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Flood Reconstructions in the Namib Desert, Namibia and Little Ice Age Climatic Implications: Evidence from Slackwater Deposits and Desert Soil Sequences

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Abstract: Fluvial silts, accumulated in some Namib Valleys, to date are interpreted as records of reduced precipitation in the catchments. Our investigations show that these fluvial silts are slackwater deposits (SWD) which document hydrologic and climatic conditions during the late Holocene that cause extreme flash floods in the valleys. We describe SWDs of some Namibian Desert valleys and present ^{14}C dates of their ages. The youngest accumulation phase occurred during the Little Ice Age (LIA, ca. AD 1300 to 1850). The biggest flash floods of the LIA, in most catchments, experienced water levels in the valleys that exceeded the most extreme floods of the last 100 to 150 years. In the northwestern Namib Desert, flash floods of the LIA were more frequent and more extreme than in the central Namib Desert. This may be caused by small shifts of the tropical-temperate-troughs (TTT) in southern Africa and the southwest Indian Ocean that correlate with changes of cosmic ray intensity.

Keywords: Slackwater deposits, Palaeofloods, Little Ice Age, Namib Desert (Namibia).

INTRODUCTION

Droughts and floods represent extreme conditions, and are precisely those that are foreseen to increase in future with global change. Knowledge of long-term rainfall variability is essential for water management in Namibia. Data relevant to determine this variability are scarce because of the lack of long instrumental climate records and the limited potential of standard high-resolution proxy records. In northern and eastern Africa the reconstructions of Holocene tropical lake-level changes prove alternating phases of desiccation and of high stands with lake-levels more than 100 m above the present level (Gasse, 2000). These document palaeohydrological changes which are greater than all records of modern instrumental observations. Such sudden and dramatic changes of the hydrologic regime within timescales that are relevant for the human society are not known from southwestern arid Africa (Namib Desert) to date.

Slackwater deposits (SWD) are reported to document big flood events in the valleys of arid to semi-arid areas (Baker, 1987; Kochel and Baker 1982). High-magnitude floods are also reported from the classic monsoon region of India according to modern, historical and palaeoflood (slackwater deposits) records (Kale et al. 1994; Kale 2002). SWDs represent the most accurate palaeoflood evidence for reconstructing the magnitude and recurrence frequency of floods that are hundreds to thousands of years old (Zawada, 1997; Baker et al. 1987). SWDs occur in many valleys of the Namib Desert (Namibia). Until recently, late Quaternary SWDs from the Namib Valleys have been described as sediments representing river endpoint accumulations or deposits of an aggrading river, controlled by a change in the hydrological regime in the catchment area (Dollar, 1998). Heine and Heine (2002) pointed out that the late Quaternary SWDs of the Kuiseb Valley in the Namib Desert were deposited in areas of the floodplain that are sheltered from high-velocity flood flows and thus represent extremely big flood events. Recent work (Heine, 2004) shows that the last period of the accumulation of SWDs in the Namib Desert occurred during the Little Ice Age (LIA). Here I present further evidence for establishing palaeoflood histories from SWDs of the Namib Desert valleys during the last ca. 1000 years.

THE NAMIB DESERT

The Namib Desert is a relatively narrow tract of land extending ca. 1800 km from South Africa to southern Angola

(Fig.1). Lying between the South Atlantic Ocean and the Great Western Escarpment, the desert is mostly less than 200 km wide (Seely, 1987, p.9). From the sea to the east the Namib Desert rises to about 1000 m ASL. Rainfall is increasing from the coast (<20 mma^{-1}) to the inland. The 100 mma^{-1} rainfall line matches approximately the footslopes of the Great Escarpment.

Twelve major ephemeral rivers are found in the central and northern Namib Desert of Namibia (Fig. 1). A number of smaller rivers originate in the arid desert itself. The

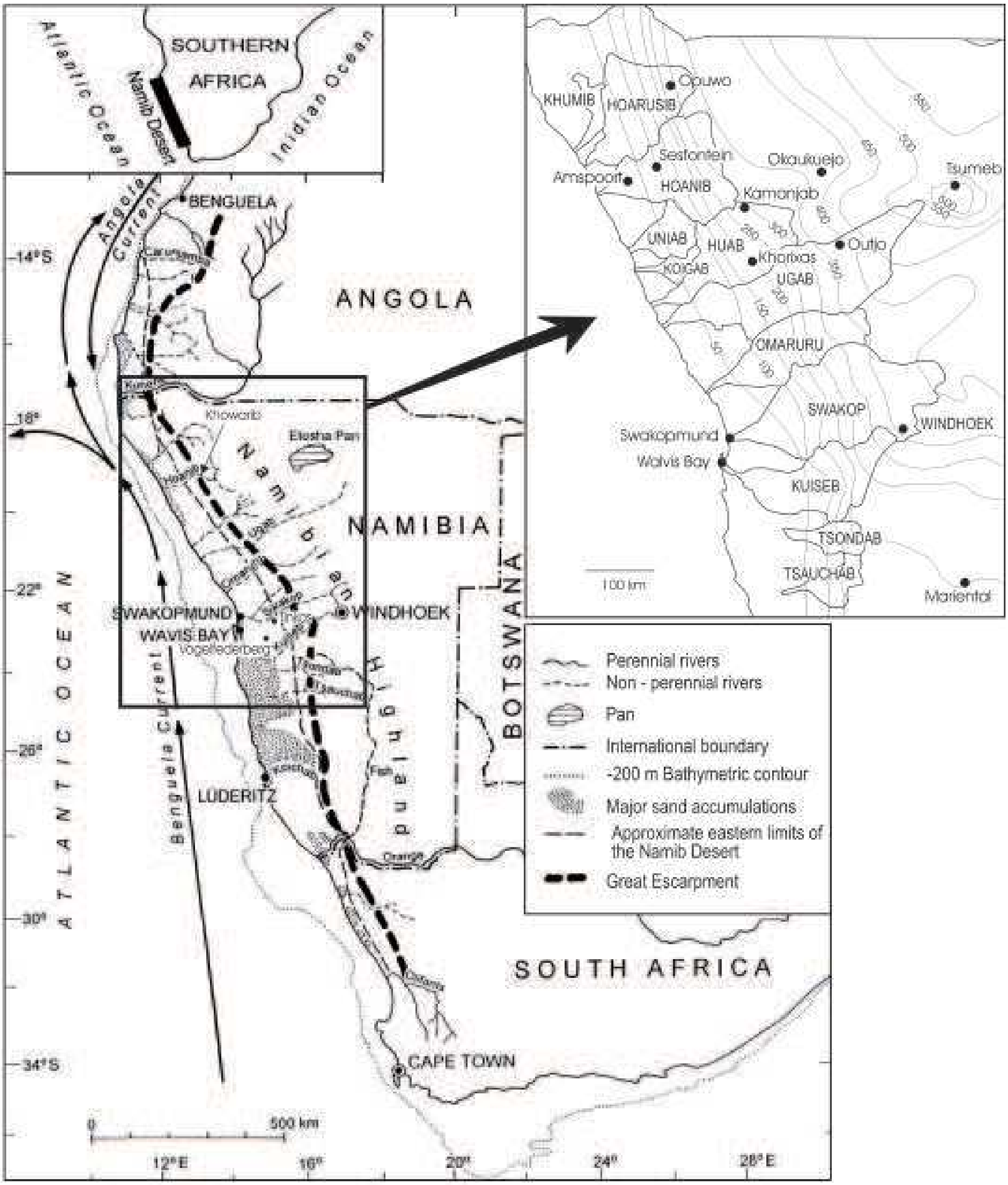

Fig. 1. The Namib Desert. Map with sand accumulations. Inset map shows the major drainage systems and rainfall isohyets (mma^{-1}).

frequency of flooding in the valleys is related to catchment size, average rainfall, and, in some areas, upstream dams (Jacobson et al. 1995, p.9). Today, the frequency of flooding, which varies from valley to valley, affects the vegetation and water resources each river supports. These geographical, climatic and biological features, in addition to the variable geology, make each catchment unique (Jacobson et al. 1995, p.9). A detailed description of the ephemeral river systems and their resources is presented by Jacobson et al. (1995).

METHODS

Sedimentologic and stratigraphic studies of SWD sequences combined with radiocarbon dating is used to establish a Holocene palaeoflood record for three Namib Desert valleys. We mapped SWDs and compiled information about the sedimentation processes. We analysed the grain size distribution (standard techniques, sieve, pipette), carbonate content (Scheibler and Finkmer technique, see Ellerbrock, 2000), contents of organic material (UV-VIS spectrometer with Lambda 2), colour (Munsell) and clay mineral associations (X-ray diffraction, Siemens X-ray unit D 5000) to differentiate between different palaeoflood sediments with different provenance. Sedimentary structures usually show flat lamination, implying suspension settling by moderate rates of deposition, as suggested by Zawada (1997) for South Africa, rather than sudden or rapid rates as is documented for the lower Pecos River in Texas,USA by Kochel and Baker (1982).

Detailed investigations of many soil sections of the central Namib Desert in the area of the Swakop and Kuiseb Rivers (Heine and Walter, 1996a; Bao et al. 2000) supplement the analyses carried out on the SWDs and allow reconstructions of extreme precipitation events (sheet floods).

^{14}C age determinations were done by the laboratory in Hannover (M. A. Geyh) and AMS ^{14}C by the laboratory in Erlangen (W. Kretschmer). The ages younger than AD 1951 were inferred from a diagram elaborated by M. A. Geyh. The ^{14}C data are published by Heine (2004).

SLACKWATER DEPOSITS (SWD) OF THE NAMIB VALLEYS

General

SWDs are found in all valleys of the Namib Desert from the Republic of South Africa to southern Angola, as well as in adjacent areas (Heine, 1998a; Heine et al. 2000). They occur in areas with winter rain regime (Mediterranean climate) in the south, in the extremely arid central part of the desert with occasional, but very rare rains during the whole year, and in the northern summer rainfall region.

The SWDs consist of silts and fine sands. The thickness of individual layers of one flood event comes to less than a centimetre or to >30 cm. At many sites sequences of SWD layers occur that may add up to more than 30 m of flood deposits. The SWDs are found as small ledges along steep slopes (Fig. 2) or as terrace-like sediments in embayments, in back-flooded tributary mouths as well as in the lower parts of side-valleys (Fig. 3) and downstream of abrupt channel expansions where eddies associated with flow detachment during floods occur, upstream of channel constrictions due to backwater effects, in the lee of in-channel obstructions such as large boulders and bedrock outcrops and bedrock caves and alcoves along the channel or valley-wall in which flow detachment and ponding occurs (Zawada, 1997). The SWDs accumulate rapidly by suspension settling during the flash floods, especially in overbank low-energy flow areas. The SWDs of the Namib Valleys are found where the backwaters of large floods accumulate thick sequences and where, because of the extreme aridity, the rains do not erode the SWDs even during thousands of years (Heine and Heine, 2002; Heine et al. 2000).

In the Namib Desert valleys, the fine-grained SWDs show that at sites that experience sudden reductions of flow regime, many successive floods may have contributed to their accumulation. Floods inundating a previously accumulated SWD will deposit a new layer on top of the previous one; smaller floods will deposit sediment as insets (Zawada, 1997).

Trace fossils represent an important component of the sedimentary successions and depositional systems of the SWDs of the Namib Desert. Until now, only Smith et al. (1993) report about the ichnofacies of the Kuiseb Valley SWDs near Homeb. According to the model of non-marine ichnofacies of Buatois and Mángano (1998), the Homeb Silts contain the *Termitichnus* ichnofacies that characterizes subaerial, fully terrestrial environments. The traces of the ichnofacies represent an interruption in accumulating SWDs as do weathering records in between the silt layers.

According to the age determinations of different authors, the SWDs of the Namib Valleys accumulated during the late Quaternary. Some remnants of silt deposits are even older than 120 ka BP (Heine et al. 2000; Heine 1998a, 1998b). During the Holocene, SWDs formed around 10 to 8 ka BP and between ca. 2 ka BP and the present (Fig.4).

Fig.2. High-level slackwater deposits along steep slopes of the Hoarusib Valley west of Purros. The SWDs are visible along the valley between Purros and the Atlantic (photo: K. Heine 1996).

Fig.3. Terrace remnants of tributary-mouth slackwater deposits (SWDs) of the Kuiseb River at Hope Mine, near Homeb (photo: K. Heine 1998). These SWDs accumulated during the Last Glacial Maximum (ca. 20 ka BP, Heine and Heine, 2002).

Slackwater Deposition during the Little Ice Age

The SWDs of the valleys of the Hoanib, the Swakop/ Khan and the Tsauchab were investigated in more detail (Figs.1 and 4). In the Hoanib Valley, Holocene SWDs were deposited around 9 ka BP and during the Little Ice Age (LIA). The LIA slackwater sediments of the Hoanib Valley document very big recurring floods. In the Khowarib Gorge (Fig.1) fluvial and colluvial sediments were used to reconstruct the following sequence of sedimentation and erosion phases (Heine, 2004). The accumulation of red-brown consolidated silts (silt member 2) of unknown Pleistocene age (Fig. 5) was succeeded by the deposition of

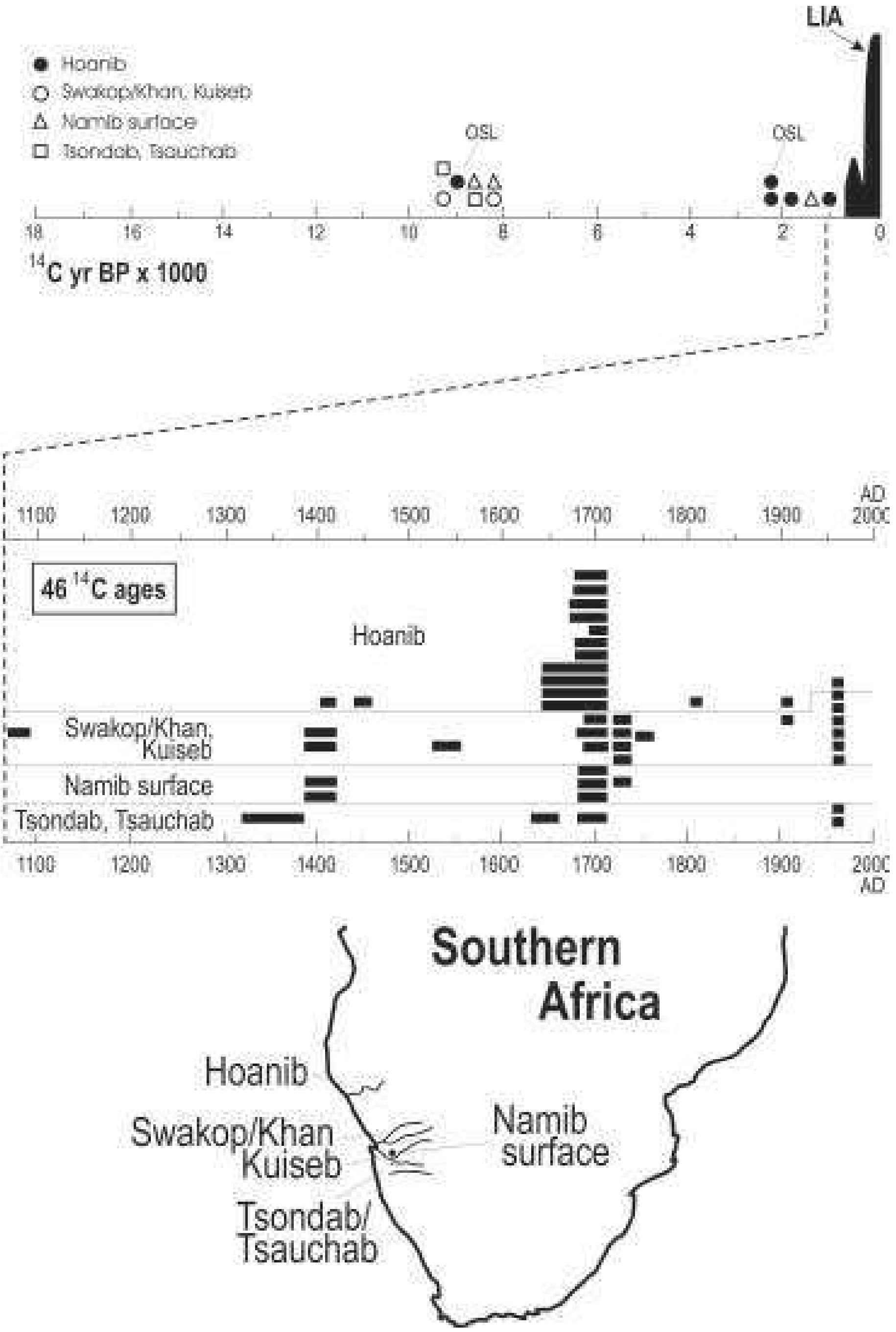

Fig.4. ^{14}C ages of Holocene slackwater deposits and colluvial desert surface deposits of the Namib Desert.

greyish sands and silts (silt member 1). A phase with erosion followed, leading to the accumulation of slope debris on top of silt member 1. Intensive dissection and gullying occurred during the late Pleistocene (Last Glacial Maximum?). The deposition of brown silts (SWD member 2), to date slightly consolidated, is dated by OSL to ca. 9 ka BP (Eitel et al. 2001). In the Khowarib Gorge no SWDs accumulated between ca. 9 ka BP and the LIA. For more than 8000 years erosion processes caused dissection of the sediments and gully development. The second Holocene phase with SWD deposition occurred during the LIA (ca. AD 1650 - 1720). The LIA slackwater deposits are interbedded with colluvial material washed into the valley from the slopes. This is evidence for precipitation events in the area of the Khowarib Gorge during the LIA.

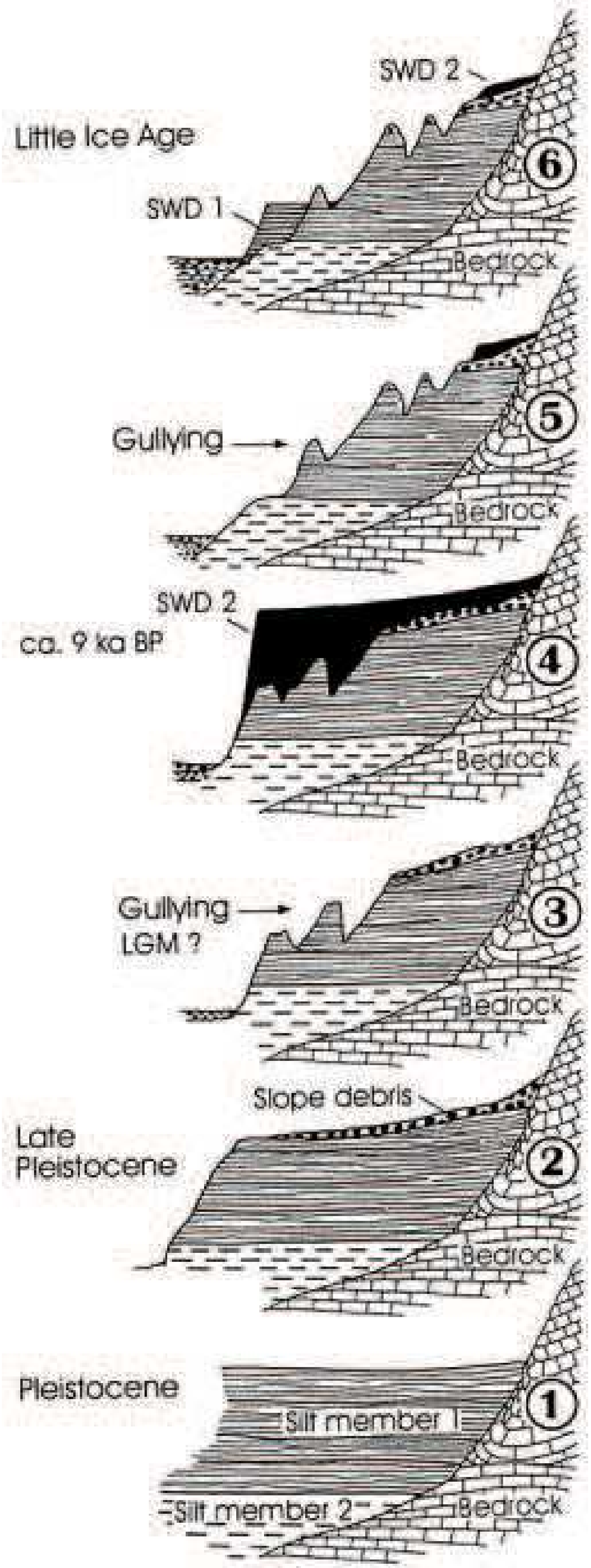

Fig.5. Schematic development of different SWD members in the Khowarib Gorge. For explanation see text.

Apart from the observation of young Holocene (Neoglacial) slackwater deposition in parts of the Hoanib Valley (Heine, 2004), there is evidence that, during the LIA, flash floods of the Hoanib built a sequence of flood-out sediments in the area of Amspoort. These flood-out sediments buried a riparian acacia-forest (Vogel and Rust, 1987, 1990a, 1990b). Vogel and Rust (1990b, p.27) suppose a concentration of the accumulation to only 70 years from AD 1640 to 1710.

In the Swakop and Khan Valleys (Fig.1), the youngest SWDs have early Holocene and LIA ages (Fig. 4) (Heine, 2004). SWDs on top of the sediments of the LIA document younger flood events. According to ^{14}C ages these SWDs probably were accumulated during the floods of the year AD 1985.

Evidence of LIA flood deposits comes from the Tsauchab River (Fig.1) too. Yet, the Tsauchab SWDs are only thin silt layers reaching only 1.0 to 1.3 m above the present river channel. Like the SWD sequences of the Swakop and Khan Rivers, the Tsauchab SWDs are topped by younger flood sediments. These consist of fine-grained sands and probably accumulated during the last decades.

Silt Deposition in the Vleis of the Dune Fields

The Tsondab and Tsauchab Rivers (Fig.1) end in vleis (pans) in the high dunes of the main Namib Sand Sea (Namib Erg). Each flood brings silts to the vleis. The vlei sediment sequences show an alternation of fluvial silt and aeolian sand accumulation (Heine, 1987, 1993). It is obvious that thick silt layers are restricted to early Holocene accumulation processes and that the LIA is not represented by more than normal silt accumulation. Thus, the vlei sediment sequences add to the observation in the Tsauchab River that the LIA experienced not the extremely big flash floods like the valleys in the northern Namib (for example, Hoanib).

SOILS, CAVE SEDIMENTS AND DRIFTWOOD OF THE NAMIB DESERT

Soils

Characteristic soils of the central Namib Desert are gypcretes (Heine and Walter, 1996a, 1996b). Gypcretes or gypsum crusts (Watson, 1985) occur in warm desert environments receiving less than 250 mm of annual rainfall. The gypsum layers are located down to a depth of 10 m below the surface. They consist of gypsum accumulation, 0.1 m to 5.0 m thick, with more than 15% by weight gypsum and at least 5% by volume more gypsum than the underlying horizon. Here I refer to ‘gypcretes’ even if initial gypsum formation shows only a slight increase in pedogenic gypsum (Heine and Walter, 1996a).

In the central Namib Desert, the gypcretes (Fig. 6) show a regular composition independent of the relief position. The soil horizons consist of single layered units of para-autochthonal material. Most of the thin layers that rarely exceed 10 cm in thickness were redeposited earlier than the main phase of calcrete development during the Upper Tertiary (Heine and Walter, 1996a). Some additional phases of intensive redeposition of surface material must have occurred during the Pleistocene when weathering debris was spread over the desert plain by sheet-wash processes. The thin loose sediments form the material of the soil development in places where calcretes do not reach the surface (west of 15° 25'E). The Namib Desert soils are extremely weakly developed. Nevertheless, soil horizons formed by pedogenic processes and associated with the original lamination of the sediments, are clearly visible. In the western Namib Desert, the surface sediments show a 1 to 2 cm thick redeposited layer, becoming deeper to the east. After rainstorms, this surface layer may saturate with water and move in suspension from higher to lower ground. Beneath this layer gypsum accumulates and contribute to the formation of gypsum crusts (Heine and Walter 1996a; Bao et al. 2000; Bao et al. 2001). According to our investigations of the gypcrete sections, gypcrete formation dominated the pedogenic processes in the central Namib Desert at least since the late Pleistocene times without any interruption by fluvial climatic phases. Apart from some small areas with raw mineral soils and calcretes, gypcretes developed all over the area of investigation of the Namib Plain between the Kuiseb and Omaruru Valleys.

From the east to the west, a zonal distribution of different patterns of the gypcretes can be documented (Fig. 6). The Namib soils can be divided into 5 zones: (1) soil zone I characterizes the calcrete areas in the east; (2) soil zone II shows gypsum in the calcretes which are overlain by thick loose surface material (transition zone), (3) soil zone III is characterized by regularly developed gypcretes beneath thin (<3 cm) layers of loose material. The amount of gypsum and pore volume increases to the west. Calcretes at the base of the sections are absorbed by the gypcrete development; (4) soil zone IV is composed of NaCl-rich carbonate/gypsum mixed crusts overlain by up to 30 cm thick loose material, and (5) soil zone V is characterized by aeolian processes combined with pedogenic processes. This zone is more or less free of gypsum.

A schematic soil profile of the central Namib Desert gravel plain (Fig. 6) shows from top to bottom the following horizons: (1) layer of 2-3 cm of aeolian material, with a desert pavement of quartz, rock fragments, feldspar, remnants of calcrete etc., composed of a layer of angular to subrounded gravels one or two stones thick sitting on a mantle of finer stone-free silty-sand; (2) gypsum crust of varying thickness; in the upper part characterized by pendants of fresh gypsum minerals that were formed on the top of cone-shaped gypsum aggregates; these form a gypcrete, (3) gypsum crust mixed with weathered carbonate cementations, calcretes, or decomposed bedrock, (4) horizon rich in $CaCO_3$ or/and decomposed bedrock with gypsum minerals formed by crystallisation from descending soil water; (5) similar to layer 4, but without visible gypsum, and (6) bedrock or calcrete.

The gypcrete sections of the central Namib Desert show that during the Holocene, sheet-wash processes were nearly absent on the Namib Plain. It was only during the Little Ice Age (LIA) that a marked change of the geomorpho-dynamic processes occurred. Flat pan-like deflation hollows of the Namib Plain contain sheet-wash material as thin layers on top of the characteristic gypcrete section. ^{14}C age determinations of organic material of the gypcrete and sheet-wash layers document that rain storms occurred during the LIA, but there is no evidence for such events during the earlier Holocene times (Heine, 2004).

Cave Sediments

Near the Swakop Valley, the small cave system of the Tinkas Cave (Heine, 1992, 1998b) is developed. Washed-in sandy sediments contain organic material (parts of plants, wood, bones, etc.) that was AMS ^{14}C-dated. The wood sample (KOO 636) yielded the date 487 ± 165 cal yrs BP (Erl-2718; 2 sigma: AD 1298 - 1520 and AD 1567-1628), the bone sample (KOO 634) a date of 1,266 ± 38 cal yrs BP (Erl-4849; 2 sigma: AD 664-870), and a plant sample (KOO 635) an age of AD 1962 or AD 1975-1977 (Erl-4850; 2 sigma). We suppose that the bone sample gave an age too old because of contamination with remaining carbonate, whereas the wood sample represents the main layers of the washed-in LIA sheet flood sediments. The subrecent plant sample stands for exceptionally heavy Namib rainy seasons of the years AD 1977-1978; yet, the washed-in cave sediments of the most recent floods are very thin compared to those of the LIA.

Driftwood

Big flood events (sheet-wash) are responsible for the transportation of tree trunks on the desert plain over distances of more than 40 km (Heine and Walter, 1996b, p.245). The ^{14}C age of the outer annual rings of a sheet-

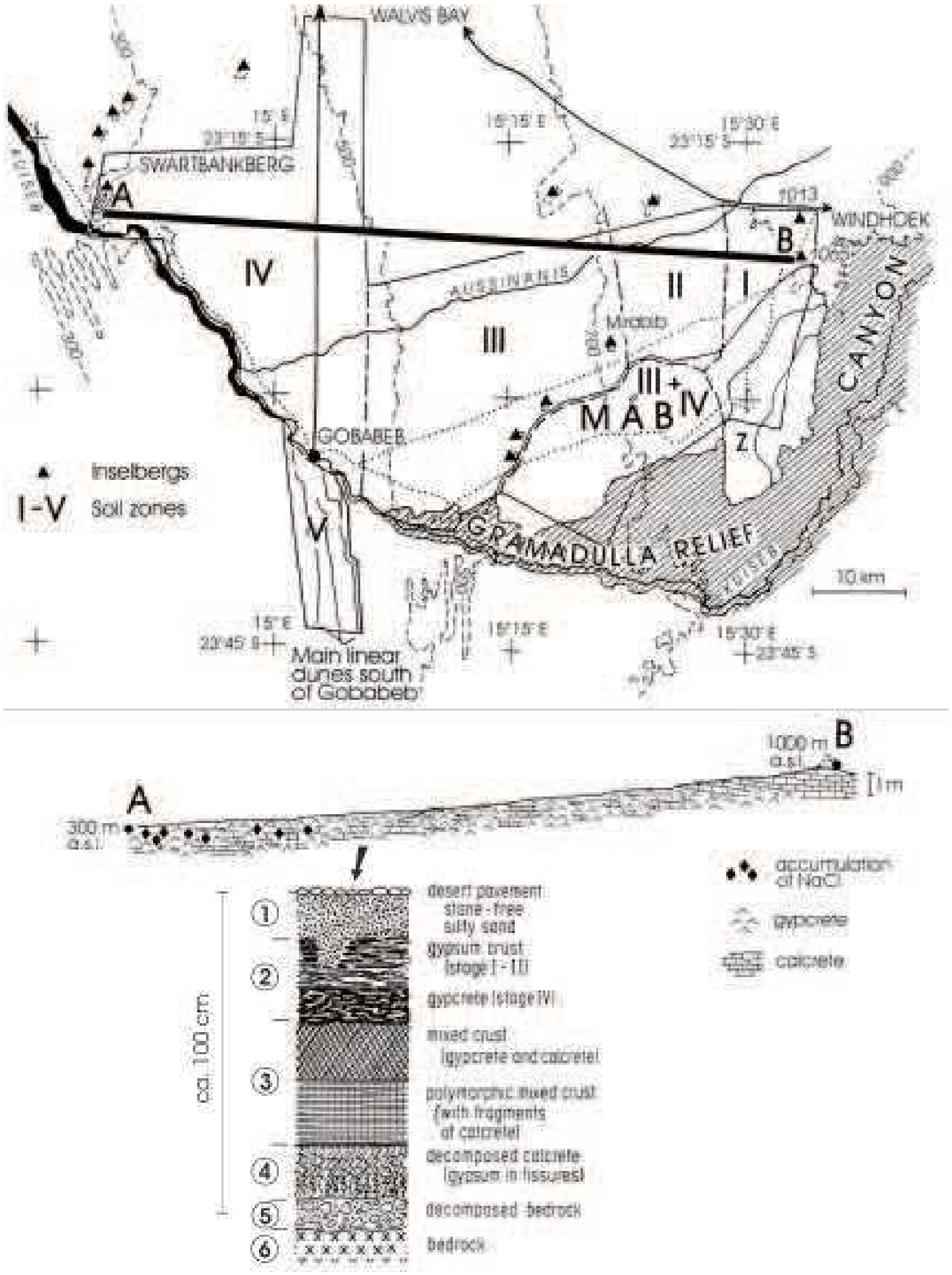

Fig. 6. The top figure shows the soil zones and zonal occurrence of duricrusts in the central Namib Desert. For explanation see text. The bottom figure shows a schematic cross section through the central Namib Desert with soil zones I to IV (A-B) and schematic section of gypcrete soils of soil zone IV (*after* R. Walter, Unpublished data).

wash transported trunk about 6.5 km south of the Vogelfederberg documents that the tree was moved during the LIA.

Driftwood along the lower Kuiseb Valley was ^{14}C-dated by Vogel and Visser (1981). The wood occur high above the present river channel. Dating provides information on exceptionally large floods in the past. The radiocarbon dates are (Vogel and Visser, 1981):

Pta-2583	$\delta^{13}C = -24.2‰$ 940±35 yrs BP (ca. cal AD 1140-1200)
Pta-2582	$\delta^{13}C = -25.8‰$ 155±35 yrs BP (younger than AD 1660)
Pta-2632	$\delta^{13}C = -25.6‰$ 290±35 yrs BP (cal AD 1490-1630)
Pta-2638	$\delta^{13}C = -25.1‰$ 140±60 yrs BP (cal AD 1660-1950)

Whereas these dates document high flood events in the lower Kuiseb, especially during the LIA, two ^{14}C dates from Kuiseb River sand at 21.4 and 13.7 m depth near the mouth of the river show rapid sand accumulation during the second half of the 19th Century (Vogel and Visser, 1981) as consequence of reduced discharge during floods:

Pta-689	$\delta^{13}C = -25.9‰$
Pta-604	$\delta^{13}C = -26.0‰$

Vlei Sediments

Till date there is no evidence that, during the LIA, in the Tsondab Vlei and Sossus Vlei of the Great Namib Sand Sea exceptionally big flood events have occurred. On the contrary, the stands of dead acacia tree in Sossus Vlei indicate that the trees died out during the LIA around AD 1400 and in Tsondab Vlei around AD 1700 (Vogel, 2003; Heine, 1987, p.123).

Considering the driftwood and cave sediment data together, it may be argued that this reflects rainfall conditions (in comparison with the current conditions) with heavier occasional rains in the central Namib Desert itself as well as in the catchment area of the Kuiseb River during the LIA.

DISCUSSION AND CONCLUSIONS

There are numerous observations about floodplain sediments from different parts of the southwestern Africa. Brunotte and Sander (2000) report about sandy-silts in the Kunene Valley between Epupa and Ruacana. Older floodplain sediments are cemented by $CaCO_3$ and seem to be accumulated around 8 ka BP. Charcoal of the unconsolidated, loose silts are dated by ^{14}C (16 dates) to AD 1200-1650, only 3 dates are older (AD 650-1285). In the Hoarusib Valley between Purros and the coast, a lower terrace of silty material is visible (Fig. 2). Four ^{14}C dates of plant material document the sedimentation around ca. AD 1160-1270 (Vogel and Rust, 1987). In the Huab catchment, Eitel et al. (2001) report about silt deposits with IR-OSL dates of 8.2 ± 0.6 yrs BP and 8.3 ±1.0 yrs BP. No younger silt layers are documented. According to our investigations (Heine and Heine, 2002; Heine, 2004) I interpret the Kunene floodplain sediments as well as the Hoarusib and Huab silts as slackwater deposits (SWD). Only heavy precipitation events can liberate years, decades or centuries of accumulated sand, silt and clay from the slopes of the catchment and the river channel, and deposit it onto the beaches (Kunene) and in wide basins (Huab). This was shown recently by a torrent that was produced artificially by hydrologists in the Grand Canyon, USA (Powell, 2002). It is noteworthy that, further south, during the LIA the trees in the Tsondab and Sossus Vleis died out (Vogel, 2003).

During the Holocene, SWDs of the Namib Desert valleys accumulated between ca 10 and 8 ka BP and between ca. 2 and 0 ka BP (Fig. 4). The SWDs of the Namib Desert show that flood events occurred in the *northern* Namib (Hoarusib, Hoanib) during the LIA. In the *central* Namib (Swakop/ Khan, Kuiseb, Tsauchab), there is also some evidence from SWDs for LIA floods, but the field data point to magnitudes of these floods that exceed only little or not at all the values of the most recent river discharges. From the *southern* Namib Desert (Fish River Canyon) so far no SWDs of LIA are known.

The best regional high-resolution record for palaeoclimate reconstruction from the middle Holocene to the present in southern Africa is the stable isotope record for the Makapansgat Valley in northern South Africa (Holmgren et al. 1999). Lower $\delta^{18}O$ values indicate cooler and drier conditions. The five centuries of cooling associated with the Little Ice Age (LIA) from AD 1300 to 1800, following the Medieval Warming (MW) AD 900 to 1300, are clearly documented. Maximum LIA cooling occurred around AD 1700 (ca. -1° C). This cold period was coeval with cool events recorded in a large variety of proxy data from all sites over southern Africa and from corals in the ocean off southwestern Madagascar (Tyson et al. 2001).

The degree to which the South African (Makapansgat) and the East African (Lake Naivasha) records have varied inversely over the past millennium is striking (Verschuren et al. 2000; Holmgren et al. 1999; Tyson et al. 2002a) (Fig. 7). The inverse correlation is similar to that which occurs during present-day ENSO events. The LIA in southern Africa was dry and punctuated with extended wet periods (Tyson and Lindesay, 1992), in Kenya it was wet and interspersed with extended dry intervals (Tyson et al. 2002 b, p.12). This reverse relationship is also clearly evident in the meteorological record of the 20th Century (Nicholson and Entekhabi, 1986; Ogallo, 1988; Nicholson, 1986). The LIA at Makapansgat terminated abruptly. The LIA data of the Namib Desert SWDs correlate with cool phases in South Africa (AD 1300-1500; AD 1675-1780; Tyson and Lindesay, 1992) (Figs. 4 and 7). In South Africa the LIA cool phases experienced a drier climate than the periods AD 1500-1675 and AD 1790-1810 which were warm and wet (Huffman, 1996).

The records from South and East Africa can be put versus the curve of detrended $\delta^{14}C$ presented with 1σ error bars versus calendar age. The East African high lake-levels correspond to periods of reduced solar activity (Mauquoy

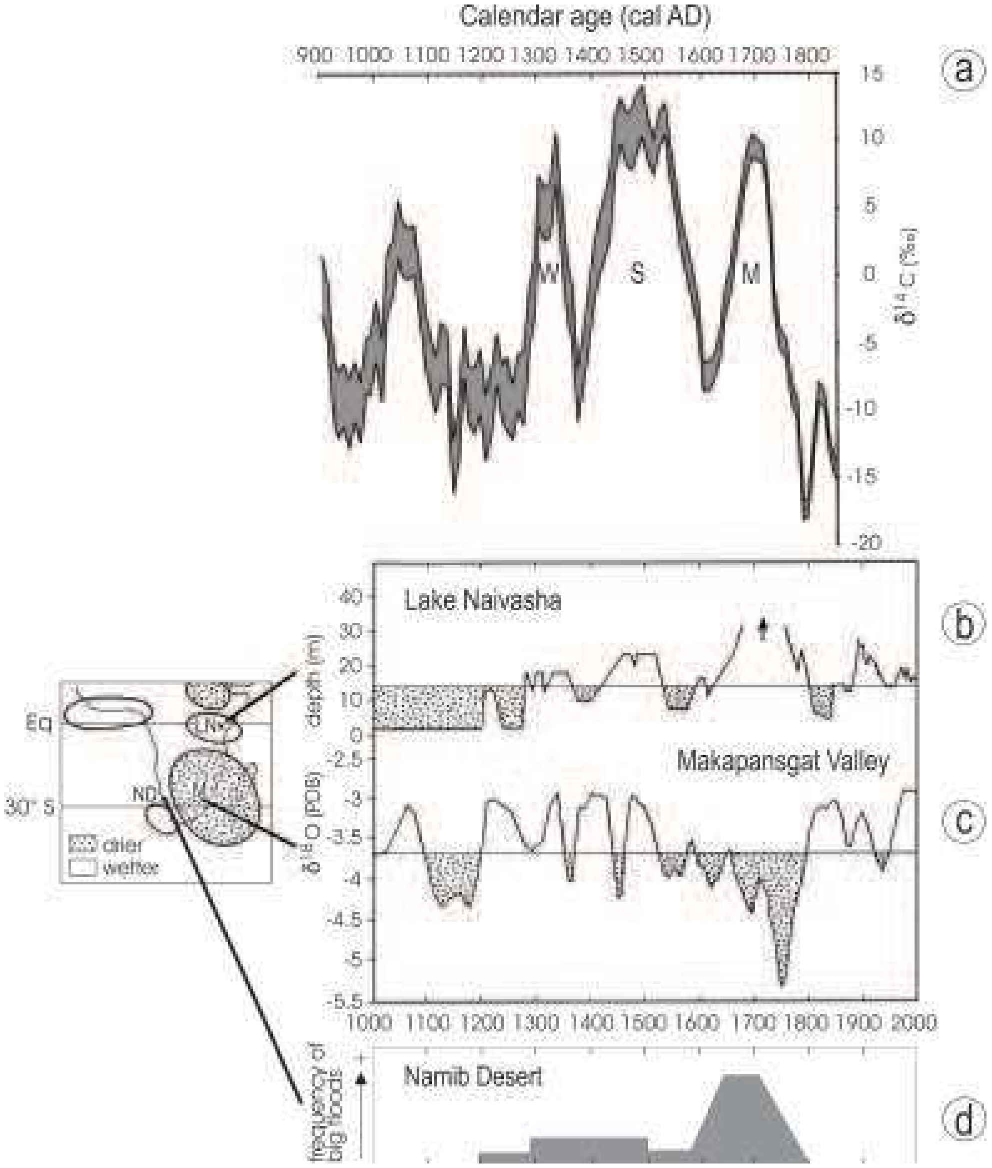

Fig. 7. Inset maps gives the areas in eastern and southern Africa showing teleconnection patterns associated with El Niño (LN = Lake Naivasha, M = Makapansgat, ND = Namib Desert). (**a**) detrended $\delta^{14}C$ presented with 1σ error bars versus calendar age (W = Wolf, S = Spörer, M = Maunder, D = Dalton) (Mauquoy et al. 2002), (**b**) the Lake Naivasha lake-level record (Verschuren et al. 2000), (**c**) Makapansgat stalagmite $\delta^{18}O$ variations (Holmgren et al. 1999; Tyson et al. 2002), and (**d**) LIA slackwater deposits (SWD) of the Namib Desert.

et al. 2002), so do the dry cool phases of the Namib Desert (Fig. 7). Related to these dry cool phases of southwestern Africa are the SWDs of the LIA. I suggest that the extreme flood events that cause the deposition of the SWD in the Namib Valleys are produced by circulation anomalies over southern Africa. A significant proportion of summer rainfall is derived from tropical-temperate troughs (TTTs), (Todd and Washington, 1999) which extend over both continental southern Africa and the adjacent south western Indian Ocean. By using daily data, Todd and Washington (1999) find that rainfall associated with TTTs over southern Africa results from distinct patterns of anomalous low-level moisture transport, which extends to the planetary scale. The principal mode of precipitation variability is a dipole structure with bands of rainfall orientated northwest to southeast across the region. The position of the temperate trough and the TTT cloud band alternates between the southwestern Indian Ocean and the southeast Atlantic.

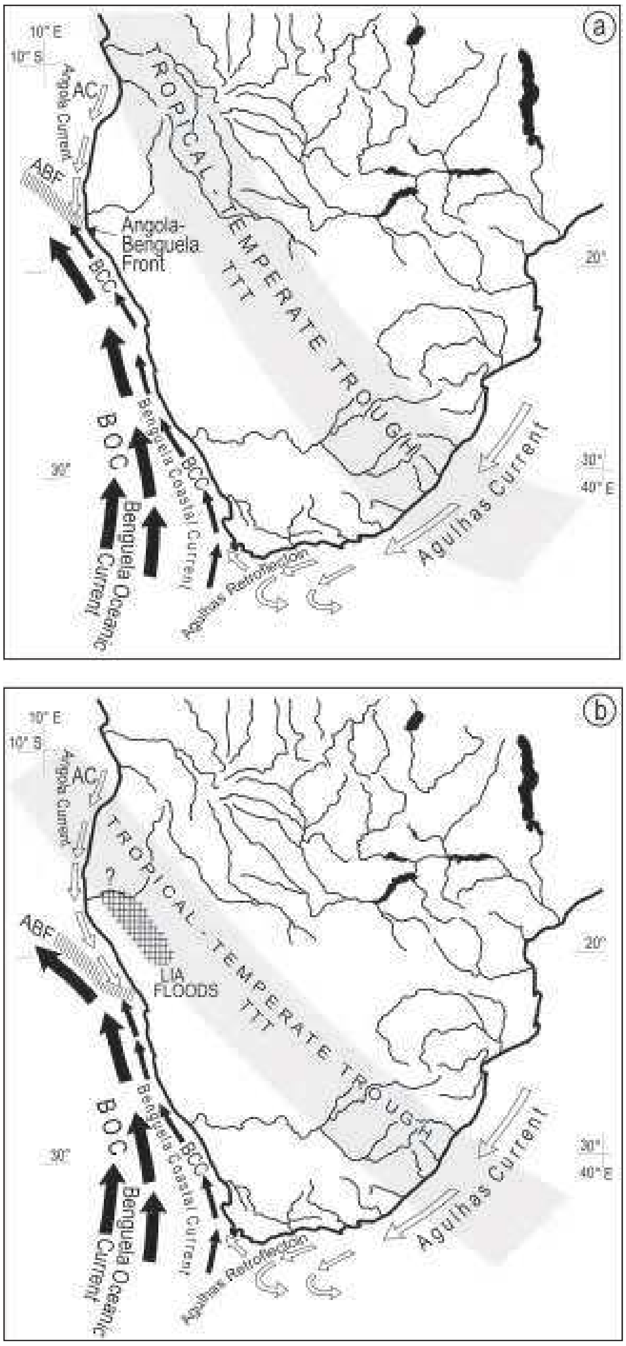

Fig.8. Ocean currents (after Wefer et al. 1996) and situation of tropical temperate troughs (TTT) during exceptional precipitation events in arid Namibia (**a**) during the last 100 years and (**b**) during the LIA with areas afflicted by exceptional floods.

The synoptic scale TTT events over southern Africa/ southwestern Indian Ocean often result from large-scale planetary circulation patterns. Tropical and extra-tropical dynamics are involved in producing these TTT cloud bands over southern Africa (Todd and Washington, 1999) and influence their regional occurrence and, hence, the distribution of rainfall in the Namib Desert. These TTTs occur more frequently over the Namib Desert during phases when the radiation maximum is in the southern hemisphere and when reduced solar activity occurs. Both, radiation maximum of the southern hemisphere *and* reduced solar activity, produce atmospheric circulation patterns favourable for TTTs reaching further west than normal over southern Africa, thus, producing heavy rainfall in the Namib Desert and adjacent areas (Heine, 2004).

It has been proposed that the Earth's climate could be affected by changes in cloudiness caused by variations in the intensity of cosmic rays in the atmosphere. A cosmic ray-cloud interaction (Carslaw et al. 2002) and a cosmic ray-global sea level interaction (Kessler, 2002) explain how a relatively small change in cosmic rays (sun spot activity) can produce much larger changes in global climate (Chambers et al. 1999). Changes of ocean surface currents may be caused by physical phenomena related to small changes in solar output. I suggest that during the Maunder Minimum (and during other periods of reduced solar activity) the warm Angola Current could push the Angola-Benguela-Front to the south (Fig. 8). This situation may be responsible for a shift of the TTTs further than normal to the west. In this case the northern Namib Desert may experience exceptionally heavy rains, whereas the southern Namib Desert will not necessarily show flood events. According to our investigation of the LIA palaeofloods documented by the SWDs, we suggest that the long-term changes of cosmic ray intensity could substantially influence climate in the extremely arid southwest African areas.

It should be emphasised that climatic phases during which SWD sequences were accumulated do not represent climatic phases with greater annual precipitation values as is stated by many authors (Lancaster 2002, p.771-3). The evidence from the Namib Desert shows that SWDs accumulated when the climate in southern Africa was cooler and drier than normal. These cool dry phases from AD 1300 to 1500 and from AD 1675 to 1780 must have influenced the annual rainfall in the catchment areas of the Tsondab and Tsauchab Valleys with the consequence of lowering of the groundwater table in the endpoint pans between the dunes. Thus, it can be assumed that extremely high SWD-forming floods are restricted to drier and cooler climatic phases in the southern African summer rainfall areas. Consequently, SWDs cannot be used as palaeoclimatic archives with respect to reconstruct annual precipitation values.

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