

# THERMAL WATERS ALONG THE SWAKOP RIVER, SOUTH WEST AFRICA

by

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[Plates I—XI]

## ABSTRACT

Three thermal springs are located along the northwestern flanks of the Khomas Highlands, over a distance of 20 miles, within the broad valley of the Swakop River.

At Gross Barmen hot water issues naturally from some 12 individual closely spaced orifices, as well as from 2 bore-holes. Temperatures vary from 41.6 to 69°C. The yield of the natural springs is 2,060 gallons or 9.4 cb.m. per hour. The temperature of the hot spring at Klein Barmen, 7 miles away, is 62°C, the yield being 960 gallons or 4.34 cb.m. per hour. The water of the Okandu spring, 13 miles distant, is only tepid (38°C); owing to absence of well defined orifices its yield could not be measured.

Five new chemical analyses are presented. Total dissolved solids range between 944 and 1094 p.p.m. Sodium by far predominates among the *cations*, the dominant *anions* being sulphate, chloride and bicarbonate. These waters therefore belong to the mixed *alkaline-sulphate-muriate* class. Silica is relatively high and at Gross Barmen small amounts of siliceous sinter occur. Gas bubbles are composed mainly of nitrogen. Radioactivity is insignificant. The origin of major, minor, and trace elements is discussed in relation to rocks traversed. Comparison is made with ordinary ground-water of semi-arid and arid regions and the conclusion reached that the springs are of meteoric origin. Details are given of the contamination by the saline springs of the "fresh" subsurface water of the Swakop runoff course.

The springs at Klein Barmen and Okandu rise within aplitic granite and no structural control outside jointing is apparent. Dolerite dykes are too distant to be held responsible. The Gross Barmen springs issue from highly jointed, banded biotite and quartz-biotite schists and structural control is evident in a pronounced shear-zone, parallel to strike, involving marked drag-folds, bedding-slip and fracture-cleavage. Along the latter are aligned innumerable large porphyroblasts of andalusite.

## CONTENTS

INTRODUCTION .. .. .	158
I HISTORICAL .. .. .	159
II LOCATION OF THERMAL SPRINGS .. .. .	160
III TOPOGRAPHY .. .. .	160
IV CLIMATE .. .. .	161
V GENERAL GEOLOGY .. .. .	163
VI DESCRIPTION OF THERMAL SPRINGS .. .. .	164
1. Gross Barmen .. .. .	164
2. Klein Barmen .. .. .	168
3. Okandu (Sneyrivier) .. .. .	169
VII CHEMICAL AND SPECTROGRAPHIC ANALYSES .. .. .	171
VIII DISCUSSION OF ANALYTICAL RESULTS .. .. .	
a. Dissolved Solids .. .. .	174
b. Gases .. .. .	177
IX RADIOACTIVITY .. .. .	178
X CLASSIFICATION OF THERMAL WATERS .. .. .	179
XI THERAPEUTIC VALUE OF THERMAL WATERS .. .. .	179
XII SPRING DEPOSITS .. .. .	180
XIII ALGAL SLIME .. .. .	181
XIV CONTAMINATION OF SUBSURFACE WATER IN THE SWAKOP RIVER BY SALINE SPRING WATERS ON GROSS BARMEN .. .. .	181
XV ORIGIN OF THERMAL SPRINGS .. .. .	184
LITERATURE INDEX .. .. .	189

## INTRODUCTION

During 1957 the farm Gross Barmen, site of one of the earliest landmarks in the history of missionary endeavour and European settlement in South West Africa, was acquired by a syndicate headed by Dr. Erich Lübert, whose great interest in the past history and future development of the Territory is well known. Dr. Lübert's interest also in scientific matters prompted him to suggest to the senior author the desirability of a detailed investigation of the well-known hot springs on Gross Barmen.

Some time previously the South West African Administration had purchased 98·4668 hectares of ground around the hot springs and the ruins of the old Rhenish mission established in 1844. Dr. H. Martin, Chief Geologist to the Administration, had visited the locality and drawn up a brief preliminary report on the geology of the immediate surroundings of the spring site.

Furthermore, the Water Treatment Research Division of the National Chemical Research Laboratory of the Council for Scientific and Industrial Research, Pretoria, had established a branch laboratory in Windhoek. Under its Chief Chemist, Mr O. Hart, it had begun a more detailed continuation of the work on the chemical composition of subsurface water in and along the Swakop River initiated by T. W. Gevers and J. P. van der Westhyuzen, then geologist and chemist respectively to the South West African Administration, in 1930 and published in 1937. (8)\*

The authors wish to express their indebtedness to the South West African Administration, especially Dr. O. Wipplinger, Director of the Water Affairs Branch, for permission to publish this paper, as well as to the Council for Scientific and Industrial Research, particularly the Directors of its National Water Research and Chemical Research Laboratories, for laboratory facilities and permission to use the chemical analyses here presented. Indebtedness is expressed also to the chemists responsible for analyses additional to those carried out by O. Hart, viz. Miss M. Schotten, Mr. P. F. Hamman and Dr. F. W. Strelow, of the C.S.I.R. Chemical Laboratories in Windhoek and Pretoria. Thanks are also due to the farm owners and managers who assisted in various ways, in particular Mr. F. W. Schmidt of Gross Barmen and Mr. K. Schneidenberger of Rūdenau. The Administration of South West Africa kindly authorised the publication of the air-photo (Plate II), a portion of Photo No. 2433, Strip No. 8, Job No. 294, taken in 1957.

Above all, the authors wish to record their deep gratitude to Dr. Erich Lübert for his stimulating interest and generous assistance. His recent death will be mourned by all who knew this unusual man, whose deep and abiding love for South West Africa and inherent generosity caused him to sponsor and support every conceivable form of scientific endeavour within the Territory.

This paper was compiled and written by T.W. Gevers, who is also responsible for geological field-work, maps, text-figures and photographs, as well as petrographical investigations. In the latter he was assisted by Mr. J. McIver and during field-work (in 1959) by Mr. C. Roering, both of the Geology Department, University of the Witwatersrand. Mr. O. Hart has been responsible for the new chemical analyses of the thermal waters and the investigation of their contaminating effects on ground-water within the Swakop River (Chapter XIV). From his vast fund of knowledge of the geology of South West Africa, Dr. H. Martin contributed many valuable suggestions.

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\* Bracketed numerals refer to Literature Index

## I. HISTORICAL

With the exception of the rivers that form its boundaries in the south, north, and northeast (Orange, Kunene and Okavango), South West Africa possesses no perennial streams. In a land of such universal aridity it is only natural that flowing springs, when so few and far between, should represent landmarks in the history and development of the Territory. It is also not surprising that many of them, particularly those of greater and steadier yield, should stem from greater depth and therefore be warm or hot.

The site of the capital, Windhoek, was determined by the hot springs there, called *lai-llgams* (*lais=fire, llgams=water*) by the original Nama (Hottentot) inhabitants. They are the hottest (79.8°C) in the whole Territory. It was here that the notorious Cape Coloured adventurer Jonker Afrikaner established himself in the thirties of last century and from where, at the head of his Hottentot followers, he undertook frequent marauding expeditions against the neighbouring Herero of Bantu stock. It was at the hot springs of Klein Windhoek that the first Rhenish missionaries from Germany took up their abode in 1842. Later in the same year they penetrated to Okahandja, 45 miles to the north, where several chiefs of the Herero, originally hailing from the Kaokoveld, had settled with their herds around a spring close to the banks of an unusually wide (Herero: *handja=wide*) and sandy dry river bed. (1)

The two missionaries, Hahn and Kleinschmidt, built a small house at Okahandja, but mostly stayed at Windhoek until high-handed Jonker Afrikaner and his unruly band of Hottentot cattle-thieves in 1844 drove them to seek permanent abode among the Herero. But the spring and water-holes at Okahandja had dried up due to drought and the Herero had abandoned the place. The missionaries therefore decided to establish themselves at *Otjikango* (Herero=*place of white stones*, referring to saline incrustations), 15 miles away, where a number of closely spaced hot springs not far from the banks of the Swakop River provided a copious supply of water. The Herero also referred to the hot springs as *Otjomuise* (= the place of smoke). The missionaries renamed the locality *Neu Barmen*, after the headquarters of their Mission Society in the Rhineland of Germany.

Here, in the latter months of 1844, they built a house of flat stones (Plate III, Fig. 1), constructed a dam, laid out a garden and planted palm trees. In 1847-48 the first church was erected (Plate III, Fig. 2) and a school founded (2).

But Jonker Afrikaner and his Hottentots at Windhoek, the only people in possession of firearms, continued to disturb the peace with incessant cattle-raiding and killings. The Herero, under their chiefs Kahitjene and Tjamuaha, had re-occupied Okahandja and with better rains their flocks had prospered. In August 1850, Jonker Afrikaner fell upon them and in a frightful bloodbath exterminated men, women and children, taking all their cattle away with him to Windhoek. A few Herero survivors fled to Neu Barmen. From then onwards Jonker Afrikaner made life miserable for the Herero, whose spears, arrows and kieres were no match for the Hottentots' guns. Jonker roved farther and farther afield, finally robbing cattle from as far away as the Kaokoveld and even Ovamboland. To establish his reign of terror over the Herero more firmly, he transferred his stronghold from Windhoek to Okahandja, where, a victim to chronic alcoholism, he finally died in 1861 (1).

Raids and killings continued under Jonker Afrikaner's successor, Christiaan.

The bulk of the Herero had now withdrawn to Otjimbingwe, where the Swedish explorer Andersson had established a trading station and begun supplying them with firearms. Christiaan decided to wipe out this new centre of resistance. A horde of 800 heavily armed Hottentot bandits swept through Neu Barmen in August 1865 and were ordered by their commander Hendrik Zes to pillage the mission and annihilate every living soul. The resident missionary Brinker was saved from death only by the intervention of Christiaan himself.

But in the attack on Otjimbingwe the Herero, under their new energetic chief Maharero and with the active help of Andersson, decisively defeated the Hottentots, Christiaan himself being killed. The Herero now returned to Okahandja, while the Hottentots, under their new leader Jan Jonker, withdrew to their original stronghold at Windhoek. Re-inforced by Nama kinsmen from the south, Jan Jonker once more attempted to subjugate the Herero clans, but in the battle of Otjikango (Neu Barmen) in 1880, Maharero's son Wilhelm completely routed him and Hottentot domination in Hereroland finally came to an inglorious end (1 and 2).

After the German occupation a police fort was established at Barmen in 1896 to guard the ox-waggon road that now passed from Windhoek through Otjimbingwe to Walvis Bay. Several small garden plots and two trading stores were established by settlers in the vicinity of the hot springs; but after the building of the railway in 1902 the old "Bay Road" fell into disuse and all traffic passed through Okahandja.

After the Herero rebellion and its suppression in 1904 the region was gradually occupied by settlers and the farm on which the hot springs are situated came to be designated as *Gross Barmen*, while that on which a smaller hot spring occurs, 7 miles down the Swakop valley, was named *Klein Barmen*.

The ruins of the mission house, church, and police fort, depicted on Plate III and Fig. 1, Plate X, still proclaim Gross Barmen as an important landmark in the history of South West Africa.

## II. LOCATION OF THERMAL SPRINGS

(See Geol. Map, Plate I)\*

Three thermal springs, or groups of springs, are described in this paper:

1. *Gross Barmen*, situated 15 miles southwest of Okahandja, at latitude, approximately,  $22^{\circ} 6\frac{1}{2}'$  south and longitude  $16^{\circ} 45'$  east; roughly 350 yards west of the Gross Barmen farm house.
2. *Klein Barmen*, situated  $7\frac{1}{2}$  miles west-southwest of the Gross Barmen hot springs, at latitude, approximately,  $22^{\circ} 8\frac{1}{2}'$  south and longitude  $16^{\circ} 38'$  east; roughly 200 yards south of the Klein Barmen farm house.
3. *Okandu* (Herero="fountain"), situated 13 miles southwest of the Klein Barmen hot spring, at latitude, approximately, of  $22^{\circ} 13'$  south and longitude  $16^{\circ} 30'$  east, in rather inaccessible, hilly terrain traversed by the Swakop River.

## III. TOPOGRAPHY

The hot springs of *Gross Barmen* are situated at an elevation of approximately 3,700 feet (1,200 metres) above sea level,  $1\frac{1}{4}$  miles north of the Swakop River bed, on open flat ground below a prominent range of pegmatite hills. (Air-photo, Plate II). On Gross Barmen these rise to 4,030 feet above sea level but increase in altitude westwards to 4,498 feet on the adjacent farm Rüdenu.

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\* The geological map and legend (Plates I and Ia) are to be found with the succeeding paper: "Geology Along the Northwestern Margin of the Khomas Highlands."

After emerging from the narrow gorge, cut into quartz-biotite schists of the northeastern Windhoek Highlands, at the steep escarpment formed by the northern continuation of the well-marked Windhoek hot spring fissure-zone (5), the Swakop River, on being joined near Osona by the broad and sandy Okahandja runoff course, meanders along the bottom of a broad and open valley adjacent to the northern flanks of the Khomas Highlands. While northwards the gently rising plain of Hereroland is surmounted only by occasional "inselberg" hills and ridges, of which the Waldau Ridge (4,948 feet) is the most prominent, to the south the terrain is much more broken, representing, as it does, the highly dissected edge of the extremely rugged Khomas Highlands (Nama: *lomas*=mountains) which rise to heights of close on 6,000 feet (9). This topographic contrast is due in the main to different rock types, the region to the north being largely underlain by granites, while more resistant quartz-mica schists build the rugged highlands to the south.

The high ridge of closely spaced pegmatites, rising in the Coltenberg to 800 feet above valley floor, terminates rather abruptly at the boundary between Rüdenu and Klein Barmen, so that the hot spring of the latter is again situated on rather flat open ground at 3,675 feet (1,192 metres) above sea level (Plate X, Fig. 2 and Plate XI, Fig. 1). The strongly meandering course of the Swakop here takes a turn to the south, so that the hot spring of Klein Barmen is situated a little over 2 miles north of the river. From here onwards the bed of the river becomes more deeply incised, the terrain along its southern bank being mountainous with crests rising to over 4,700 feet.

The warm springs of *Okandu* (Plate XI, Fig. 2) on the farm Sneyrivier are situated roughly 3,475 feet (1,125 metres) above sea level, near a right-angle bend of the Swakop River a few hundred yards from its northern bank, in topographically highly diversified country through which the river passes in a narrow gorge. Still farther west the Swakop has mountainous terrain also along its northern banks, where the Lievenberg rises to a height of 4,949 feet above sea level (Plate I).

Except in a few narrow gorges the sand-filled bed of the Swakop River is broad and flat, and frequently more than a hundred, often two hundred, yards wide. Along its low sandy banks *kameeldoring* (*Acacia giraffae*) are common, in places also great *Ana* trees (*Acacia albida*). Also some of the tributary runoff courses, particularly those joining the Swakop from the more open terrain to the north, are often astonishingly wide, in places wider than the trunk-stream itself, although they may only extend away from the latter for not much more than a dozen miles. One of these, the Sneyrivier, only some 15 miles long but several hundred yards wide, supports one of the finest stands, almost a forest, of huge *Ana* trees in all South West Africa.

#### IV. CLIMATE

##### 1. Rainfall

The general climate is typical of semi-arid regions, i.e. dry and cloudless for by far the greater part of the year. Relative humidities are normally low and evaporation greatly exceeds precipitation. Rainfall is strictly periodic, the main rains falling during the months of January to March. Frequently, during dry years, these months provide the only precipitation. The latter is erratic and subject to wide fluctuations, as shown in the following table.

TABLE I

(a) <i>Mean Annual Rainfall over the last decades</i>			
Okahandja	(15 miles east of Gross Barmen):		374.7 mm = 14.8 inches
Okaundua	(6 miles east of Gross Barmen):		328.0 mm = 12.9 inches
Klein Barmen	(7½ miles west of Gross Barmen):		333.5 mm = 13.1 inches
(b) <i>Highest and Lowest Rainfall Recorded</i>			
Okahandja	1934: 1097.8 mm = 43.2 inches;	1941:	134.4 mm = 5.3 inches
Okaundua	1934: not measured	1946:	121.2 mm = 4.4 inches
Klein Barmen	1934: 930.1 mm = 36.6 inches;	1930:	138.4 mm = 5.4 inches

(Data kindly supplied by Weather Bureau, Windhoek)

## 2. Temperatures

Within, or close to, the bottom of the Swakop valley, day temperatures are noticeably higher than over the adjacent higher-lying ground, particularly the Khomas Highlands to the south. The maximum recorded shade temperature at Okahandja is 42.6°C = 108°F (13 November 1917). The mean annual air temperature here is 20.0°C = 68°F.

The hottest period normally is from October till the beginning of the rains. Should the so-called "little rainy season" in November-December fail to materialise, as it often does, it can indeed be very hot *by day* during these months.

A saving feature, however, is the afternoon west wind. As the hot air over the interior rises, cold air is drawn in from the coast. Coming, as it does, from the extremely cold Benguella current flowing northwards along the fog-enshrouded Atlantic coast, this cool afternoon wind in summer is indeed a godsend. Usually arriving between noon and two o'clock, it gradually mounts in intensity as the afternoon proceeds, to fall off and die down after sunset and dusk. Only rarely does it fail during the dry hot months.

At night, temperatures always drop markedly throughout the whole year. Radiation from the earth's surface is intense. There are normally no clouds, the humidity of the air is low, vegetal cover is sparse and bare soil, sand, and rock surfaces are common. Along broad sandy river beds containing ground-water at shallow depth, particularly the Swakop River, there is a further loss of heat due to evaporation. Night temperatures therefore depend largely on situation relative to the bottom of runoff courses. The lowest temperatures are reached just before sunrise, the air being warmed up rapidly thereafter.

Temperature differences between day and night are often astonishing. On several days during the first week of October, 1957, noon shade-temperatures at Gross Barmen were in excess of 32°C (90°F), but dropped to between 3 and 5°C (37-41°F) at night. In the middle of July 1959 sunrise temperatures of -5°C (21°F) rose to 28°C (82°F) in the shade soon after noon. Night frosts are not rare during the cool season (April-September), when conditions due to the above-mentioned factors are normally aggravated by cold air fronts from the south. Temperatures as low as -14°C (7°F) have been recorded along the Swakop River at Okaundua, although this region lies within the tropics.

Vegetationally the environs of the thermal springs along the Swakop River are still "bushveld", i.e. low open "bush", mainly of thorn trees, interspersed with shrubs and grasses (Air-photo, Plate II). Unless the rains fail, the area represents excellent cattle- and sheep-ranching country. Ground-water for drinking is readily obtained from the Swakop and larger sand-filled tributaries. Water provision by means of bore-holes away from large runoff courses is less easy, often difficult.

## V. GENERAL GEOLOGY

The rocks traversed by the Swakop River and its tributaries in this region are folded, metamorphic sediments of the DAMARA SYSTEM, which together with a host of granitic rocks, build up the greater part of central South West Africa (4, 6, 7). In the immediate neighbourhood of the thermal springs the rocks are mostly biotite and quartz-biotite schists of the *Khomas Series*, the upper division of the DAMARA SYSTEM, and intrusive light-coloured aplitic granites, aplites and pegmatites (Map, Plate I, and Plate V, Figs. 1 and 2, Plate X, Fig. 2).

The schistose rocks, representing altered clays and sandy clays, are in part thinly laminated and often contain a profusion of large andalusite crystals (Plate IV, Fig. 1), as well as intercalated narrow bands of light-coloured biotitic quartzites (clayey sands) and layers of amphibole-pyroxene-garnet granulites. The composition of the latter, together with residual grains of calcite, indicate them to be highly altered calcareous and ferruginous clays (marls.)

Age determinations on radioactive elements, contained in pegmatite minerals occurring in the Karibib district and region of the Khan Canyon farther to the west, suggest the folding, granite intrusion, and metamorphism of the sediments of the DAMARA SYSTEM to have taken place some 550 million years ago, viz. during the late Precambrian or early Cambrian periods.

Details of rock types, stratigraphic succession and structure are given in the succeeding paper (17).

To a much later age (Lower Jurassic), roughly 180 million years ago, belong the fairly numerous dolerite dykes that cut across all previously mentioned rocks. Many of them no doubt represent feeding channels for the basic lavas of the widespread KAOKO (KARROO) period of volcanicity.

Another volcanic episode occurred again at a later time of crustal fracturing, approximately during Mid-Cretaceous times. To this period, roughly 90 million years ago, belong the trachyte and phonolite plugs of the Auas Mountains and the fissures extending from them. The most persistent of the latter, the great Windhoek Hot Spring Fissure, extends with a N-S trend to within a dozen miles or so of Okahandja (5).

Then followed a prolonged period of denudation and erosion culminating in the evolution of the great African land surface (Mid-Miocene) some 20 million years ago. Subsequent upward warping movements of the crust, both parallel and transverse to the coast, however, deformed the latter. The large interior basin of the Kalahari came into existence, sending out lobes far to the west into the Rehoboth, Sandveld, and Etosha depressions. Separating swells, e.g. the broad Khomas Highlands and Otavi Mountainland, were maintained and re-accentuated at intervals (9).

A final considerable elevation of the subcontinent in Late Tertiary times, over the last few million years, caused rivers to incise their beds and form spectacular gorges at numerous places. Also the Swakop River reacted to these earth movements, at times broadening its bed and infilling it, at others deepening it and scouring out deposits of gravel and sand, depending on rock formations traversed, local topography, and vicissitudes of climate. Above its junction with the Otjisewa River at Okaundua the broad valley-fill of Osona was developed with its arable alluvium and abundance of shallow groundwater (Plate I).

The level stony flat of *Otjikango*, around the hot springs of Gross Barmen, was cut by stream erosion in geologically recent times. This is indicated by several patches of coarse conglomerate and grit, cemented by silica to form bouldery sur-

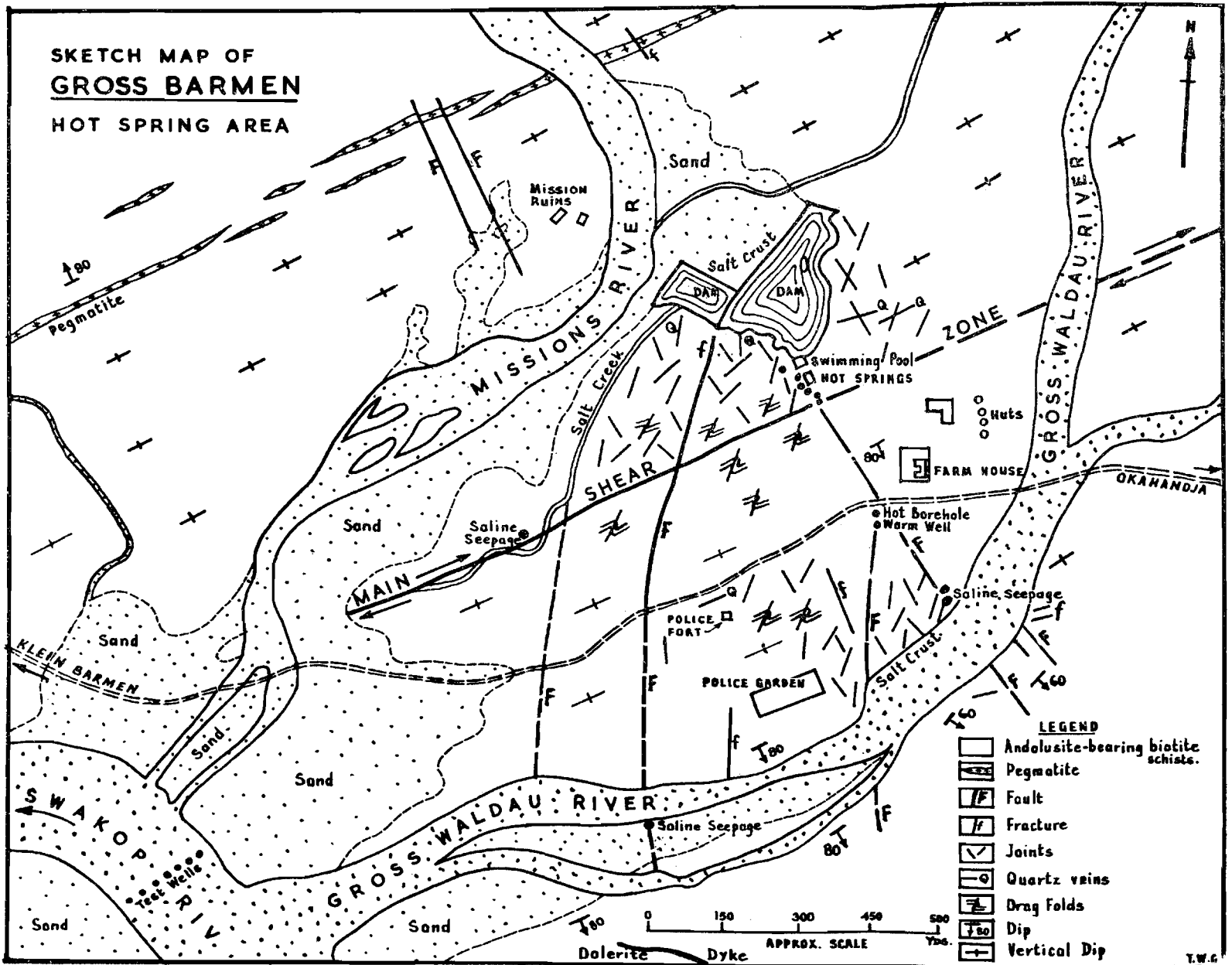


Fig. 1



face-quartzites (Plate IV, Fig. 2), into which the Gross Waldau and Missions rivers subsequently incised their present beds (Plate II).

It is of interest that minor earthquakes in the central highlands of South West Africa indicate slight movements, probably along faults, still to be going on at the present time (Kent, 12, p.258).

## VI. DESCRIPTION OF THERMAL SPRINGS

### 1. Gross Barmen

The hot springs of Gross Barmen emerge on a stony fiat of bevelled mica schists between the broad and sandy runoff courses just mentioned, a little less than a mile from their junction with the Swakop River (Plates, I, II and Fig. 1). The absence of trees is striking, a fact which, together with an abundance of saline incrustations (Plate II), immediately singles out this locality from its bush-clad surroundings and also makes the ten tall *hyphaene* palms planted many years ago around the warm swimming pool (Plate IX, Fig. 2, and Plate X, Fig. 1), as well as the ruins of the old German police fort with its rectangular watch tower (Plate X, Fig. 1), all the more conspicuous.

#### (a) Geology

ENE-WSW ribs of dark biotite and quartz-biotite schists project above intervening patches of white, salt-encrusted soil, grey saline mud and dark green, often swampy sedge (Plate II). The vertically dipping schists are everywhere extensively fractured, two directions, NNE-SSW and NNW-SSE to NW-SE being dominant (Fig. 1 and Fig. 2). Sliced by innumerable, frequently closely spaced fractures obliquely across their strike, the well-bedded, often flaggy schists in many places tend to break up into pointed and sharp-edged polygonal blocks (Plate VI, Fig. 1).

The majority of fractures are only of short extent, but several of greater continuity can be followed over several hundred yards. At least some of them are probably faults, particularly since intense marginal shattering is sometimes evident. Behind the old Mission ruins two more extensive fractures can be seen actually to displace pegmatite dykes by small amounts, up to 2 feet (Fig. 1). The more extensive fractures usually show more abundant iron hydroxide staining than the shorter, indicating the issue of water over a wider area in former times. In the case of the strongest fault near the old Mission ruins, the middle of a 5-6 feet broad, iron-stained, shatter-zone is formed of a 1-3 feet wide zone of silicification, in places grading into a highly silicified reddish or yellow breccia, which over a short distance stands out as a wall. These features are very reminiscent of the widely distributed iron-stained chalcidonic breccias of the hot water fracture system at Windhoek. But also this fault does not appear to be of any considerable extent, being no longer marked among well exposed ribs of schist only a few hundred yards to the south-east (Plate II).

The more extensive fractures with strongest shattering often appear as shallow grassed trenches, occasionally small gullies, crossing low ribs of schists. The accompanying air-photo (Plate II) shows up several quite clearly, e.g. the one extending from the main dam wall, west of the hot springs, southwards to the north bank of the Gross Waldau River southwest of the old Police Fort ruin, its initial NNE trend changing to almost N-S. A small saline seepage (white speck on air-photo) is located on it along the north bank of the long island south of the main channel (Fig. 1). Another similar feature parallels this fracture a little to the

west. A third, marked by a shallow gully just east of the old Police Fort palm garden and exhibiting strong shattering and slight displacement, heads, with approximately similar trend, from the north bank of the Gross Waldau River straight into the hot farm bore-hole (Plate VI, Fig. 2, and Map, Fig. 1).

Though many of the water and gas issues of the closely spaced hot springs can be seen to rise from fractures (Plate IX, Fig. 1), there is no sign of marked faulting or even of *one* controlling "master joint". Nevertheless, the elongation of the hot springs trends towards the hot farm bore-hole (originally a warm seepage), the warm natural well, and the distinct seepage on the banks of the Gross Waldau River (Plate II and Fig. 1). Projecting this line, which trends roughly parallel to the fault fractures just described, and allowing for the usual variations in strike, NNW-wards beyond the dam there is evidence of a very slight displacement of the first large pegmatite on opposite sides of the sand-filled Missions River (Plate II). A little eastwards the same pegmatite is cut by a marked fracture-zone (Fig. 1). No pronounced shattering, iron-staining or silification can be seen here, however.

A zone of intense shearing, several yards wide and parallel with the strike of the schists, is exposed over several hundred yards between the lower end of the saline creek draining the overflow of the hot springs via the two dams into the Missions River and the easternmost seepage swamp (Fig. 1). Within it the schists have been reduced to an almost slaty cleavage (Plate VII, Fig. 2). It hence also forms a shallow grassed trench (Plate VII, Fig. 1), which is clearly visible on the air-photo (Plate II). This is only the widest and most persistently exposed of a number of zones of strong shearing, parallel to the strike of the schists, found over a several hundred yards wide belt. A consistent pattern of innumerable minor folds and strong fracture-cleavage has been developed within the latter (Plate VIII, Fig. 1). The orientation of these structures indicates the operation of a force couple, viz. strong differential movements involving shear, between two blocks moving more or less horizontally in opposite directions, the northern being shifted to the northeast relative to the southern (Khomas Highlands) (Fig. 1).

Summarising, it appears that the hot springs of Gross Barmen are located in an area of very pronounced fracturing and shattering where a wide zone of strong ancient shearing parallel to the strike of the banded schists is crossed by a number of faults of small displacement.

Details of the geologic structure along the northwestern margin of the Khomas Highlands are given in the succeeding paper (17).

#### (b) *Location of Hot Springs and Boreholes*

The number and extent of individual small seepages encountered depend not only on the season of the year, but to some extent also on the time of the day. With the prevailing low humidity of the air, the evaporation rate is extremely high. During the cold month of July, 1959, water could be seen to ooze or trickle from rock fractures at innumerable places over an area several hundred yards in diameter; where covered with soil and rubble there existed as many moist patches. As temperatures rose during August and strong winds set in, these seepages gradually became reduced in number. During the heat of October 1957, seepages outside the main spring area were comparatively few. Since the water is saline, the wide distribution of salt incrustations is thus not surprising. The temperatures of all these small seepages naturally conform with that of the air.

Ignoring several swampy, sedge-overgrown, permanent seepages with in-

significant yields, hot water issues naturally at more than a dozen individual points closely spaced within an area measuring 24 by 14 yards (Fig. 1). The two southernmost, 9 yards apart, have the largest orifices and strongest flow; but also in their case the hot water can be seen to issue from several distinct points, mostly clearly discernible fractures (Plate VIII, Fig. 2 and Plate IX, Fig. 1). Gas bubbles rise at several places, usually intermittently and not in large quantity. Qualitative tests showed the presence of carbon dioxide ( $\text{CO}_2$ ). There is usually a noticeable smell of sulphuretted hydrogen ( $\text{H}_2\text{S}$ ). The temperatures of individual springs range from  $41.9$  to  $69.1^\circ\text{C}$  ( $115$  to  $156^\circ\text{F}$ ).

Eighty-six yards to the NNW of this main spring area (Fig. 1) is another issue of hot water artificially opened up by a shallow bore-hole and steep-walled trench. The bore-hole emits a more constant and abundant stream of gas bubbles than any of the natural springs, but also here the quantity of gas is not really large. Again tests showed the presence of carbon dioxide. On the other hand, there is no pronounced odour of sulphuretted hydrogen. The temperature of the water is only  $41.6^\circ\text{C}$ .

The natural springs are situated near the edge of predominantly rocky ground beyond which the surface slopes towards a low depression within which several pools and two large dams have been constructed (Plate II and Fig. 1). The various streamlets and swampy seepages first drain into a sedge- and reed-fringed shallow pool (Plate IX, Fig. 2), whose southern margin is flanked by a thick, slimy deposit of reddish, reddish-brown, and yellowish colour, largely of algal origin (Chapter XIII). The same type of slime also coats the bottoms and sides of most of the spring orifices and streamlets issuing from them.

From this pool (Fig. 1) a narrow furrow then leads the hot water, still measuring  $46^\circ\text{C}$ , into a small crude bath ( $45.4^\circ\text{C}$ ), mainly used by people seeking relief from rheumatism, and thence into the main reed- and palm-fringed swimming pool. Where the water cascades into the latter the temperature is still  $37.9^\circ\text{C}$ . The warm water mainly floats out along the surface, and temperatures within the pool are therefore variable. Close to the eastern bank,  $34.4^\circ\text{C}$  was measured at the surface.\* From this pool the water, now augmented by a small stream from the "bore-hole spring," then finds its way into a number of dams, the largest of which measures 300 by 170 yards (Plate X, Fig. 1). Finally the water seeps into a small swampy, salt-fringed creek, which eventually discharges the now much more concentrated saline water into the Missions River (Fig. 1) and thence into the Swakop to contaminate the normally "fresh" ground-water within the latter (Chapter XIV).

Close to the main road, some 300 yards to the SSE of the natural hot springs and within the same zone of fracturing, there are two windpumps (Fig. 1 and Plate VI, Fig. 2). One, erected over a shallow bore-hole, 20 feet deep, supplies water to the farm house of Gross Barmen. When not being pumped, the water rises to within a few inches from the bore-hole collar. On the cold morning of 25 September, 1957, the temperature was  $43.2^\circ\text{C}$ , but at 10 a.m. on 5 October, after three hours of pumping, the thermometer registered  $51.8^\circ\text{C}$ . The temperature of water overflowing from the roof tank of the farm house, roughly 200 yards away, then was  $49.3^\circ\text{C}$ .

The other windpump, only a few dozen yards away, stands over a shallow well.

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\*All temperature measurements, except where otherwise stated, were made on 21st Sept., 1957.

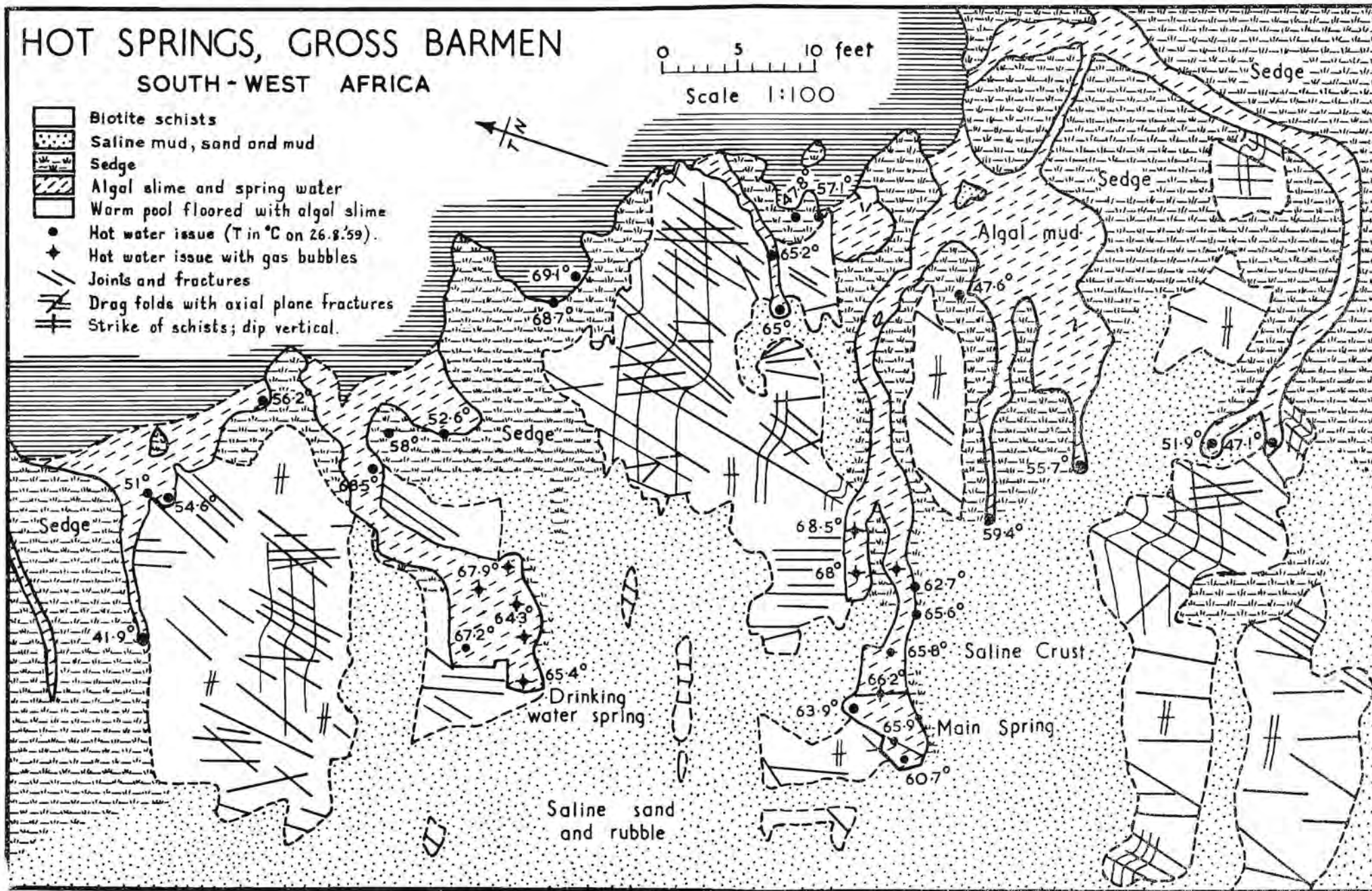


Fig. 2

On the cold morning of 25 September, 1957, the temperature of the surface water was 35°C.

In line with these two windpumps and the main natural springs there occur a few seepages of saline water above the rocky banks of the Gross Waldau River (Plate II and Fig. 1). The schists here are still strongly fractured. These saline seepages, together with another issuing from a fault fracture-zone south of the Police Fort ruins, contaminate the ground-water not only of the Gross Waldau but also of the Swakop River, into which the latter discharges (Chapter XIV).

### C TEMPERATURES

TABLE II

(21 September, 1957)

(a) Natural springs in Main Spring Area. (See Plate XIII for positions).	Temperature °C
No. 1. First small spring from south .. .. .	49.2
2. Very small spring, one yard to west .. .. .	46.1
3. Small spring, three yards westwards .. .. .	56.6
4. Very small orifice .. .. .	57.4
5. Next slightly larger orifice .. .. .	57.2
6. Uppermost point in southern Main Spring .. .. .	61.2
7. Crack, in rock, southern Main Spring .. .. .	66.1
8. Gas issue in sandy bottom, southern Main Spring .. .. .	66.0
9. Gas issue, a little to east, southern Main Spring .. .. .	65.3
10. Adjacent rock embayment, southern Main Spring .. .. .	64.1
11. Gas issue lower downstream, southern Main Spring .. .. .	65.2
12. Lower rock embayment, southern Main Spring .. .. .	67.1
13. Gas issue lower downstream, southern Main Spring .. .. .	61.1
14. Small orifice towards edge of pool .. .. .	63.0
15. Small spring on edge of pool .. .. .	68.4
16. Second small spring on edge of pool .. .. .	69.1*
17. Fracture in uppermost part of Main "Drinking Water" Spring .. .. .	65.4
18. Embayment in upper part of Main "Drinking Water" Spring .. .. .	64.2
19. Rock fracture in upper part of Main "Drinking Water" Spring .. .. .	67.0
20. Gas issue lower downstream, Main "Drinking Water" Spring .. .. .	68.0
21. Gas issue still lower down, Main "Drinking Water" Spring .. .. .	62.0
(b) Bore-holes and wells.	
22. "Bore-hole Spring", 86 yards to NNW .. .. .	41.6
23. Farm bore-hole 300 yards to SSE after 3 hours pumping (5 October 1957) .. .. .	51.8
24. Windpump well (25 September 1957) .. .. .	35.0

\* Highest temperature recorded.

When again measured on 26 August 1959, differences of up to several degrees centigrade were noted, compared with readings obtained with the same thermometer on 21 September 1957. The later were in many instances higher than the earlier readings though air temperatures were considerably lower. Owing to interference with the cumulative outflow it was not possible to ascertain whether the total yield had also changed. The reasons for these differences in temperature are obscure. Strange, too, is the fact that the highest temperature (69.1°C) should be found in one of the smallest orifices of low yield. Accumulations of ordinary ground-water cannot be appreciable, as shown by the results of drilling in the general region away from the Swakop River and other large runoff courses. It is worth pointing out in this connection that when a surface seepage of low temperature was drilled into to a depth of only 20 feet (farm bore-hole), the temperature when fully pumped rose to 51.8°C. This fact makes the high temperature of a very small, low-yield orifice all the more puzzling.

With 69°C these springs rank third in temperature among the hot springs of South West Africa, being exceeded only by the Windhoek hot spring (79.8°C) and

that located near Omburo, east of Omaruru, on the great Etjo fault (76·5°C) (12).

(d) *Yields*

The combined yield of the main hot spring area was measured by damming up the furrow where it cascades down into the swimming pool and found to be 2,050 gallons or 9·4 cubic metres per hour, or 49,000 gallons or 225·6 cubic metres per day (3 October 1957).

The only other flow worth mentioning is that from the "bore-hole spring" which joins the swimming pool overflow. This was measured as being only 270 gallons or 1·2 cubic metres per hour.

The yield of the hot farm bore-hole is considerable. After 3 hours pumping (motor driven) through a 3 inch pipe ( $\pm 2$  cubic metres per hour) the drawdown was less than a foot and within a few minutes the water level had returned to normal (5 October 1957). There seems no doubt that the total quantity of water available at Gross Barmen can be considerably increased by drilling and pumping, in the same way as was done at the hot springs of Windhoek when the natural flow became insufficient for the town's growing water needs.

## 2. Klein Barmen

The hot springs of Klein Barmen issue from a small low hummock of aplitic granite, rising only a few feet above sedge-overgrown swamps and adjacent cattle kraals. Westwards the same type of granite builds a number of larger mounds and hillocks projecting above sand (Plate X, Fig. 2).

Issuing from a number of irregular cracks in the hard granite, three sealed concrete "boxes" have been erected over the main feeding fractures. Within these the water rises a few feet and for the most part enters a built-up swimming pool (Plate XI, Fig. 1), from where the overflow joins the extensive swampy area, bright green with sedges, that adjoins the spring in the east and south. A small trickle of water flows thence for several hundred yards down the eastern side of a runoff depression into whose sand-filling it finally disappears, giving evidence of its continued presence at shallow depth through recurring salt crusts.

(a) *Geology (Map, Plate I)*

The white aplitic granite from which the spring issues is mostly surprisingly fresh, though in places, as in other granite outcrops within a few dozen yards to the SW, kaolinisation is obvious. There is no visible trace of a distinct fault or fault-zone. The granite merely exhibits numbers of fractures, by no means particularly closely spaced.

The exposed fractures in the aplitic granite, around the concrete hot water "boxes", are all narrow and clean-cut. Similar fractures can be seen in the white granite outcrops several dozen yards to the SW. One of them, more continuous than most, shows kaolinisation over a width of a few inches. On one of the steeper granite hummocks in this area a small amount of moisture oozes from a crack several feet above the surrounding ground level. This indicates that water under pressure is present in fractures also away from the main spring site. Some may even issue underneath the very extensive swamp adjacent to the latter.

A dolerite dyke, cutting across the elongation of the aplitic granite and strike of the adjacent intruded schists, crosses the road a few hundred yards to the NE; it does *not* head for the spring site but stays at least 200 yards to the east of the latter. About a mile to the SSE quite a large dolerite dyke crosses the runoff course into which the hot spring drains; but no water issues from it.

The structural reason for the hot spring site thus remains vague. Unfortunately the swamp and sand obscure much of the geology.

(b) *Temperature*

Since the main water issues are covered by concrete "boxes" it was not possible to measure temperatures at actual orifices. Gas bubbles were seen sparingly immediately adjacent to the eastern "box". Qualitative tests indicated the presence of small amounts of carbon dioxide. In contrast with the hot springs at Gross Garmen, no pronounced odour of sulphuretted hydrogen was noticeable. At this gas issue the temperature of the water ranged between 57.8 and 59.6°C.

On opening the plug at the base of the large southern "box", the temperature of the water, flowing more strongly than from the other concrete "boxes", finally remained steady at 62.0°C=143.6°F (2 October 1957). Previous references to this spring quote 61°C (Gevers, 1932). After water from both tanks had flowed steadily for an hour, the surface temperature (at noon) in the middle of the shallow swimming pool was 39.8°C and at the overflow, some 15 yards away, 39.6°C. Due to slight currents, however, pool temperatures showed fluctuations of several degrees.

Regarding temperature the hot spring of Klein Barmen ranks fourth in South West Africa.

(c) *Yields*

A fairly considerable seepage takes place from the vicinity of the eastern concrete "box" into the adjoining swamp. After the opened pipes of all "boxes" had flowed freely for an hour, the overflow from the swimming pool, into which they drain, was measured as 960 gallons (4.3 cubic metres) per hour or 23,000 gallons (104.2 cubic metres) per day (2 October 1957).

### 3. Okandu (Sneyrivier)

This warm spring on the farm Sneyrivier is rather inaccessible, being only used by cattle and game for drinking. With the exception of that depicted in Fig. 3 and Plate XI, Fig. 2, the points of water issue are rather ill-defined, there being a swamp, some 50 yards wide and 120 yards long, extending down the slope of a granite spur projecting into a rectangular bend of the Swakop River bed. The latter in this hilly and mountainous region is narrow and rocky. The bulk of the water appears to emerge along the upper edge of the sedge-covered swamp, at an elevation of roughly a hundred feet above the river bed.

Apart from several shallow pools in black mud, the main visible issue of water is from a clear pool, bordered by granite, along the SE edge of the swamp (Plate XI, Fig. 2). Rather sparing gas bubbles are emitted and on being passed through lime water the presence of free carbon dioxide was indicated. Tests for sulphuretted hydrogen remained negative. The peculiar odour of the place is probably due to rotting swamp vegetation.

(a) *Temperature*

The temperature of the water in this pool, at 2 p.m. on 27 September 1957, was 38°C (100.4°F). As outlined by L. E. Kent in his paper on the thermal waters of the Union and South West Africa (12), it appears to be largely a matter of opinion and local usage where the dividing line should be drawn between thermal and non-thermal waters. The classification proposed by the International Society

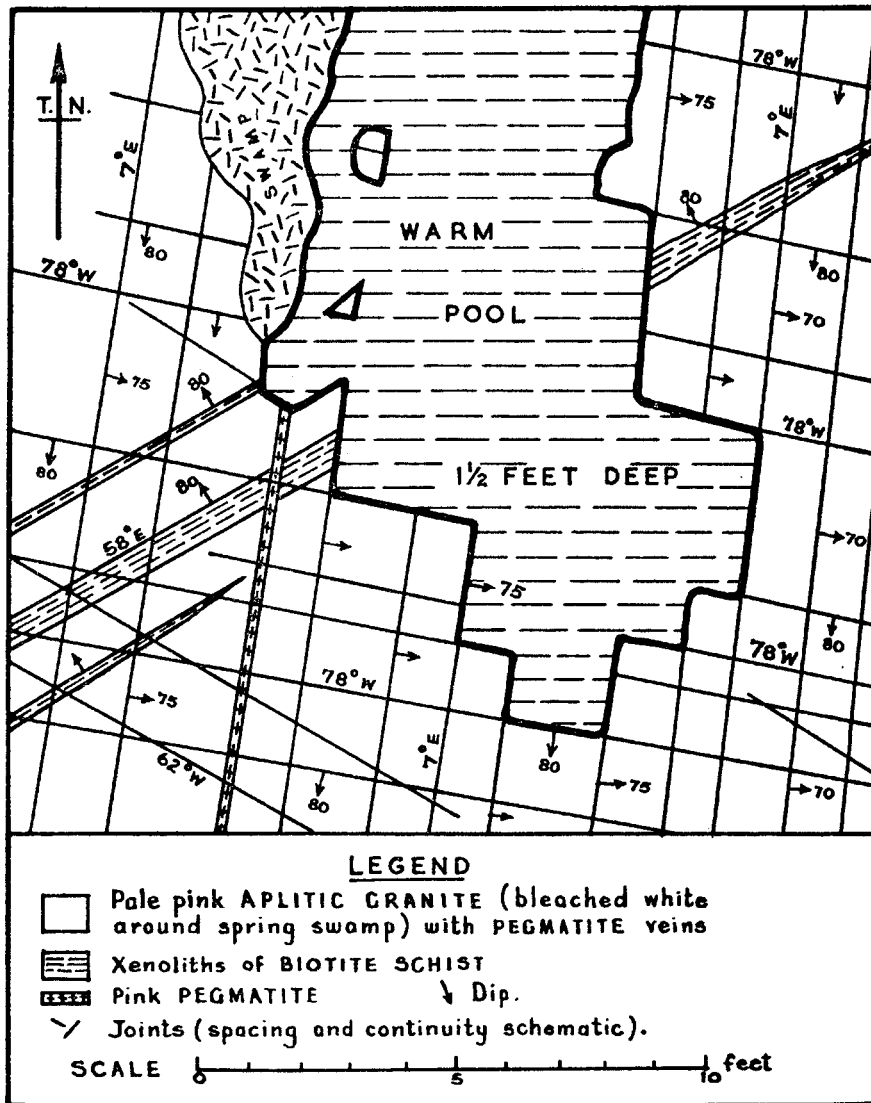


Fig. 3

Main visible spring orifice at Okandu.



of Medical Hydrology (I.S.M.H.) defines spring waters below 20°C as *cold*, between 20 and 37°C as *subthermal*, from 36 to 42°C as *thermal*, and above 42°C as *hyperthermal*.

Taking into account mean annual air temperatures in Southern Africa, L. E. Kent (12) has proposed 25°C (77°F) as the dividing line between thermal and non-thermal waters. He further subdivided thermal waters into : *warm* (25-37°C); *hot* (or hyperthermal) (37-50°C); and *scalding* (above 50°C). The normal temperature of human blood is thus utilised for separating *warm* from *hot* waters. Obviously, however, what will strike investigators as *cold* or *warm* depends on the temperature of the surrounding air at the time. When the air temperature at noon of 27 September 1957 was 34°C (93°F), the Okandu spring water (38°C or 100.4°F) certainly did not *feel* warm. In any case, on the scale of the I.S.M.H., this spring would be classed as *thermal* and those of Klein and Gross Barmen as *hyperthermal*; according to Kent the latter two would be *scalding*, which with temperatures of 62°C (143.6°F) and 69°C (156.2°F) they certainly are.

In this connection it is interesting to note that the temperatures of most measured borehole waters in South West Africa, tapping aquifers at depths of 100-200 feet, are in the neighbourhood of 25°C, thus exceeding mean annual air temperatures. The reason for this is to be sought in the sparse vegetal cover, which normally allows soil temperatures to rise considerably above air temperatures by day, whilst at night the soil does not get colder than the air. Kent's lower boundary for thermal waters (25°C) therefore seems more appropriate for South West Africa than that of the I.S.M.H.

(b) *Yield*

Owing to the scattered nature of the water issues within an extensive swamp, it is difficult to measure the total yield. This could only have been done by digging operations at the lower end of the swamp. Even then underground seepage and losses due to evapo-transpiration would not be accounted for. As springs go in arid South West Africa outside sizeable runoff courses, the yield, however, is considerable, as already indicated by the fact that the Herero refer to the place as "the fountain". The yield of the largest point of issue, previously referred to, was measured as approximately 800 gallons per hour, or 19,300 gallons per day (October 1959).

(c) *Geology (Map, Plate I)*

The granite surrounding the spring swamp is rather aplitic in nature, i.e. poor in feric minerals. On the walls of an old quarry, near the eastern margin of the lower end of the swamp, a migmatitic zone of dark sandy and knotted schists, veined by aplite, is exposed, striking N 58°E and dipping vertically to steeply NW. This 45 feet wide zone heads for the main spring issues, where numbers of narrow biotitic schlieren are also visible. It is, however, most unlikely that this feature exerts any sort of structural influence. Though mostly concealed, the water undoubtedly issues from joints, as indicated by the shape of the main visible spring (Fig. 3). The straight walls of the pool follow a well-marked intersecting fracture system with 7°E, 62°W, and 78°W trends. The first and last are the best developed and water can actually be seen to ooze from several 7°E joints a little to the NE of the main pool, as well as from much more subordinately developed 13°W joints. Several narrow pink pegmatites occur along these two joint directions, thus indicating them to have been subjected to stretching at the time of residual

magma intrusion. Though closely jointed, no pronounced "crackling", shattering or brecciation of the granite is visible anywhere.

While the aplitic granite of the surroundings is normally pale pink in colour, outcrops around the swamp are whitish, due, probably, to kaolinisation and some measure of leaching (Plate XI, Fig. 2).

A rather imperfectly exposed dolerite dyke occurs along the western edge of the swamp. Striking roughly NNE-SSW, it can be followed in intermittent outcrops over several hundred yards. In its NNE prolongation there is no sign of dolerite in the rocky bed of the Swakop River which loops around the spring site; SSW-wards, however, dolerite still crops out on the northern bank, where it can be seen to form a narrow sheet, only a few feet wide, dipping at a shallow angle to the west. No further outcrops were found south of the river.

This body of dolerite is quite insignificant when compared with numerous other really thick and extensive dykes in this region in the vicinity of which *no* springs, either warm or cold, are to be found. Its structural influence on the Okandu spring is not obvious, since the main issue of water rises from joints in granite at a distance of more than 100 yards from its nearest outcrop. It is, however, closely adjacent to the western margin of the swamp.

A further significant fact is that two additional, but very much smaller cold springs and seepages occur 1 to 1½ miles to the west in the same pale pink to white aplitic granite. The water can be seen to seep from prominent vertical joints conforming more or less with the trend of the best developed fractures at the Okandu spring. No dolerite intrusions were found at these localities.

Were the dolerite sheet the only structural feature of importance at Okandu, the water should be expected to issue at the lowest point, i.e. in the rocky bed of the Swakop River. This, however, it does *not* do, but emerges near the crest of a granite spur approximately a hundred feet above the valley floor. No distinct fault or fault-zone, however, can be observed. The structural control of the Okandu warm spring therefore remains almost as vague as that of the hot spring at Klein Barmen. It is possible, even probable, however, that the spring orifice was established before the Swakop accomplished the last 100 feet incision of its bed and that the spring originally *did* emerge in the deepest portion of the valley floor. Once the more or less vertically rising water had enlarged the relevant fissures sufficiently to allow of free flow, subsequent downward cutting of the river bed need not necessarily have affected the location of the spring.

It should be noted, in this connection, that all three thermal springs of this region emerge more or less on the same, probably end-Tertiary or early Pleistocene land surface.

## VII. CHEMICAL AND SPECTROGRAPHIC ANALYSES

The earliest available chemical analysis was carried out by F. Rintelen in July 1909 on "five bottles of water from Klein Barmen" for the "Deutsche Farm-gesellschaft" in the laboratory of the "S.W.A. Minensyndikat" in Swakopmund. An analysis of hot water from Gross Barmen, by C. Grimme, was published in 1911 ("Untersuchungen über die Weideverhältnisse in Deutsch SüdwestAfrika"). In 1939 Mr P. W. Ewest, previous owner of the farm Gross Barmen, submitted samples of water, apparently from the warm well previously described, to the Division of Chemical Services, Department of Agriculture, Pretoria, for analysis and

advice as to the best means of counteracting the brackishness induced in the soil after prolonged irrigation.

The early analyses exhibit such discrepancies in many items that, from the recent analyses, errors in determination must be assumed, particularly of alkalies

TABLE 3

	<i>Gross Barmen</i>		<i>Gross Barmen</i>		<i>Klein Barmen</i>		<i>Ohandu</i>	
	Main	Hot Spring	Hot Farm	Bore-hole	Main	Issue	Main	Spring Pool
Temperature	65°C		51.8°C		62°C		38°C	
Conductivity in micro-ohms	1500		1450		1400		1350	
Hydrogen Ion Concentration (pH)	7.45		7.3		7.65		8.1	
Total dissolved solids at 180°C	1094 p.p.m.		1102 p.p.m.		1033 p.p.m.		944 p.p.m.	
Ions in parts per million or mgms per litre	mgms per litre	N/1000	mgms per litre	N/1000	mgms per litre	N/1000	mgms per litre	N/1000
Lithium Li <sup>+</sup>	0.28	0.04	0.66	0.10	0.35	0.05	0.56	0.08
Sodium Na <sup>+</sup>	320.00	13.91	320.00	13.91	320.00	13.91	300.00	13.04
Potassium K <sup>+</sup>	19.00	0.49	19.00	0.49	17.00	0.44	11.00	0.28
Calcium Ca <sup>++</sup>	14.00	0.70	15.20	0.76	13.20	0.66	17.00	0.86
Magnesium Mg <sup>++</sup>	1.68	0.14	1.68	0.14	1.44	0.12	0.72	0.60
Iron Fe <sup>++</sup>	0.03	0.00	0.16	0.01	0.08	0.00	<0.01	0.00
Manganese Mn <sup>++</sup>	0.06	0.00	0.48	0.03	0.10	0.00	>0.05	0.00
Aluminium Al <sup>+++</sup>	n.d.*	—	n.d.	—	n.d.	—	n.d.	—
SUM OF CATIONS	355.05	15.28	357.18	15.44	352.17	15.18	329.29	14.86
Fluoride F <sup>-</sup>	4.90	0.25	8.60	0.45	9.50	0.50	6.60	0.35
Chloride Cl <sup>-</sup>	129.00	3.63	129.00	3.63	106.00	2.98	215.00	6.14
Sulphate SO <sub>4</sub> <sup>''</sup>	322.00	6.71	301.00	6.27	255.00	5.31	193.00	4.49
Bicarbonate HCO <sub>3</sub> <sup>'</sup>	152.50	5.08	183.60	6.12	178.60	5.93	134.00	4.47
(Phosphate PO <sub>4</sub> <sup>3/2</sup> )	<0.1	—	<0.1	—	<0.1	—	<0.1	—
Nitrate (as N)	nil	—	nil	—	nil	—	nil	—
Nitrite (as N)	nil	—	nil	—	nil	—	nil	—
SUM OF ANIONS	608.40	15.67	622.20	16.47	549.10	14.72	548.60	15.45
(Silica SiO <sub>2</sub> )	(80.00)	—	(70.00)	—	(105.00)	—	(85.00)	—
expressed as Silicic acid H <sub>2</sub> SiO <sub>3</sub>	104.00	—	91.00	—	136.50	—	110.50	—
Free Carbon dioxide CO <sub>2</sub>	16.00	—	23.00	—	8.00	—	3.75	—
TOTAL SUM OF ITEMS	1083.45	—	1093.38	—	1045.77	—	992.14	—
Dissolved Sulphuretted Hydrogen H <sub>2</sub> S†	0.92	—	0.92	—	—	—	nil	—

DATE

1958-1959

Analysts: O. Hart; M. Schotten; P. F. Hamman; F. W. E. Strelow, C.S.I.R. Chemical Laboratories, Windhoek and Pretoria.

\* n.d. = not determined;

† for dissolved H<sub>2</sub>S see text.

and calcium. They are hence not reproduced, being already cited by Kent (12, p.262). The high potassium contents, to which the latter drew attention (12, p.261) "assuming their accuracy", are not supported by the new analyses, which clearly indicate these waters to differ in no significant way in this respect from other thermal springs of this nature elsewhere in Southern Africa. Improved analytical techniques and *not* significant change in composition of the waters over a period of 50 years are no doubt responsible. The results of the 1939 analyses are so similar to those of the recent that their citation does not appear necessary.

The recent analyses (1958-59) by the Windhoek C.S.I.R. Laboratory (Water Treatment Research Division, Analysts: O. Hart, M. Schotten, P. F. Hamman) and the C.S.I.R. National Chemical Laboratory, Pretoria. (Analyst: Dr. F. W. E. Strelow\*) are listed below. Table 3 is in accordance with the modern standards of the International Society of Medical Hydrology. In Table 4 probable, or at least possible, saline compounds have been computed, according to the conventional procedure, for the benefit of lay readers not familiar with the details of chemical terminology. Table 5 presents spectrographic data on saline residue of the main spring of Gross Barmen, kindly carried out by Dr. W. R. Liebenberg of the Government Metallurgical Laboratory, Johannesburg.

TABLE 4  
PROBABLE SALINES

		Milligrams per litre or parts per million			
		GROSS BARMEN		KLEIN	OKANDU
		Main Hot Spring	Hot Farm Bore-hole	BARMEN	
Sodium sulphate	Na <sub>2</sub> SO <sub>4</sub>	476.2	445.3	377.2	285.5
Sodium carbonate	Na <sub>2</sub> CO <sub>3</sub>	220.4	271.9	269.1	184.7
Sodium chloride	NaCl	178.9	147.1	149.4	324.0
Potassium chloride	KCl	36.2	36.2	32.4	21.0
Calcium carbonate	CaCO <sub>3</sub>	35.0	38.0	33.0	43.0
Magnesium carbonate	MgCO <sub>3</sub>	5.8	5.8	5.0	2.5
Sodium silicate	Na <sub>2</sub> SiO <sub>3</sub>	—	—	59.1	—
Silicic acid	H <sub>2</sub> SiO <sub>3</sub>	104.0	91.0	99.7	110.5
TOTAL		1056.5	1035.3	1024.9	971.2

TABLE 5  
QUALITATIVE SPECTROGRAPHIC ANALYSIS OF SALINE RESIDUE OF HOT WATER FROM THE MAIN GROSS BARMEN SPRING

MAJOR ELEMENTS: Sodium (Na), Potassium (K), Calcium (Ca), Magnesium (Mg), Silicon (Si)  
 MINOR ELEMENTS: Lithium (Li), Manganese (Mn), Iron (Fe), Aluminium (Al), Titanium (Ti)  
 Strontium (Sr), Boron (B).  
 TRACE ELEMENTS: Barium (Ba), Germanium (Ge), Vanadium (V), Copper (Cu), Nickel (Ni), Zinc (Zn), Chromium (Cr), Platinum (Pt).

Analyst: W. R. Liebenberg.

The trace of Pt was probably derived from the platinum dish used for evaporating the water. Since the latter was collected, transported and stored in plastic containers, the boron must be an original constituent and is *not* due to contamination from glass. No chrome-bearing spatulas or copper electrodes were used. Elements such as sulphur, fluorine, carbon, and selenium are not detectable by the method employed.

\* Determination of PO<sub>4</sub><sup>'''</sup>, F<sup>'</sup>, Li<sup>'</sup>, Fe<sup>''</sup>, Mn<sup>''</sup>, as well as dissolved H<sub>2</sub>S and CO<sub>2</sub>, and analysis of gas samples.

## VIII. DISCUSSION OF ANALYTICAL RESULTS

(a) *Dissolved Solids*

Regarding the content of dissolved solids (1094, 1102, 1033 and 944 p.p.m.) the waters are of medium salinity only. They are less saline than the thermal water at Warmbad in southern South West Africa (2113·9 p.p.m.), but rather more concentrated than the Windhoek hot springs (642-899 p.p.m.) (5, p.p. 8-12).

The general composition of the Gross and Klein Barmen waters is very similar. It is not surprising that the natural springs and hot farm bore-hole on Gross Barmen, situated only a few hundred yards apart, should be practically identical within the limits of analytical error and equilibrium conditions at varying temperatures. The latter feature makes itself felt in a higher content of free  $\text{CO}_2$  and consequent greater amounts of bicarbonate in the farm bore-hole of lower temperature. Another notable difference is the much higher fluoride content of the latter. That the water at Klein Barmen,  $7\frac{1}{2}$  miles distant, is yet so closely similar to that of Gross Barmen, is perhaps less readily to be expected. The main *cation* contents ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^+$ ,  $\text{Mg}^{++}$ ) correspond very closely in spite of the different types of rock traversed, at least near surface. The relative proportions of the main *anions* ( $\text{SO}_4^{--}$ ,  $\text{Cl}^-$ ,  $\text{HCO}_3^-$ ), however, show considerably greater variation. The overall aspect of the water from Okandu, 13 miles farther to the SW and of much lower temperature, is still similar, but several important differences can be noted.

In all waters sodium is by far the dominant *cation*, potassium, calcium and magnesium being quite inconspicuous in comparison. Sulphate is the most abundant *anion* in all waters except that from Okandu. At Gross and Klein Barmen it is greatly in excess of both bicarbonate and chloride, but at Okandu chloride exceeds sulphate somewhat. For the hot waters of Gross and Klein Barmen the main salts resulting on evaporation would therefore be, in order of abundance, sodium sulphate (Glauber Salt), sodium carbonate and bicarbonate, and sodium chloride (common salt); but in the only tepid water from Okandu the latter would exceed sodium sulphate.

The geological significance of the relative proportions of *cations* and *anions* will be again referred to in the discussion of the origin of these thermal waters (Chapter XV).

It is not surprising, in view of the high contents of sodium carbonate, that *silica* should also be high in all four waters, ranging from 70 to 105 p.p.m. Bond has shown that in South African ground-waters the highest average silica content occurs in alkaline sodium carbonate waters rising in Old Granite and Bushveld Granite environments, i.e. rocks rich in alkalis. Seldom, however, does it exceed 50 p.p.m. (11, p.167).

It is not proposed to enter here into the much debated question as to whether silica occurs in the ionic condition as an *anion* or in the colloidal form. This problem has been discussed both by Bond (11, p.168) and by Kent (12, p.239). All waters are alkaline and with the exception of Klein Barmen the total millinormality of the *anions* exceeds that of the *cations*. Silica can thus hardly be present as *anions* or the ionic balance would be completely disturbed. (12, p.240). In the particularly silica-rich water of Klein Barmen this condition does not hold and accordingly some sodium silicate has been computed among the probable salines (Table 4).

The *fluoride* content throughout is considerable; in the case of Klein Barmen and the hot bore-hole on Gross Barmen it is even high (9·5 and 8·6 p.p.m.). Bond

found only sodium carbonate- and bicarbonate-bearing waters to contain appreciable amounts of fluoride (over 1 p.p.m. ). Apart from the high fluoride regions of the Transvaal Bushveld and Pilanesberg, where the astonishing values of 35·1 and 67·2 p.p.m. were found, also many ground-waters of the NW Cape, rising in a geological setting and climate rather similar to those along the Swakop River, contain appreciable fluoride contents, up to 8·3 p.p.m. (11, p.169).

The association of high fluoride content with soda alkalinity indicates the presence of highly soluble sodium fluoride. The natural mineral fluorite,  $\text{CaF}_2$ , is rather resistant to weathering but is, nevertheless, slowly decomposed. But, owing to the similar size of fluorine and hydroxyl ions, this element is a common constituent of hydroxy-silicates, such as the micas, amphiboles and tourmaline. The first two are major constituents of dominant rock types along the Swakop River and many of the innumerable pegmatites are full of black tourmaline.

Regarding minor cations, *lithium* is rather widely distributed in small quantities in many rock types, notably granites and pegmatites. It is often enriched in micas and also found in amphiboles and pyroxenes, all of which are abundant in the environs of the springs under discussion. Lithium is found in small quantity in many thermal waters, being leached out of the rocks traversed as the easily soluble chloride and carbonate.

*Aluminium*, *iron* and *manganese* are very low throughout, in spite of the richness of granites and biotite-schists in the first two elements. On decomposition, aluminium remains dissolved only in acid ( $\text{pH} < 4$ ) and alkaline ( $\text{pH} > 9$ ) solutions; at intermediate pH values it is precipitated as the hydroxide. Mostly the latter again reacts with silica to form clay minerals.

The primary factors regarding the manner of migration of iron are the presence or absence of oxygen and carbon dioxide. Both ferrous carbonate and ferrous sulphate are unstable in the presence of dissolved and atmospheric oxygen. The former is decomposed to ferric hydroxide and carbon dioxide; the latter, after oxidation to ferric sulphate, is rapidly hydrolyzed also to form ferric hydroxide. As has been stated, the more extensive fractures at Gross Barmen are frequently heavily stained with yellowish and brownish ferric hydroxides.

Manganese, though considerably less abundant than iron, is nevertheless widely distributed in the earth's crust. Dark silicate minerals containing hydroxyl, e.g. biotite and hornblende, often contain appreciable amounts of manganese, as do the garnets almandite and spessartite. Garnet of almandite type, as well as being disseminated in some schists, is abundant in narrow layers of garnet-hornblende-pyroxene granulites within the latter. It also occurs within the pegmatites, and in smaller amount also in the granites. During weathering manganese is dissolved mainly as the bicarbonate.

The manganese content throughout is higher than that of iron. Manganese is dissolved in  $\text{CO}_2$ - and sulphate-bearing waters more readily than iron and, although readily precipitated in much the same way as the latter, its bicarbonate is more stable than that of iron and in weathering solutions manganese consequently tends to become enriched relative to iron.

Apart from independent mineral species, such as sphene found in garnet-hornblende-pyroxene granulites within the schists, *titanium* is extensively incorporated in other mineral structures, of which titaniferous magnetite is the most common. Small amounts are regularly concealed in ferric minerals such as pyroxenes, amphiboles and biotite, which are present in bulk in the environs of the

Swakop River. On weathering titanium goes into solution, but the soluble salts of titanium are very readily hydrolyzed. This element therefore tends to be enriched in the products of weathering and is retained in solution in only small quantities.

The presence of *boron* as a minor and not merely a *trace*-element in the Gross Barmen spring water is a noteworthy feature (Table 5). While very small amounts of boron are trapped in hydroxyl-bearing minerals (biotite, amphibole) during magmatic crystallisation, its bulk is enriched in the final end-products, particularly in the tourmalines of pegmatites. Black tourmaline is widely present in the pegmatites of the Swakop region, often in great abundance. During chemical weathering boron goes into solution as boric acid and soluble borates and by way of springs and rivers ultimately reaches the sea. Many marine sediments are therefore comparatively rich in boron. Shales metamorphosed to biotite schists may therefore also hold appreciable amounts.

*Strontium* and *barium* are among the most abundant trace-elements within the upper part of the crust. Strontium constantly accompanies calcium, while barium in minerals and rocks is extensively substituted for potassium, e.g. in feldspars and micas. Strontium may also enter calcium-bearing amphiboles and pyroxenes. The isotope Strontium<sup>87</sup>, moreover, results from the decay of radioactive Rubidium<sup>87</sup>, which is often present in appreciable amount in the lithium-mica lepidolite, found in pegmatites, as well as in biotite.

During weathering these two elements go into solution mainly as bicarbonates and chlorides, but under certain conditions also as sulphates. On account of the sparing solubility of barium sulphate, an increase in the concentration of sulphate *anion* may result in the precipitation of barium sulphate (barite). In the hot spring water of Gross Barmen, so rich in  $\text{SO}_4^{--}$ , strontium is hence more abundant than barium, its amount being greater than mere trace-element distribution.

Among the latter (Table 5) *germanium* is one of the most abundant. Independent minerals of this metal, e.g. the sulphide *germanite*, are comparatively infrequent and germanium used to be considered an extremely rare element. More recently, however, it has been shown to be concealed in numbers of silicate minerals, substituting for  $\text{Si}^{++}$ , e.g. in garnet. Granites contain appreciable amounts of germanium, being particularly concentrated in later phases, e.g. greisens and pegmatites. These rock types abound along the Swakop River. During weathering germanium is readily extracted and transported as soluble salts. It has been found to be enriched in siliceous sinters deposited from silica-rich thermal springs.

Concerning the other metallic trace-elements listed in Table 5, their presence is by no means necessarily indicative of the occurrence of independent mineral species in the rocks traversed by the thermal waters, or even of ore-deposits at depth. All of them may enter the structure of more common minerals by diadochic (ionic) replacement. Thus the bulk of *nickel* and *cobalt* within the upper part of the earth's crust is concealed in silicate minerals, nickel replacing magnesium and cobalt ferrous iron in ordinary rock-forming ferromagnesian minerals, such as biotite, amphiboles and pyroxenes. *Zinc* may also replace the same two ions in these minerals, biotite usually showing the highest content. Even small amounts of *chromium*, substituting for ferric iron and aluminium, may be concealed in these same minerals.

*Vanadium* is a very widely distributed trace-element. Common magnetite may contain appreciable amounts. Biotite, amphiboles and pyroxenes nearly always carry small quantities. As a result vanadium has been shown to be present in many thermal and mineral springs.

Apart from forming sulphides, its main normal abode, *copper* in traces may substitute for ferrous iron in certain silicates, such as tourmaline and pyroxenes. Copper-bearing sulphides are in places enriched in the general region of western Damaraland in pegmatites and at limestone contacts, as well as in hydrothermal deposits within the *Khomas* schists.

(b) *Gases*

*Carbon Dioxide.* On being passed through lime water the gas issuing at all three localities showed the presence of  $\text{CO}_2$ . Comparing the rate of formation and intensity of resulting turbidity with that produced on breathing into a test tube filled with the same lime water, the amounts present can only be small. At Gross Barmen a larger proportion was indicated than at Klein Barmen and Okandu.

The results of a mass-spectrographic analysis of two samples of gas collected at the main issue and "bore-hole" spring on Gross Barmen, carried out by C.S.I.R. laboratories in Pretoria (Dr. F. W. E. Strelow), are listed in Table 6.

TABLE 6  
GAS ANALYSES

	<i>Main</i>	<i>Southern Spring</i>	<i>"Borehole" Spring</i>
Nitrogen $\text{N}_2$		93%	97 %
Argon A		1	0.5
Carbon Dioxide $\text{CO}_2$		6	3
Oxygen $\text{O}_2$		nil	nil

(Accuracy of the order of  $\pm 5\%$  as indicated by a repeat run using a standard).

These results are in keeping with the general finding throughout South Africa that the gas bubbling up from thermal springs in ancient crystalline rocks is mainly composed of nitrogen, often with varying small amounts of oxygen (Kent 12, p.244). This fact indicates the gas to be mostly ordinary air from which the oxygen has been abstracted to varying degrees by oxidation processes. In this particular case the removal of  $\text{O}_2$  appears to have been complete. The source of carbon dioxide in these thermal waters is obscure; there is no evidence to suggest a volcanic origin.

*Sulphuretted Hydrogen*

The 1911 analysis (page 171) indicated 4.37 parts per million of dissolved  $\text{H}_2\text{S}$  in the water from the hot springs on Gross Barmen, which the analyst described as smelling strongly of this gas. Since  $\text{H}_2\text{S}$  is readily oxidised and the sample submitted showed a slight turbidity probably due to the precipitation of sulphur, he suggested that at the actual spring site the  $\text{H}_2\text{S}$  content in all probability would be considerably higher. Consequently he described Gross Barmen as a *sulphur* spring. Also the analyst of 1939 mentions an odour of  $\text{H}_2\text{S}$  in the sample submitted to him.

The determinations carried out in Pretoria on two samples, in which any  $\text{H}_2\text{S}$  present was immediately fixed on the spot with  $\text{CdCl}_2$ , however, yielded only 0.92 p.p.m., i.e. very slight quantities. When O. Hart thoroughly cleaned the strongest point of issue and took samples by means of a tube inserted into the actual orifice, tests for  $\text{H}_2\text{S}$  remained negative. It must be presumed, therefore, that the characteristic odour of  $\text{H}_2\text{S}$ , usually so distinctly noticeable in the main spring area, is due to the reduction of sulphates, abundantly present in the water, by surface agencies. The latter may be organic matter in general or specific sulphate-



reducing bacteria. By accession of organic matter, dissolved sulphates may be reduced to sulphides, and carbonic acid (free  $\text{CO}_2$ ) acting on the latter may produce  $\text{H}_2\text{S}$  and carbonates (15, p.210).

The 1911 sample must therefore have accumulated under conditions particularly favourable for sulphate reduction. Local inhabitants of Gross Barmen claim that the odour of  $\text{H}_2\text{S}$  at the spring site is variable in intensity, being considerably more pronounced at certain times than at others. If sulphate-reducing bacteria are responsible, this would indicate variations in their abundance and activity.

A puzzling feature is the fact that the odour of  $\text{H}_2\text{S}$  appears to be most pronounced over the two main points of issue, where the water flows strongest. These are clear and clean apart from coatings of algal slime on the floor of channels that lead the water into the large adjacent pool. Although algal slime is much more abundant in the latter and there is a surfeit of organic matter derived from sedges and reeds, the characteristic odour appears to be less marked in its vicinity; but when dark muds accumulated on the bottom of the reed-fringed swimming pool, several dozen yards away, are stirred up, there is an overpowering reek of  $\text{H}_2\text{S}$ .

#### IX. RADIOACTIVITY

The fallacy of the general belief among the public that hot springs are the most highly radioactive and that the higher the temperature the greater the radioactivity, has already been commented on in connection with the Windhoek hot springs (5, p.7). As a matter of fact, one of the world's most highly radioactive springs, Brambach in Saxony, is cold. Apart from the fact that radon ("radium emanation") is a gas, whose solubility would decrease with increase of temperature, naturally much depends on the presence, or otherwise, of radioactive minerals in the rock traversed by the spring water.

In April 1932, using an old-fashioned calibrated electroscope ("fontactoscope"), Gevers determined the radioactivity of water at the hot springs of Gross and Klein Barmen as 4.9 and 15.9 Mache units respectively. This latter figure would make Klein Barmen the most highly radioactive spring in South West Africa so far tested. Since it rises through aplitic granite rich in potassium and associated in the neighbourhood with a profusion of granite pegmatites, the main host-rocks throughout the world of high-temperature uranium, thorium and rare-earth minerals, this would not be surprising.

In the present investigation a small portable Phillips scintillometer\* of rather low sensitivity was used. The Mache units cited for Gross and Klein Barmen represent only slight degrees of radioactivity. The scintillometer gave similar results, the needle oscillation at no time exceeding  $\pm 10$  c/s. At Gross Barmen activity directly over all hot springs tested was no higher than general background. Over the hot spring of Klein Barmen the instrument registered somewhat more frequent oscillations of slightly greater magnitude, but differing in no significant way from activity over the surrounding aplitic granite. At Okandu, where water of lower temperature ( $38^\circ\text{C}$ ) also issues from aplitic granite, activity was much the same, i.e. low. The highest activity, but still by no means appreciable, was noted over massive pegmatites in the hills of Rüdenu, adjacent to Gross and Klein Barmen.

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\* Kindly loaned by Dr. R. A. Pelletier, of New Consolidated Goldfields, Johannesburg.

It must be concluded, therefore, that the thermal springs in question possess only a slight degree of radioactivity. By comparison it may be stated that the famous Karlsbad Sprudel in Czechoslovakia has from 9 to 40 Mache units, and one of the main springs at Aix-la-Chapelle 8 to 50; Brambach, just cited, on the other hand is really highly radioactive with several thousand Mache units. This spring rises in the well-known region of uranium mineralisation of the Erzgebirge.

#### X. CLASSIFICATION OF THERMAL WATERS

Regarding temperature, as already noted, the hot springs of Gross and Klein Barmen (maximum 69 and 62°C), have to be placed in the upper (*very hot or scalding*) bracket of *hyperthermal* waters (above 42°C, I.S.M.H.),<sup>1</sup> while the farm bore-hole at Gross Barmen (51·8°C) belongs to the lower division (*hot*) of this group. According to the classification suggested by Kent (12) it would still have to be classed as *scalding*. Okandu (38°C) just falls within the *thermal group* (37-42°C).

With respect to total saline content, all four waters are *hypotonic*, i.e. they have a lower salt content than human body fluids. All are far below the *isotonic* point of about 9000 mgms per litre (13). Total dissolved solids are highest at Gross Barmen (1102 and 1094 p.p.m.), slightly lower at Klein Barmen (1033 p.p.m.), and lowest for Okandu (944 p.p.m.). This compares with 174-280 p.p.m. in ordinary subsurface water in the Swakop River at the new pumping plant used for irrigation on Gross Barmen.

All four waters are *alkaline*, with pH values ranging from 7·3 (Gross Barmen) to 8·1 (Okandu). All contain appreciable quantities of dissolved bicarbonate and carbonate, "probable" sodium carbonate being the second most abundant saline in all but Okandu.

Sulphate is the most abundant *anion* in all except, again, Okandu, thus placing these waters in the *sulphate* group. Chloride *anion* is everywhere abundant enough to allocate these waters also to the *chloride* or *muriate* class; at Okandu the latter actually preponderates over the former.

Summarising, the waters under description are of *mixed type* and belong to the *alkaline-sulphate-muriate (chloride)* group of thermal waters.

The content of sulphuretted hydrogen is too slight, as previously outlined, for Gross Barmen to be classed as a sulphur spring.

#### XI. THERAPEUTIC VALUE OF THERMAL WATERS

This is not the place to discuss the medicinal value, or otherwise, of mineral and thermal springs. It is certain that in many cases, particularly the so-called *indifferent* waters with no appreciable content of dissolved substances (variously given as less than between 200 and 1000 mgms per litre) and of rather low temperature (subthermal), subsidiary factors such as "change of scene", supervised diet, exercise, rest, relaxation, etc., are often mainly responsible for improving physical and mental health. There is no doubt, however, that in many instances curative effects are directly attributable to the waters themselves, whether used internally through drinking or externally for bathing. Reference should be made to relevant balneological literature and "The Medicinal Springs of South Africa" by L. E. Kent, (13).

With regard to the thermal waters under discussion the following points may be noted. Alkaline waters may be beneficial in certain digestive ailments. They

act as antacids and soothe the gastric mucous membranes. Taken internally, salt waters, if not too saline, stimulate the flow of gastric juices and are thus indicated in cases of hypo-acidity. They are also diuretic, i.e. accelerate fluid discharge from the body. There is, however, a surfeit of "brack" waters in arid South West Africa. Sulphate waters, particularly when warm or even hot, have an aperient effect and, when taken over a sufficient period of time, are "slimming" if, in addition, the diet is regulated. A combination of chlorides and sulphates in drinking water thus helps to "flush out" the system. Sufferers from stomach ulcers, however, should avoid saline waters.

Owing to the high fluoride content, resulting in "mottled teeth", young children under the age of eight years should not drink these waters over any length of time.

Finely divided sulphur, taken internally or applied externally, is said to be highly beneficial to the skin. The bluish opalescent sheen of sulphur spring pools is due to finely divided colloidal sulphur in suspension, derived from the oxidation of  $H_2S$ .

Application of heat normally relieves pain, not only "rheumatic", but also generally neuritic, e.g. sciatica. Bathing in thermal waters of sufficient temperature is therefore beneficial in many cases. Patients suffering from authentic ailments of the heart and certain disturbances of the vascular system, however, are warned against complete immersion in hot water, above all for too long a time.

In treatment by immersion, the action of water is primarily one of stimulating the nerves and capillaries of the skin. The degree of this stimulation is governed mainly by the temperature, duration and extent of immersion and, to a lesser extent, the mineral and gas content of the water. The respiration rate, pulse, blood pressure, and metabolism are affected. By redistribution of blood, congested organs may be relieved and the elimination of toxins is increased by the greater activity of the sweat glands. Of dissolved minerals, salt ( $NaCl$ ) and sulphates are claimed to be particularly active as skin stimulants.

Both Gross and Klein Barmen thus present many features acclaimed as highly curative for a variety of ailments in many well-known European *spas*. In temperature they far exceed the majority. Already in its present undeveloped state Gross Barmen offers a considerable range of water temperatures for bathing, ranging from hot to tepid, or even cold. With its bathing pool, overshadowed by tall *hyphaene* palms, and big reed- and sedge-fringed dam, crowded with coots and wild ducks, Gross Barmen provides an unusually attractive scenic feature in arid South West Africa (Plate X, Fig. 1). Already it is a very popular picnic spot over week-ends. If further developed, care should be taken not to spoil the natural charm of its present setting.

## XII. SPRING DEPOSITS

Although the new analysis of Klein Barmen spring water shows an even higher silica content (105 mgms per litre) than the old 1909 analysis (99 mgms), only insignificant sinter deposits in the form of silica-cemented rubble are to be found there. This may be due to the fact that the water drains into an extensive sedge-covered swamp.

Also at Gross Barmen, with 80 mgms  $SiO_2$  per litre, spring deposits are very restricted. Only along the southern edge of the swimming pool do shallow caps of spring sinter of small extent occur. The material is light grey in colour with patches

of white, softer matter, in part filling cavities. Isolated irregular fragments of light brown resinous material of organic origin are also present. Treatment with dilute HCl indicates only minor amounts of carbonate, the bulk being silica. Under the microscope the *siliceous sinter* is seen to be composed mainly of a cryptocrystalline groundmass enclosing numerous irregular small grains of quartz, flakes of biotite, some decomposed feldspar, a few grains of garnet, and odd small fragments of the underlying biotite-quartz schists.

Spectrographic analysis (W. R. Liebenberg) indicates: silicon, calcium and magnesium as major, aluminium, sodium and potassium as minor, and titanium, iron, vanadium, strontium, barium, boron, copper, nickel, and chromium as trace-elements.

### XIII. ALGAL SLIME

Samples of the reddish, reddish-brown, and yellowish slime coating the various spring orifices and channels at Gross Barmen and thickly covering also the shallow portions of the pool into which these drain, were submitted to Miss F. D. Hancock of the Botany Department, University of the Witwatersrand. Unfortunately many diagnostic features of detail were rendered unrecognisable by the use of too strong a formalin preservative; but the following were identified:

#### ALGAE

CHLOROPHYTA: *Spirogyra* in great abundance.

BACILLARIOPHYTA (diatoms): high percentage of *Epithemia ocellata*; fair percentage of *Surirella (ovalis?)* and *Amphora (caffaeiformis?)*; also present: *Cymbella* sp, *Navicula* sp, *Achnanthes* sp, *Pinnularia* sp, *Gomphonema* sp, *Nitzschia* sp, *Frustulia* sp, and *Tropidoneis (lepidoptera?)*.

CYANOPHYTA: sp. of *Chroococcus*, *Aphanothece*, *Scytonema*, *Oscillatoria* and *Anabaena*.

CHRYSOPHYTA: *Botryococcus braunii* (Kutz.) in great quantity.

#### BACILLI

Some samples were very rich in two types of bacillus, one short and the other long and attenuated. These could well be sulphur bacteria; but definite identification was impossible.

#### ANIMALS

The ostracod *Cypria* sp., the rotifers *Lepadella (ovalis?)*; and a species of *Philodinavis*.

### XIV. CONTAMINATION OF SUBSURFACE WATER IN THE SWAKOP RIVER BY SALINE SPRING WATER ON GROSS BARMEN

Everywhere along its total length of approximately 230 miles the sand-filled bed of the Swakop River contains ground-water at shallow depth. As already mentioned, the actual channel is generally more than a hundred yards, in places even more than two hundred yards wide. The depth of infilling with highly porous sand and grit, interspersed with gravel layers, is naturally variable, but often exceeds a dozen feet. In the lower reaches it may be as much as 60 feet. In the Osona region near Okahandja, where the river valley is particularly broad and flanked by extensive flats of alluvium, the normally rather coarse sediments also include a layer, up to 3-4 feet thick, of fine-grained clayey silt.

Depending on the amount of precipitation in the interior, runoff water travels for varying distances down the normally dry river bed. Extensive and heavy rains in the uplands are necessary before surface water penetrates right through the Namib Desert as far as the river mouth at Swakopmund. When the river "comes down" in flood it rapidly saturates the highly porous filling of its bed with water, which continues to flow seawards when the surface flow has again subsided. Only rarely does the river flow for more than a few days, even in its source area.

The depth to ground-water is therefore very variable, depending on volume, duration, and frequency of the floods. Where rock bottom is shallow, or the river bed narrow, or where harder rocks, such as dykes of pegmatite, diabase or dolerite, have led to the formation of submerged knick-points, the ground-water may rise to very near the surface, causing moist patches and often enabling game to scrape down to it with their hooves. After floods open water may persist for some time at such localities.

The quantities of ground-water available are often large, particularly where dammed up by rock barriers. Thousands of gallons per hour may be pumped from individual shallow wells. Formerly these were only sunk at suitable points along the banks where the porous infilling extends for sufficient depth beyond the present runoff channel. Nowadays they are frequently placed also within the latter, sealed and covered against damage by floods. The most recent development is pumping from covered-up perforated pipes, of wide enough diameter, driven down into the unconsolidated river sediments.

River beds such as those of the Swakop, Khan, Omaruru, etc., although dry throughout by far the greater part of the year, nevertheless represent economically important "arteries" of ground-water, not only for stock-raising, household purposes and small farm gardens, but at several localities also for irrigation on a bigger scale. Usually the availability not of water but of suitable strips of alluvium is the limiting factor, apart, of course, from considerations of transport or market for crops. In addition to vegetables, also lucerne and tobacco are planted. Night frosts during the cool season unfortunately make citrus-growing impossible in the upper and middle reaches of the Swakop. In the Osona region, where suitable alluvial soils are most widely available, individual irrigated agricultural holdings reach up to 50 hectares in extent.

The quality of the water in a land of such high evaporation rates is obviously of as great importance as its quantity. The gradual increase of salinity of the sub-surface water on its way down to the sea, and the nature of the progressively concentrated salts, were investigated in a preliminary way by T. W. Gevers and J. van der Westhuyzen in 1930-32 (8). The recently established C.S.I.R. (Water Treatment Research Division) Laboratory in Windhoek, together with the Department of Water Affairs, have now embarked on a very extensive and detailed investigation of ground-water availability and composition in South West Africa, an all-important factor in the economic development of a territory so singularly lacking supplies of surface water. The Swakop River catchment area is the first to be tackled and the results will be published in due course.

At selected localities testing sections across the Swakop and certain tributary runoff courses were established by driving perforated steel tubes into the infilling of sand and gravel and taking water samples from different levels by means of a motor-driven pump. The first samples in each pipe were taken at a depth of 5 feet below the surface and, if ground-water was present, at further depth intervals of 4 feet.

Conductivity, pH, total dissolved solids (T.D.S.), total hardness, alkalinity, sulphate and chloride contents were then determined. The ratio of sulphate to chloride, of these two radicles to the T.D.S. content, as well as variations of the latter, are used as a means of determining the addition or otherwise of waters of different composition and concentration.

A large amount of information has been accumulated, of which only that relevant to Gross Barmen is quoted.

A narrow dolerite dyke, a few feet wide, crops out intermittently between the Gross Waldau River, near its junction with the Swakop (Map, Fig. 1), and the Gross Barmen-Ravensberg Ost road, heading for a protuberance of a very thick and extensive dolerite dyke just across the Swakop River on the latter farm. To test the possibility of this dyke being in any way connected with the hot saline springs, two sections above its prolongation across the two river beds were investigated. In each case analytical results showed that this dyke barrier contributes *no* mineralised water whatsoever to the groundwater in either bed. This result is of significance not only with regard to the structural control of the thermal springs on Gross Barmen, but also of those on Klein Barmen and at Okandu.

As already mentioned, saline seepages from fracture-zones enter the sand-filling of the Gross Waldau River at several places (Fig. 1). While total dissolved solids within the Swartkop River vary between 174 and 280 parts per million (average 223), within the Gross Waldau the concentration is very much higher, ranging from 886 to 1319 p.p.m. The average, 1015 p.p.m., is very close to the T.D.S. content of the hot springs (1094 p.p.m.) and farm bore-hole (1102 p.p.m.).

Whereas in the Swakop water the average ratio of chloride to T.D.S. is only  $\cdot 108$ , and that for sulphate  $\cdot 09$ , the main component probably being bicarbonate, in the Gross Waldau runoff course, these ratios rise to  $\cdot 118$  and  $\cdot 274$ , indicating the addition of considerable amounts of sulphate. The average sulphate-chloride ratio accordingly goes up from  $\cdot 881$  to  $2\cdot 277$ .

As previously described, the overflow of the dams fed by the Gross Barmen hot springs enters the Missions River by way of a small flowing creek and also subterraneously (Plate II and Fig. 1). The amount of water visible varies with the time of the year, i.e. temperature and winds. In the cool winter months, surface water may run almost as far as the site of the section, where three samples showed a T.D.S. content ranging from 2111 to 2900 p.p.m. Thus over a distance of approximately  $\frac{3}{4}$  mile the salinity of the hot springs water has been concentrated by evaporation to from 2 to 3 times the original value. The average sulphate-chloride ratio is  $2\cdot 520$ .

A section with 7 test holes approximately 30 yards apart was taken across the approximately 230 yards wide bed of the Swakop River between the entries of the Gross Waldau and Missions Rivers (Plate II and Fig. 1). The results indicate that along the northern bank, from which side the two saline tributaries enter, there is at first little dilution by Swakop water, total dissolved solids at a depth of five feet, nearest the bank, remaining as high as 1592 p.p.m. These values drop to 714 p.p.m., at the same depth, farther out but rise again to 1184 p.p.m. four feet lower in the same test-hole. This indicates that the less salty water tends to spread out over the more highly saline, though conditions are complicated here by a thin layer of silty clay, below which a test hole indicated rather fresh water with T.D.S. contents of only 384 to 456 p.p.m. The next three test holes again show an increased salinity, ranging from 606 to 741 p.p.m. at all depths. The last test hole,

adjacent to the southern bank, indicated ordinary, barely contaminated, Swakop water with T.D.S. contents of only 233-329 p.p.m.

There is thus no doubt that the Gross Waldau River has a considerable effect on ground-water within the Swakop River, the *average* saline content at this particular time having been increased from 205 to 663 p.p.m. While the chloride-T.D.S. ratio remained constant, that between sulphate and T.D.S. increased from 0.093 to 0.235, with a corresponding increase in the sulphate-chloride ratio.

The last relevant section was taken across the Swakop River approximately a mile below the Missions River confluence (Plate II and Fig. 1). All 5 test-holes, spread out at equal intervals across a river width of about 200 yards, show an appreciably increased salinity compared with ordinary Swakop water. T.D.S. contents range, at various depths, from 445 to 716 p.p.m., i.e. from twice to more than three times the normal salinity. A noteworthy point is that the belt of fresh water along the southern bank, clearly shown up by the previous section, has now disappeared, one of the highest values (708 p.p.m.) now being located here. Most Cl: T.D.S., and  $\text{SO}_4$ : T.D.S., and  $\text{SO}_4$ : Cl ratios have risen above the values of the previous section, thus indicating a notable addition not only of sulphates, but also of chlorides by way of the Missions River.

The effect of the Gross Barmen hot springs, however, does not extend very far down the river, whose sand and gravel filling here holds a large enough volume of water to effect dilution. It is well known that under certain conditions diffusion is slow and relatively fresh water may be found in fairly close juxtaposition to saline, e.g. along certain seashores. This feature is clearly shown by the section described above, where fresh water was found along the southern bank of the Swakop in close proximity to more saline. It would appear that here the river "comes down" in flood often enough for fairly rapid dilution and also appreciable flushing to take place.

#### XV. ORIGIN OF THERMAL SPRINGS

There was a time when a high fluorine content and the presence of boron was sufficient for such thermal springs to be suspected of volcanic origin. It is now known, however, that these elements may be widespread not only in thermal waters of purely meteoric derivation, but also in ordinary ground-water. Also, the presence of free carbon dioxide was mostly considered to be indicative of association with volcanism; but this too is by no means conclusive evidence.

The hot springs of Windhoek were considered by all investigators prior to Gevers (1931) to be of volcanic (magmatic) origin merely on account of their high temperature ( $79.8^\circ$ ), the alleged constancy of yield, and the assumed presence of considerable free  $\text{CO}_2$ . When Gevers (5) subsequently showed that these waters actually issue from fissures connected with an abundance of volcanic plugs (trachyte and phonolite) in the Auas mountains nearby, all evidence produced by him to the contrary (5, pp.24-27) did not suffice to dispel entirely the suspicion in some minds that these hot springs *were* actually of volcanic origin. (Discussion of (5)).

Since the main fractures at Gross Barmen conform to some extent with the orientation of the numerous "spring fissures" in the Windhoek area (5, Plate I) only some 50 miles away, and since, moreover, identical wall-alteration (iron-staining and silicification) and fissure-filling (chalcedonic breccia) have been found in at least two of the fault-fractures at Gross Barmen, it seems relevant briefly to repeat the arguments.

The Auas volcanism of trachyte and phonolite vents took place in mid- to late Cretaceous or very early Tertiary times, some 80-60 million years ago. While hot springs and carbon dioxide exhalations may persist in volcanic regions for a long time, measurable in hundreds of thousands, even several million years, after cessation of surface eruptions, they cannot rationally be expected to last for the long period mentioned, during which the earth's surface was lowered by erosion to sufficient depth to expose in some instances the causative bodies of magma.

Besides, actual gaugings of the Windhoek hot springs, when still freely flowing, did *not* indicate a constant yield, but very considerable fluctuations apparently related to the incidence of rainfall, but with a considerable time lag (5, pp.25-26). Furthermore, the general chemical characteristics of the water are by no means typical of volcanic parentage. It can be accepted that these springs are of ordinary meteoric origin, i.e. represent rain water that has become heated by percolation down to great depth and retained a high temperature through being able, along sufficiently open fissures, to rise again to the surface comparatively rapidly.

There is a widespread notion in South West Africa that the thermal springs at Windhoek and at Gross and Klein Barmen, as well as those at Omapyu and Omburo near Omaruru, being the hottest in the entire Territory, are all part of one large "hot water system". This, however, is most unlikely.

It is true that the waters of Windhoek, Gross and Klein Barmen are rather similar in general composition, being of the same "mixed type". In all three sodium is by far the most abundant *cation* and sulphate, chloride and bicarbonate are the major *anions*. But while at the latter two localities sulphate dominates, at Windhoek bicarbonate is considerably in excess of sulphate. From Omapyu and Omburo no chemical analyses are available. Generally, chemical data on ground-water in South West Africa are as yet too meagre for comparative purposes. It is likely that chemical composition will not only vary with geologic and climatological environment, but in the case of deep-seated springs will in some measure also be a function of depth penetrated, since not only solvent power is influenced by temperature, but also certain chemical equilibria resulting in the elimination of some constituents and the enrichment of others.

In any case, thermal waters of this general composition occur at widely separated localities in southern Africa; there is therefore no necessity to assume direct connection between the hot springs in South West Africa just enumerated.

Regarding the various constituents of the thermal waters along the Swakop River, it has been shown in Chapter VIII that *all* minor and trace-elements, including fluorine and boron, are contained within the rock types traversed. The same applies to the major *cations*. Their relative proportions, however, show no direct relationship to the composition of the exposed country rocks. Thus although the Klein Barmen spring is located within magnesium-poor aplitic granite, nevertheless its Mg-content is only insignificantly lower than that of the thermal waters at Gross Barmen, which issue from Mg-rich biotite schists. The Mg-content at Okandu, however, is noticeably lower, though still disproportionate. Here there is a zone of biotite schist xenoliths within the spring area, and at Klein Barmen it is quite possible that below surface the granite is similarly contaminated. Extensive schist xenoliths are common within the granite, which moreover here is an intrusive tongue within biotite schists.

Similarly the calcium content bears no direct relationship to that of the surrounding rocks.



Frequent attention has been drawn to the comparative paucity of potassium in ground-waters occurring within rocks rich in that element, even when it is considerably in excess of sodium. This applies even to highly concentrated brines in a K-rich geological environment, e.g. the Pretoria Salt Pan. This striking disproportion in the amounts of K and Na is no doubt mostly attributable to the well known high adsorption of K, compared with Na, by clayey products of weathering. Bond (11, p.172) cites the experiments of Crawley and Duncan, who found that a layer of clayey soil only 6 inches deep will adsorb 98% of K-salts present in solution, but will let practically all of the Na-salts pass through.

All four thermal waters issue from rocks, biotite schists and aplitic granite, rich in K. No chemical analyses of these rocks are available, but from their mineralogy, K must be greatly in excess of Na, particularly in the schists. Yet all springs show Na to be vastly in excess of K. The varying degree of kaolinisation of the granite around the spring orifices at Klein Barmen and Okandu has already been mentioned. Yet it seems highly doubtful whether the degree of kaolinisation shown on surface is sufficient to continue to adsorb and retain by base exchange vast quantities of K over a very prolonged period of time, measurable at the least in hundreds of thousands of years. Even if the extent of kaolinisation is very much greater at depth, there must be a limit to the adsorption and retention capacity of clayey products of decomposition, even if it be assumed that this is still progressing.

Assuming that rock decomposition eventually comes to a halt when all fracture surfaces are coated with clayey products, beyond which percolating water can no longer reach, not only the supply of K, but also that of Na would be cut off. At Gross Barmen, moreover, many fractures along which hot water is issuing to-day show very little clayey alteration of the biotite-schists, though along the larger fractures, now dry, it is often considerable. Coupled with other features, to be described presently, one is led to suspect, that in spite of the high solvent power and potential for wall rock alteration of hot water, a large proportion of the dissolved salts has been carried down to depth from near the surface.

Bond has discussed the relative proportion of the carbonate, chloride and sulphate *anions* in South African ground-waters. A high sulphate content is nearly always associated with a very high chloride content, but cases where the former is in excess are relatively rare (11, p.166). His ground-water map shows "highly" saline waters with dominant Cl' and appreciable SO<sub>4</sub>" to be confined, apart from certain coastal areas, to the drier parts of the country. They are particularly common in northern and northwestern Cape Province (Namaqualand, Kenhardt and Gordonia). Apart from climate, these regions are also geologically comparable in that granites, gneisses and a variety of schistose rocks are widespread. Outside the arid regions and certain coastal tracts, where connate sea water in young sediments or the proximity of the present shore-line can be held responsible, isolated high sulphate contents in South Africa can usually be directly attributed to the oxidation of sulphides, e.g. in pyritiferous shales of the lower Karroo System.

Much more detail regarding chemical composition of ground-waters in South West Africa is required for purposes of comparison. But it is known that boreholes tapping ordinary shallow ground-water in the drier parts of the country sometimes yield water with astonishingly high salinities—very much higher than those of the thermal springs under discussion—in which chlorides and sulphates greatly preponderate over bicarbonates. Also in the artesian area of the Auob-Nossob rivers in the Kalahari along the Bechuanaland border, many waters are

more saline than those of the thermal springs of the Swakop River and often have high sulphate contents (3, p.67).

Regarding near-surface waters in runoff courses, the 1930-32 investigations by Gevers and Van der Westhuyzen of ground-water within the shallow valley-fill of the Swakop River (8) showed that, apart from local variations, from the source region as far as the beginning of the Namib desert calcium is the most abundant *cation* and bicarbonate the most common *anion*. The proportions of sodium, as well as of chloride and sulphate, gradually increase, until already in the interior portion of the Namib desert they predominate and finally completely overshadow calcium and bicarbonate. In the upper reaches of the river, where bicarbonate dominates, sulphate is generally in excess of chloride, but in the drier regions to the west the latter gradually increases until west of Gross Barmen—Rüdenau it is usually, but not always, in excess of sulphate.

The more extensive investigations currently carried out by the C.S.I.R. laboratory in Windhoek will provide much further detail. Relevant results already to hand indicate that, near Gross Barmen in Swakop water uncontaminated by the saline springs, combined chloride and sulphate make up only 20% of the total dissolved solids, bicarbonate, mainly of calcium, being far in excess. Of 17 samples, taken in two sections across the dry river bed, 14 showed  $\text{Cl}'$  to be in excess of  $\text{SO}_4''$  (in 4 greatly so) and in only 4 did the reverse obtain. In the spring and hot farm bore-hole water of Gross Barmen, by comparison, combined  $\text{Cl}'$  and  $\text{SO}_4''$  make up 41.2 and 39% respectively, sulphate being greatly in excess of chloride.

It will be seen from this discussion that the thermal springs along the Swakop River conform with the general characteristics of near-surface waters, i.e. ordinary ground-water, in the more arid regions of South West Africa and adjacent north-western Cape Province. Regarding concentration when compared with the very near-surface waters of the Swakop River, it should be born in mind that the latter represents a major artery of surface runoff flushed out by floods several times each year. Bore-holes away from the river generally show a much higher concentration of salines. Regarding dominance of  $\text{Cl}' + \text{SO}_4''$  over  $\text{HCO}_3'$  in a rainfall region where, at least in the Swakop River, this relationship normally does not as yet hold, it should be remembered that: (1) no chemical data are available for bore-holes yielding ground-water after percolating generally to a depth of more than 200 feet; (2) the bicarbonates of calcium and magnesium being not only much less soluble but also highly unstable and much more easily precipitated than chlorides and sulphates, in this case of sodium, percolation to very great depths could quite easily account for this feature. Not only are near-surface crusts of carbonate, mainly of calcium, viz. calcrete, very widespread in this general climatic environment, but joints and fractures are normally impregnated with such material down to considerable depths, thus proving its precipitation and extensive removal from ground-water.

Subtracting the mean annual air temperature (Okahandja 20°C) from that of the hottest spring at Gross Barmen (69°C), yields an increase of 49°C. The geothermal gradient of this region is not known, but is likely to be as low as in other parts of southern Africa of similar geologic environment. Taking the gradients quoted by Kent (12, p.263) the minimum depth to which surface water must have percolated downwards is between approximately 7,000 and 10,000 feet. This is sufficient to eliminate, in the absence of abundant free carbon dioxide, the bulk of the carbonates of calcium and magnesium.

Regarding sulphate being in excess of chloride at Gross and Klein Barmen, it should be noted that this is also the case in some samples of near-surface water from the Swakop River. Again no data are available for bore-holes. In the only tepid water at Okandu this relationship does not hold, Cl' exceeding SO<sub>4</sub>''. Since disseminated metallic sulphides are not altogether rare within rocks of the DAMARA SYSTEM and even concentrations are found locally, the SO<sub>4</sub>'' contents normal to ground-water within this climatic region, particularly in the still more arid zone to the west, may conceivably have been increased by oxidation of such sulphides to sulphate.

In any discussion of this kind the complex effects of changing equilibria, including interaction between solutes and between solutes and wall-rock, as well as the laws of mass action, should always be kept in mind. The availability of free CO<sub>2</sub> is of particular importance regarding stability of bicarbonates and their elimination or retention. In the Windhoek hot springs, for instance, which rise from still greater depths, bicarbonate is the most abundant anion. In the one analysis where free CO<sub>2</sub> was determined (5, p.10) this is considerably in excess of the values found in the thermal waters along the Swakop River, which throughout are low.

Presence of free carbon dioxide in thermal waters issuing from depth is least readily explained without recourse to volcanic origin. It has been noted that the gases issuing at Gross Barmen are mainly nitrogen, residual from dissolved air. Since oxygen was completely abstracted through oxidation processes, CO<sub>2</sub>, although only a weak acid, should be expected to have been removed as well. The concentrations of dissolved free CO<sub>2</sub> and its content within the gas bubbles, moreover, exceed its relative proportion in ordinary air. In the soil and ground-water, CO<sub>2</sub> is normally always greatly enriched in relation to its concentration in air and rain-water, due to the oxidation of organic matter. It seems doubtful, however, whether the rather sparing vegetation and soil flora in this semi-arid region could achieve such a proportionate increase.

Carbon dioxide is also generated by the action of acids on carbonate minerals and rocks, as has been suggested for the extensive CO<sub>2</sub> exhalations in southern Natal (10, p.277). Sulphurous and sulphuric acids, for instance, can originate from the oxidation of sulphides. The possibility of sulphate enrichment due to this cause has already been mentioned. The thermal waters under discussion are all alkaline. This does not exclude, however, the possibility of accession below surface of minor amounts of more localised water carrying sulphide-derived acids. Calcite is not only present *en masse* in the general succession, but also occurs within garnet-hornblende-pyroxene granulites interspersed with the schists from which at least the Gross Barmen springs directly issue.

In any case, the content of dissolved CO<sub>2</sub> is only small and gas bubbles not only sparing but also low in free CO<sub>2</sub>. Certainly this gas is nothing like as much in evidence as in typical "bubbly" springs and gas exhalations in volcanic regions. Kent (12, p.245) lists CO<sub>2</sub> contents as high as 3.5% in nitrogen-rich gases emanating from South African thermal springs that most certainly have no volcanic affiliations.

Considering all the evidence, there is little, or no, doubt that the thermal waters along the Swakop River are of ordinary meteoric, i.e. rain-water, origin.

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DESCRIPTION OF PLATE II

The Swakop River loops through the left bottom corner of the photo, where it is joined first by the Gross Waldau River coming down from the top right and, a few hundred yards westwards, by the Missions River coming down from the top left.

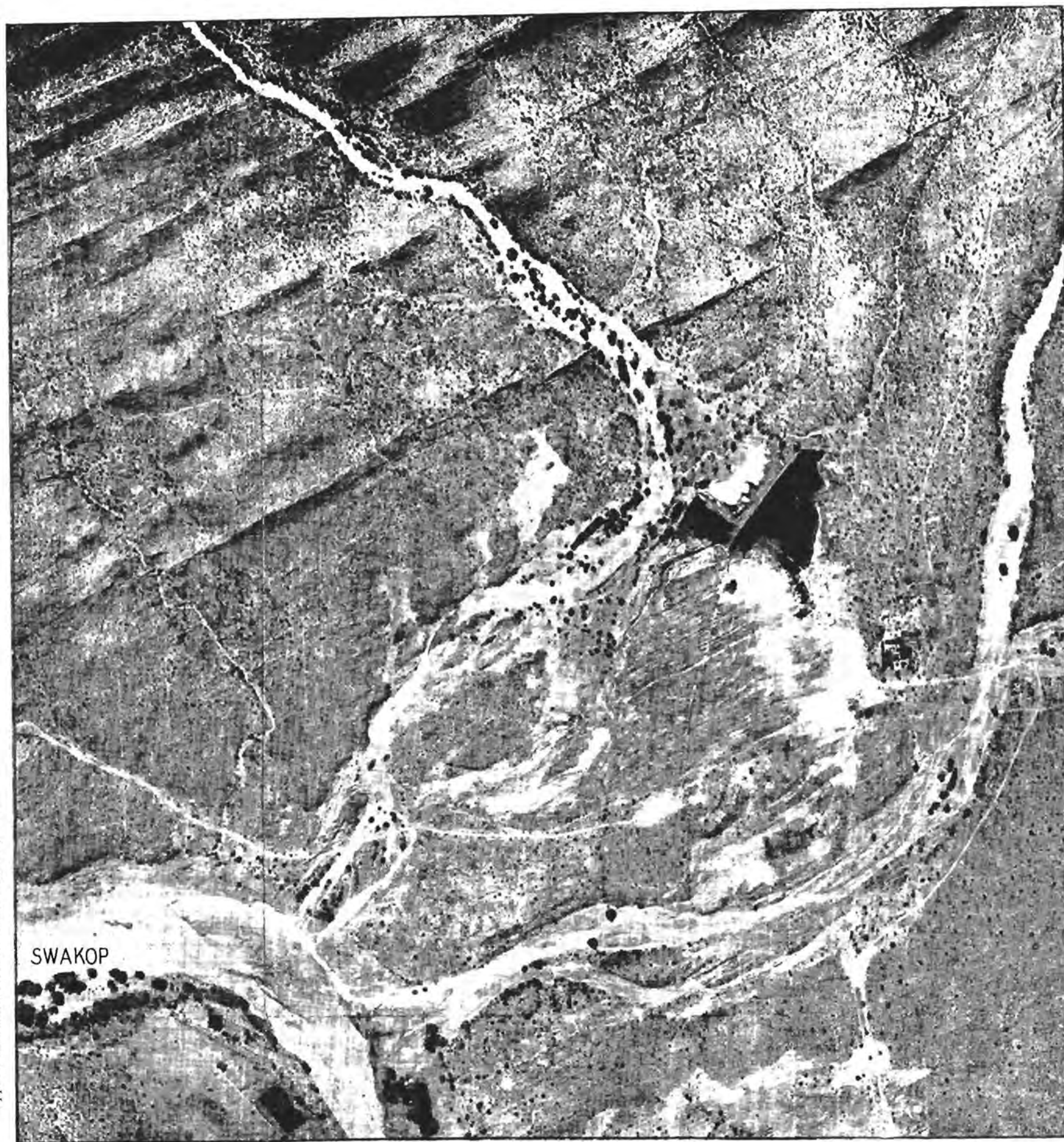
The lower *Khomas Schists* can be seen to strike regularly at approx. 60°E through top portion of photo, seamed by large numbers of very regular, discontinuous, concordant pegmatite dykes. Except for the southern banks of the Gross Waldau River and southwards, where the dip varies from 60-70° South (Fig. 1) the dip of the schists and pegmatites is vertical.

The road from Okahandja can be seen to cross the Gross Waldau River just below the junction of a minor runoff course coming in from the east. Where this road runs into the large white area of saline encrustations, the Gross Barmen farm house can be seen among trees north of the road. Immediately to the south, near the small patch of dark sedge, are situated the hot farm bore-hole and the warm water well. An almost N-S fault zone can be seen to run into them up from the northern bank of the Gross Waldau River. The white patch on the left bank of the latter marks the site of a seepage with white saline encrustations. In line from this point, through the hot farm bore-hole and the centre of the whitest elongate patch just west of the farm house, can be seen the dark zone of the main *Hot Spring* area, trending NNW into the SE corner of the main dam, showing up black together with the adjacent smaller dam.

The little flowing creek of highly saline water can be seen issuing from the SE corner of the smaller dam and, after an initial straight course within a ENE fracture zone, to run in a broad curve, with heavy saline encrustations, towards the Missions River, which it just fails to reach on surface north of where the main road crosses the latter a few hundred yards above its junction with the broad Swakop River.

The vertical ribs of ENE-SSW striking biotite-andalusite schists can be well seen to the left (W) and S of the hot spring area. The *main shear zone* stands out as a white line running from the dark sedge patch at the SE end of the hot spring area towards the salty creek, the lowermost course of which is in its prolongation, as is also the north bank of the Swakop River west of the latter's broad bend. The main shear zone can be seen to be crossed by two more or less parallel NNE-SSW trending fracture zones (faults), the westernmost containing the upper course of the salty creek. The eastern extends from the SW corner of the main dam across the main shear zone, from where it bends into a N-S trend, marked south of the road by a straight line of trees, to cross the main northern arm of the Gross Waldau River to the small white seepage patch on the island (Fig. 1).

The old Police Fort is the dark spot on a white mound  $\frac{1}{2}$  inch (150 yards) to the east of where this fracture zone crosses the main road. The ruins of the Mission house and church can be seen just west of the Missions River,  $\frac{6}{10}$  and  $\frac{8}{10}$  inch NW from the NW corner of the smaller dam. To the west is another white patch of saline encrustations marking the site of former hot springs and seepages along two parallel NNW trending faults marked by silicified breccia. The second pegmatite to the NNW can be seen to be slightly displaced by these faults (Fig. 1). In their SSE prolongation no trace of these minor faults is to be seen in the area SW of the two dams.





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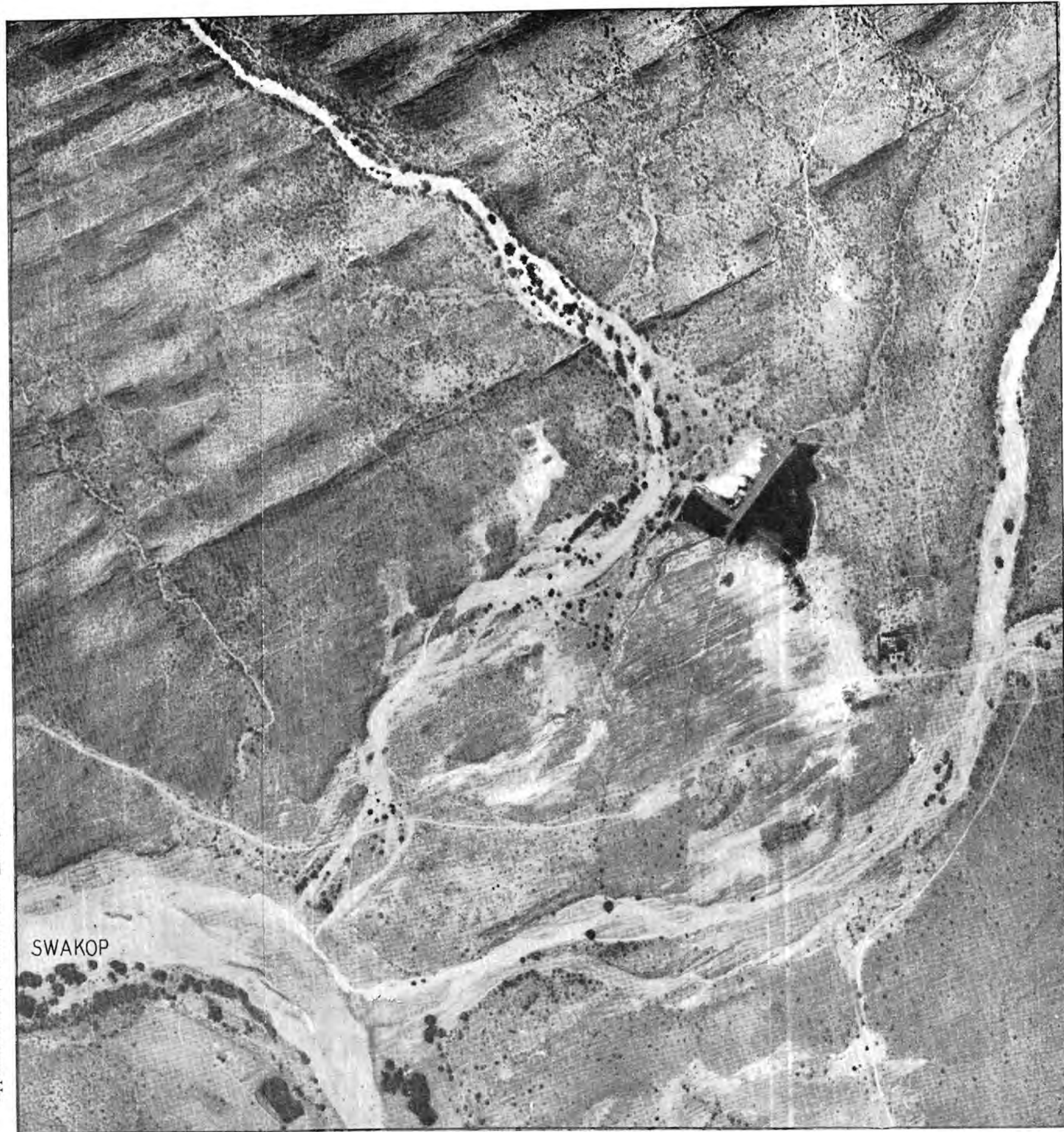




Fig. 1—Ruins of Mission House, built in 1844. Gross Barmen.



Fig. 2—Ruins of Mission church, built in 1847-48, Gross Barmen.





Fig. 1—Large platy andalusite porphyroblasts developed along fracture-cleavage in biotite schists. Gross Barmen, Southwest of Hot Spring area.



Fig. 2—Recent silica-cemented fluvial conglomerate incised by Gross Waldau River, south of Farm Bore-hole, Gross Barmen.



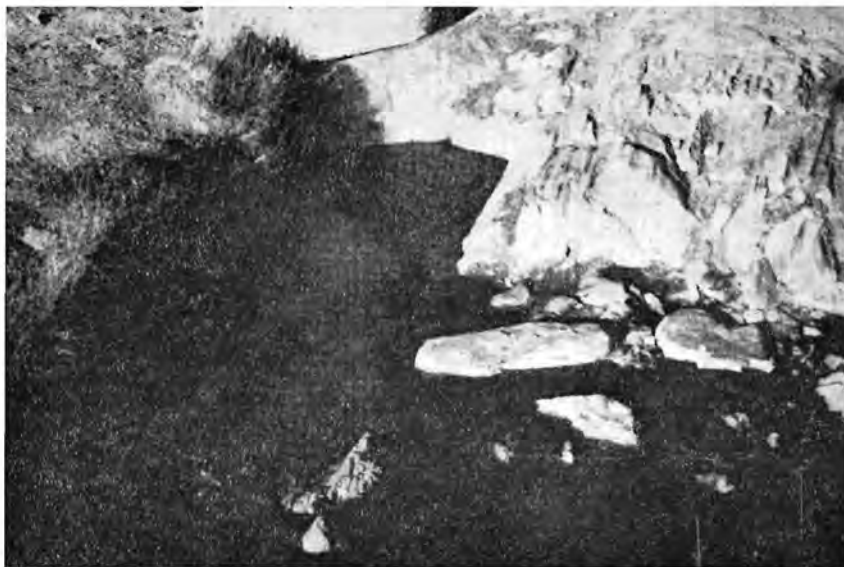


Fig. 1—Main orifice of "Drinking Water" Hot Spring, Gross Barmen. Note strike of vertical schists crossed by transverse fractures.



Fig. 2—Hot Spring area on Gross Barmen, showing hot water streamlets draining into pool floored with algal deposits; Hyphaene palms around swimming pool and large dam beyond. Pegmatite ridge in background. Note white saline encrustations.

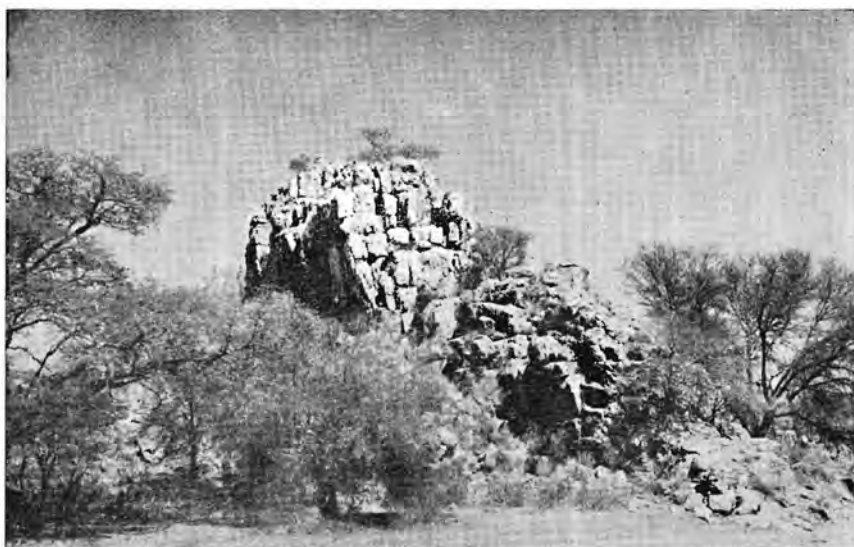


Fig. 1—Thick faulted pegmatite behind Mission Ruins, Gross Barmen.



Fig. 2—Mural weathering of vertical "Chinese Wall" Pegmatite. Gross Barmen.



Fig. 1—Polygonal fracturing of schists at Gross Barmen. Vertical bedding schistosity, striking ENE-WSW, from left to right, crossed by numerous parallel transverse joints trending NNE-SSW.



Fig. 2—Trench in biotite schists along fault heading for hot Farm Bore-hole and Warm Well (windpumps). Gross Barmen farm house in upper right background.



Fig. 1—Main shear-zone, 3-4 yds wide, near Gross Barmen Hot Springs, parallel to strike of schists (ENE-WSW), cut by transverse NNE-SSW fault appearing as narrow white grassed line in upper part of photo.



Fig. 2—Intense parallel shearing of schists in main shear-zone, Gross Barmen.



Fig. 1—Chevron type minor fold in laminated biotite schists fractured between axial-plane joints oriented at approx.  $40^{\circ}$  to ENE strike of schists. Gross Barmen, southwest of Hot Spring area.



Fig. 2—"Drinking Water" Hot Spring. Gross Barmen.



Fig. 1—Main dam, Gross Barmen. Hyphaene palms around swimming pool. Old Police Fort immediately to left of palms.



Fig. 2—Outcrops of white aplitic granite next to Hot Spring at Klein Barmen.





Fig. 1—Impounded Hot Spring at Klein Barmen. Khomas Highlands in background.



Fig. 2—Main visible orifice of warm springs at Okandu. White aplitic granite in foreground. Khomas Highlands in background.