Gypsum Deposits of the Coast of South West Africa

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ABSTRACT

The Namib desert covers the coastal area of Southwest Africa, extending 80 miles inland from the Atlantic to the Great Escarpment. The escarpment is displaced landward in this area because of major coastal rivers, which although episodic have caused extensive erosion of the Great Escarpment.

The desert slopes from the foot of the escarpment to sea level, a change of 1100 meters in 90 miles and the desert plain is covered with typical arid weathering products, predominantly felspathic sands, caliche, gravels and grits.

Extensive gypsum deposits occur particularly in the area from the Ugab River to the diamondiferous dunes south of the Kuiseb River, varying from a few inches to 100 feet near to the coast, but decreasing inland, grading into calcrete. Gypsum often occurs as a massive bed immediately overlying the Damara Schist floor. These beds often pass up into nodular masses of gypsum crystals and then into powdery gypsum just below the surface. Near the present shoreline marine lagoonal gypsum occurs.

Two suggested modes of origin for the non-lagoonal gypsum are (a) sea mist blown in from the ocean over the desert surface, causing 100% humidity lasting until early morning. This mist has been recorded 50 miles inland and has high sulphate content. (b) Saline ground waters in the area, salinity increasing rapidly from the escarpment to the desert.

There is some faunal evidence of a past warmer, more humid climate which suggests the proximity of the cold Benguela current to the coast of Southwest Africa is a very recent phenomenon.

INTRODUCTION

Modern deserts contain concentrations of mi erals that are normally ascribed to lake or marir origins. Calcite, gypsum, halite and minor amoun of anhydrite, nitrates and other complex anh drous and hydrated salts occur in many arid area

The Namib Desert of South West Africa contair very extensive evaporites which were not deposite in a basin, either marine or non-marine, but in th surficial sediments of the coastal platform. Th study of the origin of these deposits, the subject c this report, suggests that evaporation and precipit tion of evaporite minerals in surficial sediments c arid lands may have been a formerly unrecognize important source for secondary evaporite concer trations in lakes and marine basins.

In the Namib Desert, anhydrite is present i association with extensive gypsum deposits. Th associations indicate that the type of groundwate brine present has a significant amount of contr over whether gypsum or anhydrite is formed.

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MORPHOLOGY AND CLIMATE

The Namib Desert forms the western limit of the southern part of South West Africa. The desert extends from the area of Mossamedes, Angola in the north to the mouth of the Oliphants River in the south. The north-south distance is approximately 2100 kilometers and the desert extends from the coast inland a distance of 11 kilometers in the north and from 80 to 145 kilometers in the south.

This investigation is primarily concerned with the Central Namib, located between the Ugab River in the north and the Kuiseb River in the south, between latitudes 21° and 23.5° S. (Fig. 1). South of the Kuiseb River the pediment surface is covered with sand dunes which are among the highest and most spectacular in the world. The dunes are grey at the coast and gradually change to red inland; they can be used for air navigation purposes, the dune color indicating the distance inland. The dune valleys have extensive calcite developed on the sand surfaces. Dunes may be completely fossilized by silcrete at the base with gypsum above and calcite at the top of the dune.

North of the Kuiseb River, the surface cover is thin desert sands and gravels ranging from 0 to several meters in depth; some small dunes are present. The gravels thicken to greater than 5 meters near the major rivers only. Evaporite deposits are interbedded with the surficial sediments and are less extensive in the northern part of the desert.

The Central Namib Desert is the major drainage basin for the central highlands of South West Africa, and within it are the major episodic rivers of the desert including the Ugab, Omaruru, Kuiseb and Swakop. These rivers are predominantly dry, although on occasion they may carry significant floodwaters. The river beds however, always carry large amounts of subsurface waters which supply the coastal towns.

These rivers are associated with the extensive dissection of the Great Escarpment, a prominent feature of southern Africa, which is poorly developed in this central area although in both the north and south it is a definite topographic feature.

The desert slopes about 7.6 meters per kilometer from the highlands at an altitude of 1200 meters to sea level at the coast. The 100 meter contour line is usually within 10 kilometers of the coast, and the 100 mm isohyet is located parallel and very close to the inland edge of the desert and the remains of the Great Escarpment.

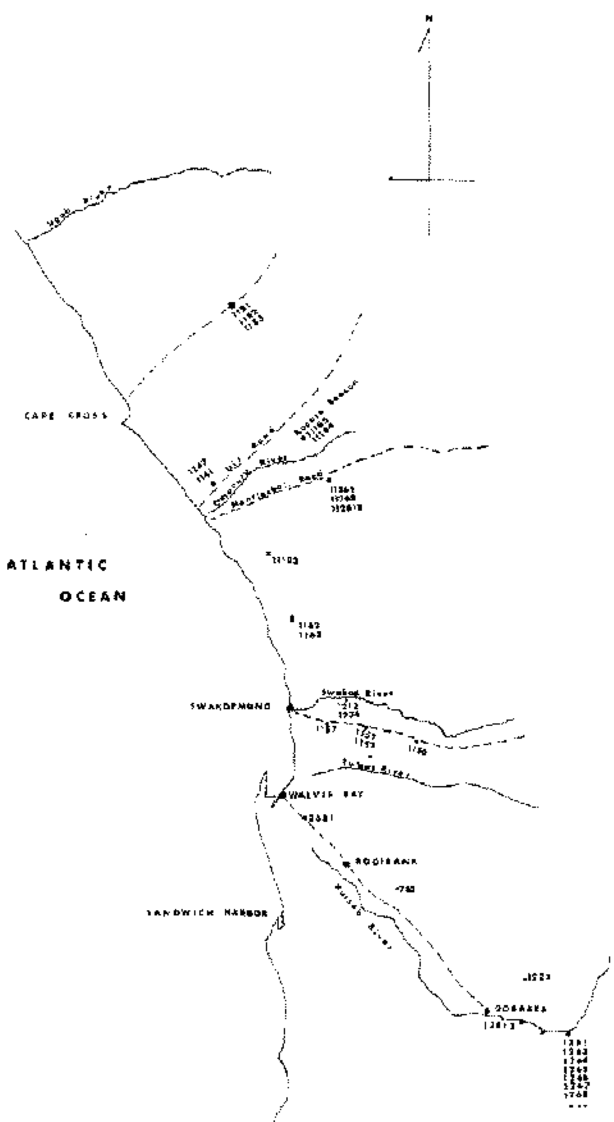

Figure 1. Index map of the Namid Desert, South West Africa.

GEOLOGIC SETTING

The stratigraphic sequence of rock underlying the desert represents an extensive time interval. The oldest rocks cropping out in this area are the eugeosynclinal sediments of the Damara System which is 450 to 550 million years old (Clifford, 1967). They are overlain by the Karroo sediments of Early Permian age and lavas and dolerite dykes of the Early Cretaceous.

The major rock type underlying the gypsum deposits is the Khomas Schist. The rock is predominantly a quartz biotite schist with minor amounts of scapolite, feldspar, cordierite and calcite. The marbles of the Hakos Series form extensive ridges in the desert which are very prominent in the Gemini photograph of the area. These Precambrian marble ridges show little evidence of chemical weathering as would be expected in an arid climate. Intrusive granites and granite pegmatites with extensive white quartz veins are prevalent and often form inselbergs.

The Damara represents the last major orogeny in this area. Extensive post-Damara peneplanation occurred before deposition of the Karroo sediments. Remnants of these deposits are found in the areas surrounding the Brandberg Mountains where they were preserved by the intruding granites. This bed is the only one known to contain some gypsum interlayered with the shales of the Dwyka Tillite. There is a remnant of the shale with interbedded gypsum near Brandberg West. Near Cape Cross there are questionable Dwyka Tillite remains in a depression in the schist and covered with Pleistocene sediments. The Karroo sediments were covered with extensive lava flows (Kaoko lavas) in the Early Cretaceous (Siedner, 1968).

Extensive erosion and possible rejuvenation occurred during the Cretaceous and Tertiary. In the south, located in the diamond fields, there is some evidence of Upper Cretaceous-Lower Tertiary marine sediments on the coast, but these extend only a short distance inland. The only evidence for marine deposition in the central part of the desert is the terraces at 24 and 12 meters above sea level near Cape Cross. The upper terrace fauna contains representatives of the warmer waters of the southern coast of Africa (ex. *Ostrea prismatica*) whereas the lower terrace and the lagoons contain a fauna transitional between the earlier warmer and present day colder waters. This change from warm to cold waters has been attributed to the introduction of the Beneguela Current to this coast which probably changed the climatic conditions in the central area of the desert. The youngest sediments are the weathering products and gravels that contain the gypsum and anhydrite deposits which will be described in detail in the next section.

From the known geological section the following points are of importance to the origin of the evaporite deposits:

(1) There is no evidence for a marine source for these deposits later than Early Permian.

(2) There is no evidence of Tertiary-Recent marine transgressions which might have contributed oceanic salts to the formation of the evaporites.

(3) There is evidence of long periods of weathering and denudation by mass wasting.

(4) There is evidence of prior more extensive dune coverage in the central desert which is indicative of a more arid climate.

Table 1. Section of the coastal sediments north of Cape Cross.

Lithology	Thickness in cm
sand and weathered gypsum	42
angular dolerite, lava, massive gypsum	128
fine yellow sand	25
well rounded qtz. pebble cgl.	18
grey sand layer	8
well rounded qtz. pebble cgl.	12
greyish yellow crossbedded sand with gypsum roses and fossil coral	25
quartz pebble cgl.	7
grey sand with gypsum crystals	8
chert and qtz. pebble cgl.	19
unconsolidated yellow sand	10
consolidated gypsum and calcrete with *Ostrea Prismatica*	15
unconsolidated yellow sand with layers of gypsum	11
consolidated yellow sand with gypsum stringers	16
well indurated calcrete with some silcrete	16
Total thickness	360

(5) The Beneguela Current caused an alteration in the climate to the present cool, arid condition. The removal of the sands and the cutting of the major rivers probably occurred during a wetter period prior to the establishment of the climatic modification produced by the shift in the Beneguela Current (Late Pliocene to Middle Pleistocene).

DISTRIBUTION OF THE GYPSUM

The gypsum deposits are located throughout the desert area from the Ugab to the Kuiseb Rivers. Inland they are replaced by a hard laminated layer of calcrete and occur interbedded with the desert sediments, on the tops of the dolerite dykes and in the shallow depressions between terraces. The deposit may best be described as a blanket overlying the surficial sediments from the coast inland. A typical section of the coastal surficial deposits can be seen in Table 1. There are reports from borehole records at the Geological Survey in Windhoek that the gypsum continues under the dunes to the south and reappears at the coast, but these occurrences are within the diamond areas to which access is forbidden.

The gravels of the desert are found in the coastal terraces and near the major rivers. The areas between the major rivers and away from the coastal terraces contain gypsum also.

The surface is composed of massive calcrete and gypsum underlain by indurated gypsum layers with varying amounts of sand. In two areas there are well defined halite layers below the indurated gypsum. A layer of barren gravel or weathered schist or granite rests upon the basement rock.

The sediments, excluding the evaporites, appear to have been formed through the weathering of the underlying bedrock rather than through fluvial action or beach deposition as in the gravels and coastal deposits.

The section from the coast inland changes much more radically than the north-south section of the Namib Desert. Immediately behind the terraces, approximately 150 meters above sea level, the gravels disappear, and the sections are composed of weathering remnants of the underlying rock. The section near the coast is predominantly gypsum with some halite and sodium sulfate in the surface material. As the distance inland increases, the amount of calcrete increases, and the gypsum layers are found below a more evident calcrete layer. Two sections illustrate this change. The section at Hugel Beacon located 1.6 kilometers inland on top of a dolerite dyke includes:

Thickness in cm	Lithology
0-5	Hammada desert surface containing large cobbles of the underlying dolerite
5-30	weathering residue with disseminated gypsum
30	gypsum layer immediately above massive dolerite.

The amount of calcrete increases and the amount of gypsum decreases inland. At approximately 82 kilometers inland, the following section is typical:

Thickness in cm	Lithology
0-1	powdery calcrete layer or indurated calcrete
1-3	indurated gypsum layer
3-63	disseminated gypsum and sand.

Approximately 105 kilometers inland, the gypsum disappears completely, and the calcrete becomes indurated with the formation of laminations in the surface due to alternating solution and precipitation as a result of the higher rainfall of the area. These deposits in which the gypsum is absent lie 750 meters above sea level. In this area the grasses which require a greater amount of rainfall become prevalent, and the area becomes a semi-arid zone.

The coastal-inland sequence of gypsum-calcrete occurs throughout the central area of the desert from the Ugab to the Kuiseb River.

Throughout the Central Namib, it is evident that the gypsum deposits disappear at an altitude of 750 meters above sea level and a distance inland of from 100 to 120 kilometers.

The main conclusions drawn from the gypsum distribution of the Namib Desert are as follows:

(1) The deposition of the gypsum is independent of the composition of the underlying bedrock, and the medium of precipitation must reflect this independence.

(2) The distribution of the deposits appear to have climate as one of the controlling variables.

ANHYDRITE DEPOSITS

The majority of the deposits examined consisted of gypsum and other more soluble salts. However, two of the areas examined contained anhydrite. One of the areas contained anhydrite with halite and a more complex salt, whereas the other area included layers of gypsum and anhydrite.

The first of these deposits containing anhydrite is located near the Kuiseb Canyon south of Gobabeb Research Station on the road to Natab (See section 1264-1267 on map). The deposit is located 82 kilometers inland and at an elevation of 600 meters. The deposit is composed of a 70 cm section of anhydrite and fragments of weathered schist. The basement rock is a quartz biotite schist disrupted by salt crystallization. The size and abundance of the coherent schist fragments decreases upwards through the section. The deposit is overlain by a 10 cm layer composed predominantly of small quartz pebbles. The amount of anhydrite remains constant upward to a point about 60 cm below the surface and then begins to decrease towards the surface. The surface layer is brown and appears weathered, and there is some gypsum present. Most of the anhydrite appears to have been formed in situ. Halite and an unidentified complex salt occur intermixed with the anhydrite. Thin sections of the sediments show some biotite, plagioclase feldspars, tourmaline and quartz. The outlines of the biotite flakes are sharp, and there appears to be little decomposition by chemical weathering.

The second anhydrite exposure consists of a large stream cut near Brandberg West (See sample

1182) and is composed of calcareous shales at the base with a cover of alluvial gravels. The gravels are cemented with massive gypsum and small amounts of halite. The anhydrite occurs as a massive layer overlying a crystalline layer of gypsum which is deposited around the upper surface of a cobble. The gypsum crystals are oriented perpendicular to the surface of the cobble, and the anhydrite forms as a fine-crystalline, white mass about 10 cm thick on top of the gypsum layer. The anhydrite identification was confirmed by X-ray patterns and petrographic analysis.

COASTAL LAGOONAL AND TERRACE DEPOSITS

The coastline of the Namib Desert is dotted with lagoons which have formed either through the deposition of sands by the northward flowing Beneguela Current or in depressions in the schist which were formed in previous weathering cycles. Both mechanisms are instrumental in the formation of the pans and lagoons. The only prominent bay along the coastline (Walvis Bay) is formed by the northward extension of a large sand spit. Meigs (1966) attributes the lack of harbors to the absence of coastal mountains and the nonsubsidence of the coastline.

Generally the lagoons are shallow and contain a fauna that indicates that the formation of the lagoons is synchronous with the arrival of the present cold waters of the Beneguela Current. The fauna is either transitional between cold and warm water fauna or it is representative of the modern cold water assemblage.

The largest pan on the coast is Cape Cross with is 15 kilometers long and 1 to 2 kilometers wide. A salt industry is located here.

Halite found in the area of Cape Cross is pink at the surface of the pan and becomes green and then purple within 30 cm of the surface. The brine intersects the salt at 30 cm and has a definite hydrogen sulfide odor. Tasch (1963) mentions the pink color in evaporating pans in western Peru, and this coloration has been attributed to red algae by Tasch and various other authors. Tasch also reports that both red and green algae are found in the Peru salts. Either the decomposition of the algae, different species of algae or the Eh and pH changes due to the more reducing environment at depth is responsible for the change in color.

There are areas of the pan where surface gypsum deposits have been reported (Gevers, 1931); however, this investigator could find no extensive gypsum crusts in the surface of the pan. There is a good possibility that gypsum is forming in th southern part of the lagoon, however, guano col lecting activities prevented work in this area. Th salts, however, do contain small crystals of gypsun throughout the first 30 cm of the pan.

The pan contains over 7,000,000 tons of sal (Gevers, 1931), and the surface layers are underlai by a brine from which salt might also be recovered There are extensive dark clay beds in the lagoon which are composed predominantly of illite.

The coastal salts are deposited at a rate of 17 t 18 cm per year in the evaporation pans (Gevers 1931). In the inland pans that are fed by under ground continental waters the evaporation rate i somewhat higher, approximately 20 cm per yea (Roper). The inland pans are from 5 to 20 kilo meters inland, and the increase in evaporation rat reflects the decrease in relative humidity inlan and an increase in temperature. The inland pans ar groundwater fed from springs which are controlle by the dolerite dykes surrounding the pan. Th waters are highly saline (see groundwater sectior Sample A 11-4-9) and contain 32,000 ppm NO_3 They deposit gypsum near the orifice of th springs.

Numerous authors have discussed the origin c the lagoonal salts. Kaiser *et. al.*, (1932) conclude that the major source of the salts was the grounc water of the interior, whereas Gevers (1931 thought the marine sources were predominan Both sources are undoubtedly represented in th pans.

The terraces behind Cape Cross have recentl been investigated for diamonds. The oyster, *Ostre prismatica* has been found in the terraces, and th fossil is the "guide fossil" to the southern diamon fields. Investigation of this area disclosed two te races, one at 9.1 meters and the other at 21. meters above sea level. The lower terrace contains fauna related to the modern colder waters of th Beneguela Current while the upper terrace contair *Ostrea prismatica* which is associated with th warmer waters of the southern coast. This warr water fauna has been found in several places alon the coast and has been interpreted as indicating th absence of the displacement offshore of th Beneguela Current in the Plio-Pleistocene.

SULFUR ISOTOPES

Selected samples were taken from various are and forwarded to Dr. H.R. Krouse of the Unive sity of Alberta for sulfur isotope analysis. The fo lowing results are preliminary. The values found d not allow one to ascribe a definite origin to th gypsum or anhydrite, but it may be said that the similarity of the ratios from samples taken from coastal and inland localities indicates that the gypsum was derived from a common source. It is particularly interesting that the sample taken from Fishery Beacon which is a beach terrace has a similar sulfur ratio to gypsum and anhydrite samples further inland.

The S^{34} values have an average ratio of 16.1 which differs significantly from the value for modern sea water which is close to 20.

THE ORIGIN OF THE DEPOSITS

Pedogenic processes have been given as the main processes by which the layers of calcrete and gypsum are formed in arid and semiarid zones. Formation by this method requires the presence of water as a solvent as does precipitation from ground water. However, these two methods will be discussed separately due to the differences in the transport distance and the source of the sulfates. Soil formation and groundwater formation are intimately related through the process of weathering. Soil is formed, soluble salts are leached by groundwater and then reprecipitated near the surface. However, the pedogenic process assumes that the salts are weathered in the A horizon and deposited in the B or C horizon depending upon the amount of water available for transport. Thus this process requires an arid or semiarid climate because a more abundant water source would remove the soluble salts.

The processes of calcification and gypsification are the predominant pedogenic processes in deserts of the world. These desert soils are classified in the Order Aridsoils and are formed with the calcrete layer on the surface and the gypsum layer below. The layers are assumed to have formed by the downward movement of waters from the weathered zone into the lower horizons. The waters are then evaporated leaving the soluble salts behind. These layers vary in depth below the surface.

Halomorphic soils or those that contain salts more soluble than gypsum are attributed to formation by irrigation waters and or groundwaters which contain high concentrations of soluble salts. These soils may contain $NaCl$, $CaCl_2$, $MgCl_2$, $MgSO_4$, $Na_2SO_4 \cdot 10H_2O$, $NaNO_3$, KNO_3, Na_2CO_3, $NaHCO_3$ and some borate compounds. These salts may form in layers below the gypsum and calcrete or they may appear on the surface depending upon the conditions of precipitation. An excellent example of the complexity of layers that may form is found in the nitrate deposits of Chile where the nitrates occur below layers of calcrete, gypsum and halite. The major nitrate deposits are found on the slopes of the playas and not in the playas themselves (Rich, 1942). Any nitrates that occur in the playas are found on the surface.

These desert soils are considered to require a long period for formation when compared with the formation of soils in humid areas. The low rate of weathering is due primarily to the absence of plant life which in turn means a low P_{CO_2} in the soils. The weathering of silicates requires carbonic or some other acid for the hydrolysis reaction. The very low CO_2 in desert soils which is derived solely from the atmosphere is insufficient for buffering of the solution to occur, and the alkalies which are released during the weathering of feldspars quickly alter the pH to alkaline, thus greatly reducing the hydrogen ion content and slowing the rate of hydrolysis. Hutchinson (1957) states that under a partial pressure of carbon dioxide of 0.0003 atmospheres the concentration of ionic calcium is not likely to be greater than 10^{-3}. This sets the upper sulfate limit before the formation of precipitate as 0.1 to 0.2 M. This concentration only occurs in very saline waters.

The formation of the gypsum layers solely by pedogenic processes would require a more humid climate than exists presently for the development of the necessary plant life which would provide soil carbon dioxide for the chemical decomposition of the amount of rock required to precipitate the gypsum present. There is some evidence for the presence of wetter climates in the Namib Desert in the past, but there is no evidence that this climatic change was significant. The amount of sulfate required for deposition of gypsum by the pedogenic process in the parent rocks is also very large. There have been no measurements made on the amount of carbon dioxide required to cause significant weathering of calcium containing minerals. Such a measurement would be very valuable in the determination of the type of climate required for the deposition of calcrete and gypcrete layers through pedogenic processes alone.

Since it is doubtful that the deposits are related to the Lower Permian Dwyka, another source for the gypsum must be found.

Such extensive deposits of gypsum in the Namib Desert requires a transport system capable of concentrating large amounts of sulfate. There is no evidence of aeolian transport of salts and no inland source from which the wind could derive the salts.

With the elimination of aeolian transport, derivation from sea water or from groundwater from the highlands appears to be the most logical explanation for gypsum concentration.

There is no evidence of marine transgression since the Permian, and Martin (1963) consequently proposed that the sea mist which contains sea salts produced the deposits. Large amounts of hydrogen sulfide are produced in the upwelling waters of the Beneguela Current, and he hypothesized that the mist would be carried inland, the hydrogen sulfide reacting with the calcrete already present to form gypsum. While there is no question that large amounts of sulfide are produced off the coast, there are several facts which discount this mechanism as the major process of sulfate concentration:

(1) There are large amounts of calcium carbonate in the coastal dunes over which the sea mists constantly blow.

(2) There is calcium carbonate overlying the gypsum in parts of the coastal area.

(3) The mist is considered to extend inland for 55 to 60 kilometers. The gypsum extends inland for 105 kilometers, and inland is overlain with a layer of indurated calcrete.

(4) In the movement of the sea mist inland, the first salt to be formed through evaporation will be gypsum and then the chlorine salts. One would expect that the gypsum would be deposited near the coast and the halite further inland. However Hutchinson (1957) states that the gypsum forms stable aerosols which are nonhydroscopic. The chlorine acts as a condensation nuclei and is washed out of the air by rainfall. Therefore the inland air will become enriched in sulfates. This is not the case with the fog which condenses in the desert at night and evaporates during the day. Therefore one would expect both gypsum and halite in areas covered by the fog. This association is found within several miles of the coast, but not in the inland sediments.

(5) The hydrogen sulfide rapidly oxidizes in the atmosphere and forms SO_2 which slowly forms sulfuric acid. The acid reacts with the calcium present in the droplet and forms gypsum. The pH of the Namib mist is between 7 and 8 and does not reflect the presence of any acidic component.

GROUNDWATER

Groundwater in the Namib Desert, as in other deserts throughout the world, increases in total dissolved solids from the highlands or more temperate zones to the more arid zones. The most common waters found in semi-arid and arid climates contain Na^+, CO_3^-, SO_4^-, and Cl^- ions necessary for the deposition of all the salts found in the deserts today. The Namib Desert is unusual in the respect that there is no evidence of a prior evaporite source for the salts as there are in many other arid areas.

Analyses of the waters present in the Namib Desert are shown in Tables 2 and 3. All the samples except A 11-4-9 were analyzed by the Water Affairs Branch, Windhoek, South West Africa, and A 11-4-9 was analyzed by the United States Geological Survey Water Quality Branch in Albuquerque, New Mexico.

Sample A 11-4-9 is taken from an inland pan north of Henties Bay. Halite is collected from these pans about every three years. The source of the solutions in the pans is underground flow which comes to the surface at this point due to the disrupting of the strata by the surrounding dolerite dykes. Logan (1960) cites the presence of other saline water sources in the desert. Middle Tinkas is a major waterhole of the Namib and consists of a poor seep of water in a stream channel. This hole is 100 kilometers from Swakopmund on the coast. The water here is slightly saline but potable. However, the water in the Grosser Tinkas, four-tenths of a kilometer north is more saline but also potable. Grosser Ubib, a waterhole 72 kilometers east, southeast of Walvis Bay is more saline and deposits of salt are evident around the orifice of the spring.

Groundwaters obtain their salts by two major mechanisms, weathering in the humid and arid zones and the slow changes in chemical composition that occur through long transport and residence. Soluble salt addition to groundwater, while involving the same chemical principles, differs greatly between the humid and arid zones because of variations in chemical decomposition and leaching rates. In the humid zone chemical decomposition occurs in the upper layers of the soil, and the soluble salts are leached out of the upper zones and into the water table. In comparison, the less the amount and frequency of rainfall, the more concentrated the soluble salts become in the upper layers of the soil. This is due to the inability of the available waters to leach the soluble salts out of the soil layers before evaporation reclaims the water. In the rare instance of a heavy rain, the accumulated salts are added to the groundwater. The magnitude of this addition to the groundwaters is suppressed by the lack of CO_2 and the amount of sulfate and more soluble salts in the surface sediments.

The second mechanism concerns the addition of meteoritic waters to the groundwaters in the high-

Table 2. Analysis of well and surface water samples from the Namib Desert (in ppm).

Number	C2373	C2374	C3618	C3617	C1643	C2785	C2372	C2729
total dissolved solids	330	280	9410	9200	2532	3608	305	140
Na	28	22	1830	1410	320	560	23	15
K	8.6	9.0	80	76	8.4	49	7.6	9.6
sulfates	20	15	1140	1070	253	525	19	12.6
Nitrate	tr	—	166	234	68	39.4	2.0	2.8
Nitrite	—	—	0.5	0.3	0.3	1.03	—	tr
Silica	7.5	—	50	50	25	15	10	10
Flouride	0.3	0.3	4.0	2.4	1.5	2.9	0.3	0.04
Chloride	25	15	3900	3800	845	1460	20	25
Total Alkalinity	250	220	615	335	325	195	210	58
Total Hardness	245	205	3600	4420	1340	1640	220	72
Calcium hardness	135	145	1451	2195	949	755	130	60
Mg-hardness	110	60	2149	2225	391	885	90	12
pH	7.2	7.7	6.9	6.8	7.4	7.1	7.3	7.5
sample location	borehole Farm Spes Bona	borehole Farm Spes Bona	borehole Farm Swartberg	borehole Farm Swartberg	borehole Achab	mine Farm Swartberg	borehole Farm Spes Bona	well Farm Tsaobis

Table 3. Analysis sample A 11-4-9 from the inland salt pans north of Hentisbay and 32 kilometers inland (in ppm).

Silica	46
Calcium	27,500
Magnesium	15,900
Sodium	75,200
Potassium	8,000
Iron	0.22
bicarbonate	340
carbonate	100
sulfate	568
Chloride	200,000
Fluoride	55
Nitrate	22,500
Boron	157
TDS	350,000
pH	8.4

lands and their slow movement toward the desert. These waters will be continuously modified in the passage through the various rock types of the highlands and the Namib Desert. These rocks are principly the Khomas Schist and the various granites, pegmatites and dolerites of the desert. The chemical processes involved are oxidation-reduction, base exchange concentration and precipitation.

The oxygenated zone in rocks is often restricted to contact with the atmosphere, and waters may become reducing below the contact with the atmosphere. Nitrites in the South West African waters indicate that reducing conditions exist. These conditions or the presence of aneorbic bacteria may produce the H_2S which was described by Martin (1963) inland from the coast.

The mechanism of base exchange is very important in that the composition of the groundwaters may be completely altered by this mechanism during a long residence in the subsurface. Base exchange is a cation exchange between a substrate and a solution. The degree of exchange depends upon the valence and hydration number of the ion. The relative amount of ions adsorbed, since this is a reversible reaction, depends upon the concentration of the ion in solution, and the reaction may approach equilibrium over long periods of time. The reactions may significantly alter the cation ratios in water and the following ratios in particular. K/Na, Na/Ca, Na/Mg and Mg/Ca (Schoeller, 1959). This mechanism may have some effect in decreasing the amount of NaCl available for deposition in inland basins and increasing the amount of calcium thus bringing the Na/Ca ratios closer to one.

Mineralized waters upon entering the arid zone begin to concentrate by evaporation. Gypsum may be precipitated due to its decrease in solubility in concentrated sodium chloride solutions. Evaporation apparently can occur to great depths in deserts through the movement of gases and capillary waters upward to the surface. Schoeller (1959) and others mention that through the above mechanism the waters may obtain the same composition as sea water without a connate sea water source or saliferous beds, i.e., Cl > SO_4 > CO_3 and Na > Mg > Ca.

The section through the Namib Desert correlates well with the diagram showing the relationship between composition of groundwater precipitates and climate given by Borchert and Muir (1964, p. 180). The lack of a marine precursor for these deposits and the presence of these saline waters in the deserts of the world suggest that the mechanism proposed by Schoeller (1959) for the formation of waters with the composition of sea water is applicable to the deposition of the salts in the Namib. The peculiar situation in the Namib where there is no precursor source for the chlorine presents the problem of the source of the chlorine. The Khomas Schist contains Cl and F combined in amounts of 0.12 to 0.47 per cent and SO_3 in amounts of 0.27 per cent (Clifford, 1967) which is significant when the amount of time available for the interactions between soil formation and groundwater equilibration are studied. This investigator could find no other source for the salts in these deposits other than an extensive combination of weathering and groundwater formation and their evaporation in the desert.

There is still a major problem in the determination of the age of the surficial desert deposits due to the lack of datable materials. However, there is extensive evidence that suggests that this area has been arid or at least semi-arid for a long period of time.

CONCLUSION

From the prior evidence it appears that the formation of these deposits are primarily connected with the concentration and evaporation of meteoritic waters which have derived their mineral salts through the slow chemical interactions over a long period of time with the Precambrian Khomas Schist. There are also minor contributions to these waters from pedogenic processes in the desert and near the coast by the precipitation from the sea mist. The groundwaters in passing from the highlands to the desert assume a higher salinity as suggested by the analysis of desert waters. These waters upon evaporation in the arid zone produced the gypsum deposits.

Further work with oxygen isotopes and the offshore sediments should clarify the actual mechanisms and their respective contributions to the formation of these deposits.

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