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Assessment of the thermal springs of Swaziland

by

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SUMMARY

Eleven thermal springs are known to discharge from Pre-Cambrian rocks in Swaziland with temperatures ranging from 25 to 52°C. The water is meteoric in origin and is not heavily mineralised. It is heated at depth during circulation in cracks and fractures associated with two deep seated and parallel structural trend lines. Geothermometers indicate maximum temperatures of less than 120°C are achieved during deep circulation.

1. INTRODUCTION

The kingdom of Swaziland has an area of 17,364 square kilometres. It is situated in south-eastern Africa between parts of the Republic of South Africa and the Peoples Republic of Mocambique.

There are eleven known thermal springs in Swaziland (Figure 1). They include the Ezulwini springs which supply a therapeutic spa and tourist complex some 10 km south of Mbabane; the springs at Lobamba, patronised by the royal family; and those at Siphofaneni, which in the past have attracted numerous visitors. The other thermal springs, however, are largely unknown.

1.1 Objectives

The aim of the study is to provide a preliminary assessment of the geothermal resources of Swaziland by means of observations and measurements on the thermal springs, their discharge water and their geological setting. The work may be regarded as a first phase investigation to determine if more detailed and more expensive research (such as geophysics and exploratory drilling) is likely to be worthwhile .

1.2 Previous work

Various references to thermal springs occur in geologists field notes since the 1930's. Discharge and temperature measurements show remarkable consistency with those observed more recently and these early references provide the key to the relocation of several of the lesser known springs.

Kent (1949) described the thermal springs of South Africa and included the Swazi springs of the Ezulwini Valley. The therapeutic values of the spring waters were discussed by Kent (1952). The geological setting of the Ezulwini springs was reported by Gevers (1965) who also presented hydrochemical data. Gevers showed that the dissolved gases indicate that oxygen and carbon dioxide have been removed from any dissolved air by oxidation and carbonation whilst the water circulated underground. Spargo (1965) described the location and geological setting of the Mkoba springs near Piggs Peak.

Hunter (1968) described and classified according to temperature the eight thermal springs then known. He described the geological environment of the springs and discussed the chemical analyses undertaken during the 1950's and 1960's for the Geological Survey and Mines Department. These samples were taken on a casual basis and the analytical results should be treated with caution (open file correspondence Geological Survey and Mines Department). Hunter quoted the following discharge figures (1/s):

Mkoba	1.2	Ezulwini	5.3
Mvuntshini	0.8	Lobamba	0.9
Mawelawela	0.8	Siphofaneni	1.9

Hunter noted that the springs occur along two parallel trend lines passing from Natal and Zululand into Swaziland and that these trend lines may correlate with some deep seated line of crustal weakness.

Mazor et al (1974) showed that the springs derive water from a meteoric source by means of Ne, Ar, Kr, and Xe concentrations and δD and $\delta^{18}O$ values. The noble gases and stable isotopes indicate closed circuit conditions and palaeotemperatures at the time of infiltration of between 21 and 31°C. These are compatible with present day summer (rainy season) temperatures. ^{14}C concentrations indicate ages in the order of thousands of years, depending on the correction model chosen, and tritium concentrations vary from 0.2 to 1.1 TU against 46 to 53 TU in nearby rivers (Table 1).

Measurements of the geothermal gradient have not yet been made in Swaziland. However, a mine at Barberton on the northern

Table 1 : Chemical Data (mg/l) after Hunter (1968) and Mazor *et al* (1974)

Spring	Temp °C	pH	Ca	Mg	Na	K	F	HCO_3	SO_4	Cl	Total ions	Tritium TU
Mkoba (M)	51.5	8.0	4	1	58	1	6	103	6	21	200	1.1 ± 0.2
Ezulwini (H)	46.0	7.3	7	1	28	2	nd	70	8	10	126	nd
Ezulwini (M)	45.0	8.6	4	2	35	1	6	53	11	11	123	0.5 ± 0.2
Lobamba (H)	52.2	8.4	0	5	32	nd	7	82	7	12	145	nd
Lobamba (M)	44.0	7.9	4	1	48	1	6	81	8	14	163	1.3 ± 0.2
Lobamba (M)	45.0	7.9	4	1	45	1	6	81	6	14	158	0.4 ± 0.2
Lobamba (M)	44.0	8.0	4	1	45	1	7	74	6	14	152	0.6 ± 0.2
Mawelawela (H)	33.3	8.0	9	0	37	2	nd	97	7	13	165	nd
Mawelawela (M)	35.0	7.9	9	2	45	1	7	87	6	14	171	0.2 ± 0.2
Mpopoma (H)	33.3	9.7	0	0	58	nd	15	34	10	28	145	nd
Siphofaneni (H)	40.0	8.7	4	0	127	4	nd	68	18	134	355	nd
Siphofaneni (M)	44.0	7.9	2	1	135	4	7	101	30	121	401	0.4 ± 0.2

H = Hunter (1968)   nd = not done

M = Mazor *et al* (1974)

border of the country has an observed gradient of 20°C/Km (open file correspondence, Geological Survey and Mines Department) and Krige (1948) found the gradient to vary between 7 and 14°C/Km in deep boreholes in the Orange Free State and Transvaal Provinces of South Africa.

Percentages by volume of the gases dissolved in the waters of the Siphofaneni and Ezulwini thermal springs were analysed by the United Kingdom Atomic Energy Authority. The results are reproduced from Hunter (1968) :

	Siphofaneni	Ezulwini
Nitrogen	80.10	92.10
Oxygen	11.50	1.36
Argon	1.66	1.62
Carbon dioxide	1.11	0.20
Methane	0.12	0.02
Hydrogen	0.04	0.01
Helium	5.54	4.70

1.3 Procedure

The eight thermal springs listed by Hunter were located. Additional springs were located at Madubula (from a pre-war mining concession map) at Mbondela and at Fairview below the new dam. Hunter's Ezulwini 2 has been renamed Mvuntshini, and Manzane (literally Siswati for hot spring) renamed Mpopoma. It is doubtful if all the thermal springs are now on record and it is anticipated that more may be found in due course.

The geology at each spring has been described and dominant joints, or the presence of faults or dykes noted. The discharge of each source was measured, or estimated where measurements could not easily be taken, and the source temperature recorded. Discharge measurements were made by timing a known volume and contain an error of ± 10%; temperature was recorded with a mercury-in-glass thermometer within an error of ± 0.5°C. Observations on gases particularly hydrogen sulphide associated with the spring discharge were made, and the presence of any encrustation was recorded. The specific electrical conductance of the discharge water at the source was measured with a temperature compensating conductance bridge from which all readings are adjusted to 25 °C within an error of ± 2%. It was also intended to measure pH and bicarbonate concentration at the source, but the pH meter batteries were incapable of storing sufficient power away from the mains electricity supply for field use, and the limited supply of glassware was liable to damage away from the laboratory. No pH or bicarbonate concentration is available for the Mbondela spring but measurements were generally taken on all the other samples within 24 hours of sampling. The same observations and measurements were taken at nearby cold groundwater sources in order to estimate the degree of mixing between the shallow cold groundwater and the hot water rising to the spring orifice. However, no suitable cold ground-water source could be found at Fairview or Mbondela.

Finally, samples were submitted for further chemical analysis at the Institute of Geological Sciences laboratory at Wallingford. The samples were contained in two completely filled and sealed 500 ml, high density polythene bottles, one bottle being acidified to pH 1.5 with HCl and both bottles pre-filtered. A separate sample diluted 1:1 with distilled water is customary for SiO_2 analysis, but this was not taken due to the dubious quality of available distilled water.

The samples were analysed for Ca, Na, K, SO_4, Cl, SiO_2, Sr and F ion concentrations. Reservoir temperatures are estimated using Na-K-Ca, Na-K, and SiO_2 geothermometers but a mixing correction could not be applied.

2. GEOLOGY, LOCATION AND DESCRIPTION OF THE SPRINGS

2.1 Regional geology

Hunter (1961) described the geology of Swaziland and Wilson (1976) amended the nomenclature and certain stratigraphical relationships. Swaziland lies across the eastern escarpment of the Pre-Cambrian Basement plateau with Pre-Cambrian granite exposed along the base of the escarpment, east of which the sediments and lavas of the Karroo system are exposed. The major geological (and topographical) trends are north-south and include the Lebombo monocline which is parallel with and to the west of the Mocambique border. The structure within the crystalline Basement rocks is complex and is dictated largely by the historical formation of the various rock types. There is a secondary north-east, south-west trend within the Pre-Cambrian rocks which is particularly well developed in the granodiorites.

2.2 Spring locations

The location of the thermal springs, and access to them was described by Robins et al (1978). Table 2 shows the 1:50,000 topographical sheet number and the grid reference (East African Belt G) for each spring. The number of eyes or sources at each spring is also listed.

TABLE 2: Location of thermal springs

Spring	Sheet number	Grid Reference	No. of sources
Mkoba	2631AB	284700E 1619800N	3
Mvuntshini	2631AC	267700E 1582300N	1
Ezulwini	2631AC	268100E 1579800N	3
Lobamba	2631AC	271100E 1576400N and 272300E 1575200N	3
Mawelawela	2631CA	266900E 1558800N	1
Ngwempisi	2631CA	271000E 1546900N	1
Mpopoma	2631CC	263700E 1517400N	2
Mbondela	2731AA	261100E 1505600N	2
Madubula	2631CB	286700E 1546500N	2
Fairview	2631BA	317900E 1609500N	1
Siphofaneni	2631DA	318400E 1548400N	2

2.3 Description of the springs

All the springs occur at or near valley bottoms and emanate from Pre-cambrian crystalline rock. The last igneous activity in the region was in Jurassic times so it is likely that the overall geothermal gradient is low. However, the spring waters clearly have access to deep circulation and the spring orifices at the surface indicate that joints and cracks provide the means for the water to circulate underground.

1). Mkoba

There are three sources all on the east bank of the Mkoba stream and none more than 2m above the stream bed. At each there is a sulphurous smell and occasional bubbles, but there is no encrustation. The most southerly source yields about 1.5 l/s and the northerly pair combine to yield 2.5 l/s giving a total of 4 l/s. The springs emanate from north-south trending joints in Ag3 granite. The springs, which are in a line 250m long, discharge with temperatures of 49°C (north); 48°C (centre) and 52°C (south). The lower temperatures of the northerly sources may be induced by a partial cover of soil.

2) Ezulwini

There are three sources along a distance of 50m. The upper source supplies the Cuddle Puddle and Health Spa from a shallow well whose casing is driven into a joint in granite gneiss and pumped at about 4 l/s. The water temperature at the pump is 37°C. This same joint which trends south-east discharges water 25m away adjacent to a small dolerite dyke and at a temperature of 40°C with a discharge of 2 l/s. The dyke is perhaps 2m wide though its full extent is concealed by soil and vegetation. There is also a seepage from the other side of the road beneath the road embankment at 40°C but of indeterminate discharge. There is no sulphurous smell or encrustation although bubbles rise from the middle source.

3) Lobamba

There are three sources each piped to adjacent washing baths. They each have a slight sulphurous smell but no encrustation. There are two sources near the Government VIP Guest House some 50m apart and their temperatures are 48 and 47°C and their discharges are 1 and 2 l/s. Some 500m to the south-east a third spring discharges at 1.5 l/s with a temperature of 43°C. All three emanate from weathered granodiorite about 3m above the bed of the Mbabane River.

4) Mvuntshini

This spring seeps from overburden beneath a small copse of gum trees with a discharge of 4 l/s. The solid geology is migmatitic granites and gneisses. The discharge temperature is 45°C and bubbles release a very faint smell of H_2S, but there is no encrustation.

The Ezulwini, Lobamba and Mvuntshini groups of springs are all in the Ezulwini Valley. This is a fault controlled valley trending north-west to south-east.

5) Mawelawela

Water is discharged at about 6 l/s at a temperature of 35°C. There is no encrustation or any sign of gas being released, although there is a slight sulphurous smell. The source is a north-west trending joint in Ag5 granite, about 0.5m above the mean river level.

6) Ngwempisi

The spring discharges from beneath a massive granite boulder at a discharge of 3.5 l/s with a temperature of 46°C. The spring is at the flood level of the river. There is a strong sulphurous smell and minor encrustation. A flame spectrum of the encrustation shows it to be dominantly sodium and calcium, though barium may be present in minor quantities. Access to the spring, which is at the bottom of the Ngwempisi Gorge is extremely difficult.

7) Mpopoma

The spring discharges through overburden at two adjacent seepages, one at 3 l/s and the other at 1 l/s. The temperature is only 33°C and there is a slight encrustation and a strong sulphurous smell. The springs are about 3m above the Mpopoma river bed.

8) Mbondela

The two sources are about 500m apart in the Mkondo valley. The main source discharges at 2.1/s at a temperature of 25°C and the subsidiary source at 0.5 l/s at a temperature of 28°C. Locally the Mkondo river follows a north-west lineation, probably a major joint trend. The main spring issues from the junction between garnetiferous gneiss and alluvium at the valley bottom and the subsidiary spring (from which the sample was taken) from alluvium. There is a sulphurous smell emanating from bubbles and a thin encrustation.

9) Madubula

The springs straddle the Ngwempisi River discharging an estimated 2 l/s on the north-bank and 8 l/s on the south bank and in the river bed. There is a strong sulphurous smell, bubbles and slight encrustation, and with a temperature of 52°C the water is too hot to hold a thermometer below the water to the source. The spring discharges through river sand beneath Ag5 granite boulders and is at the flood level of the river.

10) Fairview

This spring emanates through two ponds in river alluvium overlying mylonitised grandiorite at a point where a fault and a joint appear to intersect according to air photographs. Both ponds discharge at about 1 l/s which with seepages from the surrounding area give a total estimated discharge of 3 l/s. Bubbles rise from the bottom of the ponds but there is no smell or encrustation. Discharge temperature is 38°C.

11) Siphofaneni

The springs discharge through overburden resting on granite. There is a slight sulphurous smell accompanied by bubbles but there is no encrustation. There are two sources some 50m apart which have been developed to form a mens bath and a womens bath. Both sources discharge 3 l/s with a temperature of 39°C. The sources are about 2m above the mean water level of the Usutu River.

2.4 Reservoir configuration and water circulation

Mazor et al (1974) shows that the discharge water is meteoric in origin. ^{14}C shows the age of the water to be of the order of 4 to 5000 years and tritium levels indicate that the water is "pre-bomb" water. Thus in groundwater terms the water is young and may be contained in a continuously moving circuit or system of circuits comprising open cracks or joints. The water may infiltrate these cracks at some elevation higher than the springs, pass down to the depth where the water is heated and return under the hydraulic pressure of incoming cold water up separate joints to the springs. Onceestablished, flow in the system will be enhanced by the convection cell principle.

In order for the groundwater to be heated by 20°C, it has to circulate at depths of at least 1000m. This estimate assumes a geothermal gradient of 20°C/Km but it may be considerably greater locally and possibly enhanced by some exothermic reaction within the country rock such as the decomposition of sulphides.

Under normal conditions open cracks and joints at depths of 1000m are uncommon due to applied stresses but they may occur in association with major faulting. The springs lie along two distinct and parallel trend lines: from Mkoba through Mbondela and down into Natal as far as Entembeni, some 200km south-south-west of Mkoba; and from Fairview through Siphofaneni, as far as Lilani (Robins 1978). It is possible that these lines of springs delineate some features of crustal weakness or some features of future crustal instability, particularly as they are aligned roughly parallel to the Lebombo Monocline. The Madubula spring is situated between the two lines and may owe its existence to some transverse feature between the two major ones. Conversely the springs along the two major lines can be joined by a series of east-north-east trending <u>en echelon</u> lines, but in neither case do these trend directions equate in any way either to the topography or the near surface geology such as joint and fault trends recorded at the springs. Whatever the features are, they are geologically young and have not yet developed sufficiently to exhibit any surface expression.

3. <u>HYDROCHEMISTRY</u>

The analytical anion-cation balances are seen to be frequently rather poor - up to ±15% discrepant. Whilst no analyses of magnesium are available, the discrepancy arises probably from the generally low to very low total dissolved solids (up to only about 400 mg/1) which makes the balance very sensitive to analytical error. Also the delay in analysing for HCO_3 may contribute to error, though this is probably not significant to the present discussion. Analytical results are appended.

The thermal springs are all dilute Na-HCO_3-(Cl) water with the exception of Madubula and Fairview which are Na-Cl-HCO_3 type and Siphofaneni which is Na-Cl-(HCO_3) type. Siphofaneni and Fairview have greater Na-Cl dominance and the highest total dissolved solids and this suggests that the trend from HCO_3 to Cl dominance is caused by a greater contact with rock and an increased uptake of salts. Thus the variations are due to small differences in the extent of water-rock reaction. Adjacent cold groundwaters are less mineralised and tend to contain a lower proportion of Na with respect to Ca (Figure 2). There is abundant evidence (Mazor et al, 1974) that the waters are of meteoric origin with a circulation period of several thousand years. They have assumed a Na-Cl character during deep circulation in granites (the sources of NaCl are not clearly defined, but could be due to alteration of rocks containing saline fluid inclusions); the low level of salinization probably reflects the confinement of water to 'well-flushed' fissure systems. The low pH values of springs relative to cold groundwaters is symptomatic of the participation of the thermal waters in silicate alteration reactions in which H^+ is consumed in alteration to clays e.g. kaolinite.

The saturation indices of thermal waters with respect to calcite are all close to, or just below, zero (similar indices for cold groundwaters are highly negative - representing undersaturation). Thus the Ca^{2+} and HCO_3^- levels (particularly the latter) are controlled by calcite equilibrium at temperatures close to surface discharge temperatures for the thermal springs. Presumably there is abundant carbonate on fissure surfaces (as is often the case in granitic terrains) which can control this equilibrium. Saturation indices with respect to fluorite are also close to zero, i.e. equilibrium, for the thermal springs; this is a common feature in granitic terrains in which fluorite is commonly available as a buffering phase.

Geothermometry on these springs can be attempted by the SiO_2 and the Na-K-Ca methods (using program HYL26 - Bath, 1978). Correlation between the two (using $\beta = 4/3$ for the Na-K-Ca computation) is fairly good, as shown in Figure 3, although the quartz temperatures are relatively slightly elevated. In neither case are base temperatures in excess of 100-120°C indicated. It therefore, seems that these springs are all typical of deeply circulating fault-line waters in a granitic terrain. Further adjustments of the computed base temperature using the silica dilution model (Truesdell and Fournier, 1977) or the pCO_2 correction to Na-K-Ca temperatures (Paces, 1975) are probably not applicable in this case. There is no evidence for a systematic dilution of thermal springs by cold groundwater - inspection of the trilinear plot (Figure 2) in the light of the relative order of temperatures of the springs shows no obvious mixing series; it is therefor not possible to apply the simple mixing model which results in the prediction of inordinately high base temperatures (>200°C). The correlation in Figure 3 and also the correlation with order of measured surface temperatures (Figure 4) suggests that computed quartz temperatures assuming no dilution are probably a close approximation. Computed pCO_2 values for the thermal springs are all low - the highest values is 5.3×10^{-3} atm. for Ezulwini whilst most values are in the range 10^{-3} to 10^{-5} atm. pCO_2. Calculation of the corrections to Na-K-Ca temperatures using the method of Paces (1975) lowers the computed temperatures by up to 40-50°C in some cases, but by 20-30°C in most cases; when plotted against measured discharge temperatures no general correlation is observed, though a few points do agree roughly (Figure 5). In some cases the corrected temperature is below the observed value, in these cases clearly invalidating the model on which the Paces correction is based.

4. CONCLUSION

The Swaziland thermal springs represent deep circulating groundwaters, undergoing slight chemical modification by reaction with fissure wall-rock surfaces. Temperatures achieved during deep circulation are probably approximated at maximum by computed quartz solubility temperatures (i.e. <120°C), and in some cases may be somewhat lower as suggested by the Na-K-Ca geothermometer (though at these low temperatures some sort of disequilibrium model such as Paces' may be applicable in some cases).

The geothermal potential available in Swaziland is, therefore, of limited value and further investigation cannot be recommended on economic grounds. However, should an opportunity arise whereby an existing deep borehole may be utilised in order to measure the geothermal gradient, particularly along one of the two known lines of springs, it should not be passed over.

Acknowledgements

The valued assistance in locating thermal springs and sampling the Mbondela spring provided by Alan Wilson is gratefully acknowledged. Thanks are due to Jenny Cook and her colleagues for the chemical analyses.

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FIGURE 1

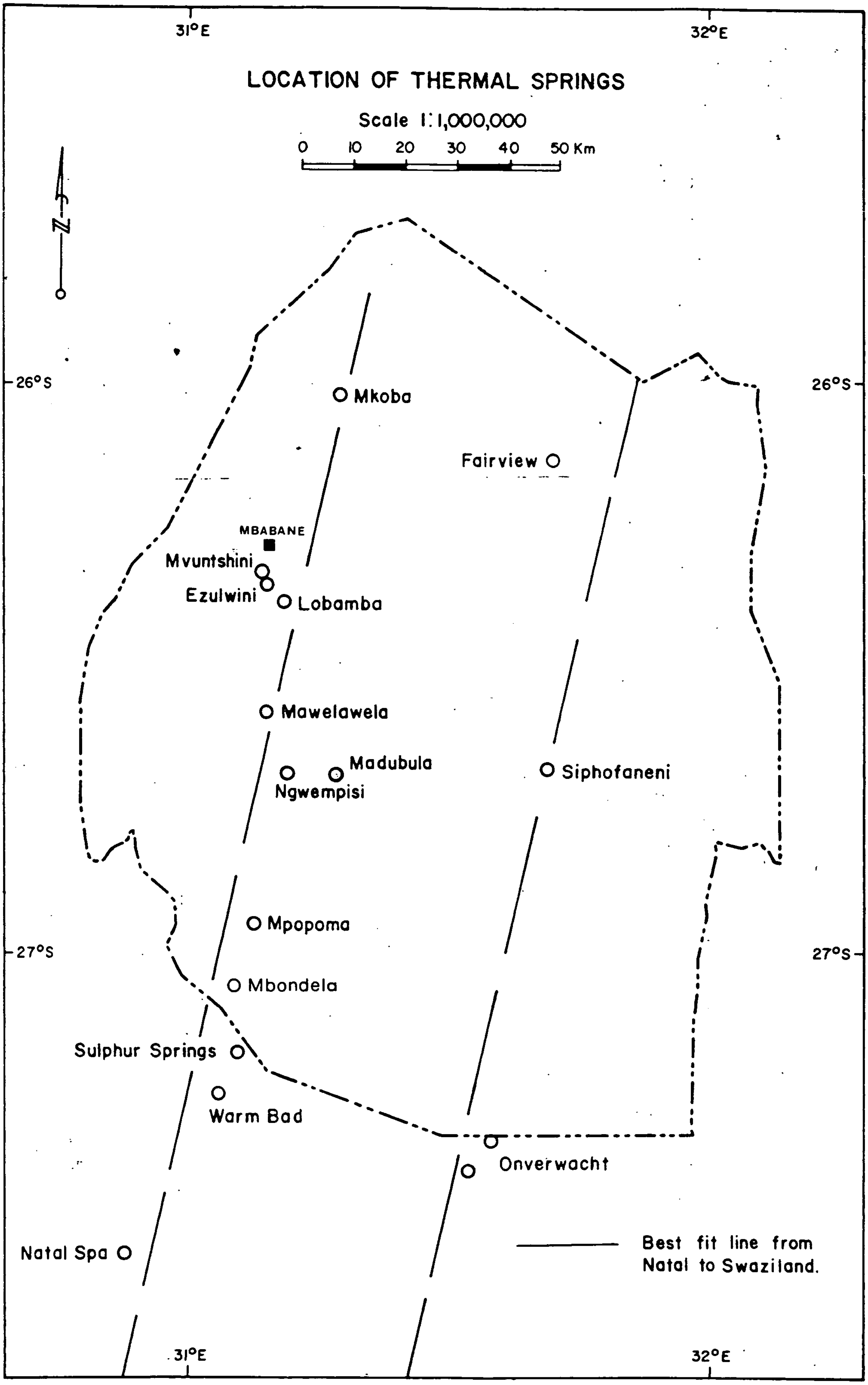
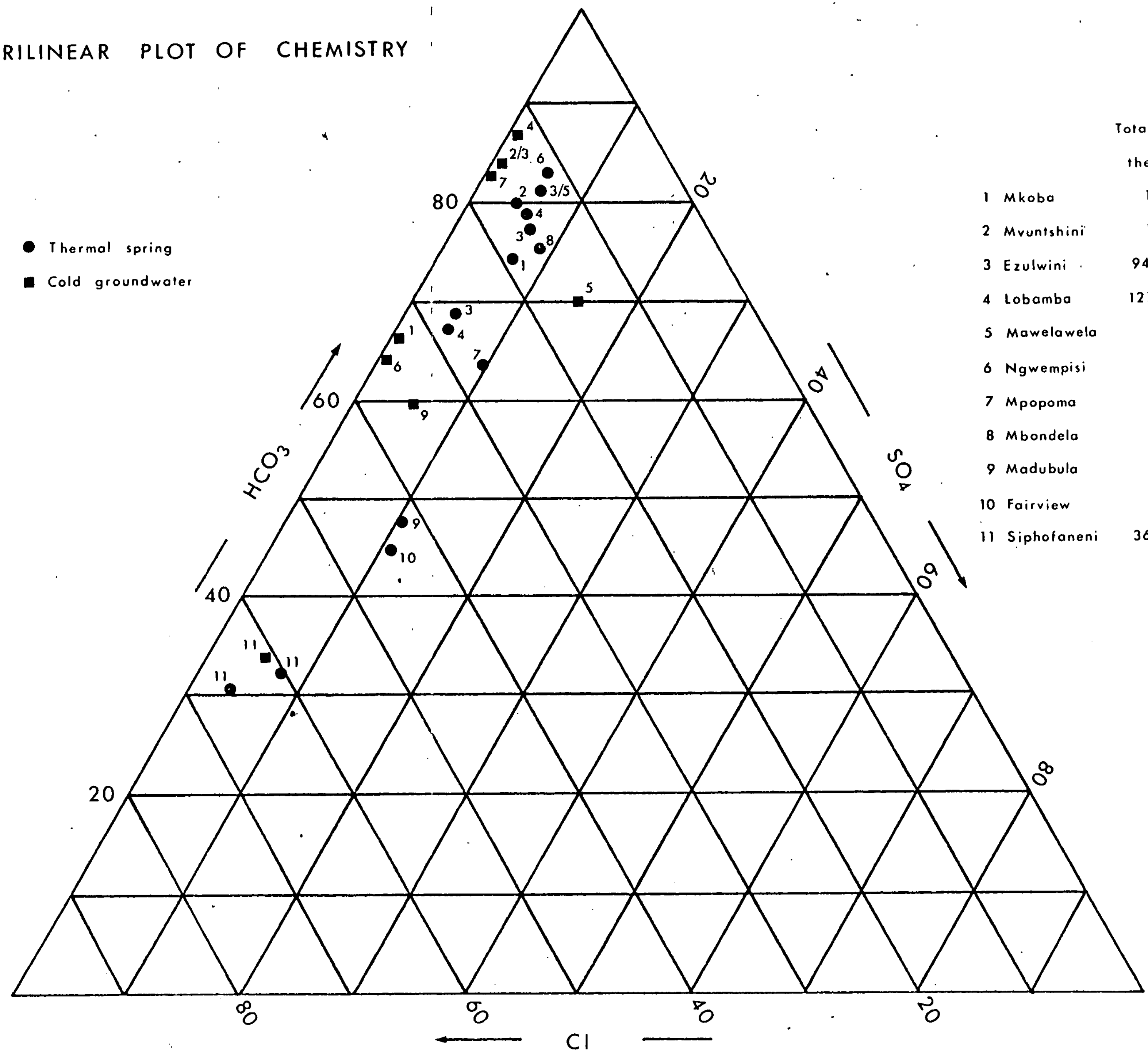

31°E
32°E
LOCATION OF THERMAL SPRINGS
Scale 1:1,000,000
0 10 20 30 40 50 Km
N
26°S
27°S
Mkoba
Fairview
MBABANE
Mvuntshini
Ezulwini
Lobamba
Mawelawela
Madubula
Ngwempisi
Siphofaneni
Mpopoma
Mbondela
Sulphur Springs
Warm Bad
Onverwacht
Natal Spa
Best fit line from
Natal to Swaziland.

FIGURE 2

TRILINEAR PLOT OF CHEMISTRY

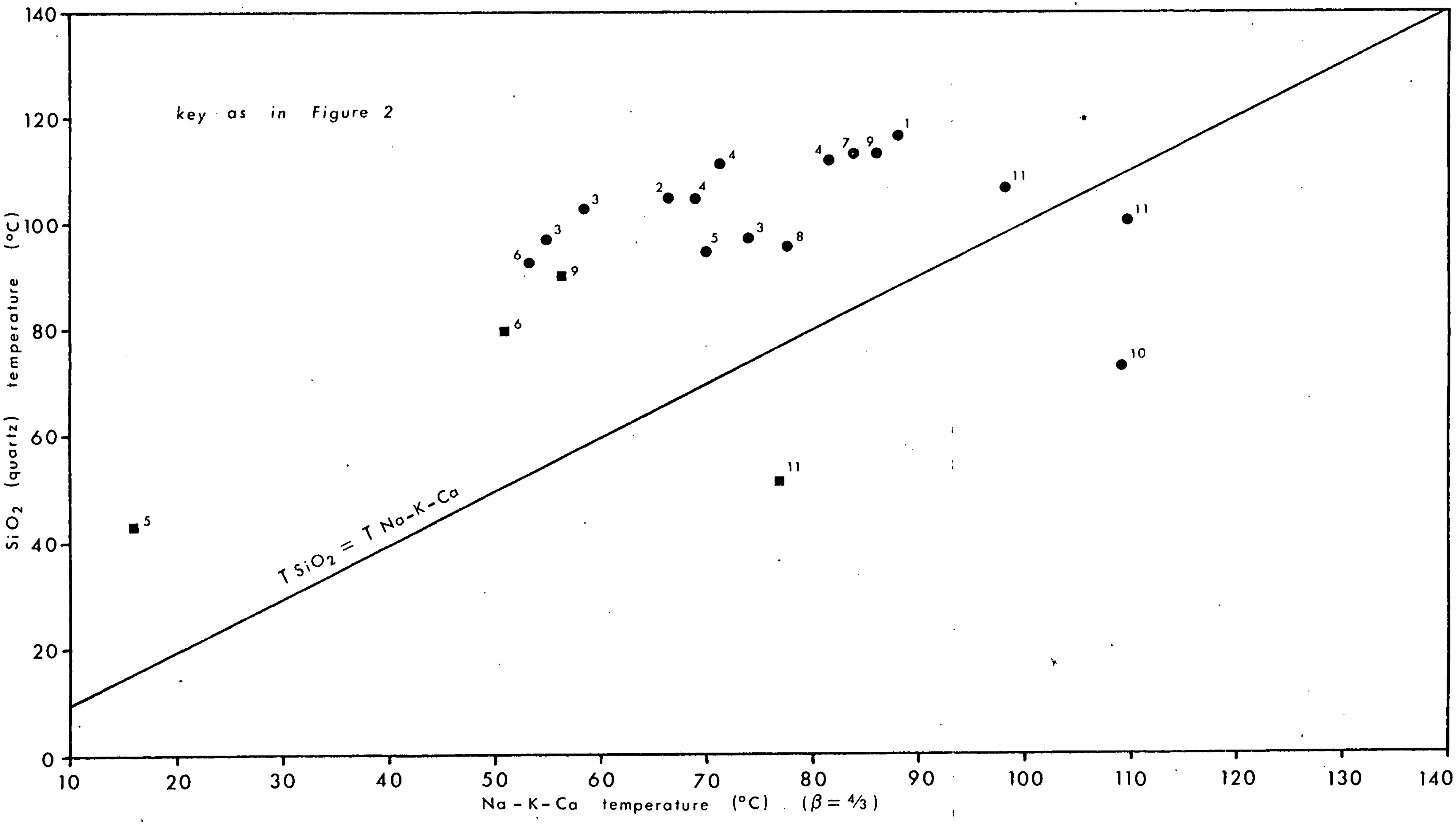
● Thermal spring
■ Cold groundwater



	Total disolved solids (mg/l) thermal	cold
1 Mkoba	162	42
2 Mvuntshini	121	42
3 Ezulwini	94-124	42
4 Lobamba	127-151	51
5 Mawelawela	153	81
6 Ngwempisi	118	68
7 Mpopoma	205	66
8 Mbondela	139	-
9 Madubula	197	184
10 Fairview	282	-
11 Siphofaneni	367-406	423

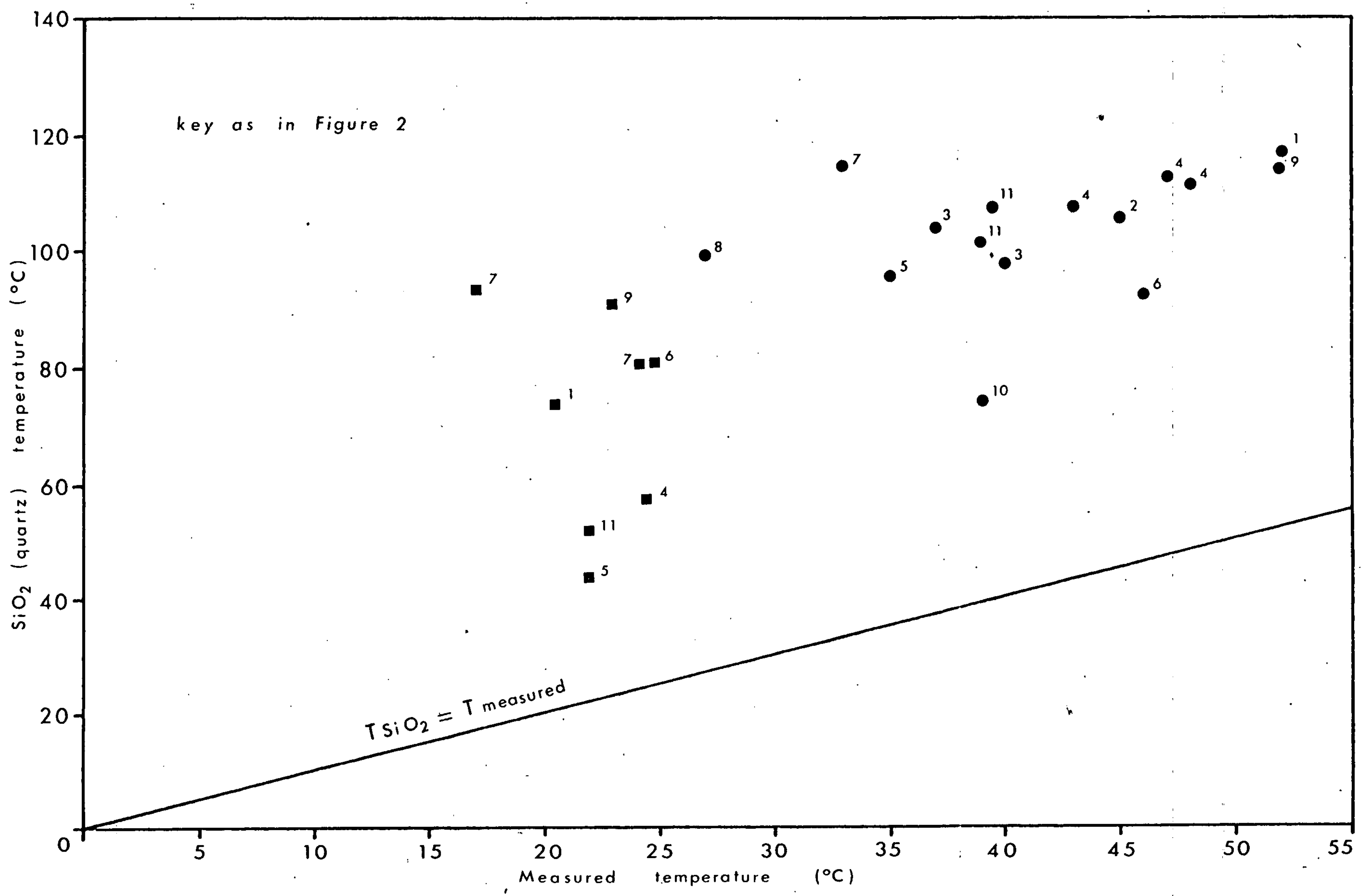
Na-K-Ca - SiO_2 (QUARTZ) TEMPERATURE CORRELATION

FIGURE 3



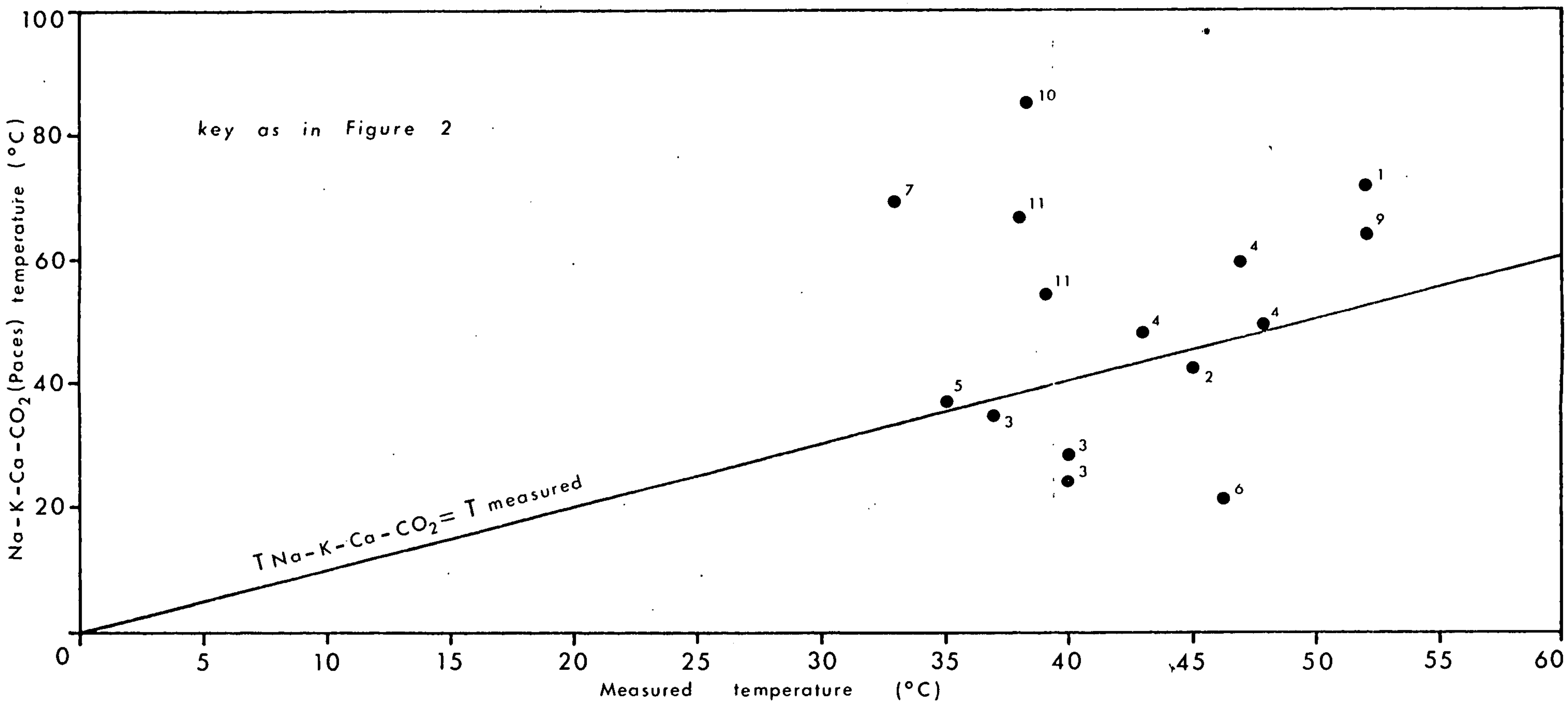
SiO$_2$ (QUARTZ) TEMPERATURE CORRELATION

FIGURE 4



Na-K-Ca-CO_2 (PACES) TEMPERATURE CORRELATION

FIGURE 5



APPENDIX 1 - analytical data

A. Major ion concentrations (mg/l)

B. Minor ion concentrations (mg/l)

C. Total concentrations and analytical charge balance

D. Geothermometers

E. Table of computed $p(CO_2)$ and SI values for calcite and fluorite

SEQ NO		LOCALITY		DEPTH,M WELL	SMPL	DATE	TYPE	NA	K	CA	MG	HCO3	SO4	CL
								ANALYSES, MILLIGRAMMES PER LITRE						
78	486	SWZLND	EZULWN HOT			0478	26	32.	1.5	5.		54.0	4.	6.
78	487	SWZLND	EZULWN HOT			0478	26	26.	1.3	4.		55.0	3.	5.
78	488	SWZLND	EZULWN HOT			0478	26	32.	2.6	5.		66.0	3.	15.
78	489	SWZLND	LOBOMBA COLD			0478	02	7.	.4	4.		37.0	0.	3.
78	490	SWZLND	LOBAMBA G HOT			0478	26	43.	2.2	3.		79.0	5.	19.
78	491	SWZLND	LOBAMBA G HOT			0478	26	44.	1.4	3.		77.0	5.	19.
78	492	SWZLND	MKOBA HOT			0478	26	37.	1.8	1.		99.0	8.	14.
78	493	SWZLND	MKOBA COLD			0478	02	9.	2.9	1.		22.0	0.	6.
78	494	SWZLND	LOBAMBA HOT			0478	26	39.	1.5	3.		71.0	4.	8.
78	495	SWZLND	MAWELAWELA HOT			0478	26	41.	1.4	3.		95.0	4.	9.
78	496	SWZLND	MADUBULA COLD			0578	02	47.	2.1	9.		90.0	4.	31.
78	497	SWZLND	MADUBULA HOT			0578	26	68.	2.1	3.		75.0	12.	37.
78	498	SWZLND	SIPHOFANENI HOT			0578	26	140.	5.1	9.		113.0	19.	120.
78	499	SWZLND	MPOPOMA COLD			0478	02	14.	.7	3.		43.0	0.	5.
78	500	SWZLND	SIPHOFANENI HOT			0578	26	125.	4.4	4.		104.0	11.	119.
78	501	SWZLND	NGWEMPISI COLD			0478	02	14.	1.6	5.		37.0	0.	11.
78	502	SWZLND	MAWELAWELA COLD			0478	02	13.	.4	5.		48.0	8.	6.
78	503	SWZLND	NGWEMPISI HOT			0478	26	34.	1.3	5.		69.0	4.	5.
78	504	SWZLND	SIPHOFANENI COLD			0578	02	150.	1.5	4.		127.0	13.	128.
78	505	SWZLND	MPOPOMA HOT			0478	26	70.	1.5	2.		96.0	12.	24.
78	506	SWZLND	EZULWN COLD		20.	0478	07	5.	.5	4.		29.0	0.	3.
78	513	SWZLND	FAIRVIEW HOT			0578	26	106.	2.9	2.		99.0	17.	55.
78	514	SWZLND	MVUNISHINI HOT			0578	26	37.	1.4	3.		69.0	4.	7.
79	248	SWAZI	MBONDELA SPR			0379	26	40.	2.2	3.		77.0	7.	9.

*TYPE CODES ARE 02SPRING,03STREAM,07BOREHOLE/WELL,08SHALLOW WELL,09DEPTH SAMPLE,10PUMPED SAMPLE,11ARTESIAN FLOW,12MINE DRAINAGE(SURF),13MINE DRAINAGE(U/GROUND),17INTERSTITIAL,23COND.STEAM,24ENTRAINED WATER,25THERMAL G/WATER,26THERMAL SPRING,27DRILL STEM TEST

APPENDIX I-A

MILLIGRAMMES PER LITRE

SEQ	LOCALITY	SR	LI	RB	CS	F	BR	I	ORTHPO4	B
78 486	EZULWN HOT	.100				6.1000				
78 487	EZULWN HOT	.180				4.9000				
78 488	EZULWN HOT	.060				5.9000				
78 489	LOBOMBA COLD	.040				.1600				
78 490	LOBAMBA G HOT	.060				8.1000				
78 491	LOBAMBA G HOT	.060				8.1000				
78 492	MKOBA HOT	.050				7.2000				
78 493	MKOBA COLD	.180				.0800				
78 494	LOBAMBA HOT	.080				7.9000				
78 495	MAWELAWELA HOT	.090				5.4000				
78 496	MADUBULA COLD	.100				6.9000				
78 497	MADUBULA HOT	.090				14.5000				
78 498	SIPHOFANENI HOT	.140				18.0000				
78 499	MPOPOMA COLD	.020				.8700				
78 500	SIPHOFANENI HOT	.090				16.0000				
78 501	NGWEMPISI COLD	.030				1.1000				
78 502	MAWELAWELA COLD	.080				.6200				
78 503	NGWEMPISI HOT	.040				6.0000				
78 504	SIPHOFANENI COLD	.040				17.5000				
78 505	MPOPOMA HOT	-.010				12.5000				
78 505	EZULWN COLD	.010				.1200				
78 513	FAIRVIEW HOT	.090				21.0000				
78 514	MVUNTSHINI HOT	.070				7.2000				
79 248	MBONDELA SPR	.000				6.0000				

APPENDIX I-B

SEQ		LOCALITY	MEQ/L CATIONS	ANIONS	BALANCE (PERCENT)	MG/L TOT.DET.IONS	SAR*	TU TRITIUM
78	486	EZULWN HOT	1.6662	1.1292	19.21	101.85	4.06	
78	487	EZULWN HOT	1.3651	1.1007	10.72	94.15	3.58	
78	488	EZULWN HOT	1.6930	1.5693	3.79	123.40	4.06	
78	489	LOBOMBA COLD	.5044	.6952	-15.91	51.45	1.05	
78	490	LOBAMBA G HOT	2.0715	1.9285	3.58	150.80	6.95	
78	491	LOBAMBA G HOT	2.0746	1.8957	4.51	148.60	7.66	
78	492	MKOBA HOT	1.7304	2.1881	-11.68	161.50	8.32	
78	493	MKOBA COLD	.5380	.5339	.38	41.60	2.47	
78	494	LOBAMBA HOT	1.8796	1.4767	12.00	126.60	6.31	
78	495	MAWELAWELA HOT	1.9441	1.8900	1.41	152.70	7.14	
78	496	MADUBULA COLD	2.5710	2.4430	2.55	184.05	4.20	
78	497	MADUBULA HOT	3.1564	2.5225	11.16	197.00	11.00	
78	498	SIPHOFANENI HOT	6.6745	5.6316	8.47	406.20	12.78	
78	499	MPOPOMA COLD	.8090	.8499	-2.47	66.60	2.18	
78	500	SIPHOFANENI HOT	5.7696	5.2811	4.42	367.40	16.41	
78	501	NGWEMPISI COLD	.8671	.9208	-3.01	68.10	1.73	
78	502	MAWELAWELA COLD	.8277	1.1287	-15.39	80.80	1.70	
78	503	NGWEMPISI HOT	1.7680	1.3469	13.52	118.05	4.15	
78	504	SIPHOFANENI COLD	6.7417	5.9618	6.14	423.05	21.77	
78	505	MPOPOMA HOT	3.1719	2.5001	11.84	205.25	14.37	
78	506	EZULWN COLD	.4473	.5641	-11.55	42.10	.74	
78	513	FAIRVIEW HOT	4.7950	3.5275	15.23	282.10	19.68	
78	514	MVUNISHINI HOT	1.7900	1.4137	11.75	121.40	5.98	
79	248	MBONDELA SPR	1.9510	1.6757	7.59	138.80	6.26	

* Sodium absorption ratio

APPENDIX I-C

SEQ NO	LOCALITY		MEASURED DATA TEMP DEGC	PH	TDS MG/L	SIO2 MG/L	GEOTHERMOMETERS, IN DEG C AMPHS	SILICA QZ	CHALC	CRIST	NA/K/CA B=4/3	B=1/3	NA/K B=0	Pates corrected B=4/3
78 486	SWZLND	EZULWN HOT	37.0	8.60	102.	51.3	-13.0	103.2	71.6	52.6	58.0	130.3	121.0	34.1
78 487	SWZLND	EZULWN HOT	40.0	8.40	94.	44.9	-18.2	97.0	64.9	46.6	55.2	131.5	126.5	27.9
78 488	SWZLND	EZULWN HOT	40.0	7.20	123.	44.9	-18.2	97.0	64.9	46.6	73.7	153.8	166.5	24.3
78 489	SWZLND	LOBOMBA COLD	24.0	6.60	51.	16.5	-51.9	56.6	22.1	7.5	18.4	122.0	142.2	
78 490	SWZLND	LOBAMBA G HOT	47.0	9.00	151.	62.0	-5.1	112.2	81.5	61.6	81.9	140.6	125.4	59.5
78 491	SWZLND	LOBAMBA G HOT	48.0	9.00	149.	59.9	-6.6	110.5	79.6	59.9	70.8	121.5	90.4	49.8
78 492	SWZLND	MKOBA HOT	52.0	9.30	161.	68.4	-.9	117.1	86.8	66.4	88.3	141.0	121.3	71.3
78 493	SWZLND	MKOBA COLD	21.0	5.70	42.	25.7	-38.2	73.3	39.6	23.5	96.3	218.5	352.7	
78 494	SWZLND	LOBAMBA HOT	43.0	9.00	127.	53.5	-11.3	105.1	73.6	54.5	68.6	126.7	103.6	48.4
78 495	SWZLND	MAWELAWELA HOT	35.0	8.40	153.	42.8	-20.1	94.8	62.5	44.4	70.1	123.5	95.2	37.2
78 496	SWZLND	MADUBULA COLD	23.0	6.90	184.	38.5	-24.0	90.2	57.5	39.9	56.3	126.3	112.9	
78 497	SWZLND	MADUBULA HOT	52.0	9.00	197.	64.2	-3.7	113.9	83.3	63.2	85.5	125.3	88.4	63.3
78 498	SWZLND	SIPHOFANENI HOT	39.0	8.10	406.	55.6	-9.7	106.9	75.7	56.4	98.3	134.5	99.7	53.7
78 499	SWZLND	MPOPOMA COLD	17.0	6.50	67.	40.6	-22.0	92.5	60.1	42.2	35.8	121.8	121.3	
78 500	SWZLND	SIPHOFANENI HOT	38.0	8.30	367.	49.2	-14.7	101.2	69.4	50.7	109.5	136.7	97.3	66.5
78 501	SWZLND	NGWEMPISI COLD	24.0	6.60	68.	29.9	-33.0	79.5	46.2	29.5	50.9	157.9	206.0	
78 502	SWZLND	MAWELAWELA COLD	22.0	5.90	81.	11.1	-62.7	43.1	8.1	-5.3	16.4	99.6	86.2	
78 503	SWZLND	NGWEMPISI HOT	46.0	8.20	118.	40.6	-22.0	92.5	60.1	42.2	53.1	122.2	105.9	21.4
78 504	SWZLND	SIPHOFANENI COLD	22.0	7.10	423.	13.9	-56.7	50.6	15.9	1.8	77.2	89.7	24.9	
78 505	SWZLND	MPOPOMA HOT	33.0	9.40	205.	64.2	-3.7	113.9	83.3	63.2	84.0	112.7	63.8	69.8
78 506	SWZLND	EZULWN COLD	24.0	5.90	42.	29.9	-33.0	79.5	46.2	29.5	17.1	133.9	179.7	
78 513	SWZLND	FAIRVIEW HOT	38.0	9.20	282.	25.7	-38.1	73.3	39.6	23.5	109.1	128.3	80.6	85.8
78 514	SWZLND	MVUNTSHINI HOT	45.0	8.80	121.	53.5	-11.3	105.1	73.6	54.5	66.0	125.3	102.4	42.0
79 248	SWAZI	MBONDELA SPR	27.0	.00	139.	46.0	-17.3	98.1	66.1	47.6	79.6	142.3	131.3	(40.9)[1]

GEOTHERMOMETRY FORMULAE ARE THOSE SUGGESTED BY TRUESDELL(1975). IF MEASURED TEMP IS ABOVE 95DEG,THEN QZ TEMP IS ADIABATIC ELSE IS CONDUCTIVE. USE B=4/3 TEMP IF LESS THAN 100 DEG ELSE USE B=1/3 TEMP

[1] $P(CO_2)$ estimate used

FIN

APPENDIX I-D

APPENDIX I-E

Seq. No.	Locality	$P(CO_2)$, atm[1]	SI(calcite)[2]	SI(fluorite)[2]
78/486	Ezulwini (hot)	1.4×10^{-4}	-0.25	-0.22
487	" "	2.5×10^{-4}	-0.44	-0.50
488	" "	5.3×10^{-3}	-1.46	-0.28
489	Lobamba (cold)	9.6×10^{-3}	-2.61	-3.30
490	Lobamba G.Ho.(hot)	7.2×10^{-5}	+0.05	-0.33
491	" " "	7.1×10^{-5}	-0.02	-0.40
492	Mkoba (hot)	3.2×10^{-5}	-0.02	-0.80
493	" (cold)	4.3×10^{-2}	-4.30	-4.37
494	Lobamba (hot)	6.5×10^{-5}	0.00	-0.30
495	Mawelawela (hot)	4.2×10^{-4}	-0.48	-0.60
496	Madubula (cold)	1.1×10^{-2}	-1.59	+0.32
497	" (hot)	6.5×10^{-5}	-0.01	+0.11
498	Siphofaneni (hot)	1.0×10^{-3}	-0.17	+0.87
499	Mpopoma (cold)	1.3×10^{-2}	-2.81	-1.79
500	Siphofaneni (hot)	5.9×10^{-4}	-0.33	+0.48
501	Ngwempisi (cold)	9.5×10^{-3}	-2.51	-1.53
502	Mawelawela (cold)	6.0×10^{-2}	-3.14	-2.01
503	Ngwempisi (hot)	5.8×10^{-4}	-0.36	-0.29
504	Siphofaneni(cold)	9.5×10^{-3}	-1.74	+0.64
505	Mpopama (hot)	2.4×10^{-5}	+0.04	-0.07
506	Ezulwini (cold)	3.8×10^{-2}	-3.36	-3.50
513	Fairview (hot)	5.3×10^{-5}	+0.09	+0.38
514	Mvuntshini (hot)	1.2×10^{-4}	-0.13	-0.38
79/248	Mbondela	(7.9×10^{-4})[3]	(-0.97)[3]	(-0.32)[3]

Notes:

1. Partial pressure of CO_2, computed from pH and HCO_3^- measurements assuming equilibrium between carbonate species.

2. Saturation indices for calcite and fluorite. Zero value indicates equilibrium, negative undersaturation and positive oversaturation. Computed SI values are significant at ± 0.1 level approx.

3. The computations for Mbondela have been made using an <u>assumed</u> pH approximation of 8.0, therefore they are of very limited significance.