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Microclimate and weathering in the central Namib Desert, Namibia

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Abstract

Data on rock surface microclimates at four sites (Kleinberg, Vogelfederberg, Gobabeb, and Ganab) along a transect across the central Namib Desert over a 3-year period have been collected, alongside some shorter term data sets. Rock surface temperature (RST), air temperature, wind, relative humidity, and surface wetness data are presented here. Weathering of exposure blocks of local marble and granite has also been monitored over the 3-year period, with change observed visually and with scanning electron microscopy. Complex temporal patterns of rock temperature fluctuations are observed over the 3 years, although the four sites show very similar overall trends, suggesting spatial homogeneity in the rock surface temperature regime. Relative humidity and surface wetness data show clear differences between the four sites, related to the frequency of fogs. Granite blocks show no visible changes after 2 years of weathering, whereas marble blocks (especially those at Ganab) show SEM evidence of structural weakening after 1 year.

Keywords: Granite; Marble; Rock surface microclimate; Rock surface wetness; Temperature; Weathering

1. Introduction and aims

Much remains enigmatic about weathering in desert environments. Uncertainty still exists, for example, as to what the dominant weathering processes are and how they operate, where and why rates of weathering are fastest, and how weathering contributes to landform development. Heating and cooling, salt weathering, and weathering by rock surface biofilms have all been noted to be efficacious processes in a range of desert environments, but little consensus has emerged over how they operate both individually and in combination (Smith, 1994; Goudie, 1997). Some weathering rates in desert environments have been found to be extremely rapid (e.g., the spectacular disintegration of rock blocks after only 2 years in saline hyperarid coastal pan environments in Namibia observed by Goudie et al., 1997), but such results may only be applicable to limited areas over short timescales. The contribution of various weathering processes to the development of small-scale landforms such as alveoli and tafoni has been hotly

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debated (Mustoe, 1982; Young, 1987; Turkington, 1998; McBride and Picard, 2000), and uncertainty still remains as to how weathering relates to larger scale, longer term landform development. In order to make progress on answering many of these questions, two major types of research need to be done. Firstly, more longer term and wider scale monitoring of weathering and the rock surface microclimate is required. Secondly, more modelling should be carried out which can simulate the evolution of weathering processes and features. This paper addresses the first of these issues.

The rock surface microclimate exerts a critical control over weathering, erosion, and biological community development. Rock surface temperature (RST) fluctuations, near surface humidities and wind speeds as well as rainfall and fog receipt are all critical factors in weathering and plant growth. Within arid and semiarid areas, a range of short-term studies of microclimate on rocky and sandy surfaces have been carried out, building on pioneering work during the early twentieth century such as the studies of Williams (1923) and Peel (1974). Recent investigations include those by Jenkins and Smith (1990) from Tenerife; Warke and Smith (1998) from Death Valley, California (these studies assessed temperatures on rock blocks at 15- and 1-min intervals, respectively); and Kidron et al. (2000) from the Negev, Israel who measured temperatures on microbiotic sand crusts using unspecified time intervals. These studies usually take place over timescales of a few days to a few months. However, larger scale and longer term studies are called for, linked to monitoring of weathering and more general geomorphic and ecological change.

The work presented in this paper aims to provide a 3-year quantification of microclimates across a ca. 100-km transect from the coastal plain inland across the central Namib Desert. The data collected are related to weathering of exposure blocks cut from rocks naturally occurring in the central Namib and used to make inferences about the more general relationships between microclimate, weathering, biotic communities, and geomorphology in this area. This study is novel in its timescale (3 years of data have been collected so far out of a planned 10-year project), the integrated nature of the microclimate and weathering monitoring, and in the use of locally relevant rock types.

2. The study area

The central Namib desert (see Fig. 1) is a hyperarid desert located around the Tropic of Capricorn, on the SW coast of Africa. The desert extends from around 14°S to 32°S and from around 12°E to 16°E, stretching some 120–200 km inland from the coast (Goudie, 2002). The area is dominated geologically by a suite of ancient rocks, especially schists, granites, and marbles of Precambrian/Palaeozoic age. Topographically, it forms a gently sloping plain stretching from the edge of the great African escarpment down to the coast, interspersed with inselbergs and dykes. In terms of geomorphology, a number of ephemeral rivers cross the plain, creating a heavily dissected landscape in many places. The surface alternates between expanses of bare, weathered rock and gravel-covered plains, often with gypsum-encrusted soils (gypcrete). Rainfall increases from the coast inland. Mean annual rainfall at Swakopmund on the coast is around 18 mm, at Gobabeb (some 55 km inland) it is around 21 mm, and at Ganab (over 100 km inland) it is almost 50 mm (Lancaster et al., 1984; Henschel et al., 1998). Year-to-year variability in rainfall is high, with Shanyengana et al. (2002) quoting coefficients of variation of between 120% and 135%. Fog exerts a major influence on the central Namib environment, with coastal areas affected by frequent fogs and less common fog episodes farther inland. Precipitating fogs occur, on average, around 65 days a year at Swakopmund, producing fog precipitation of ca. 34 mm per year (Lancaster et al., 1984). The receipt of moisture from fog is more predictable than that from rainfall, with a coefficient of variation of 41% (Shanyengana et al., 2002). The fog climatology is quite complicated (Seeley and Henschel, 1998), with different types of fog affecting coastal and inland areas. Coastal areas are affected by advective fogs that form under SW wind conditions, especially from May to September. Inland fogs are referred to as “high fogs“ and their occurrence peaks between August and October and in March related to the occurrence of NNE winds. Vogelfederberg and Gobabeb, although roughly the same distance from the coast, experience very different patterns of high fogs, with Vogelfederberg experiencing such events much more frequently.

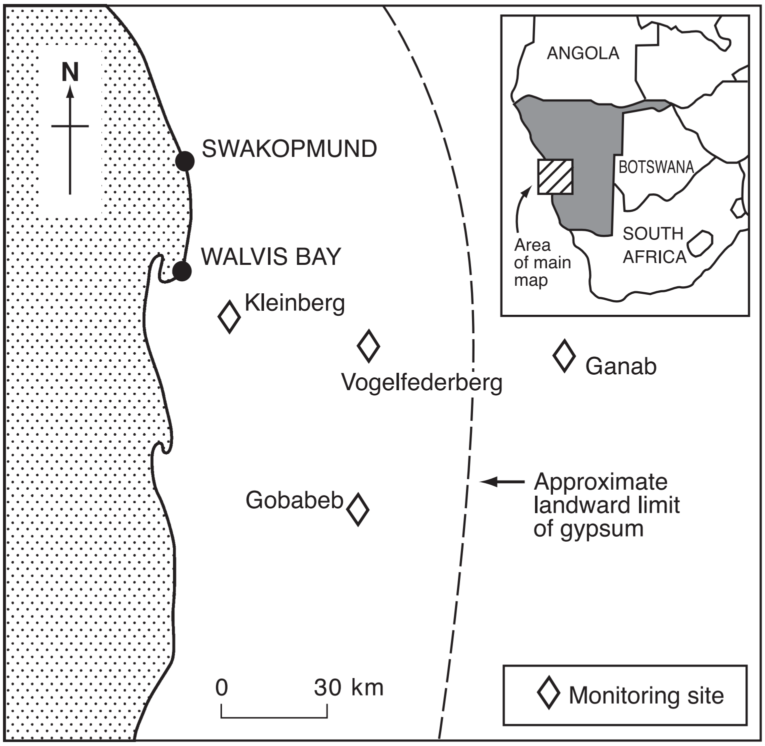


Fig. 1. Map showing the location of the four study sites.

Evidence has been put forward that weathering in the central Namib Desert is dominated by salt weathering (Goudie, 1972; Goudie et al., 1997), with biological weathering by lichens (Viles and Goudie, 2000), and dissolution of carbonate substrates by fogwater (Sweeting and Lancaster, 1982) also important; but most studies have only investigated weathering in a small area and generally only considered single processes. Rock breakdown is also encouraged by wind action (Sweeting and Lancaster, 1982), with wind fluting and ventifaction common. A wide range of geomorphic features is associated with these processes. Tafoni and alveoli, for example, are common on granite outcrops around Gobabeb; whilst outcrops of marble are commonly dissected by wind flutes, and occasionally by dissolution runnels as well as being pitted by lichen action. Flaking and granular disintegration are common in salt-rich areas, where granites and other usually resistant rocks are often highly weathered. Weathering in the central Namib is also an important source of dust and fine-grained sediment, as can be seen from the ramparts of disintegrated material found around many weathered boulders and outcrops. Fig. 2 illustrates some of the rock breakdown features found here.

Weathering has played a key role in landscape evolution in the Namib Desert over the past few million years. Weathered material becomes entrained by wind or moved downslope through runoff and removed by episodic ephemeral river flows. Recent studies using cosmogenic isotope dating have suggested that, over the last 2–5 Myr, denudation rates have been extremely slow within the Namib desert and great escarpment areas. Van der Wateren and Dunai (2001) found rates of 0.1–1 m Ma^{-1} over the past 5 Myr, for example, whilst Bierman and Caffee (2001) identified rates of between 1 and 16 m Ma^{-1} over the Pleistocene. Furthermore, Bierman and Caffee (2001) found no significant difference in rates across the Namib desert and escarpment, despite a fivefold gradient in rainfall, nor did they find any significant lithological differences in denudation rate. Bierman and Caffee (2001) also illustrate that many surface clasts on flat-lying desert gravel surfaces appear to be extremely old, with surface exposure

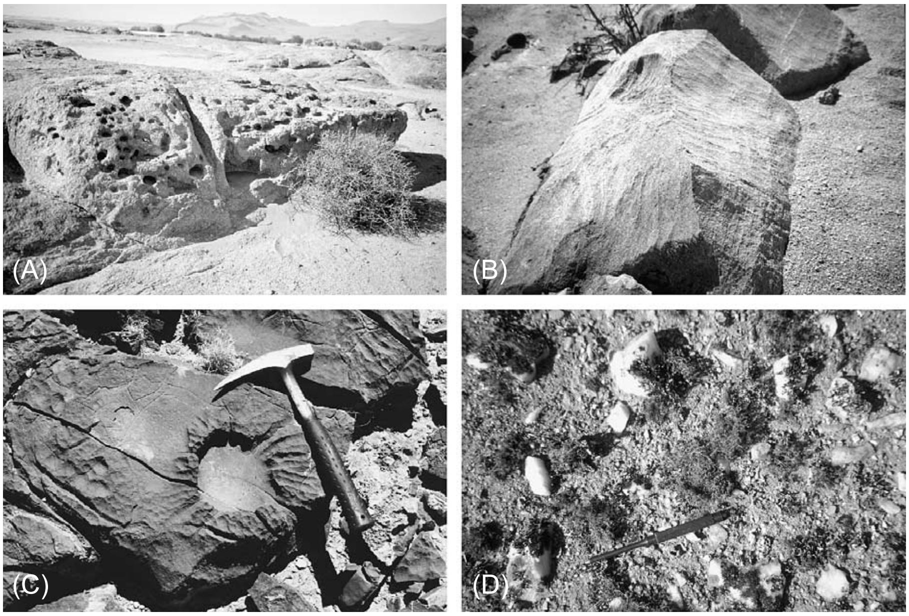


Fig. 2. Examples of rock breakdown features in the central Namib desert: (A) alveoli developed in granite; (B) wind fluting (on right side of image, which corresponds to east-facing) and lichen colonization (on left side, corresponding to west-facing) on marble; (C) microkamenitza developed in limestone; (D) quartz pebble-strewn desert surfaces with foliose and crustose lichen development. Chisel for scale is ca. 10-cm long.

histories approaching 3 Myr, indicating very slow rates of rock breakdown.

3. Methodology

A transect of four monitoring sites has been established across the central Namib, located at meteorological stations set up by the Desert Research Foundation of Namibia (DRFN) in order to collect microclimatic and weathering data. Site details are given in Table 1. Kleinberg is a near-coastal site in the zone that commonly receives coastal advective fogs and very low rainfall amounts. Vogelfederberg and Gobabeb are both around 50–60 km from the coast, with Vogelfederberg typically receiving more high fogs than Gobabeb. Ganab is around 112 km inland in a zone characterised by relatively high rainfall and very low fog precipitation. At each site, preweighed blocks 15×3×3 cm in dimensions cut from locally quarried Karibib marble and Damara granite have been emplaced to monitor weathering. Five blocks of each type were placed directly on the ground surface at each site, with five blocks of marble placed on a weathering platform at ca. 30 cm above the desert surface and five blocks of granite half-buried in the soil. Marble blocks

Table 1
Details of monitoring sites

Site name	Kleinberg	Vogelfederberg	Gobabeb	Ganab
Distance from coast (km)	25	60	55	112
Height asl (m)	100	500	400	970
Rock type			Granite	
Surface characteristics	Gravel plain/gypcrete	Gravel plain	Rocky outcrop	Calcrete
Ecology	Lichen field	Sparse lichens	No lichens, sparse grasses	Mixed grasses
Marble temperature record	Continuous April 1999–March 2002	ca. 2 weeks missing data	Continuous April 1999–March 2002	ca. 1 month missing data
AWS data records	3 months missing data	6 months missing data	Record starts November 2000	11 months missing data

were emplaced in April 1999 and granite blocks in July 2000.

The experiment was designed to investigate differences in weathering experienced by blocks submerged within the desert surface, those resting on the desert surface and those isolated from the desert surface but exposed to the same climatic conditions. Within the central Namib Desert, there often seems to be a concentration of weathering activity at the surface/rock interface that should be picked up by this study. Logistical constraints meant that blocks of both rock types could not be emplaced in all three microenvironments without reducing the number of replicates, which was thought to be undesirable. Locally relevant materials were used in order to relate the experimental results more closely to the natural weathering experienced in the area. Karibib marble is a calcareous marble of Proterozoic age formed between 600 and 850 Myr ago, often very white in colour (as in the blocks used in this experiment which were almost pure white) with a very low water absorption capacity (0.06–8% as measured under laboratory temperatures and pressure after 1 week of soaking in water). Damara granite is a pinkish-brown, coarse-grained granite dating back some 470–650 Myr. Porphyritic and biotite-rich, with large crystals (often several millimetres in dimensions), Damara granite is also only slightly porous in unweathered form, with a water absorption capacity of 0.16%. Although no precise measurements have been taken of the blocks, albedo values on the marble are much higher than on the granite, whilst thermal conductivities have in general been found to be higher on igneous rocks than on limestones and marbles (e.g., McGreevy et al., 2000). Lower thermal conductivities control the difference in temperature between the outside and inside of a block and thus its susceptibility to spalling (Goudie et al., 1992). McGreevey et al. (2000) document the importance of both albedo and thermal conductivity to maximum surface temperatures and surface–subsurface temperature gradients.

A Gemini Dataloggers rock surface temperature probe attached to a Tiny Tag datalogger was attached to the top of one of the marble blocks on the ground surface at each site, set to record every 3 h. A tight fit of the probe tip against the rock surface was achieved by strapping the end of the probe attached to the wire closely to the rock sample with tape. The top surface of each probe was covered with aluminium foil in order to prevent direct heating from above. The aluminium foil cover was shaped so that it also helped to anchor the probe firmly onto the rock surface. Data were downloaded after periods of between 9 and 18 months, providing an almost complete data series for the whole period. At each site, a DRFN automatic weather station recorded air temperature, wind speed and direction, rainfall and fog, solar radiation, and relative humidity hourly, although there are some gaps in the record because of equipment malfunction. At three of the four sites (all but Kleinberg), the automatic weather station also has a rock surface probe recording rock surface temperatures on a rock outcrop (which varies in lithology and size from site to site) at hourly intervals and a leaf wetness sensor measuring surface wetness on

Fig. 3. Experimental setup at Gobabeb: (A) automatic meteorological station with rock surface temperature probe and exposure blocks in front; and (B) detailed view of rock surface probe, weathering platform, and granite and marble exposure blocks.

a semiquantitative basis. Fig. 3 illustrates the experimental setup. Data are presented in this paper for the 3 years of monitoring from April 1999 to March 2002.

Allied to this long-term data collection exercise have been two short-term monitoring programmes, in April 1999 and July 2000, when data on rock surface temperatures and surface wetness were collected every minute over 24-h cycles. Observations have also been taken of sediment chemistry (conductivities and chloride, and sulphate contents) at all sites following the methods outlined in Goudie et al. (1997). One sample of surface and near-surface sediment, down to a depth of ca. 5 cm, was analysed. Conductivities were measured using a laboratory conductivity metre after soaking sediment samples for 5 days in distilled water. Chloride and sulphate contents were measured using a Dionex ion chromatograph. Finally, simple observations have also been made of the weathering status of a subsample of blocks after 1–3 years of exposure using optical and electron microscopy. Marble blocks resting on the ground surface were sampled in 2000 (after 1 year of exposure) and 2002 (after 3 years of exposure), and granite blocks (both those resting on the ground and those half buried in the sediments) were sampled in 2002 (after 2 years of exposure). Blocks were fractured using a geological hammer and cold chisel, and both top surfaces and cross-sections from the outer face into the centre of the block were observed in detail. Control samples were also observed for comparative purposes. After an initial pilot study, a range of marble samples (both exposed and control) were observed after gold coating using a Cambridge Stereoscan 90 electron microscope in order to test whether there were any visible signs of deterioration at this scale. In the pilot study, the more complex mineralogically and geochemically complex Damara granite did not show any clear signs of weathering observed on the granite under the SEM that might usefully be used to compare the nature and degree of weathering at each site.

4. Results

4.1. Long-term microclimatic data

Three-hourly rock surface temperature (RST) data from one marble block resting on the ground surface at

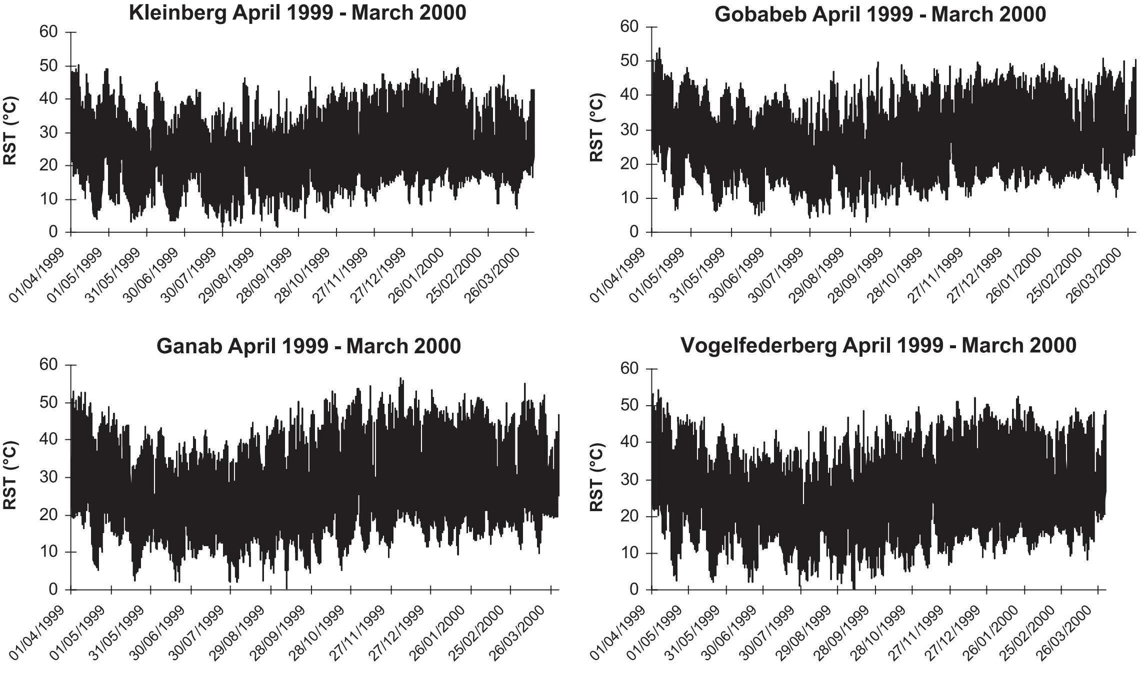


Fig. 4. April 1999–March 2000 three-hourly rock surface temperature data, all four sites.

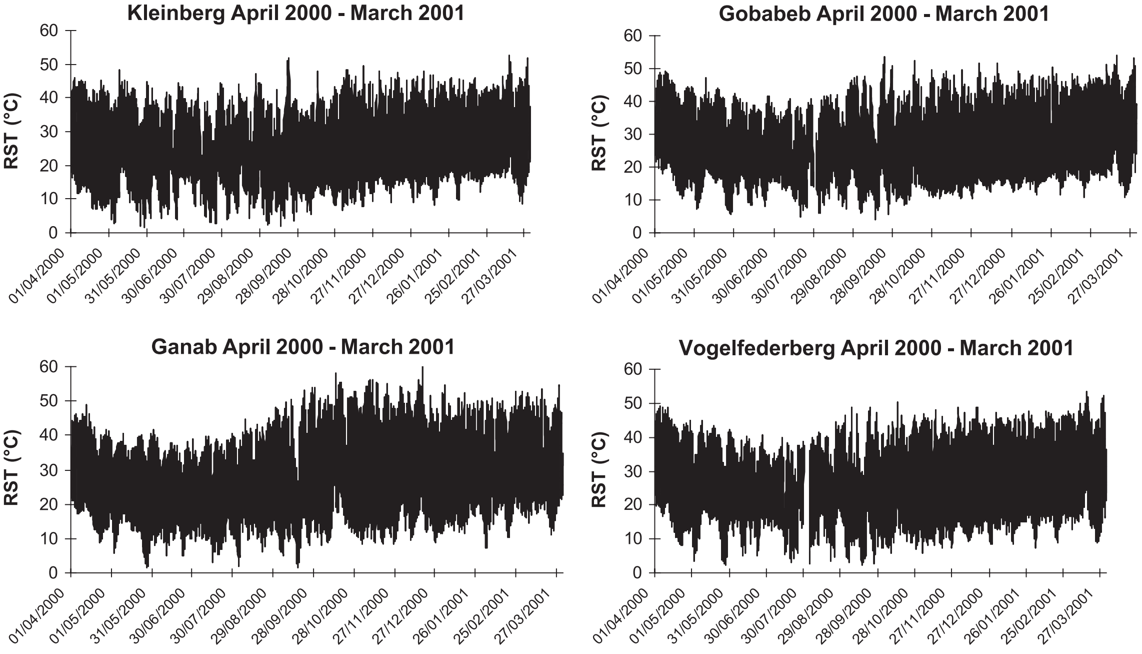


Fig. 5. April 2000–March 2001 three-hourly rock surface temperature data, all four sites.

each of the four sites are presented in Figs. 4–6 and summarised in Table 2. Figs. 4–6 illustrate the similarities in the general pattern of annual rock surface temperature regime at each site, with, for example, July–August 2001 showing a similar unusual pattern of a few hot days followed by a much colder period at all

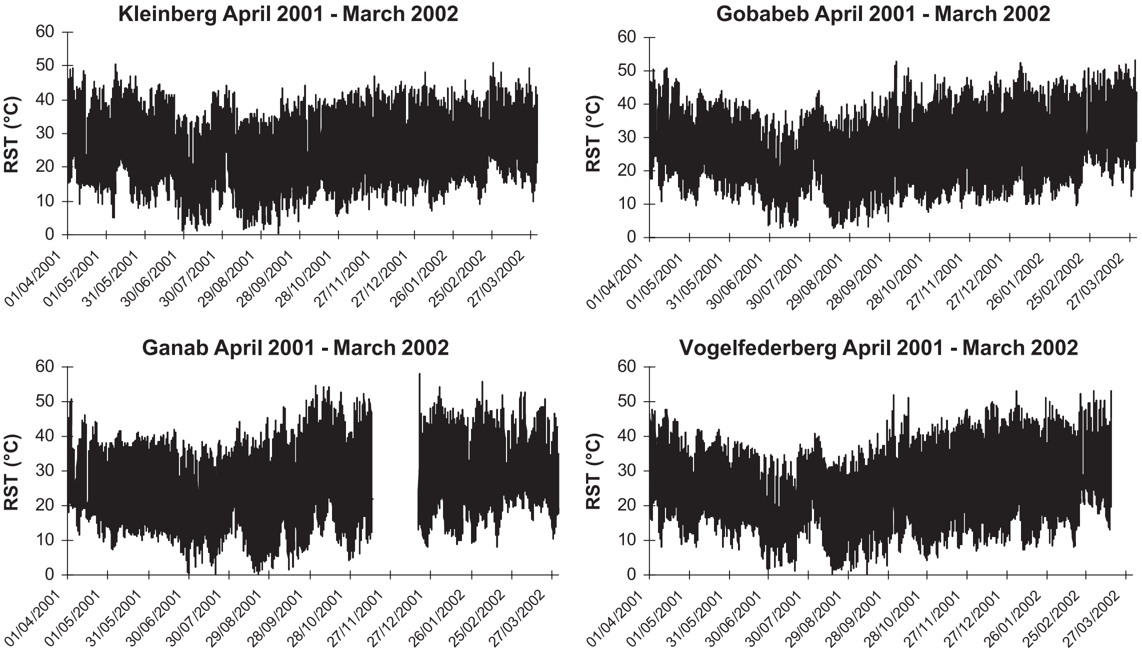


Fig. 6. April 2001–March 2002 three-hourly rock surface temperature data, all four sites.

Table 2
Summary of three-hourly rock surface temperature data

Site	Year	Mean RST (°C)	Max RST (°C)	Min RST (°C)	No. of days>50 °C	No. of days<0 °C	Notes
KB	1999–2000	21.94	49.71	1.47	0	0	
	2000–2001	22.32	52.7	1.68	5	0	
	2001–2002	22.48	51.04	0.69	2	0	
VFB	1999–2000	23.76	54.13	0.48	15	0	
	2000–2001	23.83	52.9	2.2	7	0	
	2001–2002	23.07	53.13	0.06	11	0	0.5 months missing data
GB	1999–2000	24.63	54.04	3.23	9	0	
	2000–2001	24.97	53.63	3.85	15	0	
	2001–2002	24.61	53.05	2.8	16	0	
GA	1999–2000	25.13	56.36	0.73	59	0	
	2000–2001	25.27	61.52	1.35	86	0	
	2001–2002	24.17	57.64	−0.33	34	2	1 month missing data

four sites. Furthermore, comparison of the graphs for the 3 years at each site indicates that there is considerable variation in the detail of annual rock surface temperature regime from year to year. However, all sites exhibit a general seasonal pattern of warm summer rock surface temperatures from around

Table 3
Conditions in February and August each year at each site (ND = no data)

Site	Month	Mean RST (°C)	Max RST (°C)	Min RST (°C)	Mean air temperature (°C)	Max air temperature (°C)	Min air temperature (°C)	Rain (mm)	Mean wind speed (knots)	Max wind speed (knots)	Dominant wind direction
KB	Feb 2000	25.57	47.24	13.23	19.23	30.64	13.22	ND	4.9	11.2	68% W–N
	Feb 2001	24.97	45.69	9.57	19.23	29.87	9.45	ND	4.4	9.5	55% W–N
	Feb 2002	26.10	51.04	9.02	21.98	40.38	9.31	ND	4.3	9.5	41% W–N
VFB	Feb 2000	25.23	48.46	10.97	19.52	32.5	12.44	0.2	5	12.5	78% W–N
	Feb 2001	26.30	47.13	7.32	20.43	32.49	8.78	0	4.4	8.5	63% W–N
	Feb 2002	27.67	52.32	7.95	22.77	37.97	9.38	5.2	4.4	9.1	49% W–N
GB	Feb 2000	25.79	47.96	13.55	ND	ND	ND	ND	ND	ND	ND
	Feb 2001	27.52	48.15	11.17	23.2	35.27	11.92	0	4.2	8.7	56% W–N
	Feb 2002	28.34	50.61	10.11	25.20	39.77	11.73	7.5	4.1	10.3	42% W–N
GA	Feb 2000	27.21	50.78	12.47	22.03	34.58	12.22	10.1	4.1	10.6	57% W–N
	Feb 2001	28.98	52.7	7.39	23.65	35.64	9.27	0	3.9	9.6	40% W–N
	Feb 2002	28.67	54.86	8.47	24.56	37.23	10.50	41.7	4.2	12.5	33% S–W
KB	August 1999	18.25	46.29	1.9	16.13	39.93	2.88	ND	4.4	16.2	28% S–W, 28% E–N
	August 2000	20.17	46.97	3.73	17.62	38.85	4.95	ND	4.2	16.5	31% S–W
	August 2001	18.33	44.37	1.92	15.34	35.58	2.51	ND	4.1	13.9	35% S–W
VFB	August 1999	19.02	44.39	2.84	17.11	37.19	4.75	0.1	4.4	16.5	31% E–N
	August 2000	22.51	44.1	2.68	20.45	36.74	5.64	0.5	4.4	16.5	35% E–N
	August 2001	17.86	40.56	0.06	16.05	33.78	2.69	0.1	3.8	14.4	33% S–W, 31% E–N
GB	August 1999	20.09	46.94	4.46	ND	ND	ND	ND	ND	ND	ND
	August 2000	23.34	46.64	4.84	ND	ND	ND	ND	ND	ND	ND
	August 2001	19.78	43.96	2.8	18.10	36.16	4.28	0	3.4	14.5	41% S–E
GA	August 1999	20.18	44.5	2.16	18.56	33.28	3.75	0	4.5	15.8	35% S–E
	August 2000	22.41	48.32	2.12	20.91	33.90	6.49	0	4.5	12.8	45% S–E
	August 2001	19.30	44.9	−0.33	16.74	31.84	4.24	0.1	3.6	11.7	39% S–E

December to March and a notable winter cool period between about June and September. At the finer scale, Figs. 4–6 illustrate a sequence of weather patterns over periods of a few weeks, producing bundles of colder followed by warmer episodes. These patterns probably relate to the passage of major depressions and anti-cyclones over southern Africa. At the diurnal scale, Figs. 4–6 illustrate the huge variation in temperature over each daily cycle, usually around 35 °C. Table 2 and Figs. 4–6 also indicate the major differences between rock surface temperature regimes at the four sites. Kleinberg, in the fog belt, shows a much more

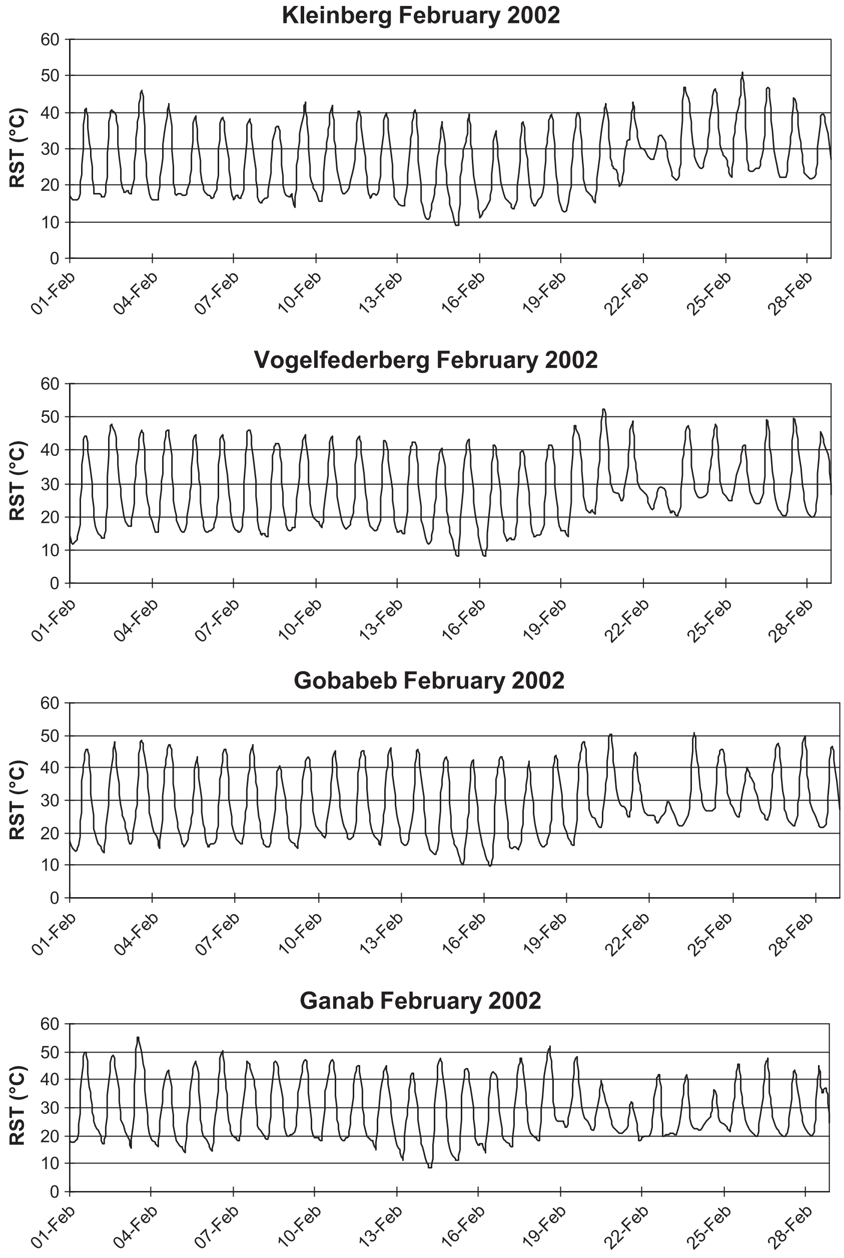


Fig. 7. Three-hourly rock surface temperature data for February 2002 for all four sites.

muted temperature range with relatively few days per year where temperatures reach above 50 °C. Vogelfederberg and Gobabeb, at roughly 55–60 km inland, experience a more variable temperature regime; whilst Ganab experiences the most pronounced fluctuations in temperatures with at least 50 days in most years having maximum temperatures over 50 °C, and with the year 2001–2002 experiencing temperatures less than 0 °C on two occasions.

In order to simplify the data set and provide some more detailed analyses, data from February and August each year have been extracted to represent, respec-

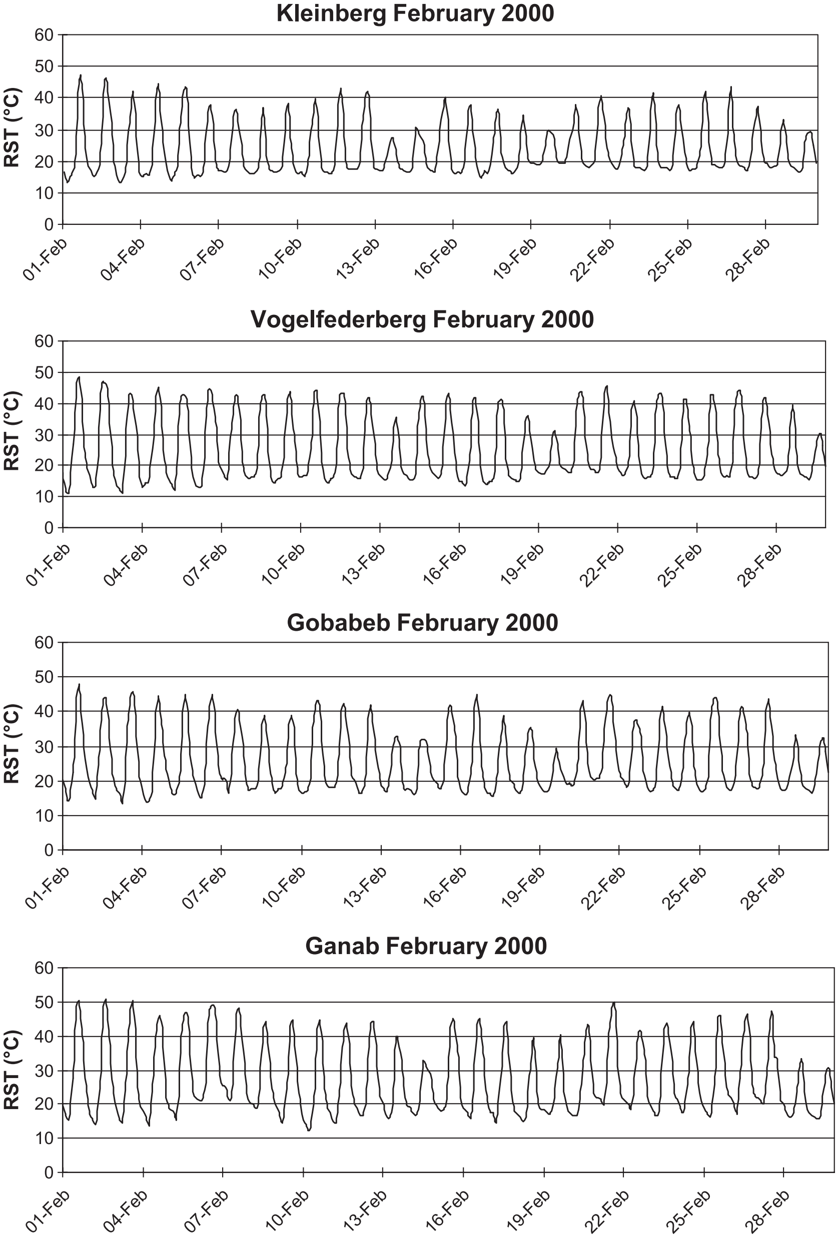
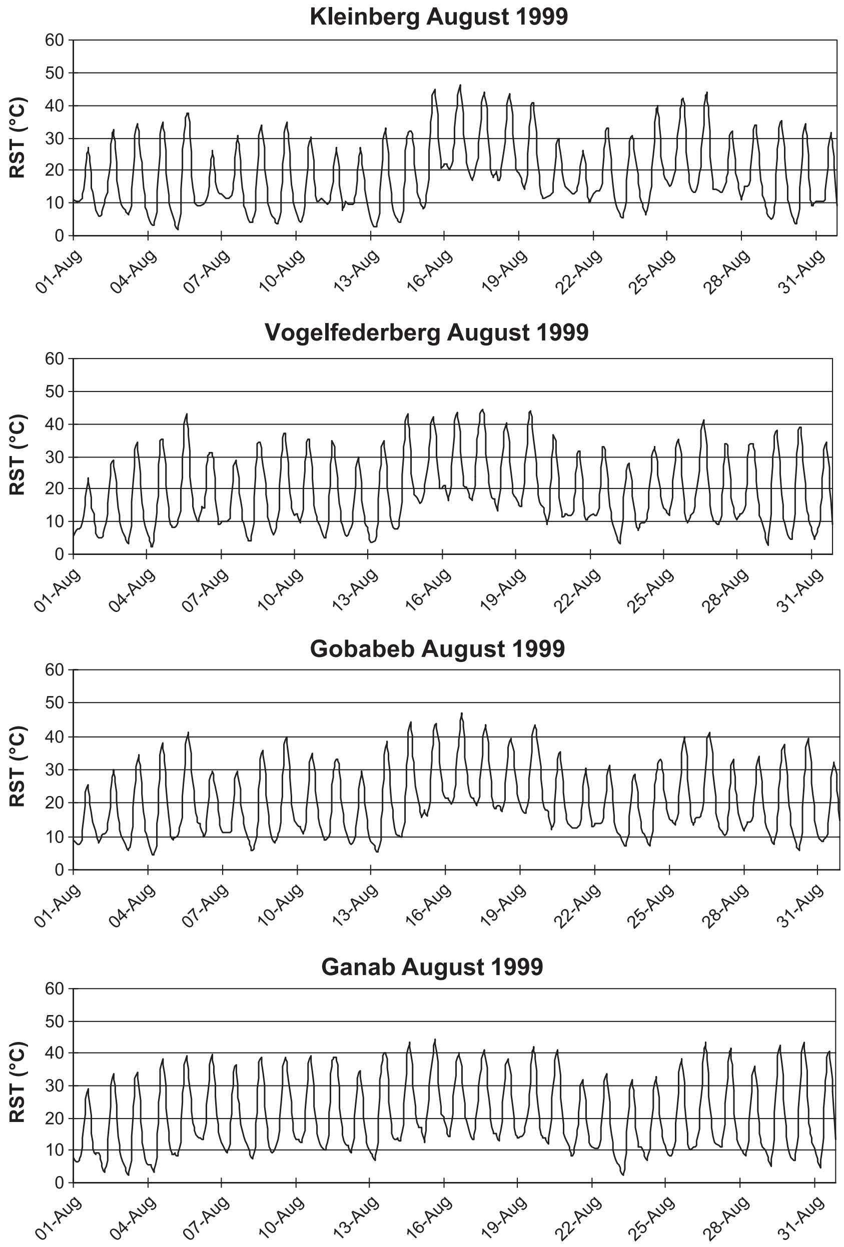


Fig. 8. Three-hourly rock surface temperature data for February 2000 for all four sites.

tively, late summer and late winter conditions. Summary data are presented in Table 3 and reveal clear seasonal differences as well as variability between different years. Looking first at data from each site for February, at all sites and in each year rock surface temperatures on the marble block very rarely drop below 10 °C and, unless a fog event occurs, rise to over 40 °C everyday. The synchroneity of weather patterns across the desert is also apparent; with, for example, fog conditions experienced on 22.2.02 at Kleinberg,


Kleinberg August 1999

Vogelfederberg August 1999

Gobabeb August 1999

Ganab August 1999

Fig. 9. Three-hourly rock surface temperature data for August 1999 for all four sites.

Vogelfederberg, and Gobabeb, with a muted temperature range a day earlier at Ganab (Fig. 7). Similarly, fogs were experienced on 13 and 14 February 2000 at Kleinberg and Gobabeb and on 14 February at Ganab (Fig. 8). Turning to August data, as summarised in Table 3, much cooler conditions at night are evident, although there are several warm spells during the daytime. At Kleinberg from 13 to 16 August 1999, rock surface temperatures range from about 2 to 45 °C, as a couple of cold days are followed by a warm spell (see Fig. 9). August 2001, in comparison, exhibits a much more consistent pattern of rock surface temperature fluctuations at each site (see Fig. 10).

Table 3 allows us to compare rock surface temperatures with air temperatures for February and August data sets, although the incomplete air temperature data

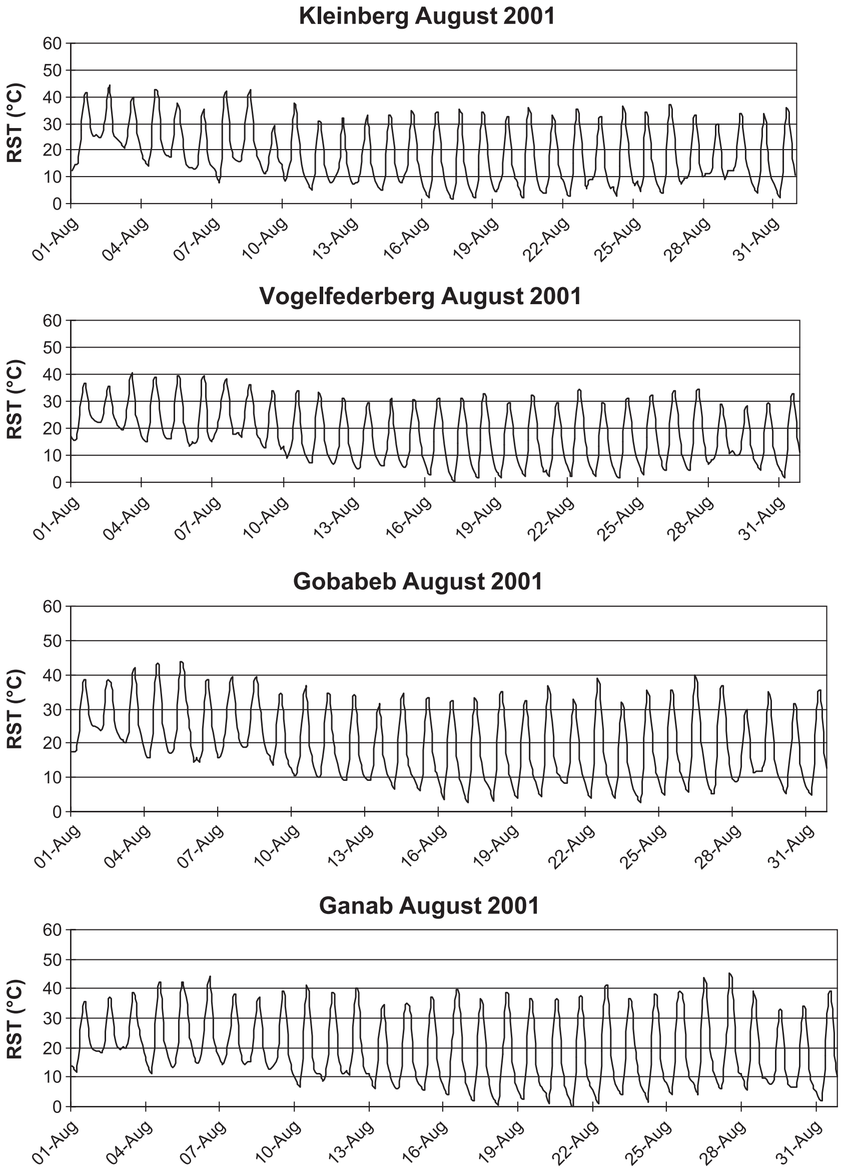


Fig. 10. Three-hourly rock surface temperature data for August 2001 for all four sites.

set from Gobabeb precludes a detailed analysis for this site. At all the other sites, February mean rock surface temperatures are between 3.5° to 6° above mean air temperatures; whereas in August, they are between 1.5° and 3° above. Maximum rock surface temperatures exceed maximum air temperatures in February by up to 18 °C and in August by between 6° to 13°. For both months, the greatest difference between rock surface and air temperatures is found at Ganab. Looking at minimum temperatures, most sites have February rock surface temperatures around the same as air temperatures (especially at Kleinberg) or below air temperatures by up to 1.5° to 2°; whereas in August, rock surface temperature minima are 1° to 4.5° below air temperatures.

Table 3 also contains summary data on wind speed and direction at each site for February and August during the 3-year period. Broadly similar patterns of wind speed occur at each site, with August exhibiting higher maximum wind speeds than February each year. No clear interannual pattern emerges. In terms of direction, again, a clear seasonal pattern is evidenced with August at each site dominated by winds coming from between W and NNW; whereas in February, a more complex pattern emerges with a less obvious dominance of any one wind direction at each site. Kleinberg is generally dominated by winds from S–WSW, with Vogelfederberg receiving winds from E–ENE dominantly, and Ganab winds from E–SSE. These data exhibit very similar trends to those recorded by Lancaster et al. (1984) from 3–5 years of monitoring at similar sites. As Lancaster et al. (1984) pointed out, the central Namib Desert is dominated by winds from three sectors, W–SSW, NW–NNE, and NE–E. From December to February, winds from the N to W dominate; whereas between May and August, those from the E to NE occur most frequently, whilst between September and November, winds from the S to SW dominate. The calmest months generally are April and August. Strong easterly winds (known as Berg winds) occur between April and September when regional pressure gradients normal to the coast produce high velocity winds (up to 50–60 km/h). These winds will both encourage rock surfaces to dry out and entrain dust and sand which can abrade rock surfaces. East-facing marble outcrops across the Namib desert often show spectacular wind fluting, whilst west-facing outcrops are covered with lichens.

Table 4 contains data on surface wetness for August and February each year for Vogelfederberg, Gobabeb, and Ganab. Only a limited data set on relative humidity was available for Kleinberg. The surface wetness indicators provide semiquantitative assessments, and here, a cut-off point of 25% has been taken as representing observable wetness, and then the number of wet events was calculated per month. As might be expected, Ganab has the least number of surface wetness-producing events, with Gobabeb and Vogelfederberg showing similar patterns, although in most months Vogelfederberg has a few more surface wetness-producing events (see, for example, the data set from August 1999 in Fig. 11). Data on relative humidity at Kleinberg for August 1999 shown in Fig. 11 illustrate the more frequent presence of 100% humidity there as compared with the other sites, which will be reflected in higher numbers of surface wetness-producing events. These data also confirm the studies of Lancaster et al. (1984) that showed that fog precipitation events are most common near the coast, with relatively high levels at Vogelfederberg and very low levels at Ganab. However, although surfaces might become moist through fog, it is difficult, without sampling subsurface moisture contents, to know how significant fog is as an agent of water ingress to the subsurface zone of rocks.

Table 4
Number of days with wet surface events (where wet surfaces identified as >25% on wetness indicator scale) (ND = no data)

Site	Month	Year	No. of days with wet surface events
Vogelfederberg	February	2000	26
		2001	25
		2002	26
Gobabeb	February	2000	ND
		2001	27
		2002	19
Ganab	February	2000	14
		2001	11
		2002	12
Vogelfederberg	August	1999	11
		2000	9
		2001	17
Gobabeb	August	1999	ND
		2000	ND
		2001	14
Ganab	August	1999	6
		2000	3
		2001	14

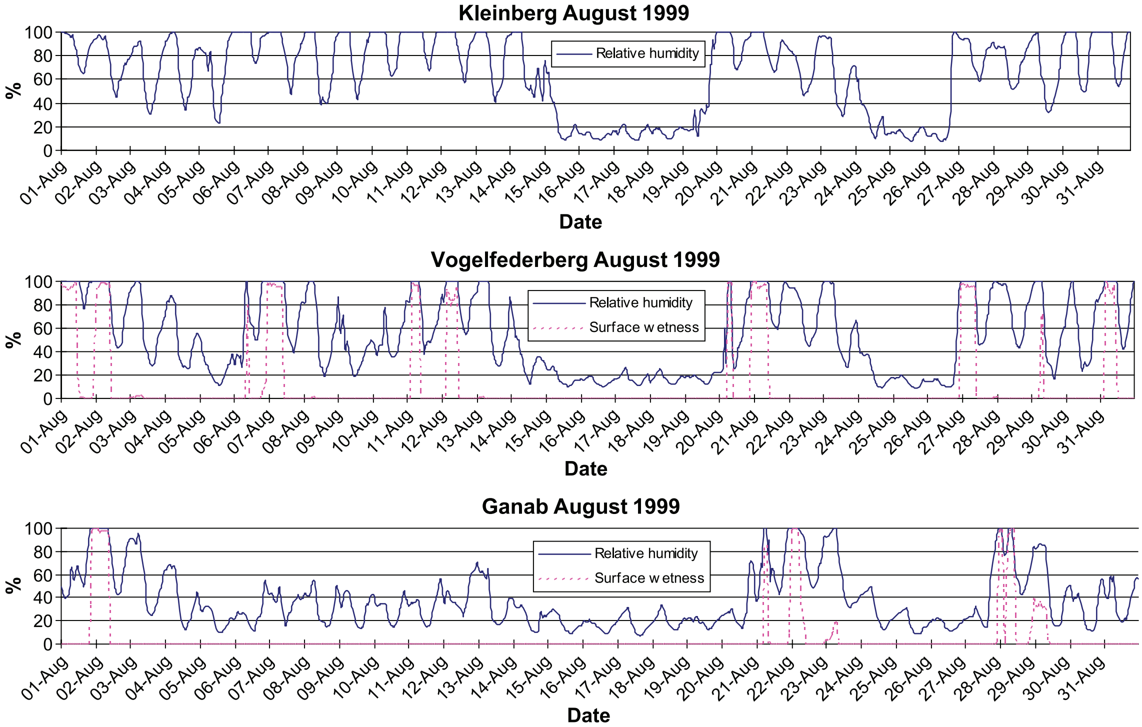


Fig. 11. Relative humidity and surface wetness data from August 1999 for Kleinberg, Vogelfederberg, and Ganab (surface wetness was not measured at Kleinberg).

4.2. Short-term microclimatic data

Short-term data can be used to investigate in more detail the microclimatic characteristics of the rock surface environment. Three data sets involving data collected every minute are presented here. Firstly, rock surface temperature data were collected on a marble and a granite block in July 2000 over a 24-h cycle at Gobabeb to examine the different responses of the two rock types. As illustrated in Fig. 12, the granite block heated up more than the marble block during the early afternoon (reaching a maximum of 41.56 °C as opposed to 38.64 °C on the marble surface, almost 3 °C higher). This was an expected

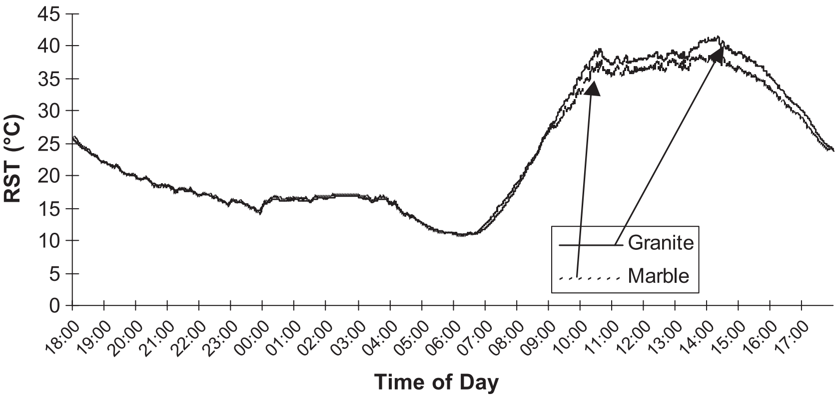


Fig. 12. One-minute rock surface temperature values for a granite and a marble block over a 24-h cycle.

result, as the darker granite surface has a lower albedo and thus will absorb more of the incident radiation. The mean temperature over the 24-h period was slightly higher on the granite block (23.94 °C as opposed to 23.38 °C), and the marble block surface cooled to 10.64 °C minimum temperature compared with 10.87 °C on the granite. These results indicate that long-term monitoring, if carried out on the granite rather than marble block, would have revealed higher overall temperatures. Both temperature profiles show short-term fluctuations superimposed on the general diurnal trend, and Fig. 13 illustrates these as changes in temperature per minute. The marble block experienced wider fluctuations in temperature per minute (up to ca. 1.3 °C) than the granite. Neither block experienced changes in temperature of 2 °C or greater per minute, which is seen by many workers as the threshold rate for the production of thermal shock damage (Hall and Andre, 2001). However, the rates of change observed may well produce thermal fatigue in sensitive rocks.

However, a second data set indicates the possibility of thermal shock occurring when wetting affects a heated surface. An experiment was carried out in July 1999, monitoring temperature every minute over 1 h between 2 and 3 p.m. on a dry granite natural rock surface and on an adjacent artificially wetted natural granite surface at Gobabeb. Results are shown in Fig. 14. Temperature gradients of >2 °C/min did not occur at all on the dry rock surface but occurred as the wetting event took place and then subsequently as water evaporated on the other surface. If such cooling on wetting and evaporative cooling have a significant impact on the underlying rock, then thermal shock weathering may occur.

A third short-term data set illustrates the links between surface wetness and the diurnal temperature changes. Rock surface temperatures were collected on

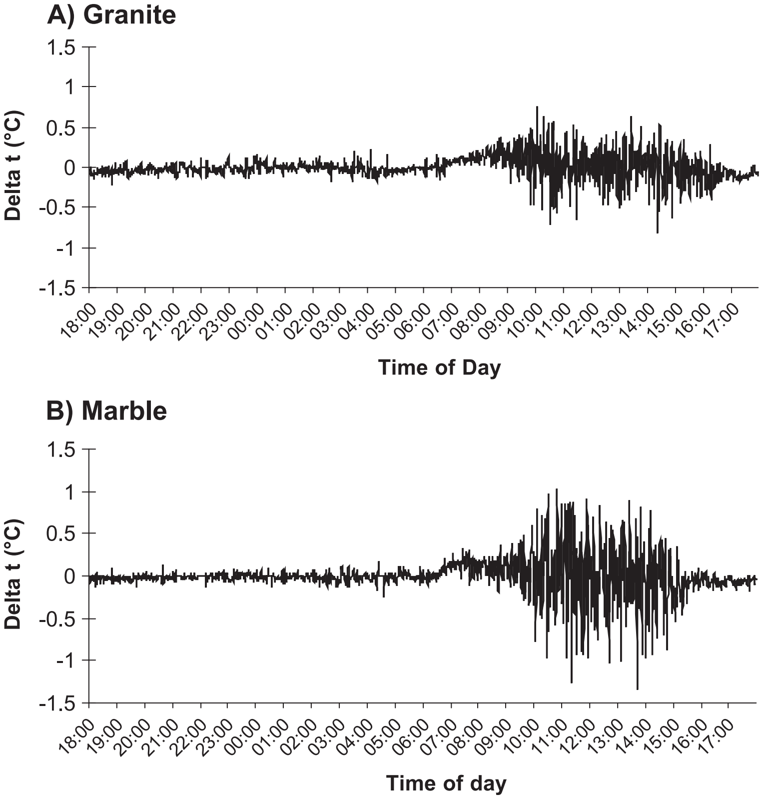


Fig. 13. Changes in temperature per minute on (A) granite and (B) marble block over a 24-h cycle.

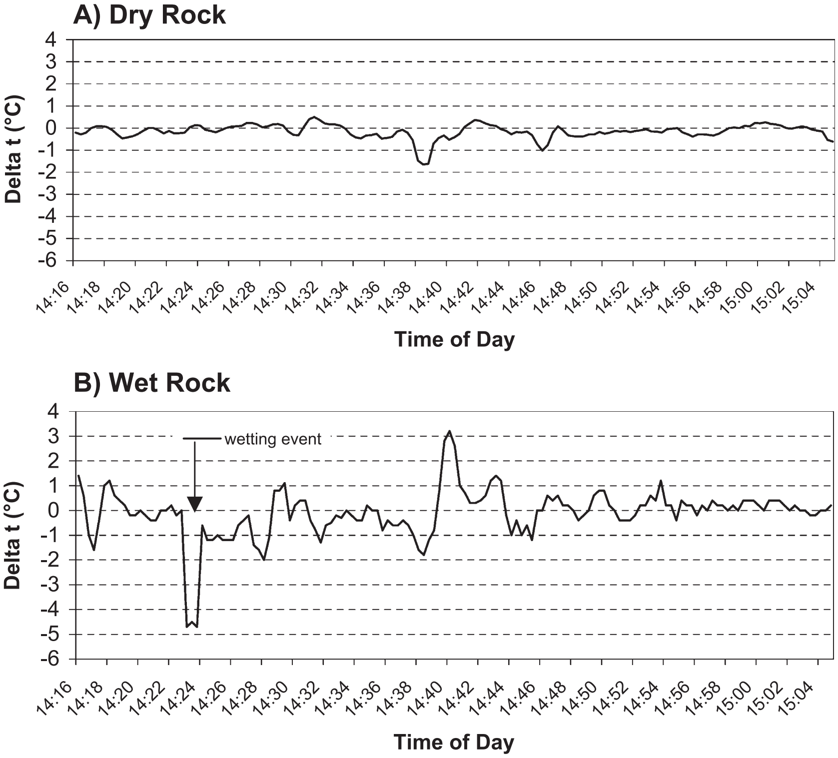


Fig. 14. Rock surface temperature changes every minute on (A) dry granite and (B) wet granite rock surface over a 1-h period.

a marble block with a leaf wetness sensor lying next to it over a 24-h cycle in August 2000 at Gobabeb. Results are shown in Fig. 15. The marble block surface reached a maximum temperature of 34.29 °C around 1 p.m., with a minimum of 5.73 °C and a mean 24-h temperature of 16.94 °C. No fluctuations in temperature of greater than 1.5 °C/min were observed, ruling out thermal shock. Using a cut-off of 25% on

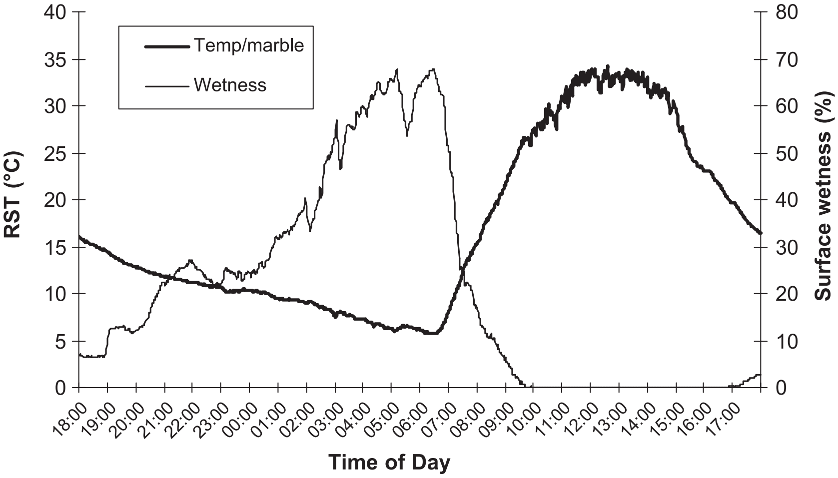


Fig. 15. Surface wetness and rock surface temperature on a marble block over a 24-h period.

the wetness scale with values above this representing a wet surface, and for the 24-h cycle monitored, a flat smooth rock surface would have been wet over night from around 11:00 p.m. to 7:30 a.m. The trends would probably have been very different if a foggy day had been studied, as found during other short-term monitoring exercises in this area when much higher surface wetness values have been observed for long periods during the day.

4.3. Weathering response and surface characteristics

One of the problems of linking microclimatic data to weathering response in field-based studies is the slow, subtle changes that occur to test substrates over a 1–5-year period. In this study, some insights into the weathering behaviour of the two rock types come from the optical and electron microscopy. The most notable visual change to blocks seen under the optical microscope and also visible by eye was a patchy cover of dust. Dust may contribute to both weathering and the production of rock coatings (Ollier, 1965; Bishop et al., 2002) and its role in the Namib needs further investigation. Ollier (1965) recorded shattered quartzite boulders on the desert pavement at Coober Pedy, South Australia that he hypothesized were caused by expansion and contraction associated with temperature changes and movement of dirt in cracks.

Neither granite nor marble blocks showed any clear visible signs of decay, unlike similar marble blocks exposed for 2 years in a near-coastal salt pan north of Swakopmund between 2000 and 2002 that showed intense surface sugaring and deterioration. Neither were there any visible microorganism communities colonizing the blocks nor lichens growing on the block surfaces. However, SEM observations showed the marble blocks to be undergoing internal weakening through widening of grain boundaries and occasional cracking of calcite crystals—in a very similar manner to the experimentally heated and cooled marble blocks observed by Goudie and Viles (2000). Control blocks were not so affected, with grains still tightly interlocked. The block exposed for 3 years at Ganab seemed to be the most affected of the field-exposed blocks, crumbling to granular debris easily when subsampled with a geological hammer and cold chisel. Ganab is the site with least fog events and the highest diurnal temperature ranges. Marble is very susceptible to thermal degradation because of anisotropy in the thermal response of calcite. According to Royer-Carfagni (1999) and as found experimentally by Goudie and Viles (2000) and Zeizig et al. (2002) and modelled numerically by Weiss et al. (2003), calcite expands more in the direction of its optical axis than perpendicular to it, producing granular disintegration of marble made up of tightly interlocking calcite grains. In the absence of any SEM evidence for dissolution, biological weathering or salt crystallisation occurring on the marble blocks, thermal expansion, and contraction producing fatigue and crack development is proposed as the most likely process occurring during the initial stages of breakdown.

Conductivity analyses on the sediments revealed that Kleinberg had the saltiest sediments (conductivity of 7340 μS cm^{-1}), followed by Gobabeb and Vogelfederberg (838 and 534 μS cm^{-1}, respectively), with Ganab having the lowest salt contents (186 μS cm^{-1}). These results can be compared with conductivities of up to 104,000 μS cm^{-1} obtained from surface sediments in a near-coastal salt pan around 100 km north of Swakopmund where marble blocks exposed for 2 years suffered considerable breakdown. Ion chromatography identified the major anions at each site as chloride and sulphate, suggesting the presence of halite and gypsum within the surface sediments, as has been recorded by other studies in the central Namib Desert (Goudie et al., 1997). Ganab, the site possessing the least salts within its surface sediments and exhibiting the least number of fog events per year, is surprisingly enough the site showing the greatest breakdown in the marble exposure blocks.

In order to set the behaviour of the blocks in context, it is important to briefly describe the local geomorphology and ecology at each site (see Table 1). Observations of surface biology at each exposure site showed that only Kleinberg has appreciable lichen cover, as it is the only site clearly within the fog belt. Here, most large clasts and some of the gypsum-encrusted surface sediments are covered with an array of crustose and foliose lichens. As shown experimentally by Carter and Viles (2003), lichen cover may act to reduce thermal stresses within rocks as it maintains moisture at the surface. The Ganab, Vogelfederberg, and Kleinberg monitoring sites are all situated on clast-strewn geomorphic surfaces with no major rock outcrops, whereas the Gobabeb site is situated on a sediment covered granite surface, with some heavily weathered granite outcrops (as shown in Fig. 2A). There is no obvious difference in the nature of weathering features across the desert, which might be related to any climatic gradient; in contrast, it appears that lithology is the major control.

5. Discussion and conclusions

The data presented in this paper indicate some key general similarities between the rock surface microclimates in four locations across a ca. 100-km transect from the coast inland in the central Namib Desert. The weekly to annual pattern of rock surface temperature fluctuations at each site is very similar, as revealed by the similarities between the graphs from each site in Figs. 4–6 (annual trends) and the similarities between February and August rock surface temperature fluctuation patterns for each site in each year. However, study of the data in Table 2 indicates a trend in mean rock surface temperatures from the coast inland, with the near-coastal site (Kleinberg) experiencing a much more muted diurnal temperature regime compared to the inland site of Ganab. Such trends are echoed in the mean rock surface temperature and mean air temperature data for each site for February and August—which illustrate a general difference between Kleinberg and Vogelfederberg (cooler) and Gobabeb and Ganab (warmer). However, an important component of interannual variability occurs within the data sets that makes any generalisations hard to uphold, even over a 3-year timespan. The data also illustrate some differences between sites in terms of surface wetness event frequencies and rainfall patterns (see Tables 3 and 4), with Vogelfederberg recording more frequent wetting in comparison with Gobabeb and Ganab, probably related to fog occurrence, in which case Kleinberg will also show frequent wetting; but a fuller data set is needed before any clear conclusions can be reached.

The rock surface temperature data can be compared with that collected from other desert areas. The limited temperature data from microphytic surface crusts in the Negev compares well with that from Namibia presented here, showing peaks of ca. 30–50 °C in the early afternoon and lows of 5–20 °C in the early morning before sunrise (Kidron et al., 2000). In contrast, the data collected by Warke and Smith (1998) in Death Valley, California in August 1992 reveal a much more dramatic afternoon peak in rock surface temperatures (allied to higher air temperatures than those found in the Namib), with dark Antrim basalt samples heating up to 72.65 °C. In the Negev, Kidron et al. (2000) also measured dew and fog precipitation through surface wetness sensors for south- and north-facing slopes in October and November 1992. Fifteen to 27 events per month were recorded at their site, in comparison with the 3–27 events recorded noted at three sites in February and August between August 1999 and February 2002 presented in this paper. These findings confirm the nature of the Namib Desert as being a comparatively mild desert in terms of temperature and fog precipitation regime.

The data sets presented in this paper can be used to make some inferences about the relative efficacy of different weathering processes at the different sites. The short-term data sets from Gobabeb in July and August illustrate the lack of temperature changes of 2 °C per minute or more, unless wetting of surfaces occurs. The fact that Gobabeb is one of the warmer sites implies that thermal shock is also unlikely to be important at either Kleinberg or Vogelfederberg. Further work needs to be done in the extreme environment at Ganab to assess the likelihood of thermal shock there. The temperature cycling which does occur may well, however, produce thermal fatigue, which may be an important component of rock breakdown processes here. The lack of diurnal cycles around 0 °C (apart from very rare instances at Ganab) indicates that freeze-thaw weathering is unlikely to play any current role in weathering in the central Namib, despite the relative frequency of surface moisture during the colder periods of diurnal cycles. The presence of frequent episodes of surface wetness overnight illustrates the likelihood of chemical reactions causing weathering of susceptible rocks. For example, calcite within the marble may be dissolved under even quite small amounts of moisture, as found by Sweeting and

Lancaster (1982) who found smallscale rillenkarren developed in similar marble outcrops nearby in the central Namib Desert.

Salt weathering has often been proposed as a major initiator of weathering in the central Namib Desert. Understanding the frequency of cycling around critical temperatures and relative humidities (in relation to known hydration and crystallisation of different salts) can aid an assessment of the likely role of salt weathering. Such analysis is made complicated by the dynamic mixtures of salts present within the Namib Desert surface. However, based on the work of Price and Brimblecombe (1994), which investigates the thermodynamics of single and mixed salt solutions, some simple calculations can be made. Taking sodium sulphate (commonly found in arid environments) as an example, Price and Brimblecombe (1994) note that, at 20 °C, there are two stable forms, the anhydrous form, Na_2SO_4, which is stable below 71% RH, and the decahydrate, $Na_2SO_4.10H_2O$, which is stable between 71% and 93% RH. Above 93% RH, the decahydrate form dissolves. Thus, hydration damage can occur when the RH rises above 71%, and crystallisation damage can occur as the RH falls below 93%. Table 5 indicates the number of episodes at each site during each February and August during the monitoring period during which RH goes above 71% or below 93%. The records suggest that Vogelfederberg is particularly likely to suffer from frequent cycling around these critical RH values (although Kleinberg with a similar microclimate will also probably incur similar frequent cycles). Price and Brimblecombe (1994) also identify a “danger zone“ of RH between 75% and 100% at 20 °C, where mixed sodium chloride and calcium sulphate solutions occur (quite likely in a near-coastal, gypsum-rich environment such as the central Namib). Table 5 illustrates that such conditions may occur frequently at Vogelfederberg, and for a few days, a month at Ganab and Gobabeb. The calculations are oversimplified, as no account has been taken of temperatures during these RH phases. Furthermore, other combinations of salts may well occur. Price (2000) has developed an

Table 5
Number of oscillations around critical RH thresholds for ideal salt hydration and crystallisation damage (ND = no data)

Site	Month/year	No. of times RH rises above 71%	No. of times RH falls below 93%	No. of oscillations of RH between 75–90%	Notes
Kleinberg	Feb 2000	ND	ND	ND	
	Feb 2001	ND	ND	ND	
	Feb 2002	ND	ND	ND	
Vogelfederberg	Feb 2000	29	29	28	Leap year/multiple episodes
	Feb 2001	29	27	22	Multiple episodes
	Feb 2002	25	23	22	Some missing data
Gobabeb	Feb 2000	ND	ND	ND	
	Feb 2001	27	20	12	
	Feb 2002	25	22	18	
Ganab	Feb 2000	22	12	9	
	Feb 2001	15	7	3	
	Feb 2002	17	11	6	
Kleinberg	Aug 1999	24	19	17	
	Aug 2000	ND	ND	ND	
	Aug 2001	ND	ND	ND	
Vogelfederberg	Aug 1999	21	18	16	
	Aug 2000	14	14	12	
	Aug 2001	23	25	21	Multiple episodes
Gobabeb	Aug 1999	ND	ND	ND	
	Aug 2000	ND	ND	ND	
	Aug 2001	24	21	9	
Ganab	Aug 1999	7	6	6	
	Aug 2000	7	5	3	
	Aug 2001	16	8	6	

expert thermodynamic model for a range of common salt mixtures over temperature ranges of −40 to +50 °C that may provide a useful basis for further investigations of the likelihood of salt weathering in this area.

The data sets presented in this paper can also be used to illustrate the oversimplicity of "Namib" weathering cycles as used in many environmental cabinet weathering experiments. Goudie and Parker (1998), for example, in an experiment using Cretaceous Chalk, exposed the blocks to over 70 diurnal air temperature cycles with peaks of 35 °C and lows of 15 °C. All the sites studied in this paper recorded much more complex cycling of temperatures over a 3-year period, which are likely to provide much more complex weathering responses. Running comparative weathering simulations using their data set and the real data collected in this study to see whether different weathering outcomes result would be an interesting exercise.

In conclusion, the data presented in this paper illustrate the overall spatial homogeneity of the rock surface microclimate across the 100-km transect through the central Namib Desert. Each site is characterised by slightly different temperature, fog, and rainfall regimes, but the overall climatic patterns are very similar. The weathering response to the microclimatic conditions has been found to be very slow—hardly any visible manifestations of weathering over a 3-year period. The site showing greatest signs of deterioration of the marble exposure blocks (in the form of internal weakening) is Ganab, which is characterised by the highest temperature fluctuations and lowest levels of surface wetness and sediment salt contents. This is in sharp distinction to highly salt-rich, near-coastal pans ca. 100 km north of Swakopmund. Here, conductivities of surface sediments were found to be over an order of magnitude higher than those at Kleinberg. At this site, disintegration of similar marble blocks has been observed over a 2-year period, although even at this "weathering hot spot", similar-sized Damara granite blocks have shown no visible signs of weathering at all.

Both the almost imperceptible rate of weathering and the style of breakdown observed across the Namib desert over 3 years in this study may be at least partially related to the use of blocks cut from fresh stone. The surfaces of the blocks are very smooth and there are virtually no imperfections such as visible cracks. At the microscale, the production of a network of cracks through thermal expansion and contraction may be a necessary precursor to more dramatic chemical and physical breakdown. At a larger scale, once weathering starts to produce topographic features (such as alveoli), then microclimatic variations are likely to become enhanced, encouraging increasing complexity in the microclimate/weathering system. The very slow rates of weathering identified in this study so far do, however, back up the long-term picture of slow denudation rates put forward by Bierman and Caffee (2001) and Van der Wateren and Dunai (2001).

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