

A PRELIMINARY LIMNOLOGICAL INVESTIGATION OF TWELVE
SOUTHERN AFRICAN GEOTHERMAL WATERS

P.J. Ashton & F.R. Schoeman

National Institute for Water Research,
Council for Scientific and Industrial Research, P.O. Box 395,
Pretoria 0001, South Africa.

SUMMARY

The ionic composition and algal flora of twelve geothermal waters in southern South West Africa and north-western South Africa are described, many for the first time. Water temperatures ranged from 24,9 to 66 °C and salinity values indicated moderate mineralization. A trend of increasing sodium and sulphate dominance with increasing water temperature was evident. Green algae were confined to springs with low water temperatures (below 31 °C) while diatoms and blue-green algae were recorded in all the springs, at temperatures up to 66 °C. Flexibacteria (*Chloroflexus*) were recorded only in the hotter springs, above 40 °C.

INTRODUCTION

Geothermal springs, with elevated temperatures brought about by subterranean heating, occur in a wide variety of climatic regions on every continent except in regions of permanent ice (Castenholz 1969). Geothermal waters tend to be mainly of meteoric origin and their temperatures are regulated by flow rates and the depth to which the water has penetrated the earth's crust before emerging (Du Toit 1954). Lukewarm (≈24 °C) waters and artesian springs issuing freely from artificially-tapped sources are also considered to be geothermal when their temperatures are consistently several degrees Celsius above the mean annual temperature of the geographical region in which they are situated (Bond 1946; Kent 1949; Castenholz 1973).

A large number of geothermal springs and artesian boreholes with temperatures ranging from 24 to 101 °C have been identified in southern Africa (Kent 1949, 1969; Bond 1953; Gevers, Hart & Martin 1963; Carvalho 1969; Mazor, Verhagen & Negreanu 1974; Mazor & Verhagen 1976, 1983; Hoffmann 1979; Huyser 1982); their distribution and thermal characteristics are shown in Figure 1 and Table 1. Apart from the taxonomic notes made by West (1912), Welsh (1964, 1965) and Cholnoky (1966) who listed the species of diatoms and blue-green algae found in and near a few South West African thermal springs, very little attention has been paid to the fauna and flora of these waters.

In this paper we report on the temperature, ionic composition and algal flora of twelve geothermal waters (ten springs and two artesian boreholes) from the north-western Cape Province of South Africa and southern South West Africa/Namibia. The water

temperatures of six of the geothermal sources examined in this study have been previously documented by Kent (1949), who also provided hydrochemical data for two of these springs. Tredoux & Kirchner (1981) described the hydrochemistry of the two geothermal artesian boreholes (springs 1 & 2) investigated in this study. Thus, the hydrochemical features of eight of the geothermal springs examined in this study have not been previously described. The major aim of this study was to provide essential ecological data for subsequent taxonomic investigations of the algal flora in these geothermal waters. The wide range of temperatures and ionic concentrations spanned by the twelve geothermal waters also permitted examination of the algal flora for evidence of habitat partitioning on the basis of temperature or salinity.

LOCATION OF THE THERMAL SPRINGS

The distribution of the twelve geothermal waters examined in this study is shown on the map in Figure 1 and the geographical position of each is listed in Table 2. Ten of the thermal springs are located in southern South West Africa/Namibia and the remaining two are in the north-western portion of the Cape Province, South Africa, close to the South West African border.

The two artesian boreholes (springs 1 and 2) form part of an irrigation scheme in the upper reaches of the Auob River valley. The remaining springs all have shallow pools built around the spring source and, except for springs 5 and 8, overflow waters are diverted away through troughs or pipelines. At springs 5 and 8, emerging waters flow for a short

TABLE 1. The numbers and thermal classification of known geothermal springs (SPR) and artesian boreholes (ART) in southern Africa

Thermal Classification	South Africa ^a		South West Africa ^b		Zimbabwe ^c		Swaziland ^d		Mozambique ^e	
	SPR	ART	SPR	ART	SPR	ART	SPR	ART	SPR	ART
Warm	39	6	9	24	-	5	1	-	1	-
Hot	24	2	4	1	2	-	5	-	2	-
Scalding	6	1	8	-	6	-	1	-	2	-
Unknown	5	-	3	8	12	4	2	-	-	-
Total	83		57		29		9		5	

Data sources, a: Kent 1949; Hoffmann 1979; this study.
b: Kent 1949; Gevers, Hart & Martin 1963; Huyser 1982; this study.
c: Bond 1953; Mazor & Verhagen 1976; Thornton 1980.
d: Mazor *et al.*, 1974.
e: Carvalho 1969.

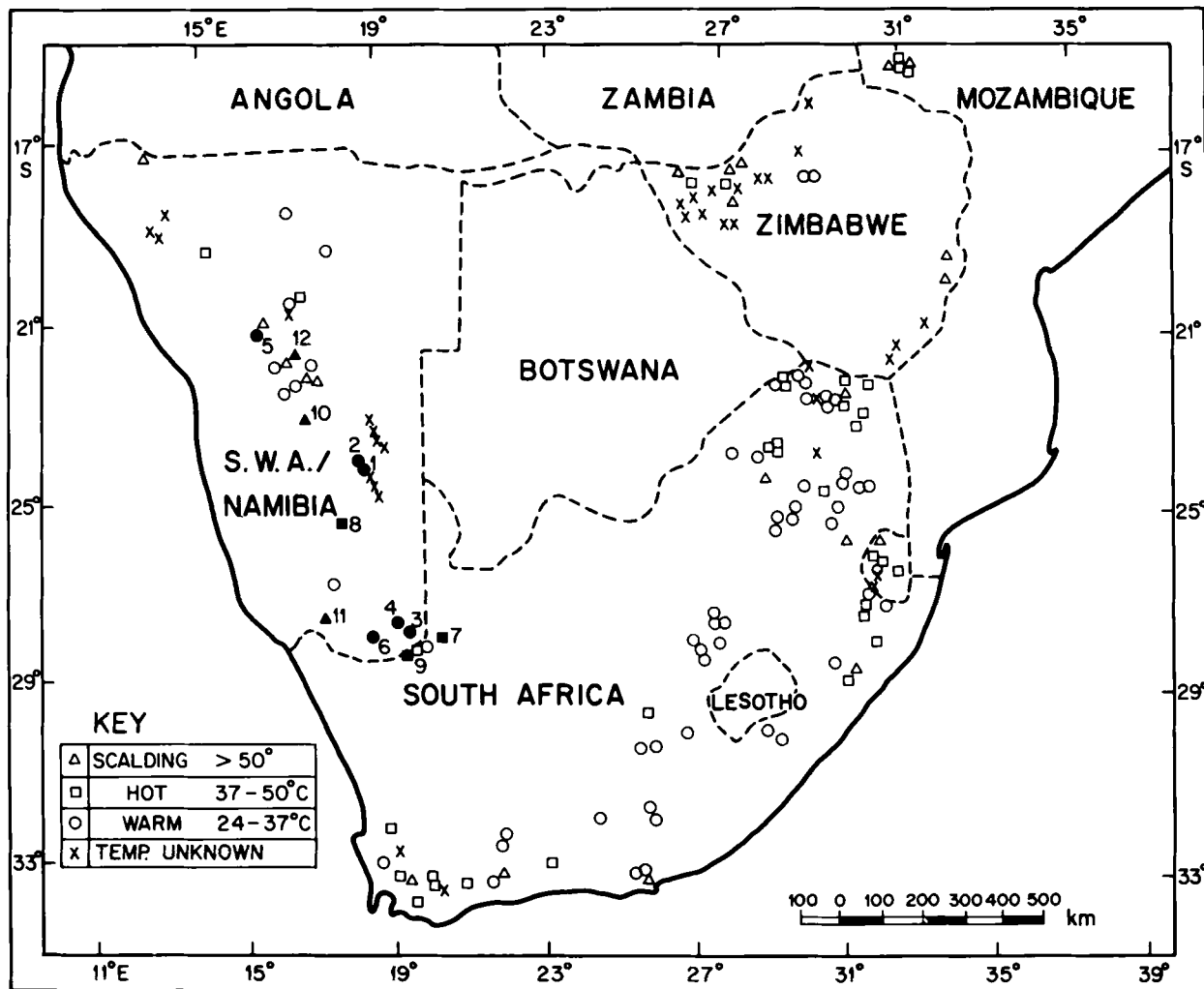


Figure 1. The distribution of southern African geothermal springs and artesian boreholes. The thermal classification system is that used by Kent (1949), and data sources are listed in the footnote to Table 1. (Numbered, solid symbols indicate the twelve springs examined in this study).

TABLE 2. Latitude and longitude of the twelve thermal springs examined in this study, listed in order of ascending temperatures. (Algal sample numbers are included to facilitate cross-referencing with the NIWR diatom collection.)

Spring No.	Name	Latitude	Longitude	Algal Sample No.
1	Osterode Süd	24°25'S	18°29'E	G58
2	Stampriet	24°20'S	18°23'E	G60
3	Gründorn	28°21'S	19°44'E	G166
4	Blydeverwacht	28°18'S	19°37'E	G170
5	Omappy	21°34'S	16°07'E	G94
6	Warmbad	28°28'S	18°44'E	G175
7	Riemvasmaak (RSA)	28°28'S	20°17'E	G14
8	Ganikobis	25°50'S	18°01'E	G128
9	Warmbad Noord (RSA)	28°34'S	19°33'E	G184
10	Rehoboth	23°20'S	17°05'E	G74
11	Ai-ais	27°55'S	17°29'E	G153
12	Gross Barmen	22°07'S	16°44'E	G89

distance over sand and gravel beds before sinking underground. The three hottest springs (10, 11 and 12) have been developed as medicinal spas for public use. The spring source at Rehoboth (spring 10) has

been completely enclosed except for a small hatchway and algal samples could therefore not be collected from the spring source.

MATERIALS AND METHODS

Field measurements and sample collection

At each spring, water temperatures were measured with a standard mercury thermometer graduated at 0,1 °C intervals. pH measurements were made with an Orion 201 portable pH meter equipped with a glass electrode after correction for water temperatures and calibration with fresh pH 7,0 buffer solution (Merck). A portable Werkstätten DB12 conductivity meter was employed for conductivity measurements in the field. Where possible, series of temperature, pH and conductivity measurements were made along the course of channels leading from the springs.

Two 500 ml capacity polyethylene bottles of water were collected from each sampling site for chemical analysis. Saturated HgCl_2 (1 ml per litre) was added to one bottle of each pair immediately after collection to preserve nitrogen and phosphorus compounds. The other, unpreserved, water sample was analyzed for major ionic constituents. All water samples were stored in the dark during transport to the laboratory.

Samples of benthic algal material were scraped from rocks as close as possible to the source of each spring. All algal samples were preserved in 4% (v/v) formaldehyde for transport to the laboratory.

Chemical analyses

All water samples were filtered prior to analysis (pre-washed Whatman GF/C filters). Because several samples had a high solute content, all samples were diluted with deionized distilled water, to give final dilutions of 1/10 and 1/100, before analysis.

At the NIWR, chemical analyses are derived from published methods (Environmental Protection Agency 1974; A.P.H.A 1975), and are carried out with Technicon Autoanalyzers (NIWR 1974). Total (dissolved) nitrogen was calculated as the sum of Kjeldahl nitrogen and nitrate plus nitrite. All water analyses were within 5% of chemical balance, and salinity was calculated as the sum of the major ionic constituents (Hutchinson 1957).

Algal samples

In the laboratory, a representative portion of each formalin-preserved algal sample was acid-cleaned and mounted in Naphrax (Cholnoky 1968) to facilitate identification of diatom species. Other algal species were identified by examining temporary

(aqueous) slide mounts of untreated, preserved algal material.

RESULTS

Thermal and chemical characteristics

For convenience, the thermal classification system proposed by Kent (1949) has been adopted here and the twelve thermal springs examined during this study may be categorized as shown in Figure 1. Water temperatures at the sources of the twelve springs ranged between 24,9 and 66 °C, permitting their categorization as either warm, hot or scalding. No cool springs (i.e. temperatures below 24 °C) were examined during this study.

Details of the thermal and chemical features of the twelve springs are shown in Table 3, ranked in order of ascending temperatures. The spring waters were moderately mineralized with salinities ranging from 500 to 2 700 g m^{-3} and their pH values ranged from neutral to slightly alkaline (8,3). Silica and fluoride concentrations tended to increase gradually with increasing water temperatures while calcium concentrations showed a somewhat erratic decrease with increasing temperature. Variations in the concentrations of other cations, anions and total phosphorus did not appear to be related to changes in water temperature. Total nitrogen concentrations were very variable, the highest values being recorded from the artesian boreholes (springs 1 and 2) and the lowest values from the three scalding springs. High nitrate values accounted for over 80% of the total nitrogen in those springs where total nitrogen concentrations exceeded 1 g m^{-3} (Table 4). The presence of H_2S was detected by smell only at the three scalding springs (10, 11 and 12).

The ionic proportions of the twelve springs are shown in Table 4 and compared with world average freshwater and seawater values (Rodhe 1949) in the ionic diagrams in Figure 2. The cation field diagram indicates the marked differences in composition between the artesian boreholes (springs 1 and 2), which contain high proportions of calcium and magnesium, and the other springs, which show a steadily increasing dominance of sodium and potassium with increasing temperature (Table 4). The anion field diagram indicates a change in anionic dominance from carbonate and bicarbonate through chloride to sulphate with increasing temperature. This is also shown by the increase in the SO_4/Cl ratios indicated in Table 4. The ionic dominance orders of the twelve thermal springs show closer affinities with seawater than typical freshwater ratios and this is reflected by the low values for the ratio between divalent and monovalent cations (Table 4).

TABLE 3. Physical and chemical characteristics of the twelve thermal springs examined in this study. All concentrations are in g m^{-3} except total alkalinity ($\text{g CaCO}_3 \text{ m}^{-3}$).

Spring No	Temp. (°C)	pH	Conductivity (mS m^{-1})	Na	K	Ca	Mg	Si	SO_4	F	Cl	Total Alkalinity	Total N	Total P	Salinity
1	24,9	8,3	179	91	11	40	43	30	30	0,8	100	306	14,6	0,1	580
2	26,2	7,9	164	74	7	41	36	34	17	0,8	90	260	19,3	0,2	540
3	27,8	8,2	270	410	6	34	8	31	320	2,1	390	128	8,1	0,2	1330
4	28,6	7,8	165	340	9	40	6	28	250	1,7	280	185	8,3	0,2	1140
5	30,6	7,2	150	330	27	28	9	25	220	2,1	340	137	10,3	0,1	1120
6	36,8	7,5	350	560	15	40	8	36	450	2,0	610	44	0,8	0,2	1760
7	38,0	7,0	540	835	18	40	19	38	590	2,9	870	206	6,3	0,1	2620
8	43,0	7,2	420	737	9	30	18	47	750	3,2	520	270	8,2	0,2	2380
9	43,0	7,5	400	840	16	20	12	52	930	3,8	590	154	3,2	0,2	2610
10	57,5	7,0	400	510	50	13	6	58	700	4,0	190	226	0,3	0,1	1750
11	65,5	7,4	495	770	28	10	5	69	940	5,7	490	84	0,2	0,2	2400
12	66,0	7,1	260	420	18	6	1	68	530	5,2	150	166	0,3	0,1	1360

TABLE 4. Ionic proportions (milliequivalent percentage of the sum of cations or anions) and ionic ratios in the twelve thermal springs examined in this study.

Parameter	Spring Number											
	1	2	3	4	5	6	7	8	9	10	11	12
Na	41	38	88	84	84	89	90	90	94	90	96	96
K	3	3	1	2	4	1	1	1	1	5	2	2
Ca	20	24	8	11	8	7	5	5	3	3	1	1
Mg	36	35	3	3	4	3	4	4	2	2	1	1
F + Cl	29	31	54	47	57	63	60	41	43	22	38	23
SO ₄	7	5	33	31	27	34	30	44	50	60	56	59
CO ₃ + HCO ₃	64	64	13	22	16	3	10	15	7	18	6	18
(Ca + Mg)/(Na + K)	1,27	1,44	0,12	0,16	0,14	0,11	0,10	0,10	0,05	0,05	0,02	0,02
SO ₄ /Cl	0,24	0,16	0,61	0,66	0,47	0,54	0,50	1,07	1,16	2,73	1,44	2,57
NO ₃ /Total N	0,89	0,92	0,80	0,80	0,81	0,85	0,32	0,81	0,82	0,41	0,60	0,56

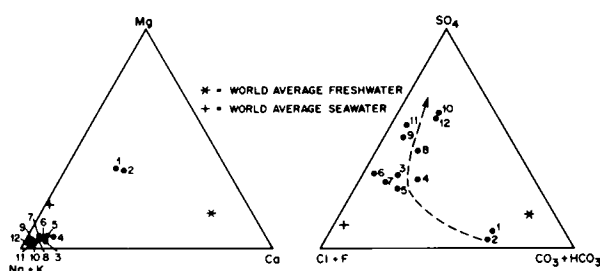


Figure 2. Ionic diagrams for the twelve geothermal springs examined in this study. Dashed line in anion field diagram indicates trend of changing anionic composition with increasing water temperature.

Algal studies

At each of the eleven sites where algal samples were collected, algal growth ranged from sparse to luxuriant and varied in colour from olive-green to bright green. The algae formed thin mats (1 to 5 mm thickness) on rock surfaces around the periphery of each spring. No algal growth was found on the constantly agitated gravel and coarse sand that formed the floor of each spring. Many of the algal mats contained small crystalline aggregates as well as fine sand and mica (biotite) particles. At springs 8, 9, 11 and 12 the underside of each algal mat was buff-orange in colour. The walled-in spring source at the Aiais Medicinal Spa (spring 11) appeared to have been recently scraped clean and the only sample of algal material obtained was found just above the water level. Luxuriant algal growths were found on the pipe orifices and splash boxes at the two artesian boreholes (springs 1 and 2).

The algal genera found growing at the source of each of the geothermal sites are listed in Table 5 and the temperature ranges spanned by the major algal taxa are summarized in Figure 3. A further group of organisms, tentatively identified as 'Flexibacteria', have also been included in Table 5 and Figure 3. The identity of these organisms is tentative since they were identified on morphological criteria only. Confirmation of this identification by spectrophotometric pigment analysis was not possible on the preserved samples. These Flexibacteria were found only in samples from the hottest springs (8, 9, 11 and 12) and appeared to be confined to the lower layers of the algal mats. In contrast, green algae

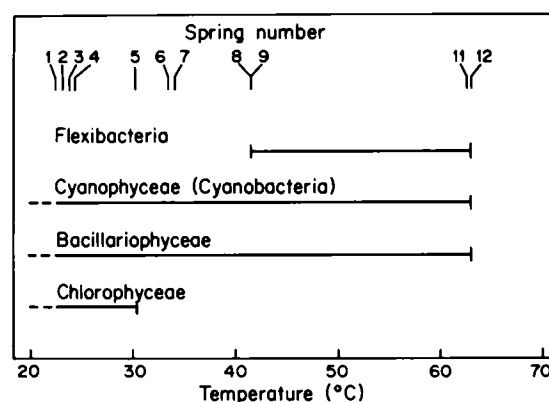


Figure 3. Diagrammatic representation of the range of water temperatures for eleven geothermal springs in which the different algal taxa and flexibacteria were found. Spring numbers are included to indicate the groups of organisms that were found at each spring.

(Chlorophyceae) were found only in the cooler springs (1 to 5) and were particularly abundant at springs 1 and 2. Diatoms (Bacillariophyceae) and blue-green algae (Cyanophyceae) were recorded in all the geothermal springs, the blue-green algae dominating at the higher temperatures.

Achnanthes and *Nitzschia* were the only two diatom genera to occur in all the springs (Table 5) and no clear pattern of temperature tolerance or preference was found. Conversely, *Oscillatoria* was the only genus of blue-green alga found in every spring (Table 5). However, *Synechococcus* and a small-celled genus tentatively identified as *Chroococcus* were abundant in springs 11 and 12 but declined at lower temperatures. *Phormidium* and *Mastigocladus* were found only in springs with intermediate temperatures, while *Lyngbya* was confined to springs 1, 3, 4 and 5 (Table 5). Very few of the blue-green algae possessed heterocysts. A systematic account of the algal flora from the geothermal springs is being prepared for publication (Schoeman, Archibald & Ashton: in preparation).

DISCUSSION

With the exception of the temperatures given for Gross Barmen (spring 12) and Warmbad (spring 6), there are several differences between the temperature

TABLE 5. Distribution of algal genera and flexibacteria in eleven geothermal springs. (+ = genus present).

	Spring Number										
	1	2	3	4	5	6	7	8	9	11*	12
Temperature (°C)	24,9	26,2	27,8	28,6	30,6	36,8	38,0	43,0	43,0	65,5	66,0
Algal genera											
Chlorophyceae											
<i>Dictyosphaerium</i>			+	+	+						
<i>Euglena</i>		+	+	+							
<i>Oedogonium</i>	+	+		+	+						
<i>Spirogyra</i>	+	+	+								
<i>Zygnema</i>	+										
Bacillariophyceae											
<i>Achmanthes</i>	+	+	+	+	+	+	+	+	+	+	+
<i>Amphora</i>	+	+	+	+					+		
<i>Anomooneis</i>						+			+		
<i>Caloneis</i>								+			+
<i>Cymbella</i>	+		+					+			
<i>Fragilaria</i>										+	
<i>Frustulia</i>											+
<i>Gomphonema</i>				+				+			
<i>Hantzschia</i>							+				
<i>Mastogloia</i>										+	
<i>Navicula</i>				+				+			+
<i>Nitzschia</i>	+	+	+	+	+	+	+	+	+	+	+
<i>Rhopalodia</i>											+
<i>Surirella</i>								+			
<i>Synedra</i>	+	+	+			+					
Cyanophyceae											
<i>Calothrix</i>	+	+		+	+	+	+	+	+		
? <i>Chroococcus</i>					+	+	+	+	+	+	+
<i>Lyngbya</i>	+		+	+	+						
<i>Mastigocladus</i>							+	+	+		
<i>Oscillatoria</i>	+	+	+	+	+	+	+	+	+	+	+
<i>Phormidium</i>						+	+	+	+	+	+
<i>Synechococcus</i>								+	+	+	+
Flexibacteria											
? <i>Chloroflexus</i>								+	+	+	+

* Algal sample collected from rocks above water level.

data provided by Kent (1949) and those obtained in this study (Table 6). The most marked of these is the 30,4 °C difference in water temperatures for Omapyu (spring 5), the other temperatures differing by between 0,7 and 10,5 °C. However, the lack of pertinent climatological and hydrological data pertaining at the time 'Kent's' measurements were made (76 to 98 years ago), prevents firm conclusions being drawn as to the reasons for the discrepancies between them and the present (September 1983) data.

TABLE 6 Comparison of the water temperature data for six geothermal springs provided by Kent (1949) with values obtained during this study. (Figures in parentheses indicate year in which 'Kent's' temperatures were measured by various observers).

Spring No.	Spring Name	Water temperature	
		Kent	This study
12	Gross Barmen	65 (1896)	66
5	Omapyu	61 (1885)	30,6
11	Al-ais	55 (1907)	65,5
10	Rehoboth	52 (1896)	57,5
8	Ganikobis	40 (1907)	43,0
6	Warmbad	37,5 (1907)	36,8

The salinity range (500 to 2 700 g m⁻³) of the twelve geothermal sources examined in this study is characteristic of moderately mineralized waters (Bond 1946) and similar values have been measured in other southern African geothermal springs (Kent 1949; Gevers *et al.* 1963; Carvalho 1969; Mazor & Verhagen 1976, 1983; Mazor *et al.* 1974). Nevertheless, the twelve springs may be classified in two distinct groups (Figure 2; Tables 3 and 4):

- A relatively fresh group with salinities below 600 g m⁻³, represented by the two geothermal artesian boreholes (springs 1 and 2). Here, no cations dominate specifically but the anionic composition is dominated by carbonate plus bicarbonate ions and sulphate values are low. Measurements of the ionic composition of these two artesian boreholes made during the present study show close agreement with analyses published by Tredoux & Kirchner (1981) and Huysler (1982). Fluoride concentrations were relatively low (<1 g m⁻³) though nitrate values ranged from 12,9 to 18,1 g m⁻³, contributing over 88% of the total nitrogen content of these waters.
- A more saline group with salinity values above 1 000 g m⁻³ represented by the remaining 10 geothermal springs (springs 3 to 12). In this group sodium was the dominant cation (contributing over 84% of the total cations) while

chloride or sulphate were the dominant anions (Tables 3 and 4).

The chemical analyses for Gross Barmen (spring 12) and Warmbad (spring 6) published by Kent (1949) differ radically from our values (Table 3) though the ionic proportions are quite similar (Table 4).

The replacement of chloride by sulphate as the dominant anion in those springs with higher temperatures (Table 4, Figure 2) suggests that this chemical process might in some way be linked to the water temperature. However, other workers (e.g. Kent 1949; Gevers *et al.* 1963; Carvalho 1969; Mazor & Verhagen 1976, 1983; and Mazor *et al.* 1974) indicate that there does not appear to be a particular temperature threshold above which sulphate becomes the dominant anion. Instead, the sulphate content of different geothermal waters is regulated by the chemical composition of local geological formations and their relative solubilities (Bond 1946).

The gradual increase in fluoride and silica concentrations with increasing temperature (Table 3) is consistent with the observations of Kent (1949) and Castenholz (1969) that the solubility of these elements increases with increasing temperature, particularly in alkaline waters. Similarly, the decrease in calcium concentrations with increased temperatures (Tables 3 and 4) reflects the decreased solubility of this element at elevated temperatures brought about by losses of CO₂ and ion exchange reactions with the surrounding rock (Castenholz 1969). Indeed, calcareous tufa (probably calcite) has been deposited in the form of a crust on the rocks around the spring sources at the three scalding springs (springs 10 to 12).

Total nitrogen values were very variable (Table 3), again reflecting regional differences in geology, soils and vegetation (Bond 1946). High total nitrogen values (>1 g m⁻³) were always due to elevated nitrate concentrations and showed no relationship to variations in water temperatures.

The distribution of the three major algal groups (Chlorophyceae, Bacillariophyceae and Cyanophyceae) in the geothermal springs (Table 5, Figure 3) indicated that only the Chlorophyceae were limited by increasing temperature. However, since the algal sample at spring 11 was collected just above water level, it may be assumed that the temperature at this point was lower than the water temperature. This sample should therefore be omitted from the analysis.

In the present study, the presence of cell contents within diatom valves was accepted as evidence that the diatoms were alive at the time of collection. The presence of low numbers of several diatom genera in samples from spring 12 with a temperature of 66 °C contradicts the upper temperature limit of 50 °C put forward by Castenholz (1969) for this algal group. However, earlier investigators (e.g. Boye Petersen 1946; Baudrimont 1968; Biebl & Kusel-Fetzmann 1966) have recorded living diatom populations in European and Icelandic hot springs with temperatures of 66 °C, 54 °C and 55 °C, respectively. These workers indicated that the presence or absence of diatoms in thermal springs was primarily regulated by temperature, but that salinity also had marked effects. The salinity values recorded in this study appear to be too low to exert any marked effect (Boye Petersen, 1946). The numbers of living diatoms found in spring 12 were far lower than the numbers recorded at the other springs, indicating that very few diatoms could tolerate the high water temperature.

The distribution of different blue-green algal genera in the geothermal springs (Table 5) provided an

indication of the range of temperatures tolerated by each genus. The temperature ranges spanned by each genus are very similar to those found by Castenholz (1969, 1973) in saline, alkaline geothermal springs in North America, Iceland and New Zealand. This indicates that the blue-green algal flora of geothermal springs throughout the world share several similar features. The luxuriant growth of blue-green algae in springs with temperatures between 30 and 50 °C (springs 5 to 9) provides clear evidence of the thermophilic nature of this algal group (Castenholz 1969). The virtual absence of heterocysts in all the blue-green algal samples indicated that very little nitrogen fixation occurs. This is to be expected in view of the high to very high levels of inorganic nitrogen in the spring waters (Castenholz 1969). Nevertheless, one of the high-temperature genera recorded in this study, *Mastigocladus*, has been shown to be capable of active nitrogen fixation at water temperatures up to 54 °C in North American geothermal springs (Stewart 1970).

Castenholz (1973) has noted that the photo-heterotrophic flexibacterial genus *Chloroflexus* appears to have a world-wide distribution despite its restriction to thermal environments with temperatures between 40 and 70 °C. The organisms tentatively identified as *Chloroflexus* in this study are morphologically similar to those described by Castenholz (1973) though it was not possible to confirm their identity by pigment analysis. If this identification is correct, this is the first record of their occurrence in southern African thermal environments. In this study, the observation that *Chloroflexus* was confined to the lower layers of algal mats found in the hottest springs (8, 9, 11 and 12) agrees with the findings of Castenholz (1973).

It appears, therefore, that the algal and (perhaps) bacterial flora of alkaline southern African geothermal environments share several similarities with the flora of chemically similar thermal springs in North America, Iceland, Europe and New Zealand. The range of ionic compositions found in the springs examined in this study was insufficient for conclusions to be drawn as to the effects of salinity on habitat partitioning. Nevertheless, the large number of geothermal springs in southern Africa (Figure 1; Table 1) provide a wide range of chemical and thermal environments for different groups of algae and bacteria. From this study, it is evident that further taxonomic and physiological studies are essential for a better understanding of southern African geothermal environments.

ACKNOWLEDGEMENTS

Thanks are due to Messrs A.C. Jarvis and T.A. Fenn for assistance with data collection in the field. Drs T.H.E. Heaton and A.S. Talma of the Natural Isotopes Division, NPRL, and several colleagues at the NIWR are thanked for critically reviewing the manuscript. This paper is published with the approval of the National Institute for Water Research.

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KEYWORDS

Thermal springs, artesian boreholes, ionic composition, green algae, diatoms, blue-green algae, South West Africa, South Africa.