the most promising sites for geothermal resource development. In particular, this region contains the existing 45MWe geothermal facility at Olkaria East were three units of 15MWe each were commissioned between 1981 and 1985. This site received initial priority because of successful early well tests, and its close proximity to existing transmission lines and major roadways.

Figure 1


SUDAN
ETHIOPIA
UGANDA
KENYA
SOMALIA
TANZANIA
INDIAN OCEAN
BARRIER (TELEKIS)
SUGUTA VALLEY
EMRANGOGOL'AK
SILALI
PAKA
LAKE BARINGO
LAKE BOGORIA
KILOMBE
MENENGAI
EBURRU
OLKARIA
LONGONOT
SUSWA
NAIROBI
NGONG
OL ESAYUT
OL ESAYEITI
OL ORGESAILLE
LAKE MAGADI
LENDERUT
SHOMBOLE
LEGEND
INTERNATIONAL BANK FOR RECONSTRUCTION AND DEVELOPMENT
MINISTRY OF ENERGY AND REGIONAL DEVELOPMENT
NATIONAL POWER DEVELOPMENT PLAN OF KENYA
GEOTHERMAL RESOURCE AREAS

Results of more recent exploratory drilling in the northeastern and western zones of Olkaria indicate a total proven, probable, and possible geothermal potential of over 1,200 MW electrical. Prospects at Eburru 30 kilometers to the north of Olkaria are equally promising with probable and possible geothermal reserves in the order of 1,000MW electrical.

Other Prospects

Numerous other geothermal prospects occur in the Rift Valley for which preliminary investigations have been undertaken including: Lake Baringo, Lake Bogaria, Menengai Crater, Longonot, Suswa, and Lake Magadi. While no estimates of geothermal power potential at these additional sites are currently available, it appears that these resources are considerable.

Current Status of Development

Despite the fact that Kenya Power and Lighting Company has committed almost $150 million to date toward the development of this important renewable energy technology in the Rift Valley, no U.S. firms have played a role in characterizing or developing Kenya's extensive geothermal resources potential. A United Nations Development Program - funded exploration program was begun in 1970 culminating with the drilling of six successful exploratory wells between 1973 and 1976. Subsequent site-specific assistance has included: participation by Italian and Icelandic firms in surface work at both Longonot and Suswa; preliminary field assessment work at Eburru by the Japanese; extensive surface work at Lake Bogaria by the Italians; field management and drilling assistance at Olkaria by the Canadians; and a comprehensive study of the geothermal resources development potential at the Menengai Crater by the Italians.

In addition, New Zealand firms have been quite active in Kenya. For instance, KRTA Limited has completed several detailed geothermal resource assessment studies culminating in a definitive 1985 report utilized as the key reference in updating Kenya's national power development plan, and GENZL continues to provide ongoing technical assistance for Kenya's drilling investigations at Olkaria. Interestingly, these two firms have won contract awards totalling more than $10 million without having contributed any official bilateral aid.

Finally, for the existing 45MWe of installed geothermal generating capacity at Olkaria, the team of Merz and McLellan of the United Kingdom and M/s. Virkir Consulting Groups Limited of Iceland won the engineering design award, while Mitsubisi Heavy Industries of Japan won the turbine-generator and balance of plant award.

III. RESPONSIBILITIES FOR DEVELOPING THIS RESOURCE

The overall responsibility for developing Kenya's geothermal resources fall under the purview of the Ministry of Energy. In additon, Kenya Power and Lighting Company (KPLC) and Kenya Power Company (KPC) play important operational roles.

Ministry of Energy

The Ministry of Energy was established by Government in December 1979, with official responsibilities for: energy policy and development, electric power development and coordination, oil and other fossil fuels exploration, and the development of indigenous and non-conventional energy sources (including goethermal). By Kenyan bureacratic standards, the Ministry of Energy is a relatively small organization. Within the Ministry itself, the Resource Development Division is responsible for establishing overall geothermal resource assessment policies, and exercising management oversight of Kenya's ongoing geothermal exploration activities.

Electric Power Supply Companies

On the operational side, two parastatal electric utility companies are presently involved in various aspects of developing and managing Kenya's geothermal fields. The first of these companies is Kenya Power and Lighting Company (formerly the East African Power and Lighting Company), which is presently the sole distribution company in Kenya. As such, KPLC coordinates all aspects of electricity generation in Kenya, and its technical personnel both staff and manage Kenya's major power generating companies like Kenya Power Company and the Tana River Development Company. The second operating company of importance to geothermal resources development in Kenya is the Kenya Power Company which is responsible for the development of the Olkaria geothermal filed. In addition, it appears that KPC has also established a near-monopoly position regarding geothermal drilling activity throughout Kenya today.

IV. KENYA'S PROPOSED POWER EXPANSION PROGRAM

In early 1986, work began on a comprehensive review of Kenya's existing power system, load projections, and indigenous resource base, as well as re-evaluation of Kenya's options for future power development in an effort to formulate a new, least-cost generation and transmission plan. This task was completed over a twelve-month period, and the Main Report entitled Kenya National Power Development Plan 1986-2006 published in March 1987. This report was prepared for the Government of Kenya by Acres International Limited under the auspices of the Joint UNDP/World Bank Energy Sector Management Assistance Program. Funding for this activity was provided by the Canadian International Development Agency on a grant basis.

Major New Role For Geothermal

The recommended development program in this plan represents a major shift from the historic hydro-dominated supply plans of the past. The revised program plan includes a major new emphasis on geothermal development for base-load generation, and combustion turbines for peak load supply for the foreseeable future.

Specifically, the least-cost generation expansion plan includes one new hydroelectric plant of 49MWe at Miriu to be commissioned in 1996, as well as 280MWe of new geothermal generation, 240MWe of coal-fired steam generation, and 180MWe of combustion turbines by the year 2006. Details for planned geothermal expansion are highlighted in Table 1 below:

TABLE 1
Planned Additions to Geothermal Capacity

On-Line Date	MWe	Likely Project Location
1994	30	Olkaria Northeast
1995	30	Olkaria Northeast
1998	55	Olkaria West
2001	55	Olkaria West
2003	55	Olkaria West or Eburru
2005	55	Olkaria West or Eburru
Total	280	

Program Goals Accelerated

Since publication of this revised national power plan, however, recent shortfalls in installed generating capacity have exceeded planning projections by between 20 and 30 MWe, necessitating costly and unplanned increases in electricity imports from both Uganda and Tanzania. Accordingly, KPLC officials have had to accelerate planning efforts for the 2 X 30MWe program at Olkaria Northeast so that the first unit is now expected to be on-line by 1992 and the second by 1993, rather than the previously targeted dates of 1994 and 1995 respectively.

Proposed World Bank Project

The World Bank is presently evaluating a $55.8 million Geothermal Development and Energy Pre-Investment Project for Kenya. While project areas include geothermal development, hydroelectricity development, and energy sector study activities, fully $46 million is earmarked for geothermal resources development encompassing the following components: procurement of a 3,000 meter capacity drilling rig, 24 development wells, feasibility and environmental studies, detailed engineering report for 2 X 30MWe geothermal power plants, scientific equipment, technical assistance and training. The World Bank board is expected to vote on this package early next year.

While a World Bank loan will be the primary source of funding for this pre-investment project, bilateral donor funds are also being solicited by both the World Bank and Government of Kenya for procurements covered by this package. To date, the Italians have offered the equivalent of $26 million in grant funding for the drilling program, tied to the purchase of a 5MWe geothermal plant on a take it or leave it basis. In addition, New Zealand has recently offered to provide $100,000 for the required environmental study under this project.

Feasibility Study for the 60MWe Program

With respect to the detailed feasibility study for these 2 X 30MWe plants to be sited at Olkaria Northeast, the Government of Kenya has already selected the short-list of competitors for submittal to the World Bank for certification. These firms include: Merz and Mc Lellan of the United Kingdom, Minenka of Canada, and Eubanks Priest of the United Kingdom. The team was unable to determine levels of bilateral assistance expected to be offered, if any, by the respective governments of these three firms to secure this all-important feasibility study. While the team was told that it was already too late for U.S. firms to be included on this list, Ministry of Energy and KPLC officials went out of their way to encourage U.S. firms to actively pursue the detailed engineering design study, as well as competitive procurement downstream for the turbine-generators and field collection systems for these two plants.

Additional Study Requirement

Mention was also made to the team by Government of Kenya officials regarding a very recent World Bank requirement for a prioritization or optimization study which must be completed prior to release of funds for activities covered under the Geothermal Development and Energy Pre-Investment Project. Essentially, this new study requirement entails undertaking a least-cost ranking of existing sites including some reservoir modelling; drawing up model contracts for the sale of steam and/or electricity to the grid on a long-term, take-or-pay basis; and formulation of an appropriate geothermal industry organizational structure and framework for encouraging private investments in this sector.

V. HIGHLIGHTS OF TECHNICAL OBSERVATIONS

This section summarizes the preliminary findings and comments made by the four private sector participants in this joint industry-government definitional trade and investment mission regarding the status of geothermal technology and resources development in Kenya today.

Low Well Productivity

The consensus opinion of the technical team members is that the existing Olkaria site represents an outstanding geothermal field with exceptionally high quality steam and little evidence of hydrogen sulfide emissions, and that from a short-range perspective at least, the Kenyans along with their New Zealand consultants are producing reliable, low-cost steam. However, while KPLC staff members appear to be well-trained and technically competent in maintaining geothermal power plants of a technology vintage approximately ten-years old, Kenyan field development and field management practices are clearly outmoded. They are presently averaging 2-3 MW per well whereas fields elsewhere in the world average between 5 and 10 MW per well. Indeed, the current U.S. average is around 8-9 MW per well.

Kenya's low well productivity can probably be attributed to the fact that GENZL recommended a minimal cost field development program that drilled shallow, vertical wells into the hottest portion of the field rather than directionally across vertical fractures. As a result, they have decreased the possibility of intersecting vertical fractures which typically recharge more readily than horizontal stratigraphic horizons.

Calcite and Silica Precipitation

The team also observed that a steam cap appears to be forming thereby causing precipitation of calcite and silica within the producing formation and decreasing permeability. Here again, the team feels that GENZL gave the Kenyans bad advice on field development and turbine design concepts in the early stages of project development and implementation. The approach utilized at Olkaria for the existing 45MWe facility and associated field development is to flash in the reservoir and utilize the clean steam on the surface in conventional turbines, as opposed to the U.S. practice in most California fields of drilling deeper to hit the water phase, flashing in the plant on the surface, and redesigning the turbines to handle such steam conditions.

Reservoir Decline

In addition, the team noted that non-condensible gases are being vented to the atmosphere and waste brine is being stored in surface ponds rather than reinjected into the reservoir in an attempt to replenish the field and extend its useful life. The existing Olkaria field consists of 30 wells total, of which 24 are production wells. Currently, KPLC is drilling at least 2 wells per year just to keep abreast of reservoir decline--a good portion of which in all probability can be attributed to the lack of reinjection.

Expensive Construction Design

Finally, with respect to the existing power plant at Olkaria, the team was puzzled as to why so much of the construction budget had been devoted to building a large facility for housing all three units under one roof. Traditional U.S. practice in this area is to employ open-air construction.

VI. SUMMARY OF TECHNICAL RECOMMENDATIONS

The following technical recommendations for Kenya were shared with KPLC senior technical staff during an informal technical seminar at Olkaria:

- KPLC would be well advised to concentrate future exploratory drilling programs in the ring fracture areas of the major calderas;
- Intermediate temperature fields (150-200°C) should be added to the resource base and systematically developed;
- Reinjection should be initiated to maintain reservoir pressure, as well as recharge the system;
- Direct gas injection into the reservoir should also be considered for new fields;
- A program of directional drilling should be undertaken, and KPLC should explore the possibility of purchasing a larger drilling rig under the World Bank-funded Pre-Investment Project than currently under consideration;
- Exploratory efforts should be expanded to include locating permeable zones, as well as field "hot zones";

- Open-air construction should be considered for the 2 x 30MWe geothermal power plants currently under consideration;

- Specifications for these plants should call for larger dual entry turbines for increased brine utilization;

- Cooling towers for the new plants should use fiberglass piping rather than more costly stainless steel as is currently the case at Olkaria; and finally,

- In designing the new plants, consideration should be given to distributed control systems rather than a graphic panel system, more two-phase flow lines from wells to separators, and easier access to wellhead piping.

VII. U.S. EXPORT POTENTIAL

From a trade development perspective, the team was interested in evaluating the potential for providing U.S. equipment and technical expertise in the the following areas:

- Geothermal resource assessment and field development services;

- Drilling rigs and services;

- Associated scientific calibration and monitoring systems;

- Geothermal power plants including control systems and turbine generators; and

- Architect-engineering and project management services.

Near-Term Export Opportunities

Near-term U.S. export opportunities associated with the two Olkaria Northeast units are probably limited to the following components and projected total estimated costs as indicated in Table 2 below.

TABLE 2
Near-Term U.S. Export Opportunities
(in millions of 1986 dollars)

Component	Total Estimated Cost
Drilling Rig	3-5
Drilling Services for 24 Wells	27
Scientific Calibration & Monitoring Equipment	2
2 X 30MWe Geothermal Power Plants	66-90
Field Gathering System	6
A/E & Project Management	3-4
Range of Costs	$107-$134

While almost all of the total estimated cost of $107-$134 million for the next 60MWe to be added at Olkaria will have to be imported, it is highly unlikely that any one country will win awards for all of the equipment and related technical services required for this project. Since project funding will be provided primarily through a World Bank soft credit loan, the project will be broken up into several standard competitive procurement packages rather than put out for bid on a turnkey basis. In addition, the World Bank and Government of Kenya will be encouraging bilateral assistance programs for selected project components, thereby further diminishing the probability of any one country winning almost all of the procurement awards for this project. Thus, U.S. export potential for the first 60 MWe of Kenya's planned geothermal expansion program will be in all probability something considerably less than $107-$134 million, but still worth pursuing commercially.

Imported Scope for the Entire Program

With respect to an estimate of the likely imported scope for the entire 280MWe of planned geothermal capacity to be added between now and the year 2005, Acres International Limited of Canada has made the following projections contained in Table 3 below:

TABLE 3
Potential Imported Scope for Entire 280MWe Program
(in millions of 1986 dollars)

Project Unit	Total Estimated Cost	Imported Scope
Olkaria Northeast (30MWe) First Unit	57.8	43.4
Olkaria Northeast (30MWe) Second Unit	56.8	42.6
Olkaria West (55MWe) First Unit	94.7	71.0
Olkaria West (55MWe) Second Unit	90.9	68.2
Exploratory Drilling (2 X 55MWe)	18.9	0
Eburra (2 X 55MWe)	185.6	139.2
	$504.7	$364.4

Other Potential Geothermal Projects

In addition to the considerable major project potential embodied in Kenya's planned 280MWe geothermal expansion program, the team identified at least two smaller project opportunities which may be of potential interest to the U.S. geothermal industry. These projects include: a potential 3-5MWe off-grid plant at Lake Bogoria intended to provide electricity to three resort hotels in the Baringo/Bogaria area, as well as promote rural electrification among local indigneous tribes in a politically important region of the country; and, a similarly sized off-grid plant for the Magadi Soda Company at Lake Magadi in southern Kenya to meet future electricity requirements and/or to replace existing diesel generators. In both instances, a closed-loop binary system would in all probability be the most optimal geothermal plant design given the cooler temperatures of the resource base at these two sites compared to the Olkaria and Eburra fields. Regarding U.S. export potential, the team estimates that each project would entail imported scope of approximately $10 million, not including drilling which would be provided locally either by KPLC or its operating company Kenya Power Company (KPC).

VIII. CURRENT BUSINESS CLIMATE

Kenya is the most industrialized country in East Africa. Nairobi serves as a commercial hub for most of East and Central Africa with excellent telecommunications and air connections, especially to Europe and the United States. Over 120 U.S. businesses currently have regional operations based in Nairobi. Kenya has a president as chief of state and head of government, and has never missed an interest payment on its external debt since achieving independence from the United Kingdom in 1963. During team briefings in Washington, D.C. prior to departure, officials of the Export-Import Bank of the United States indicated that their loan window with Kenya was open, that all Ex-Im Bank loans with Kenya are presently being repaid on-time, and that they would welcome more loan applications for exports to Kenya.

The Kenyan Economy

Last year, the Kenyan economy grew at a healthy rate of 4.8 percent with a gross domestic product (GDP) equal to approximately $7 billion per annum. Estimated population is 23 million, with a high current annual growth rate of 4.1 percent. Per capita income (1986) was $322. The Kenyan work force consists of 1.1 million wage earners.

Regarding various sectors of the economy, the formal industrial sector accounted for 13.7 percent of GDP in 1987, primarily from petroleum products, cement, beer, and light manufacturing. Agriculture remains the largest sector of the economy and accounted for about 30 percent of Kenya's GDP for the same period. Indeed, 75 percent of the population is employed in some fashion in the agricultural sector, despite the fact that less than 20 percent of Kenya's land area is suitable for cultivation. Major agricultural products include: corn, wheat, rice, surgarcane, coffee, tea, sisal, pineapples, pyrethrum, horticulture products, meat, hides and skins.

Kenya's known commercial energy resources are basically hydro and geothermal. A major exploration program by French and American international oil companies has yet to find any evidence of oil or gas deposits. Kenya currently faces two major energy problems. First, the cost of imported fossil fuels for both the transportation and electrical power sectors is becoming an increasingly heavy burden on the balance of payments. Second, deforestation is worsening as woodfuels are being consumed at about four times the annual rate of incremental growth and production.

Role of International Trade

Major markets for Kenyan exports are: The European Community, United States, Canada, Zambia, Iran, Japan, Australia, India, and China. Exports typically average about $1 billion annually, and are led primarily by coffee, refined petroleum products, cement, pyrethrum, and soda ash. Major suppliers include: the European Community, United States, Canada, Saudi Arabia, Japan, Australia, India, China, and the United Arab Emirates. Kenya's import bill has averaged approximately $1.8 billion in recent years, mainly from crude petroleum, machinery, vehicles, iron and steel, pharmaceuticals, and fertilizer. Tourism is the single largest generator of foreign exchange for Kenya.

U.S. exports to Kenya have risen rapidly in recent years. According to the U.S. Department of Commerce, total U.S. exports to Kenya rose 31 percent in 1987, with the manufactured component of these exports rising fully 54 percent. Finally, for the first six months of 1988, U.S. exports to Kenya were up 85 pecent when compared to the first six months of 1987.

Doing Business in Kenya

Despite what many international observers say about Kenya having the best business climate in all of East Africa and Central Africa, formidable political and financial difficulties will confront any company that goes after Kenya's planned geothermal resources development program. However, given the overall magnitude of this program, the need for Kenya to develop indigenous energy resources, and the potential commercial benefits to be derived from winning just one of the planned projects, it would appear well worth trying to overcome these difficulties.

With respect to potential difficulties, political indecision is an endemic problem. Kenya inherited a multi-layered bureacracy from the British; it continues today compounded and fueled by wide-spread political patronage. In doing business in such an environment where even minor decisions may take up to six months and where any contract must be approved by the cognizant minister, it is paramount to develop a local relationship with an individual or firm that has good political access. Indeed, it is fair to say that a politically well-connected local agent or joint venture partner is mandatory for doing business successfully in Kenya today.

Another fact of life in doing business in Kenya is that financing is a critical component in any project bid, and, at times, seems to be the only criteria for selection by the Kenyans. In meetings regarding the current status of planning for the 2 X 30MWe geothermal power plants, Ministry of Energy and KPLC officials simply stated that they would be open to any bilateral grant offers regarding this project. It was clear to the team that a U.S. firm would have to bring "competitive" financing to the table to be taken seriously. This financing package would have to encompass both offshore and local financing sources. Regarding the former, it would be advisable to include official as well as private sources of financing for the foreign exchange component, since the Kenyans feel more comfortable with official involvement. A successful project proposal should also attempt to maximize local shilling financing and content, since Kenya recently agreed to an International Monetary Fund ceiling of $75 million a year in new foreign debt with a term of twelve years or less. However, World Bank loans currently being contemplated for the 2 X 30MWe plants will not be scored against this ceiling since they will be from the International Development Authority, which is the Bank's soft loan window and whose forty year term puts it beyond the range of this accord.

Remitting Payments from Kenya

Central Bank approval is required whether for reservicing debt on capital equipment or for repatriation of profits, since all foreign exchange from local and respondent banks must be turned over to the Central Bank for accounting and allocation. This is becoming a problem in Kenya today because foreign exchange reserves are dwindling. For instance, the average que for foreign exchange for overseas payments associated with non-priority accounts is currently running appproximately eighteen months from the date of application.

IX. BEST U.S. STRATEGY FOR PARTICIPATION

The best overall strategy for successful U.S. commercial involvement in Kenya's proposed geothermal expansion program is one that recognizes the need for closer coordination between industry and government throughout all phases of the geothermal field and project development process. In this regard, the U.S. Government should be prepared to make a long-term commitment to working with both the Kenyans and interested firms of the U.S. geothermal industry at each stage of the process, including a willingness to provide as a minimum: grant funding for planning services and preliminary engineering design studies, strong official representations on behalf of U.S. firms on short lists, "competitive" finance terms for the U.S. export component of project bids, and longer-term bilateral training programs in the power sector. Similarly, the U.S. private sector should be prepared to work more closely with government than in the past, and also be more aggressive and willing to undertake innovative project financing approaches. Several important aspects that must be addressed and accomodated in such a joint industry-government context are discussed below.

Need for a U.S. Door Opener

No U.S. geothermal firm is presently on any short list of companies being considered for a major contract award in Kenya today, whether for drilling services, feasibility study analysis, field development, or project management. In particular, no U.S. firm is currently being considered for any phase of development for the World Bank - supported 2 X 30MWe goethermal power plants at Olkaria Northeast. As has been previously mentioned, no U.S. firm was considered by the Kenyans for the key feasibility study for this project. According to Ministry of Energy officials, they did not think that the United States was interested since U.S. architect-engineering or consulting firms had not even bothered to approach them about this project. Only one U.S. geothermal firm to date has talked to Kenyan officials about their planned 280MWe expansion program, but only as it relates to the possibility of privatized power development opportunities.

The sad truth is that few U.S. companies in the geothermal industry are known to Kenyans, despite the fact that we have long been recognized as a pioneer and world leader in the development of geothermal technology. The theme or story line developed by the team during the visit to Kenya was that essentially: the United States has over 2,200 MWe on-line at present; this amount of installed capacity is more than twice as great as that of the Philippines, three times that of Italy and Mexico, and seven times as great as Japan; U.S. - developed technology has been deployed for fully 49 percent of the world's installed geothermal capacity; and therefore, Kenya should get to know us better since the marketplace has clearly established the U.S. geothermal industry as a leading provider of geothermal equipment and technical expertise in the world today.

However, the need remains for U.S. geothermal firms to establish themselves in Kenya and to get a foot in the door for one of the largest geothermal export opportunities remaining in the world today. Perhaps the only way to achieve this goal in the very near-term is for the U.S. Government to look for a study or funding mechanism which allows U.S. companies access to key governmental decision-makers, as well as field development plans and data. Fortunately, such a vehicle exists in the form of the optimization study which would: rank Kenyan geothermal development sites according to priority, develop options for the Government of Kenya regarding private sector investor involvement in local geothermal development, and draft a model geothermal exploration lease and long-term supply contract between potential private power developers and KPLC for supply of steam and/or electricity.

Near-Term Marketing Activities for U.S. Firms

Just as it is important for the U.S. Government to find an immediate door-opener, it is critical that U.S. geothermal firms begin to establish a higher profile in Kenya as soon as possible. Successful access and close working relationships with Kenyan Ministry of Energy and KPLC officials will take time to develop. A good local partner can be extremely helpful in this regard. In any event, any serious efforts will require establishing a presence in Kenya.

Principal near-term marketing goals and activities for U.S. firms interested in participating in Kenya's planned geothermal resources development should include:

- Meeting with senior technical officials responsible for geothermal development to express interest in being included on bid solicitations and to present corporate credentials -- the two most important indivuduals in this regard are Mr. William Okoth, Chief Geologist for the Ministry of Energy, and Mr. E.D. Wasunna, Chief Generation Manager for Kenya Power and Lighting Company;

- Paying courtesy calls on the Honorable Nicholas K. Biwott, Minister of Energy, and Mr. S.K. Gichuru, Managing Director of KPLC;

- Working closely with American Embassy and USAID Mission staff, especially Mr. Richard Benson, Commercial Attache of the U.S. and Foreign Commercial Service, and Mr. Lawrence Hausman, Deputy AID Mission Director;

- Finding an appropriate local agent or joint venture partner such as H.Z. and Company;

- Talking to other U.S. firms and banks that already have a presence in Kenya regarding local business conditions and practices -- in this regard, John Rosshirt, Managing Director of Amoco Kenya Petroleum Company, and Mr. Bruce Bouchard of Equator Bank are extremely knowledgeable;

- Expressing interest in bidding on the geothermal site-optimization study with Ministry of Energy and KPLC officials; and finally,

- Getting acquainted with the World Bank program regarding both the Pre-Investment Project and proposed implementation phases for the 2 X 30MWe geothermal power plants, as well as World Bank procurement packaging concepts -- Mr. Jurgen Franz at the World Bank's Washington Headquarters is the Senior Financial Officer for this planned expansion program.

At the same time, thought should be given toward pursuit of a dual-track marketing approach. U.S. firms should certainly pursue procurement packages under the World Bank-supported 60MWe program at Olkaria Northeast. However, it is the team's view that a parallel marketing effort should also be mounted to develop the remaining 220MWe of proposed geothermal expansion as privatized power projects similar to the manner in which California's geothermal resources were developed. This second approach is a uniquely American way of competing against overseas competitors who buy into projects with concessional financing for portions of a proposed project (e.g. - the Italian offer of a $26 million grant for the 60MW drilling program). In any event, success for either track or path will require close collaboration and support from the U.S. Government at each stage of the process.

Emphasis on Financial Engineering Approaches

U.S. firms will probably not have access to concessional financing as practiced by our European, Canadian, and Japanese competitors. While several bilateral programs exist to provide partial support for U.S. firms in their efforts to win procurement awards for resource assessment, exploratory drilling, field development, power plant design, and construction activities associated with the World Bank-supported 60MWe geothermal resources development project at Olkaria Northeast, they will in all likelihood prove ineffective or inadequate against a competitor with access to significant grant funding for such project implementation activities. Innovative financial engineering approaches will be mandatory for U.S. geothermal firms if they hope to win major commercial project awards in Kenya. This opportunity is not a situation where all a Vice President for Marketing has to do is answer the phone and take an order. Nor is it one in which the best technology will win out in the end. Rather, finance options that do not add percipitiously to external debt will in all probability carry the day.

Accordingly, the team feels that probably the only sure way to particpate in Kenya's proposed geothermal expansion program is to focus on a joint industry-government strategy of getting the Kenyans to assign one geothermal field (such as Eburru) to the U.S. for total systems development, and then working with them at every stage of the process to develop the field and associated geothermal power plants as a build-own-operate (BOO), privatized power project. The component steps of but one hypothetical financial engineering scenario, designed to give U.S. geothermal firms a higher probability of commerical participation in Kenya's proposed expansion program than simply bidding piecemeal on World Bank procurement packages, are outlined below. See Figure 2 for an illustrative overview of the various build-own-operate contractual arrangements embodied in the highlights that follow.

- The U.S. Trade and Development Program (TDP) can be utilized to grant fund the required optimization study so that U.S. firms will know which is the next best field for development, as well as insure the existence of a standard energy sale contract;

- At the same time, the U.S. Department of Energy through the National Geothermal Association should sponsor visits to the United States for key Kenyan decision-makers in the energy, planning, and finance sectors, the focus of which would be the manner in which the State of California developed its geothermal potential in concert with regulated utilities and private investors;

- An interested U.S. geothermal field development firm (or group of geothermal firms) should form a new project company for the express purpose of developing, for example, 2 X 55MWe geothermal power plants in the Eburru field as a build-own-operate project;

- This company or group should also approach TDP for official support for an investor study for this proposed project;

- In the meantime, the American Embassy can be supportive by pointing out that such a privatized power approach can be good for Kenya since it creates competition, diversifies the power sector, and allows Kenya to proceed with its geothermal expansion program at a pace faster than it otherwise could have attempted given its limited technical, managerial, and financial resources --and all without adding to official debt;

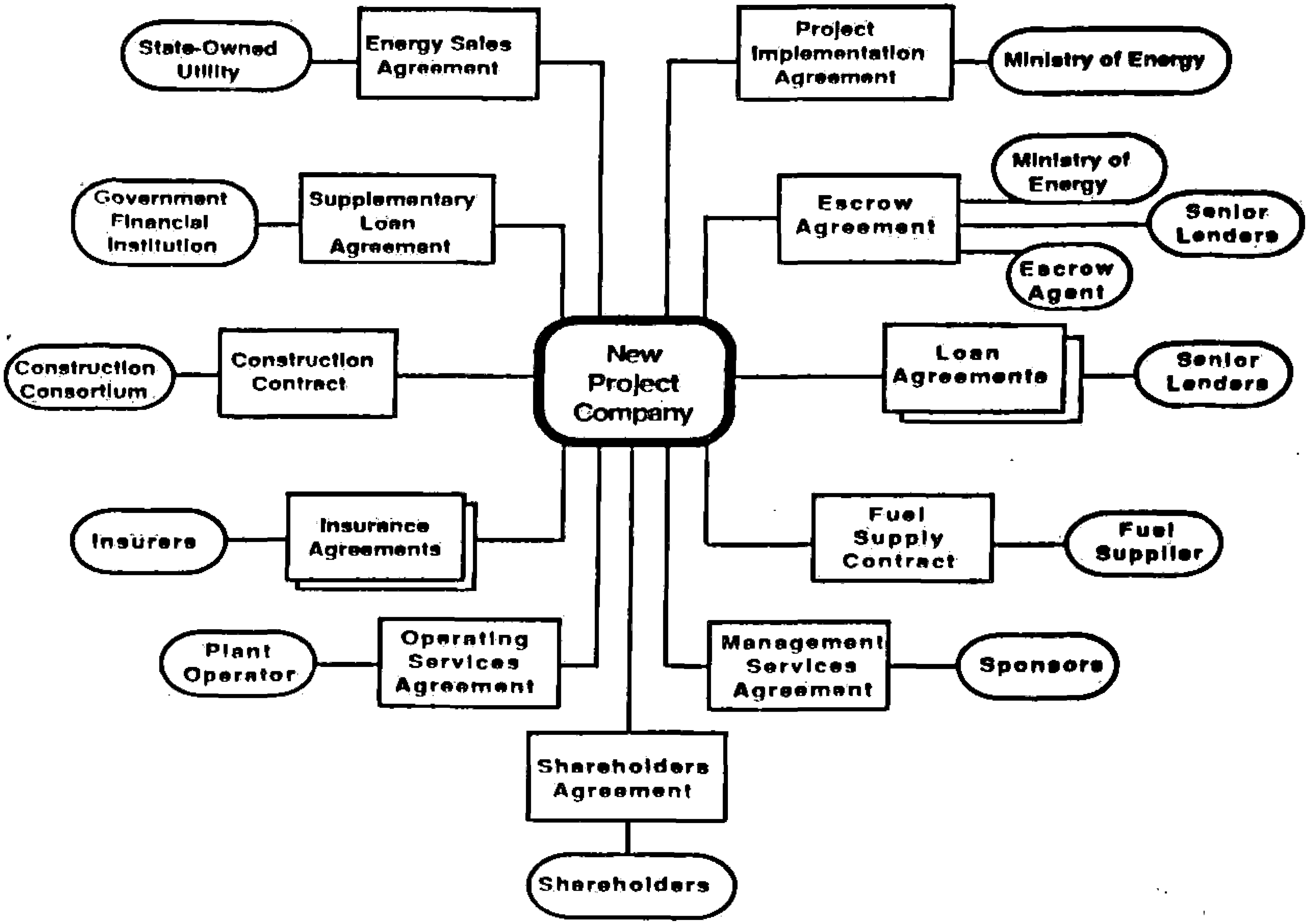
- The new project company selects a politically influential local agent or joint venture partner in Kenya;

- The new project firm seeks initial investor backing and negotiates a shareholders agreement for the proposed project;

- Next, the new project company concludes a project implementation agreement with the Ministry of Energy, including provisions for forming a local joint venture company, and also negotiates an energy sales agreement with KPLC;

Figure 2

Typical BOO Power Project Contractual Structure



- Similarly, the new project company concludes an agreement with Ministry of Finance and Central Bank officials regarding high-priority access to foreign exchange for servicing interest on capital during construction and repatriation of downstream profits;

- Secure primary loan agreements with the long-term, take-or-pay sales contract from KPLC, and negotiate a supplementary loan agreement or guarantee from a governmental financial institution (whether World Bank, Kenyan, U.S., or some combination thereof);

- Establish an escrow agreement with the Ministry of Energy and senior lenders;

- Other arrangements that must be negotiated include insurance, management, and operating services agreements, as well as drilling and construction contracts;

- In looking for local currency financing, the new project company should explore the possibility of blending in one or more of the following options; U.S. Commodity Import Program, official counterpart funds, and possible debt-equity swaps;

- To the extent that a short-fall still exists after private investor funding subscriptions, Export-Import Bank financing (with up to a 40 percent grant component) should be explored as a possible last resort;

- USAID should be approached regarding the possibility of integrating Kenyan power sector training requirements into the Kenya AID Mission's five-year master training program, especially for such skill areas as geothermal power plant operators, shift supervisors, and senior technicians; and finally,

- To the maximum extent possible, the new project company should avail itself of the full spectrum of Overseas Private Investment Corporation (OPIC) programs and services designed to encourage such U.S. investments overseas.

The approach outlined above has at least one distinct advantage over the manner in which our major competitors from Canada, New Zealand, Japan, Italy, Iceland, and the United Kingdom intend to proceed -- it is better for the Kenyans in the longer-term. Rather than perpetuating an inefficient, under-capitalized, state-run monopoly; adding significantly to external debt; and locking Kenya into drilling practices, inappropriate field management approaches, and outdated technology, this strategy proposes to develop a major portion of Kenya's geothermal resources by creating a more efficient and competitive electric power sector; transferring current state-of-the-art technology in field development and turbine design to Kenya; and bringing both competent management and private capital to the table. It might also bring on-line 2 X 55MWe geothermal power plants faster than any other approach. Time will mean money to the new project company, thereby providing a powerful incentive to keep the project on schedule. On the other hand, separate World Bank procurement packages coupled with piecemeal bilateral grants from several different donors could prove difficult to manage and integrate in a timely fashion.

X. RECOMMENDATIONS FOR U.S. AGENCIES

The following recommendations are intended to support a dual-track commercial policy approach (as outlined in the previous section) in an effort to maximize the probability of success regarding participation by U.S. firms in Kenya's planned geothermal resources expansion program. To date, the U.S. Trade and Development Program (TDP) has been the only U.S. Government agency willing to provide funding support for activities designed to evaluate project opportunities and assist U.S. industry in winning commercial awards associated with geothermal resources development in Kenya. This definitional trade and investment mission was funded in its entirely by TDP. Tangible site-specific project opportunities have been identified in Kenya in an energy resource area where the U.S. has an acknowledged technological lead. Moreover, as the U.S. dollar has realigned downward vis-a-vis the currencies of our major overseas competitors, U.S. geothermal equipment and related technical services are again becoming competitive in the international marketplace. World Bank or privatized financing options exist for project development. However, the challenge in the marketplace today, and the need for U.S. Government support of our private sector in winning major project awards overseas, has never been stronger.

U.S. Trade and Development Program

While it is now time for technical line agencies such as the U.S. Department of Energy and USAID to play a more active role in support of joint industry-government efforts regarding Kenya geothermal resources development, TDP's continued involvement and project-specific planning service support is essential if U.S. geothermal firms have any hope of winning project-related awards in Kenya. In particular, it is recommended that TDP:

- Formally offer to provide grant funding to the Ministry of Energy for the site-optimization study (the team estimates that the proposed scope of work could be accomplished by a U.S. geothermal resources development firm for about $250,000);

- Permit up to 20 percent of the above grant to be utilized in-country for services to be performed by a potential local joint venture partner;

- Consider the possibility of either grant funding as a bilateral backout for World Bank funds or perhaps an interest rate buydown approach so that a U.S. architect-engineering firm will be selected to perform the detailed engineering-design study for the 2 X 30MWe geothermal power plants to be built at Olraria Northeast;

- Authorize the utilization of U.S. consultancy trust funds at both the World Bank and African Development Bank to support Kenya's planned geothermal resources expansion program; and

- Encourage greater use of its investor study program by relaxing some of the more prohibitive administrative restrictions currently applying to program access and utilization.

U.S. Department of Energy and CORECT

DOE's geothermal technology program office has yet to play a major role in supporting efforts by U.S. geothermal firms in penetrating promising markets overseas. Kenya's planned 280 MWe expansion program represents a significant opportunity for both DOE and the U.S. geothermal industry. In addition, smaller project opportunities in the 3-5 MWe range exist at Lake Magadi and Bogoria/Baringo. It is time for DOE to consider building upon earlier TDP-funded definitional efforts by playing a more active role in assisting industry to pursue these potential projects. In this regard, it is recommended that DOE:

- Through its leadership role in the Committee for Renewable Energy Commerce and Trade (CORECT), assign one individual within the U.S. Government to serve as a single contact point for industry, and to provide overall coordination of governmental support activities with respect to Kenya geothermal resources development;

- Consider the possibility of implementing a formal geothermal technology information exchange agreement with the Ministry of Energy and KPLC; and

- Sponsor a visitors program for key Kenya decision-makers through the National Geothermal Association, including meetings with senior program officials in Washington, visits to major California geothermal installations, and discussions with State of California energy officials and utility executives regarding the success of privatized power concepts in developing U.S. geothermal resources.

U.S. Agency for International Development

USAID is in an excellent position to provide meaningful support assistance in the areas of geothermal energy applications, privatized power concepts, and training now that TDP has opened the way. For instance, USAID's Office of Energy has established an excellent reputation in recent years for successfully demonstrating U.S.-developed renewable and indigenous energy technologies throughout the developing world. With respect to geothermal technology development and applications, this office has access to superb technical staff support through its contracts with both Oakridge Associated Universities and Los Alamos National Laboratory. Similarly, this office is managing a highly innovative program on private power generation, including an overseas seminar program on build-own-transfer concepts. In addition, the USAID Mission in Kenya has expressed interest in possibly considering the inclusion of geothermal training needs into its overall, long-term training program for Kenya. Specific recommendations for USAID include the following proposed actions:

- The Office of Energy should consider assisting U.S. geothermal firms in efforts to develop the two potential off-grid geothermal sites identified by this mission, especially the small binary plant application at Lake Magadi;

- The Office of Energy should also add Kenya to its planned 1989 overseas seminar program on privatized power concepts, as well as be prepared to offer matching funds to the private sector for innovative approaches to developing Kenya's geothermal resources without adding appreciably to foreign debt; and

- The AID Mission in Kenya should be prepared to include requests for geothermal training related directly to the support of specific U.S. commercial projects in the Mission's longer-term master training plan for Kenya, as well as encourage the Ministry of Energy and KPLC to seek nearer-term technical assistance in such areas as geothermal resources assessment and field development techniques.

U.S. Department of Commerce

Commerce can play three important roles regarding the commercial development of Kenya's geothermal resources. First, by disseminating updated commercial intelligence from Kenya to interested firms in the U.S. geothermal and drilling industries; second, by having its World Bank project liaison officer begin to more closely track likely procurement actions related to the planned 60MWe program at Olkaria Northeast; and third, play a stronger facilitative role through its Commercial Attache assigned to the U.S. Embassy in Nairobi. In support of these roles, it is recommended that Commerce:

- Begin to report on this commercial opportunity through its Major Projects Tracking System, as well as include this planned expansion program on the agenda of the next formal meeting of the Major Projects Interagency Coordinating Committee;

- Obtain all World Bank documents pertaining Kenya's proposed geothermal resources expansion program for the Major Projects Reference Room;

- Continue informing interested U.S. corporations and consulting companies about Kenyan business opportunities through the Export Now breakfast meeting series; and

- Designate the Commercial Attache in Nairobi as the lead liaison officer in country for all government and industry contacts or inquiries regarding planned geothermal resources development in Kenya.

Overseas Private Investment Corporation

OPIC has been quite active in several interagency fora such as CORECT and the Coordinating Committee for the President's Initiative on sub-Saharan Africa, regarding support of project and investment activities in the region. OPIC also has a full array of political risk insurance and project finance programs that will be extremely important to any company or group of U.S. firms considering privatized financing options for developing Kenya's geothermal resources. In addition, OPIC has an extremely effective investment mission program that could be utilized to stimulate or promote investor interests in this planned program expansion. Moreover, OPIC is exploring the possibility of inaugurating a privately subscribed Energy Investment Bank Export Facility which could be utilized in part by a U.S. consortium attempting to structure a privatized power project in Kenya. Specific recommendations for OPIC include:

- Consideration of a highly focused investment mission to Kenya in 1989, possibly in conjunction with a USAID seminar on privatized power concepts; and

- Designation of a single individual within OPIC with responsibility for pulling together a cohesive package of all OPIC programs that might prove helpful to interested U.S. geothermal firms, and serving as a contact point within OPIC for encouraging U.S. investments in Kenya geothermal resources development projects.

Kendrick W. Wentzel

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MEMORANDUM

DATE: September 30, 1989

TO: Fred Eberhart

From: Dennis L. Nielson

Re: Notes from discussions in Kenya concerning Geothermal development

The following comments are from my notes of discussions with Kenyan officials and private concerns pertaining to geothermal development. As you know, I was in Kenya on a business development trip sponsored by UURI between July 9 and 14, 1989 to investigate geothermal opportunities. I was accompanied by Kendrick Wentzel of K & M Engineering.

Our strategy was to meet at the Ministerial or Permanent Secretary level in the Ministries of Finance and Energy. We eventually succeeded in making appointments with the Permanent Secretary of Finance. However, we were kept waiting a number of hours, and the meeting never did take place.

Since we were not able to meet with people at high levels, Ken Wentzel prepared a white paper on private geothermal development that was forwarded to the Ministry of Finance, Ministry of Energy, and Kenya Power & Lighting Co. through the U. S. Embassy.

Notes from some of the more important meetings are presented below.

Parkin Low
Project Director
GENZL (New Zealand)

GENZIL has a contract from KPLC to manage production well drilling at Olkaria and Eburru. This drilling is being done by a Belgian drilling company. Kenya Power & Lighting Co. has its own rigs, and they are operated with Canadian assistance (Petro Canada International Assistance Corp.)

Responsibilities for geothermal development within the Kenyan government have been shifted recently. KPLC is responsible for all development and the Ministry of Energy is responsible for regulation.

William S. Okoth
Chief Geologist
Ministry of Energy

Mr. Okoth did not show up for the first appointment. He was very apologetic about this at the second appointment.

The Ministry of Energy has prepared the Terms of Reference for the TDP project. The U. S. Embassy has a copy of this document as does Karen Venable; however, I was not able to obtain a copy. They currently have $280 K from the World Bank for a similar study and are thinking about funding one part of the project with World Bank funds and the other part with TDP funds. It is not clear whether the project will be done through KPC or the Ministry of Energy. The draft Terms of Reference is in the legal department at this time.

Privatized power development has been discussed at great length within the government. It is now their view that private companies should assist in resource development since Kenya does not have the money to perform exploration. The regulations governing private geothermal development are now being published. Generally, companies will be given exploration concessions, but the granting of these concessions will probably not involve open bidding. Copies of all exploration data must be provided to the Ministry. Following a discovery, the company could apply for an exclusive geothermal development permit.

The Embassy had requested with Okoth that I be allowed to visit the geothermal operations at Olkaria, however, Okoth informed me that I needed formal permission that would require at least two days.

Geoffrey Muchemi
Geologist
The Kenya Power and Lighting Co.
Olkaria Geothermal Project
Naivasha

Without official permission, I went to the Olkaria geothermal field and spent several hours with Muchemi. He is quite well educated having spent time at both the New Zealand and Iceland geothermal training programs.

Production declines are being experienced at Olkaria with present generation at 40 MWe, down from 45 MWe. There has been no reinjection, although they are about to experiment with injection into one well. In this regard, he was quite interested in the tracer work being done at UURI, and I have sent him several papers.

The fluid flow at Olkaria is lateral, and their main area of interest is to the north of the present production where they feel the principal upflow zone is located. The highest priority exploration site is Eburru where all of the current drilling is taking place.

UNDP and the British Geological Survey have been doing surface geological work at the Longonot and Suswa geothermal areas.

E. D. Wasunna
Chief Projects Development Manager
Kenya Power & Lighting Co.

J. M. Riungu
Projects Manager (Generation)
Kenya Power & Lighting Co.

Wasunna had attended a recent reverse trade mission to the U. S. that was run by the National Geothermal Association. Richard Bensen of the U. S. Embassy reported Wasunna was not happy with the experience, but I was not able to get this response from him. He did state that the U. S. government did not support its companies to the extent that other nations did. The California Energy Commission was present at the reverse trade mission he attended, but Wasunna mentioned that they only assist California companies. He thought it would have been beneficial to have a representative of DOE present.

Mr. Riungu will be attending a nuclear seminar in Illinois this fall. He promised to contact me so that meetings with USDOE officials and others could be arranged.

The draft rules for private geothermal development are presently being reviewed by the Attorney General. UNOCAL has been there with a strong delegation that has met with the Minister of Energy. In addition, Wasunna visited UNOCAL's Geysers operations during the reverse trade mission. UNOCAL has proposed a general geothermal survey covering areas that have not been previously identified as having geothermal potential. Following this survey they would choose an area for development and would be granted a concession. UNOCAL would generate electricity or sell steam at the option of KPLC.

The Italians have expressed an interest in doing detailed exploration Menengai, Suswa, and Longonot.

Wasunna stated that it was not clear to him that the government was in favor of private power development. (This contrasts with Okoth's statement.)

When asked about the TDP geothermal project, Wasunna responded in the same way as Okoth; that they were considering combining the TDP and World Bank money to perform the required work.

In conclusion, the reception I received from the Kenyan government was generally polite, but it is apparent that we were stonewalled. Appointments at the Ministerial and Permanent Secretary levels failed to materialize although contacts were made far in advance by the U. S. Embassy. Through the Embassy, I had offered to give technical seminars on geothermal research developments in the U. S.; however, there was no interest in this at either the Ministry of Energy or KPLC. Field excursions that were requested in advance would have required an inordinate amount of time spent in bureaucratic approvals. The reason behind these tactics is not clear.

cc: Ralph Burr (DOE)
Marshall Reed (DOE)

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To: Fred Eberhardt

Date: August 25, 1989

From: Dennis L. Nielson Den L. Nielson

Re: Notes from discussions in Kenya concerning Geothermal development

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A number of attempts were made to visit with the Permanent Secretary of the Ministry of Finance. Several appointments were made, and we were kept waiting several hours. However, the meeting never materialized.

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Project Director
GENZL (New Zealand)

GENZIL has the contract to manage production well drilling at Olkaria and Eburru. This drilling is being done by a Belgian drilling company. Kenya Power & Lighting Co. has its own rigs, and they are operated with Canadian assistance (Petro Canada International Assistance Corp.) Responsibilities for geothermal development within the Kenyan government have been shifted recently. KPLC is responsible for all development and the Ministry of Energy is responsible for regulation.

William S. Okoth
Chief Geologist
Ministry of Energy

Mr. Okoth did not show up for the first appointment. He was very apologetic about this at the second appointment.

The Ministry of Energy has prepared the Terms of Reference for the TDP project. The U. S. Embassy has a copy of this document as does Karen Venable; however, I was not able to obtain a copy. They currently have $280 K from the World Bank for a similar study and are thinking about funding one part of the project with World Bank funds and the other part with TDP funds. It is not clear whether the project will be done through KPC or the Ministry of Energy. The draft Terms of Reference is in the legal department at this time.

Privatized power development has been discussed at great length within the government. It is now their view that private companies should assist in resource development since Kenya does not have the money to perform exploration. The regulations governing private geothermal development are now being published. Generally, companies will be given exploration concessions, but the granting of these concessions will probably not involve open bidding. Copies of all exploration data must be provided to the Ministry. Following a discovery, the company could apply for an exclusive geothermal development permit.

The Embassy had requested with Okoth that I be allowed to visit Olkaria, however, Okoth informed me that I needed formal permission that would require at least two days.

Geoffrey Muchemi
Geologist
The Kenya Power and Lighting Co.
Olkaria Geothermal Project
Naivasha

Without official permission, I went to the Olkaria geothermal field and spent several hours with Muchemi. He is quite well educated having spent time at both the New Zealand and Iceland geothermal training programs.

Production declines are being experienced at Olkaria with present generation at 40 MWe, down from 45 MWe. There has been no reinjection, although they are about to experiment with injection into one well. In this regard, he was quite interested in the tracer work being done at UURI, and I have sent him several papers.

The fluid flow at Olkaria is lateral, and their main area of interest is to the north of the present production where they feel the principal upflow zone is located. The highest priority exploration site is Eburru where all of the current drilling is taking place.

UNDP and the British Geological Survey have been doing surface geological work at the Longonot and Suswa geothermal areas.

E. D. Wasunna
Chief Projects Development Manager
Kenya Power & Lighting Co.

J. M. Riungu
Projects Manager (Generation)
Kenya Power & Lighting Co.

Wasunna had attended a recent reverse trade mission to the U. S. that was run by the National Geothermal Association. Richard Bensen of the U. S. Embassy reported Wasunna was not happy with the experience, but I was not able to get this response from him. He did state that the U. S. government did not support its companies to the extent that other nations did. The California Energy Commission was present at the reverse trade mission he attended, but they only assist California companies. He thought it would have been beneficial to have a representative of DOE present.

Mr. Riungu will be attending a nuclear seminar in Illinois this fall. He promised to contact me so that meetings with USDOE officials and others could be arranged.

The draft rules for private geothermal development are presently being reviewed by the Attorney General. UNOCAL has been there with a strong delegation that has met with the Minister of Energy. In addition, Wasunna visited UNOCAL's Geysers operations during the reverse trade mission. UNOCAL has proposed a general geothermal survey covering areas that have not been previously identified as having geothermal potential. Following this survey they would choose an area for development and would be granted a concession. UNOCAL would generate electricity or sell steam at the option of KPLC.

The Italians have expressed an interest in doing detailed exploration Menengai, Suswa, and Longonot.

Wasunna stated that it was not clear to him that the government was in favor of private power development.

When asked about the TDP geothermal project, Wasunna responded in the same way as Okoth; that they were considering combining the TDP and World Bank money to perform the required work.

In conclusion, the reception I received from the Kenyan government was generally polite, but it is apparent that we were stonewalled. Appointments at the Ministerial and Permanent Secretary levels failed to materialize although contacts were made far in advance by the U. S. Embassy. Through the Embassy, I had offered to give technical seminars on geothermal research developments in the U. S.; however, there was no interest in this at either the Ministry of Energy or KPLC. Field excursions that were requested in advance would have required an inordinate amount of time spent in bureaucratic approvals. The reason behind these tactics is not clear.

cc: Ralph Burr (DOE)
Marshall Reed (DOE)

A SUMMARY OF MODELING STUDIES OF THE EAST OLKARIA GEOTHERMAL FIELD, KENYA

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ABSTRACT

A detailed three-dimensional well-by-well model of the East Olkaria geothermal field in Kenya has been developed. The model matches reasonably well the flow rate and enthalpy data from all wells, as well as the overall pressure decline in the reservoir. The model is used to predict the generating capacity of the field, well decline, enthalpy behavior, the number of make-up wells needed and the effects of injection on well performance and overall reservoir depletion.

INTRODUCTION

Geothermal exploration of the Oklaria geothermal field in Kenya started in the 1950s; by 1958 two exploration wells (X-1 and X-2) had been drilled in the area (Noble and Ojiambo, 1975). The lack of productivity of the wells and intensive development of hydropower delayed further development of the area until the early 1970s. At that time the Kenyan government received financial support from the United Nations to undertake an extensive exploration project; a feasibility study was carried out in 1976 after six additional wells had been drilled and tested. The study concluded that development at Oklaria for power production was feasible (United Nations, 1976).

During the last decade, production drilling has been carried out in the eastern part of the field (East Olkaria) and a power plant with three 15 MW_e units has been constructed. The first unit came on line in July 1981, the second one in December 1982, and the third unit started power production earlier this year (1985).

Numerical modeling studies have been used to aid in the development of the field. Bodvarsson (1980), Bodvarsson and Pruess (1981), and Bodvarsson, Pruess, Lippmann and Bjornsson (1982) have used numerical modeling techniques to investigate the effects of vertical and horizontal permeabilities on the generating capacity of the Olkaria field, and also have investigated the effects of exploiting aquifers at different depths. The results of these simulation studies indicate that the present well-field area (East Olkaria) is well capable of providing steam for 45 MW_e power production.

The primary objective of the present work is to develop a numerical model of the Olkaria field that can be used to predict with confidence the future behavior of producing wells, the effects of reinjection, and the overall depletion of the reservoir. The model is fully three-dimensional, with all existing wells represented individually (well-by-well model). This allows for history matching of flow rate and enthalpy data from all wells, as well as the average reservoir pressure decline. Using this model we predict future flow rate decline of the existing wells, the appropriate well spacing, the generating capacity of the East Olkaria field, effects of injection on field performance, and the number of development wells needed. A more detailed description of this work is given by Bodvarsson and others (1985a, 1985b).

OLKARIA GEOTHERMAL FIELD

The Olkaria geothermal field in Kenya is in the Great Rift Valley, about 100 km northwest of Nairobi (Figure 1).

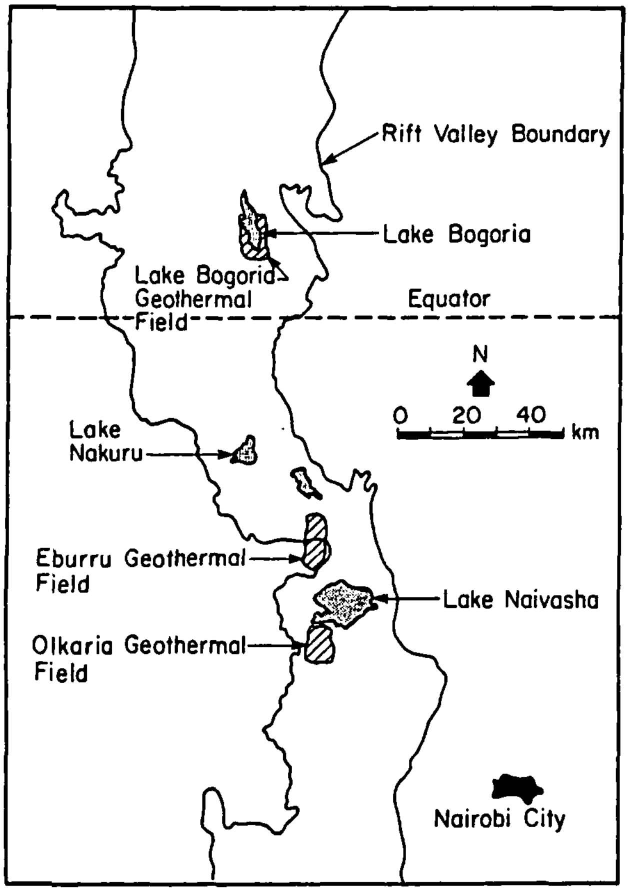

Figure 1. Location of the Olkaria geothermal field in the Rift Valley (From Svanbjornsson and others, 1983)

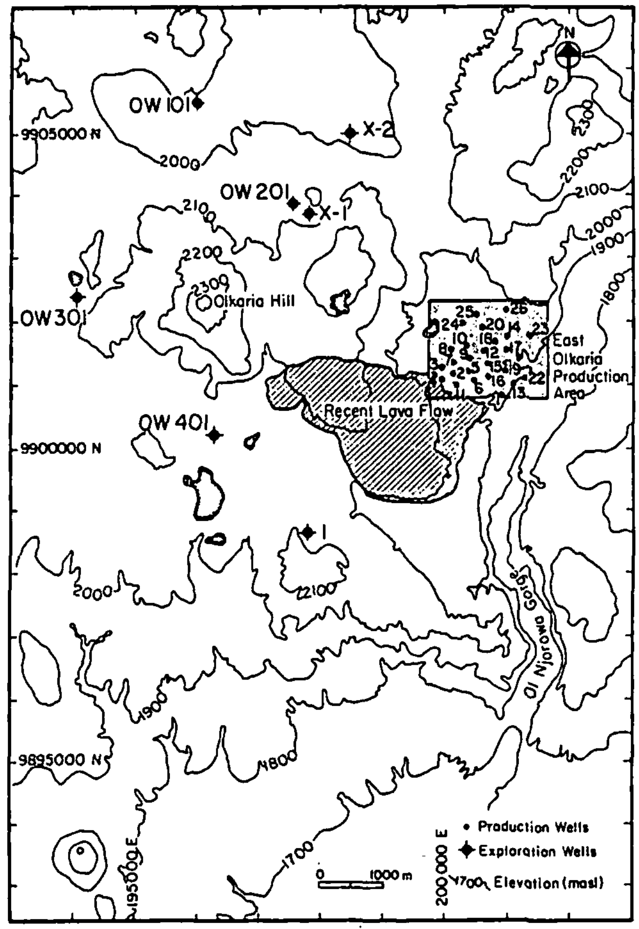

Figure 2. Well locations at Olkaria (from Kenya Power Company, 1984c)

The areal extent of the geothermal field has been estimated at about 50 km² based on shallow temperature gradients and the occurrence of fumaroles (Noble and Ojiambo, 1975). Resistivity surveys have indicated a larger anomaly, some 80 km² in areal extent (United Nations, 1976). Natural heat losses from the field amount to some 400 MW_t (Glover, 1972).

To date, 25 wells have been drilled in the present production area in the eastern part of the Olkaria field; 22 are supplying steam to the power plant (Figure 2). Figure 2 also shows the locations of exploration holes in other areas of the field. Data from the wells have identified the presence of a thin steam layer (50 to 150 m thick) overlying a thick liquid-dominated two-phase reservoir (Figure 3). The rocks encountered are volcanic, with basaltic rocks dominating at 500 to 700 m depth and acting as a caprock to the system. The reservoir rocks consist primarily of fine-grained lavas and tuffs (Kenya Power Company, 1981a, 1982a, 1983a, 1984a; Browne, 1981). Fluid flow is concentrated along contraction joints in the lavas, scoria zones, and lava contacts (Kenya Power Company, 1984b). Most of the wells have multiple feed points, often with internal flow between feed points in the steam zone and underlying liquid-dominated zone (e.g., Kenya Power Company, 1984b).

The reservoir fluids are of the sodium-chloride type with only about 200 to 700 ppm of chloride. Noncondensible gas content is small (approximately 500 millimoles per kg steam). The chloride concentration increases both with depth and from south to north. This, along with a pronounced pressure decrease (11 bar/km) from north to south strongly suggests the presence of an upflow zone north of the present well field (Figure 3). A detailed description of the conceptual model shown in Figure 3 is given elsewhere (Kenya Power Company, 1982b, 1984b).

The large areal extent of the geothermal system at Olkaria (~80 km²) and the large thickness of the reservoir (~2000 m) suggest a large power potential of the resource. The generating capacity of the resource has been estimated to be 500 to 1000 MW_e for a production period of 30 years (Kenya Power Company, 1981b). However, the rather low average reservoir permeability (1 to 10 md) may make it impractical to recover more than a fraction of the energy in-place. For reliable estimates of the energy that can be economically extracted, numerical simulation studies are required.

The work presented in this report is based upon data collected by various experts from Kenya Power Company (KPC), and their consultants. Key references include numerous reports by KPC experts, status reports prepared by Virkir, and Merz and McLellan, and overview reports by Waruingi (1982), Svanbjornsson and others (1983) and Kenya Power Company (1984c).

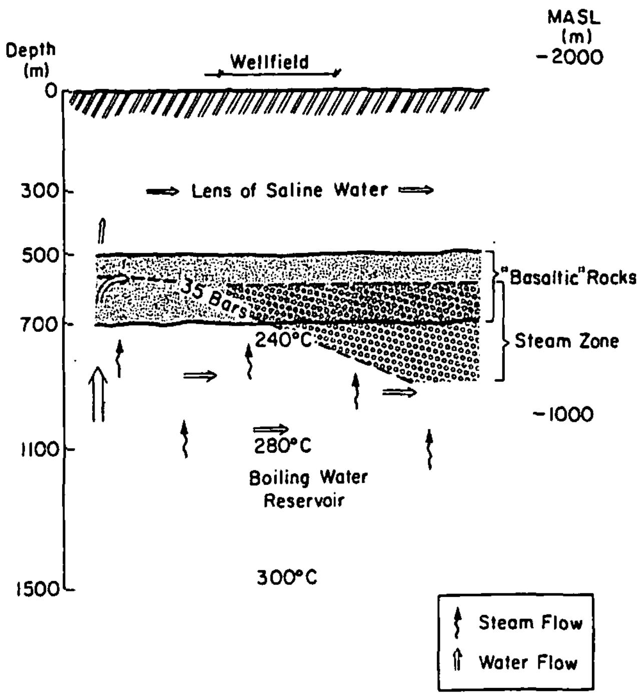

Figure 3. Schematic north-south section through the Olkaria geothermal reservoir (from Kenya Power Company, 1984b)

HISTORY MATCH OF WELL PERFORMANCE

The primary data used for the history match of the Olkaria wells are the flow rate and enthalpy data. Flow testing of some of the early wells started in 1975 on a rather small scale; more significant fluid extraction began in mid-1977. We neglect the small fluid mass extracted before July 1977. From July 1977 until the end of 1983 (the simulation period) wells 2 through 23 were tested periodically; wells 2, 5 to 7, and 10 to 12 were continuously produced after the first 15 MW_e unit came on line in 1981; and wells 13 through 19, after the second unit came on line (August 1982). In the simulations we model the actual flow history of each well. The simulations are carried out using the two-phase, three-dimensional simulator MULKOM (Pruess, 1982).

One major approximation in our simulations is the use of a porous medium model for the fractured rocks at Olkaria. A porous medium model is used because of the limited fracture data available, and the lower computational cost involved. As we will illustrate in a later section, the porous medium model matches well the observed data.

Computational Approach

Figure 4 shows an areal view of the integral finite difference grid used in the history match simulations; the grid was later extended in all directions for the prediction studies. In developing the grid shown in Figure 4, the surface locations of wells 2 through 26 were used as nodal points (represented by the dots). In order to represent the well more realistically a radial mesh was embedded into all of the well elements. The outer elements provide recharge to the well field.

In order to determine the appropriate vertical dimension of our model, we considered the locations and relative strengths of feed zones for all of the wells (Figure 5). The figure shows that most of the wells are cased to a depth of about 500 to 600 m; well 19 is cased through the steam zone (at a depth of 600 to 750 m). Most of the wells have two or three feed zones; often one of the feed zones is located in the steam zone. The presence of the steam zone makes a three-dimensional model necessary, and it was decided to use a three-layer model. The top layer (100 m thick) represents the steam zone; two layers of 250 and 500 m thickness, respectively, represent the underlying liquid zone. The bottom of the reservoir was assumed to be at a depth of 1500 m, which is the depth to the deepest major feed zone (well 19). Note that by neglecting recharge from greater depth the results should be somewhat conservative.

Flow into a well is allowed through all layers in which the well has one or more feed points. We do not prescribe the flow from each layer, but calculate it based upon the following deliverability model (Pruess and others, 1984):

$$q = \sum_{\beta = \text{liquid, vapor}} \frac{k_{r\beta}}{\mu_\beta} \cdot \rho_\beta \cdot PI \cdot (p_\beta - p_{wb})$$

where $k_{r\beta}$, μ_β ρ_β and p_β are relative permeability, viscosity, density and pressure of the β-phase, respectively. PI is the productivity index and p_{wb} is the flowing well pressure opposite the feed zone. Values of p_{wb} are obtained from pressure profiles of flowing wells; average values used for the steam zone and the upper and lower liquid zones are 8, 12 and 22 bars, respectively. The total flow rate from a well is simply the sum of the flow rates from all connected layers.

In order to obtain a reasonable match with observed flow rates and enthalpies of the wells, numerous iterations were necessary. The parameters adjusted during the

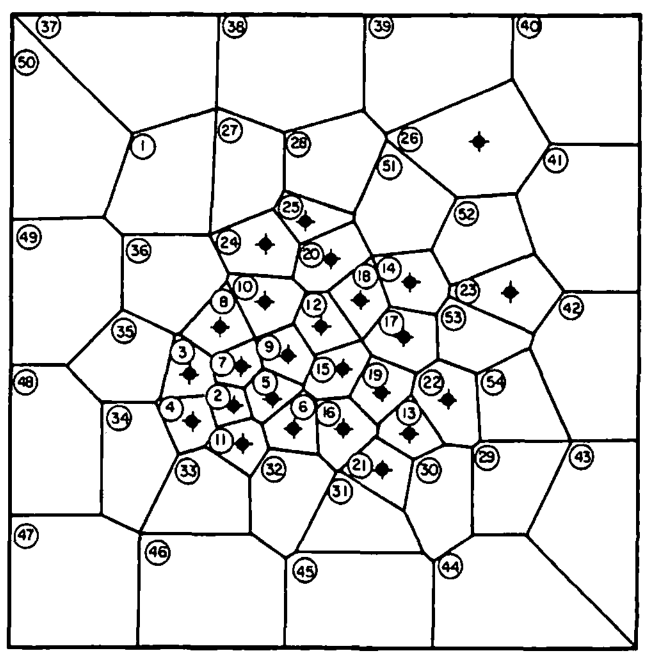

Figure 4. Mesh used for history match

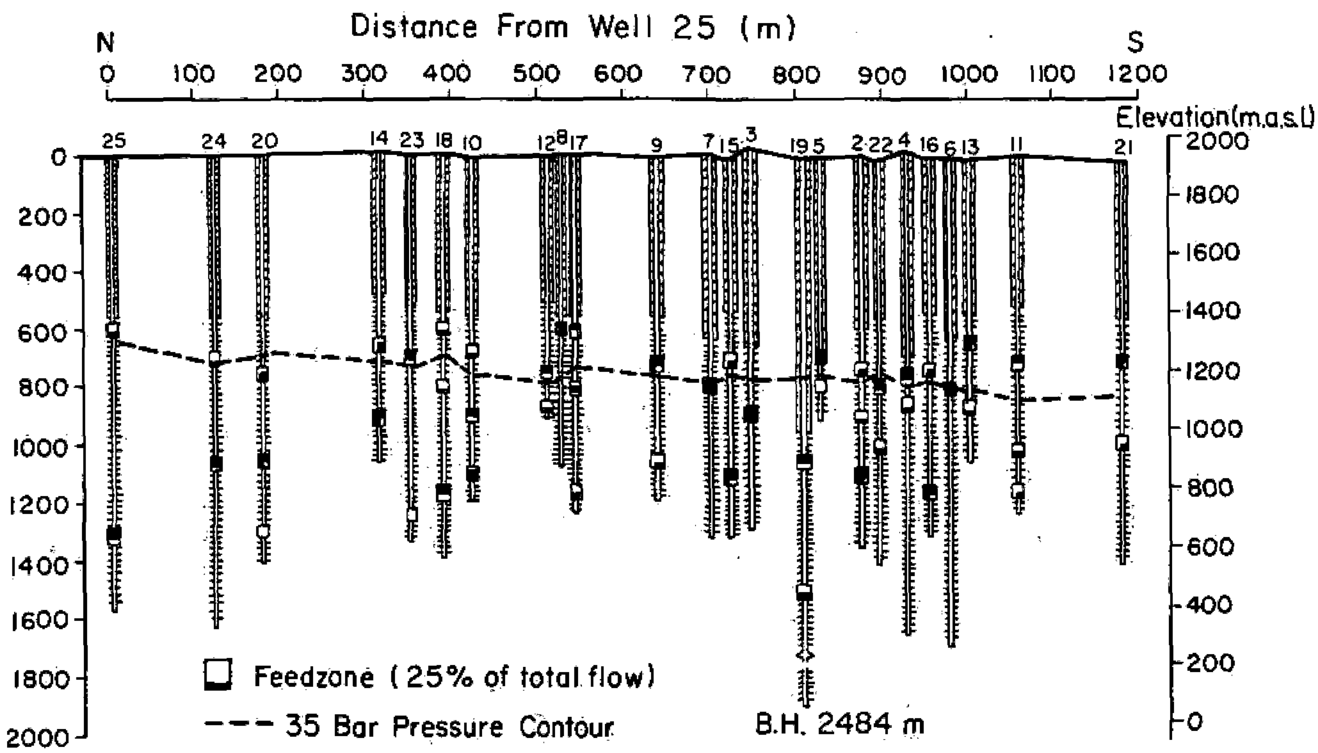

Figure 5. Major feed points in wells

iteration process were the productivity indices, permeability, and porosity. Although the effects of these parameters are coupled, each of them affects the flow rates and enthalpies in a very different way. The productivity index mostly affects the flow rate at relatively early time; consequently, we use this parameter to fix the initial rate from a layer. For the time scale of interest here (months or years), the permeability primarily controls the flow rate decline with time, and the porosity controls the enthalpy transients.

Simulation Results

After numerous iterations we obtained reasonable matches with flow-rate and enthalpy transients for all of the wells. As an example, Figure 6 shows the match obtained for well 11. The enthalpy data are in the upper half of the figure, with the flow rate data occupying the lower part; the solid lines represent the measured values. The match between the observed and calculated values is reasonable, especially if one considers the approximate nature of flow-rate and enthalpy measurements. In general, our matches for all wells are within 100 to 200 kJ/kg for the enthalpy and 1 to 2 kg/s for the flow rate (Bodvarsson and others, 1985a). The average calculated enthalpy of the produced fluids from all wells and the cumulative mass extracted also show good agreement with the measured values.

In general, the flow rate decline of the wells is mostly due to phase mobility effects; i.e., changes in vapor saturation in the producing elements. Because the density of vapor is smaller than that of liquid, an increase in vapor saturation will cause a flow rate decline, even though the element pressure may change very little. Therefore, when a well is put on line and boiling starts in its vicinity, causing increases in vapor saturations, the enthalpy generally rises and the flow rate declines. At the end of the simulation period (end of 1983), most of the wells had reached quasi-steady conditions, with a rather gradual enthalpy rise and flow rate decline. In comparison to other geothermal fields, the enthalpy rise for the Olkaria wells is large, primarily because of low reservoir porosities and permeabilities.

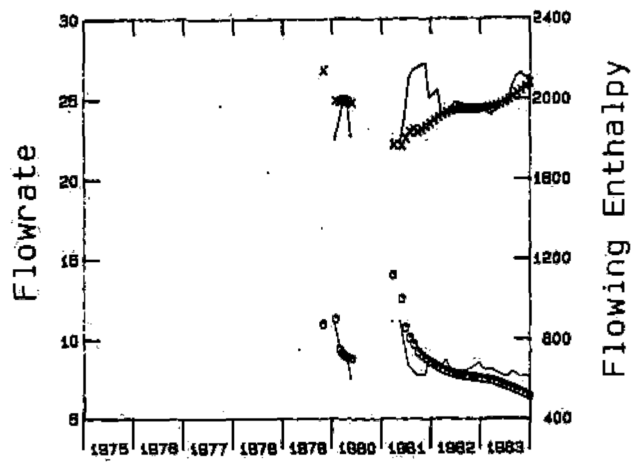

Figure 6. History match for well 11 at the Oklaria field

By calibrating the model to field data we determined the effective porosity and permeability distribution in the reservoirs. In both the upper and lower liquid zones an average porosity of 2 percent is obtained, with variations ranging from 0.25 to 6 percent. Note that due to lack of enthalpy variations in fluids coming from the steam zone, we are not able to estimate the effective porosity in that zone. It should also be noted that the porosities determined

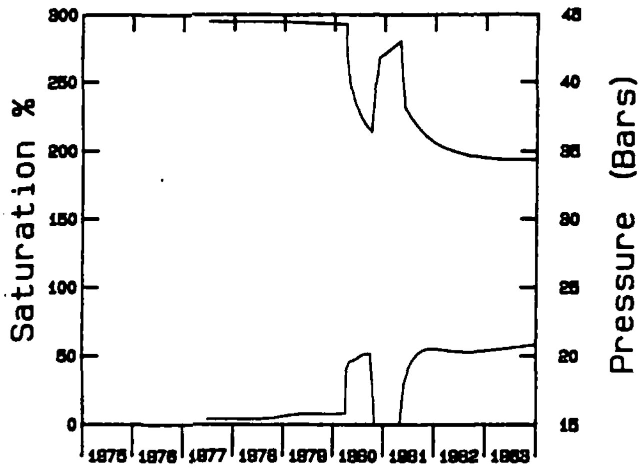

Figure 7. Pressure and vapor saturation changes with time for history match-well 12, upper liquid zone

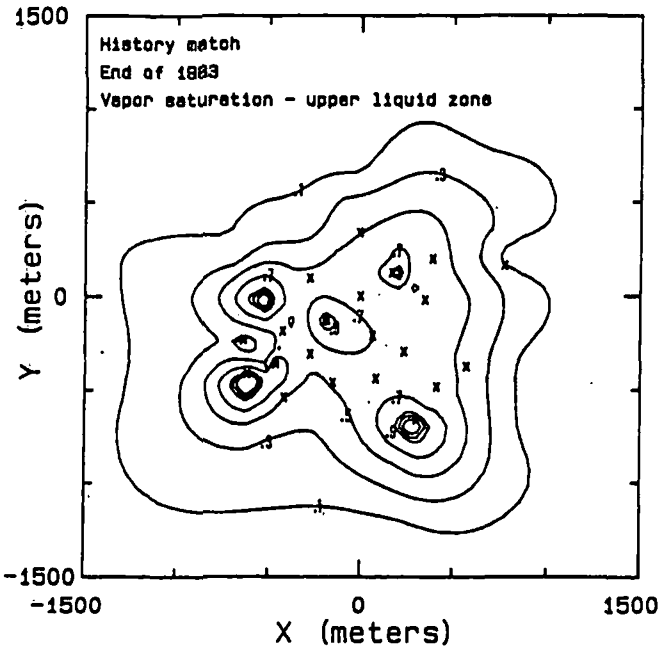

Figure 8. Vapor saturation distribution in the upper liquid zone at the end of 1983

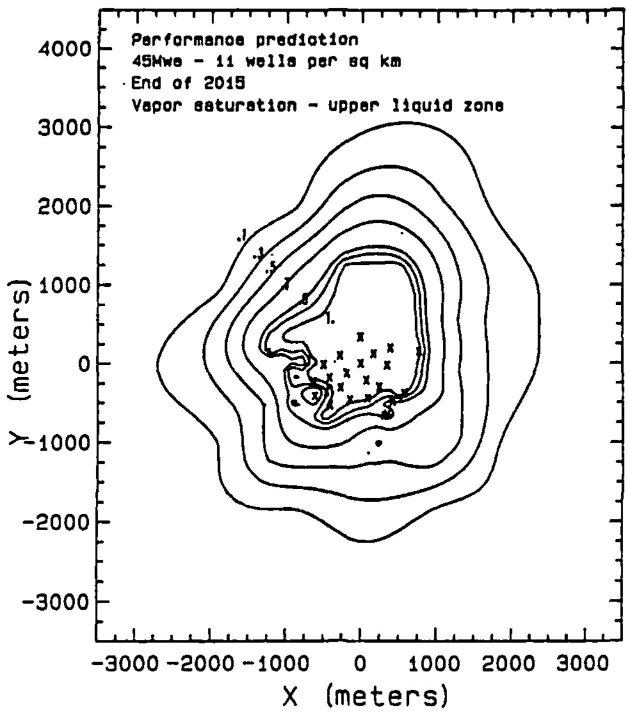

Figure 9. Vapor saturation distribution in the upper liquid zone at the end of 2015

represent the fracture porosity of Olkaria rocks rather than the matrix porosity. Average matrix porosities of Olkaria rocks vary from 8 to 16 percent depending on the rock type and depth (Mwangi and Muchemi, 1984). Our modeling results indicate that average permeabilities of the steam, upper liquid and lower liquid zones, are 7.5, 4.0 and 3.5 md, respectively. Variations in the permeability range from 0.25 to 25 md, with no apparent spatial trends, except for a distinct high permeability anomaly in the lower liquid zone, extending north-south through wells 12, 15 and 16. These permeability values are somewhat higher than those inferred from well tests of individual wells. However, the well test data are somewhat questionable as they do not correlate well with well outputs.

The percentage of flow from different layers is compared to estimates made by KPC (1984b), and for many wells the agreement is quite good. Our simulation results indicate that about 60 percent of the produced fluids come from the liquid zone, and only about 40 percent from the steam zone. The basis of this estimate is the enthalpy variations in the wells, which clearly suggest significant inflow of low enthalpy fuilds from the liquid zone at early times. Later on, the enthalpy of most wells increases rapidly due to boiling in feeds in the liquid zone. The relatively high inflow rate from the liquid zone supports deep drilling, as opposed to shallow drilling; i.e., completing the wells only in the steam zone.

From the well-by-well model, we obtained estimates for the downhole pressure and vapor saturation transients in each flowing well. Figure 7 shows these data for the upper liquid feed of well 12. The lower curve represents the vapor saturation and the upper curve the pressure transients. The well had a short flow test in 1980, but was connected to Unit 1 in 1981. The figure clearly shows the pressure drop and vapor saturation rise due to exploitation. Note the over-recovery in the vapor saturation after the initial flow test due to heat mining, which is consistent with theoretical results (Sorey, Grant and Bradford, 1980).

The actual pressure drawdown in the reservoir must be compared to calculated pressure data from nonproducing ("observation"). wells. The simulation results predict very small pressure drawdowns in the field to date (1984), or on the average, 4, 2 and 1 bars in the steam, upper liquid, and lower liquid zones, respectively. This small calculated pressure decline has been verified by field measurements (Haukwa, 1984).

Figure 8 shows the vapor saturation distribution in the upper liquid zone at the end of 1983. The figure shows that the vapor saturation changes do not extend far outside the well field area because of the high compressibility of two-phase mixtures. Over most of the well field the vapor saturation has increased from 10 to 50 percent, with local maxima around the producing wells.

PERFORMANCE PREDICTIONS

From the history match we obtained a model that can be used to predict the response of the reservoir and individual wells to various exploitation schemes. At present the main interest at Olkaria is to investigate the reservoir response to power productions of 45 and 105 MW_e, to study the effects of injection, and to determine proper well spacing for future drilling. The following scenarios were studied:

(1) 45 MW_e power production with future ("development") wells at a density of 11 wells/km².
(2) 45 MW_e power production with development wells at a density of 20 wells/km².
(3) 105 MW_e power production with development wells at a density of 11 wells/km².
(4) 45 MW_e power production with 40% reinjection and development well density of 11 wells/km².
(5) 45 MW_e power production with 100% reinjection and development well density of 11 wells/km².

For the history match, the model was calibrated against 6.5 years of data (July 1977 to December 1983). As a general rule one should not expect to be able to predict the behavior into the future with confidence for more than the calibration time, i.e., approximately to the year 1990. However, it is useful to compare predictions for different scenarios for a longer time span, and therefore we have calculated the various cases for a period of 30 years, to the year 2015.

Because of the long performance prediction period and the high production rates, the mesh used for the history match (Figure 4) had to be extended to accommodate an expanding well field. The extended mesh includes the old one as the central part, and covers an area of 8 x 12 km². The grid was extended further to the north than in the other directions because of available drilling area there; we also assumed that some of the future wells will be drilled to the west. Reservoir conditions and parameters are believed to show little lateral variation over the area covered by the extended mesh. Therefore, outside the well field we used the average permeability and porosity values obtained for the well field from the history match.

When a constant electrical power production is desired, appropriate constraints must be placed on the steam rate at the separators. Following Bodvarsson, Vander Haar, Wilt and Tsang (1982) and Bodvarsson and Pruess (1981), the steam rate from a well at the separators was calculated assuming iso-enthalpic flow up the well. When the total steam rate of the existing wells fell below that required (e.g., 125 kg/s for 45 MW_e), additional development wells outside the present well field were automatically added during the course of the simulation.

45 MW_e Power Production

Two cases are considered, 11 and 20 wells per km². The results of both cases show that the readily available drilling area in East Olkaria is sufficient for power

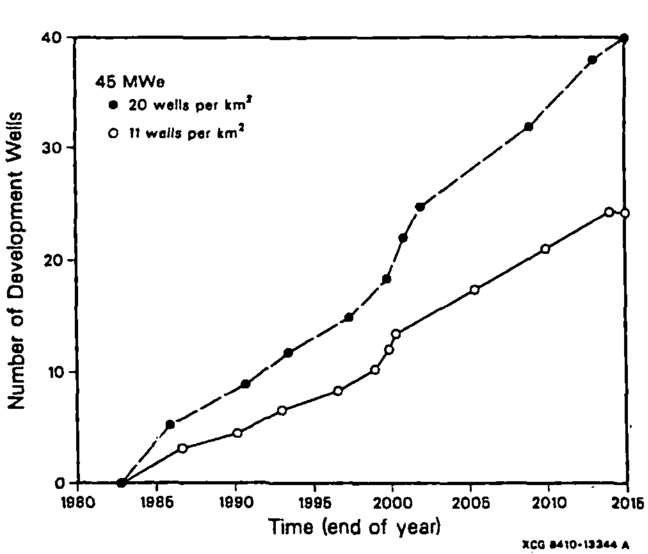

Figure 10. Number of development wells needed to maintain 45 MW_e, using different well spacing and with 100 percent injection

production of 45 MW_e for 30 years. The total new development area needed is approximately 2 km², bringing the total well field area to 4 km² by the year 2015. Within the next decade all of the existing production wells will become pure steam producers, thus continuing the present trend (average enthalpies have increased from 1900 to 2400 kJ/kg during the last 6 years). The rapid enthalpy rise is primarily due to the low effective porosities and permeabilities at Olkaria. Figure 9 shows the vapor saturation distribution inthe upper liquid zone at the end of 2015. The pure vapor zone extends farthest to the north because most of the development wells are sited north of the present well fields; note also the rather small areal extent of the disturbance (2 to 3 km radius) after 30 years of 45 MW_e power production.

The results for the two cases with well spacings of 11 and 20 wells per km² are very similar. Basically the same areal extent of the well field is required and the enthalpy behavior of the wells is similar. The similar results can be explained when one considers that the well field boils dry rather quickly and the flow from the wells is limited by the recharge from the outside. Since the permeability of the outside rocks is low, the fluid flow to the well field is the limiting factor. However, a large difference emerges when one considers the number of development wells needed to maintain 45 MW_e power production. Figure 10 shows that 24 and 40 additional wells are needed for well densities of 11 and 20 wells per km², respectively. These results strongly suggest that the present well density at Olkaria of 20 wells per km² is far too high. Although drilling wells with relatively small well spacing appears to be advantageous in the short term, in the long run, larger well spacing is predicted to provide similar steam flow with considerable economic benefits.

Other Cases Studied

Due to space limitations, it is not possible to describe the results obtained for cases involving 105 MW_e power production or cases with reinjection. For those results and more detailed information on all the simulation studies the reader is referred to Bodvarsson and others (1985a, 1985b).

CONCLUSIONS

A detailed three-dimensional model of the East Olkaria field that includes descriptions of individual wells has been developed. The model matches reasonably well the flow rate and enthalpy history of all Olkaria wells. The results of the simulation studies indicate that:

(1) Effective porosities of the liquid zone are low, on the average 2 percent. These porosities represent the average fracture porosities of Oklaria rocks. Average permeabilities are estimated to be 7.5, 4.0 and 3.5 md for the steam, upper liquid and lower liquid zones, respectively.

(2) Our results indicate that 60 percent of the produced fluid comes from the liquid zone and 40 percent from the steam zone. This supports deep drilling with substantial open intervals for flow from the liquid-dominated zone.

(3) Well densities at Olkaria (20 wells/km^2) are too high; for future wells a well density of 11 wells/km^2 is recommended.

(4) The present well field area (East Olkaria) can easily handle power production of 45 MW_e for 30 years; the well field must be extended by some 2 km^2.

ACKNOWLEDGEMENTS

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EAST AFRICAN POWER AND LIGHTING CO. LTD.

M.T. -5- E.X. Survey

in the

Olkaria Area (Kenya)

July 5, 1976 ----- August 4, 1976

INTERPRETATION REPORT

September, 1976

GENERAL ELECTRO-MAGNETIC

PROSPECTING, INC.

3060 Cleveland Avenue – Santa Rosa, California 95406 (U.S.A.) – P.O. Box 6853

Telephone (707) 525-0620 Telex: 340-935

I. INTRODUCTION

On the 4th day of May, 1976, a Service Agreement for Geothermal Exploration in the Olkaria Area (Kenya) was concluded between EAST AFRICAN POWER AND LIGHTING CO. Ltd. and GENERAL ELECTRO-MAGNETIC PROSPECTING, INC.

G.E.M.P. on behalf of EAPL conducted a geophysical measurement survey using the M.T.-5-E.X. method. The present report sets forth the corresponding analysis and interpretation of the data gathered during the field survey.

The decision of EAPL to use the M.T.-5-E.X. in Kenya was based on the success of previous applications of this method in other geothermal areas: Italy (Travale, Tuscany), the French West Indies (Guadelupe), Indonesia, and in California.

These steam producing areas showed very sharp lateral electromagnetic anomalies directly linked to the resistivity variations within steam reservoirs.

1. Definition and Goals of the Survey

The survey involved 44 M.T.-5-E.X. soundings. 31 soundings were distributed in the Olkaria geothermal area proper; 4 soundings were located 4 km to the south of the Olkaria area; 9 soundings were located 2-3 km North--Northwest from this steam producing area. Using this sounding distribution, it was expected that the steam producing zone would provide conductance anomalies similar to those discovered in previous M.T.-5-E.X. surveys. Furthermore, it was hoped to localize possible extensions of the known steam producing zone.

2. <u>Schedule of Operations</u>

G.E.M.P. personnel and equipment arrived in Nairobi on June 25, 1976. The field registrations began shortly thereafter, but the crew observed that the natural electromagnetic signals had some unusual characteristics due to the equatorial latitude. Thus, several days of experimentation were required before starting the actual survey on July 5, 1976. The last soundings were registered on August 4, 1976. The crew and equipment left Nairobi on August 5th.

3. <u>Equipment</u>

Registrations were conducted with the M.T.-5-E,X. GEMP Laboratory Number 75 003. This is a portable set of instruments supplied by batteries and shipped in two aluminum containers. In addition to this, there were three aluminum containers holding sensors, spare parts, test equipment and an inflatable tent used to shelter the instruments during the field survey.

4. <u>Data Storage</u>

The field data was stored in digital form on Phillips type magnetic cassettes. One cassette is sufficient to hold the data from three or four soundings.

5. <u>Data Processing</u>

The cassettes were processed in Santa Rosa at the G.E.M.P. computer terminal. This terminal controls the processing of the field data on a CDC Cyber 76 located in Minneapolis, Minnesota.

II. M.T.-5-E.X. GEOPHYSICAL RESULTS

1. Numerical Results

The numerical results are presented in two booklets: The first contains the listings of the processed data; the second contains the set of the apparent longitudinal resistivity curves. For a clear understanding of the concepts used in this report, the reader's attention is directed to a paper in GEOTHERMICS, Vol. 2, No. 2, June 1973:

> "A Five Component Magneto-Telluric Method in Geothermal Exploration: the M.T.-5-E.X. by Louis M. Musé. . . "

When beginning to analyze the results, the reader will be immediately conscious of the great volume of numerical data tabulated for each station included in the survey.

Description

The processed results from five-component records are tabulated in nine columns in the accompanying data sheets (Booklet No. 1).

The first column, headed "RATO," lists in decreasing order the values of the square root of τ ($\sqrt{\tau}$), with all other calculated values expressed as functions thereof.

Column "THETA" lists the absolute values of the angle θ between the principal longitudinal direction and the axis OX. The values of θ and its sign are determined independently. The average value of θ and its sign appear below the main table. θ defines the direction of the so-called "main trend." The main trend varies only slightly as a function of τ.

Generally in geothermal exploration, the geological structures are sufficiently different from the horizontally layered tabular case, so that the calculation of θ is possible. Nevertheless, by checking the columns ROATRA, ROATRARE, ROALORES and ROAVERT, it is possible to determine if the criteria of a cylindrical or a more complicated model have been satisfied.

The columns "ROALON, ROATRA, ROALORES, ROATRARE, ROAVERT, ROX and ROY" refer respectively to:

- Apparent longitudinal resistivity calculated along the main trend,
- Apparent transverse resistivity,
- Residual longitudinal resistivity,
- Residual transverse resistivity,
- Apparent vertical resistivity,
- Apparent resistivity along axis OX,
- Apparent resistivity along axis OY.

Generally speaking, there is only a small numerical dispersion of the values of ROALON, as computed from the field record. For each sounding, the value of the longitudinal conductance is computed from ROALON.

Regarding "ROATRA", it should be borne in mind that in a truly cylindrical medium the electric field tends to parallel the cylindrical axis. It follows that the electro-magnetic field in the transverse direction is weak and that the values of "ROATRA" are rather random.

"ROATRARE" and "ROALORES" values often are rather random but their only purpose is to indicate, by their order of magnitude, whether or not a case of cylindrical geometry has to be dealt with.

"ROAVERT" values may similarly be rather random, and only their order of magnitude yields information. Actually, small values are indicative of proximity to a significant geological discontinuity.

The columns "ROX" and "ROY" indicate the apparent resistivities in the directions OX and OY respectively, as derived from electric and magnetic components in these given directions.

2. Plates

We will now discuss the accompanying maps. These maps are presented on three plates as follows:

- Main trends map (No. 1)
- Longitudinal conductance map (No. 2)
- Vertical apparent isoresistivity map for the time constant τ = 64 seconds. = 0.0156 Hz

A. Main Trends Map (Plate 1)

The main trends map shows the axis of cylindrical symmetry along which the longitudinal conductance is calculated. Experience has shown that the main trend θ corresponds to the directions of the conductivity anomalies and, furthermore, reveals the tectonic features connected with the underground resistivity distribution.

As the main direction for each station varies very little as a function of the time constant τ, a general map of the main directions can be drawn which shows three kinds of main trends.

(a) NW - SE and N - S

This type of main trend appears on the soundings located in the northern part of the survey, and also on some soundings within the Olkaria steam field proper. In contrast, the area near OLK 1 does not exhibit these main trends.

(b) NE - SW
This type of main trend is found only in the Olkaria steam field.

(c) WNW - ESE
This type of main trend appears on the soundings No. 28, 34, 16, 20, 35, and 14 in the Olkaria steam field and also in the southern part of the survey near OLK 1.

We observe that (a) and (b) main trends correspond with the recent fault direction, and that (c) main trends show the old fault direction.

B. Longitudinal Conductance Map

Definition of Conductance:

The conductance function C expresses the effect of conductive media on the electromagnetic waves in a given place. More precisely, let us assume any tabular resistivity-depth distribution in a given location. As regards the "skin-effect," when the time constant τ becomes large enough, the curve of the apparent resistivity ρ_a takes the shape of a straight line with a slope of 2 (See Booklet No. 2).

The physical invariant C is then expressed as

$$C = \frac{10^3}{\sqrt{2\pi}} \sqrt{\frac{10\tau}{\rho_a}}$$

where

ρ_a is given in ohm·meters
τ is given in seconds
C is given in mhos.

The practical geophysical meaning of conductance must then be taken into consideration. The conductance is homogeneous with a ratio of the type h/ρ where h is a formation thickness in meters and ρ a resistivity value in ohm.meter. By definition, h is the depth of penetration into a formation showing resistivity ρ_a for the value of τ being considered.

Because of the fact that the time constant τ was taken large enough to let the highly resistive basement stand out, the conductance C as expressed above can be written as

$$C = f\left(\sum_{i=1}^{i=n} \frac{h_i}{\rho_i}\right)$$

n being the index of the deepest layer above the highly resistive basement. The general quantitative distribution of conductive media in a given area is indicated by differences encountered in the calculated conductance values.

By using an analogy to the tabular case it is possible to determine the conductance from the apparent resistivity curves obtained in non-tabular cases.

The longitudinal conductance map gives the maximum conductance contrast because it calculates the resistivities in the direction of the conductive zones.

The anomalies present a high variability in values found between the different soundings, sometimes even in those close together, with thin, elongated conductive zones separating the resistive zones.

We consider as resistive the areas exhibiting conductance values of less than 300 mhos. In contrast, the areas with conductance values larger than 300 mhos are classified as conductive zones. When the conductance zones become sharply higher, we use the symbol  to indicate the discontinuity on the map.

Information gathered previously from several M.T.-5-E.X. surveys on different geothermal areas enables us to say that a resistive zone indicates rocks where the presence of reservoirs containing hot fluids is practically excluded. On the other hand, the high conductance zones can be explained by a localized fault system which contains hot water of different degrees of salinity.

C. Vertical Apparent Isoresistivity Map (Plate 3)

This map defines the zones where the chosen vertical apparent resistivity (τ = 64 sec) is less than 500 ohm.m. These zones are, therefore, characterized by a greater relative influence of H_z (vertical component of the magnetic field) and this indicates the presence nearby of some tectonic discontinuity.

This map also shows the same trends as the two preceding ones, and suggests the hypothesis that these thin conductive zones are affected by particular fracture systems.

III. Discussion of the Geophysical Results and Practical Conclusions

1. The OLKARIA Geothermal Zone Proper

- As mentioned in paragraph I, 1. this zone was surveyed with 31 M.T.-5-E.X. soundings. Unfortunately, it was impossible for practical reasons to put any M.T.-5-E.X. sounding exactly on the spots where the OLKARIA 2, 3, 4, 5, 6 wells are located, except for sounding No. 34 which shows the OX (N - S) direction as resistive, and the OY (W - E) direction as very conductive. As the OY direction reaches the steam producing well OLK 5, this result seems in agreement with those gathered previously from different geothermal areas.

- Nevertheless, we are able to delineate a possible extension of the producing steam area: this interesting zone is indicated by crosshatching on the vertical resistivity map within the five hundred mhos contour line (Plate No. 3) and includes the soundings No. 35, 15 and 19.

  This is supported by the following information:

  A) The high longitudinal conductance values

  B) The low vertical isoresistivity values

  C) The crossing of different main trends corresponding to both the recent and the old fault directions,

- Sounding No. 37, although isolated, indicates an interesting possibility for the same reasons.
- The fault system outlined by soundings No. 32, 31, 38 and 27 seems interesting, but needs to be more precisely defined by further soundings.

2. The Southern Part of the Survey

On soundings No. 1, 3, 4 and 5, the very low conductance values and the very high vertical resistivity values indicate that this zone is not as promising for the location of a possible steam reservoir. Nevertheless, this conclusion needs to be supported by a more detailed survey.

3. The Northern Part of the Survey

This zone indicates interesting possibilities for the presence of steam on soundings No. 13, 41 and 6. This evaluation also needs more details.

* * *

Before closing this report, the reader must be warned to keep in mind that possible drilling locations in the zones selected as promising should be placed exactly on the favorable sounding locations rather than somewhere within the area delineated by the contour interval on the map. This advice is suggested because the extremely discontinuous nature of the geothermal reservoir at this scale of detail, prevents us from being sure of the absolute location of the contour intervals obtained by interpolating between conductances values distributed on the area.

Louis M. Musé

KENYA PROJECT COORDINATES OF THE M.T.-5-E.X.

SOUNDINGS ESTIMATED FROM THE TOPOGRAPHIC MAP

Sounding	Long. E	Lat. N	Sounding	Long. E	Lat. N
1	197710	9898770	23	199710	9902160
2	199610	9901720	24	199500	9901340
3	197000	9899150	25	200150	9001300
4	196550	9899875	26	199945	9901045
5	196475	9899410	27	199525	9902020
6	199400	9903660	28	200335	9900820
7	199250	9904425	29	201015	9901125
8	198710	9904950	30	200530	9900985
9	198825	9905060	31	199870	9901720
10	198375	9905525	32	199840	9901380
11	198450	9904790	33	200070	9901485
12	198150	9905030	34	200390	9901180
13	198525	9905200	35	200355	9901560
14	200500	9901695	36	200305	9901670
15	200545	9901515	37	200245	9901785
16	200560	9901405	38	199910	9902230
17	200765	9901260	39	200215	9902085
18	199740	9902825	40	200075	9902285
19	200430	9901385	41	199000	9905300
20	200680	9901390	42	200280	9901385
21	200020	9902595	43	200160	9901680
22	199775	9902645	44	200015	9901985

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GEOTHERMAL RESOURCES OF ZAMBIA

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Abstract—The hot springs of Zambia are associated with zones of major deep seated fault and fracture systems along which water of mainly meteoric origin circulates to great depths and is heated by normal geothermal gradients. The chemistry of the hot spring waters at the surface represents the effect of a predominantly hot water rock interaction process and a mixing with little juvenile water. Geochemistry also provides evidence in some waters of a mixing between deep, hot waters and shallow, cooler waters. Interpretations of geochemical data and estimates of underground temperatures for some springs indicate the existence of exploitable low enthalpy geothermal resources in most parts of the country.

INTRODUCTION

Hot springs have been known to exist in Zambia for a long time. The earliest description of hot springs in Zambia is that by Wallace in 1889, who visited and described the springs on the southern edges of lakes Mweru Wantipa and Chishi and observed the production of salt by villagers (Legg, 1974). Other early references are contained in a letter to Bechuanaland Exploration Company urging the latter to preserve hot springs for future interests. Ferguson (1902) made chemical analyses of springs in the Zambezi Valley and attempted to relate them to mineral occurrences. Guernsey (1941) compiled data on hot springs from different sources and listed 31 geothermal occurrences in the Luangwa concession area. Since 1950 some springs have been examined by the Geological Survey of Zambia in the course of routine regional mapping exercises and others by the Department of Water Affairs and the mining companies. These data were summarized between 1963 and 1969. Little else was done to utilise the hot spring waters for industry. In a country with abundant sunshine, forests and hydropower, many uses of hot water, especially in crop growing and drying, may not be economically viable as would be the case in the colder regions of the world. Oil was then cheap too.

The global economic recession, which began with high oil prices in the 70s, has greatly affected many development programmes in Zambia including the ambitious rural electrification programme which was launched soon after independence in 1964. Depressed copper prices meant less government revenue, prompting reorientation of research and development programmes. In the field of power development, research into financially competitive sources of energy, particularly suited for the lower income rural communities, lying far from the major sources of electricity, has received tremendous impetus.

Legg (1974) presents detailed geochemical data on the major hot springs and speculates on their potential as a source of geothermal energy. He also presents the first concise genetic model of the hot springs.

Two hot springs, Kaimbwe and Kaputa, were studied in 1976. Shallow exploration holes of up to 80 m depth were drilled to intercept feeder zones of high salinity from which brines could be tapped and processed for salt. Although unsuccessful in its primary objective the project has provided a solid inventory for present and future geothermal activities.

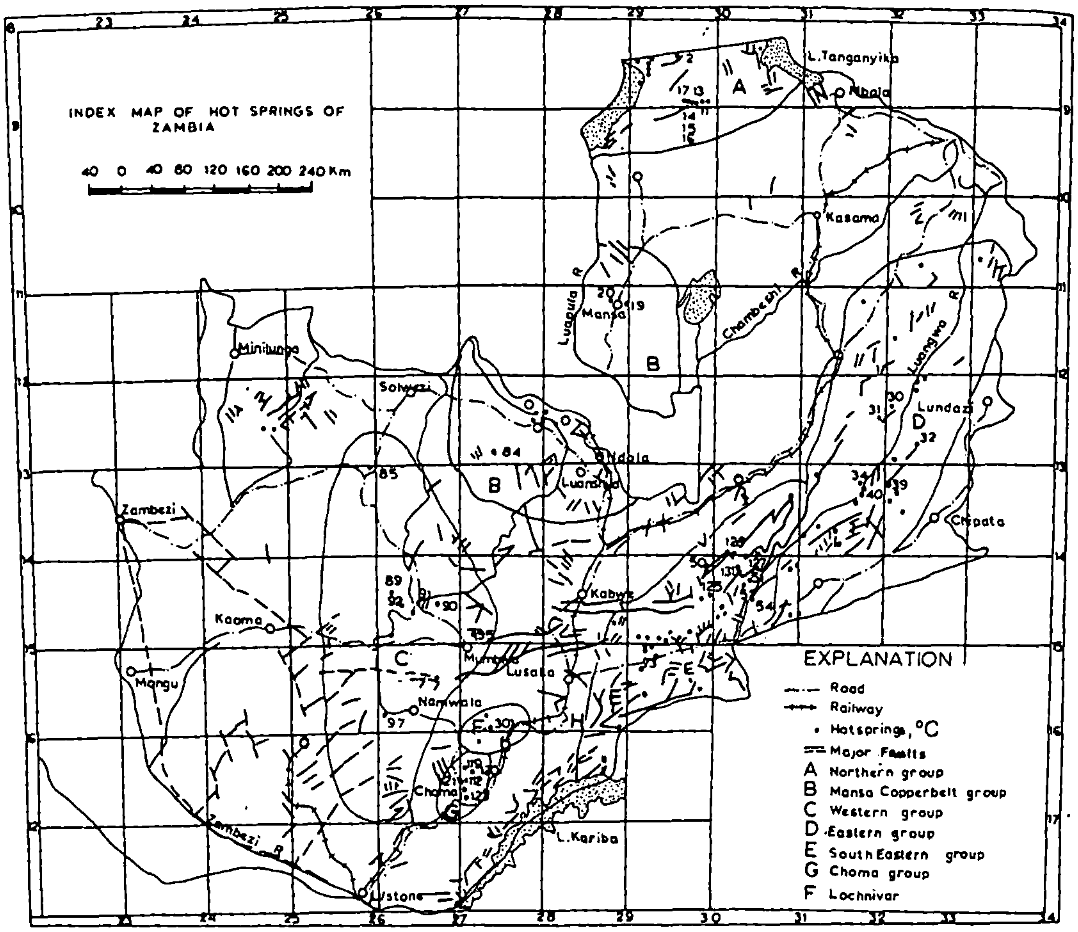

Fig. 1. Sketch map of the hot springs of Zambia.

GEOGRAPHIC AND SOCIO-ECONOMIC SETTING OF THE MAJOR HOT SPRINGS IN ZAMBIA

Zambia's major mineralised springs are divided into seven geographical groups (Fig. 1): northern, western, south–eastern Luangwa, Choma, Lochnivar, eastern Luangwa and the Mansa–copperbelt groups.

Many of the hot mineralised springs are located in remote and isolated areas, inhabited mainly by low income farming communities, many of them in National Game Parks. The population density in these areas is low and villages are scattered unevenly over wide areas. However, there is a strong potential for tourism development in the areas owing to the abundant game and spectacular scenic views. In the area of Lakes Mweru and Tanganyika, besides tourism, there exists a fairly well-developed fishing industry on both small and commercial scales.

GEOLOGY OF THE HOT SPRINGS

The hot mineralised springs are located along fault zones cutting thick sequences of rocks ranging in age from Precambrian to Karroo (Fig. 2). The largest number of hot and mineralised springs is found in the eastern and south-eastern Luangwa Valley where over 60 are known.

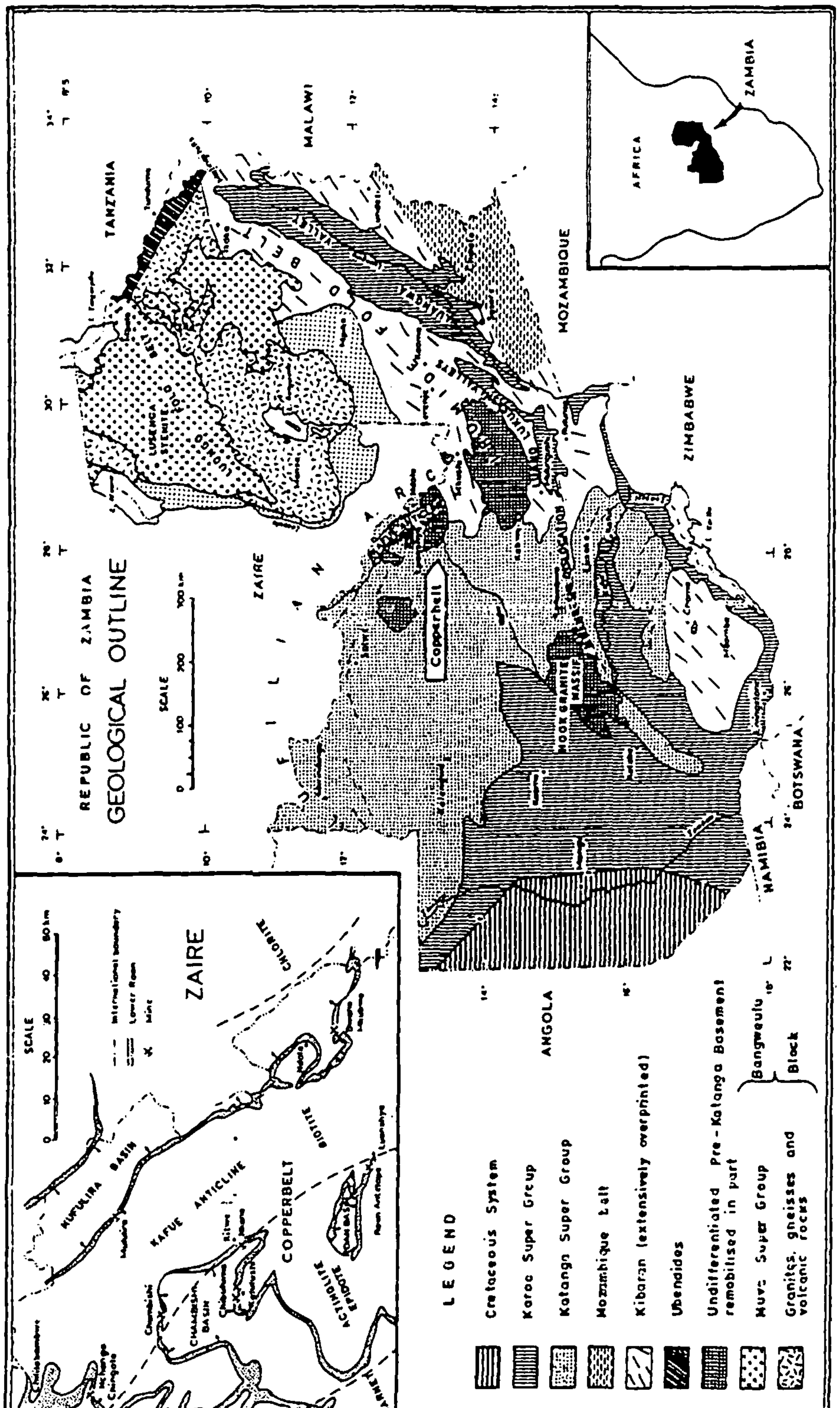

Fig. 2. Geological outline of Zambia.

There exists a striking concordance between many of the fault zones and older orogenic trends. This "coincidence" between the older and younger structures seems to suggest that the faults have existed since the Precambrian, reactivated during successive orogenic events.

The northern group of hot springs are structurally related to the East African rift system, a region of probable positive thermal anomaly within which local anomalies are associated directly with volcanism and/or hydrothermal systems. In the East African rift the crust is thin; in restricted spreading zones it may be absent. In northern Zambia, the reverse may be true.

Major negative Bouguer gravity anomalies have been delineated over some areas where the main hot mineralised springs in Zambia are located, particularly over the Luangwa Valley and the Lakes Mweru and Tanganyika area. The gravity anomalies may be indicative of deep-seated faults.

The spring waters for most of the geothermal manifestations flow out at the surface as clear low salinity waters. Temperatures vary from ambient to 94°C. The most favoured location for the hot springs is the intersection of fault or fracture systems.

Other hot springs, particularly in the western and Choma groups, which are located near granitic domes and intrusions, could be related to circulations along faults developed by the tensional and compressional effects of the igneous bodies on the country rocks, enhanced by subsequent tectonic activity.

GEOLOGY AND STRATIGRAPHY OF ZAMBIA

Five major geological units have been identified so far in Zambia.

(a) *Basement complex*

The basement complex consists of two major lithostratigraphic units. These units are polycrystalline, having undergone several cycles of tectonic deformation and metamorphism. In the Zambia copperbelt where the geology is known in detail, the older of the two rock units consists of schists and gneisses known as the Lufubu. The Lufubu sequence is intruded by granitic bodies dated geochronologically at 2000 My which implies pre-Paleozoic (Eburnian) age (1800–2000 My) or more for the rocks. The Muva Super Group is a post-Eburnian unit comprising sedimentary (Banguela Block) and metasedimentary rocks (schists, quartzites, migmatites and conglomerates).

(b) *Katanga super group*

The world famous Co–Cu-bearing Katanga rocks were deposited during a transgression period which led to the deposition of the Kitwe formation of the Lower Roan Group in the copperbelt of Zambia at about 10.5 My. A two fold division into a lower Mine series and an upper Kundelungu formation has been effected. The Mines series show a transgression from coarser clastics at the bottom to fine shales and carbonates at the top. The Kundelungu is a succession of tillites (Grand Conglomerate) at the bottom through limestones and shales at the top. The exposure of these rocks is confined to the southern, central and north–western parts of the country.

(c) *Karroo super group*

The Karroo (Permo-carboniferous) is a succession of rift-controlled sedimentary rocks deposited in intra-continental down-faulted basins. The basal clastics of the Karroo represent glacial moraines deposited in a glacial environment. Overlying the glacial moraines (the Dwyka formation) is the Siankodobo Sandstones formation which was formed in an arid-fluviatile environment. Deltaic coal measures overly the Siankodobo sandstones formation.

A succession of lacustrine environment clastics overly the coal measures. Tectonic activity at this time resulted in coarser clastics being deposited above the lacustrine molasses. A later succession of mudstones and sandstones was deposited above the coarse clastics, representing a cyclic environmental change. The Batoka volcanic sequence which marks the end of the Karroo sedimentation and probably all known magmatic eruptions in Zambia, covers all these sequences.

(d) *Kalahari super group and recent deposits*

The rocks of the Kalahari Group are separated from the Karroo by a major unconformity. They are mainly an eolian–fluvial type deposit. The main rock types are consolidated and semi-consolidated quartzites, marls, sandstones, duricrusts and loose sands, spread over wide areas of the western, north–western and southern parts of Zambia. Alluvial deposits are restricted to and around major drainage basins of the major rivers and their tributaries (Money, 1986).

(e) *Local Geology of the hot springs*

Northern group. The hot springs of this group are located along Cenozoic and recent rift-like faults which produced grabens accommodating the large lakes of Tanganyika, Mweru and Bangweulu (Unrug and Anderson, 1984). The faults cut across impervious porphyritic and tuffaceous rhyolites and andesites belonging to the final phase of the Ubendian (>1830 My) tectonic-thermal event and fluviatile molasses comprising shales, conglomerates, sandstones and arkoses of the Muva Super Group. The above units rest on an older basement of schists and granitoids. The schists are micaceous or chloritic quartzofeldspathic rocks derived from acid volcanics and semi-pelitic to psammitic sediments. Quartzites and meta-arkose are minor constituents of the older basement rocks. The andesites and rhyolites have a K-calc-alkaline chemistry. Pyrite is disseminated in the more acidic volcanics.

Eastern and south-eastern Luangwa groups. These groups occur mainly along fault scarps defining contact boundary faults which separate Karroo rocks from Muva and pre-Muva lithologies. The Karroo rocks are often poorly exposed in some parts of the Luangwa Valley, but where exposure is good, mainly along fault scarps, the rocks observed are quartzo-feldspathic sandstones and grits. Occasionally breccias of underlying mudstones are also exposed. Basement rocks, where exposed, are mainly granite gneisses, quartzites and metavolcanics as at Chinyunyu, Chikowa and Msoro hot springs.

Western group. The Lubungu hot spring occurs in a medium-grained pink granite which may represent the roof of an extensive post Pan-African granite intrusion (Hook granite). The Lubungu fault, along which the spring is located, is thought to define the eastern boundary of a northward-trending graben of down-faulted rocks of assumed Katangan age. The fault zone shows intense brecciation, tourmalinisation and hematitisation locally. A branch of the Lubungu fault, which is outlined by the patch development of metasomatic magnetite, hematite and tourmaline, and the alteration and brecciation of the Hook granite trend ENE near the Kafue–Lunga rivers confluence. The fault may have been initiated by tensional diapiric effects of the Hook granite and enhanced by subsequent cooling and other regional tectonic effects. Other springs belonging to this geographical group display similar genetic-structural relationships to Lubungu; notable exceptions being Kaimbwe, which occurs along mainly north-west trending faults in the Kundelungu formation of the Katanga super group and Bilili which is located along the margins of the 1100 My old Kalomo batholith (see below).

Lochnivar group. The geological strata which underlie the Lochnivar group of hot springs can be divided into two. The uppermost unit consists of rocks of the Karroo super group. The lower rock unit is composed of Basement complex gneisses and quartzites, marbles and undifferentiated calcium–silicates. The two rock units are separated by a major fault zone of variable trend but mainly NE–SW, defined by a 3 m wide quartz vein and fragments of mudstones and sandstones. There are small amounts of pyrite and fluorite. The faults in this zone are closely spaced, subparallel and steeply dipping.

Choma group. The springs occur in an area underlain by quartz-feldspar gneisses and quartz biotite schists interlayered with thin horizons of marbles and calc-silicates at the top and metasomatic and migmatitic granite gneisses at the bottom, belonging to the Basement complex. These have been intruded by an adamellitic granodiorite assigned to the 1100 My old Kalomo batholith. The hot springs are located at the intersections of N–S and E–W fractures and shear zones on the margins of the Kalomo batholith.

Mansa–copperbelt group. There are two sets of springs in this group: one clustered around Mansa and the other scattered over the copperbelt of Zambia. The springs around Mansa town occur along shear zones located on the margins of a gneissic granitic intrusion. The fractures trend N–S to N–W. The granite is intrusive into andesite and rhyolite volcanics.

WATER CHEMISTRY OF HOT SPRINGS

Northern group

This group of hot springs, except for Katete, is characterised by low TDS (<500 ppm). A geothermal gradient of 1°C $(10\ m)^{-1}$ was recorded at Kapisya over the first 10 m of a test bore-hole.

The lack of linear ionic/temperature correlations, low TDS and the predominance of CO_3 over Ca^{2+} and Mg^{2+} may be indicative of a considerable mixing of the thermal waters with superficial waters. A dilution factor of three has been estimated for Kapisya.

In contrast, Kaputa has extremely high TDS (>2000). Temperatures are low in most of these hot springs, with the exception of Kapisya (surface 85°C). The geothermometers give temperatures of between 126° (SiO_2) and 164°C (Na–K). Flow rates vary from 25 $l\ s^{-1}$ at Kapisya to as low as 1 $l\ s^{-1}$ at Kalaye No. 2 hot spring (Table 1).

Eastern and south-eastern groups

These groups of hot springs form part of the NE trending rift-type graben system of the Luangwa valley. Most of the hot springs lie along fault boundaries between the Karroo and Basement complex rocks. A variation in chemical composition of the waters is apparent from the south-western end of the Luangwa valley to the north-west. The springs to the south-west (eastern group) are generally dilute and less homogeneous in composition. At the north-eastern extremity of the Luangwa Valley (eastern group) the hot spring waters become dilute.

Surface temperatures vary between 28°C for Kanunshya hot spring (not in Tables) to about 87°C at Chongo. Flow rates are highest at Chongo hot spring which discharges about 25 ls^{-1}. Good subsurface temperatures based on the Na/K, Na–K–Ca and SiO_2 geothermometers have also been predicted for the majority of the hot springs in this group (Tables 2 and 3).

Western group

There are major differences in the water chemical compositions reported by Legg (1974) and the new data reported by the Zambian–Italian Geothermal Project (1986). A compositional–

Table 1. Chemical analysis of northern group hot spring waters

Table 1. Chemical analysis of northern group hot spring waters

Spring	Ref. No.	T (°C)	Flow (ls^{-1})	pH	Concentration (ppm) Ca	Mg	Na	K	CO_3	Cl	SO_4	Li	SiO_2	TDS	Molecular ratios $\frac{Na}{K}$	$\frac{Na}{Li}$	$\frac{Na}{Ca}$	$\frac{Cl}{SO_4}$	Geothermometer temperature (°C) SiO_2	Na–K	Ca–Na–K
Kapisya	1	85	25	8.65	10	1	207	27	225	124	268	0.7	92	<500	13.0	900	0.9	0.5	126	164	148
Kaputa	2	22	2	7.6	103	7	880	9	30	1050	158	1	30	>2000	129.0	378	7.1	0.8	75	85	96
Kaputa Well	2W	52	—	—	103	7	880	9	30	1050	158	—	30	1800	191.5	—	7.3	12.1	—	—	—
Kalaye No. 2	11	27	1	—	12	1	44	2	30	56	—	—	16	<500	38.0	—	3.1	—	—	—	—
Kalaye No. 6	13	43	2	—	13	2	86	2	66	86	6	—	32	<500	37.0	—	5.3	24	—	—	—
Kalaye No. 4	15	45	5	—	22	1	75	1	66	66	10	—	24	<500	33.0	—	3.0	4.8			
Kalaye No. 3	16	46	4	—	14	2	82	2	66	62	25	—	40	<500	36.0	—	36	3.4			
Kalaye No. 1	17	51	7	—	22	2	85	4	60	100	12	0.6	20	<500	37.0	37	3.4	9.3			

Table 2. Chemical analysis of the eastern group waters

Spring	Ref. No.	T (°C)	Flow (ls^{-1})	pH	Concentration (ppm) Ca	Mg	Na	K	CO_3	Cl	SO_4	Li	SiO_2	TDS	Molecular ratios $\frac{Na}{K}$	$\frac{Na}{Li}$	$\frac{Na}{Ca}$	$\frac{Cl}{SO_4}$	Geothermometer temperature (°C) SiO_2	Na–K	Ca–Na–K
Chongo	30	87	25	7.84	44	2.4	574	70	122	213	1950	2.8	100	1000	12.5	59.2	13	0.1	160	240	206
Nabwalya South	31	67	2	7.34	64	2.4	483	19.5	378	177	1180	1.5	55	1000	42	105	7.6	0.2	108	150	143
Kasakaza	32	55	4	8.61	90	4	445	15	30	60	1050	0.2	40	1000	48.3	193	5	0.1	95	138	131
Musaope	40	75	7	8.04	68	5	460	35	183	177	1432	0.8	90	<500	22.2	200	7	0.1	129	194	173
Chilube	126	30	—	—	20	8	325	30	486	16	16	—	24	>1000	16.4	—	4	1.6	75	—	187
Monze	34	29	5	—	3	2	142	2	10	100	—	0.1	24	<500	61	610	47	—	75	—	103
Macro	39	58	5	—	105	1	315	20	24	104	800	0.7	20	1000	27.2	136	3	0.1	70	181	154

Table 3. Chemical analysis of the south eastern group waters

Spring	Ref. No.	T (°C)	Flow (ls^{-1})	pH	Ca	Mg	Na	K	CO_3	Cl	SO_4	Li	SiO_2	TDS	Molecular ratios Na/K	Na/Li	Na/Ca	Cl/SO_4	Geothermometer temperature (°C) SiO_2	Na–K	Ca–Na–K
					Concentration (ppm)																
Masaka	50	—	—		35	14	420	20	30	920	250	0.3	32	500	—	—	—	—	—	—	—
Mafwasa	128	65	2	7.5	360	1	270	14	50	48	520	0.6	40	<500	39	117	7.6	0.14	84	—	146
Kampoko	131	44	8		44	12	690	3.9	238	25	163	0.2	30	500	300	1000	15.7	0.14	84	53	75
Bwingi Riv ('65)	53	—	—		10	9	3	—	35		4	—	—	<500	—	—	0.6		70		
Bwingi Riv ('73)	53	—	—		3	2	2	—	10	2	—	—	20	<500	—	—	13.6	0.3	70	—	—
*Mikwa River	125	60	2	—	6	4	2	1	20	2	—	—	20	<500	5	—	0.3	—	70	400	199
Chinyunyu ('69)	73	61	6	—	16	5	320	18	60	150	480	—	—	1000	18	—	15	0.4*	95*	145	145
Chinyunyu ('86)	73	60	6	8.5	8	2.6	140	4.6	55	57.7	321	0.01	80	<1000	64 5	—	17.5	0.2	124	137	131

Table 4. Chemical analysis of western group waters

Spring	Ref. No.	T (°C)	Flow (ls^{-1})	pH	Ca	Mg	Na	K	CO_3	Cl	SO_4	Li	SiO_2	TDS	Molecular ratios Na/K	Na/Li	Na/Ca	Cl/SO_4	SiO_2	Geothermometer temperature (°C) Na–K	Ca–Na–K
					Concentration (ppm)																
Kaimbwe	85	52	2	8.5	180	10	3700	95	244	5611	440	5	84	<10000			206.0	12.8	126	120	143
Lupiamanzi	90	73	15	9	11	2	150	6	369	72	10	4	110	<500			13.6	10.0	138	144	138
Lubungu	91	77	25	7.5	360	70	550	30	92	868	1000	4.5	95	>2000			1.5	0.8	149–131	170–102	145–108
Chibemba	92	57	1	—	160	5	400	30	240	315	750	5	45	2000			2.5	0.4	104	193	162
Chibili	95	38	0.5	6.9	44	7	161	12	531	81	48	3	—	>800			3.6	·	—	191	157
Longola	97	70	10	—	<50	<5	491	18	43	206		0.3	40	<2000			49.0	0.2	95	157–88	147–107

time variation in water chemistry is strongly reflected in these two sets of data (Table 4). Surface temperatures range from 38°C (Chibili) to 73°C at Lupiamanzi. The SiO_2 geothermometer gave temperatures between 95 and 149°C, which are generally lower than those obtained with the Na/K and Na–K–Ca geothermometers. Permeability is expected to be good at all the hot springs, as observed at Kaimbwe and Lubungu where bore holes have been drilled. A geothermal gradient of 0.5°C $(10\ m)^{-1}$ has been reported at Lubungu.

The springs clustered around the Kafue–Lunga river confluence, in spite of their close proximity and similar geology, show wide chemical disparity. Analysis of travertine at Lubungu hot spring shows that there has been a change in the composition of its water from $CaCO_3$-dominated in the past to Fe–Mg rich emissions at present. TDS values exceed 2000 mg l^{-1} while silica content is also high (95 mg l^{-1}). The high H_3BO_3 and NH_4 values analysed at Lubungu may partly be due to a deep-seated hydrothermal source and partly to the wall rock composition, a brecciated, hematised and tourmalinised granite. The other hot springs in the vicinity, (e.g. Chibemba and Lupiamanzi) vary in water composition from SO_4–Na–K-dominated waters with high silica (50 mg l^{-1}) and TDS (2000 mg l^{-1}) contents to alkali carbonate waters with TDS of less than 300 mg l^{-1}.

Kaimbwe hot spring has a very high TDS, acquiring a higher NaCl content than the other springs. Bilili, west of Choma in the southern province of Zambia, is SO_4 rich with TDS values between 500 and 2000 mg l^{-1} (Table 4).

Choma–Lochnivar groups

These groups of hot springs show a remarkable homogeneity in their water chemistry. The Lochnivar group of waters is essentially of the sodium-sulphate type. The TDS values in this group lie between 500 and 2000 mg l^{-1}.

The Choma group of hot springs are similar in composition to the Lochnivar group, being of the alkali–sulphate type, but with TDS of <500 mg l^{-1}.

Surface water temperatures are high for the Lochnivar group (Gwisho, 72°C and Bwanda 94°C). Subsurface temperatures of 192°C (Ca–Na–K), 180°C (Na–K) and 103°C (SiO_2) have been calculated for Bwanda. Gwisho hot spring has higher Ca–Na–K (192°C) and Na–K (180°C) geothermometric temperatures than Bwanda. The SiO_2 geothermometer gives a lower temperature at Gwisho (95°C). The temperatures recorded for the Choma group are generally lower, with Muckleneuk Main being the hottest (74°C) although geothermometrically they rank the same as the Locknivar group of hot springs (Table 5).

Mansa–copperbelt group

The waters of this group show a wide variation in water chemistry although springs found within a restricted locality may show similar characteristics. The waters of the Mansa copperbelt group, however, could be classified loosely as belonging to the Na–SO_4–Cl type with variable CO_3 and Mg contents.

The geothermometric temperatures are very high in some cases, despite the low surface temperatures at most of the springs, the only exception being Casho, where a surface temperature of 80°C has been measured (Table 6).

ORIGIN OF THE HOT SPRING WATERS

Apart from the northernmost parts of the country, which are structurally related to the East African rift system, Zambia lies in a tectonically stable zone with low seismicity. The last major known volcanic activity occurred at the close of the Karroo rifting and sedimentation phase. Geological considerations alone would thus rule out any significant direct magmatic contribution

Table 5. Chemical analysis of the Choma and Lochivar group waters

Spring	Ref. No.	T (°C)	Flow (ls^{-1})	pH	Ca	Mg	Na	K	CO_3	Cl	SO_4	Li	SiO_2	TDS	$\frac{Na}{K}$	$\frac{Na}{Li}$	$\frac{Na}{Ca}$	$\frac{Cl}{SO_4}$	SiO_2	Na–K	Ca–Na–K
					Concentration (ppm)										Molecular ratios				Geothermometer temperature (°C)		
Choma Group																					
Samahwa R.	112	36			36	3	95	6	108	12	15	0.1	40	<500			2.6	0.3	95	180	143
Chibimbi north	119N	58			3	1	100	4	84	20	65	—	40	<500		—	33	0.3	95	149	142
Chibimbi south	119S	48			4	1	100	4	36	18	130	—	32	<500		—			—	—	—
Mosali	120	58			7	1	140	10	60	24	190	0.8	40	<500			20	0.1	95	190	168
Sportsman Den	121	48			4	1	110	7	72	22	108	0.1	40	<500			27	0.2	95	181	163
Mucklenuek Main	123	74			5	1	110	6	60	24	124	0.1	40	<500			22	0.2	95	170	154
Lochnivar Group																					
Gwisho (1972)	301	69			80	17	350	32	72	440	350	3	40	500			4.7	1.2	95	180	174
Gwisho (1974)	302	71			11	1	760	50	36	480	980	3	45	500			.69	0.5	95		174
Gwisho East A	303	71			90	10	370	36	54	480	340	3	45	500			4	1.4	100		178
Gwisho East–	G725	71			86	12	252	35	50	440	720	3	60	500							
Bore Hole	GEB	75			83	13	370	30	60	450	360	3	45	500							
Gwisho West ('72)	GW	45			98	14	380	32	72	500	380	3	30	500							
Gwisho (1973)	G731	72			94	5	620	45	36	420	980	1.2	40	500							
Namulula	400	52			72	9	540	45	60	300	900	0.7	32	500			7.5	0.3	87		177
Lochnivar Gate-Bore Hole ('72)	LG72	—			81	24	39	7	224	12	13	0.02	60	500							
Bwanda East '72	200	67			74	1	620	50	36	320	1040	1	40	500			7	0.7	80	—	172
Bwanda East '72	201	68			67	3	320	30	42	275	405	1	30	500			8	0.3	95	180	180
Bwanda (1974)	202	93		8.8	8	1	650	50	30	280	1040	1.3	40	500			6.0	0.6	76	—	
Bwanda (1972)	203	94			60	3	450	35	50	260	710	2	50	500			7.5	0.4	103	—	174
Bwanda (1973)	204	93			9	1	700	50	36	300	1100	1.3	40	500			77	0.3	95	—	192

Table 6. Chemical analysis of Mansa–copperbelt hot spring waters

Spring	Ref. No.	T (°C)	Flow (ls^{-1})	pH	Ca	Mg	Na	K	CO_3	Cl	SO_4	Li	SiO_2	TDS	$\frac{Na}{K}$	$\frac{Na}{Li}$	$\frac{Na}{Ca}$	$\frac{Cl}{SO_4}$	SiO_2	Na–K	Ca–Na–K
					Concentration (ppm)										Molecular ratios				Geothermometer temperature (°C)		
Mansa	18	49	4	—	37	1	72	5	12	116	75	0.8	25	<500	31	31	2.0	2.0	130	240	206
Kabunda	20	42	3	—	64	1	200	18	72	300	75	2	40		17	29	3.1	4.0	131	208	168
Casho	84	80	30	7.5	337	5	980	65	43	1614	960	0.5	84	>2000	26	420	2.9	1.7	126	184	166
Chondwe	83	62	3	6.14	360	35	80	20	152	525	360	2	78	<500	70	12	0.2	1.5	123	190	310

to the evolution of the hot spring waters in Zambia. This is further supported by geochemical considerations which indicate that interactions between meteoric water and rocks along fault systems are the dominant mechanism.

The alignment of some hot springs along zones of major negative Bouguer gravity anomalies suggest that some spring waters percolate to great depths along very deep-seated fracture and fault systems.

GEOTHERMAL EVALUATION AND DEVELOPMENT PROJECT

The Zambian–Italian geothermal project was the result of a bilateral agreement between the Governments of Zambia and Italy in 1984. The project consisted of a study of all known geothermal manifestations, in order to estimate the geothermal potential of Zambia as regards generating electric power for the low income, small rural communities. The contract was awarded to Dal.in.te.sa Co. of Milano, Italy, to draw up a programme for the exploration of the hot springs and installation of two demonstration turbo-generators.

On completion of the first and second phase of the project, Dal.in.te.sa concluded that a potential effectively exists for the utilization of low enthalpy geothermal resources to generate electricity on a small scale, to meet the energy requirements of the poorer sections of the

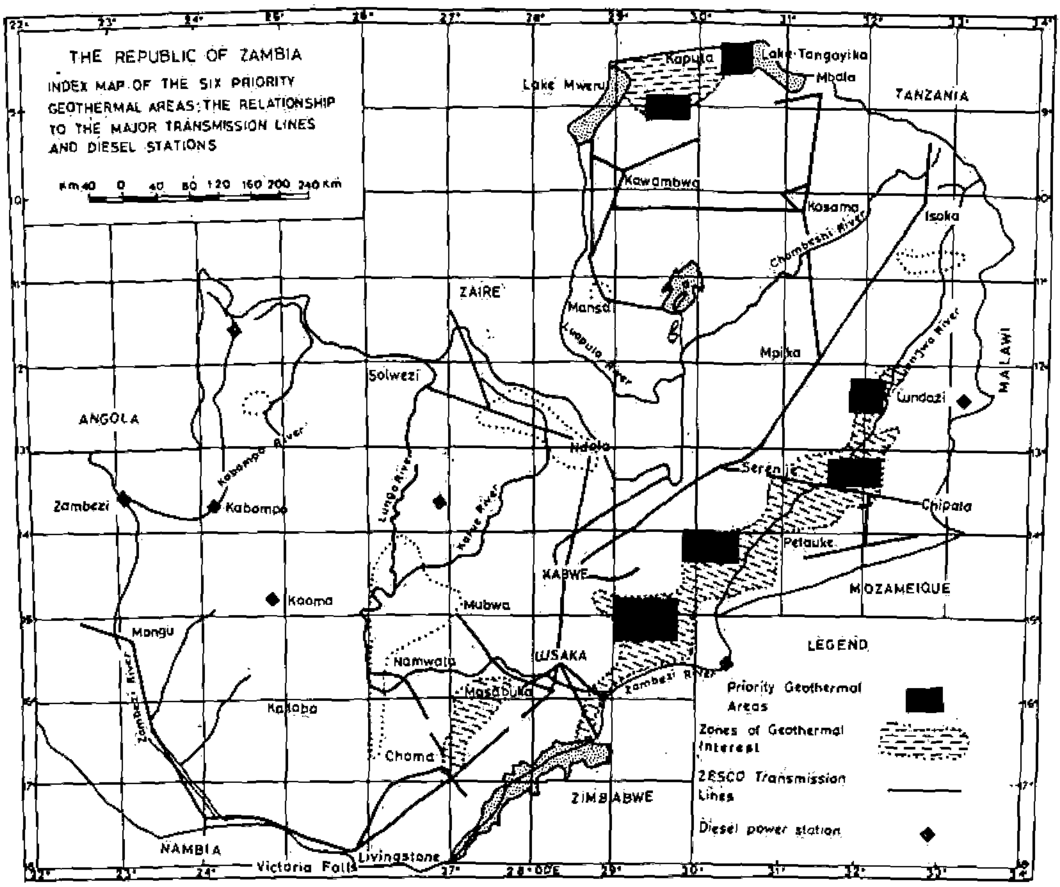

Fig. 3. Six priority geothermal areas in Zambia, the transmission lines and diesel stations.

Zambian population. The high cost of transmission lines per km, of step-down transformers, switching gear and complete substations has in the past greatly hindered the rural electrification of even small villages located under high tension transmission lines (Fig. 3).

Deep exploratory wells are now being drilled in four areas: Kapisya hot spring (one well), Lubungu (two wells), Casho (three wells) and Chinyunyu (one well).

The average well depth in the exploratory stage is 150 m. The final production wells are expected to have an average depth of between 200–300 m.

A geothermal gradient of 0.5°C $(10\ m)^{-1}$ has been recorded in these and previous wells.

Once suitable sites have been established, two Organic Rankine Cycle turbo-generators will be installed.

Acknowledgements—I am greatly indebted to Messrs S. Mabuku and B. Singoyi of the Geological Survey of Zambia, Drs Ugo Della Pierre and Riccardo Balsotti of Dal.in.te.sa for their assistance. I would also like to extend my gratitude to Professor F. Aumento, Director of the Zambian–Italian Geothermal Project for his special guidance over the years I have known him; Miss P. Mumba who typed the manuscript and lastly to Mr N. Money, Director—Geological Survey of Zambia, for permission to publish some of the data.

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REPORT ON GEOTHERMAL MISSION TO UNITED REPUBLIC OF TANZANIA

AND

CONCEPT FOR GEOTHERMAL ASSESSMENT AND DEVELOPMENT

By

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Not For Public Distribution

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CONTENTS

1. SUMMARY AND RECOMMENDATIONS

This report summarizes the results of a geothermal mission to the United Republic of Tanzania. The mission was funded by the University of Utah Research Institute, and its objectives were to investigate the status of geothermal assessment, determine the level of interest in geothermal development, and formulate a strategy for that development.

At present, there is no geothermal utilization in Tanzania; although, a World Bank study anticipates a 650 MWe potential. The present development plans call for a concentration on hydropower resources. However, the level of knowledge concerning geothermal resources is not sufficient for it to be discussed with other power alternatives.

The only geothermal assessment completed in Tanzania was a reconnaissance program in 1976 and 1977 under funding from the Swedish International Development Authority (SIDA). This study provides a good summary of fluid chemistry but does not provide necessary information on hot spring deposits, distribution and age of volcanic rocks, and subsurface temperatures. The study did define the Mbeya and Arusha areas as being most prospective.

Geothermal resources in Tanzania are under the purview of the Ministry of Energy and Minerals. This Ministry feels that more assessment is required to allow geothermal energy to be compared with other alternatives. They are now seeking support to continue the geothermal assessment.

The first step in developing U. S. export opportunities is to increase the knowledge of the geothermal resource to a level where it can be discussed on an equal basis with other energy alternatives. In neighboring Kenya, it was determined that geothermal is the least-cost power development option. An analysis of 50 MWe of geothermal development shows a capital requirement of US $110 million, US $108.5 million of which are for goods and services that must be imported into Tanzania.

UURI is working with the Ministry of Energy and Minerals to develop a request to the U. S. Trade and Development Program for a geothermal assessment of two areas of Tanzania that appear to have the highest potential for geothermal development. The objective of this assessment would be to define prospect areas for exploratory drilling and estimate the total potential for geothermal development. This would be a joint project with the active participation of the Ministry of Energy and Minerals and its associated organization the Tanzania Petroleum Development Corporation. Subsequent geothermal development would be carried out either by the Ministry of Energy and Minerals or private developers.

2. INTRODUCTION

2.1 Background and Purpose

Tanzania is located along the East African Rift, the geologic structure that is responsible for Olakaria and several other geothermal fields under development in Kenya. Faults associated with this structure are shown in Figure 1. The potential for geothermal development in Tanzania is high, and there is a definite possibility for considerable involvement by U. S. firms. There is presently no activity by countries that have been traditionally the dominant players in exporting geothermal technology (Japan, Italy, Iceland, New Zealand). The past success of these countries is largely attributable to government subsidies such as resource assessment grants to set the stage for equipment purchases and tied aid.

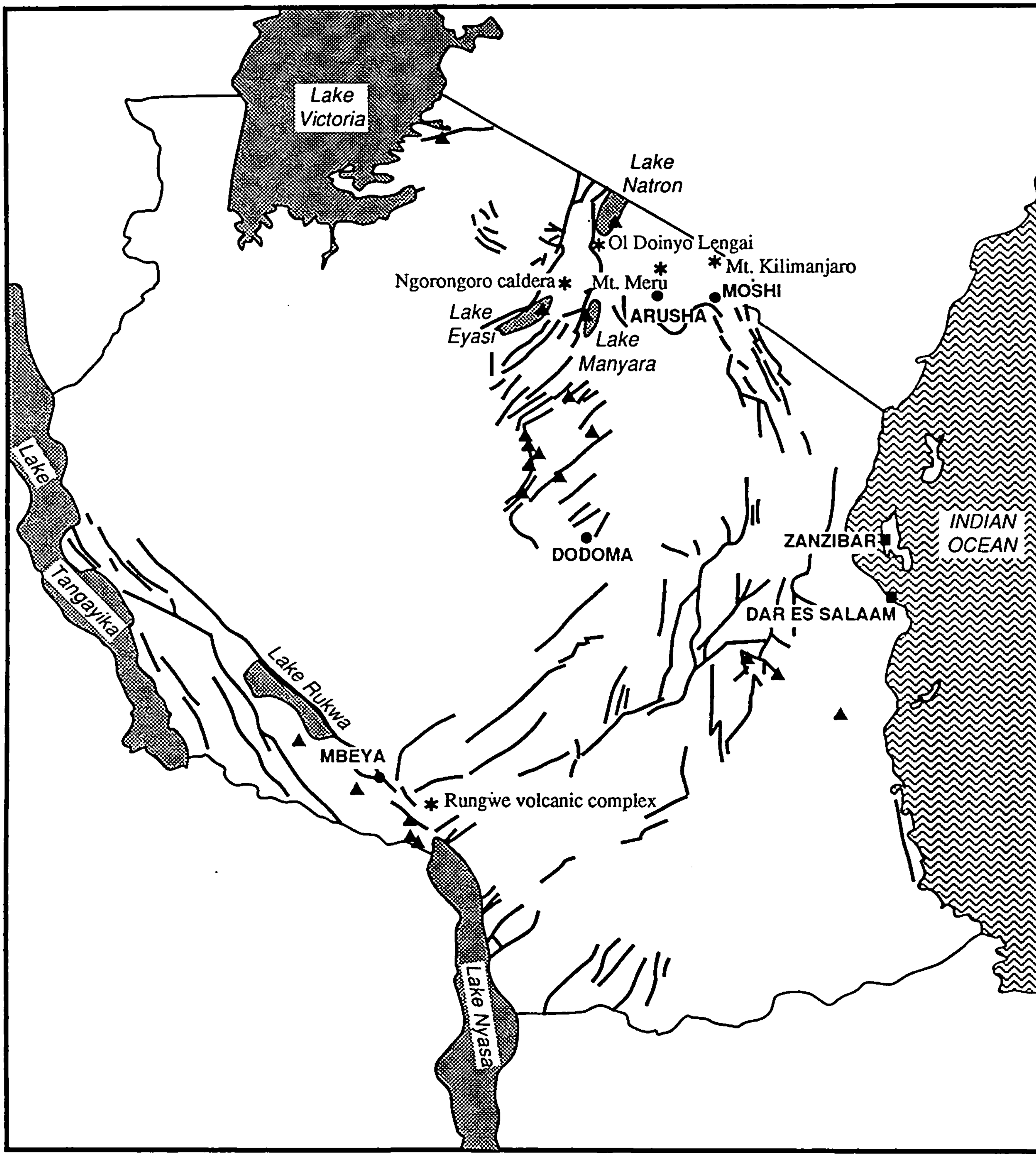


Figure 1. Location of Hot Springs (▲), Young Volcanoes (✱) and Faults in Tanzania (SIDA, 1978; Makundi and Kifua, 1985).

A visit was made to Dar es Salaam between July 16 and July 18, 1989 by Dr. Dennis L. Nielson of the University of Utah Research Institute (UURI). His schedule was arranged by Gayleatha B. Brown of the U. S. Embassy. Bernard Kimalando, Commercial Specialist, assisted in the appointment schedule.

This mission was financially supported by the University of Utah Research Institute. The purposes were 1. to investigate the status of geothermal assessment, 2. to determine the players and interest in geothermal development within the government of Tanzania, and 3. to formulate a strategy for geothermal development.

2.2 Status of Power Development

There has been no geothermal development in Tanzania although an independent study by the World Bank has projected a potential of 650 MWe.

The present power demand on the national power grid is 217 MW. This grid generally covers the northeast portion of the country with a line running to Mbeya in the southwest. Off-grid and some on-grid power is supplied by diesel generators. The largest of these is a 60 MW plant in Dar es Salaam that is presently inoperative due to lack of spares and maintanence. The average plant size is about 10 MW. Diesel is a very unattractive alternative because fuel and spare parts must be imported and the service and distribution system is very unreliable.

Present power sector alternatives concentrate on indigenous resources, principally hydropower with some coal and natural gas. Natural gas has been discovered off-shore, but has not been developed. A pipeline is planned to bring the gas to Dar es Salaam for industrial applications. Coal is being used to generate 6 MW at the mine site; the coal is used principally for cement and paper production.

Hydropower has received the most attention with assessment done through grants from Scandanavian countries. A power plant development plan to the year 2010 written by ACRES and funded by the U. N. is presently being revised and calls for a heavy concentration in hydropower with the first phase of development set for 330 MW. The level of knowledge concerning geothermal resources is not sufficient for it to be discussed with other power alternatives.

2.3 Financial Considerations

Tanzania is a poor country with an average annual income of $270 and an annual inflation rate of about 38%. It sorely needs exports to generate foreign exchange. There is presently no provision for the repatriation of profits to foreign investors. However, the government is now granting concessions to foreign natural resource development firms.

Tanzania is presently coming off restrictions imposed under the Brooke amendment. The country is in good standing with the World Bank. USAID activity in Tanzania is concentrating on the transportation sector.

3. STATUS OF GEOTHERMAL ASSESSMENT

A reconnaissance assessment of the geothermal resources of Tanzania was completed in 1976 and 1977. This was the result of a request from the Republic of Tanzania to the Swedish

International Development Authority (SIDA). SIDA contracted with the Swedish Consulting Group (SWECO) that jointly undertook the task with VIRKIR Consulting Group, Ltd. of Reykjavik, Iceland. Two reports were produced for the Ministry of Water, Energy and Minerals as a result of this work (SIDA, 1978, 1979).

The first of these reports (SIDA, 1978) described a field reconnaissance to many, but not all, of the identified hot spring locallities in the country (Fig. 1). Selected springs were sampled and the waters analyzed chemically. From these analyses chemical geothermometers were calculated. These calculations indicate approximate subsurface geothermal reservoir temperatures. The quality of these analyses was verified at UURI by calculating charge balances and recalculating the geothermometers. The analyses appear to be of excellent quality and the geothermometer calculations are accurate. The report recommends sampling areas that had been missed in the initial investigation and more detailed resource assessment work in ten areas throughout the country.

This report is open to several technical criticisms. First, the sampling was, in several cases, not comprehensive. In one case, where some 20 hot springs were present, only one was sampled. Second, the report's identification of high-temperature vs. low-temperature thermal manifestations are incorrect, even by 1978 standards. Third, there are only brief descriptions of the precipitates and character of the hot springs. These data are very important in any interpretations of the fluid chemistry. Fourth, there is little discussion of volcanic activity associated with the springs or of areas with young volcanic activity but no springs. The association between volcanism and geothermal resources has been well established in the past decade, and viable prospects are being drilled that have no evidence of surface spring activity.

The second report (SIDA, 1979) selects both the Mbeya region in southern Tanzania and the Arusha region in northern Tanzania near Mt. Kilimanjaro as the most favorable areas for geothermal development (Fig. 1). This report proposes a thirtyeight month program from reconnaissance to exploratory drilling with options that range in cost from $8.6 million to $4.7 million. This is stage I of a projected four stage program. The total program from reconnaissance to power plant design would require nine years. The costs of stages II, III, and IV are not estimated.

A critical review of this proposal indicates that the proposed program is expensive and lengthy. The methodology proposed is not focused on the objective of getting power on line.

In November, 1983 a UNDP geothermal mission visited Tanzania. Only a brief report on this mission was found (Makundi and Kifua, 1985). This mission identified the Mbeya region for additional studies. The Makundi and Kifua paper presents a brief description of the geology of this area and some partial fluid analyses.

4. ORGANIZATIONS CONCERNED WITH GEOTHERMAL DEVELOPMENT

4.1 Ministry of Energy and Minerals

Geothermal development in Tanzania will be under the auspices of the Ministry of Energy and Minerals and its associated organization Tanzania Petroleum Development Corporation (TPDC). In addition, there is geothermal expertise within the Ministry of Water. A geologic and geothermal data base, including a core repository, is maintained in Dodoma but was not visited during this mission. Electrical generation is the responsibility of the parastatal Tanesco which also reports through the Ministry of Energy and Minerals.

The following people associated with the Ministry were interviewed in Dar es Salaam.

Professor Mark J. Mwandosya
Commissioner of Energy and Petroleum Affairs
Ministry of Energy and Minerals

Mr. W. S. Lyimo
Director of Geology
Ministry of Energy and Minerals

Mr. Vincent T. Gondwe
Director of Planning
Ministry of Energy and Minerals

Mr. Theophillo Bwallea
Ministry of Energy and Minerals

Mr. M. Pondaga
Planning Geophysicist
Ministry of Energy and Minerals

Mr. S. Barongo
General Manager
Tanzania Petroleum Development Corporation

Mr. Salvator Ntomola
Director of Exploration and Production
Tanzania Petroleum Development Corporation

Representatives from both the Ministry of Energy and TPDC showed a great deal of enthusiasm for a continued geothermal assessment of Tanzania. A number of people stated that the study done by SWECO was very preliminary in nature and needed to be updated. <u>They are now seeking external support to continue the geothermal assessment.</u> In addition, both TPDC and the Ministry of Energy and Minerals expressed an interest in participating in any additional geothermal work. Personnel would be made available to work on the project; the only aspect for which they would need financial assistance is for analyses done outside Tanzania. The responsibilities within The Ministry and TPDC would be determined by Prof. Mwandosya, Commissioner of Energy and Petroleum Affairs. They would clearly welcome the educational opportunity of working with outside geothermal experts, and the participation of these organizations would improve the efficiency and greatly reduce the cost of a U. S. sponsored assessment.

A number of different project options were discussed during these meetings. These include: on-grid power generation, off-grid power generation coupled either to a population or agricultural center, and power generation associated with a natural resource development. A project mentioned by several people in the Ministry was the development of soda ash at Lake Natron that is also the site of hot spring activity. This project could utilize geothermal resources to generate 5 MW of electrical power and 30 MW of thermal energy for drying the soda ash.

4.2 World Bank

Tanzania is in good standing with the World Bank. Ian Porter, Resident Representative for the World Bank in Dar es Salaam, reports that a power development loan will be issued in 1991. A geothermal project could be included in that loan if the Ministry of Energy and Minerals desires. However, Mr. Porter also suggested that more work on geothermal resource assessment was needed before it would be considered a viable alternative.

5. OPPORTUNITIES FOR U. S. GEOTHERMAL EXPORTS

The first step in developing U. S. geothermal export opportunities is to increase the knowledge of the geothermal resource to the level that it can be discussed on an equal basis with other energy alternatives. In neighboring Kenya, geothermal has been shown to be the least-cost power alternative, and the Government of Kenya is actively developing identified geothermal systems.

Should the geothermal assessment show potential for electrical generation implied by the SIDA studies, geothermal would be competitive with the hydropower option. A strong arguement can be made for diversifying the mix of resources used to generate power. In addition, financing of relatively small geothermal options would present less of a debt burden than large hydropower projects, or, alternatively, the projects could be done using private financing.

The U. S. is a leader in geothermal development technologies and modular power plants that would be ideal for Tanzania. Opportunities for geothermal development will be principally in remote locations with limited load requirements suitable for modular units of 10 MWe or less. For areas with larger power requirements, resource risk and capital investment can be minimized by incremental development of the resource in 10 MWe units. The U. S. geothermal industry has also demonstrated the ability to devlope projects in a very short period of time. It is likely that a power plant could be installed and running in three years from the initiation of the resource assessment in contrast to the more than nine years proposed in the SIDA (1979) report.

The following cost analysis assumes 50 MWe of total geothermal development which is very conservative considering an independent estimate commissioned by the World Bank has estimated a potential for 650 MWe of development. The following table is an estimate of the capital requirements for 5 x 10 MWe geothermal power plants. It is also shown that the imported scope of such a project would be quite large.

	US $ MILLIONS	
COMPONENT	TOTAL	IMPORTED
Geology and Geophysics	2.5	1.0
5 Exploratory Wells	7.5	7.5
10 Production Wells	15.0	15.0
5 x 10 MWe power plants	80.0	80.0
Switchyard Equipment	5.0	5.0
Total	110.0	108.5

6. CONCEPT FOR GEOTHERMAL ASSESSMENT AND DEVELOPMENT

6.1 Introduction

UURI is working with the Ministry of Energy and Minerals to develop a request to the U. S. Trade and Development Program for a geothermal assessment of two areas in Tanzania that appear to have the highest potential for geothermal development.

The SIDA reports and other geologic information (Fig. 1) define the areas with the highest probability for geothermal development as the Dodoma to Lake Natron area in the north and the Mbeya area to the south. It is therefore recommended that these areas be the loci for the next level of geothermal assessment. Since the ultimate objective is the production of electrical or thermal energy, the following paragraphs outline the steps required to go from the status quo to geothermal energy production.

6.2 Resource Assessment

It is recommended that the resource assessment be a joint project between the U. S. government, UURI and the Ministry of Energy and Minerals. The objectives of this activity will be comprehensive assessment of both the Dodoma to Lake Natron and Mbeya areas to indicate the size and locations of systems with the potential for development and to prioritize areas for development. The joint effort proposed by the Ministry will improve the efficiency and lower the U. S. investment in the assessment, develop a working relationship between the U. S. and the Government of Tanzania, and provide Tanzanian scientists with hands-on educational opportunities.

It is proposed that both a report be published and a workshop for U. S. industry be held through the National Geothermal Association (NGA) when the assessment phase is complete. The NGA is the U. S. geothermal industry trade association, and it is the most efficient vehicle for alerting the industry to export opportunities. UURI is a member of the NGA.

Field work for the resource assessment should be scheduled between the months of July and November. At other times, rains may limit access to many of the potential geothermal sites.

The resource assessment should involve the following components in both of the two areas defined.

1. Data update. Since the SIDA reports were completed, a great deal of geoscience data for Tanzania has become available. This includes additional water and gas analyses, geologic mapping, radiometric dating of volcanic rocks, and measurements of temperature gradients in boreholes drilled for water and mineral exploration. These data should be compiled and interpreted in the context of the geothermal assessment.

2. Spring sampling. Additional spring sampling is required to provide information on springs that were not sampled previously and to provide additional information for those springs for which data exists. In particular, many of the fluids show evidence of mixing with cold waters which suggests that they have flowed laterally from their source area. During the sampling, the individual springs should be mapped to document faults, types and distribution of spring deposits, and rock types.

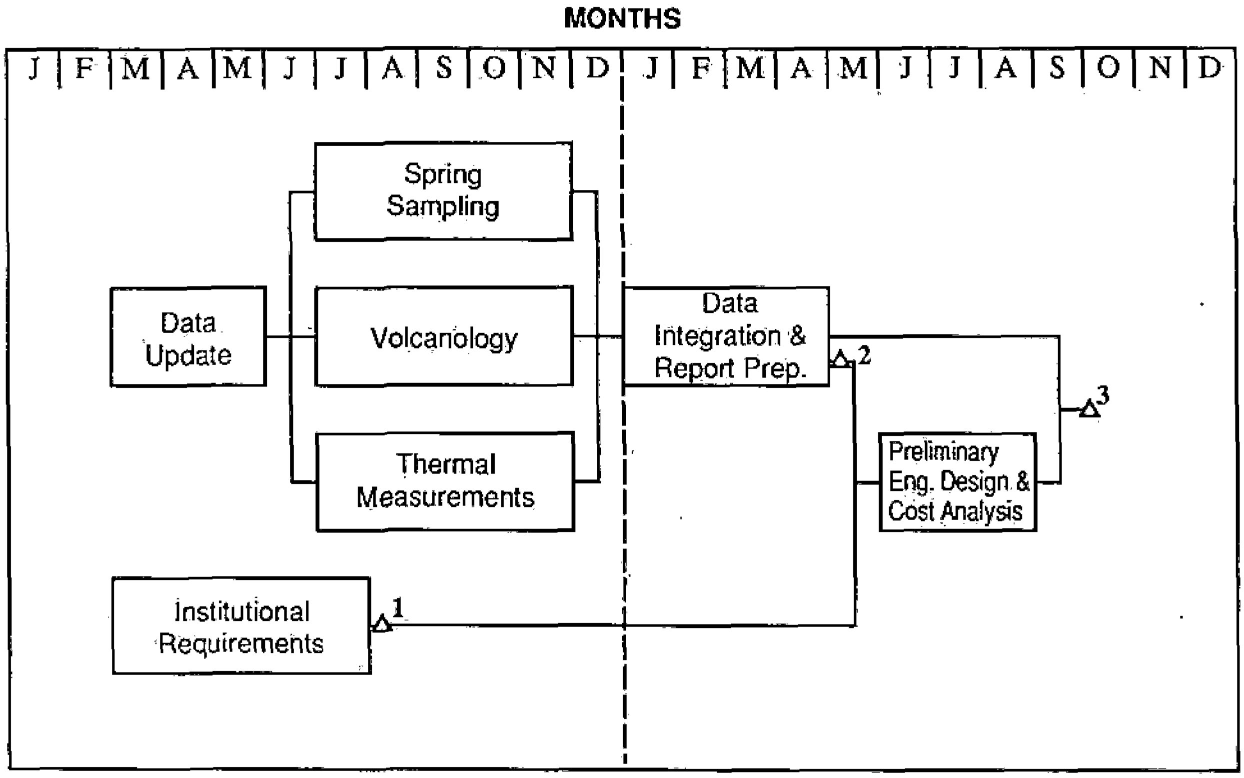
3. Volcanology. The age, chemistry and formation history of volcanic rocks have important implications for the geothermal potential. The young volcanoes within the two defined assessment areas will be visited and sampled.

4. Thermal measurements. Temperature profiles should be measured in boreholes drilled for water and mineral production. When prospect sites are identified, holes can be drilled for thermal measurements by the Ministry of Energy and Minerals.

5. Preliminary engineering design and cost analysis. Generic engineering studies can be based on estimated depth, temperature, and flow rates of the resource. These factors will determine the size, depth and number of wells, pumping requirements, optimum power generation equipment, and brine disposal options. Site-specific cost factors include proximity to the power grid or other point of utilization and infrastructure requirements for installing, operating and maintaining the plant. Weighed against these cost factors are the potential revenues from different applications.

6. Institutional requirements. For any of the privatized devlopment options listed below to be realized, Tanzania must establish institutional requirements. These include provisions for exploration concessions, environmental regulations, royalties, steam or electrical sales contracts, and provisions for repatriation of profits. The entry of U. S. companies into Kenya is presently being held up pending the publishing of rules governing geothermal concessions. Under this component of the assessment, model contracts and regulations will be provided to the Tanzanian government with encouragement for their implementation. A local partner familiar with Tanzanian governmental process would be required for this part of the project.

Figure 2 is a schedule and flow chart for the proposed resource assessment. The investigations of the resource and the institutional requirements run simultaneously. The results of both of these components are required for the preliminary engineering design and cost analysis. Following the completion of this analysis, the resource assessment report would prioritze the individual candidates for development. This report would be presented to U. S. industry at a National Geothermal Association workshop. The entire resource assessment would require approximately 1.5 years and cost approximately $700,000. The schedule shown in Figure 2 is "fast track". Visiting Tanzania, one gets the impression that delays are inevitable. Drilling offered through the Ministry of Energy and Minerals could also slow the schedule. In addition, funding considerations may make it appropriate to spread out the schedule.



Deliverables (△)

1. Recommendations for institutional requirements
2. Geothermal resource report
3. Resource assessment report and workshop

Figure 2. Schedule and Flow Chart for Resource Development.

6.3 Resource Development

Resource development can follow a number of different scenarios, all of which have potential for U. S. geothermal export. The following are some of the most likely options.

1. Ministry of Energy and Minerals. Exploration and development by the Ministry with power produced by Tanesco is one likely option. In this case, capital requirements may be satisfied by the World Bank power development loan. Export opportunities consist of sale of equipment and services.

2. Private power development. The options for Build Own Operate and Build Own Transfer power development were explained to a number of individuals and no negative response was received. However, the purpose of the mission was primarily for resource assessment and so no real attempt was made to get committments for private development. The critical problem would be repatriation of profits. The principal advantage would be that privatized geothermal power would not add to Tanzania's debt.

3. Privatized power coupled with an exportable commodity. Tanzania desires to develop its mineral resources for export purposes. Electrical and possibly thermal power will be required for these operations. By coupling geothermal development to the production of a natural resource, the issue of repatriation of profits may be avoided. The geothermal producer could be paid when the commodities are sold on the world market. The project most often discussed by the Tanzanians was soda ash at Lake Natron. However, there are also opportunities for the production of gold and diamonds.

7. REFERENCES

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