GEOTHERMAL FEATURES OF MOZAMBIQUE - COUNTRY UPDATE

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KEY WORDS - Fluid geochemistry, heat flow, preliminary assessment, Mozambique.

Key words: geothermal exploration. geothermal manifestations, heat flow, Mozambique

ABSTRACT

Geological aspects of Mozambique have been described since the beginning of this century. Tectonic trends related to the Rift Valleys have always attracted attention, mainly by researchers involved in studies related to mineral exploitation, but geothermal manifestations have usually been considered as no more than natural curiosities. Recent geochemical and geophysical evaluations confum the possible existence of significant amounts of geothermal energy. This is important in a developing country like Mozambique, where the economics and reliability of equipment play important roles when comparing energy sources.

INTRODUCTION

Mozambique has a diversity of energy resources, but relies on imported petroleum and petroleum products for 75% of its commercial consumption. Hydroelectric potential exceeds 11,000 MW, coal is being mined in remarkable volumes, gas has been found in several areas, and there is renewed interest in oil exploration. Energy is an important element in Mozambique's development strategy because it is a source of foreign exchange and a catalyst for industrial progress. However, logistic problems, shortage of qualified manpower, and financial limitations are obstacles to normal operations and to policy and planning decisions.

The main objective for the medium and long term is to become self-sufficient in energy, production. To attain this objective, Mozambique is attempting to establish conservation programs and to develop domestic energy resources for the national and international market (see also UNDP/World Bank, 1987).

THE OBJECTIVES OF MOZAMBICAN ENERGY POLICY

Table I provides estimates for the contribution of different energy forms in Mozambique (Mozambican Government Paper, 1981; U.N., 1990/91).

TABLE I

	1979 %
Hydroelectric power	44
Fuel wood	30
Oil	12
coal	10
Agriculture Waste	4

While oil represents only 12% of energy needs, it has a considerable portion of the National Hard Currency Budget.

To emerge from the existing underdeveloped situation, the current policy is to develop large amounts of cheap and renewable energy in order to meet requirements of large industrial and agriculture schemes.

A permanent attention to technological evolution of new and renewable sources of energy (including geothermal, wind, waves and solar energy) is in the objectives of Mozambican energy policy (see also S.A.D.C.C., 1982).

Geothermal energy can therefore be

considered as a potential energy source within the frame of current economic trends.

PREVIOUS STUDIES ON GEOTHERMAL ENERGY IN MOZAMBIQUE

East Africa is intersected by a system of rift faults running north-south and characterized by relatively high seismicity (Kebede and Kulhanek, 1992) and volcanic manifestations.

These tectonic disturbancies strongly affect crustal permeability and allow the development of intense hydrothermal fluid circulations.

Hydrothermal fields are well known in East Africa and some Countries, have been investigated for siting of geothermal power plants as in Ethiopia, Kenya, the Republic of Djibouti, and Zambia (see also ELC, 1982).

A preliminary evaluation of local geothermal potential in unexplored areas was completed by McNitt (1978; 1982), who considered the presence of recent volcanism, hot springs, and other geological macro-indicators. On the basis of the distribution of hot springs the Mozambican geothermal potential was evaluated at 25 electrical MW. This estimate is probably conservative since it was based on a preliminary investigation of Koenig (1981) which identified only 26 hot springs in Mozambique, while our map shows that there are at least 38 emergences. (Fig. A)

Other preliminary considerations on geothermal potential of Mozambique were made by BRGM (1980), Aquater (1980), and Direcção Nacional de Geologia (1981). On the basis of volcanological and geological features, the BRGM (1980) proposal described the following areas as promising: the Zambesi and Chire Valleys, the Cabo Delgado area, the Carinde-Zambesia area, the Manica area, and the Zambesi-Limpopo area. The Aquater (1980) proposal focussed attention on volcanological features of Zambesia, Tête, Sofala, and Manica Provinces and on the presence of hot springs. The Direcção Nacional de Geologia report delt with proposals of BRGM, Aquater and the United Nations which are compared with local knowledge mainly described in the Mapa Metalogenica da Republica Popular de Mozambique. On the basis of its evaluation the Direcçao Nacional de Geologia assigned priority to the following areas for funher study: the Chire Urema Valleys, the Zambesi Valley, the Niassa Lake area, and the areas of Ilha de Mozambique, Pebane, Vila Necungas, Espungabera and Rio Lugenda-Rovuma.

A complete check on available and past documentation on hot springs, heat flow and geological features has been carried out, and, this has resulted in a better knowledge of geothermal features of Mozambique.

GEOLOGICAL AND GEOTHERMAL FEATURES

Mozambique occupies 783,000 km², of which one-tenth lies within the East African rift system or within grabens and fracture zones marginal to the rift.

In terms of surface geology (Afonso, 1976; Afonso, 1978; Läechelt, 1985), the country can be divided into:

1 - Crystalline and metamorphic terrains, mostly of Precambrian age (but including Mesozoic and Late Paleozoic bodies) forming the northern and western half of Mozambique;

2 - Late Mesozoic and Cenozoic sedimentary cover, forming a wedge thickening to the east and south that was in part deposited on the crystalline basement.

The rift system cuts through the crystalline terrain, and either terminates against the Cenozoic cover or is buried beneath it. Earthquake seismicity suggests southward continuation of the rift zone beneath the Cenozoic cover (Kebede and Kulhanek, 1992) Tertiary and Quaternary development of the rift system is indicated in northern Mozambique by steep fault scarps, across which Quaternary sediment is juxtaposed with largely Precambrian crysstalline rock. This is especially true further north in neighbouring Malawi.

Late Mesozoic to Early Tertiary alkaline instrusive and extrusive bodies are principally located along marginal fracture systems. Basalt and carbonatite extrusive, probably of Late Tertiary age, are found along the western boundary of the rift system. Late Tertiary and/or Quaternary volcanics also appear to be located along faults marginal to the western rift boundary (along with the Late Mesozoic igneous bodies) and along the fault-controlled border between crystalline basement and Late Tertiary-Quaternary cover in northeastern Mozambique. A third possible locus of Late Tertiary-Quaternary volcanism is a graben extending from the Tanzanian border in to north-eastern Mozambique (BRGM, 1980).

At least 38 thermal springs are now recognized in Mozambique (Fig. **A).** The most interesting geothermal area is within the rift just north of Metangula on Lake Niassa where vigorously boiling water was reported at the lake's edge in the years prior to the rise in water level (de Freitas, 1959). Today, there is evidence of hot spring source, and thermal disturbances due to the vapor source affect the waters of the lake within a radius of several hundred meters. No geochemical data are available for this source, so the chemical composition of neighbouring Malawi springs were utilized for preliminary geothermometrical evaluations.

Several lower temperature springs below 60' C) issue from Mesozoic crystalline terrain along and west of major faults in the Espungabera-Manica areas, near the border with Zimbabwe. Numerous other thermal springs have been reported on the Zimbabwe side of the border, including a boiling spring (Mazor and Verhagen, 1976).

HYDROGEOCHEMISTRY

Published major element chemistry of a set of water samples from Mozambique (de Freitas, 1959, Fernandes, 1975, Serrano Pinto, 1983), together with the composition of four thermal springs located along the western shore of Lake Malawi (Muller, 1973), are reported in Table II. The composition of water samples from Zambia (Legg, 1974) and some incomplete chemical analyses are also given. The location of sample sites and the temperature of the water are shown in Fig. A and in Table II (bis).

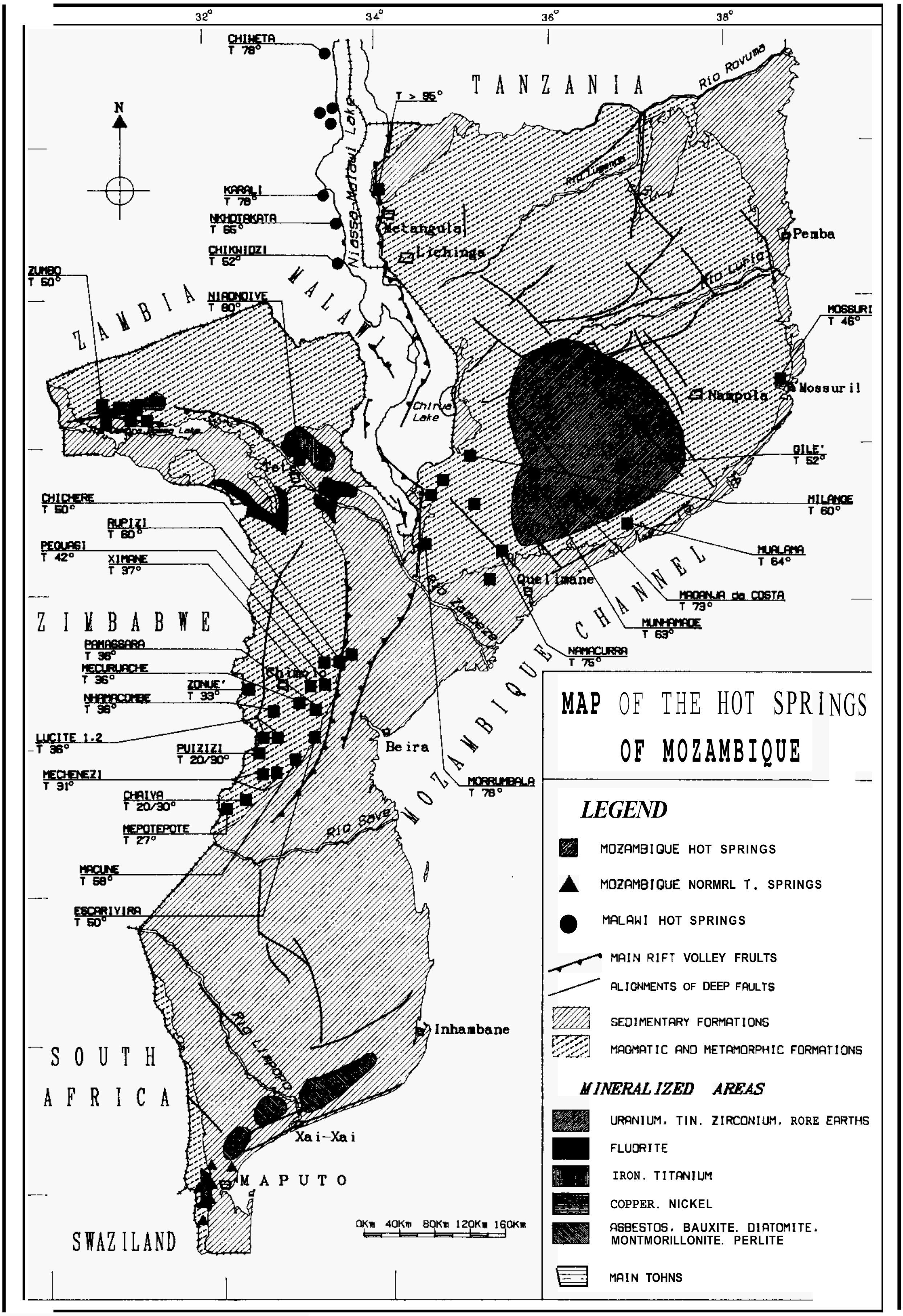
The squared diagram (Fig. B) of Langelier Ludwig (1942) suggests two distinct water groups:

a) A group of chloride-sulphate alkaline waters, essentially located in the Zambesia district and towards the south in the Sofala and Manica districts. The thermal waters belong to this group. They have sodium as the major cation and chloride ad the major anion. The highest emergence temperature is 80 'C; silica content doesn't exceed 100 mg/kg;

b) A group of acid carbonate-alkaline waters located in the southern part of the country around Maputo. They are typical CO_2-rich waters with moderate total dissolved ion concentrations and cold emergence temperatures. Sodium is the most abundant cation. This group also includes the Lake Niassa-Malawi thermal manifestations, which are characterized by high emergence temperatures (up to 78 °C), and very low concentrations of calcium and magnesium. The silica contents of these latter springs are higher than those of the first group.

The relationship between alkalinity and the total content of dissolved solids (TDS), shown in Fig. C, confirms the existence of two main water types, with the highter salinity values being observed in the chloride-sulphate waters. Salinity values even higher than those shown in Fig. B are indicated in Table II among the incomplete analyses. Even in these waters the relationship because chloride and sulphate ions and salinity point to the same pattern.

Fig. A - Locality map showing sample sites and water temperature. Main mineralized areas are also indicated.



Map elaborated by the Laboratorio Cartografico dell' Istituto di Scienze della Terra - Messina (Dr. A. Tripodo)

Table II - Chemical data for the springs discussed in this study. Ion concentrations are expressed in meq/l. Silica and total dissolved salts (TDS) are expressed in mg/kg. References: data for Mozambique waters (samples 2242) from de Freitas (1959) and Senano Pinto (1983); data for Malawi springs (samples MALI-MALA) from Muller and Forstner (1973); data for Zambia (samples Kapisya-Gwisho) from Legg (1974).

Sample	T °C	TDS	Cl	SO4	HCO3	Ca+Mg	Na+K	Na	K	Ca	Mg	SiO2
1		3190	37,50	0.71		19.20						
2		3568	38,80			19.80						
5		677	5,30	0.34		2.20						
6		24118	312,00	29.71		150.80						
7		242	0,60	0.05		2.20						
8		1103	9,40	1.01		8.40						
9		4732	54,80	12.25		13.20						
10		9948	132,10	14.17		36.40						
11		804	6,00	1.15		0.70						
12		2926	36,30	4.60		11.30						
13		4454	56,60	6.74		18.20						
15		608	7,10		2.23	3.06						
16		188	0,70		1.31	2.32						
17		563	2,20	0.76	6.51	1.40	8.13					
18		294	1,80	0.76	1.15	0.48	3.18					
19		858	6,60	0.01	7.64	8.54	5.70					
20		808	5,40	0.10	7.42	0.40	12.50					
21		224	1,10	0.01	0.53	0.60	1.00					
22		463	1,60	0.37	2.80	0.98	3.86	3.83	0.03	0.58	0.40	28.0
23		1212	1,00	1.55	10.07	2.50	10.24	10.13	0.11	1.13	1.37	67.2
24		433	1,00	0.08	1.80	0.85	2.07	2.02	0.05	0.45	0.40	49.6
25		449	1,00	0.13	1.92	0.82	2.22	2.21	0.01	0.48	0.34	38.6
26		1140	2,50	4.00	9.08	6.14	9.46	8.96	0.50	3.19	2.95	95.0
27		783	3,20	0.07	4.80	2.12	5.92	5.82	0.10	1.20	0.92	79.5
28		224	1,10	0.07	0.60	0.21	1.52	1.43	0.09	0.08	0.13	25.2
29		159	0,40	0.01	1.07	0.61	0.85	0.81	0.04	0.39	0.22	41.0
30		67	0,20	0.05	0.72	0.70	0.25	0.16	0.09	0.15	0.55	16.04
31	63	948	1,90	9.73	0.88	0.10	8.90	8.89	0.01	2.60	0.08	87.0
32	46	7982	120,80	13.42	0.60	55.90	78.92	78.70	0.22	55.40	0.48	29.0
33	33	243	0,50	0.30	2.20	0.18	2.70			0.08	0.36	72.0
34	60	602	2,20	3.10	1.92	4.85	2.37			4.85	0.01	
35	60	1073	6,70	7.15	0.82	1.74	12.90			1.58	0.16	84.8
36	47	3786	47,70	5.67	0.24	21.50	32.10			20.30	1.20	66.8
37	52	1265	4,30	12.30	0.66	4.94	12.28	11.90	0.38	4.74	0.20	81.2
38	64	1777	12,10	13.60	0.40	9.00	17.18	16.37	0.81	8.80	0.20	63.6
39	73	5489	80,60	10.06	0.29	42.91	47.79	45.70	2.09	42.84	0.07	81.0
40	75	8147	129,30	5.59	0.29	63.25	71.43	69.70	1.73	63.20	0.33	87.2
41	80	1554	12,30	9.25	0.75	3.76	18.51	18.02	0.49	3.68	0.08	95.6
42	78	626	2,70	1.58	3.68	0.39	7.52	7.31	0.21	0.30	0.09	97.2
MAL 1	78	1610	9,90	1.35	9.10	1.10	20.49	19.90	0.59	0.85	0.25	140.0
MAL 2	78	413	0,30	0.98	2.29	0.07	4.64	4.61	0.03	0.06	0.01	105.0
MAL 3	65	985	0,50	0.42	9.02	0.28	12.34	12.26	0.08	0.22	0.06	90.0
MAL 4	52	1031	0,80	0.42	10.20	0.16	11.80	11.74	0.06	0.12	0.04	80.0
kapisya	85		2,30	1.35	0.59			4.35	0.13	0.25	0.08	30.0
kaputa	51		33,90	7.40	0.49			34.78	0.15	5.99	1.48	24.0
mansa	49		3,30	1.56	0.20			3.13	0.13	1.85	0.08	25.0
luano	80		40,10	20.00	0.30			42.61	1.66	15.47	0.82	30.0
lubungu F	76		22,60	22.08	0.39			26.09	0.77	18.46	0.08	40.0
longola	70		5,80	13.54	0.59			17.39	0.46	2.50	0.41	40.0
nabwalya	67		4,80	18.96	0.39			21.74	0.67	2.00	0.08	40.0
Musaope	74		1,00	20.83	1.80			21.74	1.02	2.50	0.08	40.0
kanzi	35		3,70	2.71	0.39			11.74	0.23	17.47	0.08	20.00
mililo	65		3,40	2.08	0.79			5.22	0.26	0.85	0.08	40.0
kalingala	50		1,80	4.79	4.03			13.04	0.38	1.10	0.33	20.00
mafwas	60		1,40	10.83	0.82			11.74	0.36	1.80	0.08	40.0
chibim	58		0,30	2.40	1.77			4.35	0.10	0.15	0.08	40.0
mosali	52		0,70	3.96	0.98			6.09	0.26	0.35	0.08	40.0
bwanda	94		7,80	9.38	0.69			13.91	0.87	2.74	0.99	40.0
gwisho	72		12,70	20.21	0.79			28.26	1.15	4.74	0.16	40.0

Table II bis - List of Mozambique's waters discussed in this pages and closest place-names. Four samples from Malawi (Mal 1,2,3,4) **and sixteen samples from Zambia** (Kapisia - Gwisho) **are also listed.**

GAZA

Locality	*Sample N'*
Magude	1
Mapulanguene	S1 2
Chacana	5
Panjane	6
Chivonguene	7
Mamessane	8
Chobela	S1 9
Chobela	S2 10
Chobela	S3 11
Chobela	S4 12
Chobela	S5 13
Limaze	15
Dongo	16

MAPUTO

Locality	*Sample N'*
Porto Henrique	17
Changalane	S1 18
Changalane	S2 19
Changalane est.geof	20
Marracuene Villa Luisa	21
Quinta Herminia	22
Sabié- Moamba	23
Namaacha-Goba 2	24
Namaacha-Goba 3	25
Sabié-Ressano Garcia	26
Namaacha-Goba 5	27
Panic Ferrao-Namaacha	28

CABODELCADO

Locality	*Sample N'*
Montepuez-Inquingire	29
Mossuril	32

ZAMBEZIA

Locality	*Sample N'*
Morrumbala-Metolola	30
Munhamade	31
Milange	34
Gilé	37
Mualama	38
Mualama	38
Maganja	39
Namacurra	40
Morrumbala	42

MANICA-SOFALA

Locality	*Sample N'*
Zonué	33
Rupizi	35
Chichere	36

TETE

Locality	*Sample N'*
Niaondive	41

MALAWI

Mal 1
Mal 2
Mal 3
Mal 4

ZAMBIA

Kapisya
Kapuia
Mansa
Luano
Lubung
Longola
Nabwal
Musaop
Kanzi
Mililo
Kalinga
Mafwasa
Chibim
Mosali
Bwuanda
Gwisho

A plot of 10Mg/10Mg+Ca versus 10K/10K+Na in considered by Giggenbach (1988) as a good method of distingushing between isochemical dissolution of igneous rocks and waters having attained thermodynamic equilibrium with crustal rocks as a function of temperature. In such a diagram (Fig.D), the Mozambique thermal waters plot close to the full equilibrium line with apparent equilibrium temperatures in the range 140°-180°C. Cold bicarbonate waters plot in the upper part of the diagram, far from the equilibrium line, indicating excess magnesium and sodium. High magnesium concentrations are generally considered an indication of low temperature. As these waters are likely to have formed by direct reaction between CO_2 - charged waters and the aquifer rocks, their magnesium enrichment reflects high non-equilibrium CO_2 contents. On the other hand free CO_2 is reported to widely occur in these waters. Low temperature reactions may have also altered potassium concentrations by uptake of K from secondary clays. The thermal springs of Malawi occupy positions in Fig. D that suggest close approach to full equilibrium at moderately high temperature (<100 °C).

The trilinear diagram of Fig. E (Giggenbach, 1988) indicates the degree to which water approaches fluid-rock equilibrium The full equilibrium condition is established by the intersections of two set of isotherms describing the temperature dependence of

Table III - Geothermometrical computations on water samples from Mozambique, Malawi and Zambia.

Sample	T'C	Na	K	Ca	Mg	SiO2	TQC	TQA	TCH	a−Cbr	β−Chr	Amor - SiO2	Na/K	Na-K-Ca β = 4/3	Na-K-Ca β = 1/3
22			0.03	0.58	0.40	28 0	77	81	45	27	-18	-35			
23		10.13	0.11	1.13	1.37	67.2	116	115	87	66	18	-2	105	77	107
24		2.02	0.05	045	040	496	101	102	71	51	4	-14	153	56	125
25		2.21	0.01	0.48	0.34	38 6	90	92	39	40	-6	-24	76	21	73
26		8.96	0.50	3.19	2.93	95.0	I34	130	107	84	35	14	213	105	171
27		5.82	0.10	1.20	0.92	79 5	125	I22	97	74	26	6	130	67	118
28		1.43	0.09	0.08	0.13	25.2	72	77	41	23	-22	.39	219	107	175
29		0.81	0.04	0.39	0.22	41.0	93	93	62	43	-4	-22	194	41	138
30		0.16	0.09	0.15	055	16.4	56	62	24	7	-36	-52	329	69	261
31	63.00	8.89	0.01	2 60	0.08	87 0	130	126	102	79	31	10	I7	1	32
32	46.00	78.70	0.22	35.40	048	290	78	82	47	28	-17	-34	47	42	63
33	33.00			0 08	036	720	120	118	91	69	21	1			
34	6000			4.85	0 01										
35	6000			1.58	0.16	84 8	128	125	101	78	29	9			
36	47.00			20.30	120	668	116	115	87	65	18	-2			
37	52.00	11.90	0.38	4.74	0.20	81.2	126	I23	98	75	27	7	170	89	145
38	64.00	16.37	0.81	8.80	0.20	63.6	113	113	84	63	15	-4	203	105	166
39	73.00	45.70	2.09	42.84	0.07	81 0	126	123	98	75	27	7	1%	114	166
40	75.00	69.70	1.73	63.20	0.33	87.2	I30	I26	102	79	31	10	153	102	141
41	80.00	18.02	0.49	3.68	008	95 6	135	131	108	84	36	15	159	109	146
42	78.00	7.31	0.21	0.30	0.09	97.2	I36	131	109	85	36	16	162	131	154
MAL 1	78.00	19.90	0.59	0.85	025	140 0	157	149	133	107	57	33	165	162	163
MAL2	78.00	4.61	0.03	006	0.01	105 0	140	135	114	89	41	19	83	96	101
MAL3	65.00	12.26	0.08	0.22	0.06	90 0	131	128	104	81	32	12	79	105	100
MAL4	52.00	11.74	0.06	0.12	0.04	80.0	125	122	97	74	26	6	67	108	93
kapisya	85.00	4.33	0.13	0.25	0.08	30.0	79	83	48	30	-16	-33	I64	108	148
kaputa	51.00	34.78	0.15	5.59	1.48	24.0	70	73	39	21	-24	-40	*64*	66	80
mansa	49.00	3.13	0.13	1.85	0.08	25 0	72	77	40	23	-22	-39	188	*60*	143
luano	80.00	42.61	1.66	15.47	0.82	30.0	79	83	48	30	-16	-33	184	132	166
lubung	76.00	26.09	0.77	18.46	0.08	40.0	92	94	61	42	-5	-23	164	91	143
longola	70.00	17.39	0.46	2.30	0.41	40.0	92	94	61	42	-5	-23	157	117	147
nabwal	67.00	21.74	0.77	2.00	0.08	40.0	92	94	61	42	-5	-23	177	I48	167
musaop	74.W	21.74	1.02	2.30	0.08	40 0	92	94	61	42	-5	-23	199	155	180
kanzi	35.00	11.74	0.23	17.47	0.08	20.0	63	69	31	14	-30	-46	138	47	115
mililo	65.00	3.22	0.26	0.83	0.08	40.0	92	94	61	42	-3	-23	202	106	166
kalinga	50.00	13.04	0.38	1.10	0.33	20.0	63	69	31	14	-30	-46	164	128	154
mafwas	60.00	11.74	0.36	1.80	0.08	40.0	92	94	61	41	-5	-23	166	110	150
chibim	58.00	4.35	0.10	0.15	0.08	40.0	92	94	61	42	-5	-23	149	113	142
mosali	52.00	6.09	0.26	0.33	0.08	40.0	92	94	61	41	-5	-23	190	132	169
bwanda	94.W	13.91	0.87	2.74	0.99	40.0	92	94	61	42	-5	-23	222	138	186
gwisho	72.00	28.26	1.15	4.74	0.16	40.0	92	94	61	42	-5	-23	187	144	171

Figure B - Langelier - Ludwig diagram for the springs discussed in this study

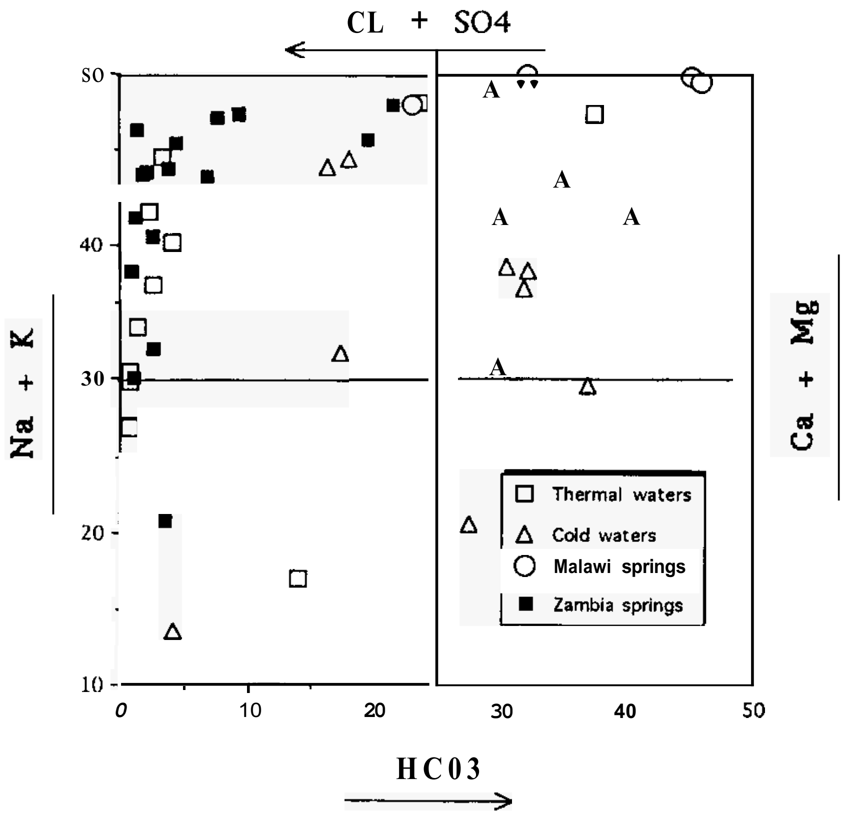


Figure C - Relationship between alkalinity and total dissolved salts

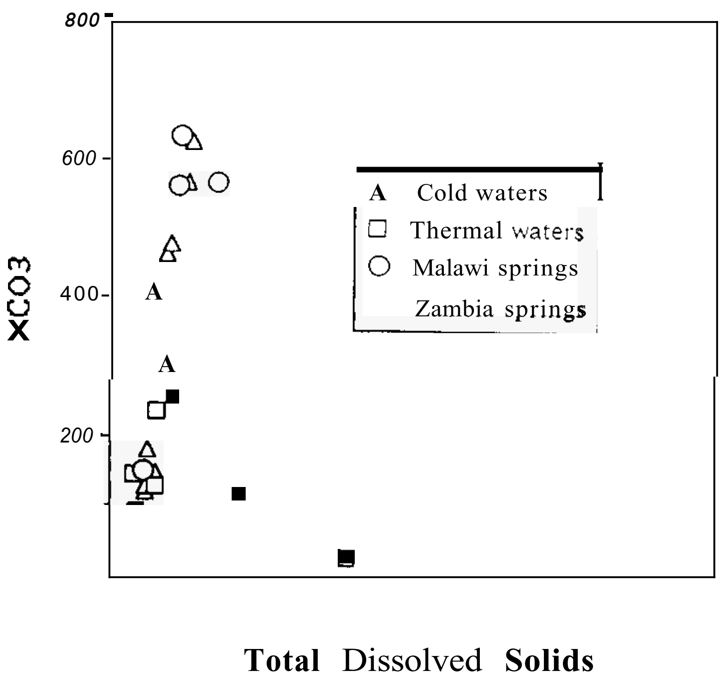


Figure D - Plot of 10Mg/10Mg+Ca versus 10K/10K+Na. The shaded area represents isochemical dissolution of basalt (BA), granite (GR) and average crustal rock (AC). The solid line indicates the expected composition of waters in thennodynamic equilibrium with an average crustal rock as a function of temperature.

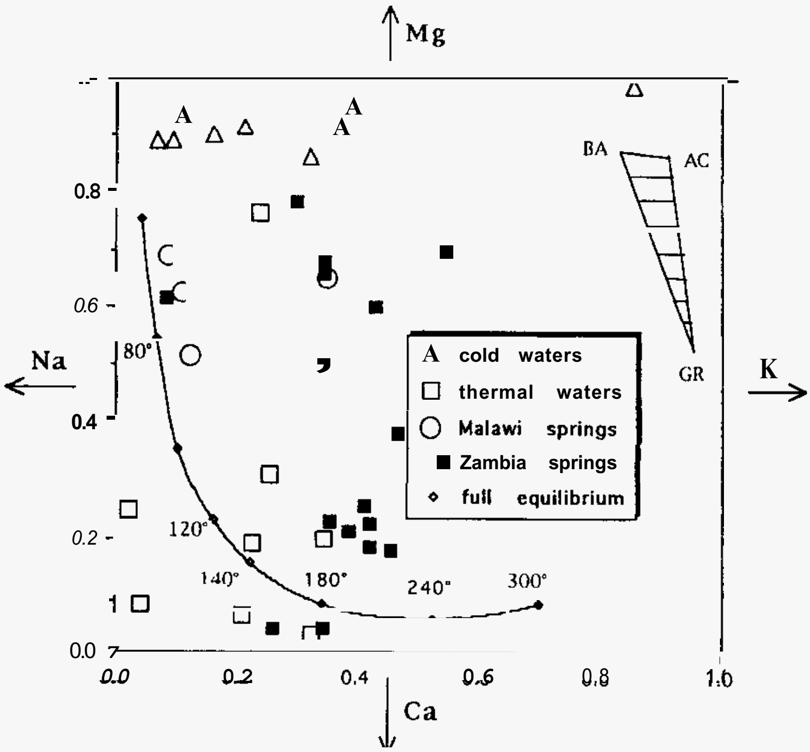


Figure E - Trilinear plot of Na, K and Mg content drawn according to Giggenbach (1988). Black dots represent Zambian samples, triangles represent Malawian samples, black squares represent Mozambican samples. white dot is the seawater.

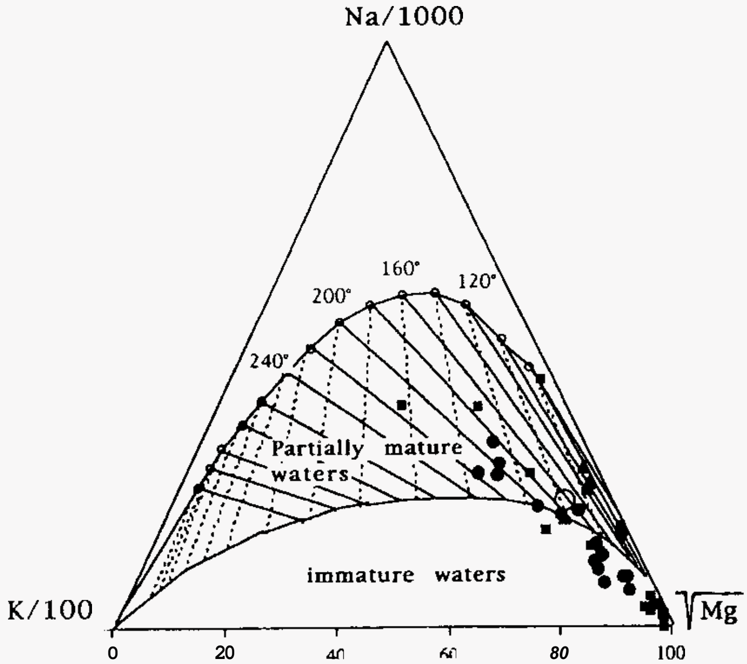
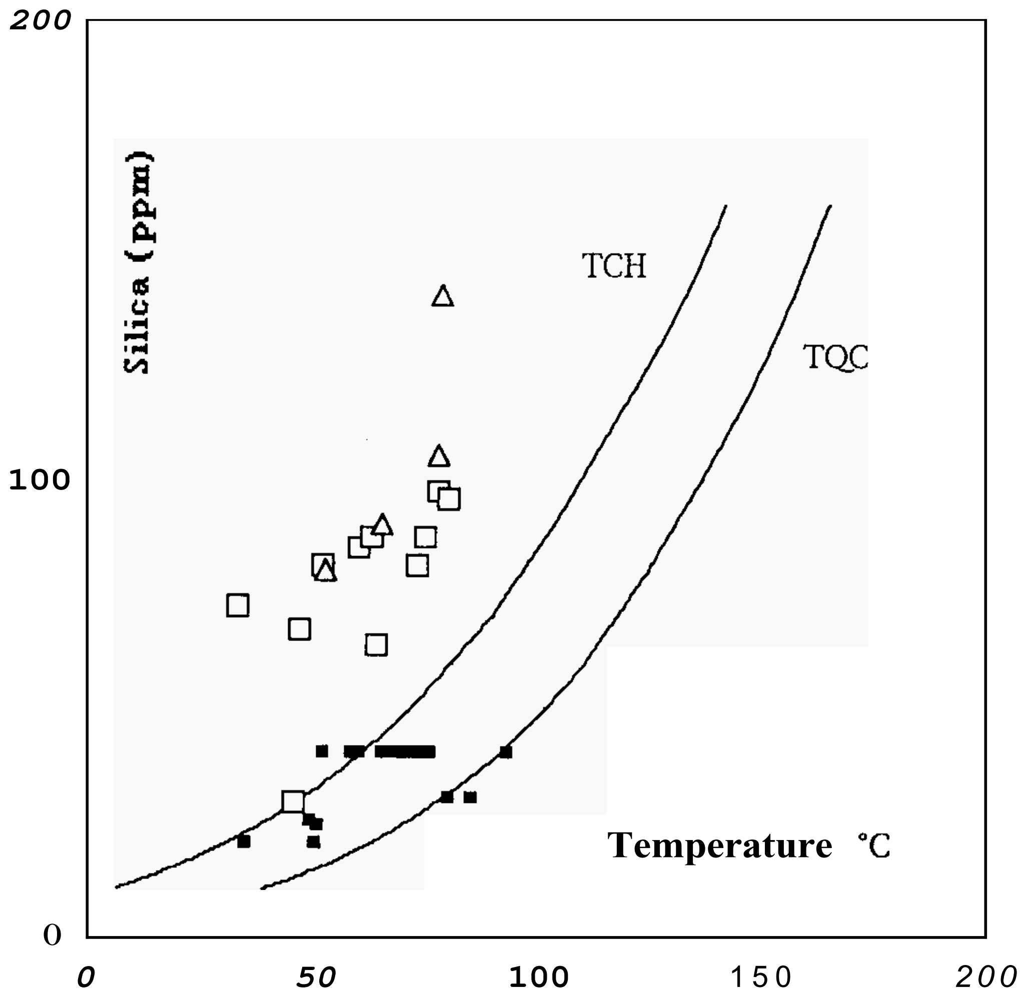


Figure F - Plot of silica content vs. measured temperature. Silica concentrations expected for chemical equilibrium with respect to quartz (TQC) and chalcedony (TCH) are also drawn. Black squares are referred to Zambia samples.



K/Na (Lkn) and K2/Mg (Lkm) ratios according to:

Lkn = log(K/Na) = 1.75 - 1390/T
with T the absolute

Lkm = log(K2/Mg) = 14.0 - 4410/T
temperature in K.

Mossuril spring and Lake Malawi thermal springs plot on the equilibrium lie, indicating attainment of water-rock equilibrium at 80°C. Among the samples falling in the field of "partially mature waters" we distinguish:

a) two springs, Maganja da Costa and Namacurra, in the middle of the triangle, which have emergence temperatures of 74°C, and

b) Niaondive spring (80°C), which is close to the lower boundary of the field suggesting attainment of partial equilibrium at higher temperature.

The remaining thermal springs and the group of the bicarbonate-alkaline waters fall in the field of "immature waters", close to the Mg comer. However, they lie above the isochemical dissolution line, suggesting removal of alkaline metals.

As suggested by Giggenbach the Na-K-Mg geothermometer may be applied with confidence for samples on or close to the equilibrum line. Therefore, the most reliable deep temperature indicated by the geothermometer seems to be around 80°C (Tab. III).

Dissolved silica in Mozambican waters ranges from 30 to 90 ppm, with an average value of 70 ppm. Fig. F depiets silica concentrations in thermal waters versus temperature. Silica concentrations expected for chemical equilibrium with respect to quartz and chalcedony are also drawn.

The data points are closer to the chalcedony curve, suggesting that this mineral phase could be controlling dissolved silica According to Arnorsson's (*1975*) data for Icelandic wells, geothermal waters below 120°C are in equilibrium with chalcedony, while saturation with respect to quartz occurrs in geothermal waters above 180°C. Even estimated reservoir temperatures based on quartz conductive and quartz adiabatic geothermometers are no higher than 110°C (Tab. III).

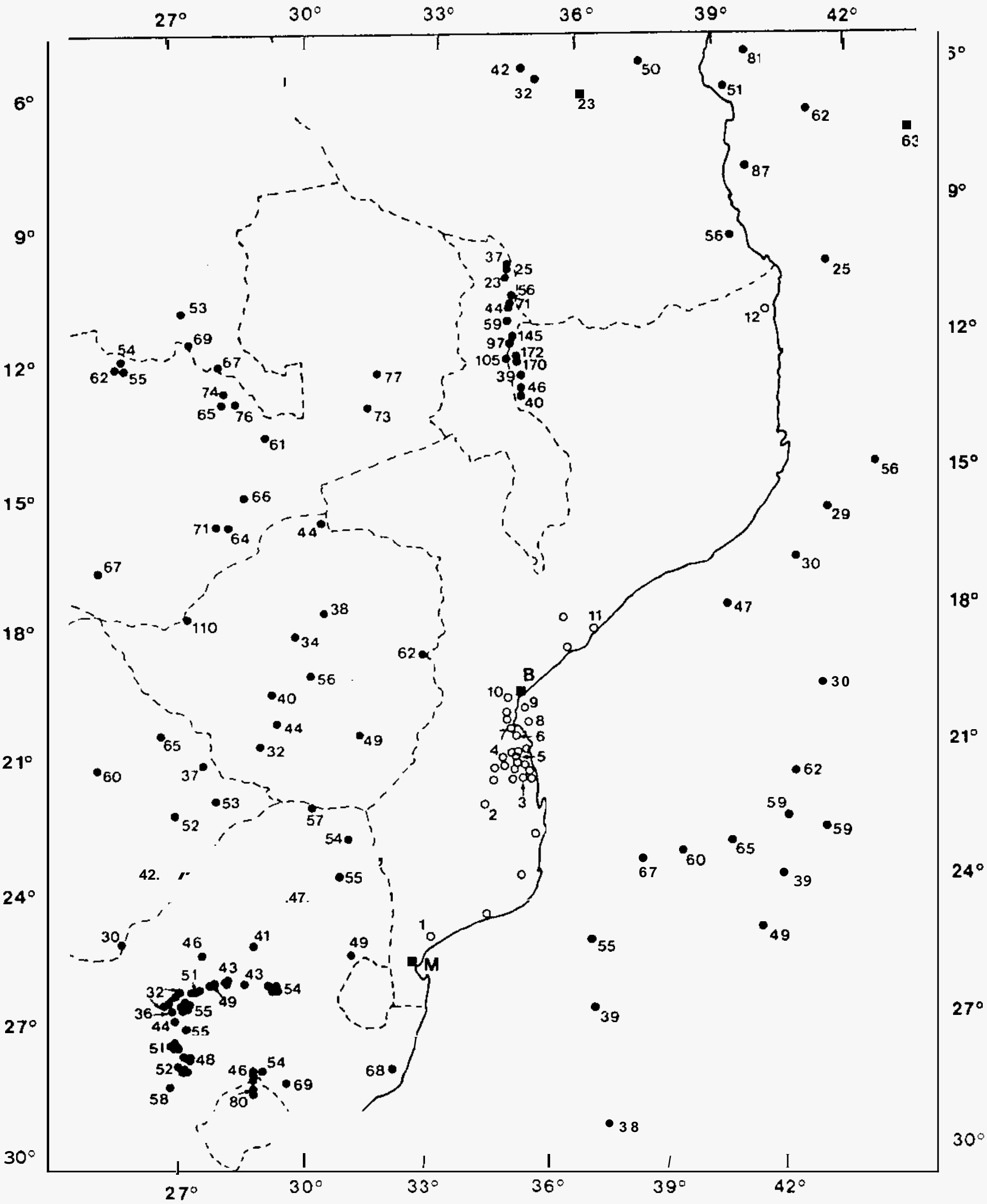
Temperatures obtained from silica content are considerably lower than those from the alkali geothermometers. However, they are similar to estimated temperatures of the fully equilibrated water samples in Fig. **E.** Similar conclusions can be drawn **for** water samples from Zambia It is unlikely that mixing phenomena are responsible for a generalized reduction of SiO_2 concentration in Mozambique, Malawi and Zambia Low silica concentrations are more probably attributable to regional petrochemical trends of relatively silica-poor rocks.

Despite these problems, general agreement obtained using independent chemical geothermorneters seems to indicate the existence of aquifers at temperature of about 100°C and these are worthy of further accurate study as sources of low-medium enthalpy geothermal energy. The fact that a number of samples reach the full equilibrium line suggests that there are consistent circulation path flows and related fluid availability.

PRELIMINARY ASSESSMENT OF BOTTOM HOLE TEMPERATURE DATA FROM PETROLEUM WELLS

To date there has been little opportunity for heat flow research in Mozambique, but bottom hole temperature (BHT) measurements in petroleum wells provide information which has been used with reasonable **success** elsewhere have [e.g. Chapman et al., 1984; Deming and Chapman, 1988; Lam et al., 1982; Majorowicz and Jessop, 1981; Majorowicz et al., 1986; Speece et al., 1985]. Here we analyze BHT data from wells in Cretaceous-Tertiary sedimentary basins of coastal Mozambique to estimate geothermal gradients and heat **flow.** Problems associated with the use of BHT data for this purpose include the accuracy of the BHT data, estimation of equilibrium temperatures from these measurements, and **assigning** thermal conductivities. Unfortunately, the available data (Koenig 1981, Salman at al. 1985) contain insufficient information for a

Figure G. Petroleum well localities in Mozambique (open circles, numbers refer to individual wells in Table IV. Published heat flow data in southeast Africa (closed circles, heat flow in mW m?; data from Ballard et al., 1987; Chapman and Pollack, 1977; Ebinger et al., 1987; Jones, 1988, 1992a, 1992b; Nyblade et al., 1990; Pollack et al., 1990; Sebagenzi et al .. 1993). M, Maputo; B, Beira.



thorough analysis, and the results must be regarded as preliminary.

BHT data from 35 wells in the Mozambique basin (Fig. G) were extracted from reports by Empresa Nacional de Hidrocarbonetos de Mqambique (ENH) and Elecmcidade de Mqambique (EDM) (Koenig, 1981; Salman et al., 1985). The reports contain little information on the history of temperature measurement, except that most recordings appear to have been made after a stabilization period of 6-10 hours. It was therefore not possible to estimate equilibrium temperatures from temperature-time plots, and nor was the gradient correction of the American Association of Petroleum Geologists attempted because of the lack of local control data (see Speece et al., 1985 for discussion). Instead, a thermal gradient was calculated from observed BHTs and a correction was applied to this value (see below).

The entire data set from the Mozambique basin is plotted in Figure H. A least squares fit to the data yields a slope of 20.8 mK m^{-1}. In an attempt to reduce the scatter we have discarded points that appear to be inconsistent. These include: (1) a number of relatively shallow points which yield spurious thermal gradients compared with deeper BHTs and which may be affected by ground water movement in upper levels of the basin, (2) some the deepest BHT data in a which also yield spurions results that may be associated to fact that some of the deeper wells penetrate Stormberg lava below the basin's sediments, and (3) all results from two wells, the first having erratic gradients and high temperatures, which were suspected as artificial (Koenig, 1981) and the second having BHT's that were offset to higher temperature by about 25 °C compared with the rest of the data set. Details of the screening process will be discussed elsewhere. The "cleaned" data set is plotted in Figure K which shows considerably less scatter, Figure H although the least squares thermal gradient, 21.1 mK m^{-1}, is not significantly different.

We also calculated temperature gradients for eleven wells with two or more BHT measured over long depth intervals. The results are summarized in Table IV. Wells that may be in extensions of the rift zone (marked "a") have a slightly higher mean thermal gradient, 21.8±2.9 mK m^{-1}, compared with the remaining results, 18.8±1.8 mK m^{-1} but there is too much uncertainty regarding the data and the tectonic setting of the wells to make firm conclusions. Cross reference with Figure G does not reveal any other systematic pattern.

In an attempt to estomate a correction for drilling transients, we note that gradients obtained from uncorrected BHTs are typically 10-15% lower than gradients obtained from corrected BHT data (Lam et al., 1982). However, unless BHT data have good temperature-time control, such corrections still tend to underestimate equilibrium temperature (Beck and Shen, 1989). A more realistic estimate may be obtained from Majorowicz and Jessop (1981). who show that reliable BHTs from wells preserved for temperature observations in the westem Canadian basin yield a thermal gradient that is approximately 35% higher than the result for BHTs measured within 10 hours. As most of the data discussed here were recorded after a stabilization period of 6-10 hours, we regard 35% as a reasonable correction for Mozambique. The thermal gradient for the data in Figure K is therefore increased to 28.5 mK m^{-1}

BHT data are also available from one well drilled by ESSO Exploration Inc. in the Rovuma basin in north Mozambique (site 12, Figure G). The data define a linear trend, and yield a least squares gradient of 39.1 mK m^{-1} (Table IV). A 35% correction yields a thermal gradient of 52.8 mK m^{-1}.

The Cretaceous and Tertiary sediments in Mozambique are similar to those in basins in the coastal plains of Tanzania and Kenya, where thermal conductivities have been reported for eleven wells [Evans, 1975; Nyblade et al., 1990]. These conductivity values were corrected for porosity and temperature effects. The reported mean values fall ,in the range from 1.5-2.5 W m^{-1} K^{-1}, and average at 1.95 W m^{-1} K^{-1}. To make a fust order estimate of the heat flow in Mozambique, we have applied a conductivity value of 2.0 W m^{-1} K^{-1} to the above

Figure H - Plot of **observed BHT data** from the **Mozambique basin. The slope** of **the regression line is 20.8 mKm-1.**

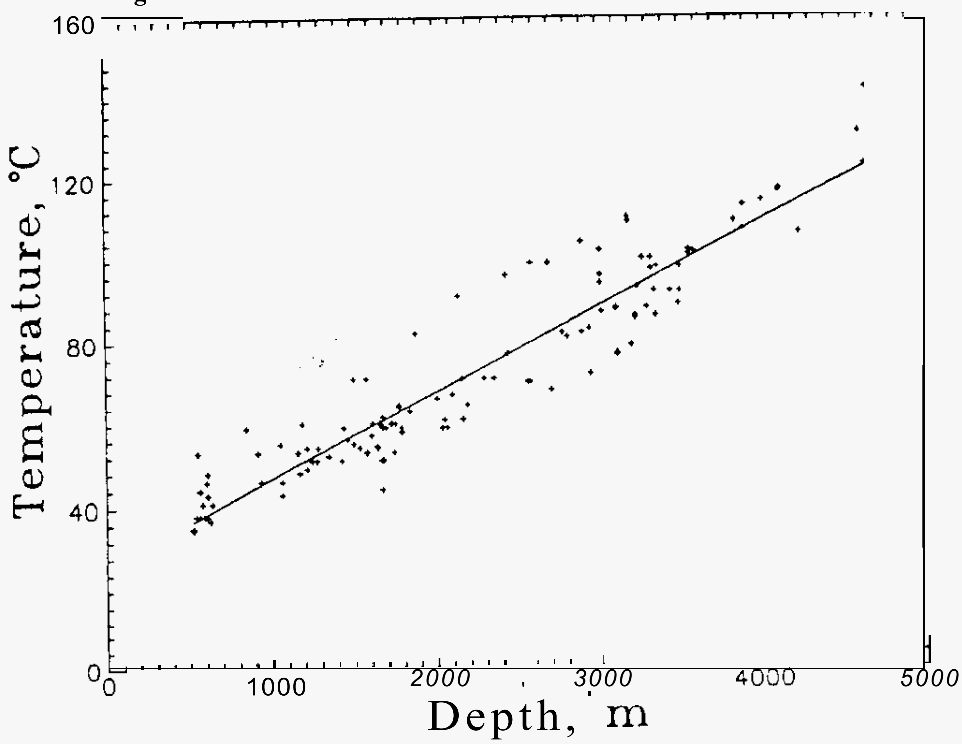


Figure K -**Plot** of **selected, but not corrected,** BHT data from the **Mozambique basin** (see **text).** The slope of the regression line is **21.1** mK m^{-1}.

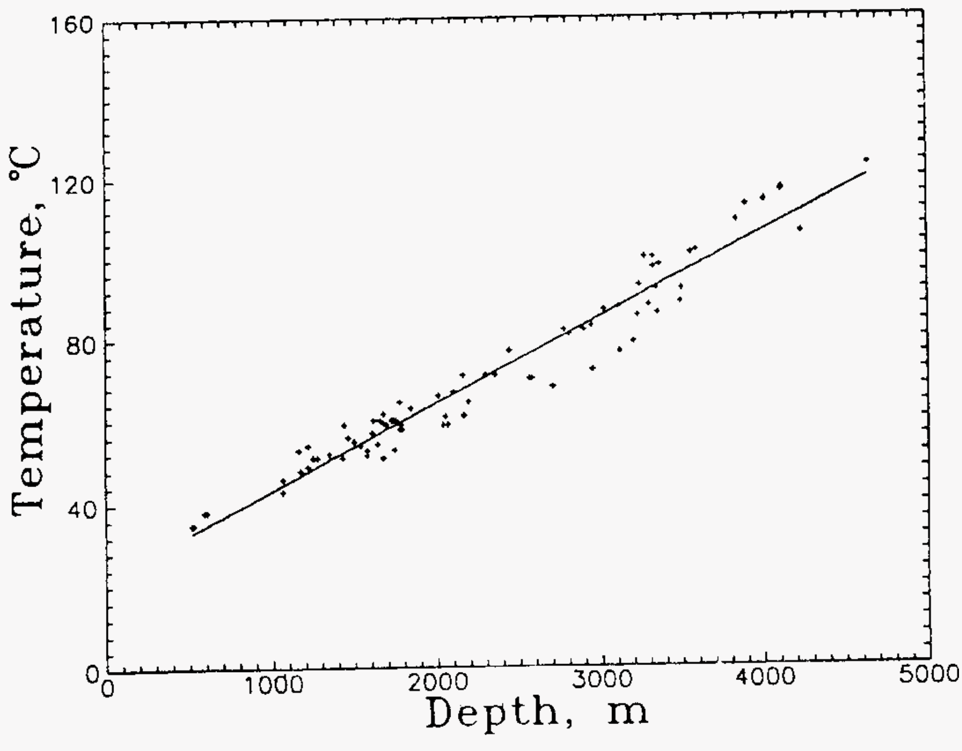


Table IV. Mean Thermal Gradients for Wells with Relatively Uniform Gradient. Well Numbers Refer to Numbers in Figure G.

No	Name	Depth, m	Thermal Gradient. mK m⁻¹	N
1	Palmeira	4232	18.8	4
2	Balane	3117	21.0	2
3	Temene	3205	15.5	7
4	Lambo	1644	17.4	2
5	Pande	3300	17.9	7
6	Marrapenhe	3111	19.7	3
7	Divinhe[a]	3838	22.2	12
8	Nemo[a]	4115	25.1	4
9	Sofala[a]	3230	18.3	2
10	Buzi[a]	3328	21.4	10
11	Micuane[b]	4606	19.2	3
12	Mocimboa[c]	3292	39.1	S

a, wells possibly in extension of rift zones; b, thermal gradient is consistent with other wells, but data are offset to higher temperature by approximately 25°C c. data from Rovuma basin.

Table V. Heat Row in Different Tectonic Environments in Southeast Africa.

Tectonic Unit	Heat Flow, mW m⁻²		N	References
	Range	Mean		
Archaean	20-47	34±11	8	Nyblade et al.. 1990
Tanzanian craton Zimbabwe craton	32-65	46±12	10	Ballard et al., 1987; Nyblade et al., 1990
Kaapvaal craton (northern sector)	25-76	47±12	15	Ballard et al., 1987. Jones. 1992a
Limpopo belt	49-57	53±4	3	Ballard et al., 1987; Jones, 1992a; Nyblade et al., 1990
Proterozoic				
Kibaran-Katangan belts (undifferentiated)	44-76	63±9	15	Chapman and Pollack, 1977; Sebagenzi et al., 1993
Mozambique belt	35-68	47±11	9	Nyblade et al., 1990
Mesozoic Coastal Basins				
Kenya	54-97	67±13	8	Nyblade et al., 1990
Tanzania	51-87	69±18	4	Nyblnde et al., 1990
Mozambique basin		57		This study
Rovuma basin		106		This study
Mesozoic Rifts				
Zambezi rift	44-110	77	2	Nyblade et al.. 1990
Luangwa rift	73-77	75	2	Nyblade et al., 1990
Modern Rifts				
Malawi rift.	23-172	75±52	20	Ebinger et al., 1987
Kivu rift'	16-187	73±70	S	Degens et al., 1973
Tanganyika rift[b]	17-151	50±35	12	Degens et al., 1971
Kenya rift'	56-101	79	2	Morgan. 1973
Mozambique Channel				
15°S - 30°S	29-67	47±13	15	Pollack et al., 1990

a, corrected for sediment blanketing effects; b, uncorrected.

thermal gradients. The resulting heat flow for the Mozambique basin, 57 mW m^{-2}, is clearly compatible with results in the Mozambique Channel, South Africa, and Zimbabwe (Figure G, Table V). Data from the Rovuma basin imply a much higher heat flow, 106 mW m^{-2}. This result is derived from only one well and must obviously be treated with caution, but it may be significant that such high values are also found in the coastal plains of Tanzania (up to 87 mW m^{-2}) and Kenya (up to 97 mW m^{-2}) (Nyblade et al., 1990).

HEAT FLOW AND GEOTHERMAL RESERVOIRS.

The range of heat flow and mean values for different tectonic units surrounding Mozambique are listed in Table V. Heat flow in the Mozambique Channel is typical of that in ocean basins. On the continent, the heat flow in Archaean terrains is more uniform and lower than that in younger terrains, an observation that is globally consistent (Jones, 1987; Nyblade et al., 1990; Nyblade and Pollack, 1993). Heat flow in the Tanzanian craton and the Proterozoic Mozambique belt are lower than usually observed in provinces of equivalent age, and the implications of this are discussed by Nyblade et al. (1990). Mean values for the Mesozoic coastal basins and rifts are slightly enhanced compared with Proterozoic belts; these means are influenced by occasional high values which may have implications for geothermal resources. The greatest variability of heat flow and the highest values are found in the modem rifts, although the means are not significantly enhanced above those for Mesozoic regions. Some very high values in the Niassa lake area (Ebinger et al., 1987) suggest that the modem rifts may be the most profitable localities for further investigations relating to geothermal energy resources.

High local heat flow anomalies are commonly linked with hydrothermal circulation as evidenced from geochemical findings. The geological setting and geochemical characteristics suggest similarities between Mozambican, Malawian, Zambian and Zimbabwean hot fluid reservoirs (Muller and Forstner, 1973: Legg, 1974; Mazor and Verhagen, 1976). Furthermore the partial or total lack of cap rocks in Mozambican geothermal reservoirs may strongly influence the areal extension of heat flow anomalies and the research strategy for future geothermal developmet (see also Dickson and Fanelli, 1990).

CONCLUSION

Geochemical and geophysical considerations have allowed a better recognition of high heat flow areas in Mozambique, and a better identification of deep fluid circulation characteristics.

The most promising areas for geothermal energy development are the Northerm and Central Provinces of the Country. The local availability of geothermally interesting fluids confirms the possibility of small-scale power generation, and warrants more detailed studies and eventual exploratory drilling. Small scale geothermal power plants are particularly suitable for Mozambique because of their relatively low vulnerability to natural hazards and relatively low costs when compared with other energy sources. Current trends of geothermal energy generation in East African Rift Countries confirm these conclusions.

ANNEX

Mozambique's Country Update Report is summarized in tables 1, 4, 6, 9, 10.

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TABLE 1. PRESENT AND PLANNED PRODUCTION OF ELE[redacted]TRICITY

	Geothermal		Fossil Fuels		Hydro		Nuc[redacted]r		Total [redacted]	
	Capac-ity MW	Gross Rod GWh/yr	Capac-iy MW	Gross Prod. GWh/yr	Capac-iy MW	Gross Prod. GWh/yr	C[redacted]		Capac-iy MW	Rod. GWh/yr
In operation in January 1995			280	435	2078	50			2358	485
Unda construction in January 1995										
Funds committed, bur nor yet under construction in January 1995										
Total projected use by 2000										

TABLE 4. SUMMARY TABLE OF GEOTHERMAL DIRECT HEAT USES

[1] Inst. thermal power (MW_t) = Max. water flow rate (kg/s) x [Inlet temp.(°C) - Outlet temp.(°C)] x 0.004184

[2] Energy use (TJ/yr) = Annual average water flow rate (kg/s) x [Inlet temp.(°C) - Outlet temp.(°C)] x 0.1319

	Installed Thermal Power[1] MW_t	Energy Use[2] TJ/yr
Space heating		
Bathing and swimming		250,000,000
Agricultural drying		
Greenhouses		
Fish and other animal farming		
Industrial process heat		
Snow melting		
Air conditioning		
Other uses (specify) Therapeutic use		250,000,000
Subtotal		
Heat Pumps		
Total		500,000,000

TABLE 6. INFORMATION ABOUT GEOTHERMAL LOCALITIES

[1] Main type of reservoir rock

[2] Total dissolved solids (TDS) in water before flashing Put v for vapor dominated

[3] N = Identified geothermal locality, but no assessment information available
R = Regional assessment
P = Pre-feasability studies
F = Feasability studies (Reservoir evaluation and Engineering studies)
U = Commercial utilization

Locality	Location to Nearest 0.5 Degree		Reservoir		Status[3] in January 1995	Reservoir Temp. (°C)	
	Latitude	Longitude	Rock	Dissolved Solids[2] mg/kg		Estimated	Measured
IETANGULA_ S0	2 32 09	34 45 10	RYST	,	R	160	
IUNHAMADE 531	8 30 11	37 02 25		)48	R	87	
IOSSURIL 532	5 06 40	40 31 16		'982	R	63	
:ONUE' 533	8 12 93	35 59 18		!43	R	72	
:UPIZI S35	8 03 55	34 09 26		.073	R	78	
:HICHERE 536	8 03 53	34 12 36		1786	R	67	
:ILE' 537	6 20 01	38 18 00		.265	R	61-145	
IAGANJA S39	8 47 51	37 31 14		;489	R	81-166	
IAMACURRA S40	7 26 35	36 38 97		1147	R	87-141	
IIAONDIVE S41	6 05 15	33 35 13		.554	R	96-146	
IORRUMBALA 54	7 26 51	35 25 21		i26	R	97-154	
'otal 11							

TABLE 9. ALLOCATION OF PROFESSIONAL PERSONNEL TO GEOTHERMAL ACTIVITIES (Restricted to personnel with a University degree)

(1) Government
(2) Public Utilities
(3) Universities
(4) Paid Foreign Consultants
(5) Contributed Through Foreign Aid Programs
(6) Private Industriy

Year	Professional Man Years of Effort					
	(1)	(2)	(3)	(4)	(5)	(6)
1990	2					
1991	2					
1992	2					
1993	2					
1994	2					

TABLE 10. TOTAL INVESTMENTS IN GEOTHERMAL IN (1994)US$

Period	Research & Development Incl. Surf. Exp. & Exp. Drilling	Field Development Incl. Prod. Drilling & Surf. Equipment	Utilization		Funding Type	
			Direct	Electrical	Private	Public
	Million US$	Million US$	Million US$	Million US$	%	%
1975 - 1984	0.02					100
1985 - 1994	0.02					100