

A Review on Late Quaternary Environmental Change in the Namibia, South-Western Africa

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Abstract

This paper focuses on the review of geomorphology and late Quaternary environmental change in the Namibia, south-western Africa. The relationship between geomorphology and climate in Namibia reveals the degree and extent to which its landscapes are determined by changing environmental conditions. Case studies of late Quaternary environmental changes in the northern, western and central Namibia are presented. Geomorphological analysis showed that the modern-scale landscape of the south and central Namibia is controlled primarily by tectonics and also by the lithology, base level and climate. At present there is debate on the behavior of Quaternary hydroclimate in the Namibia in response to precessional (19–23 kyr cycle) insolation variations and the effect of glacial versus interglacial boundary conditions. Clues from marine records regarding these debates were obtained. Lower leaf-wax δD and higher $\delta^{13}C$ (more C4 grasses) recorded in marine sediments over the last 140 ka indicates wetter summer conditions and increased seasonality during the Late Quaternary, particularly during Southern Hemisphere insolation maxima relative to minima and during the last glacial period relative to the Holocene and the last interglacial period. In the central and south-western Namibia, CNB dating suggests that the Namib Sand Sea has a residence time of at least 1 million years. Depositional ages of luminescence dating for dune sediments yields three broad areas of the sand sea, including MIS 5, later in the Pleistocene around the Last Glacial Maximum and the Holocene. The high coincidence of the luminescence ages of the linear dune complexes in the Kalahari over a distance of about 150 km suggests that dune activation in the south-western Kalahari was not the result of local effects but due to sub continental climatic changes. The major dates for dune forms in Kalahari at present are of Holocene age. In the northern Namibia, landscape degradation and desertification are developed during the Holocene. Humification of soils in this region suggests open savanna environments in the past and does not accord with the shrub lands and thornbush savanna at present. Landscape degradation seems to have started in pre-colonial times most likely as a consequence of cattle farming. These examples from different regions of the Namibia offers pointers as to how geomorphological evidence of Quaternary change can be used to assist in the better management of contemporary and future environmental conditions.

Keywords: Late Quaternary; Climate change; SH insolation; Oceanic circulation; Landform evolution; Human activity; Namibia; South-western Africa

Introduction: The Importance of the Namibia Quaternary

One of the reasons for the Quaternary environment research is that it is an imperative to understand environmental changes of the past as a key to more appropriate management of changes evidently occurring at present and in the future. The historical (documentary) record of climate change is impossibly short and a full comprehension of the dynamics of contemporary environmental systems, i.e., distinguishing 'noise' from 'oscillations' and 'trends' requires a much longer-time perspective [1]. The Quaternary is a key archive against which is measured the nature, causal factors, frequency and magnitude of contemporary environmental dynamics. The territory of Namibia is located in Southern Africa of the southern hemisphere, an area of the African continent south of approximately 19°S (19–29°S, 12–21°E) and a subcontinent with a varied but coherent set of physical geographical characteristics.

The economy of Namibia is based primarily on resource extraction, the agricultural and pastoral component of which is strongly responsive to climate variability. Integral to the variability of rainfall and other climate elements is a key issue of natural resource management. Comprehensive understanding of the details and mechanisms underlying environmental change is essential for resources management. At present, Namibia experiences semi-arid to hyper-arid conditions due its position in-between the influence of

precipitation from low-latitude tropical climate systems in the north and mid-latitude climate systems in the south [2]. A resource-related issue is the problem of desertification in Namibia. The climate of this land is inherently variable on a wide range of time scales [2,3], through seasonal, annual, decadal up to millennial and beyond. For example, Tyson et al. [4] have described the importance of a spatially coherent oscillation (18-year) in rainfall values over the summer rainfall region for the meteorological record (1910 to 1972). The existence of such fluctuations over longer time periods is also apparent [5,6]. These significant variations in the patterns of precipitation and temperature are proved to be a key component of southern Africa's environmental situation and one that needs to be elucidated as far as possible [1].

Unfortunately, due to the high aridity in Namibia, long terrestrial palaeoclimate records are rare [5,6] and thus the understanding of past environmental changes in climate remains incomplete. Especially, comprehending the regional and sub continental scale environmental

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changes in the context of General Circulation Models, which generate scenarios of future climate conditions based on Quaternary data, is an important goal of academic circles. The aim of this paper is to review the documented cases in the southern Africa for a consideration of Quaternary events in understanding the landscapes of Namibia and, furthermore, to argue that such an understanding is vital to the appropriate management of its environments.

Regional Setting and Methodology

Topographical, geomorphological and geological setting of the Namibia

Topographically, the Namibia, particularly the South Namibian Plateau (SNP) which is the major part of the South African Plateau, is strongly contrasted with a relief that varies between 0 and 2183 m [7]. The Namibian margin is characterized by a coastline that has evolved in a large escarpment with a difference in level of more than 1000 m, a coastal plain approximately 150 km wide and an inner flank. Two deserts surround this vast plateau: the Kalahari Desert to the east and the Namib Desert to the west. Four major morphological provinces or domains were spatially defined [7]. They are (1) the coastal province (CP), (2) the intermediate province (IP), (3) the upper province and (4) the lower province or Kalahari province (LP). In drainage pattern, Namibia presents two types of drainage system: one on the coastal plain and the other in the inner plateau. The coastal plain is crossed by numerous rivers with courses roughly orthogonal to the coast. Some of rivers are thrown directly into the sea, but the majority is lost in the Namib dunes before reaching the sea. The internal drainage network in the inner plateau is the oldest and is characterized by a dendritic pattern around a main collector, the Orange River (458 km), and becomes more parallel towards the north.

The geological history of Namibia includes the formation of the Damara chain during the Pan-African, the opening of the South Atlantic Ocean and the Cenozoic evolution [7]. The Cenozoic history of Namibia has been mainly sedimentary. On the coastal plain currently occupied by the Namib Desert [8], the "Namib unconformity surface" separates the older rocks of the Precambrian basement from the Cenozoic deposits. On this surface lies the oldest unit, the "Tsondab Sandstone" Formation of early Palaeocene age [8]. More recent conglomerates confirm the erosion of the escarpment during the Miocene [8]. To the east of the scarp, sedimentation is continental (fluvio-lacustrine) with the deposits of the Kalahari Sequence being the most recent (Cretaceous to Tertiary) [9]. The development of the cold Benguela current since the late Miocene led to arid conditions responsible for the current climate of the Namib Desert and the Kalahari basin was developed during the Tertiary due to the alternations of dry and humid periods [7].

The tectonic setting of Namibia is marked by two extensional phases of deformation that have affected the South African Plateau (SAP) during the Cenozoic [10]. The characteristics of these deformations are consistent with mantle dynamics that acted on the lithosphere of the SAP and impacted the landscape evolution during the Late Cenozoic [11].

Climate setting of the Namibia

Namibia in south-western Africa experiences arid conditions due to the South Atlantic Anticyclone, which is strongest and furthest south during SH winter [4]. Rainfall in the Namibia is spatially and temporally highly variable [4,12,13]. For example, average precipitation in the Namib Desert ranges from 50 to 100 mm in the far south, 5-18

mm in the central Namib and less than 50 mm along the Angolan coast in the north. There is an increase in rainfall from west (~10 mm at the coast) to east (~60 mm at 100 km inland) [14-19] producing a steep but variable rainfall gradient from the desert interior to the Namibian highland. Besides rainfall, fog constitutes a regular but minor source of moisture in the hyper-arid Namib Desert [20].

The western part of Namibia experiences the most pronounced aridity due to the cold sea surface temperature of the Benguela upwelling region, which stabilizes air and prevents convection [13]. Most precipitation delivered to Namibia is tropical convective precipitation originated from the Indian Ocean [2,21,22], which is delivered by the southernmost extension of the East African monsoon in SH summer (the northerly East African monsoon), resulting in decreasing precipitation amounts from NE to SW. Basically, Tropical-Temperate Troughs (TTTs), the Congo Air Boundary (CAB) and the Angola Low [13] all contribute to Namibia summer rainfall. In addition to tropical systems, the mid-latitude westerly winds bring a limited amount of moisture to the very south of Namibia when they shift northward during the SH winter season. The Atlantic Ocean also contributes some moisture to this region: to the north of the cold Benguela Upwelling, the SE trade winds are deflected clockwise [23,24], carrying some moisture on-land [13,21], and the winter westerlies also source moisture from the Atlantic Ocean [21].

Material and Methods

Reliable chronologies are essential for the paleoenvironmental interpretation of landforms. In arid land, however, the absence of closed geochemical systems and fossilized organic remnants or strata makes it very difficult to contribute to paleoclimatic reconstructions. For example, ¹⁴C-dating is often not able to produce reliable age data in desert areas, due to repeated cycles of carbonate mobilization in arid conditions. Similar problems can also occur when using U/Th-dating methods [25]. Over the last decadal years optical- and thermoluminescence (OSL and TL) dating of quartz and feldspar bearing sediments led to new progress in paleoclimatic research in arid regions. These techniques have successfully been used in many studies on aeolian sediments [26]. In the northern, western and south-eastern Namibia, some researchers presented OSL and TL results from aeolian and fluvial sediments [27-32]. This study combines these results to assess the paleoenvironmental evolution of landforms in the Namib and Kalahari Deserts.

Besides chronologies, geomorphological analysis is emphatically used as a method for its qualitative and quantitative approaches to reconstruct palaeo-environmental changes in arid lands, such as the principle proposed by Tricart and Cailleux [33] that any bedrock/sediment deformation or any variation of lithology has a morphological signature. In this study, the morphological review of Namibia combines (1) a literature survey, (2) analysis of geological maps at multiple scales, such as 1: 250,000, and (3) digital elevation model (DEM) analysis within ArcGIS.

Literature data and information from geological/geomorphological indices/maps allowed us to highlight the nature and the path of the geomorphological processes in a certain region [7,34]. Among these, geomorphologic assessment through morphometric indices can be used to constrain the role of lithology, tectonics and base level and to characterize and discriminate key geomorphic processes in an arid context [7]. For example, Table 1 gives several formulas, equations, parameters and related threshold values interpretation used frequently for the calculation or computation of morphometric indices.

Morphometric indices	Formulas and parameters	Threshold values interpretation
Relative relief (R)	$R = (\Delta H/P) \times 100$ ΔH : difference between the highest and the lowest altitude of a given area; P: perimeter of the same area.	R>0.5: high relative relief; R<0.5: low relative relief;
Elevation-relief ratio (E)	$E = (Me - me) / (Ma - me)$ Me, me and Ma: mean, minimum and maximum elevation.	E nearer 0: concave or broad flat terrain with isolated peaks; E nearer 1: convex or broad flat terrain with deep incision;
Hypsometric integral (HI)	$HI = (Hmean - Hmin) / (Hmax - Hmin)$ Hmean, Hmin and Hmax: mean, minimum and maximum elevation.	HI>0.6: younger stages of basin development, most of the topography is high relative to the mean; 0.3<HI<0.6: mature basins, extensive and long term erosion, associated with dissected drainage basins; HI<0.3: older basins, such as peneplains.
Valley floor width to valley height ratio (Vf)	$Vf = 2Vfw / ((Eld - Vfw) / (Esc - Vfw))$ Vfw: width of the valley floor; Eld and Esc: elevations of the left and right valley divides.	Vf > 1: broad valleys and low uplift rates; Vf < 1: V-shaped valleys, actively incising and high uplift rates.
Drainage basin asymmetry (Af)	$Af = 100 (Ar/At)$ Ar: area of the basin to the right (facing downstream) of the trunk stream; At: total area of the drainage basin.	Af > 50: the main channel has shifted towards the downstream left side of the drainage basin; Af < 50: the channel has shifted towards the downstream right side of the drainage basin.
Transverse topographic symmetry factor (TTSF)	$TTSF = Da/Dd$ Da: distance from the channel to the basin midline, Dd: distance from the lateral basin margin to the basin midline.	TTSF N 0.5: the drainage basin is influenced by the tilting of the terrain due to tectonic activity; TTSF b 0.5: the tilting does not have an influence on the drainage;
Scarp front sinuosity (Sf)	$Sf = Lf/Lr$ Lf: Length of the scarp front from a point; Lr: Length of the straight line from the same point to the same end point.	Sf low: active scarp fronts; More Sf high: older is the scarp.
Longitudinal profiles of rivers	(1) $y - y0 = (y1 - y0) / (x1 - x0) * (x - x0)$ y: elevation in normal range; x: distance in logarithmic scale; (2) $AN = Am + (((AH - AL) / (LogLm - LogLM)) * (LogLi - LogLM))$ AN: equilibrium normalised altitude value; AH and AL: highest and lowest altitude; LM and Lm: maximum and minimum length; Li = length value calculated for each considerate point in relation with the upstream.	Concave longitudinal profiles are characteristics of old rivers, in equilibrium state; Convex longitudinal profiles are characteristics of young river or old rivers reactivated by fault or affected by uplift.
Concavity index (IC)	$IC = 2 A/H$ A: difference of altitude between the middle profile and a straight line joining the two ends of the profile; H: difference in height between the channel head and the outlet.	IC close to 0: the form of the profile is close to a straight line; IC close to 1: the profile is L shaped.
Dimensionless curves (ratio of altitude-ratio of distance)	H/Ho o of a/H and Ho : stream altitudes at the point of measurement, and from the mouth at the headwaters respectively; L and Lo: stream distances at the point of measurement, and from the river mouth at the headwaters respectively.	Help to superpose and compare profiles of different river lengths
Stream-length index (SL)	$SL = (\Delta H/\Delta L) * L$ ΔH : difference in elevation between the ends of the considered reach; ΔL : length of the reach; L: distance between the measured reach and the drainage divide.	Very high or very low SL values reveal tectonic distortions if there is no correlation with lithological factors
Drainage density (Dd)	$Dd = \sum Li/A$ Li: length of river ; A: watershed area	The more a system is uplifting, the more the drainage density decreases

Table 1: Morphometric indices used for the landscape analysis: formulas and equations used for their calculation or computation and threshold values interpretation [7].

Results and Discussion

Geomorphological evolution of the Namibia

The geomorphological evolution of the Namibia has been systematically reviewed by Owono et al. [7]. In their document, the geomorphological evolution of Namibia dates essentially from the Jurassic-Cretaceous monoclinical folding of the southern African continental margin in response to the fragmentation of Gondwana. Later on, the region underwent a significant flattening. After this event, the formation of laterite occurred in Namibia during the late Cretaceous-middle Eocene [35]. Another well-described event affecting the morphology of the region is the uplift of the South Namibia Plateau (SNP). Burke and Gunnell [36] proposed a post-Oligocene age for the uplift and tied it to the mantle-related “swell” dynamics of the African continent. Partridge and Maud [37] suggested a very recent age of uplift (late Pliocene).

A morphological analysis of the modern landscapes in the south Namibia was conducted by Owono et al. [7]. Geometrical parameters as listed in Table 1 were calculated through the DEM, slope map and transverse profiles. The results showed that the modern-scale landscape of the South Namibia is controlled primarily by tectonics and also by the lithology, base level and climate.

(1) Tectonics and base level control: Seen from the calculated geometrical parameters, the negative and very low ICs (<0.3) combined with low values of TTSF (<0.5) and the Af (Table 1) occur in the south Namibia [7]. It implies that the south Namibia underwent an inhomogeneous uplift or several episodes of uplift. According to Hack [38], when the fluvial incision rate exceeds the uplift or base level lowering rates, the profile goes to a steady state with a smooth downstream concavity. This is not the case for either of the coastal network profiles in the south Namibia, where very important jumps and numerous knick points have been observed and the internal

network rivers have almost convex profiles. To attain a steady state, a profile needs a long time, and the response time is on the order of 1 Ma. Main tectonically active region under detachment-limited conditions and during periods of climate stability [39] and at least 3 Ma under stable tectonic conditions. However, all of the rivers of the internal network and their tributaries in the south Namibia are over 3 Ma, at least upper Cretaceous to Eocene for the Orange, the Fish and the Konkiep [10], and consequently should be in a dynamic equilibrium state. However, that is not the case in the south Namibia. Therefore, it can be concluded that vertical movements in the south Namibia exceed the rate of incision. The rivers and their tributaries cannot develop an equilibrium profile.

The hypsometric integral values (Table 1) for the different watersheds and sub-watersheds in the south Namibia are approximately 0.5 [7]. It means that there are still 50% of the original non-eroded masses. This result reflects the maturity of the south Namibia basins, but do not entirely reflect the hypsometric curves, whose forms according to Strahler [40] should be exclusively "S" shaped. The hypsometric curves of the different basins that constitute the different planation surfaces of the south Namibia show various and complex forms that combine concave patterns, S-shapes and more convex trends [7]. This reflects an evolution marked by an alternation of several tectonic and erosive episodes. The model of cyclic erosion leading to the formation of a peneplain [41], cannot explain the geometry of these curves according to the variable types of surfaces encountered in the south Namibia. Several phases of uplift have been described in the south Namibia [42] and reveal the shortcomings of this model. King [43] proposed a punctuated evolution of tectonic pulsations in the south Namibia followed by incision and flattening phases and a retreat of scarps or back wearing. These processes lead to the coalescence of the pediments [44] and the reduction in the reliefs of the hillocks and inselbergs are well described in the coastal surface. Finally, according to the hypsometric curves and hypsometric integral, the South Namibia landscapes consist of coalescence surfaces of different ages that have undergone a polycyclic evolution marked by more than one pediplanation and or etchplanation processes due to the different phases of uplift [7].

(2) Tectonic and lithology controls: The drainage patterns in a region are an important clue for identifying the tectonic and lithology controls and also for quantifying the base level action. According to Owono et al. [7], the inner streams in the South Namibia display convex profiles with a few knick points. Some of them are located in the contact of two lithologies, and others are related to the presence of faults, which coincide in certain cases with the contact of the different lithologies. The SL-index values (Table 1) are also high, conveying tectonic effects. The equilibrium longitudinal profiles give straight lines when they are plotted on a semi-logarithmic scale [38]. The deviations D (Table 1) measured at the outlet towards the downstream with respect to this straight line allow the type of control, either lithological or base level changes, to be determined [7]. According to Goldrick and Bishop [45], a variation of the base level involving a retreat of knick points is verified when the main course and its tributaries have the same value of D. However, the D values of the tributaries in the South Namibia are higher than those of the main courses. It implies that the control exerted by the base level is less significant. For the rivers that cross several lithologies, the D values are high [7], such as the Orange and Konkiep Rivers tributaries.

(3) Tectonic and sea level control: Although the long profiles of the coastal rivers are globally concave, they are not smooth. All of these rivers display knick points. In particular, the Isurub River

in the South Namibia presents a concave upstream portion and a linear profile downstream. This could be interpreted as the recording of a reactivation of a system partially in balance. Apart from Kp7 in the Koichab River and Kp1 in the Tsaris River, which coincide with the contact of two different lithologies, some of the streams flow on uniform lithologies. The SL-index values for the main rivers of this area in the South Namibia are very high and above 200. Such values, in the absence of any correlation with lithology, show that these knick points are due to tectonics [38,46,47]. However, these profiles have numerous downstream knick points of large magnitude and large jumps [7]. This probably reflects the recent responses of relative sea level or the recent reactivations of faults, which are probably buried under the Namib Dunes. It thus can be assumed that the coastal surface is controlled by tectonics and sea level.

(4) Climate and eustasy control: As above mentioned, the tectonic controls on the landscapes of the South Namibia are especially dominated by uplifts. Dauteuil et al. [42] have identified in the southern part of the South Namibia Plateau, close to the Orange River, three episodes of uplift: a slow uplift (10 m/Ma), followed by a second interval of uplift involving a cumulative magnitude of at least 200 m and the third stage of uplift of 60 m magnitude occurred after the Middle Miocene. Two types of networks are described in this place: one in the coastal plain, which is temporary, mainly dendritic, young or in the process of being emplaced or resulting from a series of reactivations of a system partially in equilibrium, and the other in the inner plateau, which is permanent, dendritic with a parallel trend, old and marks a continuous adjustment at least since the Eocene until the present day. The genesis and the evolution of the coastal surface are controlled by climate, eustasy and deformation, whereas climate, lithology and deformation control the interior plateau. The climate-controlled processes appear to be the leading factors for the flattening of the inner plateau, whereas the coastal area seems to be more subject to eustatic variations. The longitudinal profiles of coastal rivers, which are concave with numerous knick points and large jumps at the end of the profiles in contrast to those of the interior plateau, which are convex, with few knick points well attest to this dichotomy.

Hydroclimate change of the Namibia during the late Quaternary

Debate on precessional insolation control: At present there is debate on the behavior of Quaternary hydroclimate in the Namibia in response to precessional (19–23 kyr cycle) insolation variations.

For example, the increased land–ocean pressure gradient caused by increased local summer insolation in the Southern Hemisphere (SH) is expected to bring more warm, moist air and precipitation on land, as has been shown in the northern hemisphere [48,49] (NH). In line with this, a 200 ka long sedimentological record from Lake Tswaing in south-eastern Africa, suggests that precipitation increased during precessional Southern Hemisphere (SH) summer insolation maxima [50,51], due to an enhancement of the SH summer East African Monsoon. Similarly, a leaf-wax hydrogen isotope record from the Zambezi River [52] suggests relatively dry conditions during the mid-Holocene SH summer insolation minimum, relative to the deglacial and late Holocene. These results indicate that high summer insolation of SH leads to high precipitation and low summer insolation leads to dry conditions in the South Africa, including the Namibia.

However, a hyrax-midden record from the Namib Desert, spanning the last 11.7 ka (one half of the last precessional cycle) [53], suggests a progressive drying from the mid to late Holocene, i.e., wetter rather

than drier conditions during the mid-Holocene SH summer insolation minimum. It was thus suggested that south-western Africa responds in phase with NH summer insolation [53], namely getting wetter during high NH summer insolation and becoming drier during high SH summer insolation.

Therefore, one of the questions on the behavior of Quaternary hydroclimate in the Namibia is: if the hydroclimate of Namibia is controlled by NH summer insolation variations on precessional time scales, and what the role of the SH summer insolation?

Debate on glacial-interglacial control: In addition to precessional insolation control, the effect of glacial versus interglacial boundary conditions on the hydroclimate of south-western Africa is also under debate [54].

For example, today the central Namibia is partly savanna vegetated, partly barren. Researches have suggested, however, that more desert and semi-desert vegetation occurred during the last glacial period relative to the Holocene and last interglacial period (savanna vegetation) [55,56], which points to drier conditions in the glacial time. While, researches from a marine grain-size record [56] and a collection of terrestrial records [57] suggest that wetter conditions dominate in south-western Africa during the last glacial period. Other researches from depleted isotopes in precipitation (i.e., [58]) also point to wetter glacial conditions.

For the above-mentioned wetter glacial conditions in south-western Africa during the glacial periods, there are two different explanations in the scientific community. One interpretation is that the wetter glacial conditions in south-western Africa reflect a northward shift of the SH mid-latitude westerly wind belt during the last glacial period [56,57,59]. The second interpretation is that a southward shift of tropical rain-producing systems due to the expanded NH ice sheets is the alternative mechanism for the wetter glacial conditions in south-western Africa, as it is sometimes simulated by climate models [60].

Therefore, the question in front of us is whether the South-western Africa was wetter or drier during the last glacial period. At present many studies disagree on this question. Further, for those that do agree on the wetter glacial conditions in south-western Africa, different mechanisms have been invoked.

Clues from marine records regarding precessional insolation changes and glacial-interglacial boundary conditions: Regarding to the questions above mentioned, the effect of precessional insolation changes and glacial-interglacial boundary conditions on the climate of south-western Africa has been emphasisly investigated by researches using the hydrogen and carbon isotopic composition of terrestrial plant leaf-wax n-alkanes taken from marine sediment cores [6,54,58,61].

n-Alkanes are straight chain hydrocarbon compounds produced as part of the protective layer on terrestrial plant leaves [62,63]. The hydrogen isotopic composition (δD) of leaf wax n-alkanes is taken as a recorder of the hydrological history of precipitation [64]. The carbon isotopic composition ($\delta^{13}C$) of leaf-wax n-alkanes reflects the photosynthetic pathway of the plants i.e., the relative contribution of C3 versus C4 vegetation [65].

Based on these analysis, Collins et al. [54] suggests that an analogous scenario to present (savanna vegetated in the central Namibia with C4-dominated plants) have taken place in south-western Africa in the past 140 ka. Their marine records show that higher $\delta^{13}C$ values occurred during the last glacial period and insolation maxima, which indicates an expansion/thickening of C4 grasses across barren areas of the Namib

Desert, Namibian Plateau and Kalahari Desert. This means that the central Namibia was drier during the last glacial periods. These periods hence represent maxima in seasonality, in line with Daniau et al. [1]. The dominance of C4 grasses over C3 vegetation throughout the record suggests that semi-arid conditions and high seasonality were persistent features of south-western African climate over the past 140 ka. This is in line with indications of the persistence of aridity based on sedimentary landforms in this region [32,66].

On precessional timescales, the marine records indicate increased summer precipitation in south-western Africa during SH summer insolation maxima [6,54,58,60], which is in a greement with the record from Lake Tswaing in South Africa [37], and with relatively dry conditions during the mid-Holocene insolation minimum within the Zambezi River catchment in south-eastern Africa [52]. Together these records would suggest that SH summer insolation maxima resulted in wetter conditions throughout most of southern Africa.

However, terrestrial plant leaf-wax n-alkanes record from Collins et al. [54] contrasts with the Spitzkoppe hyrax-midden record from the Namib Desert [57], which indicates wetter conditions during the mid-Holocene SH summer insolation minimum. The hyrax-midden record reflects the climate of the hyraxes' habitat (in close proximity to the midden), situated in the Namib Desert. Marine record reflects a wider catchment including material from the Namibian plateau [67] and the Kalahari Desert [68], further east of the Namib. Consequently, climate in the Namibian Desert may indeed respond in phase with NH summer insolation, perhaps via a control on upwelling intensity, while the Namibian plateau and the Kalahari Desert respond in phase with SH summer insolation. Further records or model simulations are needed to verify this hypothesis.

Late Quaternary environmental change in the Namibia deserts: Namib Desert and Kalahari Desert

Palaeoenvironmental reconstruction in the Namib Desert: The Namib Desert stretches ~2000 km from the Olifants River in South Africa (32°S) to the Carunjamba River in Angola (14°S), forming a narrow strip, 120-200 km wide, bounded inland by the Great Escarpment. At present the region is hyper-arid to arid with lowest rainfall at the coast, owing to subsiding anticyclonic air, the cool offshore Benguela current [13,69] and the permanent, but not stationary, South Atlantic high-pressure cell along the Namib coast [70].

Palaeoenvironment in the Namib Desert had changed greatly, with climatic fluctuations being linked to variations in above-mentioned atmospheric and oceanic circulations. However, Quaternary environmental reconstruction in the Namib Desert has been limited by a paucity of sites, access difficulties, discontinuous records, difficulties of dating and uncertainty in interpreting the climatic signals from certain proxies [31,32,57,71,72].

Since the latest review for the region by Lancaster [66], Stone and Thomas have further performed a synthesis of environmental change over the past 128 ka for the Namib Desert. They concentrate on the application of cosmogenic-nuclide burial (CNB) dating and optically stimulated luminescence (OSL) dating to complex linear dunes in the northern Namib Sand Sea [73,74], fluvial deposits from five of the west coast ephemeral river catchments [75-80] and sands interdigitated with water-lain interdune deposits in the northern Namib Sand Sea [31,81].

Just like the other old sand seas in the African Continent, the sediment burial age compilation from CNB and OSL dating suggests that the Namib Sand Sea is also a long-aged desert in excess of a

million years old [31]. Depositional ages of luminescence dating for dune sediments yields three broad areas of the sand sea, including MIS 5, later in the Pleistocene around the Last Glacial Maximum and the Holocene [31,81]. Ewing et al. [82] provide age estimates for three dune types in the Namib Sand Sea based on pattern analysis and pattern evolution, linked to self-organization (without radiometric age control from the Namib Sand Sea). Based on a landscape development model for the Namib Sand Sea, Bubenzer and Bolten [83] divide the desert landscape evolution into different stages relating to the varied wind regimes. (1) During the first stage (>20 cal. kyr B.P.) the draa (or mega linear dunes, with dates of 22.5 ka at 5 m depth) were accumulated under strengthened trade winds, owing to increased pole-to-tropics temperature and pressure gradients [84], (2) At the end of the Pleistocene and start of the Holocene, strong westerly winds picked up sediment from the western flank of the draas and deposited it on the eastern flanks (with OSL ages from the eastern flank dated by Bubenzer et al. [85] spanning 10.4–8.8 ka).

At present the Namib Sand Sea has been digitally recorded by Livingstone et al. [86]. Although the digital atlas limited in coverage, they compile the new chronological data available and represents some significant developments in the studies of the Namib Desert [31]. In general, the development can be summarized as follow: (1) CNB dating of surface samples by Vermeesch et al. [87] suggests that the Namib Desert has a residence time of at least 1 million years, which accords with previous estimates of sand sea ages of ~2–3 Ma that based on sand volume and influx. (2) OSL dating of sediment burial indicates that Pleistocene deposition of dune sands had been developed in MIS 5 (110 ± 5 ka) for some areas in the north of the sand sea [31], and had been developed in 18–22.5 ka for areas in the southern part of the sand sea [85]. (3) OSL data also reveal Holocene activity in the southern sand sea at 10–8.5 ka [85] and northern extreme, with west–east migration and extensive reworking of a complex linear dune over 6 ka [73] and active superimposed features on the southern tip of a linear dune from 1.4 ka [74].

Compared with earlier analysis based on dune-patterning by Ewing et al. [82], the OSL chronologies of aeolian sediments above-mentioned are in broad accordance with the geomorphological estimates of dune development. However, it should be recognized that OSL ages could only record depositional events that are preserved at last time and might miss events that have been reworked or removed before and later the deposition.

Environmental change in the Kalahari Desert (Namibian part): The Kalahari Desert covers central parts of the large inner-continental basin of southern Africa in south of the Congo-Zambezi watershed, with the regional climate being semi-arid to sub-humid in the northern parts (northern Namibia, northern Botswana, and western Zimbabwe). The Namibian part of the Kalahari Desert is situated in the transition zone to the hyper-arid Namib Desert in the west and the semiarid Karoo in the south.

Studies concerning the paleoclimatic significance of Kalahari landforms have been intensified since the study by Grove [88]. A short state-of-the-art is given in Thomas and Shaw [89] and Shaw and Thomas [90]. But until now only a small number of results of geomorphic and (paleo-) environmental studies have been presented from the Namibian part of the south-western Kalahari [29,91–96].

Climatologically, the aridification of the Kalahari Desert is relatively old, with one of the evidence derives from the Miocene layers of the Kalahari Group sediments [29]. Since this 'Mega Kalahari phase' [97],

knowledge of Quaternary environmental changes of the south-western Kalahari (Namibia) has remained highly speculative, even the effects of Late Pleistocene and Holocene climatic fluctuations are uncertain. Due to the annual and perennial savanna grassland species, the vegetation cover in the Kalahari Desert does not respond instantly to excess and deficits of rainfall, but reflects moisture availability over a number of preceding years [94]. Therefore, Quaternary environmental change was fundamental in south-eastern Namibia.

Geomorphologically, linear dunes in the south-western Kalahari Desert were thought to be evidence of the nature of paleoclimates. A suite of OSL data presented by Thomas et al. [98] and Stokes et al. [99] and a suite of TL data provided by Blumel et al. [29] for the linear dunes in the south-western Kalahari contribute to the knowledge of Late Quaternary paleoenvironmental changes in the south-western Kalahari. It is remarkable that all typical linear dunes in the Grootpan, Swartput se Pan and the vicinity of Aroab in the Namibia Kalahari had shifted during the early Holocene (TL ages: 9.5 ± 1.8 ka at Grootpan; 8.8 ± 1.2 ka north of Swartput se Pan; 8 ± 0.6 ka and 17.5 ± 8.1 ka east of Gaukabpan). The high coincidence of the luminescence ages of the linear dune complexes over a distance of about 150 km suggests that dune activation in the south-western Kalahari was not the result of local effects but due to sub continental climatic changes.

The early Holocene age of the linear dunes [29] disagrees with the hypothesis that many of the dunes in Kalahari were stabilized by vegetation prior to 33 ka [95]. Blumel et al. [29] argued that radiocarbon data of calcretized dune sands at Soudpan (33.5 ± 0.88 ka) measured by Lancaster [93] may overestimate the age of the dune formation, due to carbon exchange in the open systems of the sandy sediments. Lancaster [95] suggested that the last major phase of dune initiation and extension took place during the Late Pleistocene dry period (ca. 20 to 12 ka). However, Thomas and Shaw [89] performed a check of all available data for dunes in Kalahari. They found that "with the exception of the peat date of 19,680 + 100 at Tsoi in the Makgadikgadi, the only absolute dates available for dune forms in Kalahari at present are of Holocene age". This indicates an early Holocene phase of dune activity in the Kalahari Desert.

Compared with the aeolian archives of Blumel et al. [29], a fluvial phase of the Molopo River ended about 14 ka [100]. This correlates with archives of many pans in the central Kalahari Desert, which indicating moist conditions after the Late Glacial Maximum (17–12 ka.). It is obvious that the linear dunes in the south-western Kalahari are younger than the main stages of pan development. The pan activity has been reduced at least since the early Holocene. Shifting sands filled up several smaller pans or buried large parts of them [29]. This youngest aeolian activity seems to correspond with data from other parts of the southern Kalahari (R.S.A. and Botswana) published by Thomas et al. [98].

Holocene environmental change and desertification in the northern Namibia

The Holocene environmental change in northern Namibia can be deduced from records of soils and sediments development in the Otjiwarongo thornbush savanna.

In the Otjiwarongo region, the fine-grained Mid-Holocene sediments and related soils rich in organic matter are an important natural resource. However, the problem of modern desertification, a resource-related issue, is becoming severe in Africa. In southern Africa, the dry lands of two countries are most affected by this process [101], one is the Namibia [102].

Work from Eitel et al. [103] shows that Vertisol–Kastanozem–Calcisol soil associations occur widely (as patches of several hundred hectares in extent). On the cause of genesis, the dark surface soil horizons of Vertisols, Kastanozems and Calcisols should be formed under open grasslands. However, Kastanozem formation cannot be explained by the environments that exist at present. The humification suggests an open savanna environment in the past and does not accord with the shrub lands and thornbush savanna at present. Therefore, degradation and desertification (man-made aridification) of dry lands in northern Namibia could be developed during the Holocene. For example, environmental studies in the Karoo show that in the Late Holocene the first degradation of the natural vegetation was initiated in pre-colonial times by hunting and gathering herders [104].

For environmental changes in the northern Namibia in modern times, Walter [105,106] suggested that landscape aridification in Namibia is primarily an anthropogenic effect on savanna ecosystems induced by intensified cattle farming. The environmental change in this region is characterized by the transformation of open savanna grasslands to shrub lands [107], which was caused by heavy stocking with cattle or increasing human population pressure [108] and concomitant accelerated erosion [109]. Using AMS ^{14}C and OSL data, Eitel et al. [103] distinguish two periods of soil degradation during the recent past. In the first phase, most of the Kastanozems and Vertisols were buried by slope wash sediments. This process started in the mid-19th century at the latest. In a second phase, the soils were affected by rill and gully erosion, indicating increased runoff. This occurred during the last decades of the 19th and the first decades of the 20th century, probably as a result of intensified cattle farming. In contrast to other parts of Namibia, the prominent river channels of the Otjiwarongo region (up to 20 m wide and 3–4 m deep) are a result of recent erosion [103].

Summary/Conclusion

This paper focuses on the late Quaternary environmental change in the Namibia in southern Africa. The Namibia is located at the interface of tropical, subtropical and temperate atmospheric and oceanic systems. The relationship between geomorphology and climate in Namibia reveals the degree and extent to which its landscapes are determined by changing environmental conditions, especially during the Late Quaternary. In the central part of the Namibia, OSL chronologies from two complex linear dune features close to Gobabeb suggest the current dunes are young (Holocene age), with important messages about the dynamics of the system and migration rates, whilst OSL ages from dunes in the southern part of the Sand Sea suggests older material of up to 24 ka at 5 m depth. Linear dunes in the south-western Kalahari Desert provide evidence of the nature of paleoclimates. These dunes have special significance because their alignments indicate a previous circulation pattern with prevailing north-westerly winds. In contrast to previous suggestions final dune stabilization took place before about 9-8 ka. This corresponds to reduced wind velocities accompanied by more humid conditions. This seems to be the last important environmental change recorded by significant landforms in the south-western Kalahari. Since about 8 ka the region remained more or less semi-arid: The long distance to seasonal south-shifting humid tropic air masses (Innertropical Convergence Zone, ITCZ) and the climatic barrier of the Namib and the Karas Mountains against Atlantic influences allowed only minor fluctuations. The Holocene is a period of reduced pan development. A record of leaf-wax δD and $\delta^{13}\text{C}$ taken from a marine sediment core at 23°S off the coast of Namibia reconstructs the hydrology and C3 versus C4 vegetation of south-western Africa over

the last 140,000 years (140ka). Lower leaf-wax δD and higher $\delta^{13}\text{C}$ (more C4 grasses) in the record indicates wetter Southern Hemisphere (SH) summer conditions and increased seasonality, during SH insolation maxima relative to minima and during the last glacial period relative to the Holocene and the last interglacial period. Nonetheless, the dominance of C4 grasses throughout the record indicates that the wet season remained brief and that this region has remained semi-arid. This research data suggest that past precipitation increases were derived from the tropics rather than from the winter westerlies. Comparison with a record from the Congo Basin indicates that hydroclimate in south-western Africa has evolved in antiphase with that of central Africa over the last 140 ka. The Holocene environmental change in northern Namibia can be deduced from records of soils and sediments development in the Otjiwarongo thornbush savanna. In this region degradation and desertification (man-made aridification) of dry lands are developed during the Holocene. The humification suggests an open savanna environment in the past and does not accord with the shrub lands and thornbush savanna at present. Desertification and aridification of landscape in this region is primarily an anthropogenic effect on savanna ecosystems induced by intensified cattle farming.

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