Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **26**, 1177–1193 (2001)
DOI: 10.1002/esp.264

THE ROLE OF PLAYAS IN PEDOGENIC GYPSUM CRUST FORMATION IN THE CENTRAL NAMIB DESERT: A THEORETICAL MODEL

F. D. ECKARDT,[1]* N. DRAKE,[2] A. S. GOUDIE,[3] K. WHITE[4] AND H. VILES[3]

[1] *Department of Environmental Science University of Botswana, Private Bag 0022, Gaborone, Botswana*
[2] *Department of Geography, Kings College London, University of London, London WC2R 2LS, UK*
[3] *School of Geography, University of Oxford Mansfield Road, Oxford OX1 3TB, UK*
[4] *Department of Geography, University of Reading Whiteknights, Reading RG6 6AB, UK*

Received 1 June 2000; Revised 27 November 2000; Accepted 7 February 2001

ABSTRACT

The formation of Namibia's extensive pedogenic gypsum crusts ($CaSO_4 \cdot 2H_2O$) is interpreted in a new light. It is suggested that gypsum primarily precipitates at isolated points of evaporitic concentration, such as inland playas, and that deflation of evaporitic-rich gypsum dust from these playas contributes to the formation of pedogenic gypsum duricrusts on the coastal gravel plains of the Namib Desert surrounding these playas. This study establishes the nature, extent and distribution of playas in the Central Namib Desert and provides evidence for playa gypsum deflation and gravel plain deposition. Remote sensing shows the distribution of playas, captures ongoing deflation and provides evidence of gypsum deflation. It is proposed that, following primary marine aerosol deposition, both inland playas and coastal sabkhas generate gypsum which through the process of playa deflation and gravel plain redeposition contributes to the extensive pedogenic crusts found in the Namib Desert region. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: gypsum; playas; sabkhas; Namib Desert; mineral dust

INTRODUCTION

Namibia's pedogenic gypsum accumulation cement covers more than 30 000 km^2 of desert colluvium making it one of the most extensive gypsum duricrust deposits known. It is contained underneath the regolith-covered stone pavement of the Central Namib Desert (Figure 1A) and despite being one of the most described gypsum accumulations (Gevers and Van der Westhuyzen, 1931; Martin, 1963; Scholz, 1963, 1972; Besler, 1972; Goudie, 1972; Rust, 1979; Wieneke and Rust, 1973; Cagle, 1975; Carlisle, 1978; Watson, 1979, 1980, 1982, 1983, 1985, 1988; Wilkinson 1990; Wilkinson *et al.*, 1992; Heine and Walter, 1996) its exact mode of formation is still uncertain.

Gypsum ($CaSO_4 \cdot 2H_2O$) is an evaporite which forms through the accumulation of calcium, sulphate and evaporation of water. As sulphur is the limiting element, the creation of gypsum is strongly coupled to the biogeochemical sulphur cycle. Sulphur is widely distributed in the lithosphere, biosphere, hydrosphere and atmosphere and subject to ongoing transfer. Potential gypsum sulphur sources can either be local, in the form of bedrock material and marine water, or distant in the form of atmospheric aerosols. Aerosols can be derived from organic and inorganic compounds of terrestrial or marine origin. Gypsum forms primarily with the *per ascensum* or *per descensum* movement of groundwater or the remobilization of previously deposited gypsum and subsequent lateral redistribution by wind and water (Watson, 1988). *Per ascensum* formation implies an upward formation of gypsum in a soil or playa section, largely due to the evaporation of groundwater. *Per descensum* formation on the other hand occurs when the movement and formation of gypsum is overall in a downward direction. This process is driven by wet and

---

* Correspondence to: F. D. Eckardt, Department of Environmental Science, University of Botswana, Private Bag 0022, Gaborone, Botswana. E-mail: eckardt@mopipi.ub.bw

Contract/grant sponsor: NERC (Natural Environment Research Council); Contract/grant number: GT4/92/18/G.
Contract/grant sponsor: Trapnell Fund for Environmental Research in Southern Africa, University of Oxford.

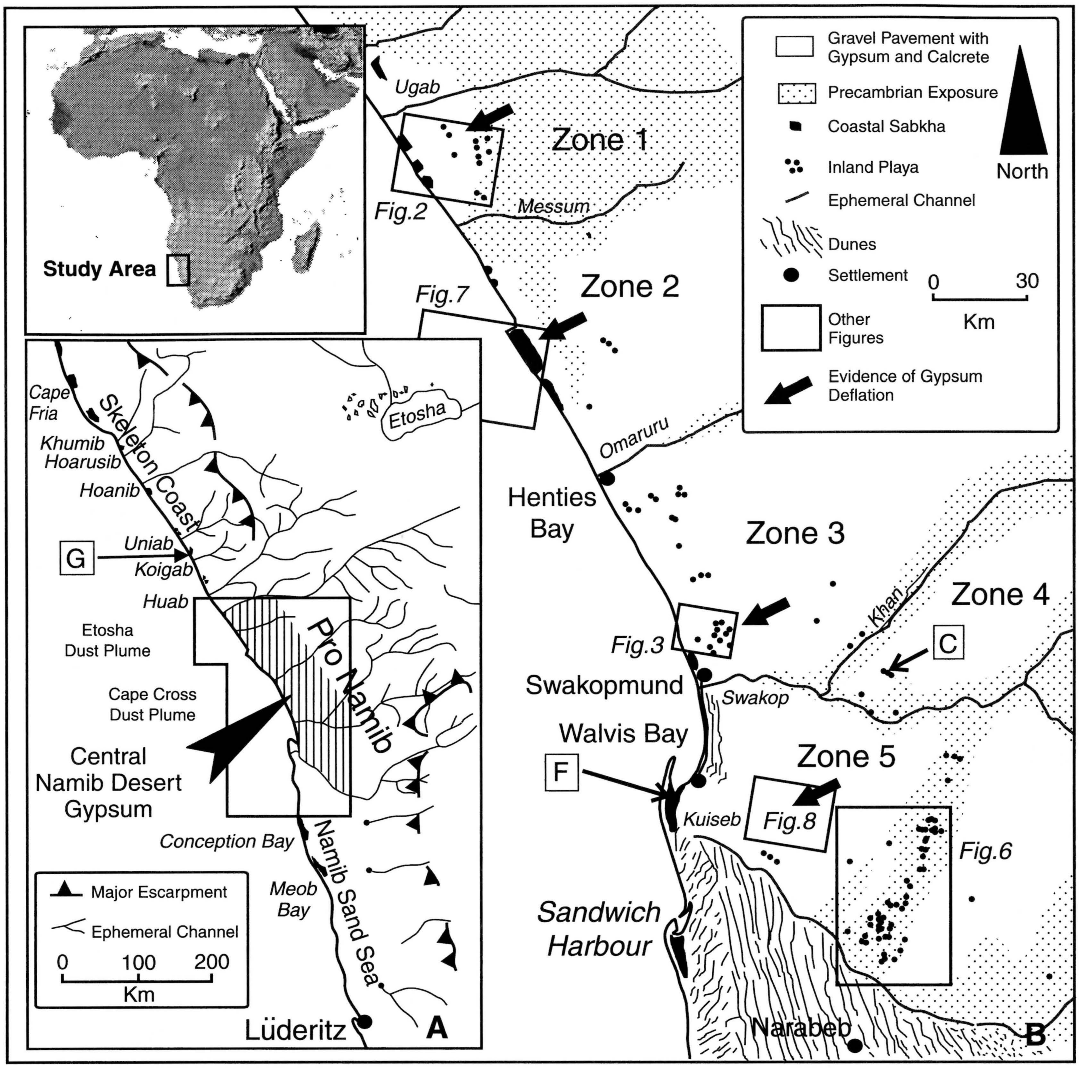

Figure 1. (A) Location of the narrow coastal Namib Desert. The Central Namib Region is home to an extensive pedogenic gypsum accumulation and a series of inland playas (B). For the purpose of this study the area is divided into zones which are determined by ephemeral highland drainage. Locations of other figures are shown. Locations of sections in Figure 5: C, Welwitschia Flats; F, Walvis Bay; G, Torra Bay

dry atmospheric surface deposition of calcium, sulphate or gypsum which is gradually introduced into the soil during sporadic high magnitude rains. Such a process favours the formation of pedogenic evaporites in particular if groundwater is at considerable depth or largely absent preventing a *per ascensum* formation. Pedogenic gypsum forms a crust also known as gypcrete which causes a consolidation and hardening of the soil. Hydromorphic gypsum on the other hand precipitates in host sediments during the evaporation of groundwater which is largely taking place in moist, salt-covered, sediment-filled depressions also known as pans which from now on are referred to as playas. When necessary we distinguish between inland playas and coastal sabkhas which are coastal saltflats. None of the playas or sabkhas are known to have been flooded during the period of this study but some feature permanent standing pools of water which we describe as springs. Namib Desert playas in general form in drainage channels whose surface and groundwater flow is obstructed by linear bedrock outcrops, in particular dolerite dykes. The origin of sabkhas is uncertain.

Previously the Namibian pedogenic gypcretes were considered to have formed by a three-stage model developed by Martin (1963). Firstly, it considers a marine atmospheric H_2S origin for sulphur. This is followed by an advective marine fog pathway for sulphur transport into the terrestrial environment. Finally authigenic formation of pedogenic gypsum occurs in the Tertiary gravel plain by a reaction of the sulphur fog with calcium carbonate in the form of calcrete deposits in the soil. This model has been widely endorsed (Besler, 1972; Goudie, 1972; Scholz, 1972; Carlisle, 1978; Watson, 1982, 1988; Wilkinson *et al.*, 1992; Day, 1993; Heine and Walter, 1996).

However, recent stable isotopic work by Eckardt and Spiro (1999) on the sulphate found in the pedogenic gypsum does not support this theory. It suggests that sulphur is largely derived from primary marine production of dimethylsulphide DMS, (CH_3SCH_3) in the cold water upwelling cells of the Atlantic. This has also been supported by ^{17}O evidence for the same deposit (Bao *et al.*, 2000). Furthermore it has also been demonstrated that the originally proposed fog is extremely low in ionic content (Eckardt and Schemenauer, 1998) and therefore an unlikely pathway of sulphur. Data on the dry atmospheric chemistry, however, suggest that both marine and terrestrial sulphate in the form of atmospheric dust (Annegarn *et al.*, 1983; Eckardt and Schemenauer 1998) is present. Determining the exact source of the aeolian sulphate, in particular the terrestrial component, is at the core of this study as it could promote the formation of the pedogenic crusts outlined above.

To date, studies in the Namib Desert have focused largely on the description and chemistry of these pedogenic gypsum crusts in the colluvium soils of the gravel plains. The exception is mining-related work, concerned with a few sabkhas and playas. The relationship between the vast pedogenic gypcrete accumulations and the pockets of hydromorphic playa gypsum has never been investigated. The aim of this research is to examine this relationship. Reworking of hydromorphic gypsum by deflation from playa surfaces and its subsequent consolidation into a pedogenic gypsum crust is a likely process, as has been demonstrated in the deserts of North Africa (Coque, 1962; Drake 1997), Australia (Chen *et al.*, 1991) the Americas (Reheis, 1987) and other parts of the world (Watson, 1979).

STUDY AREA

For the purpose of this study the Central Namib Desert is defined as the coastal desert between the Kuiseb and Ugab Rivers (Figure 1B) as it is in this region that gypsum crusts are predominantly found within an extensive Tertiary colluvium. The colluvium can attain more than 50 m in thickness and is generally underlain by the metamorphic rocks of the Damara Orogen. The eastern limit of the study area is constrained by bedrock exposures ranging from granitic outcrops, volcanics and in particular the mica-rich schists of the highland which forms part of the great southern African escarpment. These regions are devoid of gypsum as are the Namib Sand Sea to the south of the Kuiseb River (Figure 1A) and much of the remaining coastline, as dunes and bedrock are unsuitable for the formation of evaporites.

The environment and geomorphology of the Namib Desert have been described previously (Meigs 1969; Logan 1969). Rainfall gradually decreases from the semi-arid environment found in the highlands (250 mm), towards the Pro Namib Desert (70 mm) and on to the hyper-arid coast which receives less than 20 mm of rainfall per annum. Gypsum crusts generally can extend into regions where rainfall exceeds approximately 200–300 mm per annum (Watson, 1988). In Namibia, however, gypsum is not found outside the 50 mm rainfall isohyet. The eastern limit of the coast-parallel deposit is found about 50–70 km from the coast at an elevation of 400–500 m, well within the threshold imposed by the present-day rainfall. The Central Namib Desert is considered to have been hyper-arid for at least the last 5 million years (Ward *et al.*, 1983).

The gravel plain which hosts the gypcrete exhibits an extensive but subdued and poorly developed drainage system. The headwaters of the larger river networks in this system originate in the Pro Namib Desert (Figure 1A). Thus, as well as controlling the flow of surface water and groundwater produced by the infrequent rainfall events in the region, the channels in particular provide conduits for water flow from the more frequent rains in the Pro Namib into the Namib Desert proper. The gravel plain is deeply incised by the larger ephemeral river courses of the Kuiseb, Swakop, Khan, Omaruru, Messum and Ugab rivers which usually form canyons that are poorly coupled with the gravel plain drainage and are fed by more frequent flows from their headwaters in the highland (Figure 1A). These channels and canyons dissect the gypsum-rich colluvium and incise the underlying bedrock.

The colluvium-rich pedogenic gypsum of the region consist of mesocrystalline, lenticular and prismatic crystals that are commonly accompanied by fibrous gypsum and lenses of microcrystalline alabastrine gypsum (Watson, 1988). The bulk of this gypsum is stored in the upper horizons of the colluvium, cementing angular clasts and finer material that form the building blocks of the Namib Desert crusts which, judging by the few exposures, may be up to 5 m thick. A vertical segregation of carbonates, sulphates and chlorides into individual soil horizons is evident in some regions (Gevers and Van der Westhuyzen, 1931). Gypsum is concentrated at the surface but is covered by a thin lag of silt, sand and gravel. For a detailed study on variability of sections refer to Heine and Walter (1996). Localized exhumation and weathering of pedogenic meso- and macrocrystalline gypsum deposits generates microcrystalline powdery, columnar and cobble-like gypsum. Exposed gypcretes of considerable thickness may portray columnar structures, which generate hexagonal surface patterns.

While there has been no systematic survey of playas in the Central Namib Desert, a few playas have been studied in the context of brine extraction (in particular near Henties Bay and Swakopmund) and have been shown to contain gypsum, as have a number of gypsiferous springs reported by Day (1993). Coast-parallel sabkhas stretch from Angola into South Africa (Schneider and Genis, 1992). Between Meob Bay (180 km south of Walvis Bay) and Cape Fria (Figure 1A) more than 20 sabkhas have been identified with a cumulative area of at least 300 km^2. These sabkhas contain significant amounts of hydromorphic surface gypsum and halite.

While some gypsiferous playas and sabkhas have been reported in the vicinity of the gypsum crusts, a review of the literature suggests that playas in other parts of Namibia which have been studied much more extensively are gypsum-poor (Forshag, 1933; Teller and Last, 1990; Schneider and Genis, 1992), possibly due to the higher rainfall levels outside the Namib Desert region. Playas in the Pro Namib Desert on the eastern margins of the Namib Desert, such as Sossus Vlei, Koichab Vlei, Tsondab Vlei and Zebra Pan, contain few salts and mainly feature calcified silt. In the western Kalahari of Namibia playas hold Epsom salts ($MgSO_4$), halite ($NaCl$), thenardite (Na_2SO_4), anhydrite ($CaSO_4$), calcium carbonate ($CaCO_3$), magnesium chloride ($MgCl_2$) and sylvite (KCl). The playas of the Etosha Pan in northern Namibia (Figure 1A) hold thenardite (Na_2SO_4), trona ($NaH(CO_3)_2 \cdot 11H_2O$), sulphohalite ($2Na_2SO_4 \cdot NaCl \cdot NaF$) and pirssonite ($CaCO_3 \cdot NaCO_3 \cdot 2H_2O$). This review indicates that none of the other Namibian playas contain gypsum. The only playa outside the Namib Desert that is reported in the literature to hold sulphate minerals is Omongwa Pan in the Namibian Kalahari which has anhydrite ($CaSO_4$) as a minor constituent (Schneider and Genis, 1992).

From the little that is known about the Central Namib Desert playas so far, it is evident that they are rich in gypsum and could provide a repository for the aeolian reworking. In this research we aim to examine the distribution, chemistry and geomorphology of playas within the Central Namib Desert and to determine their potential for deflation. This information is then used to evaluate the relationship between the well-studied pedogenic gypsum occurrences and the little-appreciated hydromorphic accumulations in playas.

METHODS

Owing to limited ground access and the size of the study area, remote sensing is the only means by which to determine the overall distribution of the playas. Playas in the Central Namib Desert were identified from geometrically corrected Landsat TM scenes at a spatial resolution of 30 m (Path Row: 179/76, 179/75, 180/75), space shuttle large-format camera photography (1915 and 1916) and additional selected airphotos. Gypsiferous playas are often not distinguishable from the general terrain in Landsat TM true colour displays; however, in false-colour composites (red–TM band 7, green–band 4 and blue–TM band 2) gypsiferous playas show up as dark turquoise patches and are readily mapped. In addition to mapping by interpreting standard false-colour composites, mixture modelling (Settle and Drake, 1993) was used on an image subset to study the surface distribution of pedogenic crusts. This technique is able to detect subpixel gypsum occurrences and is more effective than colour composites for mapping low gypsum concentrations (White and Drake, 1993; Eckardt and White, 1997). However, field checking of the Landsat TM imagery showed that small (subpixel) playas could not be identified whereas they could be distinguished on black-and-white airphotos. In airphotos the presence of minor vegetation and thrust polygons generates a relatively dark surface compared to the bright pedogenic gypsum regolith cover. Airphotos were not purchased for the whole area but only for areas where playas were identified either in the field, from light and ultralight aircraft, or where the geology was considered favourable for playa formation such as drainage channels traversing bedrock outcrops.

While all the major regions of the Central Namib Desert have been visited by the authors, not all the locations which feature playas were accessible for sampling. This is due to the fact that off-road driving is not allowed in the region and that walking was the only means of access to most of the playas featured here. Having worked on a number of remote-sensing projects in the region (White *et al.*, 1997, Eckardt *et al.*, 1997) the authors have developed confidence in the results provided from Landsat TM data.

For the playas that were visited in the field, maps of their geomorphology and depositional environments were composed, using the remotely sensed imagery as a base map. These images were also useful for mapping the distribution of extrusive dolerite dykes that, when they traverse the gravel plain drainage, cause groundwater and surface water ponding and evaporation which commonly is the cause of playa formation. At selected locations shallow holes less than a metre deep were dug to bedrock and sections were logged in order to determine the vertical zonation of salts and sediments. Samples of salts were collected and their mineralogy was determined by X-ray diffraction (XRD) analyses. Evidence for playa deflation was investigated using both remote sensing and field indicators. Deflation events and associated meteorological conditions for the Namib Desert region are described in Eckardt *et al.* (in press) with one of the events being presented here in more detail. Field indicators of deflation were the presence of a surface lag of exposed gypsum crystals or the presence of gypsiferous aeolian sands derived from playas.

RESULTS

Five distinct inland clusters of playas can be identified in the Central Namib Desert from remotely sensed data (Figure 1B). All playas are located within the poorly developed gravel plain drainage systems, while none are found in the ephemeral rivers that dissect the gravel plain, presumably because of the frequent flushing of salts from these rivers by surface flow generated in the highlands. In general, playas are less than a metre deep, they cover an area not larger than 80 ha, all feature thin salt crusts of gypsum and halite, and have phreatophyte mounds, thrust polygon surfaces or other irregular microtopography. In the following discussion these playas will be introduced on the basis of their location relative to the ephemeral highland drainage which provides five discrete zones as shown in Figure 1B.

Zone 1: From the Messum River to the Ugab River

The playas between the Messum and Ugab Rivers are very small (<5 ha) due to the limited drainage network and a very dense network of dolerite dykes (Figure 2). The dykes affect the flow of groundwater and surface water with water seepage at the surface often being the result. They are less than 30 cm deep, contain gypsum and halite and are readily identified in the TM image as dark turquoise patches from which parallel, gypsiferous, turquoise wind streaks emanate in a southwesterly direction, attaining lengths of up to 150 m which traverse some of the dykes.

Zone 2: From the Messum River and Omaruru River

Between the Omaruru and Messum River, there are only a few isolated gypsum and halite-covered playas which are the result of both Karibib marble and dolerite dyke obstructions. Generally this region is home to very thick and broad accumulations of the Omaruru alluvium which prevents the evaporation of groundwater. Based on spot-checks, pedogenic gypsum also appears to be less common.

Zone 3: From the Omaruru River to the Swakop and Khan Rivers

The largest playas in the area are found in this zone, and have been named Silver Lake Playas in mining reports (Figure 1, zone 3, and Figure 3). The surfaces of these playas are composed predominantly of gypsum and halite, such that Ehrhorn's Playa was briefly mined for halite in the 1930s, while Eisfeld and others seem

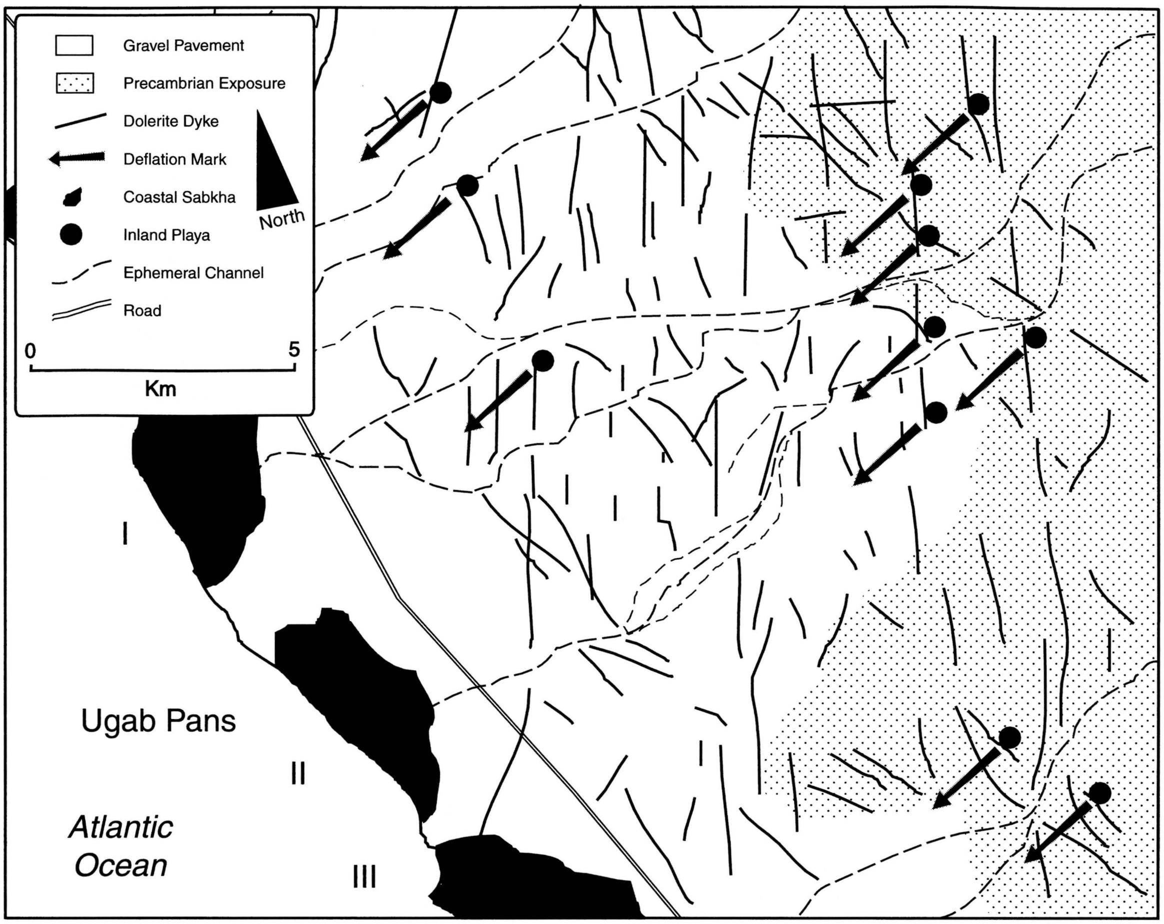

Figure 2. Playas and gypsum deflation mapped from Landsat TM image. Zone 1 features extensive dolerites dykes which promote groundwater seepage. Substantial sabkhas along the coast show evidence of fluvial inputs from the Namib Desert interior

to have been subjected to some initial prospecting (Gevers and Van der Westhuyzen, 1931; Schneider and Genis, 1992). The Silver Lake Playas have formed because relatively impermeable dolerite dykes traverse drainage channels and force groundwater to the surface, even forming standing pools of water at a number of points. Figure 3 shows that Ehrhorn Playa is clearly constrained by these dykes. Eisfeld Playa also shows that the relationship between the surface expression of the dykes, the location of playa sediments, and the gravel plain drainage can be intricate. Figure 4 also shows the spatial relationships between these features for Eisfeld Playa. The playa is located in the middle of a complex set of dykes that have been partially breached by two drainage systems but still restrict groundwater flow. Playa sediments are found in and between both drainage systems. Phreatophyte fields, presumably characterized by relatively fresh groundwater, merge downstream into more saline, smooth, dry gypsiferous mudflats. The surface of these mudflats is in places scattered with a lag of large (10–20 mm) lenticular gypsum crystals that suggest that deflation of finer gypsiferous sediments has taken place. In places the mudflats grade into bedrock, in other areas halite crusts are found, and in one region the gypsum crust is exceptionally well developed and has formed thrust polygons. The two sections obtained at Eisfeld Playa (Figure 5, sections A and B) reveal very shallow salt and sediment deposits. Landsat TM imagery shows a gypsiferous windstreak for Eisfeld Playa pointing in a southwesterly direction.

The playas in the northeastern part of this zone are also fairly large and have also been subjected to brine prospecting and mining. They contain both gypsum and halite but differ from the other zone 3 playas in that

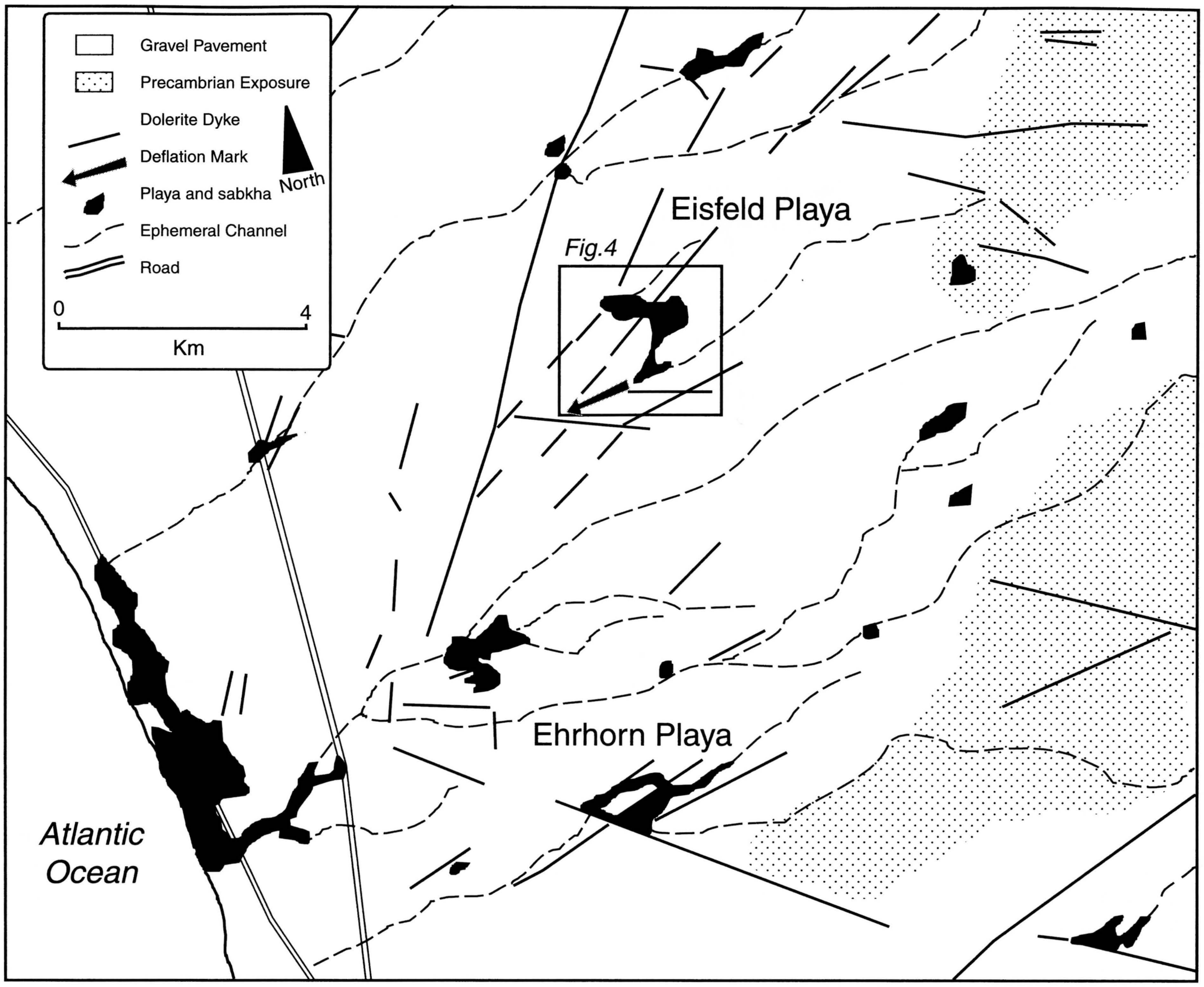

Figure 3. The Silverlake Playas in zone 3 north of Swakopmund. Mapping from Landsat TM shows dolerite dykes which are causing groundwater ponding and the formation of playas. Eisfeld is one of the largest pans in this study area with deflation being evident. The hydrological connection between inland playas and coastal sabkhas is apparent

they form behind Kuiseb schist exposures and local Karibib marble outcrops that block drainage channels and groundwater flow. Again, small standing pools of water are present.

Zone 4: From the Swakop River to the Khan River

Between the Swakop and Khan Rivers a much smaller cluster of three playas exists on the Welwitschia Flats (Figure 1B). These playas also contain gypsum and halite. They appear to be the result of groundwater ponding of the gravel plain drainage by highly resistant, Precambrian Karibib marble obstructions. The playas are very shallow (<0·5 m) and only contain a thin gypsum crust (Figure 5, section C). The presence of saline groundwater on the Welwitschia Flats also forms an unusual perched playa associated with springs on the north rim of the Swakop River canyon, 8 km upstream from the Swakop/Khan confluence (lat. 22°42′34″ S, long. 14°59′09″ E). Groundwater seepage occurs on the walls of Swakop canyon encrusting it with halite and gypsum over a length of 200 m and to a height 50 m. The aridity even allows the formation of halite stalactites and stalagmites which are likely to be flushed away during occasional high Swakop floods which on occasion may reach the canyon wall.

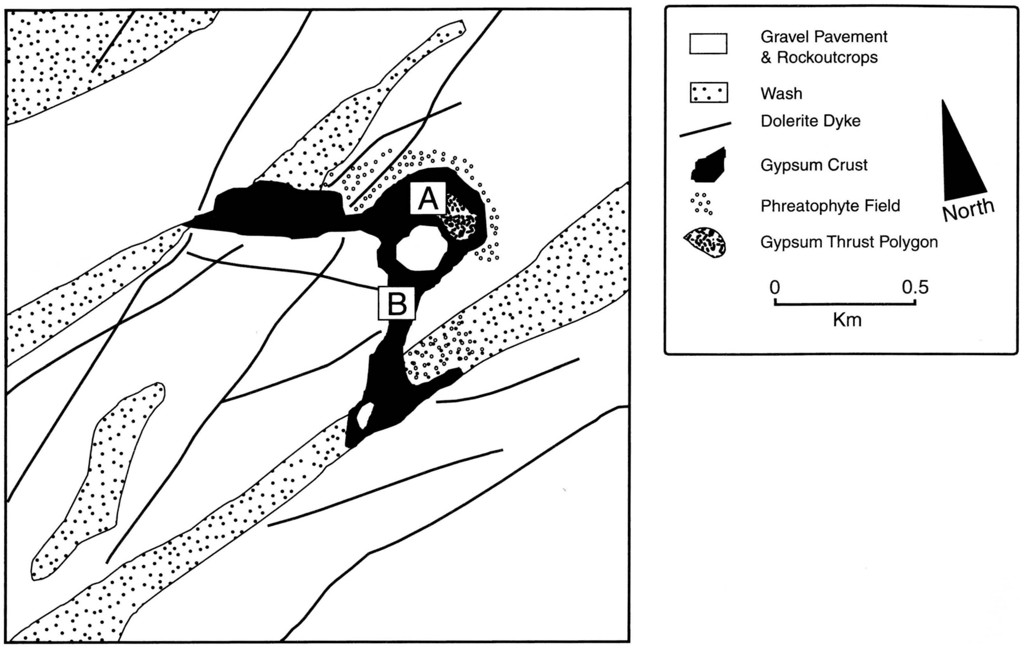

Figure 4. Eisfeld Playa, part of the Silverlake Playa complex. This map clearly shows the relation between drainage, dykes and playa formation. The playa features gypsum thrust polygons as well as phreatophyte mounds. A, B, Locations of sections in Figure 5

Zone 5: From the Swakop River to the Kuiseb River

The largest number of playas is found between the Kuiseb and Swakop Rivers where there are at least 50–60 playas. However, they are all small, generally less than 5 ha in extent. These playas form a pronounced belt which runs from Hosabes Playa near Gobabeb to Ubib spring and terminates to the west of Hotsas water hole (Figure 6).

These playas commonly form behind resistant bedrock outcrops, such as pegmatites and quartz veins, that force groundwater to the surface (or to the capillary fringe) with water seepage being common. These outcrops are found in a swarm that cut through Damara bedrock of the Tinkas schist and the Salem granite in the vicinity of the Okahandja lineament. All playas contain gypsum and halite that presumably result from the evaporative concentration of groundwater. Usually the outcrops that cross-cut the channels have been subjected to prolonged salt weathering and form indistinct topographic highs that could be readily breached in periods of shallow groundwater or surface-water discharge. Where channels are crossed by many outcrops, lines of playas are sometimes found running down the channel, behind each of these obstructions.

Pits dug into the gypsiferous areas of a number of these playas show that they generally contain shallow deposits of salts and sediments, usually less than half a metre in depth (e.g. Figure 5, section D). The deepest section excavated in this zone (Figure 5, section E) is found in a playa near Ubib. The playa surface is composed of a gypsum zone around its margins, with a well-developed halite crust at the centre that is underlain by up to half a metre of sediments. This playa is located in a channel whose outflow is completely blocked by a large dolerite dyke that could only be breached in the severest of floods events. Such dykes form a highly effective trap for salts and sediments preventing flushing of these materials further down the channel and ultimately into the Atlantic Ocean.

Though playas in zone 5 are predominantly composed of halite and gypsum, Humberstonite $(K_3Na_7Mg_2(SO_4)6(NO_3)2H_2O)$, a rare nitrate mineral, was identified by XRD at Hosabes Spring Playa (lat. 23°30′15″ S, long. 15°03′11″ E). This complex salt was found infilling the hexagonal cracks of a halite crust and as far as can be ascertained, this is the first time that Humberstonite has been reported outside the Atacama Desert (Mrose *et al.*, 1970). Sylvite (KCl) and halite were also found in a dune 70 m to the west

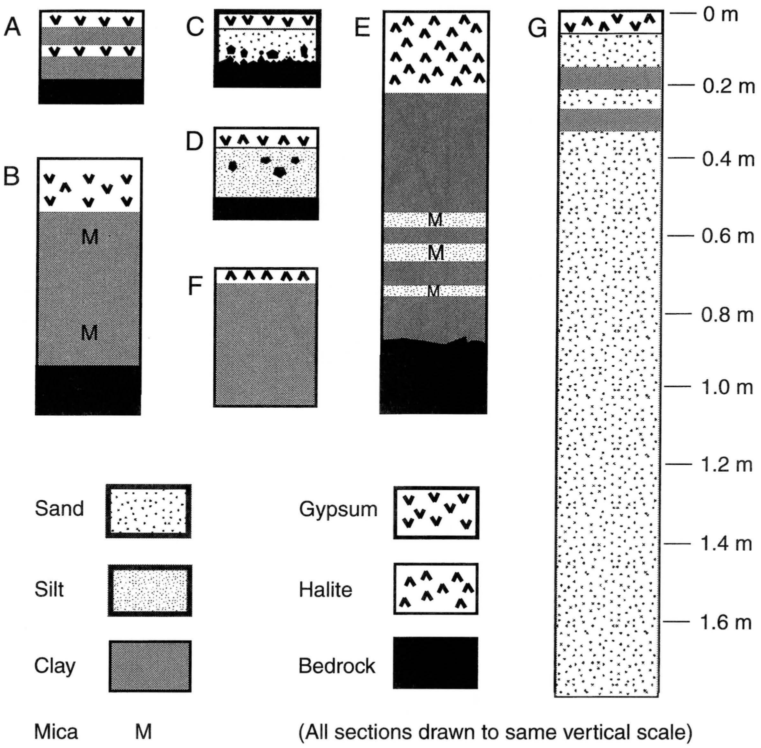

Figure 5. Sections of playas: A, B, Eisfeld; C, Welwitschia Flats; D, E, Ubib; and sabkhas: F, Walvis Bay; G, Torra Bay (Torien, 1964). All surface feature gypsum or halite or a combination of both. Playas are very shallow by comparisons with sabkhas

of Gungachoab Playa that was sampled because it appeared to be composed of deflated playa sediments. Although sylvite was not identified in Gungachoab Playa it is the most likely source. No other points of evaporative concentration have been identified in the immediate vicinity.

The Coastal Sabkhas

The presence of numerous coastal sabkhas is well established in the Central Namib Desert (Schneider and Genis, 1992) having been studied since the 1930s, with gypsum being reported from Swakopmund, Cape Cross (Gevers and Van der Westhuyzen, 1931), Conception Bay (Kaiser and Neumeier, 1932) and Torra Bay (Torien, 1964). These deposits reveal a surface crust of gypsum and halite underlain by much deeper and sandier sections than those of the playas (Figures 1 and 5, section G). Their inland margins can be less sandy and may be composed of fine clay (section F)

These sabkhas are often located at the terminus of the gravel plain drainage systems. Eckardt and Spiro (1999) have analysed the sulphur isotope composition of gypsum from some, and found that they appear to be the result of groundwater inputs from the gravel plain drainage systems, rather than from the evaporation of seawater. Thus, though geological obstructions in the catchment of these sabkhas trap some groundwater and dissolved salts to form playas, significant amounts of dissolved salt appear to pass into the sabkhas. Salts are thus lost from the gravel plain drainage systems through groundwater flow, playa deflation, and probably also through infrequent surface water flow that occurs when a significant amount of rain falls. A high loss of salts and sediments through a combination of these processes presumably explains the shallow sections of salts and sediments in the Central Namib Desert playas.

Evidence for deflation

Previous work has highlighted the presence of deflation features such as streaks and ventifacts on the Namib Desert gravel plains (Selby, 1977; Sweeting and Lancaster, 1982) but no study has yet investigated

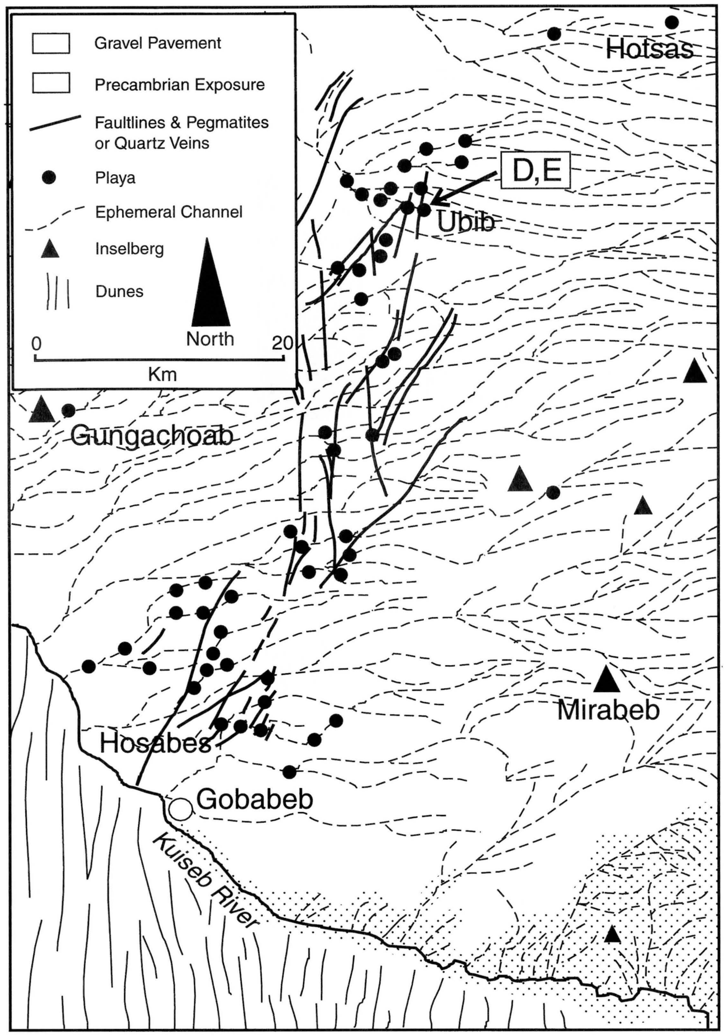

Figure 6. Extensive belt of playas stretching from the Namib Sand Sea across the gravel plain. The east is home to calcrete crusts and drainage which serves as a catchment for the structurally controlled playas. The west features substantial pedogenic gypsum accumulations. D, E, Locations of section in Figure 5

the effect of wind on the unconsolidated fine sediments provided by playas and sabkhas. We have identified deflation from Cape Cross sabkha (Figure 7) and numerous further dust-producing events that are evident in space shuttle photography of other Namibian playas and sabkhas (Eckardt *et al.*, in press) such as at Conception Bay and Etosha Pan (Figure 1A). It appears that all playas and sabkhas in Namibia predominantly deflate towards the coast. Though we have direct evidence of deflation form the sabkhas there are no direct observations of deflation from the smaller playas. However, the presence of gypsiferous gravel lags on playa mudflats, gypsiferous wind streaks emanating from playas, phreatophyte mounds common on playa margins, and deflation of other salts all provides evidence of recent and probably ongoing aeolian processes.

There is also indirect evidence of gypsum mobilization on the gravel plain and it appears that even surface exposures of pedogenic gypsum are affected. This is shown through the mapping of subpixel gypsum occurrences using mixture modelling (Figure 8). The highest amounts of gypsum are associated with a road that is made of gypsum excavated from the side of the road and tracks that reveal exposed subsurface accumulations (bright areas) (Eckardt *et al.*, 1997). The absence of gypsum (dark areas) is due to extensive

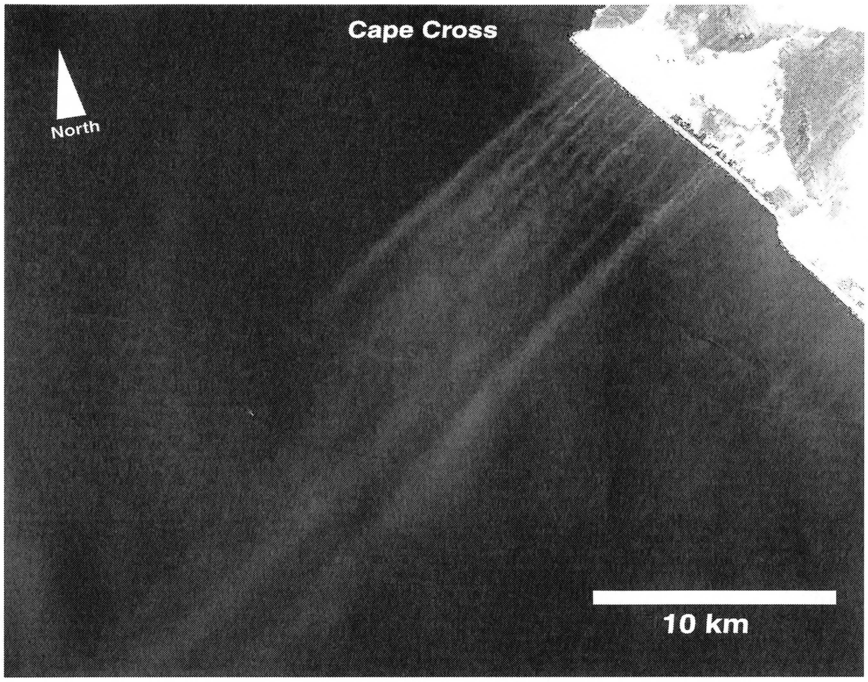

Figure 7. Deflation from Cape Cross sabkha surface in zone 2 (Figure 1A, B) during easterly Bergwind. Detailed view from Landsat TM image Band 1 (blue)

bedrock exposures of the Hamilton Range and its scree as well as river washes. Large-scale windstreaks on the gravel plains have been reported elsewhere (Wilkinson, 1990). This study suggests that the gravel plain discoloration previously reported in ordinary space photography is partly derived by variations in gypsum content on the surface. The areas of low gypsum accumulation shown in Figure 8 match those areas which are supposedly the result of windscouring, hence it appears that superficial crusts are subject to removal by wind erosion and abrasion.

DISCUSSION

We have shown that playas are a common feature in the Namib Desert stretching from the east of the Pro Namib Desert merging along the coast with sabkhas. The area occupied by the small but numerous gypsiferous inland playas is estimated to be around 3 per cent of the total study area, with the largest playas not exceeding 0·5 km^2 in size. However, this figure could be a conservative estimate. Many playas are below the spatial detection limit of Landsat while high resolution airphotos have only been employed selectively. Furthermore, there are numerous small patches of gypsum and halite crusts at constriction points in the channel network on the gravel plain which are hard to map from the airphotos, but when considered in total, may have a significant surface area. Our results also show that the salt assemblages found in the playas of the Namib Desert are considerably different from those of other Namibian playas precluding the latter as an external source of gypsum aerosols.

The marine-like gypsum and halite composition of playas suggests that marine aerosols are a significant primary source of sulphur (Eckardt and Spiro, 1999), as has been shown for the playas of Australia (Chivas *et al.*, 1991) and the coastal Atacama Desert (Noller, 1990). Indeed in the Atacama it has been estimated that the annual deposition of marine aerosols may range from approximately 1 to 7 tonnes per km^2 (Noller, 1990). Rain and fog may provide an additional but minimal chemical input (Eckardt and Schemenauer, 1998). It appears that playa gypsum is a result of the dissolution of dry aerosol deposition by rain and fog water.

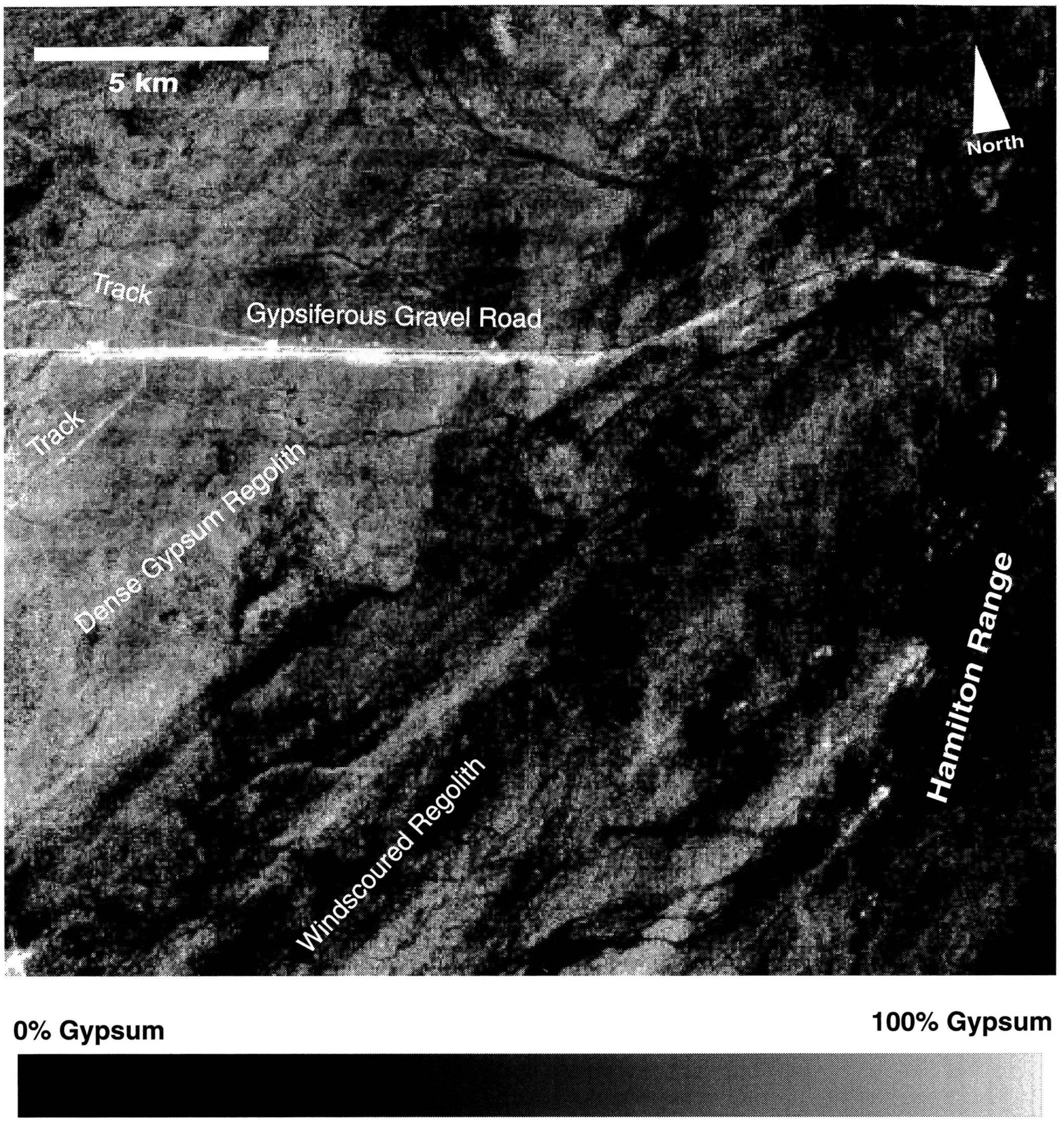

Figure 8. Mixture model output from Landsat TM image showing gravel plain west of Hamilton Range. Pedogenic gypsum outcrops are subject to windscouring resulting in variable gypsum on the desert surface

The occasional rain storms in particular promote runoff, infiltration and groundwater flow which may lead to evaporation, concentration and salt precipitation in playas.

The relative input of surface or groundwater into playas is uncertain but the presence of clay, silt and some sand-sized material in most of the playas suggests that surface water input takes place. This is likely to occur during sporadic high-magnitude rain events, which cause surface run-off and transport eroded material from inselbergs and the gravel plains into playa depressions. Most bedrock obstructions would appear not to pose significant dams to infrequent ephemeral floods. Indeed playas that have formed in drainage channels behind less pronounced bedrock obstructions have thinner sections than those behind more substantial ones. The depth of the closed depressions is less, allowing periodic floods to partially flush the drainage network of their salts and sediments. The shallow depth of playa sediments would make them ideal points for evaporative concentration and deflation but there does not appear to be much scope for extensive accumulation. The total amount of evaporites in these playas is relatively small suggesting that significant losses occur. Hydrological losses would contribute evaporites to precipitation points downstream which could include further playas or sabkhas. Dissolved salts could also be lost to the sea, in particular where gravel plain channels feed the ephemeral highland drainage systems. Ephemeral highland drainage periodically experiences floods that reach the sea. Aeolian losses on the other hand are likely to contribute to the pedogenic accumulations that are at the heart of this study.

The gypsum-rich nature of Central Namib Desert playas and sabkhas and the evidence for deflation support a link between local playa deflation and gypcrete formation on the gravel plain which is further substantiated by their identical chemistry and comparable sulphur isotope composition (Eckardt and Spiro, 1999). It appears that the easterly Bergwind is the most significant vector for deflation being associated with the greatest windspeeds (16 m s^{-1}) along the Namib Desert coast (Schulze, 1969). This low-frequency, high-magnitude wind operates only on a few days each year, in particular during the winter months when fog and rain are least common and surfaces are at their driest. At Etosha outside the Namib Desert region, dated lunette dunes at its western margin suggest that this Bergwind trajectory has been active for at least 140 000 (Buch *et al.*, 1992).

In zone 5 the easternmost extent of playas strongly correlates with the most significant pedogenic gypsum accumulations in the region. It therefore appears that the limit of gypcrete is determined by the presence of playas, not climate. This is strongly supported by the distinct absence of recent evaporites in interdune deposits of the adjacent Namib Sand Sea (Lancaster and Teller, 1988). The sands in the dune regions appear to be moderately saline due to aerosol deposition (Besler, 1979). This, however, does not translate into gypcrete formation. This includes extensive, stable interdune gravel plains of the Namib Sand Sea which provide a strong contrast to the situation on the Central Namib Desert gravel plains as drainage networks and points of evaporative concentration do not exist. Indeed groundwater appears to flow underneath the Namib Sand Sea discharging into the ocean at a number of freshwater springs between Walvis Bay and Lüderitz (Hellwig, 1968). Interdune evaporites are found only in relation with the inactive extension of the Tsondab River which produced calcified salt deposits of considerable thickness at Narabeb (Lancaster and Teller, 1988).

Evidence for contemporary gypsum deflation is wide-ranging and dispersal appears to be largely in a westerly direction driven by the regional easterly winds that carry material in a seaward direction and this would seem to limit the potential role of coastal sabkhas in gypsum crust formation. However, weather data show that the coastline is also frequently subjected to relatively strong southwesterly winds (Lancaster *et al.*, 1984) which could carry material from coastal sabkhas into the Namib Desert and this possibility is also supported by the existence of nebkhas along the coastline with tails pointing inland. It is possible that an extensive Proto-Walvis Bay sabkha of Miocene age (Miller and Seely, 1976) during higher sea level could have provided some significant aeolian evaporite input into the desert. As Namibian sabkhas produce evaporites from continental groundwater seepage (Eckardt and Spiro, 1999) a landward dispersal of sabkha evaporites would amount to recycling of terrestrial salts rather than contributing salts of evaporated seawater towards the pedogenic crusts.

Though this study has been able to put the formation of gypsum into the context of established and ongoing processes, a number of questions remain. One issue is the role of stone pavements in the formation of pedogenic gypsum crusts. An upward growth of pavements by the entrapment of aeolian material (McFadden *et al.*, 1987) would be a new proposition for the Namib Desert and especially interesting should the dust be rich in gypsum, as this could explain how the crusts were able to gain such a thickness. However, the amount of gypsum on the gravel plain will also be determined by the aridity of the climate as the amount of rainfall will control dissolution losses. Aridity has been an increasingly dominating environmental condition in the Namib Desert, which is thought to have varied between semi-arid, arid and hyper-arid conditions during the last 80 million years; hyperaridity has been on the increase (Ward *et al.*, 1983) over the last 5 million years suggesting that pedogenic gypcrete losses are minimal.

On such geological time scales the authors envisage a multitude of playa configurations provided by the variability and durability of different bedrock obstructions which, in and around playas, show signs of salt weathering. Salt weathering in the Namib Desert is rapid and effective (Goudie *et al.*, 1997; Goudie and Parker, 1998). The balance between bedrock-induced groundwater ponding and salt weathering is able to provide a highly dynamic picture for the formation of hydromorphic gypsum. Playas are likely to be significant sources of weathering agents, which in conjunction with saline groundwaters, frequent fog incursions, and high relative humidity along the coast produces a very aggressive weathering environment.

It is interesting to note that the model of gypsum crust formation proposed here is partly mirrored by the model of calcrete formation in the Namib Desert. This has been linked to the aeolian dispersal of Ca from secondary calcrete deposits, derived from the now largely denuded Damara Orogen of Namibia's central region (Eitel, 1994). Contemporary calcification has been linked to aeolian reworking of existing calcrete exposures (Heine and Walter, 1996), which is supported by the high levels of Ca enrichment in atmospheric aerosols (Eckardt and Schemenauer, 1998).

Generally the role of playas in determining downwind soil and water quality is not to be underestimated. A groundwater-fed playa measuring less than 5 km^2 can produce significant saline aerosols. This has been demonstrated on the High Plains of Texas, where Double Lake is estimated to produce 450 ± 200 tons of chlorine dust each year. This dust is detectable up 35 km from its source (Wood and Sanford, 1995).

Similar work which estimates aeolian losses needs to be carried out for Namib Desert playas as well as those found in the deserts of central and western Australia. These playas are also fed my marine aerosols (Chivas *et al.*, 1991), are positioned in drainage systems (Jacobson *et al.*, 1988; Clarke, 1994) and experience losses by deflation and overflow (Salma *et al.*, 1992). Some of the playas even feature gypsum dunes (Chen *et al.*, 1991) and equally promote pedogenic gypsum crust formation.

CONCLUSION

It appears that pedogenic gypcrete does not form by the direct deposition of marine aerosols on the gravel plain surface as previously considered. A stable soil environment alone is not sufficient in producing gypcrete as is clearly shown in the Namib Sand Sea. Marine aerosols need to be concentrated and evaporated within the aqueous geochemistry of playas in order for evaporates to form. Our findings are summarized in Figure 9. Namibia's pedogenic gypsum crusts have long been seen in an almost exotic context, but evidence suggests that they can be interpreted in the light of established and ongoing processes, which partly mirror the formation of Namibia's calcrete and can be compared to deserts elsewhere, in particular Western Australia.

We argue that pedogenic gypsum requires the primary formation of gypsum at points of evaporitic concentration provided by playas which represent an essential catalyst. The formation requires both marine SO_4

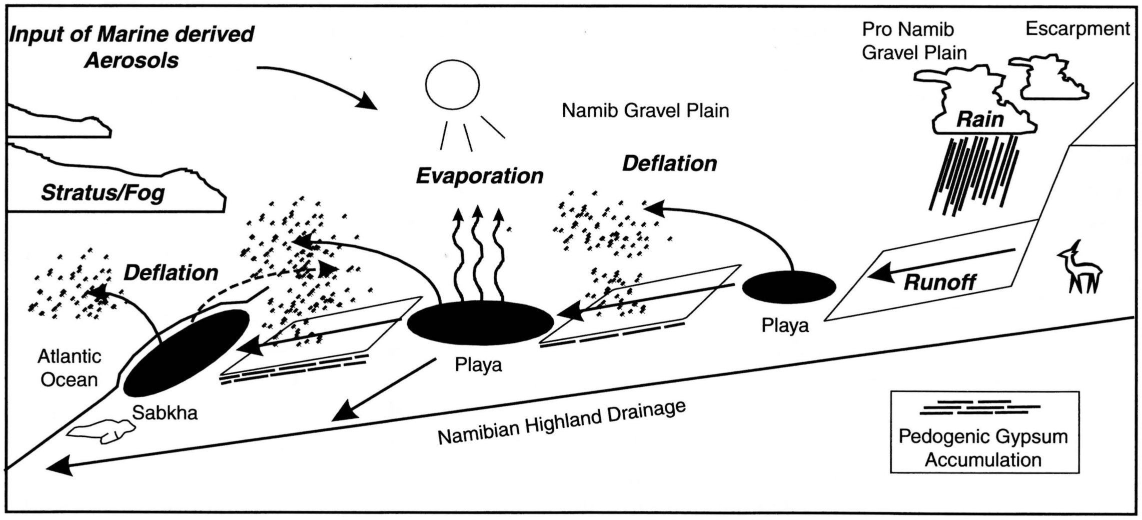

Figure 9. Model of pedogenic gypsum formation for the Namib Desert. Marine-derived dry aerosols are dissolved and mobilized through moisture provided by fog and rain water. Primary gypsum formation takes places in playas and is subjected to aeolian and fluvial dispersal. Pedogenic gypsum accumulations increase towards the coast

and terrestrial Ca which are subjected to widespread and probably subcontinental dispersal but will be mostly dissolved by rain and transported into the Central Namib Desert playas and sabkhas along the gravel plain drainage systems. Gypsum may precipitate at these points of evaporitic concentration, whence it is subjected to aeolian dispersal and added to the pavement. Halite (NaCl) partly accompanies this cycle but through time will have been subjected to preferential leaching while gypsum is less soluble and more prone to gradual accumulation. Some of the pedogenic evaporites may be subjected to further solution and subsequent secondary precipitation in playas. It is also apparent that playas and sabkhas do not differ significantly in their surface morphology. Both appear to be subject to groundwater input, prone to occasional flooding and susceptible to deflation by the easterly Bergwind. A coastal southwest wind could carry material landward but this is probably of secondary significance and limited to the coast.

While some marine aerosols might be directly incorporated into the soil section, the lack of any pedogenic evaporites in the interdune areas of the Namib Sand Sea would suggest that this is only of limited significance, and that a primary playa production is an integral part in the formation of the extensive pedogenic accumulations. Deflation rates from playas, atmospheric dust content and deposition rates for the Namib Desert need to be determined in order to further validate this model. However, the varied interactions and vast potential for the mixing of aerosols will make specific trajectory measurements of any sort a methodological but worthy challenge. Our results so far propose a complex but interesting interaction between fluvial, aeolian and pedogenic processes in an area which, at a glance, appears inert and almost devoid of significant processes and features.

ACKNOWLEDGEMENTS

We would like to thank Dr Mary Seely, Dr Baruch Spiro and Dr Robert Schemenauer for help. Funding was provided by NERC (Natural Environment Research Council) (GT4/92/18/G) and the Trapnell Fund. The Namibian Ministry of Environment and Tourism provided research permits.

REFERENCES

Annegarn HJ, Van Grieken RE, Bibby DM, Blottnitz FV. 1983. Background aerosol composition in the Namib desert, S.W.A. (Namibia). *Atmospheric Environment* **17**(10): 2045–2053.

Bao H, Thiemens MH, Farquhar J, Campbell DA, Chi-Woo Lee C, Heine K, Loope DB. 2000. Anomalous ^{17}O compositions in massive sulphate deposits on the Earth. *Nature* **406**: 176–178.

Besler H. 1972. *Klimaverhältnisse und Klimageomorphologische Zonierung der Zentralen Namib (Südwestafrika).* Stuttgarter Geographische Studien 83.

Besler H. 1979. Salinitasmessungen an Sanden als Hilfsmittel zur Rekonstruktion fossiler Gewässernetze in ariden Räumen. *Zeitschrift für Geomorphologie* **23**(2): 192–198.

Buch MW, Rose D, Zoller L. 1992. A TL-calibrated pedostratigraphy of the western lunette dunes of Etosha Pan/ northern Namibia – palaeoenvironmental implications for the last 140 ka. *Palaeoecology of Africa* **23**: 129–147.

Cagle FR. 1975. *Evaporite deposits of the Central Namib Desert, Namibia.* MSc thesis, University of New Mexico.

Carlisle D. 1978. *The distribution of calcretes and gypsum in SW USA and their uranium favourability based on a study of deposits in Western Australia and South West Africa.* US Dept of Energy Subcontract, Open File Report, 76-022-E.

Chen XY, Bowler JM, Magee JW. 1991. Aeolian landscapes in Central Australia: gypsiferous and quartz dune environments from Lake Amadeus. *Sedimentology* **38**: 519–538.

Chivas AR, Andrew AS, Lyons WB, Bird MI, Donnelly TH. 1991. Isotopic constraints on the origin of salts in Australian plays. 1. Sulphur. *Palaeogeography, Palaeoclimatology, Palaeoecology* **84**: 309–332.

Clarke JDA. 1994. Lake Lefroy, a palaeodrainage playa in Western Australia. *Australian Journal of Earth Sciences* **41**: 417–427.

Coque R. 1962. *La Tunisie Presaharienne. Etude Géomorphologique*. Armand Colin: Paris.

Day JA. 1993. The major ion chemistry of some southern African saline systems. *Hydrobiologia* **267**(1–3): 37–59.

Drake NA. 1997. Recent aeolian origin of surficial gypsum crusts in southern Tunisia: geomorphological, archaeological and remote sensing evidence. *Earth Surface Processes and Landforms* **22**: 641–656.

Eckardt FD, Schemenauer RS. 1998. Fogwater chemistry in the Namib Desert, Namibia. *Atmospheric Environment* **32**(14/15): 2595–2599.

Eckardt FD, Spiro B. 1999. The origin of sulphur in gypsum and dissolved sulphate in the Central Namib Desert, Namibia. *Sedimentary Geology* **123**(3–4): 255–273.

Eckardt FD, White K. 1997. Human induced disruption of stone pavement surfaces in the Central Namib Desert, Namibia: Observations from Landsat Thematic Mapper. *International Journal of Remote Sensing* **18**(16): 3305–3310.

Eckardt FD, Drake NA, White K. 1997. Mixture model mapping gypsum in Tunisia and Namibia from Landsat TM, a comparative study. In *Observations and Interactions, Proceedings of 23rd Annual Conference of the Remote Sensing Society*, Sept. 1997, Reading UK; Griffiths GH, Pearson D (eds). 416–422.

Eitel B. 1994. Kalkreiche Decksedimente und Kalkrustengenerationen in Namibia: Zur Frage der Herkunft und Mobilisierung des Calciumcarbonates. *Stuttgarter Geographische Studien Band 123*, 193 pp.

Forshag WF. 1933. Sulfohalite and other minerals from the Otjiwalundo salt pan, SWA. *American Mineralogist* **18**: 431–434.

Frank D, Eckardt FD, Washington R, Wilkinson J. (2001). The origin of dust on the West Coast of Southern Africa. In *Palaeoecology of Africa and the Surrounding Islands*, Vol. 27, Proceedings of the XVth INQUA Conference, Durban; 3–11.

Gevers TW, Van der Westhuyzen JP. 1931. The occurrences of salt in the Swakopmund area, South West Africa. *Transactions of the Geological Society of South Africa* **34**: 61–80.

Goudie AS. 1972. Climate, weathering, crust formation, dunes and fluvial features of the Central Namib Desert, near Gobabeb, SW Africa. *Madoqua* **2**(1): 54–62.

Goudie AS, Parker AG. 1998. Experimental simulation of rapid rock block disintegration by sodium chloride in a foggy coastal desert. *Journal of Arid Environments* **40**: 347–355.

Goudie AS, Viles HA, Parker AG. 1997. Monitoring of rapid salt weathering in the central Namib Desert using limestone blocks. *Journal of Arid Environments* **37**: 581–598.

Heine K, Walter R. 1996. Gypcretes of the central Namib Desert, Namibia. *Palaeoecology of Africa* **24**: 173–201.

Hellwig DHR. 1968. *Water resources of the Namib Desert between Lüderitzbucht and Walvis Bay*, 28th Meeting of the Steering Committee for Water Research in S.W.A. Windhoek. Council for Scientific and Industrial Research.

Jacobson G, Arakel AV, Yijian C. 1988. The central Australian groundwater discharge zone; evolution of associated calcrete and gypcrete deposits. *Australian Journal of Earth Sciences* **35**(4): 549–565.

Kaiser E, Neumaier F. 1932. Sand- steinsalz- kristallskelette aus der Namib Südwestafrikas. *Zentralblatt für Mineralogie* **6A**: 177–188.

Lancaster N, Teller JT. 1988. Interdune deposits of the Namib Sand Sea. *Sedimentary Geology* **55**: 91–107.

Lancaster J, Lancaster N, Seely MK. 1984. Climate of the Central Namib Desert. *Madoqua* **14**(1): 5–61.

Logan RF. 1969. Geography of the central Namib Desert. In *Arid Lands in Perspective*, McGinnies WG, Goldman B (eds). The University of Arizona Press Tucos, Arizona; 129–143.

Martin H. 1963. A suggested theory for the origin and a brief description of some gypsum deposits of South West Africa. *Transactions of the Geological Society of South Africa* **66**: 345–350.

McFadden LD, Wells SG, Jercinovich MJ. 1987. Influences of eolian and pedogenic processes on the origin and evolution of desert pavements. *Geology* **15**: 504–508.

Meigs P. 1966. Geography of coastal deserts. *UNESCO Arid Zone Research* **24**: 79–114.

Miller RM, Seely MK. 1976. Fluvio-marine deposits south-east of Swakopmund, South West Africa. *Madoqua* **9**(3): 23–26.

Mrose ME, Fahey JJ, Ericksen GE. 1970. Mineralogical studies on the nitrate deposits in Chile. III Humberstonite. *The American Mineralogist* **55**: 1518–1533.

Noller JS. 1990. Marine origin for salts in soils of the hyper-arid Peruvian desert. *American Geophysical Union* **71**(43): 1235.

Reheis MC. 1987. Gypsic soils on the Kane alluvial fans, Big Horn County, Wyoming. *US Geological Survey Bulletin* **1590C**.

Rust U. 1979. Über Konvergenzen im Wüstenrelief am Beispiel der südwestafrikanischen Namibwüste (Skelettküste und Zentralen Namib). *Mitteilungen der Geographischen Gesellschaft in München* **64**: 201–219.

Salma R, Barber C, Hoskins J, Briegel D. 1992. Geochemical evolution of Lake Deborah East, prototype salt lake in the relict drainage of the Yilgarn River of Western Australia. *Australian Journal of Earth Sciences* **39**: 577–590.

Schneider GIC, Genis G. 1992. Salt. Namibian Ministry of Mines and Energy, Geological Survey Namibia, Windhoek, Open File Report MRS 21.

Scholz H. 1963. *Studien über die Bodenbildung zwischen Rehoboth und Walvis Bay*. Doktorarbeit, Rheinische Friedrich-Wilhelm Universität, Bonn.

Scholz H. 1972. The soils of the central Namib Desert with special consideration of the soils in the vicinity of Gobabeb. *Madoqua, Series II* **1**(54): 33–51.

Schulze BR. 1969. The climate of Gobabeb. *Scientific Papers of the Namib Desert Research Station* **38**: 5–12.

Selby. 1977. Bornhardts of the Namib desert. *Zeitschrift für Geomorphologie* **21**(1): 1–13.

Settle JJ, Drake NA. 1993. Linear mixing and the estimation of ground cover proportions. *International Journal of Remote Sensing* **14**: 1159–1177.

Sweeting MM, Lancaster N. 1982. Solution and wind erosion on limestone in the Central Namib. *Zeitschrift für Geomorphologie* **26**(2): 197–207.

Teller JT, Last WM. 1990. Paleohydrological indicators in playas and salt lakes, with examples from Canada, Australia, and Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology* **76**(3–4): 215–240.

Torien DK. 1964. *Geologiese Verslag Oor Die Soutpanne Langs Die Weskus Tussen Swakopmund En Die Kunenemund Suidwest-Africa*. Namibian Ministry of Mines and Energy, Geological Survey Namibia, Windhoek, Open File Report EG 069.

Ward JD, Seely MK, Lancaster N. 1983. On the antiquity of the Namib. *South African Journal of Science* **79**: 175–183.

Watson A. 1979. Gypsum crusts in deserts. *Journal of Arid Environments* **2**(1): 3–21.

Watson A. 1980. Vegetation polygons in the central Namib Desert near Gobabeb. *Madoqua* **11**(4): 315–325.

Watson A. 1982. *The Origin, Nature and Distribution of Gypsum Crusts in Desert*. D.Phil, University of Oxford.

Watson A. 1983. Gypsum crusts. In *Chemical Sediments and Geomorphology*, Goudie AS, Pye K (eds). Academic Press: London; 133–161.

Watson A. 1985. Structure, chemistry and origins of gypsum crusts in southern Tunisia and the central Namib Desert. *Sedimentology* **32**: 855–875.

Watson A. 1988. Desert gypsum crusts as palaeoenvironmental indicators: a micropetrographic study of crusts from southern Tunisia and the central Namib Desert. *Journal of Arid Environments* **15**(1): 19–42.

White KH, Drake NA. 1993. Mapping the distribution and abundance of gypsum in south-central Tunisia from Landsat Thematic Mapper data. *Zeitschrift für Geomorphologie* **30**(3): 309–325.

White K, Walden J, Drake NA, Eckardt FD, Settle JJ. 1997. Mapping the iron oxide content of dune sands, Namib Sand Sea, using Landsat Thematic Mapper data. *Remote Sensing of Environment* **62**: 30–39.

Wieneke F, Rust U. 1973. Variations in sea level and morphoclimatic periods in the desert of the central Namib, South West Africa. *Finisterra: Revista Portuguesa de Geografia* **8**(15): 48–65.

Wilkinson MJ. 1990. *Paleoenvironments in the Namib Desert: The lower Tumas Basin in the late Cenozoic*. Geography Research Paper, University of Chicago 231(196).

Wilkinson MJ, Helms DR, Whitehead VS. 1992. Albedo patterns and Gypsum Generation in the Central Namib Desert: Land, Sea, Air Interactions on an Arid West Coast. *Proceedings of International Geoscience and Remote Sensing Symposium*, May 26–29 (IGARSS 92), Houston, Texas.

Wood WW, Sanford WE. 1995. Eolian transport, saline basins and groundwater solutes. *Water Resources Research* **31**(12): 3121–3129.