LATE QUATERNARY SAND RAMPS IN SOUTH-WESTERN NAMIBIA

NATURE, ORIGIN AND PALAEOCLIMATOLOGICAL SIGNIFICANCE

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ABSTRACT

Late Quaternary sand ramps in south-western Namibia
Nature, origin and palaeoclimatological significance

Sand ramps have been (and still are) neglected in geomorphological research. Only recently any awareness of their potential of being a major source of palaeoenvironmental information, thanks to their multi-process character, has been developed. In Namibia, sand ramps were *terra incognita*. This study defines, classifies and systematizes sand ramps, investigates the formative processes and examines their palaeoenvironmental significance. The study region is located between the coastal Namib desert and the Great Escarpment, between the Tiras Mountains to the north and the Aus area to the south. Two lines of work were followed: geomorphological and sedimentological investigations in the field, assisted by interpretation of satellite images, aerial photographs and topographic maps, and palaeopedological and sedimentological analytical work in the laboratory.

Two generations of sand ramps could be identified. The older generation, represented by a single sand ramp within the study region, is characterized by the presence of old basal sediments. The bulk of the sand ramps is assigned to the young generation, which is divided into three morpho-types: in windward positions voluminous ramps are found, in leeward positions low-volume ramps exist, either of very high or very low slope angle. The most distinct characteristic of sand ramp sediments is their formation by interacting aeolian deposition and fluvial slope wash. The last period of deposition, which shaped all the entire young sand ramps, but also the upper part of the old ramp, is suggested to have occurred after c. 40 ka BP, implying a highly dynamic climatic system during that time, with seasonal aridity and low-frequency, but high-intensity rainfall. A phase of environmental stability followed, most likely around 25 ka BP, supporting growth of vegetation, stabilization and consolidation of the sediments as well as soil formation. Subsequently, the profile was truncated and a desert pavement formed, under climatic conditions comparable to those of the present semi-desert. The ramps were then largely cut off from the bedrock slopes, implying a change towards higher ecosystem variability. As the final major process, recent and modern aeolian sands accumulated on the upper ramp slopes. A luminescence date for the recent sand places their deposition at about 16 ka BP, close to the Last Glacial Maximum. Regarding the source of the sands, a local origin is proposed.

For the sand ramp of the old generation the "basic cycle" of initial deposition, stabilization and denudation occurred twelve times, including a phase of calcrete and/or root-cast formation in each of them, adding up to around 60 changes in morphodynamics altogether. At least nine of these cycles took place between 105 ka BP and the LGM, indicating that the general cooling trend during the Late Pleistocene was subject to a high number of oscillations of the environmental conditions not identified before for southern Namibia. Due to the high resolution obtained by the study of sand ramp sediments, but also due to the very special situation of the study area in a desert margin, 100 km from the South Atlantic and in the transition zone between summer and winter rainfall, correlation with stratigraphies (of mostly lower resolution) established for different regions in southern Africa did not appear promising.

In conclusion, sand ramps generally serve as a valuable tool for detailed deciphering of past morphodynamics and thereby palaeoenvironmental conditions. For south-west Namibia, sand ramps shed some more light on the Late Quaternary landscape evolution.

ZUSAMMENFASSUNG

Quartäre Sandrampen in Südwest-Namibia
Charakteristik, Entstehung und paläoklimatische Bedeutung

In der geomorphologischen Forschung haben Sandrampen bislang wenig Beachtung gefunden, erst in jüngster Zeit ist auf ihr Potential als Speicher von Paläoumweltbedingungen hingewiesen worden. In Namibia waren Sandrampen *terra incognita*. Die vorliegende Studie definiert, klassifiziert und systematisiert Sandrampen in Südwest-Namibia, sie entschlüsselt ihre Bildungsprozesse und untersucht ihre paläoklimatische Bedeutung. Das Arbeitsgebiet liegt zwischen der küstenparallelen Namib und der Großen Randstufe, zwischen den Tirasbergen im Norden und der Gegend um Aus im Süden. Methodisch standen geomorphologische und sedimentologische Untersuchungen im Gelände im Vordergrund, unterstützt durch die Interpretation von Satellitenbildern, Luftbildern und topographischen Karten. Zahlreiche Substratproben wurden im Labor paläopedologisch und sedimentologisch analysiert.

Es konnten zwei Sandrampen-Generationen identifiziert werden. Die ältere Generation, im Arbeitsgebiet durch nur eine Rampe vertreten, zeichnet sich durch das Vorkommen alter basaler Sedimente aus. Alle anderen Rampen sind der jüngeren Generation zuzuordnen und lassen sich in drei Morpho-Typen unterteilen: In Luv-Positionen finden sich voluminöse Rampen, während im Lee geringmächtige Rampen von entweder extrem steiler oder sehr geringer Hangneigung ausgebildet sind. Das auffälligste Merkmal der Sandrampen ist ihre Bildung durch die Interaktion von äolischer Deposition und Hangspülung. Die letzte Depositionsphase, in der die gesamten Körper der jungen Sandrampen abgelagert und die basalen Sedimente der alten Generation überlagert wurden, hat vermutlich nach 40 ka BP stattgefunden. Dies impliziert ein hochdynamisches klimatisches System zu dieser Zeit, mit saisonaler Aridität und seltenen, aber intensiven Regenfällen. Es folgte eine Phase der Ökosystemstabilität, vermutlich um 25 ka BP, in der es zu Vegetationsentwicklung und Bodenbildung sowie zu Stabilisierung und Konsolidierung der Sedimente kam. Eine anschließende Profilkappung mit Wüstenpflasterbildung geschah dann unter ähnlichen klimatischen Bedingungen wie in der heutigen Halbwüste. Danach wurden die Sandrampen fast überall von den Hängen abgeschnitten, was einer Änderung zu höherer Variabilität im Ökosystem zuzusprechen wäre. Die jüngste wesentliche Überprägung bestand in der Ablagerung subrezenter und moderner äolischer Sande in den obersten Bereichen der Sandrampen. Lumineszenzdatierungen stellen die subrezenten Sande ins letzte Hochglazial (~ 16 ka BP). Dem Sandrampensand wird eine lokale Herkunft zugesprochen.

Für die Sandrampe der älteren Generation wiederholte sich der Zyklus von Deposition, Stabilisierung und Denudation insgesamt zwölfmal, inklusive je einer Phase von Kalkkrusten- und/oder Wurzelpseudomorphosenbildung. Insgesamt sind rund 60 Prozesswechsel dokumentiert. Mindestens neun dieser Zyklen verliefen zwischen 105 ka BP und dem letzten Hochglazial. Der generelle Abkühlungstrend während des Spätpleistozäns war also einer bedeutenden Anzahl von Schwankungen unterworfen, die bislang für Südnamibia nicht bekannt waren. Aufgrund der hohen zeitlichen Auflösung, die sich aus den Sandrampensedimenten erschließt, aber auch durch die besondere Lage des Arbeitsgebietes in einer Wüstenrandregion, 100 km vom Südatlantik entfernt und in der Übergangszone von Sommer- und Winterniederschlag, wurden Korrelationen mit Stratigraphien (von meist geringerer Auflösung), die für andere Regionen im südlichen Afrika aufgestellt worden sind, als wenig sinnvoll erachtet.

Die vorliegende Arbeit zeigt, dass sich Sandrampen generell sehr gut zur Entschlüsselung paläomorphodynamischer Prozesse eignen und damit wesentlich zur Rekonstruktion von Paläoumweltbedingungen beitragen. Für Südwest-Namibia liefern Sandrampen neue, detaillierte Informationen zur spätquartären Landschaftsgeschichte.

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1 INTRODUCTION

1.1 Background

This is a study of sand ramps in Namibia. "No known detailed studies of similar features have been made in other desert regions, and we believe the Mojave sand ramps to be unique", LANCASTER & TCHAKERIAN wrote in 1996. This statement indicates clearly how unrecognized sand ramps were until recently and, in consequence, how neglected they still are in geomorphological research. The Mojave sand ramps are surely not unique. As in Namibia, sand ramps occur in many regions of the world which are arid or semi-arid today, being important morphological features.

"A sand ramp – what is that?" was a question often met with in the course of this project. Although the term describes a still uncommon classification type for sediments, it is almost self-explanatory: Sands banked up against mountain fronts or other topographical obstacles, forming a ramp (cf. Fig. 1). As their main characteristic, sand ramps contain a variety of sediments formed in different environments, including aeolian, fluvial and talus deposits, which automatically implies that they have to be fossil forms, at least in parts. Depending on their age and on the dominant geomorphic process, sand ramps – to a certain degree – do have differing appearances, leading to the problem that they have often been misinterpreted as being either alluvial fans or topographical dunes. But alluvial fans covering 60 – 90% of the hillslopes, sometimes even burying the mountain tops? Dunes? Both BESLER (1992) and LIVINGSTONE & WARREN (1996) regard sand ramps to be obstacle dunes, climbing or falling, but indeed they are not. Dunes are exclusively aeolian accumulation forms. Sand ramps, however, are characterized by their composite nature of aeolian sand accumulations, talus derived from adjacent mountain slopes, and fluvial and colluvial sediments, which, together with their often considerable size, clearly distinguishes them from topographically controlled dunes (LANCASTER & TCHAKERIAN 1996, THOMAS et. al. 1997, MEHRSHAHI 2001). Due to these apparent difficulties simply to identify sand ramps properly, any awareness of their potential of being a major source of palaeoenvironmental information, thanks to their multi-process character, has been developed only quite recently.

Because of the scanty knowledge of sand ramps with regard to the basic aspects of recognition, definition and classification as well as their palaeoenvironmental significance, a systematic study about sand ramps was felt to be of certain value. This should be especially so with regard to southern Namibia, where sand ramps frequently occur. The region between the Namib desert and the Great Escarpment, between the Tiras Mountains and Aus shows sand ramps of seemingly different stages of development, providing a good initial basis for approaching these landforms. In addition, the development of the landscape as a whole should be better understood as these sand ramps are obviously interlinked with other landforms. By determining the morphostratigraphic role of the sand ramps and by deciphering their palaeoenvironmental record, another piece of information will be added to the complicated puzzle of Quaternary landscape evolution of southern Africa, which is still full of questions, in spite of numerous studies already conducted there. There are lots of findings and piles of hard data – and even more interpretations, as it seems; it would go beyond the scope of this introduction, though, to mention all of them. Therefore reference is only made to PARTRIDGE & MAUD (2000) and KEMPF (2000) for recent overviews and summaries of geomorphological research carried out in southern Africa, and central Namibia in particular. For further references see the following chapters.

In spite of the apparent urge for knowledge about southern Africa's landscape development in general, not all parts of the subcontinent seem to have been considered to be attractive areas of research to the same degree. In south-western Namibia, this interest used to be focused on the Namib Desert proper either for being an exceptionally dry environment, or because of its wealth of diamond-rich deposits in the coastal parts (e.g. BESLER 1980, JÜRGENS 1991, KAISER 1926, LANCASTER 1989, LOUW & SEELY 1982, RUST 1991, WARD 1987, WILKINSON 1990). Except for this comparatively small westernmost part of south-western Namibia, a sound knowledge of its Quaternary evolution is still scanty. This study therefore concentrates on a quite unexplored area, namely the desert margin, being the transition zone between the coastal Namib Desert to the steppe areas in the east.

The physical prominence of the Great Escarpment allows studies of a desert margin less influenced by processes in the hinterland than in areas without such a distinct barrier. Furthermore, margins are more easily subject to environmental change of a climatic and morphodynamic nature, which should then have been preferably recorded in the sand ramps, as they are landforms expressly originated from alternating processes, as touched on above. Aside from being an object for quenching a geomorphologist's thirst of knowledge, the ecological significance of this area, and of working on it, should not be underestimated, for both scientific and economic reasons: most of this fragile ecosystem is farmland used for grazing, and thus the economic base for the people living in the area. Increased knowledge about substrates may, for example, lead to a better understanding of the ground water bodies of the area and thus contribute to sustainable management – just one possible future application of geomorphological field work there.

Fig. 1: Panorama of the Aus sand ramp, SW-Namibia.

1.2 Sand ramps in literature

1.2.1 Mojave Desert

There has not been much research on sand ramps at all, but from the little that has been done most of it comes from the Mojave Desert, south-western USA (especially LANCASTER & TCHAKERIAN 1996, but also TCHAKERIAN 1991, ZIMBELMAN et al. 1995, TCHAKERIAN 1997). The sand ramps there (Fig. 2) have been found to be amalgamated accumulations of multiple aeolian, fluvial, and talus deposits. They result from the interaction of wind-blown sand and desert piedmont processes adjacent to mountain ranges, occurring next to regional and local sand transport corridors on the presently windward side of the mountains. The sand ramp sediments form part of a continuum of topographically controlled aeolian sand accumulations, ranging from climbing and falling dunes (> 90% aeolian sand) to 1- to 3-m-thick deposits of aeolian sand in Late Pleistocene and Holocene alluvial fan sequences. Aeolian deposits are clearly dominant, but up to 40% of measured section thickness may consist of non-aeolian sediments. Episodes of geomorphic stability are represented by the occurrence of palaeosoils.

Fig. 2: Sand ramp in the Mojave Desert.

Most sand ramps in the Mojave Desert have shown to be relict features, partly indurated and covered by talus accumulations. They were formed in periods of higher aeolian sediment supply from the shores of fluctuating and / or desiccating palaeolakes (i.e. different stages of Lake Mojave). Based on quartz TL dating and potassium feldspar TL and IRSL dating, RENDELL & SHEFFER (1996) identified two major depositional phases: 1. Late Pleistocene (20 – 30 ka) and 2. Late Pleistocene – Early Holocene (15 – 7 ka). This suggests that the main phases of accumulation and preservation, including periods of soil formation, coincide with pluvials when episodic and seasonal sand movement took place and sand was being supplied to washes and playas during periods of ephemeral flow to be taken up by subsequent deflation. The absence of Late Holocene accumulation on the majority of the ramps is interpreted as reflecting problems with sand supply, as increasing aridity reduced the frequency of ephemeral flow events. For the Mojave Desert, sand ramps help to enlighten the extent and duration of past episodes of aeolian activity and stability (RENDELL & SHEFFER 1996, LANCASTER & TCHAKERIAN 1996).

1.2.2 Central Iran

The Ardakan sand ramp in Central Iran studied by THOMAS et al. (1997) also reflects the response of aeolian processes to climatic oscillations during the Quaternary and even allows the formulation of ideas about atmospheric circulation changes during that time in this part of the world.

The fossil, stabilized sand ramp sediments consist of well-sorted aeolian sands interspersed with talus beds and incipient palaeosoils. Morphology and bedding structures imply that south-easterly winds were primarily responsible for the deposition of the aeolian sands.

Optical luminescence dating shows that the c. 25 m of deposits exposed in a stream-cut flank accumulated near the last glacial maximum, with the age of the sediments systematically decreasing upwards from 25 to 20 ka. The deposits therefore suggest the persistence of cold, dry, and probably windy conditions for approximately 5,000 years; sedimentation seemed to have ceased then. As colder and windier conditions would have led to frost shattering and aeolian transport, both of which are evident as past processes from the sand ramp sediments, the conclusion is that the Siberian high pressure system may have strongly influenced central Iran during the last glacial maximum, causing cooler temperatures and a prevalence of south-easterly winds. The findings of the Ardakan sand ramp are supported by a recent study by MEHRSHAHI (2001) looking at neighbouring sand ramp fields around the Shir Kuh mountains.

In contrast to the Mojave desert sand ramps whose sediments represent a long record of different, separated stages of accumulation in the Pleistocene and Holocene, the Iranian sand ramps are believed to have been formed within a relatively short time and under constant climatic conditions, which implies that their formation do not reflect any changes of the climatic regime and geomorphic processes during their time of development. Nevertheless, both types of sand ramps provide a good amount of information about palaeoenvironmental conditions.

1.2.3 Sahara

Although the Sahara has been intensely studied by geomorphologists, sand ramps do not seem to have been in the focus of their research. An exception is BUSCHE (1998) who described different types of sand ramps from several parts of the central Sahara. He regards sand ramps as an important link between fluvial and aeolian accumulation processes acting in the past, as they were influenced and formed by both process types alternately.

The formation of the sand ramps is thought to have happened in stages. After an initial stage of alternating aeolian accumulation and fluvial redeposition, there followed a period of stability, when the sands underwent intensive weathering, with palaeosoil formation and reddening. During a new period of activity, the sediments were reworked, again by both aeolian and fluvial processes. Then, another pedogenic overprint occurred, somewhat less intensive than the older one. These deposits were reworked once more and overlain by younger sediments. These were only slightly influenced by soil forming processes and therefore lack the intensive red colour. Finally, the sand ramps were covered by a thin layer of slope debris and eventually dissected and partly cut off from the hillslopes.

From the resulting polygenetic stratigraphy information can be gained about climatic change and several developmental stages of the Quaternary landforms. The relict nature of the sand ramps in the Sahara is indicated not only by the presence of palaeosoils, dissection and desert pavement as found on other sand ramps as well, but also by Neolithic artefacts on their surfaces. This gives a minimum age for the latest period of sand ramp formation; in correlation with alluvial fans and terraces in the area, the deposition of the final debris cover on the sand ramps is implied to have occurred after the Early Holocene pluvial. The oldest sediments of the "multi-phase" sand ramps with their red palaeosoils of course require a Pleistocene age.

1.2.4 South Africa

TYSON (1998) pioneered with her research on dryland topographical sediments in southern Africa. She investigated aeolian deposits in the southern Kalahari and the Breede River Valley, South Africa, according to their identification as to whether they were sand ramps or topographical dunes, and what their palaeoenvironmental significance was. Unfortunately (for sand ramp enthusiasts) the deposits were found to be climbing dunes due to the uniformity of the aeolian accumulation. Although the homogeneity of sand-dune material does not indicate the response of aeolian processes to climatic oscillations during the Quaternary as well as sand ramps do (THOMAS et al. 1997), some palaeoecological information could be elicited from the climbing dune deposits from luminescence dates and a palaeosoil. The results fit well into a chronology of South African Quaternary climate and environmental change as established by BAXTER (1996).

As "sand ramp" still is an uncommon classification type, it is quite possible that many sand bodies that have been regarded as dunes may in fact be misinterpreted sand ramps. This is certainly the case, for example, for a Pleistocene sand deposit in the north-eastern Cape, South Africa, investigated by MARKER & HOLMES (1993) (P.J. HOLMES 2000 pers. comm.), and this may just be the top of the iceberg.

1.3 Aim

As indicated above, sand ramps in Namibia are *terra incognita*. The objective of this study is therefore to come to understand the sand ramps within the study region as such: To investigate the formative processes, to define, classify and systematize the sand ramps, and to examine their palaeoenvironmental significance. The sand ramps' position in the landscape, their correlation with other Quaternary sediments and palaeomorphological elements will be determined. The knowledge about the palaeoclimatic, morphodynamic and morphostratigraphic role of the sand ramps will hopefully shed more light on the Quaternary landscape evolution of south-western Namibia in the region between the coastal Namib desert and the Great Escarpment, between the Tiras Mountains to the north and the Aus area to the south.

2 REGIONAL SETTING

There is practically no geomorphological literature on the region in general, and absolutely none on the sand ramps there that could be referred to. Basic data sources are topographical maps (1 : 50,000, 1 : 250,000), aerial photographs (1 : 80,000) and a satellite image (Landsat 5 TM). Literature and maps about the geology and tectonics of the study area were available, though (Maps: GEOLOGICAL SURVEY OF NAMIBIA 1999: 1 : 250,000, 1990: 1 : 1,000,000, JACKSON 1976: 1 : 100,000; MILLER 1992, RANGE 1912, SACS 1980, STOLLHOFEN 1999).

Namibia's relief can be divided into three main types of landforms: The coastal or Namib plain, the Great Escarpment, and the interior highland plateau slowly merging eastwards towards the Kalahari basin. Within this system, the study region is located on the easternmost part of the coastal plain, in the foreland of the Great Escarpment. Its general geomorphology (cf. Fig. 5) can be described as an etchplain with inselbergs, together with a variety of younger landforms such as talus deposits, debris sheets, debris and alluvial fans, slightly dissected pediments, fluvio-aeolian sandplains, river terraces, sand dunes and, of course: sand ramps.

The geological maps classify the entire cover of the etchplain as Quaternary sediments ("undifferentiated recent sediments", "dune sands", "alluvium"). The inselbergs as well as the base of the escarpment are made up of a small-scale pattern of metamorphic and intrusive rocks of the Proterozoic Namaqua Metamorphic Complex (the so called basement), overlain on the escarpment by Late Precambrian to Cambrian Nama sediments, slightly dipping to the east. The vegetation of the study area belongs to the Namib-Karoo Flora and shows characteristics of both the Semi-Desert, the Succulent Steppe, and the transitional "Escarpment zone" (according to GIESS 1998). Grasslands and succulents prevail, trees are confined to the banks and floodplains along dry riverbeds (*riviers*).

The study region is located within the coordinates S 26°05' to S 26°45' and E 16°05' to E 16°40' (Figs. 3 & 4), but not the entire area could be investigated at the same level of detail. As for the fenced-in private farmland, which comprises about 60% of the about 4,400 km^2 of the region, access was only given to areas under active farming (where the individual farmer could be asked for permission to work on his land). All efforts to obtain a research permit for the state land failed (the area of the Namib-Naukluft National Park and the Restricted Diamond Area (Sperrgebiet)). Consequently, the study region is delimited by two natural boundaries – the Tiras Mountains to the north and the Great Escarpment to the east –, and by two "limits of practicability" – Aus to the south (as further towards the Orange river almost no farmers were present), and the National Park and Sperrgebiet boundaries to the west.

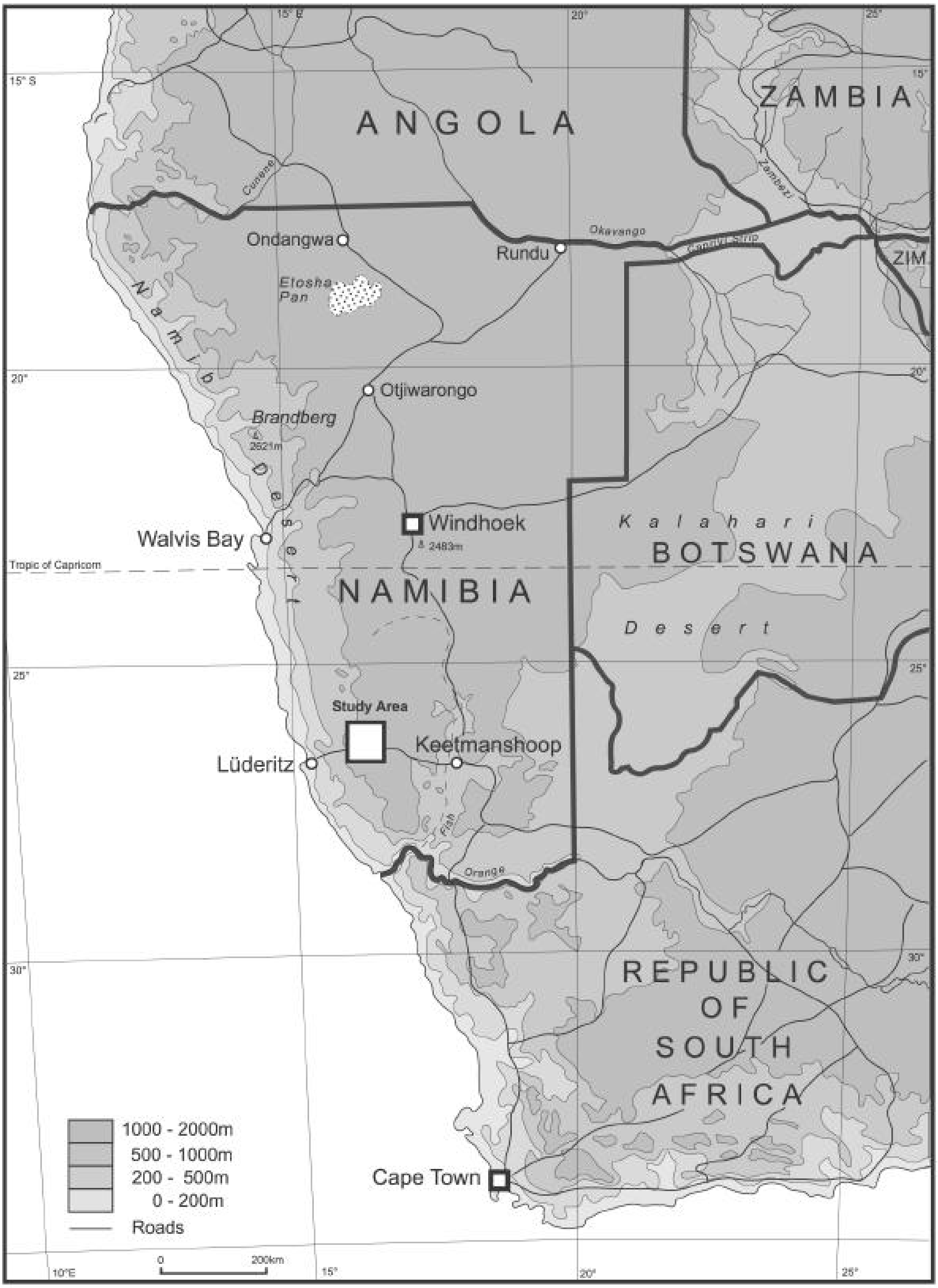


Fig. 3: Location of the study area.

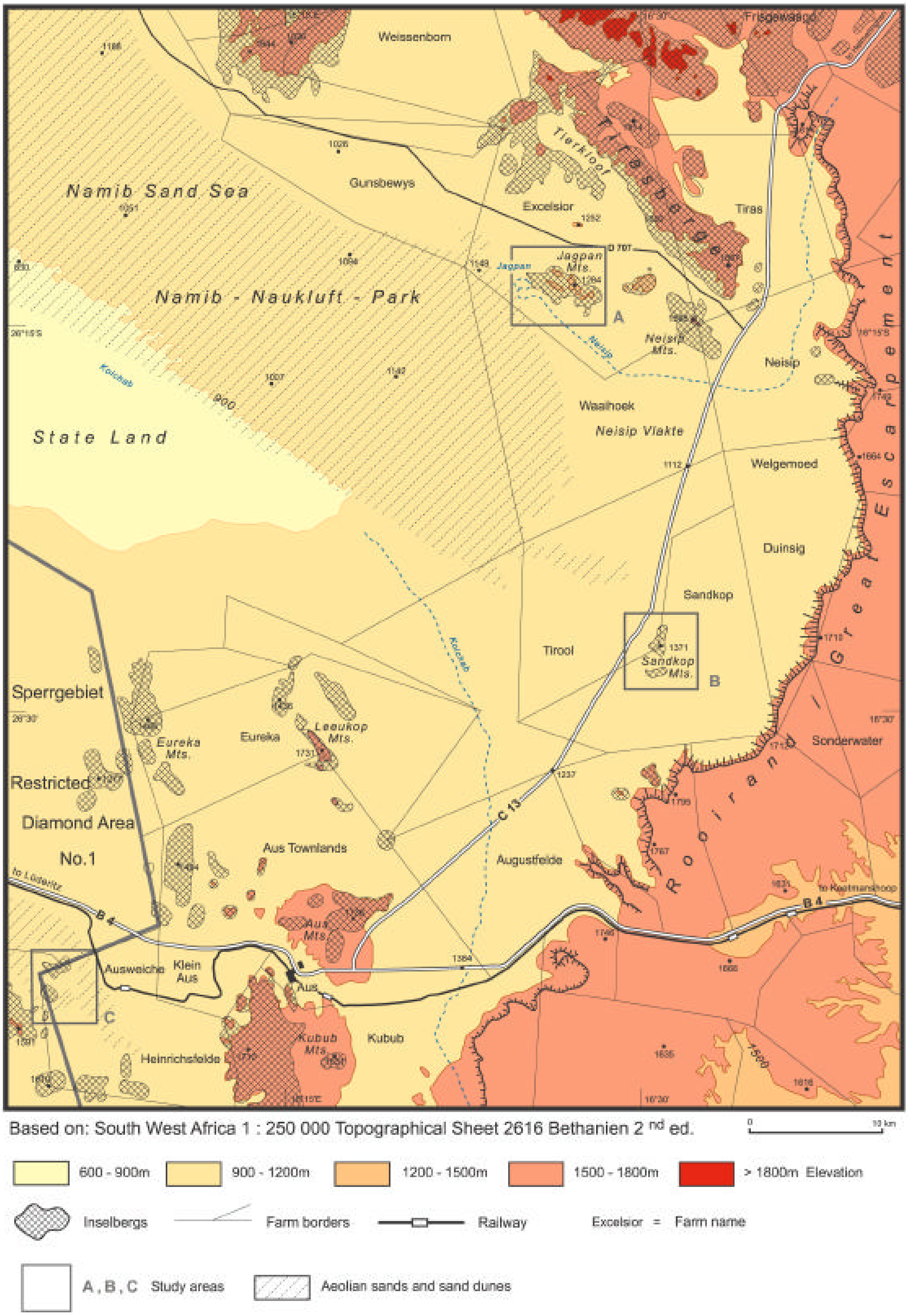
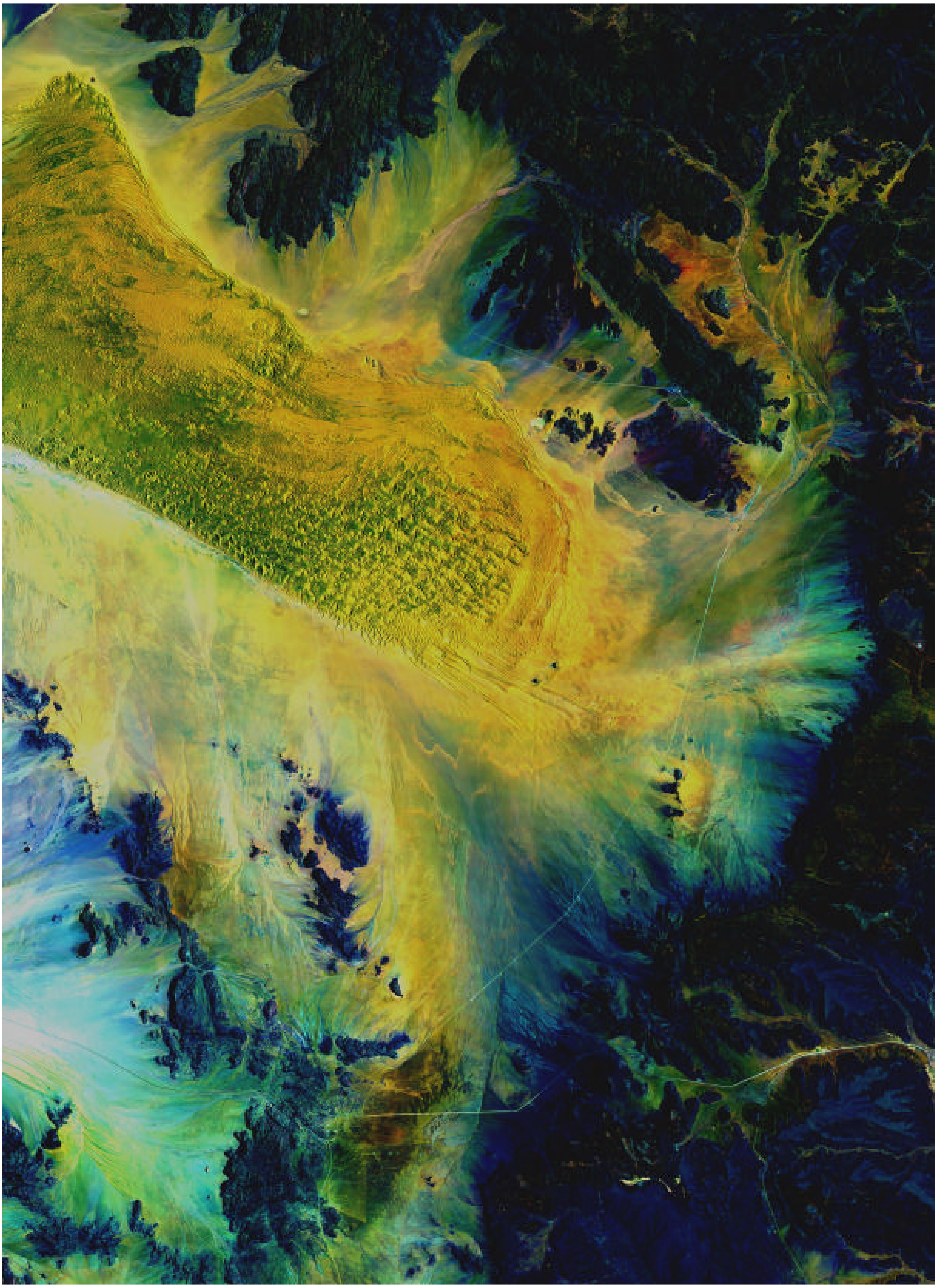


Fig. 4: Map of the study region.



N

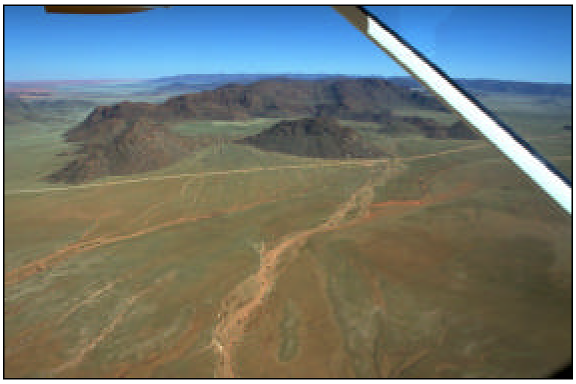
c. 5 km

Fig. 5: Satellite image of the study region (Landsat 5 TM, bands 741, high pass convolution filter, histogram stretching).

In the following section, the study region will be characterized, starting at a detailed definition of the boundaries.

2.1 Tiras Mountains

Only the southern part of the Tiras Mountains ("Tirasberge") is included in the map (Fig. 4), the mountains extending for about 15 more kilometres to the north. The southern part of the mountains (Fig. 6) has an elevation of about 1,750 – 1,800 m a.s.l.; the northern areas are some 50 – 100 m higher. A peak on farm Tiras reaches 1,867 m, whilst another one further north on farm Frisgewaagd attains 1,929 m a.s.l. The peaks are actually two of several summit plateaus, being the remains of an ancient etchplain. Two important outliers to the south are the Neisip inselbergs (1,568 m) and the Jagpan Mountains (1,284 m) (both names are only locally used, no names given on the official maps). The Tiras Mts. are a quite compact hilly inselberg mountain complex with an irregular ground plan, due to numerous reentrants. The complex still has a connection to the Great Escarpment, to which it corresponds in elevation, but is, in the southern part, separated from it by the intramontane basin of Tiras (about 15 km long and 5 – 8 km wide), a northward extension of the etchplain comprising most of the study region, drained by the Neisip River and linked to the Helmeringhausen basin to the north by an etchplain pass (Fig. 7). An even wider embayment exists further to the west, at the farm Weissenborn, without any significant fluvial dissection.



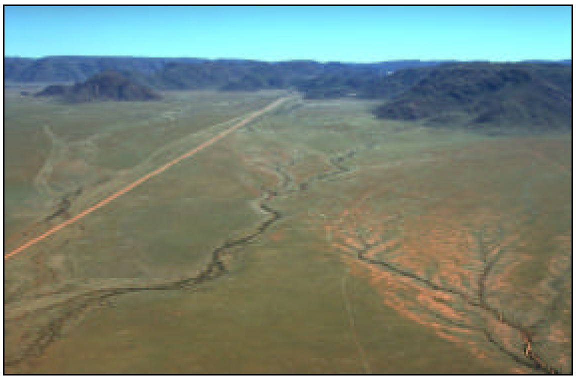


Fig. 6 (l.): Aerial view over the southern part of the Tiras Mountains, ® W.
Fig. 7 (r.): Aerial view over the Tiras basin, ® N.

The main part of the Tiras Mts. belongs to the tectonostratigraphic unit of the Sinclair sequence and consists of the Tumuab pink granite. The southern inselbergs of the complex, situated on the farms Excelsior and Tiras, are part of the Namaqua Metamorphic Complex (NMC). The main NW – SE range forming the western rim of the Tiras basin, and the inselbergs in the north-western corner of Excelsior (separated by the Tierkloof valley) are made up of intrusive rocks like the Tiras pink gneiss and the Tierkloof diorites, granodiorites and rhyolites, which intruded the sheared contact zone between the Sinclair and Namaqua rocks (JACKSON 1976). The biotite gneisses and amphibolites (among others) of the Jagpan and Neisip outliers belong to the Garub Formation within the NMC (± 1,200 Ma). All these basement rocks have been subject to Precambrian intensive chemical deep weathering (cf. Fig. 8). On Excelsior even pure kaolinite is found. In this context it is interesting to note that farmers report "70 m of sand" having been drilled through at water boreholes, even when these are located in narrow valleys of the Tiras Mts. It is quite unlikely that a valley only 20 m wide, with a very limited catchment, should have experienced a 70 m dissection and subsequent infilling by sand of unknown origin. The more realistic interpretation is that the farmers drilled through the ancient saprolite.

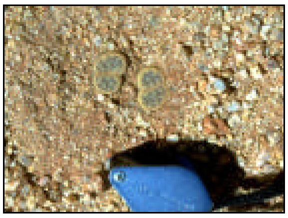




Fig. 8 (l.): Residual boulder of Tiras Granite, produced by spheroidal weathering.
Figs. 9 & 10: Lithops *sp. (m.),* Anacampseros *sp. (r.).*

Sand ramps are abundant around the Jagpan inselbergs and the small outliers north of them. The north-eastern corner of the Neisip inselbergs carries sand ramps, too. Within the Tiras Mts. sand ramps are found in the Tierkloof valley and in the north-eastern corner of farm Gunsbewys. Except for these places, no sand ramps exist elsewhere in these mountains. As the southern fringe of the Tiras Mts. obviously is the regional northward limit of sand ramps, it was taken as the northern boundary of the study region. Where there are no sand ramps, the transition from the inselbergs to the adjacent valleys or plains may either be alluvial fans, mainly at south-west facing hillslopes, or a sharp knickpoint where fine-grained fluvio-aeolian sediment has been deposited against the mountain front, apparently "drowning" them, or shallow grus ramps resulting in smooth, slightly concave profiles.

With regard to vegetation, the Tiras Mts. are part of the "Escarpment zone" as defined by GIESS (1998), comprising the Semi-Desert and the Savanna Transition. This description better fits the areas to the north, though, as in these southern parts of Namibia savanna is replaced by steppe. In this vegetation type a great variety of species are found, many of them endemic. Typical ones are *Euphorbia guerichiana*, *Adenolobus garipensis*, *Commiphora saxicola*, *Aloe dichotoma*, and *Salsola aphylla* (GIESS 1998, COATES PALGRAVE 1988). The Tiras Mts. are also famous for their rich *Lithops* flora (A. KOCH 2000, pers. comm.; Figs. 9 & 10). The Tiras basin, like the etchplain to the south of it, is covered by the typical extensive grasslands along the eastern desert margin. These grass plains almost exclusively consist of *Stipagrostis obtusa* and *S. ciliata*.

2.2 Great Escarpment

The Great Escarpment, locally known as Rooirand, forms a natural boundary of the study region to the east. As a sharp topographic discontinuity, it separates the coastal plain from the interior plateau 120 km inland (cf. Fig. 11). The escarpment rises about 450 m from its immediate foreland to 1,750 – 1,800 m (slightly lower around farm Sonderwater and a bit higher in the north, corresponding in height to the Tiras summit plateaus). In the northern part of the study region the escarpment is more or less straight and north – south oriented, then curves to the west-southwest on farm Sandkop. From farm Augustfelde southwards it is SW-oriented, whereas the outlier inselbergs around Aus further curve to the west. The central foreland plain, comprising the Neisip Vlakte (*vlakte* = plain, basin) and the easternmost outlier of the Namib Erg, is thus rimmed in a semi-circle by the Tiras Mts., the Rooirand, the Aus and Eureka mountains (cf. Fig 4). The topography of the plain consequently follows this pattern; its elevation rises more or less regularly from the erg at the lowest parts of the basin towards the encircling mountains. Where the erg comes the closest to the escarpment, the foreland consequently shows its steepest eastward rise of about 8° (farms Welgemoed, Duinsig).

Fig. 11: The Great Escarpment, ® S. Scarp-forming Kuibis quartzite in foreground.
Fig. 12: Valleys in the plateau surface of the Great Escarpment (air photo).

The basis of the escarpment, forming most of its front slopes, consists of various metamorphic and intrusive rocks of the NMC. These rocks are deeply weathered, as already mentioned above. Residuals of this deep chemical alteration are found frequently; on top of the saprolite patches of latosol and relictic quartz pebble beds have been preserved underneath the sedimentary cover of the Nama formation (< 635 Ma) (STENGEL 2000; author's personal observations), formed on an almost horizontal etchplain and only slightly tilted to the east today. The age of saprolitization can be narrowed down to the period from approximately 840 – 650 Ma by comparing rock ages of the NMC and the Nama Formation (STENGEL 2002). The Nama-age lid on top of the saprolite, forming the scarp of the Great Escarpment, consists of a layer of non-metamorphic, silicified sandstone, the Kuibis quartzite (cf. Fig. 11 foreground), not more than 3 m thick, overlain by shales, limestones and sandstones preserved further to the east of the escarpment rim (cf. MILLER 1992).

The same processes of planation that truncated the summit plain of the escarpment – etchplain formation – also has been at work up to the end of the Tertiary (KEMPF 2000), down to the level of the escarpment foreland plain. Tectonics were only involved in creating the lower etchplain, by way of updoming along the line of the present escarpment that triggered selective downwearing, possibly in some connection with the initiation of the South Atlantic ocean in the Cretaceous (~ 130 Ma) (KEMPF 2000, STOLLHOFEN 1999). As the basement rocks had already been weakened by the Precambrian deep weathering, etchplanation must have been able to proceed rapidly wherever their protective silcrete lid had been breached.

Morphologically, the escarpment today forms a prominent physical feature, effectively protecting the foreland plains from many influences of the hinterland. Between Frisgewaagd to the north and Augustfelde to the south, where there run the main roads to Helmeringhausen respectively Keetmanshoop, no additional passes have been cut into the Rooirand, and the scarp functions as a local watershed. Dissection oriented to the east on the plateau surface of the escarpment is modest in the south, and more intensive in the north, possibly due to stronger uplift there. Fig. 12 shows some valleys, oversized even in the headwater area due to erosion of the saprolitisized basement. As soon as the hard quartzite had been dissected, erosion in the underlying weak material could quickly progress. The headwaters have not been truncated, and there are no traces of backwearing of the escarpment (STENGEL 2002). There is only a single place along the Rooirand where an almost U-shaped broad valley has been lowered into the plateau surface reaching the edge of the escarpment as a hanging etchplain pass (just opposite the Neisip inselbergs). The dissection follows west-northwest – east-southeast striking faults and exposes rocks of the Excelsior-Hauchab Mylonite Zone.

Important with regard to sand ramp formation is the fact that all these valleys on the plateau are basically sand-free. Neither do they carry sand ramps (to the east the next ones to occur are at the escarpment of the Schwarzrand, about 50 km away), nor do they contain significant accumulations of fine-grained material which could be transported westwards (although the decayed basement theoretically constitutes a source of sand). Especially the U-shaped open passage mentioned above could have acted as a sand pathway in former times, but then the Tiras basin or its western rim of the Tiras Mts. would have been the first places where such aeolian material would have been deposited. As mentioned above, these places, however, are free of any sand accumulations, be they ramps or dunes. The same is true for the base of the Rooirand. Only on Sandkop, the only outlier inselberg along the straight section of the Rooirand and rising about 150 m above the surrounding plain (1,200 m a.s.l.), there is a beautiful sand ramp.

2.3 Aus

In the south, Klein Aus and Heinrichsfelde were the only farms where detailed field work was possible. Although sand ramps are frequent even further south, access there was generally prohibited, as mentioned above. The area from Aus to the Orange river was explored along the official roads, and both the farms Nieu-Tsaus (S 27°00', E 16°15') and Rooikam (south-western corner of Kubub, S 26°50', E 16°15') could be visited for a day. As the sand ramps there seem to follow the pattern observed further north, the exclusion of this area was not regarded as being too problematic. Besides, by far the largest and most interesting sand ramp was discovered on accessible terrain west of Aus, just at the border to the Sperrgebiet (S 26°40', E 16°06') (see chap. 7; Fig. 13). It is surrounded by longitudinal dunes which extend further into the Restricted Diamond Area.

Fig. 13 (l.): View from farm Heinrichsfelde onto the Aus sand ramp (® W).
Fig. 14 (r.): Aerial view of the Aus basin, south of the Aus Mountains.

Aus itself lies in between two inselberg complexes, the Aus Mountains north-northeast of the town, and the Kubub Mountains to the south. The geology shows a small-scale pattern, wherein the main rocks building these inselbergs are the leucocratic Aus and Kubub Granite Gneisses, two intrusive units within the NMC. Gneisses and granite gneisses of other units occur as well, as do amphibolite, biotite gneiss, aluminous gneiss and others. The Kubub Mts. gradually rise from east to west to an elevation up to 1,650 m a.s.l., with the highest point being 1,701 m. To the west they show a steep fall to the there lower foreland (1,250 m). The to their extension smaller Aus Mts. correspond to the level of their southern neighbours, culminating at 1,736 m in their northern part.

As clearly visible in the satellite image, west of the Aus Mts. additional inselbergs adjoin in a north-westerly direction. They are called Eureka Mountains (1,486 m), consisting of Aus Granite Gneiss and granodioritic Tsirub augengneiss. The line of inselbergs continues beyond the image frame to the NW with decreasing height and a higher proportion of metasediments. North of the Aus Mts. the outlier inselbergs of Leeukop are worth mentioning, especially as one of its tops, at 1,731 m a.s.l., is almost as high as the escarpment rim. The Leeukop Mts., too, consist to a high degree of metasediments like marble and biotite schist (NMC).

The "Eureka mountain range" is of great importance as it forms a barrier within the study region, separating a larger north-eastern from a smaller south-western part of the surrounding plain. The larger part, the Neisip Vlakte, merges westwards with the Namib Sand Sea (with its prominent outlier erg), which results in a higher proportion of fine-grained sediments in the vlakte compared to the south-western Aus basin. This borders the Sperrgebiet with its extensive rocky, gravelly and sandy plains interspersed with hills. The more barren aspect of this part is due to the fact that the Aus basin is situated at least 20 km further towards the desert than the northern areas studied (cf. Fig. 14). In contrast to the Neisip basin, which is dominantly grassland, the vegetation there is a Succulent Steppe (GIESS 1998) or Succulent Karoo (MILTON et al. 1997). Apart from species which the succulent steppe has in common with Namaqualand, a large number of plants is endemic. The hallmark of this biome is the high diversity and strong dominance of dwarf to low, leaf-succulent shrubs, especially Mesembryanthemaceae (MILTON et al. 1997). Other stem, leaf and root succulents characteristic of this vegetation are the following families: Euphorbiaceae, Crassulaceae, Geraniaceae and Liliaceae (GIESS 1998). Among the chamaephytes and herbs mainly Asteraceae (e.g. the endemic Aus daisy) and Zygophyllaceae are common. Trees, especially *Acacia erioloba*, but also *Rhigozum trichotomum* and *Parkinsonia africana*, and shrubs occur in the whole study area, but are confined to dry riverbeds.

2.4 Sperrgebiet and Namib-Naukluft Park

As mentioned above, the study region is restricted in its extension to the west not by a natural border but by the Sperrgebiet and by the boundaries of the Namib-Naukluft Park, which also include the large area covered by sand dunes – the south-easternmost part of the Namib Sand Sea – in the "middle west" of the study region. Beneath this "outlier erg" the Namib plain continues to the west, dipping towards the coast, the inselberg density decreasing in the same direction. One of the most important inselbergs towards the west is Dik Willem (S 26°28', E 16°01'), a massive, near-circular composite carbonatite complex with a flattened top at 1,505 m (about 550 – 600 m above the surrounding plain) (Fig. 15). This flat top is likely to be the remnant of an etchplain. As Dik Willem is of very young age (~ 50 Ma, REID et al. 1990) as compared to the surrounding basement in which it intruded, it was consequently not affected by intensive saprolitization, which is Precambrian, as explained above, and was therefore preserved when the region was lowered by younger planation processes. Dik Willem and some related carbonatite dykes and complexes testify for the Cenozoic volcanic activity of the region.

The outlier erg is about 18 by 55 km in size, at heights between 1,000 and 1,150 m, with the higher parts to the east and north (cf. Fig. 16). At some places along the southern rim there is a relatively steep descent (c. 150 m/km) to the dune-free plain. This southern margin of the erg is north-west – south-east oriented and very straight (cf. Fig. 17). This is likely due to erosion by today's ephemeral Koichab river, originating in the foreland of the Great Escarpment around Augustfelde, draining first north and then turning to a westerly direction when meeting the erg. Numerous wells and abundant tree vegetation along the dry watercourse are evidence of a large body of ground water which, in the Koichab wellfield 100 km north-east of Lüderitz, supplies the water for the coastal town. Radiocarbon analyses show that the groundwater in the Koichab River aquifer is fossil water some 5,000 – 7,000 years old (CHRISTELIS & STRUCKMEIER 2001). Apart from delimiting the outlier erg to the south, the Koichab also forms the southern border of the Namib Sand Sea as a whole.

Not only the southern rim of the erg is erosional, but its other borders to the north and east as well (as are the borders of the Namib Sand Sea in general (cf. LANCASTER 1989)), keeping the erg stable in its extension (cf. Fig. 5). According to BESLER (1980), the Namib Sand Sea is underlain by a plateau of a semi-consolidated red-brown aeolian sandstone of the Tsondab Sandstone Formation, the erosive borders of which, often forming east-facing scarps, correspond well with the present borders of the sand sea. This south-easterly outlier erg is supposed to rest on an up to 200 m thick layer of this sandstone, which would explain the relatively steep descent at its southern rim. Within the accessible study region and during a day trip beyond the borders of the Namib-Naukluft Park (S 26°11', E 16°14') no traces of this sandstone could be found, though.

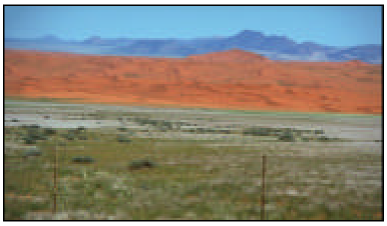


Fig. 15 (l.): Dik Willem carbonatite (with sand ramp at the right (= E) flank).
Fig. 16 (m.): Outlier erg seen from the north after good rainy season (Feb. 2000).
Fig. 17 (r.): Southern rim of the outlier erg, delimited by the Koichab river; ® N, Tiras Mts. in rear.

BESLER (1980) classifies the area of this erg as sand plain with craters, and close to the Koichab pan she identifies pyramidal dunes. LANCASTER (1989) noted a chain of star dunes along the entire Koichab valley, and in his view the erg itself consists of anastomosing and reticulate compound dunes. Regardless of which definition of dune types is favoured, the dunes are fossil forms, partly to largely fixed by vegetation (a discontinuous cover of grasses, mainly *Stipagrostis sabulicola* and *Eragrostis spinosa*), where only the crestal areas are still active. The sands show a yellowish red colour caused by a patina of iron oxide.

2.5 Climatological characterization

Sand dunes form in an arid climate. Fluvial dissection and erosion requires at least ephemerally running water. The present vegetation indicates semi-arid conditions, being closer to aridity than humidity. For any discussion as to whether and to what extent different palaeoclimatological conditions may have been responsible for the appearance of the landforms present today, a definition of the current climatological regime is necessary. To obtain reliable climatological data for the study region proved to be difficult, though.

The nearest weather stations, records of which have been frequently published, are located in the towns of Lüderitz and Keetmanshoop (e.g. FAO 1984), but both Lüderitz (located 120 km to the west at the coast) and Keetmanshoop (located 220 km further inland) are subject to climatic regimes different from that of the study region. The weather bureau in Windhoek controls 112 weather stations all over the country and publishes rainfall and temperature figures on a ten-day basis – but unfortunately without indicating the location of the stations. Concluding from the fact that the north of the country comprises the agriculturally more valuable land and is much denser populated, plus that the vast south generally is reduced to "Mariental, Keetmanshoop and Lüderitz", it seems legitimate to assume that the station network is sparse in the south, with the consequence that rainfall maps, for example, are subject to a very broad interpolation in the area of interest. Several requests for both the distribution of the station network and for detailed data were never attended to. The "reliable source" of farmers' weather records (especially rainfall figures) could not be used in the framework of this study, partly due to incompleteness of the data, and partly due to the disproportion of the possible result to the time which would have been required for manually copying the records. The climatological characterisation of the study region therefore has to be based on the National Atlas of South West Africa (VAN DER MERWE 1983) and on the author's personal observations.

Due to the atmospheric climatic circulation related to Namibia's position around the Tropic of Capricorn, and due to the typical west-coast oceanic circulation of the Benguela Current, the climate in Namibia today is arid to semi-arid with a gradual decrease of rainfall from the north-east to the south-west. The main circulation over southern Africa is anticyclonic throughout the year above the surface layer (TYSON 1986). Subtropical fields of high pressure over the southern Atlantic are responsible for the summer rains; the study area receives about two third of its annual precipitation of 80 – 100 mm from continental convective rainfalls. One third of the rainfall, maybe increasing to more than 40% towards the west-southwest, is brought by cyclonic rains during winter – branches of the westerlies that determine the Mediterranean winter climate of the Cape. 10 – 20 days a year are days with rain, in no month average precipitation exceeds 50 mm.

Following the KÖPPEN classification (1923), the study area belongs to two types of climate: its north-eastern part is classified as summer rainfall cold desert (BWkw), the south-western part as a cold desert with rare, intensive rain showers throughout the year (BWkx'). Field observations do not support this distinct boundary, of course; the region is rather to be seen as transition area. As mentioned above the whole area is subject to precipitation in both summer and winter. The main characteristic of the precipitation is its high variability in time, space and quantity, resulting in a 60% average deviation from the annual average rainfall as determined for the period 1930 – 1960. Potential evaporation is about 3,200 mm per year, which far exceeds average rainfall. Moreover, the period of highest evaporation coincides with the summer rainfall season, thereby reducing the effectiveness of the low rainfall even further.

The mean annual temperature is < 18°C, the maximum mean daily temperature during the hottest month 31 – 32°C, and the minimum mean daily temperature for the coldest month 4 – 5°C. Night time frosts occur regularly from June to September, and are not uncommon for the two months before and after this period. In some winters there is even snow. Furthermore, advective fogs are a distinctive feature, especially in winter. They occur as a result of the cooling of moist oceanic air as it passes over the Benguela Current; its effects are felt for over 100 km inland. Within the study region the south-western area around Aus is the most affected one with 15 – 20 days with fog; sometimes this fog does not even lift during the day.

In winter, strong katabatic winds from north-easterly directions down the Great Escarpment prevail, caused by a high pressure cell over the subcontinent. These winds often set off dust and sand storms, such as the ones observed on August 25th, 1999, and in late September of the same year. During the August storm a building was damaged during the night (corrugated iron roof torn off, newly build wall collapsed), and during the next day dust was kept in suspension beyond noon-time. The September storm lasted for about three days, with varying intensity. Wind velocity was high enough to transport coarse sand at least up to a height of about 70 cm over level ground, as shown by an experiment with sticky tape. The material transported was obviously taken up by the wind from the plains at the foot of the escarpment and not brought along from the highlands, as the air above the escarpment remained clear during the storm. People from Aus and Lüderitz reported that they never had experienced such a heavy wind before. During summer south-westerly winds blow almost every afternoon – a seawind due to a heat-induced low pressure field over the continent –, varying in strength from a slight breeze to a strong wind.

2.6 Fluvial systems

The semi-arid to arid climate in Namibia limits the occurrence of surface waters. No perennial streams exist except for the northern and southern border rivers, both of which have their sources outside the country. The ephemeral rivers (*riviers*) within the study region, with the Neisip and the Koichab being the most important ones, run only for a short period, generally just a few hours, after very good rains in their catchment areas. None of the rivers reaches the Atlantic; both drainage systems terminate in pans, the Jagpan and the Koichab Pan respectively.

The rivers and streamlets often lack a distinct riverbed. In most cases the incision into the Quaternary cover sediments has only resulted in a slight undulation on the etchplain. Larger undulations are sometimes incised by younger riverbeds only a few decimetres deep. The alluvial fans, especially those along the Great Escarpment, often with blocky material up to 150 cm in diameter, have generally been subject to deeper incision. This suggests that the escarpment acted (and acts) as a rain catcher, as the alluvial fans around some inselberg assemblages in the foreland, despite a larger catchment area, show less signs of incision. Morphologically, two to three phases of incision can be identified, indicating younger oscillations in fluvial morphodynamics. Additional, interspersed periods of deposition have not been observed. The alluvial fan sediments are compacted, often cemented by calcium carbonate, patinated, and, for the fine-grained components, influenced by soil formation. Together, these findings imply a relict character of the alluvial fans. Under present conditions weak incision continues; apart from that, preservation is the dominating process.

Presently the fluvial effect on the landforms is mainly by exceptional downpours, resulting in both local incision and sheet floods in other places. One of the latter was experienced west of the Kubub Mts. in April 2000 (Fig. 18). There is indeed some ephemeral fluvial activity in the area, but its results tend to be only a minor redistribution of sediment (Fig. 19). The present geomorphic environment is characterized by predominantly aeolian activity with landform stability as defined by KEMPF 2002.

Fig. 18: Sheet-flooded plain, farm Heinrichsfelde.

Fig. 19: Traces of fluvial activity between dunes near the Aus sand ramp.

The surface plateau of the Great Escarpment drains to the east, via the Konkiep into the Fish river, which is a tributary of the perennial Orange river forming the border to South Africa. As the erosion of the chemical weathered basement is relatively easy once the Nama sediments have been cut through (see above), the highland plateau is characterized by deep and broad river valleys (cf. Fig. 12).

2.7 Soils

Present soil formation is dominated by processes of physical weathering and, to a certain extent, erosion, as chemical weathering is hampered by the scarcity of water. Soils are generally shallow and weakly developed, showing no marked horizontation, but signs of soil formation are present in all sandy or loamy sediments of the study region, even in the dunes. However, the soils generally are palaeosoils. Especially in protected positions indicators of a former stronger weathering and pedogenesis are preserved, like clay and iron oxide skins, which may have been formed during the last wetter phase in the Early Holocene. In the plains, e.g. in the Neisip Vlakte, only relics of denudated Arenosols are present, and partly Calcisols with petrocalcic horizons (= calcrete) occur. Colluvisols (cf. BERTRAM & KEMPF 2002), redeposited soil sediments from older soils, typically Arenosols, are exposed by rivers especially in the area around Aus. They are mainly consisting of a skeleton of sand and grus and are depleted in finer grain sizes. Regosols, weakly developed soils on fine-grained, unconsolidated material, are typical for sand ramp deposits and dunes, Leptosols, initial, shallow, skeletic soils, are found on mountain slopes (see also FAO 1988).

3 SAND RAMPS IN GENERAL

3.1 Occurrence

Sand ramps occur in many variations at several localities within the study region, and will briefly be introduced from north to south. Within the complex of the Tiras Mts., three sand ramps (one large ramp, two smaller ones) are found in the Tierkloof valley on the farm Excelsior, and on Gunsbewys there is one ramp in the north-easternmost corner of the farm. The Jagpan mountains and the small inselbergs north of them are almost completely surrounded by sand ramps (but also by other accumulations mainly of aeolian character, see chap. 5.1) (Fig. 20). In these sand ramp complexes difficulties often arise in exactly defining the sand ramps' boundaries and to determine their number, as they frequently merge one into the other. The north-eastern flank of the Neisip inselbergs carries a sand ramp, as does a hillslope of the very small inselberg on Waaihoek further south. At the two small inselbergs on Tirool, close to the south-eastern corner of the erg, ramp-like forms are present, but due to the immediate vicinity of dunes extending from the sand sea and almost engulfing the inselbergs, it was, in a first survey, impossible to definitely classify the accumulations as true sand ramps.

The Sandkop inselbergs carry one large sand ramp. The Leeukop and Eureka mountains unfortunately could not be investigated in detail as permission for access to the area could not be obtained. From the aerial photographs available and a small aircraft reconnaissance flight a single, large sand ramp on the north-eastern flank of the Eureka mountains could be identified. The other flanks of the Leeukop and Eureka inselbergs only carry gently inclined ramps comparable to the grus ramps surrounding the inselbergs on Tiras, although some of them appear to be stronger dissected than there.

Fig. 20 (l.): Sand ramps on Excelsior (Jagpan Mts. and the mountains north of them), ® S.
Fig. 21 (r.): The sand ramp at Aus.

The largest and most complex sand ramp is located near Aus on Klein Aus / Ausweiche, at the border to the Sperrgebiet (Fig. 21). Numerous sand ramps occur farther south, but access was too limited for a detailed study, as mentioned above. Out of reach, too, was a sand ramp at the eastern flank of the Dik Willem carbonatite inselberg, within the Sperrgebiet. To complete the picture, it should be recalled that the slopes of the Great Escarpment are completely free of sand ramps.

3.2 Characteristics

The size of the sand ramps varies considerably, as does their slope angle. The Aus ramp is almost 2000 m long, in contrast, the Waaihoek sand ramp only measures 280 m. Their heights vary between 140 m (at the Jagpan) and 25 m (on Waaihoek), covering the hillslopes to different degrees, between 50% and 80 – 90%. In places even inselberg mountain passes are buried by mobile aeolian sand accumulations. The ground plan of the ramps tends to be triangular. The amount of hillslope covered by the sand therefore decreases upslope. The slope angle varies between 4 – 25° for different ramps, with a general decrease downslope. The "well-defined" sand ramps, which mostly also stand out in size and thickness of the deposit, are east- to north-oriented, while the sand ramp complexes around the Jagpan and adjacent mountains face all directions.

Most sand ramps no longer laterally merge with the adjacent bedrock slope, but have been eroded along their flanks by what appears to have been a period of linear fluvial erosion (Fig. 22). Some sand ramps are even dissected. The hillslopes above the ramps generally seem to be free of wind-blown sand, except for the passes with a fresh and mobile sand cover already referred to. At closer inspection, though, traces of sand-ramp sediment were found to have been preserved between and underneath the debris cover or the rock fragments of the desert pavement of the slopes. They are clear evidence that the ramps once reached higher up the slopes, prior to the phase of flank erosion.

Fig. 22 (l.): Ravine separating sand ramp from bedrock slope, sand ramp at Aus.
Fig. 23 (r.): Coarse desert pavement covering the sand ramp near the bedrock slope (Aus).

Except for the youngest deposits of aeolian sands mentioned, all of the sand ramps have been affected by soil formation. Cuts made in the sand ramp sediments are stable even when vertical, whereas fresh dune sand would immediately flow off to form a slope around 30°. Also no stratification is visible, obviously due to bioturbation. The slight cementation and biogenic reworking must both have taken place after deposition but before incision, as the cut flanks are steep and stable. The pedogenic overprint is also found in other fine-grained sediments within the study region, as in the sandy material on the plains (cf. chap. 2.7).

All of the sand ramp surfaces carry a desert pavement, indicating wash and deflation processes, in distinction to the mobile sands referred to and the crests of true sand dunes near and within the adjacent erg, but in accordance with all other fine-grained sediment surfaces in the area. The occurrence of this desert pavement on the sand ramps is clear evidence that there must have been a time of fluvial transport of slope debris from above the ramps down to their foot, consequently before the ramps were cut off from the hillslopes (cf. Fig. 23). This mode of transport is also supported by the observation that the grain sizes of the pavement generally diminish downslope the ramps. At their toe only grus and coarse sand tend to make up the protective pavement.

3.3 Interim results

Several conclusions may be drawn from the above description: Sand ramps occur in various orientations and appearances. They are relict forms. This raises a number of questions: Why do sand ramps occur in those places where they are found? How did they form? Did they evolve during a single event or are they the result of several stages of formation? Which landform history do they record? What were the environmental conditions during their formation? How are they related to other landforms, and what can this relationship tell about the evolution of the landscape as a whole?

Attempting to solve these problems, sand ramps have to be looked at in detail. Of the numerous sand ramps investigated, three locations that turned out to be characteristic will be presented. First, the sand ramp complexes of Excelsior (Jagpan Mts.) will be described, followed by the isolated sand ramp of Sandkop, and finally the largest ramp with the longest history, near Aus, will be dealt with. Sand ramps with similar characteristics, but from different areas, will be described shortly at the end of each chapter.

4 RESEARCH METHODOLOGY

Before going into details, a few remarks on the research methods applied have to be made, to explain the way the results presented here were obtained. Two lines of work were followed: geomorphological and sedimentological investigations in the field, assisted by the interpretation of satellite images (Landsat TM 5), aerial photographs and topographic maps, and palaeopedological and sedimentological analytical work in the laboratory.

4.1 Field work

The study of the sand ramps comprised slope profile measurements, sampling of the surface substrate for sedimentological and palaeopedological analysis, mostly along transects, description of surface characteristics (e.g. microtopography, type of desert pavement, type and density of vegetation cover) along the transects, sedimentological and pedological description of profiles in cuts, and collecting of samples for luminescence dating. In addition, for all sand ramps, including those that could not be studied in detail, a detailed photo documentation was made.

The field work on the sand ramps was of course imbedded in a general geomorphological survey of the area, including the identification and recording of characteristic sites for both types of landform and substrate, taking of surface samples at all significant localities, noting the occurrence and form / type of calcrete, wind abrasion, desert varnish, and prehistoric artefacts. As for the sand ramps, everything of interest was subject to a comprehensive photo documentation.

4.2 Laboratory

In order to verify or possibly having to discard the results and hypotheses obtained by field work, supplementary sedimentological and palaeopedological analyses were carried out. This was done to achieve more detailed information on the transport processes that shaped the sand ramps (grain size, morphoscopy), on present or former weathering intensity (grain size, pH-value [in KCl], colour [MUNSELL], thin sections), on the intensity of former calcification ($CaCO_3$-content [titration, CO_2-volumetry], polished sections), other pedogenetic processes (organic matter [loss on ignition], thin sections), as well as the absolute age of the sediments (optically stimulated luminescence dating). Most analyses were made, following the standard procedures (SCHLICHTING et al. 1995), at the geomorphological laboratory of the Department of Geography of the University of Würzburg, Germany, except for the grain size measurements with a laser-optical particle analyser, which were made at the Baltic Sea Research Institute, Warnemünde, Germany, the thin sections prepared by the Institute of Mineralogy, University of Würzburg, and the luminescence dating by Dr. Anja Maria Zander of the luminescence laboratory at the Department of Geography, University of Marburg, Germany.

4.2.1 Remarks on grain-size analysis

The determination of grain-size distributions ran into unexpected difficulties and resulted in equally unexpected methodological insights. The first problem was incurred when sieving the sand fractions (coarse, medium and fine sand (2 – 0.63 mm, 0.63 – 0.2 mm and 0.2 – 0.063 mm)), when 35 samples (out of 110) were sieved twice (2 different portions of sand from the same, well-mixed sample). In Fig. 24, the two measurements are plotted against each other. The correlations are of about the same exactness for all sand fractions and are at an acceptable level around 85%, but the results of both runs are far from identical. There are differences of as much as 30%. For instance, the amount of coarse sand in the first sieving was 40%, compared to less than 30% in the second run. This should be taken as a clear warning against over-interpretation of the grain-size data, e.g. arguing for an obvious change in process dynamics based on differences of a mere 5% in a certain sand fraction between two samples.

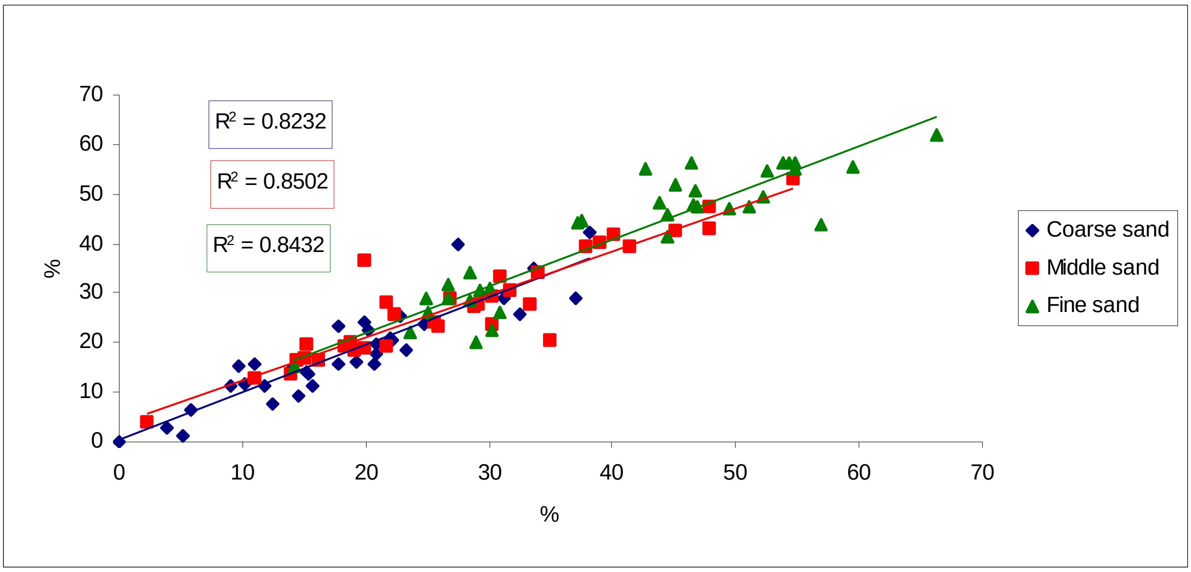


Fig. 24: Correlation of two sieving runs. The proportions of the sand fractions in per cent are plotted on the x-axis for run 1, on the y-axis for run 2.

The second problem occurred during determination of the grain sizes < 63 µm. For the samples with more than 5% of fines, the silt and clay fractions were separated by using a laser-optical particle sizer. As this method of grain size determination is not yet common among geomorphologists, the measuring principle will be briefly described here.

The analytical equipment used was a GALAI CIS-1, a laser-based particle inspection system operating on a principle called time-of-transition (TOT). It measures particle size by detecting the time length of the obscuration of a laser beam by suspended particles as they are scanned by the beam. Measurements are made on single particles, which results in a relatively high resolution. Particle size is determined by pulse width (WEINER et al. 1998). The standard measurement range extends from 0.5 µm to 150 µm in steps of 0.5 µm (JANTSCHIK et al. 1992).

The fundamental principle of the TOT works as follows: A collimated HeNe laser beam (wavelength 632.8 nm) passes through a rotating wedge prism and a focussing lens. The wedge prism, which rotates at a high constant speed (rotational frequency 80 Hz), produces a rotating laser beam, which scans the measuring area at the same constant speed. At the measuring zone, the laser, with a spot size of 1.2 µm, traces out a circular path with a scanning diameter of 600 µm. The light intensity is registered by a photodiode detector located directly behind the flow-through cell system, which presents the particles entrained in liquid to the beam. When particles are crossing the rotating beam, the signal on the photodiode is lower and pulse signals are generated, whose widths are proportional to particle size. Since the laser scans at a known speed, the particle size can be computed from the pulse signal. Special algorithms are included for excluding signals produced by off-focus particles and by those with scanning paths not passing the centre of the particles (TSAI 1996, WEINER et al. 1998).

For comparison with the laser sizer results, a traditional sedimentation method (pipette analysis, KÖHN 1928) was applied for the determination of the silt and clay fractions of 35 samples. Of course it is always difficult to compare two methods operating on completely different principles, but one should expect that they at least show the same tendencies in their results. The correlations between the laser sizer results and those of the traditional sedimentation method are disastrous, though, as shown by Fig. 25. The correlation is best for the middle silt fraction (R^2 = 0.8254), but for coarse and fine silt the values are surely unacceptable (R^2 = 0.5286 respectively 0.3657). For the clay fraction the result is worst; while the laser sizer determines the clay content to be close to zero in almost all samples, the sedimentation shows values of up to 13%. There is thus no correlation at all. Fig. 26 compares the mean of the samples; here, too, the correlation is poor (R^2 = 0.5912).

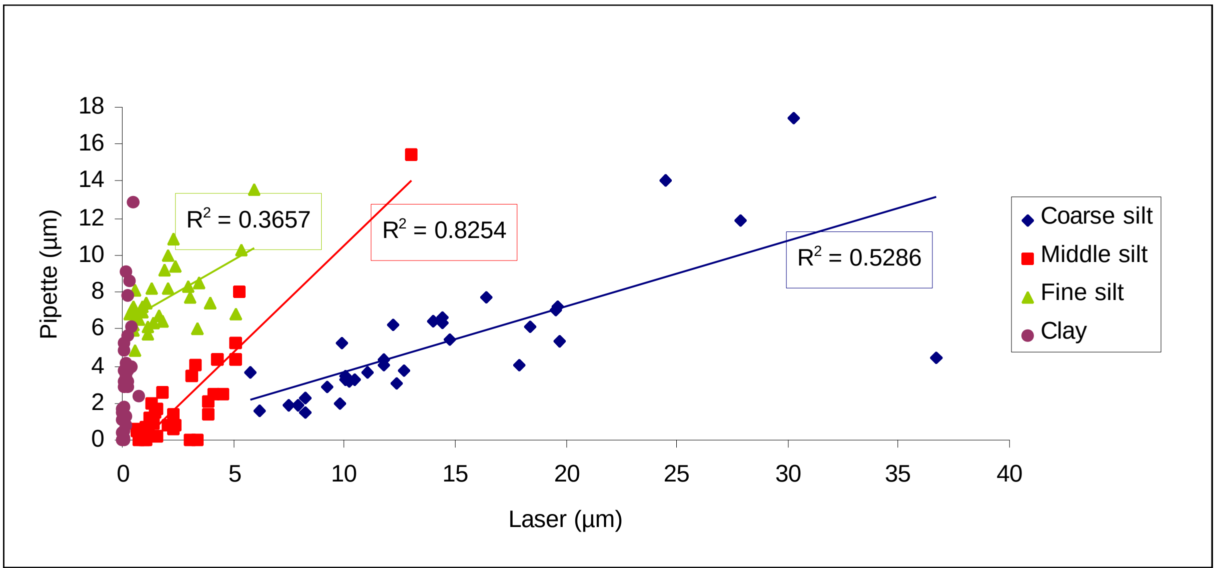


Fig. 25: Correlation of two grain size determination methods: Laser-optical particle sizer vs. Pipette.

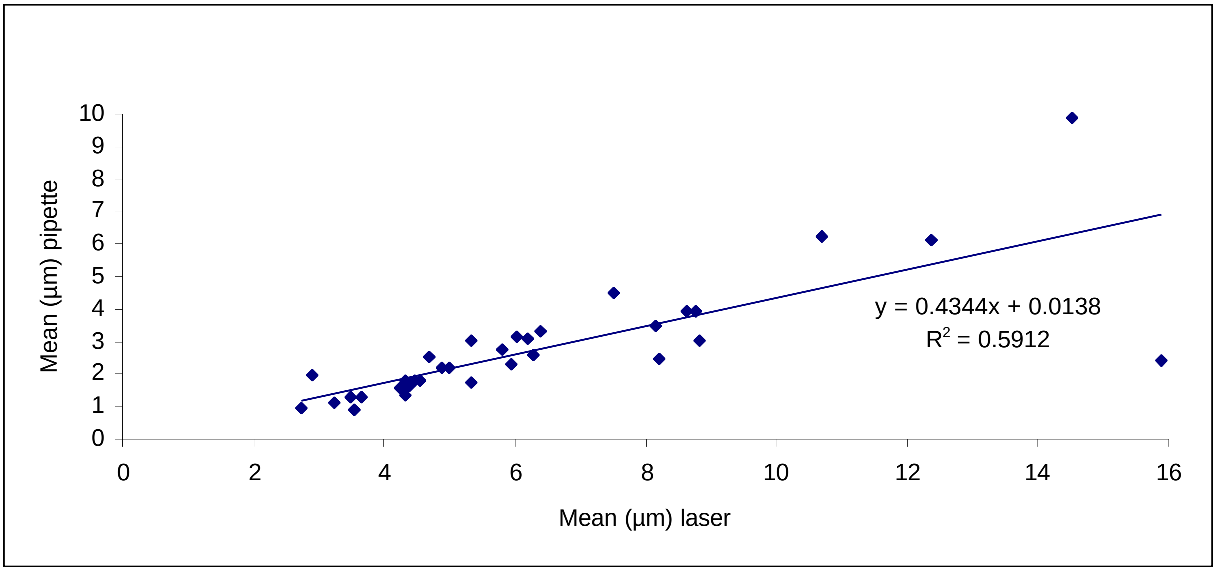


Fig. 26: Correlation of the mean determined by the laser and the pipette method respectively.

In addition to the quantitative laboratory measurements the samples were thoroughly examined, based on a certain experience in qualitatively judging grain size distribution (eyes and fingers!), and these were in favour of the traditional method, especially with respect to clay content. Together with the fact that sedimentation is a standard method within geomorphology and the soil sciences (and the laser sizer is not), the decision was easily made to rely on the results from the pipetting method for further interpretation. (The problem that clay content is underestimated by the laser sizer is also discussed, among others, by SINGER et al. (1988), HAUF (1990), BOBERTZ (1995), SCHACHTSCHNEIDER (1995).) As the silt and clay content could not be determined for all samples by the sedimentation method, due to lab time problems, samples for which only the sieving curve was available were compared to the detailed grain size curve samples based on the smallest common denominator, i.e. only by comparing the sieving parts.

4.2.2 Remarks on determination of calcium carbonate

The content of calcium carbonate was determined by applying both the titration and the gas volumetry (Scheibler apparatus) method. However, both methods seemed to underestimate the $CaCO_3$-content. For massive calcrete with clearly less than 50% of host material incorporated (visible in the polished and thin sections), the analyses resulted in $CaCO_3$-contents of only 10 – 15%. The carbonates were not masked by iron oxide, which would have impeded the reaction of the carbonate with the hydrochloric acid, neither was dolomite present, which reacts much slower with acid than carbonate and therefore would have required more time during analysis before measurements can be made. The figures of the $CaCO_3$-content are therefore to be regarded with caution. Within this study, interpretation is based on whether calcium carbonate is present or not, or on morphological evidence, as in the form of root casts. The absolute amount of $CaCO_3$ is rather neglected out of the above mention difficulties.

4.2.3 Luminescence dating

The optically stimulated luminescence dating was carried out by Dr. Anja M. Zander from the Luminescence Laboratory at Philipps-University, Marburg. The basic principle of luminescence dating is as follows (BATEMAN & BRAGG 2000): Sediments everywhere contain low natural concentrations of uranium, thorium and potassium which produce, over geological periods of time, a constant flux of ionizing radiation. This ionizing radiation is absorbed and stored by the surrounding sediments, and with stimulation this stored dose can be evicted, thereby producing luminescence. The amount of luminescence emitted is proportional to the accumulated dose, and together with the known or estimated annual dose an age can be determined. The calculated age is the time elapsed since the sediment particles were last exposed to daylight, as sunlight bleaches away the luminescence signal, thereby resetting the 'time clock'. Thus, the length of time since deposition is acquired. For physical details cf. AITKEN (1985).

$$\text{Age (a)} = \frac{\text{Total accumulated radiation dose (Gy)}}{\text{Annual radiation dose (Gy / a)}}$$

Optically stimulated luminescence dating (OSL) was first applied to quartz grains by HUNTLEY et al. (1985), and in many situations is superior to thermoluminescence dating, for example as only the signal sensitive to light is measured, which can be deleted by sunlight during transport of the sediment (WINTLE 1993). This has resulted in the application of OSL to aeolian sediments from a number of dryland settings (e.g. RENDELL & SHEFFER 1996, STOKES et al. 1997a, THOMAS et al. 1997, 2000, 2002, BATEMAN et al. 2001).

There are a variety of methods determining optically stimulated luminescence. The protocol used here is an improved single-aliquot regenerative-dose (SAR) protocol following MURRAY & WINTLE (2000). For samples from site AW I grains 100 – 200 µm large were analyzed, for the sample from site AW 6 the fraction 63 – 200 µm was measured. Palaeodose determination used green light stimulated luminescence for the quartz grains and infrared stimulated luminescence for the feldspar grains.

For the quartz, the palaeodose could not be determined for the four samples from site AW I. High thorium contents (^{232}Th) in the sediments resulted in saturation effects of the growth curve, i.e. increased radiation doses produced no further growth of the luminescence signal. The saturation dose for feldspar is higher than for quartz, but still the palaeodose could only be determined for three samples. For one of the three samples only one subsample (out of 5) could be analyzed, i.e. the results were not reproducible, meaning a high uncertainty of the generated palaeodose. As the age for this sample was higher than the age for samples in underlying horizons and as landslides or similar processes accumulating older, undisturbed sediments on younger sediments can be excluded, it was discarded. One important factor influencing the final calculation of the deposition age is the water content in the sediment over geological time. For the samples from site AW I the water content was assumed to have been 7.5 ± 5%, for the sample from site AW 6 5 ± 2%. For detailed figures of luminescence dose rates, palaeodoses and age determinations see App. I.

5 THE YOUNG SAND RAMPS

5.1 Excelsior

Fig. 27: Panoramic view of the north-facing slopes, Jagpan Mts.

On the farm Excelsior, the sand ramps around the inselberg complex east of the Jagpan were investigated in detail (location of the mountains: S 26°13.500', E 16°27.500') (Figs. 27 & 28). The inselbergs comprise southern outliers of the Tiras Mts. and cover an area of c. 5 by 2.5 km; the longitudinal axis stretches north-northwest – south-southeast. The mountains rise to elevations of 1,270 – 1,280 m a.s.l., overlooking their northern forelands by 180 m, their southern ones by 220 m.

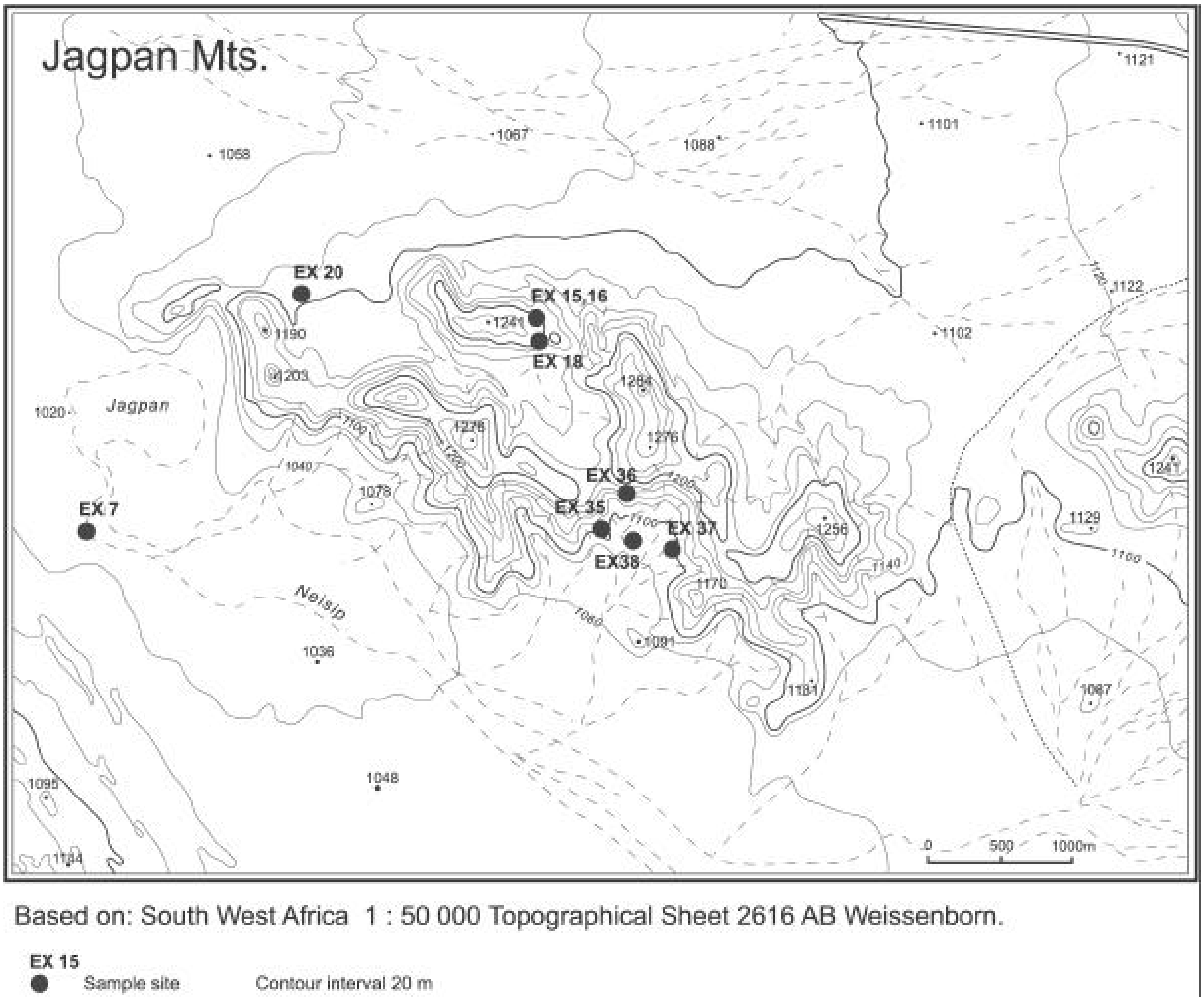


Fig 28: Topographical map of the Jagpan Mts., farm Excelsior.

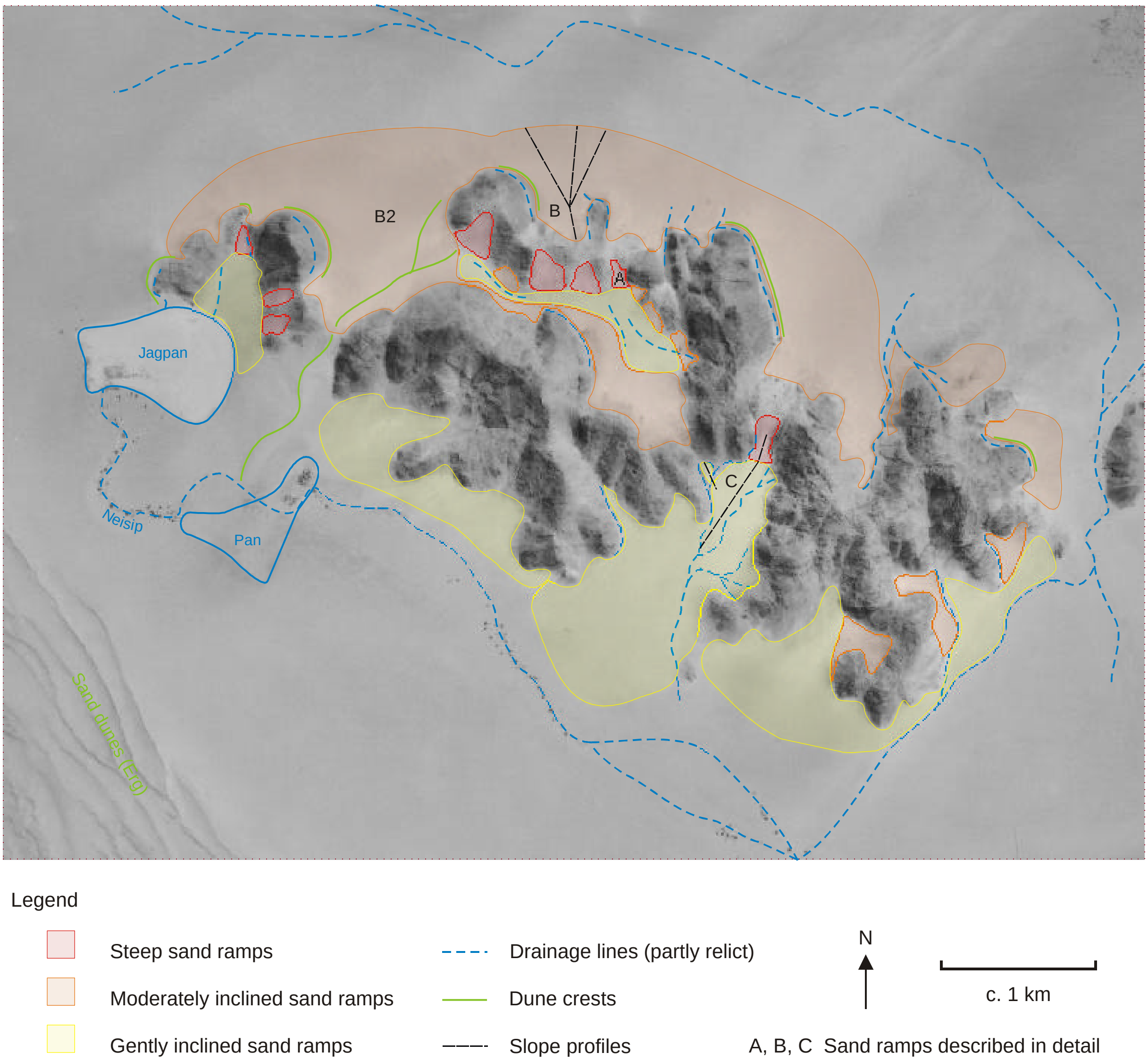


Fig. 29: Aerial photograph showing position and type of the sand ramps and sand ramp complexes, Jagpan Mts.

Geologically, the inselbergs consist of biotite gneiss (Namaqua Metamorphic Complex), in the northern middle part penetrated by granodiorite dykes (GEOLOGICAL SURVEY 1999, JACKSON 1976). They are separated from the nearby dunes (2 km distance at closest point) by the dry riverbed of the Neisip, which terminates its drainage in a pan, the Jagpan.

As indicated in Fig. 29, the inselberg complex is surrounded by many sand ramps, and they are also found within the basin, although smaller there. The ramps show a very complex character, merging into one another, and therefore to determine their exact number is a matter of opinion. The largest ramps, in terms of amount of material incorporated, are found along the northern rim, facing north and north-east (cf. Fig. 27). The highest points of the ramps, especially on the southern side, are often connected with passes in the mountains, where the ramps are still in an uneroded contact with the hillslopes. Along the falling flanks, the ramps are often cut off from the slopes. The ramps on the south side of the mountains are either thin and only weakly inclined, beginning at the foot of the rock slopes, or are very steep and limited in their lateral extent, but reaching high up the mountain flanks. Sometimes the gently inclined ramps have a steep, narrow upper part.

Except for the sand ramps, there are also other sandy deposits of mainly aeolian character. At the eastern side of the Jagpan an almost dune-like sand body (Fig. 30, rear) extends from the Neisip river up to the mountain pass west of the 1,203 m top and further north to the outlet of the basin, closing the same (Fig. 34, rear). The sands form a barrier against the spreading Neisip river, forcing it to concentrate its flow. As a result, in its final bend the river has cut a terrace up to 5 m high into the sandy to loamy sediment, strongly cemented by calcium carbonate (Figs. 31 – 33). At its lower part this aeolian deposit is certainly a relict form, showing fluvial and pedogenic overprints in its denudation morphology, surface pavements, a relatively high amount of coarse sand and grus, and stability (although the content of fines also may be the result of aeolian input from the pan). The rounded dune top and the northern part of the deposit reaching up the mountains, however, are characterized by modern aeolian activity with ripples and, on top of the mountain, a sharp crest (Fig. 34) and somewhat finer and better sorted sands. The other aeolian deposit extends from west of the pan to the western and north-western slope of the westernmost inselberg. This deposit lacks the dune-like form, it rather appears as a thick sand cover on the slope of the inselberg, but it is comparable to the eastern deposit regarding sedimentology and a presumably relict lower part overlain by younger sands shaped by the wind.

Fig. 30: Overview of the pan, framed by dune-like accumulations; ® E.



Figs. 31 – 33: Terrace of the Neisip river, cemented by $CaCO_3$; note root casts, not in situ *(r.).*

Fig. 34: Closure of basin (right) and sharp dune crest.

The unquestionably identified ramps around the Jagpan Mts. vary in their appearance: in size, slope angle and sedimentary characteristics. Therefore, three differing sand ramps were chosen for intensive studies, labelled A, B (+B2) and C (cf. Fig. 29). Sand ramp A (Fig. 35) is a very steep and narrow ramp, exposed to the south, sand ramp B (Fig. 36) is one of the voluminous ones on the north-eastern side of the inselberg complex, with a short, steep upper part, and sand ramp C (Fig. 37), located at a south-western slope, shows a steep upper and middle slope grading into an only gently inclined, extensive ramp at the foot of the bedrock slope.

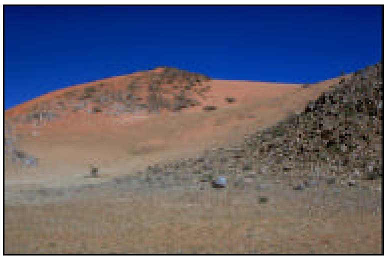


Fig. 35: Sand ramp A.

Fig. 36: Sand ramp B.

Fig. 37: Sand ramp C.

The ramps reach up to mountain passes, and common for all of them is the lack of a clearly defined uppermost margin. There rather exists a continuum of modern aeolian sands to recent aeolian sands and sand ramp material. (None of these deposits has naturally existing openings. All information on the sediments was obtained from easy-to-dig sections.)

The modern aeolian sands of yellowish red colour are mainly found upslope of the sand ramps' upper rim at the hillslopes or blanketing the mountain passes. They are well-sorted, mainly consist of fine- to medium-sized sand grains and, in a section, show typical aeolian bedding. Although the section walls are relatively stable, which would imply that the sands are not of modern age but influenced by soil formation, it is assumed that the stabilizing fines already were part of the deposited sands; this assumption is based on the fact that a large pit opened only a few years ago has been partly buried by aeolian sand since then which is perfectly bedded – and very stable. Partly the sands form small dunes or ripples, partly they are just sandy patches overlying the slope debris or filling the gaps between larger rock fragments and thus resting directly on the rock surface (Fig. 39). On the north-eastern side of larger rocks, echo effects are common. There is no evidence of underlying palaeosoils or any fine-grained sediment.

The bedrock surface and blocks lying on it near these aeolian sands are often wind-scoured and polished, in places covered by the fresh mobile sand. There is evidence of two phases of wind abrasion, an intensive one followed by a less intensive one. The older generation, with corrasion fluting, is coated with brownish, non-aeolian desert varnish and thus no longer being actively formed. The surfaces of the second phase, which still seems to be active, either shows the fresh bedrock colour or, on the old fluting, a mere polishing with a shade of blue. The most severe abrasion appears to have occurred within the mountain passes, but it is also considerable on the north-facing slopes, all the way from the bottom to the top. A case in point is the slope next to sand ramp B, where major blocks within the desert pavement were first sand-fluted by north-easterly winds, were then partly fragmented, after that coated with brown desert varnish, and finally and presently polished by resumed aeolian activity (Fig. 38). On the plain north of the Jagpan Mts., ventifacts are partly buried in the fine-grained sediments, up to 2 – 3 cm, indicating sediment input to the plains after the first, intensive period of abrasion.

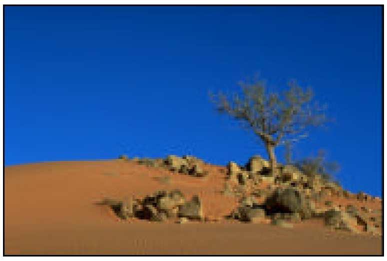
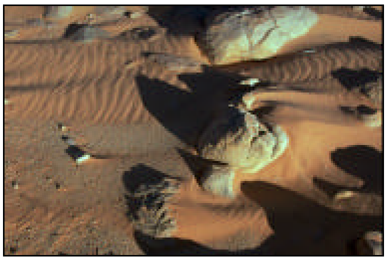




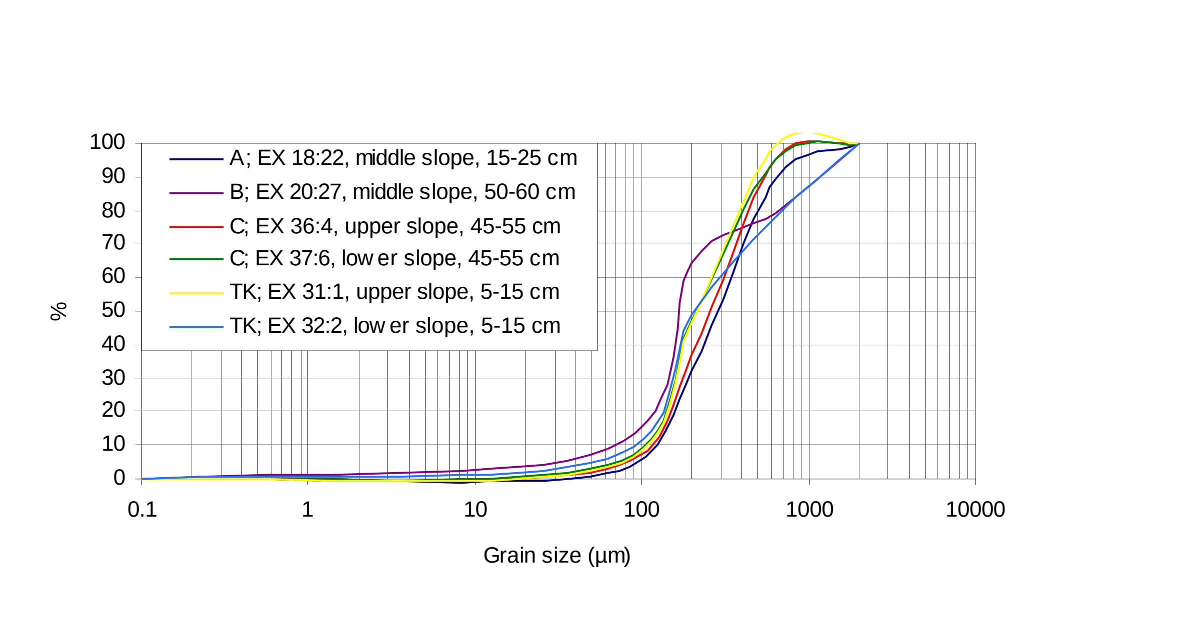
Fig. 38 (l.): Wind-scoured features on the north slope of the Jagpan Mts.
Figs. 39 & 40: Modern (m.) & modern and recent (r.) aeolian sands above sand ramp A.

The recent aeolian sands differ from the modern sands by apparently not being mobile (Fig. 40). They may occur adjacent to or underneath the mobile sands, but often the transition between the two types of sediment is gradual. This probably implies that the modern sands at least partly consist of reactivated recent sands, which would explain the content of fines providing stability. Besides, grains of the modern sands partly show iron oxide coatings – a staining resulting from weathering processes in a palaeosoil or in an older sand deposit. These coatings are generally only preserved in cracks and pits on the grain surfaces, probably being the relics of a former more complete cover, rubbed off during resumed aeolian activity. Although the medium- and fine-grained sand fractions also dominate the recent sands (c. 50 respectively 40%), their grain-size composition is more diverse, comprising more coarse sand and grus (> 10%; feldspar and quartz) than the fresh sand as well as more material < 63 µm (2 – 3%) (samples EX 15:18, EX 16:19). The coarse fractions have been enriched at the surface by deflation. Deflation also appears to have been responsible for the gentle hollows developed on these sands, the surface of these concavities often covered by angular grus, gravel and stones washed down locally from the surrounding rock surfaces. As there is hardly any evidence of present-day clast formation on the slopes of the varnished biotite gneiss and the granodiorite, the main grus and debris production must have occurred at some time in the past and in a different climatic situation. Two sections dug in these sands showed a thickness of 30 and 45 cm respectively above the bedrock or its debris cover. In the first section, a 1 cm-layer of grus and small angular fragments of gravel was found 3 cm below the surface. The colour of the recent aeolian sands is yellowish red (5YR 5/8 – 4/8). Towards the upper rim of the sand ramps the sand patches become more closely spaced and eventually merge with them.

These upper parts of the ramps are very steep (20 – 25°), their sections ranging from convex (sand ramp A) to straight or slightly concave (B, C). Generally, these parts of the sand ramps are characterized by a sparse vegetation cover and a micro-morphology formed by aeolian processes, including ripples, nabkhas or deflation surfaces. Below the steep parts of the sand ramps, which comprise different proportions of the ramps – namely almost the entire sand ramp A, but only a quarter or less of sand ramp B and C –, their morphological and sedimentological characteristics gradually change. Generally, the slope angle decreases, the micro-relief flattens, the pavement on the surface gets more dense and coarser, and the vegetation turns from the spottiness of tussock grasses to regular and increasingly dense stands of *Stipagrostis ciliata, S. obtusa*, and *S. uniplumis*.

Sedimentologically, the sand ramp sediments can be characterized as inhomogeneous and diverse. In an overview, Fig. 41 illustrates this by plotting the grain-size distribution of six sediment samples taken from the sand ramps A, B, and C, as well as from a sand ramp in the Tierkloof valley (EX 31, EX 32). A more detailed description of the sampled sections, their grain-size distribution and additional sedimentological characteristics follows below, beginning with the steep part of the ramps.

The first section focused on is located on the steep middle slope of sand ramp A: EX 18. The slope is stabilized by grasses, herbs and an unidentified species of bulbous plants, but a silt and clay content of 2 – 3% is contributing to slope stability as well; in consequence, digging sections with stable walls is easy. In this section, 40 cm deep, the upper 6 cm still show slight aeolian layering; further down the section is monotonous, probably due to turbation by roots (many very fine rootlets are present). The colour (5YR 5/8) and grain-size composition are comparable with the recent aeolian sands, although the dominance of medium-sized sand is even stronger (almost 60%). The content of particles > 2 mm, however, is somewhat smaller (less than 0.5%), likely because enrichment of large particles is impeded by the high slope angle (stronger gravity). In the upper part of the section, the grus particles are angular, while they are subangular further down. Coarse material (coarse sand and larger) is generally not found in pure aeolian sands, but occurs here. This implies that either coarse sand and grus were fluvially or gravitationally transported downslope from sources above the sand ramp (most likely disintegrating saprolite found there), or that these fractions were moved upslope or sideways by stronger winds in the past. For the dominant angular particles probably the first suggestion is applicable, while for the lower proportion of true sand grains the second theory might apply.



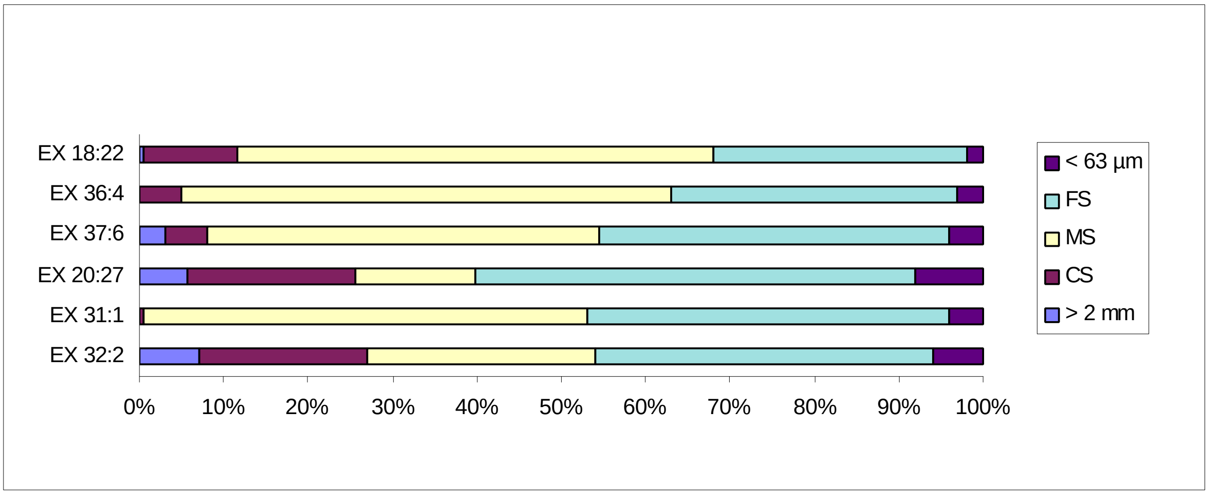


Fig. 41: Grain-size composition for six sand ramp sediment samples from four sand ramps.

Sedimentologically, section EX 18 is comparable with a section on the upper slope of sand ramp C: EX 36. It is situated beneath the steepest part of the ramp, about 50 m below the apex; the slope angle at the section is c. 18 – 19°. The thickness of the ramp exceeds 70 cm at this point. All the way down, the section is uniform and does not show any layering or other sedimentary structures; roots have a tube-like coating of sand grains. On the surface, only a few grus particles are found; within the section, material > 2 mm is not present. Morphologically, the surface is irregular, with an intensive micro-relief of ripples and small nabkhas 10 to 20 cm high.

A similar but more diverse micro-relief is found on the upper slope of sand ramp B (cf. Fig 49), almost directly oriented to the north (the orientation changes downslope to north-east for the main body). The uppermost 40 m show an even, deflated surface with a pavement of coarse sand and grus. Further downslope, single nabkhas occur. Roughly at 140 m, wind ripples have been formed. Two types of ripples can be distinguished: large (deflation?)

ripples consisting of coarse sand to medium-sized gravel with their longitudinal axes oriented south-east – north-west, overlain by smaller forms with their axes in a north – south direction. After about 250 m, the ripples get smaller and turn into wave-like forms, coinciding with the transition into the convex body of the sand ramp.

The upper slopes of sand ramp B and C are vegetated to different degrees, without showing distinct patterns. In the dry season, the degree of cover by grasses (mainly tussock-like grasses such as *Stipagrostis sabulicola*) and herbs is about 5%, which may increase to 20% during the rainy season. At about 200 m on sand ramp B, there stands a single skeleton of a tree of unknown species. This tree is no exception, but it is not the rule either – a limited number of single (mostly dead) trees occur on some sand ramps.

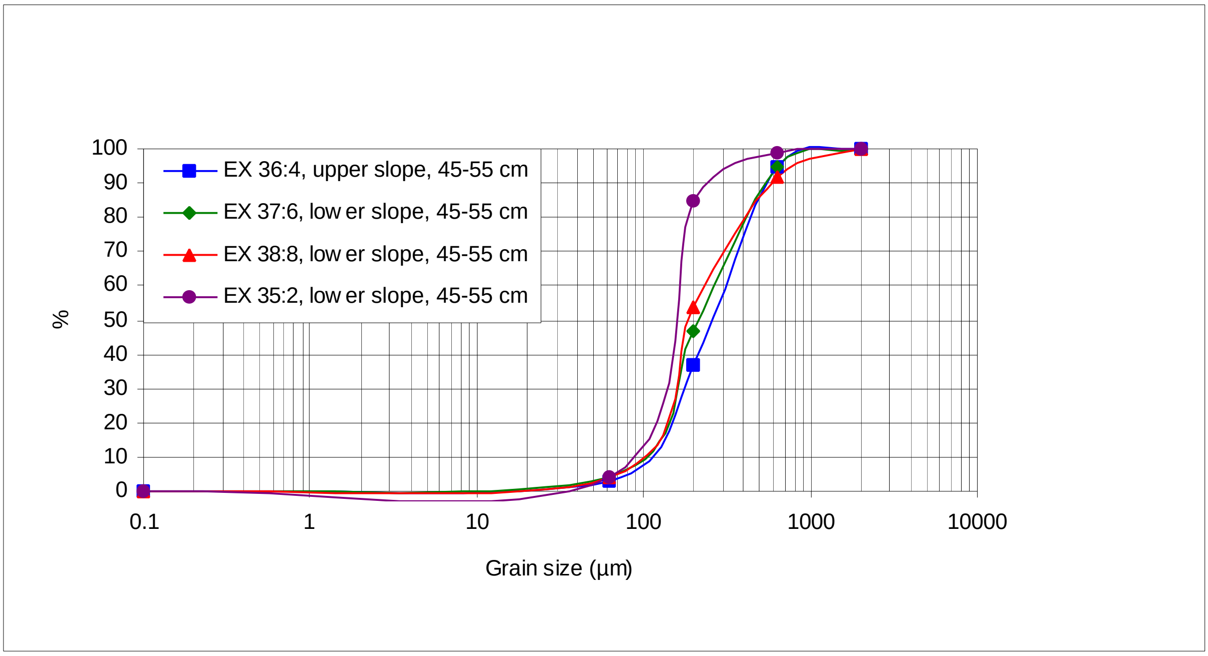


Fig. 42: Comparison of grain-size distribution curves for 4 samples on sand ramp C.

The sediments of the more gently inclined parts of the ramps differ from those upslope mainly by a higher proportion of material > 2 mm (~ 5%), and partly by their somewhat higher content of fines. In detail, the lower slope of sand ramp C is characterized by the following (sections EX 37 and 38): About 4% of the particles are > 2 mm; the size of most of those grains is only slightly larger than 2 mm, but at EX 38 also small stones up to 3 cm in diameter are dispersed throughout the section. From the fraction < 2 mm, 5 – 10% are classified as coarse sand (Fig. 42). The dominance of medium-sized sand decreases; for sample EX 37, both medium- and fine-grained sand occur with c. 45%, in sample EX 38 the proportion of fine-grained sand raises to 50%. The coarse fractions (i.e. grus and coarse sand) partly consist of rock fragments, partly of true quartz sand grains. The surface is covered by a dense pavement of grus and gravel, which has a fresh appearance, the particles not being covered by a coating of iron oxides and being angular to subangular in shape. The sediments are of yellowish red colour (5YR 5/8 – 4/8), and homogenous, without any layerings, due to bioturbation. The sections were more hard to dig than in the upper slope, probably due to the higher amount of coarse material, a somewhat more intensive pedogenesis (content of clay and silt: 4%), and increased compaction due to a stronger fluvial overprint (presence of stones up to 3 cm in diameter).

Section EX 35, in the westernmost corner of sand ramp C, serves as an example for the variability of sand ramp material. In all characteristics described above for EX 37 and 38 (surface pavement, amount and shape of material > 2 mm, amount of fines, a.s.o.) this section is fully comparable with the other two sections – only the proportion of the sand fractions is completely different. The sediment is more than 80% fine-grained sand, about 13% medium-sized sand, and only 0.5 – 1% coarse sand. This may be explained by a stronger input of aeolian sands which only influenced a minor part of the ramp. Section EX 35 is located beneath a mountain pass, which is immersed in aeolian sands, coming from north-northwesterly directions. This path is assumed to have also been active during formation of the sand ramp. Traces of a high aeolian input are also found in section EX 38, located only about 200 m east-southeast of EX 35, where half of the sediment consists of fine-grained sand. The strong spatial delimitation of the occurrence of these dune sands may be ascribed to an input of the sands not by wind but by fluvial activity (slope wash from upslope).

Section EX 20, on the middle slope of sand ramp B2 (fully comparable with sand ramp B; this location contains additional information; Fig. 43), shows the change of the sedimentological characteristics from steeper to flatter ramp parts even more explicitly. The content of material > 2 mm rises to 5 – 10%, the coarse sand fraction to 20 – 30%. Also the proportion of fines is higher, 7 to 9%, emphasizing the influence of pedogenic processes following deposition (cf. Fig. 41).

Figs. 43 & 44: Section and surface at site EX 20, sand ramp B2.

In two points, this section differs from EX 37 and 38 on sand ramp C. The first point is the occurrence of rounded pieces of calcrete, occasionally found throughout the section, in higher numbers in the upper 5 cm, and frequently at the surface due to concentration processes (Fig. 44). The calcrete pieces have a size of 1 to 4 cm and relatively smooth surfaces. On the sand ramp, they occur in an area of only about 100 m^2, with decreasing concentration away from section EX 20 in the middle. (It should be pointed out here that calcrete and root casts are even more significant for the oldest sand ramp generation; see chap. 7). Only part of the sediment of the upper 5 cm reacts with HCl, the main part of the section being free of $CaCO_3$. The pH-value within the section is 8.1, which is significantly higher than for sections without calcrete pieces; there, the pH-value lies between 6 and 7.

The shape of the calcrete pieces suggests that they are fragments of degraded root casts, and they are not *in situ*. One explanation for their occurrence is that they have originated from an older sediment upslope. The surface there must have been vegetation-covered, there must have been soil formation, and there must have been mobilization of calcium carbonate, so that conditions for root-cast precipitation were given. Eventually this soil, with its C_{ca}-horizon, must have been eroded, washed down the slope, and fragments of the root casts were redeposited downslope. There the wash layers would have been reworked, probably by bioturbation, to explain their present distribution within the sediment. As the fragments show no sharp-angled fracture planes, solution and reprecipitation processes would have occurred in the depositional environment.

An alternative explanation might be that the fragments were wind-blown upslope from an unknown source, where, however, the same pedogenic processes must have taken place. Some of the particles seem to be too large for aeolian transport, but farmers in the area confirm that they indeed have been observed to be moved upslope by strong winds due to their low weight. These calcrete pieces were found in only this location, which supports the idea of aeolian transport. In the plains north and east of the ramp calcrete and root-cast horizons are found along some dry riverbeds, which may have served as a source. Further evidence for a strong aeolian impact comes from the very high proportion of coarse sand (30% in 1 – 5 cm depth) being three times higher than in the sections on the south-western side of the mountains. This enrichment may be ascribed to strong deflation, which simultaneously resulted in a depletion of the medium-sized sand fraction (c. 15% only).

Additional indicators for stronger winds in former times are the already mentioned traces of wind abrasion, but also the sediment itself bears witness to it. At this location, the material > 2 mm mainly consists of large, fairly rounded quartz grains and only to a lesser degree of subrounded grus particles. Furthermore, the content of coarse sand is 20 – 30%, obviously typical for north-east exposed sand ramps. This high share of coarse particles may either be due to a fluvial or gravity transport downslope, but taking the subrounded to rounded shape of the grains into consideration, transport by strong winds seems a sensible alternative. There is an obvious difference from the coarse fraction on the gently inclined ramp (ramp C, sections EX 37 and 38): The coarse material there is dominantly angular, suggesting a non-aeolian, short and direct transport from the surrounding bedrock surface.

The sediment characteristics of the lower slope of sand ramp C (the gently inclined part) imply an influence of fluvial processes, supported by morphological evidence. Fig. 45 shows two slope profiles of sand ramp C, Fig. 47 illustrates their location on the base of the aerial photograph. The surface of the gently inclined ramp is very even, only interrupted by a low ridge oriented approximately NNW – SSE, and some runnels and channels of different depths. The eastern side of the ramp is more dissected, but not as deeply as the western side. In its westernmost corner, part of the ramp (the "triangular ramp") has been completely cut off from the main body by a channel almost 10 m deep (Figs. 45 & 46). The triangular ramp itself is cut off from the bedrock slope, with only a last narrow connection 2 to 3 m wide. On its western side, the main ramp also is separated from the mountain slope (cf. Fig. 47).

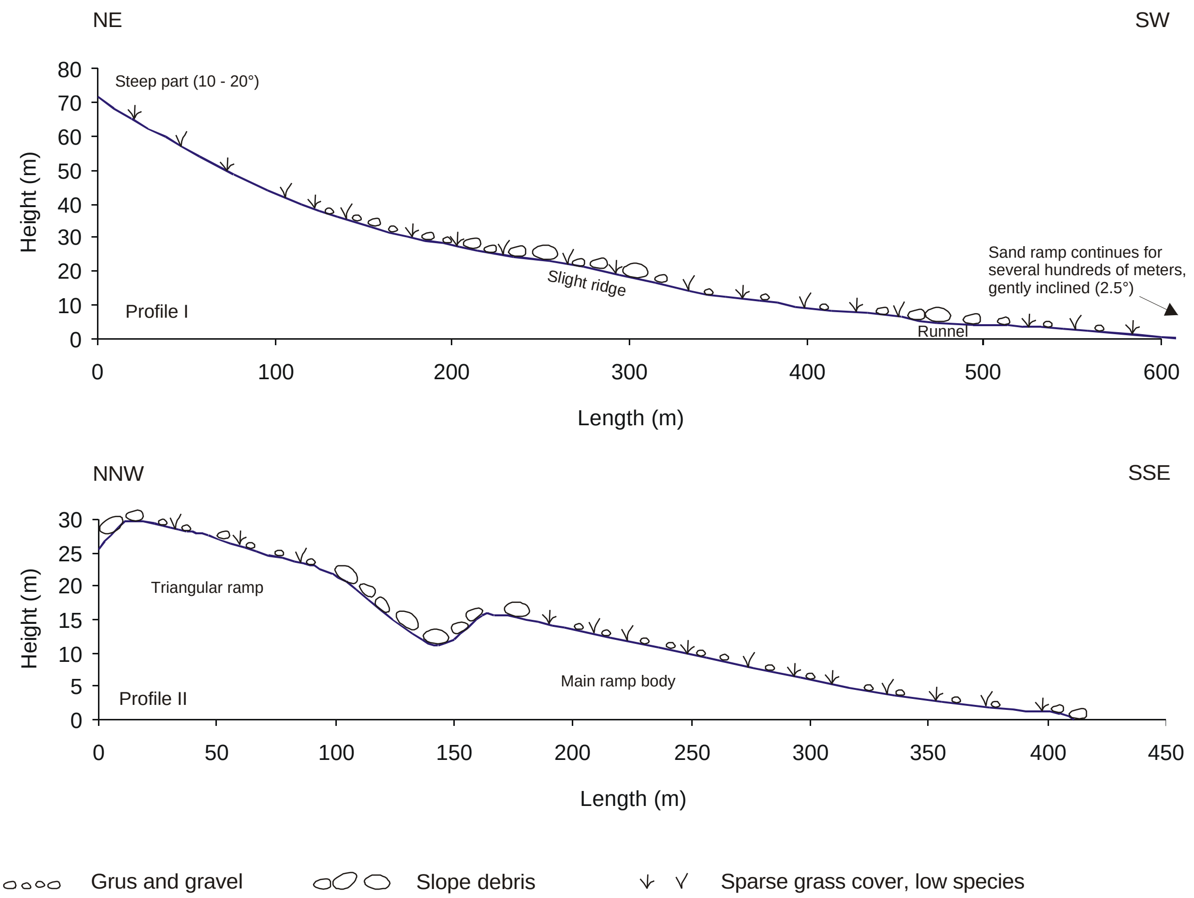


Fig. 45: Slope profiles, sand ramp C (Excelsior). Above steep ramp merging into gently inclined ramp (28 measuring points). Below triangular ramp, cut off from hillslope and the main ramp (29 measuring points).

Fig. 46: Overview of gently inclined part of sand ramp C. Note dissection and cut-off; triangular ramp in foreground.

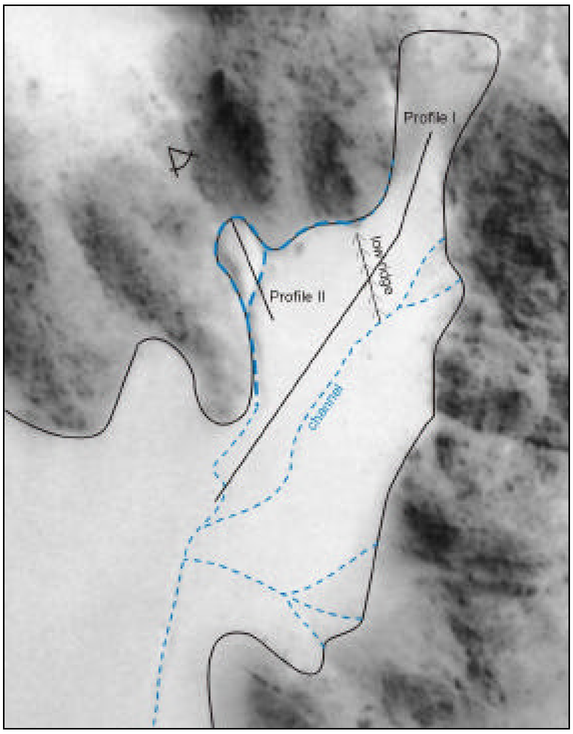


Fig. 47: Sand ramp C.

Fig. 48: Slope debris at the flank of the ramp.

In spite of this separation, slope debris is found on the slope of the gullies between ramp and bedrock slope (Fig. 48), on parts of the sand ramp close to the mountain slopes, on the low ridge, and in and along the channels. Gravitational and fluvial transport of debris from the hillslope onto the ramp must thus have occurred prior to dissection. Unlike the small rock fragments found within the sediment (EX 38), this surficial debris is quite coarse, with diameters up to 30 cm compared to 2 – 3 cm in the sediment. This suggests that there may have been only a single phase of considerably strong slope wash prior to dissection. In contrast, fluvial deposition of the sand ramp material proper must have taken place more frequently, by aeolian sand being blown over the mountain pass by northerly winds (north-northwesterly for the triangular ramp, see above) and mixed with some slope debris while being washed down the slope during occasional rains, finally resulting in gently inclined ramps.

The base of sand ramp A and all other gently inclined ramps within the basin, where sand ramp A is located, show the same sedimentological and morphological characteristics as the lower slope of sand ramp C. Their development can therefore be seen in the same way as outlined above.

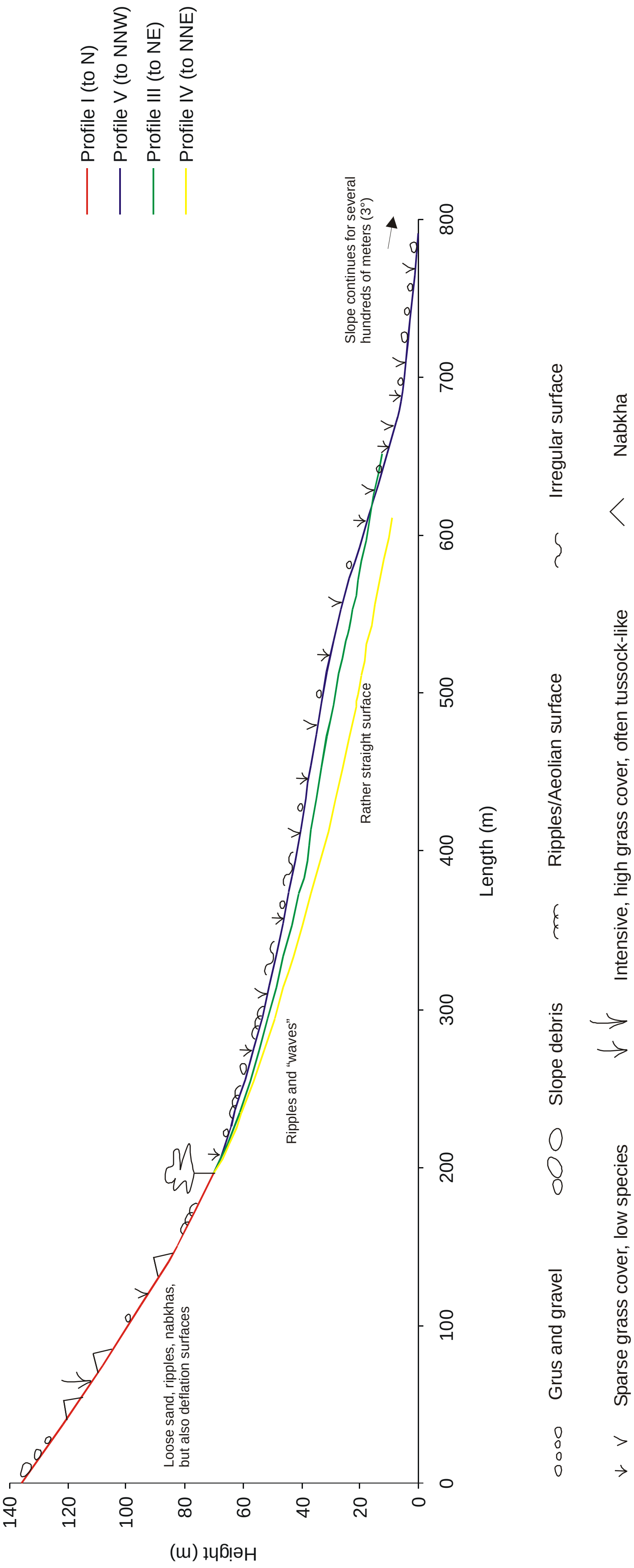


Fig. 49: Longitudinal slope profiles, sand ramp B (Excelsior). 5, 19, 18 and 26 measuring points.

Longitudinal slope profiles for sand ramp B are shown in Fig. 49 (cf. with Fig. 29 for orientation). As mentioned above, the steepest part only comprises about a quarter of the ramp (actually even less, as the profile could be extrapolated with a very low slope angle for several hundreds of meters until the sand ramp runs out towards the shallow channel). This north-east exposed sand ramp is much more voluminous than the other two ramps described above, resting as a massive body in front on the mountain slope (Fig. 50). Its overall slope is convex, though with concave parts. In the lowermost part, the slope is straight. The convexity of slope profile V between meters 500 and 700 is partly due to the fact that this profile was not taken in the dominant direction of slope, but it is also an indication of erosion of the lower slope. Coming from the straight lowest part, the convexity suddenly begins without any gradual transition, which would characterise a depositional form; therefore, the change in slope form is ascribed to erosion processes. (Four slope profile were taken altogether to illustrate the variation of the overall shape of the sand ramp; for a profile in the dominant direction of the slope cf. profile III.)

Fig. 50: Panoramic view over sand ramp B. Note person for scale (right).

On both sides the sand ramp is cut off from the mountain slopes, though not in the steep upper part. The gully on the eastern side joins the western gully of the neighbouring sand ramp (Fig. 51), forming a channel up to 8 m deep, 10 m wide and about 50 m long. Fig. 52 illustrates the channel presently running out without being connected to any major drainage channels further downslope. In the aerial photograph, however, its former course can be faintly discerned. Today, surface run-off is too weak to keep the channel open; the water infiltrates instead (notice the more dense and greener vegetation on the ground of the channel). Slope debris is found on top of the ramp all along the eroded channel, further emphazising the fluvial character. The flanks of the channel have been smoothed by wind-blown sand with active ripples. This younger aeolian overprint – the sediment is similar to the recent aeolian sands (see above) – is even more obvious at the western side of the ramp. There, a small dune rests on the rim of the rampward flank, resulting in a ravine-like form of the hollow between mountain slope and sand ramp, at first glance giving the false impression that the hollow may be due to deflation. However, the fact that the ravine has not been closed by sediments again may be ascribed to wind action (echo-effect). Alternatively, a lack of deflatable material due to the almost omnipresent desert pavement may also be a reason.

Fig. 51 (l.): Channel east of sand ramp B, joining a channel dissecting the neighbouring ramp.
Fig. 52 (r.): Downslope view in the eastern channel.

Apart from the three sand ramps described here in detail, similar ramps occur in other places as well. Around the Jagpan Mts., all steep and gentle ramps show the same characteristics as sand ramps A and C; the large sand ramps along the northern front are comparable to sand ramp B. The sand ramps at the small inselberg complex north of the Jagpan Mts. follow the pattern of the sand ramps of the Jagpan Mts., even though the ramps on its northern side are less voluminous and the proportion of recent and modern aeolian sands is higher. A single sand ramp in the Tierkloof valley (Figs. 53 & 54), north-east oriented, once more emphazises the diversity of sand ramp sediments and their catenary variation (location: S 26°08.350' E 016°27.700').

Fig. 53: Sand ramp in Tierkloof valley.

Fig. 54: Aerial overview of Tierkloof valley, sand ramp to the right.

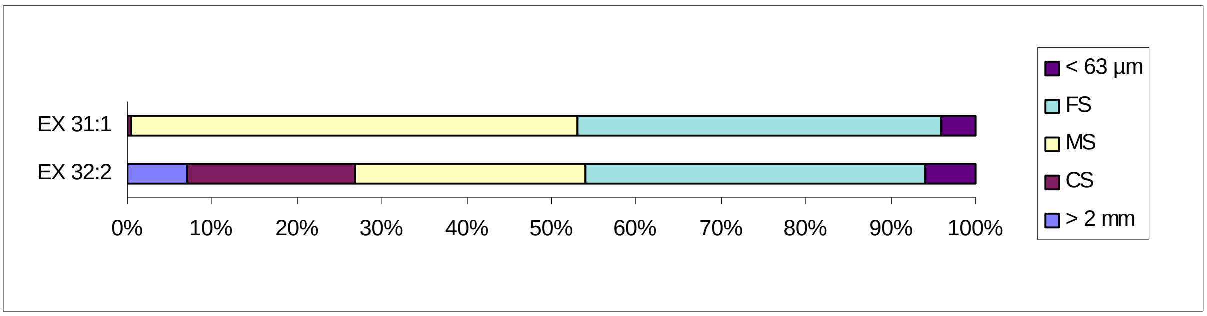


Fig. 55: Grain-size composition, comparison between upper (EX 31) and lower (EX 32) slope (at 5 – 15 cm depth), Tierkloof sand ramp.

A section on its upper slope (EX 31) mainly consists of medium to fine sand. A 3.5% content of clay and silt, its homogeneity, its stability and its slight consolidation are again taken as evidence of a former soil-forming phase under a vegetation cover. An open-spaced pavement of subangular coarse sand and grus covers the surface, bearing witness to denudation processes. The pavement becomes more dense and coarse downslope, eventually covering all of the surface with gravel-sized subangular particles partly coated with a reddish desert varnish. There is also a change in the grain-size composition of the sediment. A second pit dug on the lower slope (EX 32) contains significantly more coarse material than section EX 31 (cf. Fig. 55). Simultaneously, the amount of fines rises to 6%. Further down the ramp, on the lowermost part of the slope, there is a further increase in coarseness, changing its character from a predominantly sandy to a compact grus and gravel deposit, though with a relatively high silt and clay content of 8 – 10%. Following deposition and stabilization, fluvial erosion created a 4 – 5 m deep ravine along both flanks of the sand ramp. Along the eastern ravine, recent aeolian sand has formed a dune on the rampside flank.

5.2 Processes summarized

The sediments and morphology of the sand ramps described provide some insight into the history of sand ramp formation. At least the gravel-sized particles found on and partly below the surface of the middle and lower slopes cannot have been deposited by wind blowing up the sand ramps. They must have been washed down from the sand-free hillslopes above. This implies that repeatedly wind-blown sand was deposited on the slopes, to be partly washed down and thereby mixed with slope debris during presumably heavy rainstorms, as indicated by the coarseness of some of the slope debris. The coarsest slope debris is found on the surface, suggesting that there may have been particularly strong slope wash towards the end of the accumulation period. This must have been followed by a phase of vegetation cover and some soil formation, as indicated by the homogeneity visible in the sections dug, with no layering preserved, as well as by their slight consolidation. In a next phase, denudation of fines formed a desert pavement. Eventually fluvial erosion created ravines and channels, partly cutting off the sand ramps from the bedrock slope and dissecting sand ramp complexes (cf. sand ramp B). An aeolian phase in the recent past deposited sands in mountain passes near the sand ramps' apexes, and, as small sand dunes, on some rampward ravine flanks. At least part of the present aeolian sands seem to be reworked older sands; therefore their influence on the sand ramp sediments is limited to places where recent sands are present.

The main sedimentological difference between upper and lower slopes show in the presence of both more coarse particles (coarse sand, grus, gravel, stones) and a higher amount of fines downslope. This distribution automatically leads to increased stability and consolidation of the sediments on the lower slopes. These differences are ascribed to catenary changes.

For the spatial difference in the distribution of coarse material on the surface as well as in the sediment, several explanations may be taken into consideration, also in combination:

1. During the growth period of the sand ramp, coarse material was less available towards the end (after an intensive period when large debris was moved), maybe in correlation with a weaker fluvial impact, i.e. a decrease in intensity and/or frequency of rain storms, resulting in a lower transport capacity, only moving finer, sandy material less far.
2. For the sand ramp material at the upper slopes less coarse material could be mixed into the aeolian sands as the source area above the apex is the smallest of all.
3. The same is true for water – the more, the stronger. The largest fragments of slope debris occur close to the line of contact with the sand-free bedrock slope (short distance transport, but intensive) and along some channels (water concentration, high transport capacity).

The different amount of fines may be due to the following:

4. More water on the lower slopes also implies a higher sediment load of fines within the water ("wash-in").
5. Higher water availability and retention (due to the lower slope angle) provide better conditions for soil-forming processes, as in arid lands water is mostly the limiting factor.
6. The rock and grus fragments are all saprolitic and could thus easily be disintegrated by in situ weathering, thereby increasing the amount of fines. The more sandy sediments upslope, in contrast, will be less likely to produce silt and clay by further disintegration.

The differences in sedimentology are reflected by the morphology. Due to a lower stability, the upper slopes were easier influenced by younger aeolian processes. Evidence for that can be seen in a slight aeolian layering which is preserved in the upper centimetres of some sections of the steeper, upper slopes, but also in the micro-morphology: the occurrence of ripples, nabkhas or deflated depressions. This younger aeolian overprint is also reflected by the difficulty in exactly defining where sand ramp material ends and recent aeolian sand accumulations begin at the apex of the ramps. Where recent sands rest as dunes on the rim of ravines cut into the more stable lower slopes, the aeolian influence on surface morphology and sedimentology is spatially strongly limited to max. a few meters from the dune onto the sand ramp body.

A hypothesis held for some time during field work, namely assuming that the steeper, upper slopes with signs of aeolian activity and the lower, more stabilized slopes with a higher amount of coarse material constitute two generations of sand ramp sediments was discarded. There is no distinct change of sediment properties but only a gradual one, there are no breaks in the longitudinal slope profiles, there has been only a single phase of dissection, and there are no indicators pointing to fossil channels buried by younger sediments.

At the Jagpan Mts., all voluminous, extensive sand ramps are found in northerly and north-easterly expositions, while both the gently inclined ramps, which sometimes have a steep, upper part, only occur in south-westerly positions. This implies a sand transport from north-east to south-west, in the course of which most of the sand became deposited on the windward slopes. Only a fraction of the sand appears to have been blown through the mountain passes to the leeward side. South-westerly sites behind high mountain tops are basically free of reworked wind-blown sand and characterized by alluvial fans in their foreland. The Neisip Mts. about 5 km east of the Jagpan Mts. might serve as example. This very compact inselberg complex is about 300 m higher than the Jagpan Mts. and furthermore lies in the wind shade of the even higher Tiras Mts., only one to two kilometres to the north and north-east (cf. Fig. 4). At the Neisip Mts., no dune sand was delivered to the south-western side, and consequently only alluvial fans could develop (Figs. 56 – 58).



Figs. 56 – 58: Alluvial fans and debris depositions in a lee-position of the Neisip Mountains.

A similar situation is found in the Tierkloof valley. In the field, at first glance it appears that there has been more transport of coarse particles, up to block-size, down the south-facing slopes (in the northern part of the valley). This misconception is due to the fact that there is a much higher fraction of sand and fines in the sediment on the south side, relatively lowering the amount of coarse particles there. This differing distribution is a result of north-easterly winds, preferentially depositing the fine-grained wind-blown sediments in the southern part of the valley and covering the northern side, in a leeward position, to a far lesser degree, also indicated by a dense cover of melkbos (Euphorbiaceae), which prefers blocky ground. Furthermore, nabkhas accumulate behind small bushes, with their tails pointing to the south-west.

Probably due to the small amount of sand blown over the passes, the fluvial processes reworking the aeolian sands in the above mentioned fluvio-aeolian interaction had a larger impact on the south-western side; although the amount of rainfall can be assumed to have been about the same for the whole inselberg complex, the catchment area for runoff affecting the single sand ramps on the south-western side was larger due to a lesser cover by aeolian sands. Therefore, rather gently inclined, partly strongly dissected and well confined sand ramps, sometimes with a narrow, steep upper part, were formed there. On the north-eastern side, the high availability of sand resulted in large ramps.

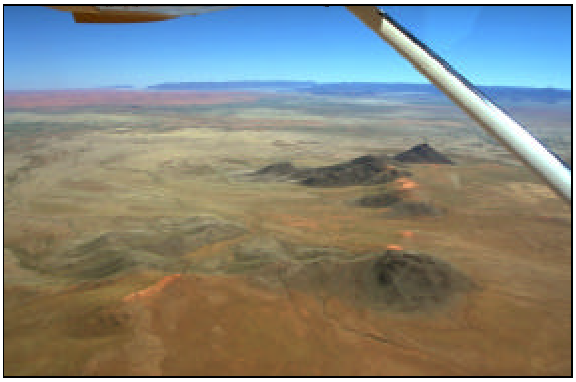
Also the aeolian sands forming the modern and recent accumulations have been deposited by winds from the north-east. Interpretation of aerial photographs and a Landsat 5 TM satellite image clearly shows that the current sand transport direction is north-east to south-west. This is identical with the orientation of the older wind-sculptured flutes described above. Also for the younger polishing north-easterly winds are suggested to be responsible. Gravelly deflation ripples found for example near the Tierkloof valley and the outlier erg, indicate strong present winds from north and east as well (Figs. 59 & 60).

Figs. 59 & 60: Gravelly deflation ripples, near Tierkloof valley (low pass with tunnelling effect, (® N)).

The possible sources of the sand and the general principles of sand ramp formation are discussed together for the young sand ramps – Excelsior and Sandkop – following the description of the latter (cf. chap. 6).

5.3 Sandkop

The Sandkop sand ramp and the morphologically and sedimentologically comparable ramps on Gunsbewys and Waaihoek are isolated ramps, well-defined in their extent. At these locations, no sand ramp complexes occur as on the Jagpan Mts. In spite of this morphological difference, the Jagpan Mts. sand ramps and the sand ramps to be described in this chapter are suggested to be of the same age.



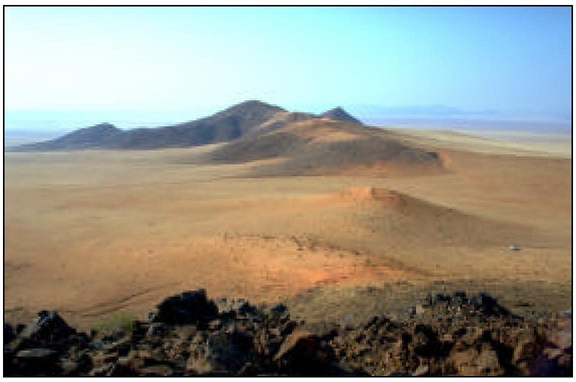


Fig. 61 (l.): Aerial overview of the Sandkop Mountains (® NW) after the rainy season.
Fig. 62 (r.): View from the southern inselberg to the north: Voluminous sand ramp at the eastern slope, uncovered slopes in the west; note car for dimensions (right).

The Sandkop sand ramp is situated at the Sandkop Mountains (located at S 26°27.150' E 16°31.500'), an inselberg complex on the farm Sandkop, c. 10 km west of the Great

Escarpment in about the middle of the study region (cf. Fig. 4, p. 8). The complex is characterized by three mountain tops oriented along a north-south axis almost 4 km long; the southernmost top (1,358 m) stands isolated, while the middle (1,371 m) and the northern (~ 1,320 m) tops are separated by a mountain pass only (Figs. 61 - 63). The sand ramp is on the eastern flank of the middle inselberg and has been cut off from the northern one by fluvial erosion (cf. Fig. 71).

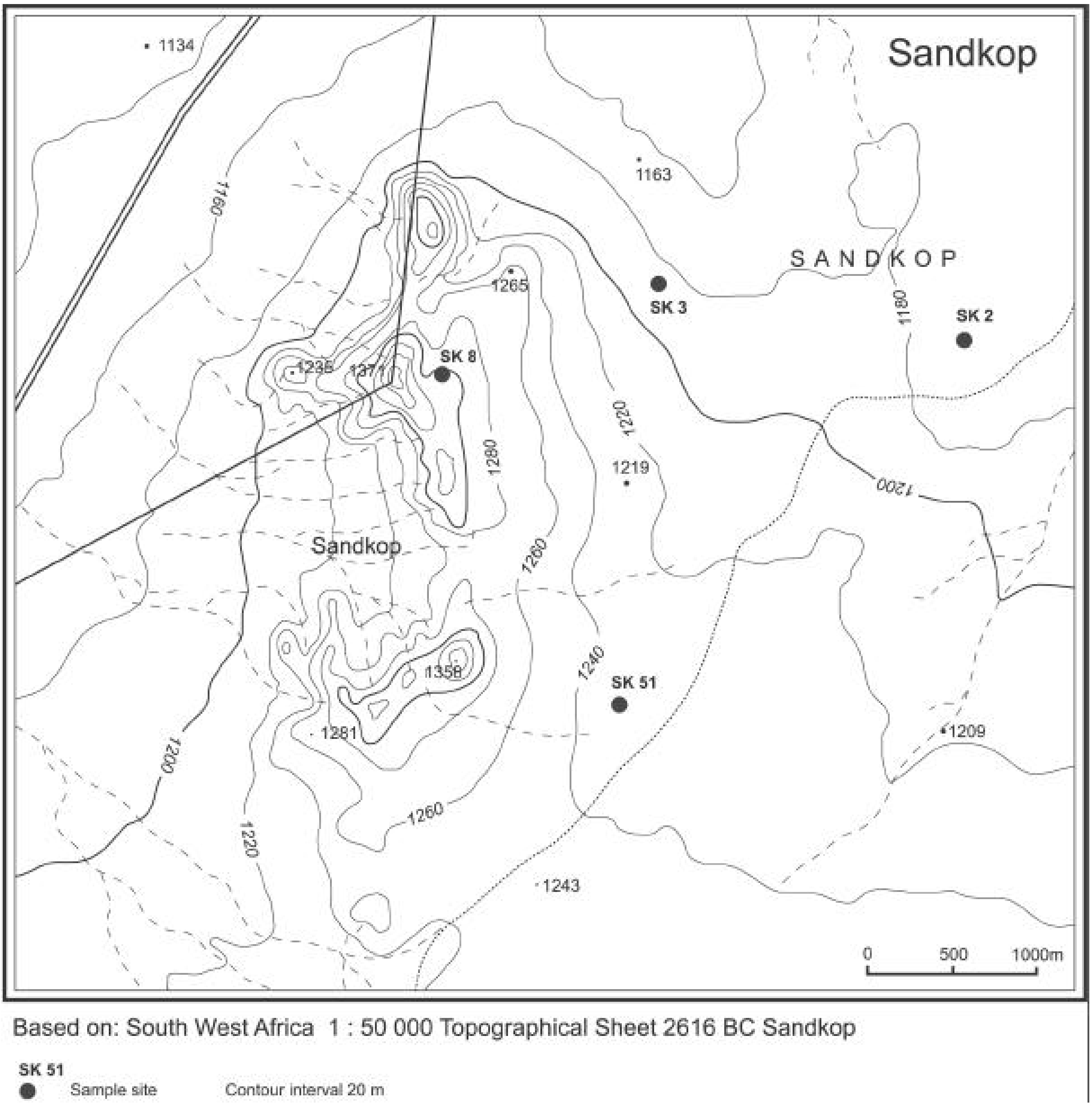


Fig. 63: Topographical map, Sandkop area.

The geology of the Sandkop Mts. is colourful, but all rocks belong to the Namaqua Metamorphic Complex, and within the NMC they are part of the Garub Formation, except for the biotite gneiss comprising the northern inselberg and a small patch of the middle one. Beyond that, the middle inselberg consists of aluminous gneiss and biotite schist, while at the southern inselberg amphibolite, metaquartzite, and aluminous gneiss occur. Furthermore, the middle and the southern inselberg show small outcrops of marble at their eastern flanks, while the middle and the northern inselberg are cut through by three mafic dykes, striking north-west – south-east (GEOLOGICAL SURVEY OF NAMIBIA 1999, JACKSON 1976).

The relief of the area shows relatively steep descents (partly > 30°) from the mountains to their western foreland at an elevation of about 1,200 m. Due to the sand ramp on the eastern side, these slopes are less inclined. This pattern is known from the Jagpan Mts., only the orientation has changed, for the less inclined slopes from NE to E, and for the steep topography from SW to W. The sands forming the ramp are assumed to have been brought in from an easterly direction. As on the Jagpan Mts., some of the aeolian sand was blown to the leeward side of the mountains through the pass already referred to. In these westside positions, like in the Jagpan Mts., gently inclined, dissected ramps have been formed, beginning near the foot of the bedrock slope. Sometimes they also show a steep, upper part, but all of these westside forms are much less well developed in terms of amount of sediment incorporated. In the wind shadow of the three mountain tops, the foreland is characterized by regular alluvial fans, as obviously no sand could be wind-transported into those protected positions, supporting the hypothesis of a sand source in the east.

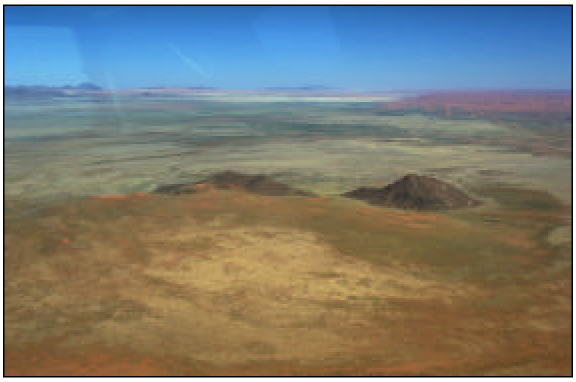


Fig. 64 (l.): Aerial overview of the sand ramp at Sandkop (® WSW).
Fig. 65 (r.): Aerial view of the Sandkop Mountains and the sand ramp (® SW).

From its apex downslope, the Sandkop sand ramp has a length of about 1,500 m, extending up the slope from the foreland elevation of about 1,200 m to about 1320 m. The slope of the main body is about 6 – 8° at the upper and middle parts, from where the ramp gently grades into the foreland without any break in slope profile. In general terms, the foreland is a gently undulating plain covered by fluvio-aeolian sediments, subjected to slight pedogenesis in the past, and covered by a partly open-spaced pavement. In detail, the plain shows a variety of material properties. In parts, rather fine-grained fluvial deposits prevail, near the escarpment surfaces covered by slope debris and old terraces incorporating it bear witness to a strong fluvial and gravitational activity in former times. In other parts, massive calcrete is found, sometimes with a thin cover of aeolian sand. The colour of the plain sediments changes from strong brown to yellowish red to greyish according to the different sediments and their pedogenic overprint. The drainage pattern is characterized by channels partly merging into another and then forming larger stream cuts, and partly running out as shallow runnels. This small-scale pattern of the plain is shown clearly on the aerial overviews (Figs. 61, 64 & 65), an impression intensified by the different vegetation types and degree of grass cover.

As mentioned above, the sand ramps of Excelsior and the one at Sandkop are comparable in terms of genesis and age. This hypothesis is supported by the sediment properties. The grain-size distribution of the Sandkop sand ramp sediments in different slope positions and pit depths is shown in Fig. 66; for comparison, the grain-size distribution of some sand ramp sediments at the Jagpan Mts. is plotted as well. The sediments of the Sandkop sand ramp fit well into the range of grain-size composition found on Excelsior. Coarse sand and grus are mainly subangular, suggesting a short transport distance and representing the fluvial input. The grains are partly stained by iron oxides, indicating former soil formation; pedologically, the sediment is a weakly developed Regosol. Although the colour of the sediment in section SK 8 on the upper slope is yellowish red (5YR 5/6) throughout, the decrease of fines from 5 to 3% between 60 and 135 cm may indicate a decrease of intensity of pedogenic processes with depth. Like the sand ramps at the Jagpan Mts., the Sandkop sand ramp also shows an increasing proportion of fines and coarse sand and grus on the lower slope, due to catenary effects (cf. chap. 5.2).

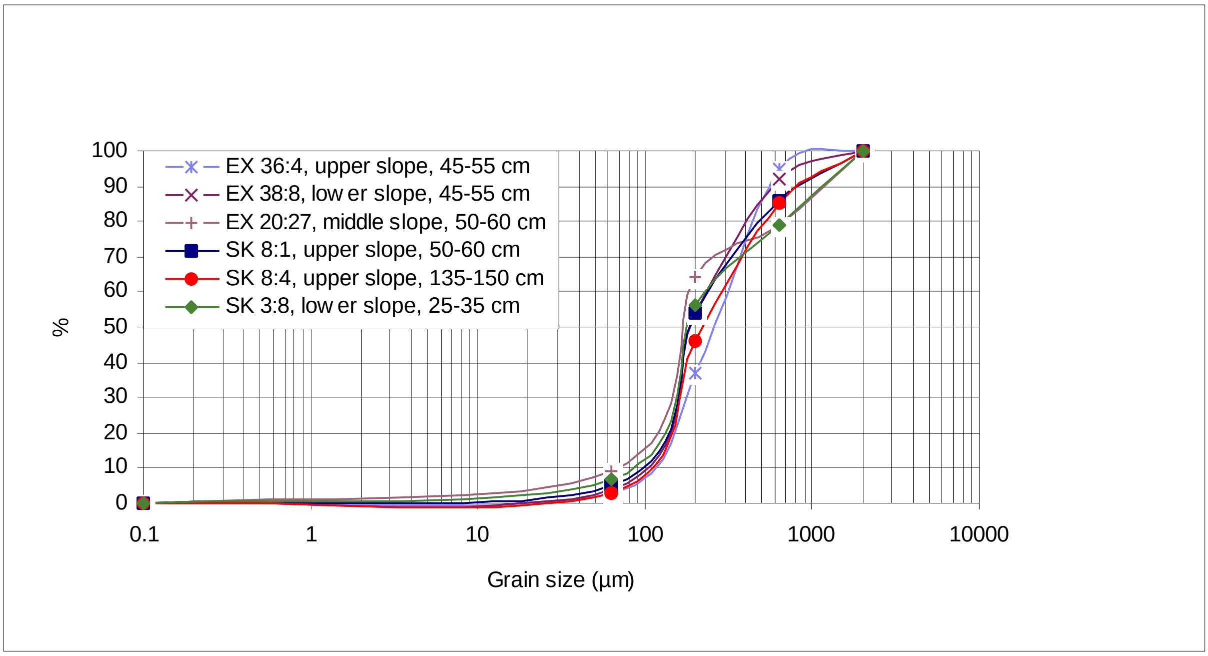


Fig. 66: Grain-size distribution of the Sandkop sand ramp sediments, compared to sand ramp material from sand ramps at the Jagpan Mts.

The major part of the surface of the Sandkop sand ramp is very even and covered by a single-layer deflation pavement consisting of coarse sand and grus. The stabilizing effect of the pavement can easily be lost by trampling, though. Section SK 3 on the low slope, in transition to the adjacent plain, is close to a waterhole frequently visited by cattle; the surface is still characterized by an enrichment of coarse sand and grus, but also by small ripples formed in unconsolidated and unstructured sand comprising the upper 8 cm of the section. Below, the typical, consolidated and stable sediment is found. (For additional sections of the surrounding plain see App. II).

The cover of present and recent dune sand at Sandkop is much less extended than on the Jagpan Mts. The modern sand is mainly concentrated at two sites (cf. Fig. 65), a partly eroded body the shape of an inverted S overlying the erosion rim of the northern half of the sand ramp (Fig. 68), and a smaller dune at the southernmost top end of the ramp where the mountain is quite low (~ 1,320 m a.s.l.) (Fig. 69 left). In both locations there are sharp dune crests and wind ripples, and their internal structure is typically aeolian (Fig. 67). These very mobile sands are unvegetated, with a sharp boundary. As on the Jagpan Mts., this active sand is underlain by older dune sand, characterized by stands of *Stipagrostis sabulicola*, in contrast to *S. obtusa*, which occurs on the sand ramp proper (Fig. 68). The transition from modern to recent sand and to the stabilized sand ramp sediment occurs within a much shorter distance than on the Jagpan Mts.; the upper slope has almost not been reworked by aeolian activity at all, except for in the immediate vicinity of the younger aeolian sand cover.

Fig. 67 (l.): Aeolian layering, accumulation at top of sand ramp, Sandkop.
Fig. 68 (r.): Modern and recent aeolian sands, next to eroded part of sand ramp, Sandkop.

Slope debris on the ramp is more closely spaced than on the Jagpan Mts. It is found on parts of the upper slope and on and near the flanks of the channels dissecting the ramp and separating it from the mountain slope. Both fairly straight and meandering channels are cut into the sand ramp sediments at the eastern and the western side of the mountains. The contact zone between the mountain slope and the sand ramp is predominantly characterized by sharp, fluvially shaped beginnings. This is especially so for the gently inclined ramps on the western side (Fig. 69). Only where modern aeolian sand occurs at the top part of the ramp, is there a gradual transition from the sediment-free bedrock slope to the sand ramp. The amount of fine-grained sediment increases from 1) the sediment-free mountain slope to 2) modern aeolian sand between the debris to 3) modern aeolian sand covering the bedrock slope to 4) recent aeolian sand to 5) sand ramp material.

Fig. 69: Panoramic view over the western slope (® S).

The main ramp on the eastern slope is clearly cut off from the northern inselberg (Figs. 71 & 72) and from the northern part of the middle one. Fig. 70 presents two slope profiles taken from the mountain slope of the northern inselberg (W), through the eroded channel, and up to the dune resting on its rim. To the east, the main body of the sand ramp continues. Profile I was taken in about the middle (lengthways) of the erosional form, profile II about 150 m downstream (→ NE). Unlike at the Jagpan Mts. the separating channel does not have the shape of a ravine, but is much broader.

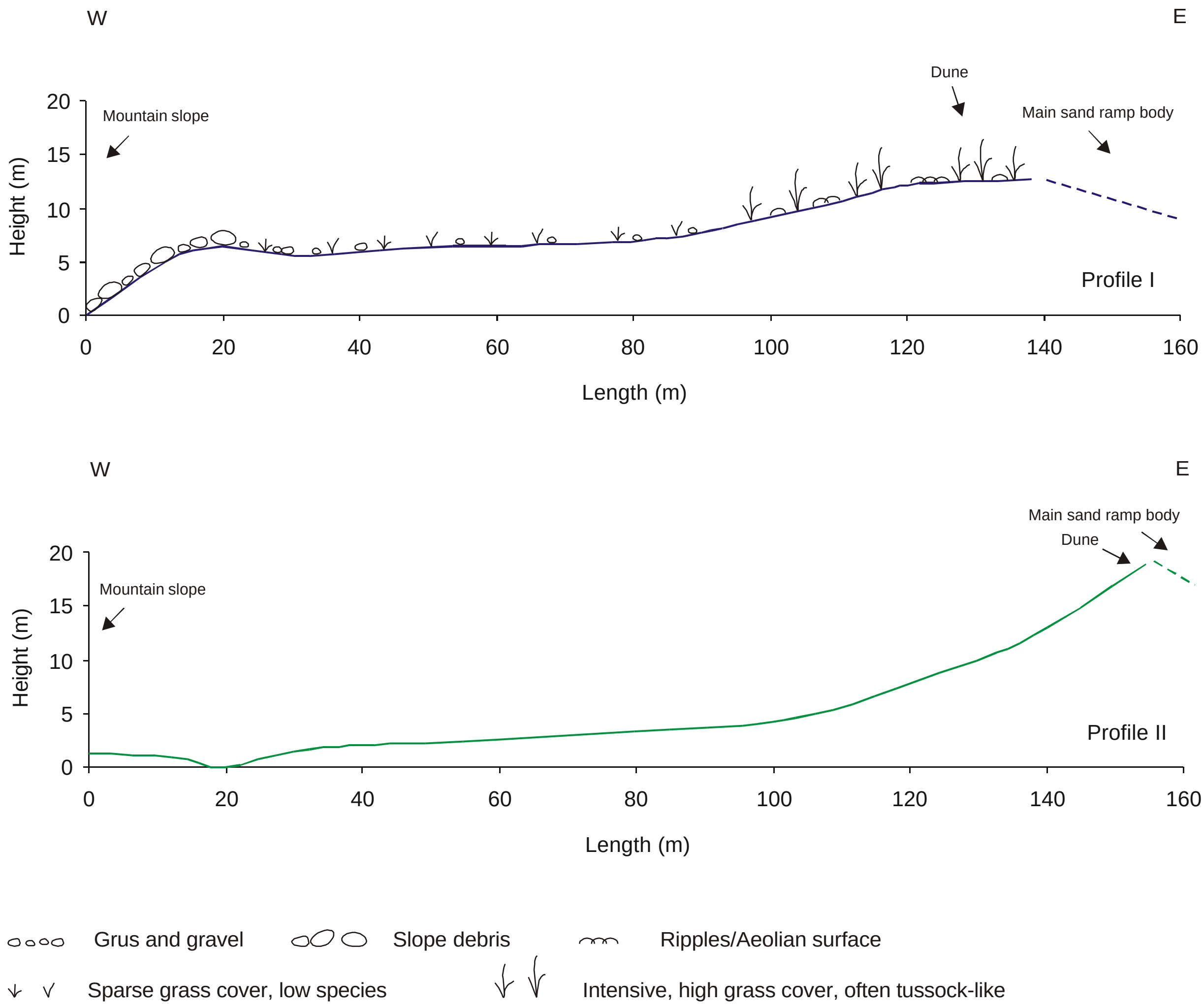


Fig. 70: Slope profiles in the stream cut separating the Sandkop sand ramp from the mountain slope. Profile I in the upstream part, profile II further down. 9 + 12 measuring points.

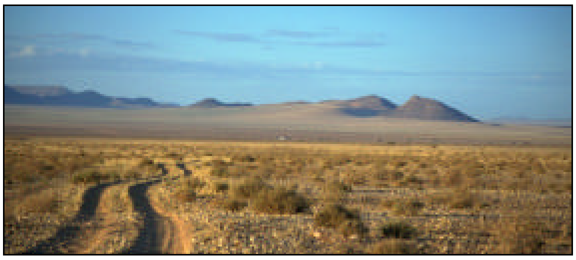


Fig. 71 (l.): Early morning view of Sandkop (® S); shadow underlines the lack of sand ramp material between the ramp as it is today and the northern inselberg.

Fig. 72 (r.): Ravine between ramp and northern inselberg and S-shaped dune along its rim.

Only in the upstream part a ravine-like form occurs next to the mountain slope; the erosional form, however, extends further to the east for about 120 m, where a sand dune marks the limit. Downstream, the ravine runs out, only slightly incised, 20 m away from the mountain slope. It has possibly been filled by sediment wash in from above. This morphology indicates that erosion must have occurred in two periods: first the wider hollow was formed, and then the ravine was cut into it. Slope debris is strewn everywhere on the flanks of the ravine, just as on the surface between the ravine and the sand dune.

There is evidence that the sand ramp sediments once reached higher up the bedrock slope by extrapolating the angle of the upper and middle slope (6 – 8°), and there are also relics of sand ramp sediment in protected positions, such as next to large blocks. The relatively low content of grus in the sand ramp sediments compared to the sand ramps on Excelsior may be an additional indicator of a ramp once reaching higher up the mountain slopes at least during certain phases of deposition. By that, less coarse material on the bedrock slope would have been mixed with aeolian sands and washed down during the fluvio-aeolian interaction. Other evidence is that wind-scour only occurs above the assumed former upper limit of the sand ramp. As on the Jagpan Mts., also on Sandkop wind erosion left its impressive traces of both the fluting and the polishing generation, shaped by winds from the north-east (Figs. 73 – 74).

Figs. 73 & 74 (l., m.): Two phases of wind erosion on top of the Sandkop Mountains.

Fig. 75 (r.): Desert varnished rock surface above the sand ramp, from where grus was supplied in the time of sand ramp formation.

The area above the sand ramp also shows that grus production is not a current process, as there is a red-brown desert varnish on all of the exposed bedrock surfaces (Fig. 75), preserved in lee-positions. This desert varnish is also found on the older wind-scour generation.

At the mountain slope of the southern inselberg remnants of massive calcrete occur between the slope debris, buried by the modern aeolian sand. Patches of calcrete of a size of c. 30 by 30 cm were found, broken into pieces of up to 10 by 10 cm (Fig. 76). The upper 3 to 4 cm suggest surficial formation, indicated by desiccation cracks and lamination; partly, also the slope debris is coated with laminae up to 3 mm thick. Below the lamination zone, the colour changes from white to pink, suggesting a reddish, fine-grained host sediment (soil? aeolian sand?). The pieces seem to rest on a strongly cemented, red-brown, fine-grained sediment, of which there are also some relics. It may be comparable to another relict soil sediment found between slope debris above the sand ramp (Fig. 77). As the sand ramp sediments are free of carbonate, the calcrete must be older. This fit with the calcretes found in the plain in positions lower than the sand ramp sediments.

Fig. 76 (l.): Calcrete at the middle inselberg above the sand ramp, Sandkop.
Fig. 77 (r.): Relict soil sediment above the sand ramp, Sandkop.

5.4 Waaihoek and Gunsbewys

Two more sand ramps, on the farms Waaihoek and Gunsbewys respectively, are similar to Sandkop in being isolated ramps and showing only a slight young aeolian overprint.

The Gunsbewys sand ramp is located in the north-easternmost corner of the farm, resting on an east-southeasterly slope within a small embayment within the Tiras Mts., east of the Weissenborn basin (position S 26°08.610' E 16°23.400'). Geologically, the surrounding mountains consist of the Tierkloof meso- to melanocratic diorite and granodiorite. The ramp is 300 m long and 40 m high. It has been deposited in front of a 220 m high mountain top, and no sands have been blown over to the other side of the mountain or higher up the mountain slope; there is only this isolated ramp, well defined in its extent. The upper slope falls with an angle of 12°, decreasing evenly downslope to about 4° at the lower slope. The ramp is covered by a closely spaced desert pavement of mainly subangular particles, increasing in size downslope, from coarse sand and grus and occasional pieces of slope debris on the upper slope to gravel-sized fragments and stones up to 20 cm in diameter on the lower slope. Two sections were dug, on the upper (GB 13) and lower slope (GB 14). The grain-size distribution, compared to the Sandkop sand ramp and the one at Waaihoek (see below), is shown in Fig. 78.

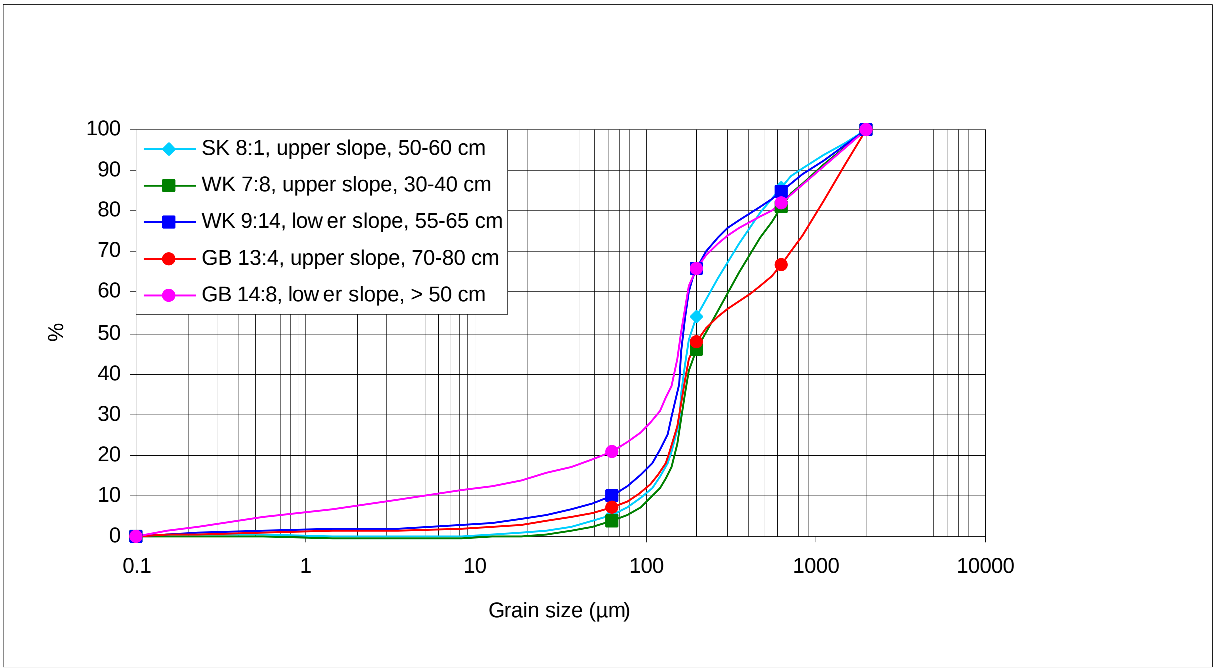


Fig. 78: Grain-size distribution for sediments from upper and lower slopes, sand ramps Gunsbewys, Waaihoek, and Sandkop.

For the homogenous section GB 13, the content of coarse sand and material > 2 mm, being angular to subangular, adds up to 30% in the upper 15 cm and > 40% at 80 cm depths. The clay and silt content lies at 6 – 7%. This shows once more that sand ramps not entirely are aeolian forms, but develop in interaction with fluvial processes, mixing and washing material downslope. Soil formation helps increase the content of fines, bioturbation deletes any sediment structures, erosion processes will concentrate the coarse particles.

On the lower slope (GB 14), both the fluvial and the pedogenic influence become even more obvious. Underlying a very coarse pavement, the consolidated section contains 30% of material > 2 mm (grus, gravel) and 11% of clay and silt at a depth of 10 cm. There is a well-defined boundary at 50 cm; below it, subangular grus and gravel are dominant (60%), forming a hard layer difficult to dig through, although the matrix, a loamy sand with a content of fines of 21%, is not cemented; it is just that the coarse elements are packed very densely. Presently, the sand ramp runs out towards a slightly incised channel; through this watercourse probably once at least part of the basal sediments of section GB 14 was deposited before the sand ramp sediment proper accumulated above it. It also strongly influenced the sand ramp sediment of this section as shown by the high amounts of coarse fractions and fines. Thus, this ramp was formed by fluvial processes in two ways: by slope wash (like all ramps), and by lateral deposition and erosion by the stream.

On the upper slope, the ramp has been cut off from the mountain slope at both sides. Some mobile sand occurs at the very top, where the ramp is still in contact with the hillslope, and along the rim of the southern ravine. The young aeolian overprint is minimal, though.

The sand ramp on Waaihoek is located on the eastern slope of the small, single inselberg south of the Neisip Mts. This biotite gneiss mountain is tiny, as is the sand ramp, only 26 m high and around 250 m long. Sedimentologically, the ramp is fully comparable with the sand ramps presented above; for grain-size distribution curves see Fig. 78.

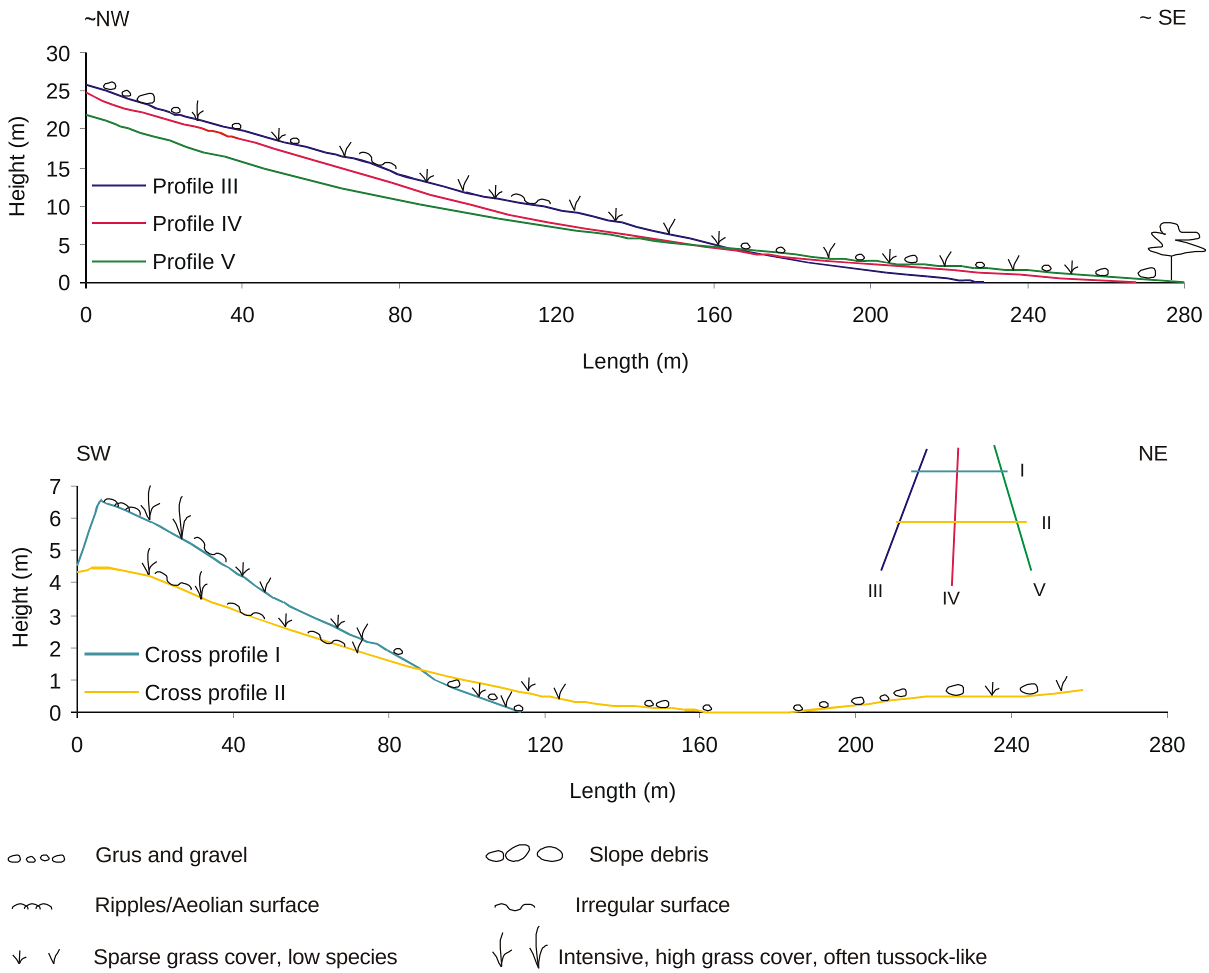


Fig. 79: Longitudinal slope profiles and cross profiles, sand ramp Waaihoek. 10, 17, 16, 12 + 14 measuring points. Note sketch for location on the ramp. Surface characteristics for longitudinal profile IV (W – E).

The morphology of the Waaihoek sand ramp is particularly interesting. Fig. 79 shows slope profiles of the ramp. Cross profile I at the upper slope shows a deep ravine at the southern side, while the northern side is not cut off from the hillslope. The ravine carries a dune of young aeolian sands on its rampward rim. On the lower middle slope (cross profile II), the ravine comes to an end, but a slight concavity is found towards the north-eastern side (fluvial influence probable?). The longitudinal profiles change from an even, slightly concave profile in the northern part of the ramp (profile V) to a very irregular one in the southern part (profile III), in agreement with a change of surface characteristics. Along the northern flank (profile

V), slope debris is frequently found on the even and consolidated surface. Towards the southern flank, the diameter of the pavement particles decreases from blocks to gravel, grus and finally to sand. The micro-relief increases to shallow irregularities of the surface (tiny ridges and runnels) as well as deflation ripples (oriented NW – SE) in the middle (profile IV), to an uneven surface dominated by aeolian sands along the dune (profile III). Also the grass cover changes from low and dense (*Stipagrostis obtusa*?) on the northern half to high and sparse towards the southern dune (*S. ciliata*? – heavily grazed, difficult to identify).

The asymmetry of the ramp may be another indicator for north-easterly winds having delivered aeolian material both in the past, as the ramp is more voluminous in its southern parts, and in subrecent to recent times, as the young aeolian sands exclusively are found along the upper southern rim.

6 NATURE AND ORIGIN OF THE YOUNG SAND RAMPS

6.1 Principles of sand ramp formation

From the morphological and sedimentological characteristics of the young sand ramps presented above, a five-stage development of these ramps can be read. These stages imply different morphodynamics, which in turn can be linked to different environmental conditions in the past.

A) Initial deposition
B) Stabilization
C) Desert pavement formation
D) Dissection
E) Aeolian overprint

The formation of the sand ramps can be assigned to the last glaciation (for OSL dates see chaps. 7.1, 7.3.2). Here, only a general overview of the climatic conditions during this period will be given; for further discussion regarding the context of landscape evolution see chap. 9. After the maximum warming around 125,000 BP, cooling occurred intermittently until coldest conditions were experienced in the Last Glacial Maximum (LGM) around 16,000 – 20,000 BP (TYSON & PARTRIDGE 2000). Palaeoclimatic models for glacial conditions of Southern Africa propose an intensified atmospheric circulation system together with an equatorward shift of the circulation belts (DEACON & LANCASTER 1988). The circulation over most of South Africa and southern Namibia was thus dominated by the westerlies, implying an increase of the proportion of winter precipitation in the present-day summer rainfall region (TYSON 1986, COCKCROFT et al. 1987). General circulation models also assume a reduction of precipitation in southern Africa by 30 – 40% (TYSON 1986, DEACON & DEACON 1999). Even if the shift of the circulation system was by about only one degree, as recently proposed (DEACON & DEACON 1999), it would have markedly affected the study region in the present transition zone of summer and winter rainfall.

Deep sea drilling cores off the Namibian coast give evidence of marked variabilities within the overall cooling trend (e.g. KIRST et al. 1999, LITTLE et al. 1997; for a detailed literature review regarding the influences of the Benguela Current on the climate of the Namib cf. KEMPF 2000). Coastal upwelling off Namibia was generally enhanced during glacial times and, for the last 150,000 years, was at maximum between 50,000 and 35,000 years BP. Higher sea surface temperatures under full ice-age conditions are explained by perturbations in the trade-wind system similar to present "Benguela Niño events" (KIRST et al. 1999). During oxygen isotope stage 2, the aeolian components in the deep sea sediments suggest an increase in the strength or frequency of seasonal easterly 'berg' winds off the desert (SUMMERHAYES et al. 1995).

Following the LGM, conditions ameliorated as the regional effect of global warming rose to a maximum during the Holocene Climate Optimum around 6000 BP (TYSON & PARTRIDGE

2000). For the Late and Mid-Holocene, short-term high amplitude climate variability has been identified (e.g. LEE-THORP et al. 2001).

A) Initial deposition

Aridity – deflation of aeolian sands – strong winds – grus production – frost – sheet wash: mixing of aeolian sand and coarse material from the bedrock slopes – rare, but intensive convective rainfall

The sand ramp sediments are a mixture of aeolian sand and fluvially transported particles, thus implying an alternation of aeolian deposition and slope wash. The aeolian processes required arid conditions, strong winds from north-easterly and easterly directions, which deposited the sands dominantly on the windward inselberg flanks, and a constant availability of sand. Sheet wash of the aeolian sands and the coarser particles must have been induced by rare, but high-intensity rainfall strong enough to overcome the high infiltration capacity of the aeolian sediment. Due to the slope wash process, the sand ramp sediments never covered the entire bedrock slopes up to the crest, though the aeolian sand cover must have been more extensive. The location of wind scour on the bedrock and the occurrence of remains of sand ramp material between the blocky slope debris bear witness to sand ramps of temporarily greater extent compared to the present situation (cf. chap. 5.3). On the bedrock slopes grus production by frost-cracking must have been active, providing the coarse particles to be incorporated into the sediments.

The origin of the sand will be discussed in the following chapter. It should be noted, though, that sand has always been present in this ecosystem (regarding the period of sand ramp development). Firstly, the Precambrian bedrock in the study region had been subject to documented deep chemical alteration both in Proterozoic and in Tertiary times (cf. chaps. 2.1, 2.2), having resulted in the formation of saprolite easy to disintegrate into grus and sand. Secondly, the outlier erg, i.e. the south-westernmost part of the Namib Sand Sea, can be assumed to have already existed at the time of the first sand ramp formation[1], having constituted a possible source providing large amounts of aeolian sand. Thirdly, relict soils older than the young sand ramps are found within the study region proper (for details cf. chaps. 2.7, 6.3, 7.4). The limiting factor was (and still is) whether sand mobilization could occur or not. An important prerequisite must have been the absence of vegetation immediately prior to and during the deposition of the sand ramps. Only then intensive rains would have been able to move the sands from their sources into riverbeds, which transported and further broke down the material. Beyond the delivery of sand, these fluvial processes would have ensured the disturbance of any pavement that would have prevented any further uptake of sand by the wind.

[1] For the age of the Namib cf. BESLER 1991, KEMPF 2000, LANCASTER 2000, WARD & CORBETT 1990.

Extreme climatic conditions with catastrophic rainfalls or strong winds are often associated with collision of air masses of pronounced differences, in particular polar and tropical air masses. It is thus suggested that climatic conditions characterized by large differences in atmospheric pressure prevailed during the phase of sand ramp deposition. Within the fluctuations of the last glacial period, this would point to an intensified atmospheric circulation, having resulted in a highly dynamic climatic system. Strong winds from easterly and north-easterly directions would have been caused by intensified trade winds or berg winds. Summers would have been dry as there would not have been a heat-induced low-pressure cell over the Kalahari like today, responsible for summer rains. Instead, a cold continental high would have prevailed, keeping out the west (or north-west) winds "normally" bringing humidity to Namibia. Only occasionally slope-wash inducing catastrophic thunderstorms would have occurred. The proportion of winter rainfall may have been higher, but the highly active Benguela Current largely impeded convection. Winter rain is thus assumed to have been low. Due to lower temperatures, the dominant proportion of the precipitation is suggested to have fallen as snow. This would have favoured frost-cracking. Together with the dry summers, vegetation growth and soil formation would have been hindered.

Slope wash of exceptional character must have taken place towards the end of the deposition period of sand ramp formation, as slope debris, in places up to 25 cm in diameter, was transported down the ramps. The debris was predominantly deposited near the mountain slopes, but some of it was washed down as far as the lower slopes. These sheet wash processes did not dissect the sand ramps, though. There is no way to be sure whether the transport of slope debris occurred in a single catastrophic event or whether there was a series of exceptionally heavy rains during a single season or over several years. It is an equally open question whether debris production occurred simultaneously or whether the debris moved had been stored on the mountain slopes from earlier periods of debris production by frost-cracking; fluvial processes prior to the extreme event(s) towards the end of sand ramp formation may only have been strong enough to move the grus fragments. It may also be argued that the final transport of slope debris was supported by a thicker cover of aeolian sand – either deposited during one major sandstorm or in the course of several dry years without significant slope wash –, constituting a richer matrix in which the slope debris could have been moved.

B) Stabilization

Environmental stability – weak winds – low-intensity rainfall – winter rains – soil formation – vegetation cover – higher temperatures

Following the fluvio-aeolian deposition of the sand ramps proper and the final spread of slope debris, there appears to have been a period of environmental stability. Aeolian processes did not play any active role any more, and fluvial processes were strongly reduced. A vegetation cover developed, hand in hand with soil formation, thereby increasing the catenary differences between upper and lower slopes, and bioturbation destroyed all sediment structures.

Compared to the climatic conditions during sand ramp formation, conditions must have been mesic, i.e. with less intensive rains, weaker winds and, most important, a lower variability of the fluvial regime (cf. KEMPF & BUSCHE 2002). This suggests lesser differences in pressure between polar and tropical air masses and thus a period of reverse motion within the general cooling trend. Climate can be assumed to have been more favourable for pedogenesis – read: it must have been wetter – than the present climate. Water must have been available in moderate amounts for longer periods, suggesting gentle rains of frontal character. This, in turn, points to higher winter precipitation, falling as rain due to slightly higher temperatures than before. Summer rains induced by trade-wind convection may also have been more productive than before, but still restricted due to the activity of the Benguela Current. If most of the rain fell in the winter season, it may further be concluded that the vegetation was adapted to these conditions. Occasional summer rains would then have been insignificant for both the vegetation and the morphodynamic processes. Today, comparable environmental conditions exist in Namaqualand (NW South Africa).

C) Desert Pavement Formation

Denudation – increase of rainfall and wind intensity

Following the phase of environmental stability, denudation was resumed, creating the desert pavement of the ramps (for details of pavement formation cf. COOKE et al. 1993). Both deflation and wash processes must have been active, implying stronger winds and more intensive rains than during the stabilization period. By denudation, the A-horizons of the soils were truncated, leaving only the lower B-horizons found today. There is no evidence of resumed deposition on the ramps, and nor is there evidence of dissection.

Climatologically, this may be explained by a continued movement towards more tropical conditions, with increasing summer and decreasing winter rainfall, comparable to the climate of the present semi-desert. The winter rain vegetation would subsequently have been replaced by annual vegetation favouring summer rainfall (C_4-grasses). As germination is induced by the first rainfalls of the season, fluvial denudation processes would have occurred just before, and deflation after the vegetation period.

D) Dissection

High-intensity rainfall – concentrated run-off – dissection – retrograde channel fill

Following the formation of the desert pavement, fluvial erosion had a strong impact on the stabilized sand ramps. Concentrated run-off cut off the sand ramps from the bedrock slopes almost everywhere, creating ravines between the inselberg flanks and the ramps, and only preserving narrow connections at the apexes of the ramps. The channels were cut into the sand ramp sediments along the entire flanks and drained to the surrounding footplains. In situations especially favourable for run-off concentration, single sand ramps or sand ramp complexes were dissected. Dissection must have occurred without transport of slope debris from the bedrock slopes, as there is no significant presence of coarse material on the channel floors. The little debris there is – fragments up to 15 cm in diameter – is likely to have originated from the desert pavement. In the channels of the low-angle ramps the transport capacity was not sufficient to wash the debris onto the surrounding plain. This was possible, though, in the channels of the high-angle ramps.

Once only an initial gully had been cut along the line of contact with the bedrock slope, erosion is likely to have been rapid in the weakly consolidated mixture of dune sand and fine-grained debris. A few catastrophic high-intensity rainfalls may have been sufficient. Consequently, there may not have been a general change of climatic conditions, unlike that for the period of desert pavement formation. On the other hand: this dissection affected *all* of the sand ramps in the region, which may suggest an increasingly unstable environment due to a changing climate.

The exceptional character of this dissection in terms of high impact and short-term occurrence is emphasized by the retrograde filling of the channels that followed it, indicating decreasing fluvial activity. Only for a single ravine in the Sandkop sand ramp two distinct phases of erosion are documented. Ever since, the blocking of the channels has prevented any further sediment transport to the foreland.

E) Aeolian overprint

a) Recent sands

1. Deflation and transport of aeolian sand – dry conditions – strong winds
2. Weak pedogenesis – stabilization – vegetation – low intensity rainfall
3. Slight deflation – higher wind speeds

1. Some unknown time after the dissection phase, aeolian sands were deposited on the upper parts of the sand ramps, above their apexes and along the rampward flanks of some ravines. There is no evidence of any significant fluvial reworking of them, in full contrast to the underlying sand ramp material. Arid conditions favoured deflation and aeolian transport. The high content of coarse sand (up to 10%) and a dominance of medium-sized sand (around 50%) bear witness to very strong winds. Climatologically this implies a movement "back" to more intensive glacial conditions in the high latitudes, resulting in less tropical influence and thus less convective rainfall. Aridity may have been supported by marine conditions (intensive upwelling of the Benguela Current). As there are no signs of frost-impact, the thermal change is suggested to have been less distinct than at the time of the initial sand ramp building, i.e. it must have been warmer. In correlation with dated sands from the Aus sand ramp (chap. 7.1), it can be stated that the recent sands were deposited in connection with the Last Glacial Maximum (according to the OSL dates around 16,000 BP).

2. After deposition the dune sands that have been called "recent" were stabilized by a slight pedogenic overprint. Bioturbation related to a vegetation cover destroyed the aeolian layering. The climatic conditions may thus have provided more and also more evenly distributed humidity than during the time of their accumulation, implying a stronger tropical influence. The stabilization is thus suggested to have occurred during the Holocene Climate Optimum.

3. After stabilization, the aeolian sands in wind-exposed positions were deflated or became strewn with grus particles in places where coarse material was nearby, indicative of somewhat higher peak wind speeds than today.

b) Modern sands

Deposition and reworking of aeolian sands – present-day climate

The cover of modern sands is even less than the cover of recent sands. Partly made up of reworked recent sands, they occur as ripples, nabkhas, low dune crests and small echo-dunes in front of major blocks and along some ravines. They are more stable than one would expect from pure dune sand due to a content of fines around 2%, either inherited from the recent sands, carried piggyback with the sand grains during accumulation (cf. LINDÉ & MYCIELSKA-DOWGIALLO, 1980) or infiltrated after dust storms. Although the present aeolian activity is moderate, being basically limited to processes like shifting dune crests with the prevailing winds, limited transport and deposition of aeolian sand may well occur, especially when flooding has reworked surfaces normally protected by desert pavement. The modern sands are thus in equilibrium with the present-day climate and morphodynamics.

6.2 Morphodynamics past and present

The different stages of sand ramp development indicate changing environmental conditions over time. Fig. 80 schematically illustrates the intensity of fluvial and aeolian activity and of soil formation during this development. Note that neither intensity nor duration of the different periods are to scale. Compared to the present climate and geomorphic processes, conditions in the past had a stronger morphodynamic effect. It should be recalled, though, that impacts caused by extreme events often leave impressive traces in the landscape easily detected even after a long time, unlike the comparatively weak impact of "average" conditions. There is no doubt, however, that the intensity of fluvial and aeolian activity during the initial deposition of the sand ramp sediments, for instance, was significantly higher than today. Reconstructing past environmental conditions always entails an increase in resolution towards the present, due to the increasingly better preservation of even small traces in the landform and sedimentary record. Therefore it is almost certain that the several phases of sand ramp formation identified do not represent all the changes in morphodynamics that actually occurred. Enough has been preserved, though, to indicate that different shifts of climate resulted in different morphodynamic changes.

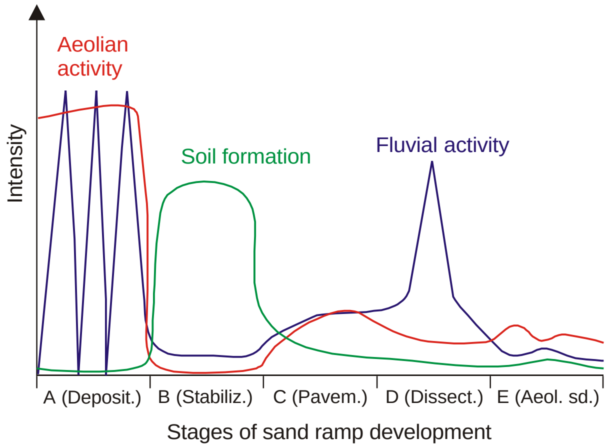


Fig. 80: Schematic representation of the intensity of fluvial and aeolian activity and of soil formation during sand ramp development as recorded by the sand ramp sediments.

6.3 Origin of the sands

Presently, aeolian transport of sand is low in the study region proper. This is due to the desert pavement protecting almost all fine-grained sediment from deflation, but also to winds not strong enough to mobilize the available sand, for example in the dry riverbeds or in the adjacent easternmost part of the Namib Erg. During sand ramp formation conditions for aeolian sand transport were much more favourable. The palaeoclimatic conditions have been discussed above. The present chapter will focus on the probable sources of the sand.

As all major ramps are located on mountain slopes facing north, north-east and east, the sand is suggested to have originated from those directions (cf. chap. 5.2). Availability of sand required either conditions favourable for sand production in the vicinity or for (long-distance) transport of sand from areas with higher availability. Presently, there is no obvious, major source of sand upwind of the Jagpan Mts. In the plains of the study region proper, however, fine-grained material is frequent – protected by a desert pavement, though. Mobilization of the sand must thus has been an important factor.

Production of sand would have implied effective weathering processes prior to or simultaneously to sand ramp formation. As mentioned above, the bedrock of the Namaqua Metamorphic Complex within the study region proper and also north and north-east of it, in the basin of Helmeringhausen, has been subject to ancient chemical deep weathering. The Nama sediments overlying them on the plateau surface of the Great Escarpment are partly sandstones and thus another possible source (cf. chap. 2.2). Thus, the geological prerequisites would have been fulfilled. In the preceding chapter low-frequency, but high-intensity rainfalls have been assumed for the time of sand ramp deposition; during those events fragments of the disintegrated bedrock will have been washed off, resulting in riverbeds with much sandy sediment that could easily be blown out. These events could also have initiated mobilization of sandy deposits already present at that time. On farm Tiras, for instance, relics of old, reddish soils are found (Figs. 81 & 82), and along the Neisip river an up to 8 m high terrace is cut into a reddish, sandy to grussy colluvium (containing coarse layers of slope debris up to a size of 15 cm in the lower half). Middle Stone Age artefacts estimated to be older than 40,000 years (VOGELSANG 1998) on the relict soil and within the terrace, 200 cm below the present surface (artefacts identified by D. NOLI), bear witness to availability and fluvial transport of fine-grained material for at least the last 40,000 years.


Figs. 81 & 82: Surface and profile of a relict soil on Tiras.

The distance from the Sandkop Mts. to the rim of the Great Escarpment is only about 10 km, and presently there are only small runnels present in the area between the two of them. Therefore one might assume that the aeolian part of the sand ramp sediments originated at least partly from riverbeds with more sandy sediment cut into the plateau surface. Evidence for sand transport from north-easterly and easterly directions is indeed found on the plateau surface of the Great Escarpment. Both ancient and recent to modern wind-scouring (as described in chap. 5.1) was found on the scarp-forming quartzite and the black limestone of the plateau, as well as on the biotite gneiss outcrops directly at the foot of the Great Escarpment on farm Sandkop. The oldest wind scour found there may be even older than the sand ramps as these forms have often been cracked. This may have happened simultaneously to production of slope debris prior to sand ramp formation. On the other hand, they are unequivocal evidence that scouring sand at some time must have been blown over the plateau and down to its foot by north-east and east winds. The younger wind scour indicates the same wind direction as the older forms: north-east. Further evidence for sand transport over the escarpment is found in small patches of two types of fine-grained material deposits in protected positions, such as behind large blocks on the plateau surface. The one is slightly consolidated and appears to be a relict soil, its colour varying from redbrown on quartzite and brownish on shales. The second sediment is aeolian sand, less consolidated than the soil. In places this sand overlies the older soil.

In spite of the evidence for sand transport across the plateau surface and to the foreland, sand input to the sand ramps from the river valleys incised into the plateau may be neglected. The aeolian part of the sand ramp sediments is poorly sorted, subangular and with a high amount of feldspar grains. Furthermore, the sand ramp sediments are rich in coarse sand, which at least partly is assumed to have been moved by aeolian processes (cf. chap. 5.1). These characteristics neither speak for long-distance transport nor for the weathering product of quartzitic sandstones as a source, although the rivers are partly cut into the chemically weathered Precambrian bedrock even on the plateau.

Long-distance transport also would not explain why sand ramps only occur on the flanks of some of the inselbergs. Why are they not found on every north-east-facing slope, and in the Tiras basin in particular, where the high mountains might have trapped any sand coming from these directions? One answer may be highly local sand mobilization, another simply the size of the inselbergs. Both Sandkop and the Jagpan Mts. are relatively low and small mountains compared to the Tiras and Neisip Mts.; the Jagpan Mts., for instance, are about 600 m lower than the Tiras Mts. Consequently, the slope length and thereby the catchment area of the latter is larger, having resulted in higher amounts of rainfall inducing more slope wash, washing down the aeolian sand completely. This would explain the extensive, but shallow ramps in the Tiras basin, consisting of sand and grus, the latter of which being supplied in high amounts from the deeply weathered Tiras granite.

Regardless of easily disintegrating bedrock and the availability of sand from the streambeds close to the sand ramps, there is also the easternmost outlier of the Namib Sand Sea as another possible source; at least some of the sand may have come from it. Evidence for disturbance of the erg comes from the dune pattern of the erg itself. As the satellite image reveals (Fig. 5, p. 9), the erg consists of a core of older sand dunes with pronounced signs of erosion (that intensive that determination of the former dune type is impossible), fringed by elongated sand dunes which appear much less worn arranged around that core, especially at the eastern and north-eastern rim (cf. Figs. 83, 84). The rim of the outlier is clearly erosional. This is particularly obvious along the southern rim, which has been eroded by the Koichab river. Dune pattern and erosional rims thus bear witness to a strong fluvial and aeolian impact onto the dune area. Large amounts of sand may thus have been available during environmental conditions favouring sand mobilization. These processes may well have occurred several times, regarding the core probably also prior to sand ramp formation.

Fig. 83 (l.): Denudated and partly vegetated dunes in the erg.
Fig. 84 (r.): Elongated dunes around the core of the erg, farm Excelsior.

Surely the erg is located downwind of Sandkop and the Jagpan Mts., but this regards only the wind direction indicated by sand ramp deposits and wind scour. Evidence for westerly or south-westerly winds in the study region may be the longitudinal dunes east of the erg; however, south-westerly winds are dominant in terms of frequency today. If somewhat higher wind speeds are assumed, deflation of aeolian sand should not have been impossible. Furthermore, the transport path may not necessarily have been a direct one from the erg to the sand ramps; interim storages may have existed. On the other hand, not even remnants of aeolian sand are preserved in south-westerly positions; the sand ramps on the south-western flanks of the Jagpan Mts., for instance, may be expected to be more voluminous. However, in the Konkiep river valley, situated about 50 km east in front of the Schwarzrand Escarpment, there are steep sand bodies closely resembling slightly eroded climbing dunes or possibly sand ramps in western expositions (identification was only possible from the official roads, excluding detailed investigations), obviously blown out from the riverbed rich in sand.

The elongated dunes around the core show the same sediment characteristics – size, sorting, shape and mineral composition, including a slight pedogenic overprint indicated by a discernible content of fines – as the recent sands on top of the sand ramps; furthermore, calcrete nodules like the ones occurring on sand ramp B are also found in interdune localities where the older sand surface is exposed. This may imply the same origin and age of the elongated dunes and the recent sands. The supplier of this sand may have been the erg, as such comparably well-sorted sands are not found anywhere else in the study region. The lesser extent of recent sands on Sandkop as compared to the Jagpan Mts. may constitute an additional argument for the erg as sand source, as Sandkop is farther away from it and located in an disadvantageous position east-south-east of the (present) erg. Another point may be that there is no evidence of any significant fluvial reworking of the recent sands which may imply less fluvial activity during the time of their deposition. The dune sands of the erg may thus have been easier to mobilize than, for instance, relict soils or disintegrated bedrock.

In summary it can be stated that the aeolian sands incorporated into the sand ramp sediments probably were of local origin. Fluvial activity triggered sand mobilization wherever it was available: on the disintegrating bedrock and on the plains, in the riverbeds and – possibly – within the erg.

A study of the geochemistry of sand ramp sediments in the Mojave Desert by PEASE & TCHAKERIAN (2003) supports the idea of a local origin. Their examination of trace elements (La, Cr, Co, Th, Sc, Rb, Sr, Ba) disproved the theory of long-distance sand transport through extensive wind corridors, and they came to the conclusion that "discrete, local sources [...] supply the bulk of sediments deposited in individual sand ramps". Surely, the Mojave Desert is not the Namib, but this is the only study reference can be made to.

7 THE OLD SAND RAMP NEAR AUS

The largest, oldest and most diversified sand ramp of those studied is located about 15 km west of the town of Aus and borders the Restricted Diamond Area (position of the ramp S 26°40.500' E 016°05.700') (cf. Fig. 4, p. 8; Figs. 85 – 87). According to the topographical maps, the sand ramp is part of the farm Heinrichsfelde; the abbreviation for the site localities is AW, however, as the farmers of Klein Aus and Ausweiche already owned the western part of Heinrichsfelde at the beginning of the field work.

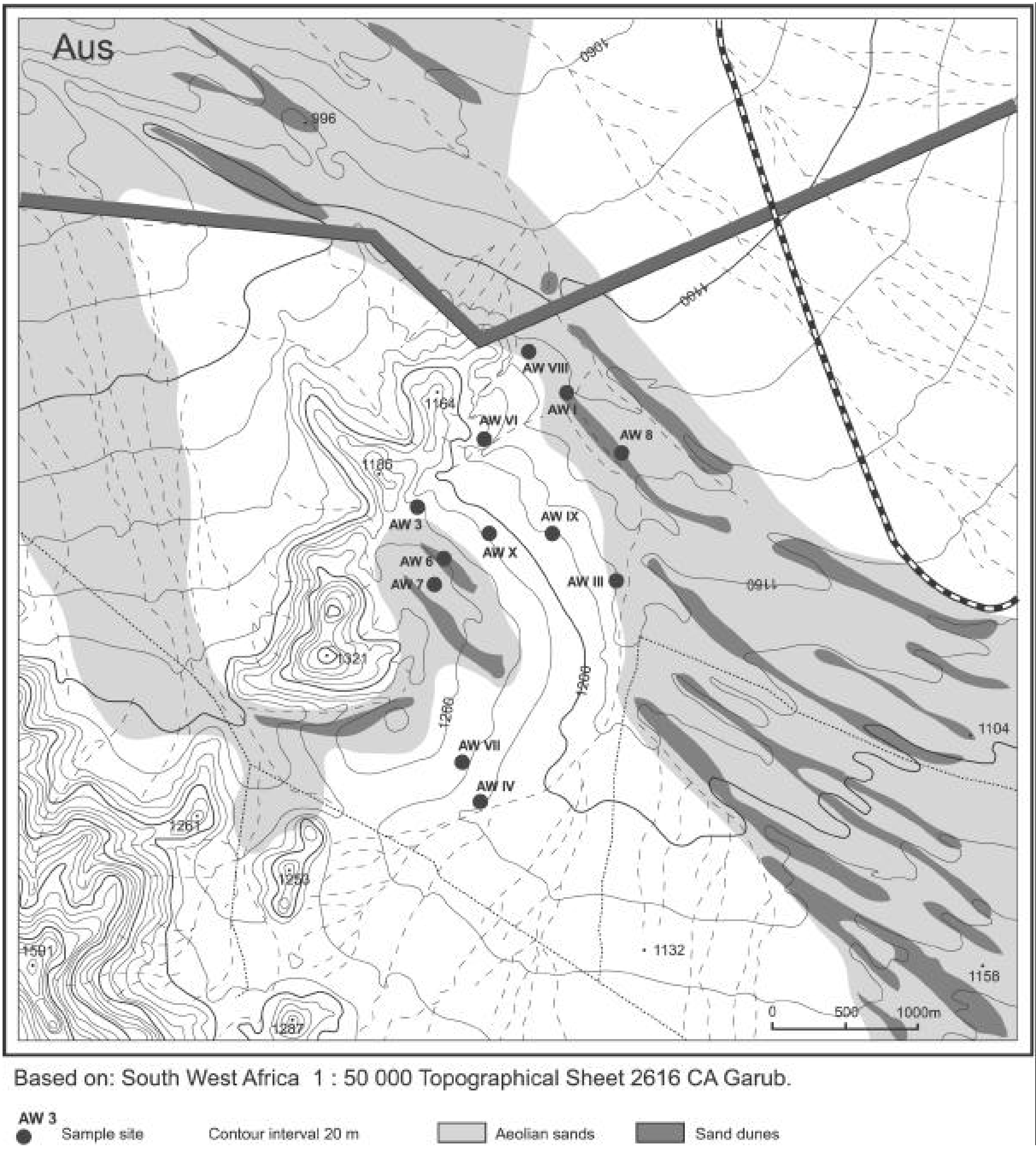


Fig. 85: Topographical map of the Aus sand ramp and its surroundings.

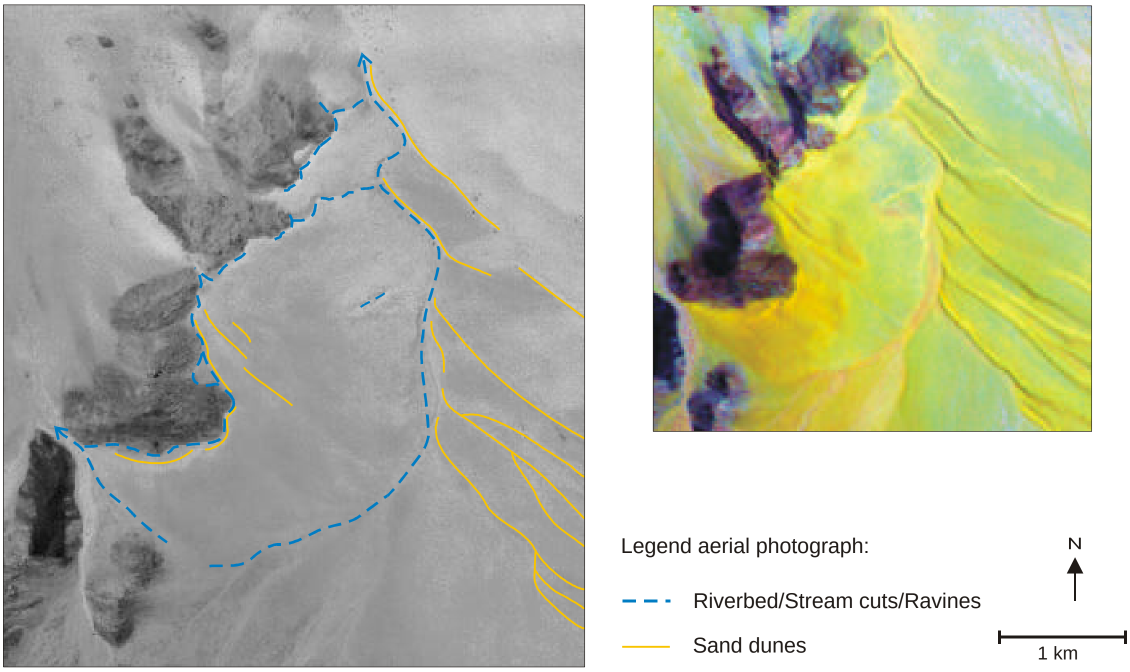


Fig. 86: Air photo and satellite image (Landsat 5 TM, bds. 742) of the Aus sand ramp.

Fig. 87: Overview of the Aus sand ramp, ® W.

The sand ramp accumulated on the eastern slope of an inselberg complex consisting mainly of aluminous gneiss, with some biotite granite gneiss and amphibolite. All lithological units are part of the Proterozoic Namaqua Metamorphic Complex (GEOLOGICAL SURVEY OF NAMIBIA 1999, JACKSON 1976). The southern part of the complex, its axis oriented north – south, is up to 1,300 m a.s.l. high, the northern mountains, running north-east – south-west, are somewhat lower, with peaks at 1,185 m and 1,164 m. As there is no sand ramp on the western side, there the bare bedrock flanks steeply rise from the foreland at about 1,060 – 1,080 m.

At the eastern flank of the southern inselberg the sand ramp has its highest point, reaching up to 1,200 m a.s.l. In absolute figures, the ramp is 120 m high and (E – W) about 2,000 m long in ground plan. It spreads over almost 4 km from north to south, delimited by a (dry) riverbed against its eastern foreland (cf. Figs. 85 & 86). In its southern part, the foreland is characterized by a gently northwards sloping (2.5°), dissected alluvial plain, while the northern part is covered by longitudinal dunes, oriented NW – SE to WNW – ESE. Dune sand is also found on the very top part of the sand ramp; the information on the geological map 1 : 250,000 describing the whole ramp as covered by dune sand is misleading.

Unlike the ramps on Excelsior and Sandkop, the Aus ramp has been deeply dissected in parts, so that vertical walls along the channels expose its interior. Where the toe of the sand ramp has been undercut by the streambed presently delineating, the exposures in the northern part are 6 – 10 m high, those to the south still 2 – 3 m (Fig. 88). Even more significant for understanding the ramp structure are several walls in downslope direction along incised stream beds oriented SW – NE (cf. Fig. 89). Up to 12 m of sediments are exposed in these cuts. In the aerial photograph (Fig. 86) a third incised channel appears in the north-central part of the ramp, which does not continue to the subsequent streambed anymore (the "incomplete cut"). Like the other ramps, the Aus ramp has also largely been cut off from the bedrock slope. Similar to the other ramps, the separation area has also partly been covered by younger aeolian sands. Fortunately in some of the ravines this young cover is incomplete, so that the sand ramp sediments are exposed there as well.

Fig. 88 (l.): Naturally exposed sediments at the toe of the Aus sand ramp.
Fig. 89 (r.): Southern incised channel.

Three units of the sand ramp can be distinguished on morphological and sedimentological grounds: 1) Longitudinal dunes resting on the upper slope; 2) sand ramp material comparable to that of Sandkop and Excelsior, forming the main body; and 3) underlying it and exposed in the channels walls, a sequence of sediments quite different from those of (2). The three units will be described and discussed below, from young to old. Fig. 90 shows a longitudinal slope profile of the Aus sand ramp with the three units indicated.

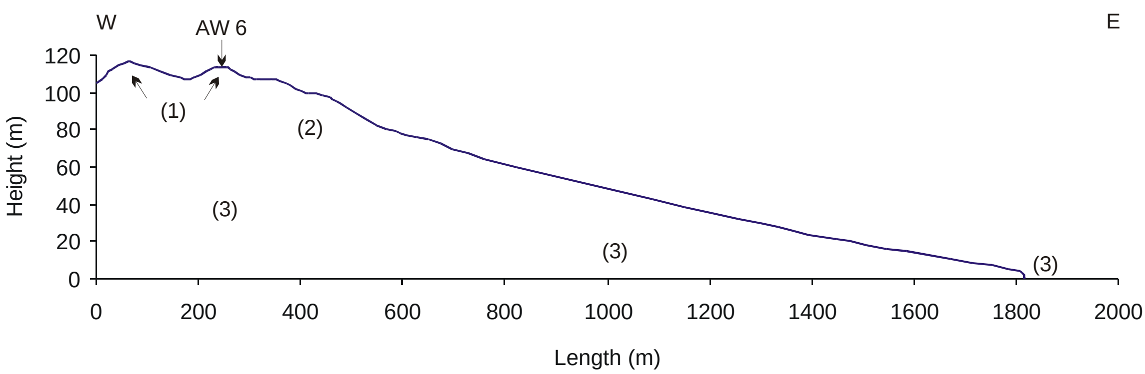


Fig. 90: Idealized slope profile of the Aus sand ramp. Site AW 6 for orientation. (1) Dunes on upper slope, (2) sand ramp material forming the main body, (3) underlying core sediments.

7.1 Sand dunes on the upper slope

On the topographical map 1 : 50,000 (cf. Fig. 85), a relatively large part of the sand ramp has been given the signature of (aeolian) sands and dunes. In fact, dune sand only exists along the rampward rims of the ravines, and in two bodies resembling longitudinal dunes that rest on the upper part of the ramp (cf. Fig. 90), oriented approximately NW – SE, with fresh ripples and occasional tussocks of *Stipagrostis sabulicola*. Further down the ramp there are three more similar, though smaller bodies. The sediment between those ridges is typical sand ramp material (see below).

The dune sands could be sampled, by digging and coring, on the highest point of the second dune, 9 m above the "interdune area" of the sand ramp, to a depth of almost 300 cm (site AW 6). Only the uppermost 10 cm show slight aeolian layering. Underneath the section is uniform, without any sedimentary structure, its colour an intensive yellowish red (5YR 5/8) and has thus obviously been subject to soil forming processes. Fig. 91 presents the grain-size composition for three samples at depths 1 – 5, 75 – 90, and 225 – 235 cm. The curves are similar, and there is no obvious vertical trend. The main difference is the coarse fraction. The middle sample, AW 6:5, with 24%, has the highest proportion, double that of AW 6:8, and also contains some grus particles > 2 mm (< 1% of the whole sample). But there is also the highest content of clay and silt in that sample, although the variance within the profile is only small, ranging from 4 – 6%. This 75 – 90 cm sample – like the sand above at 35 to 50 cm – still had retained some moisture from the last rains a few weeks ago, maybe due to its higher content of fines as compared to the more sandy layers above. Evaporation depth or infiltration speed may also explain the occurrence of moisture in just this depth.

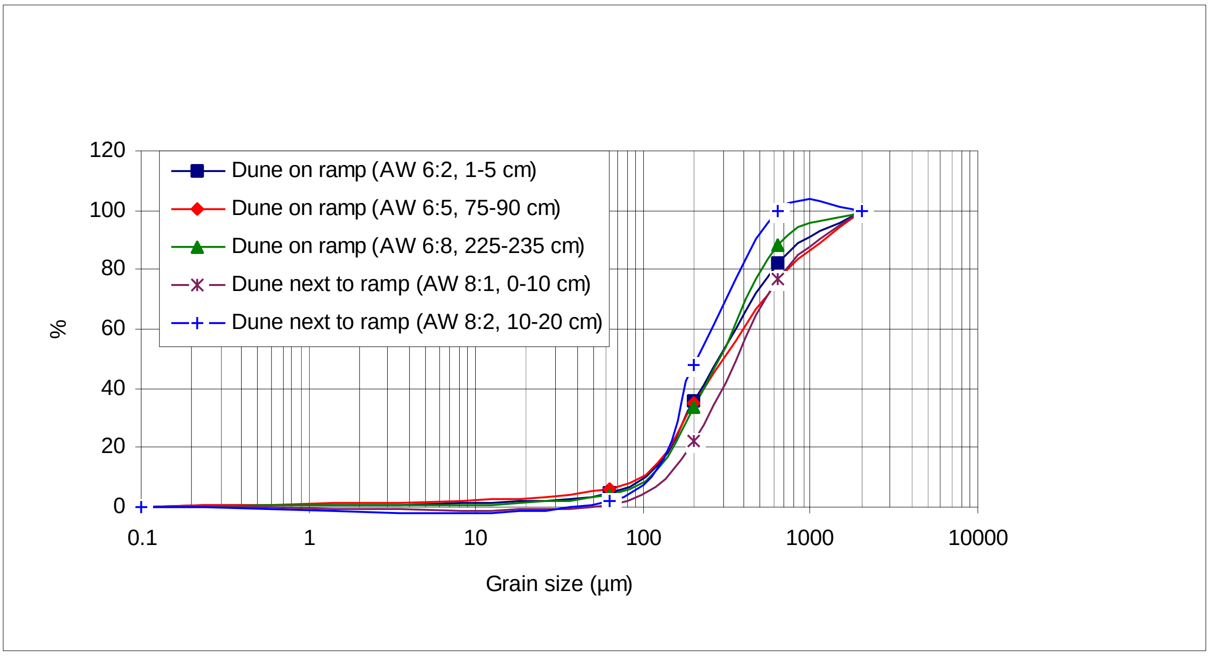


Fig. 91: Grain-size composition of dune sediments on top of and next to the Aus sand ramp.

The coarse sand is mostly subrounded, while the medium-sized sand is subangular to subrounded. Grains from both fractions show thin coatings of iron oxide, most intensively in cracks or pits, probably constituting remains of an earlier, more complete cover only preserved in protected positions. Compared to samples from other sediments of the sand ramp, the sorting within the single sand fractions is relatively good; in absolute terms, the sorting can only be classified as moderate, though.

The grain-size distribution of section AW 6 is not that of a typical dune sediment: the sorting is comparatively bad and the coarse and very fine grain-size fractions are quite high. The content of fines may best be explained by soil formation and bioturbation and thus a certain age (i.e. not modern) of the sediments. The upper 10 cm of the profile may either be the result of recent aeolian reworking or some renewed wind-blown deposition.

Not only the aspect of the sediment, but also the rounded shape of the sand body – there is no crest at all – and the grass on its lower flanks suggest that accumulation took place well before the present. Luminescence dating (OSL) from a sample at 280 cm yielded an age of c. 16,000 years BP (16.8 ± 1.5 ka for the quartz, 15.0 ± 1.1 ka for the feldspar; cf. App. I) for the time of the sand's last exposition to the sunlight, which is equivalent to the date of deposition.

The old age may explain the fines, but not the high content of coarse sand in an accumulation formed like a dune. Deflation would explain the concentration of coarse sand in layers, but not throughout the whole section. Much higher wind speeds than today are a more realistic option, strong enough to even transport quartz grains of a size around 2 mm over the higher parts of the sand ramp.

A third option would be that the original deposition on the sand ramp was fluvial. After some stabilization, part of the deposit would have been eroded, just leaving the two ridges, which then would have been subjected to aeolian overprinting. Fluvial erosion would have had to occur before the ramp got cut off from the bedrock slopes; only high-intensity rains are suggested to have induced the cut off of the ramp, but there is no sign of such a fluvial impact on the ridges, though. Assuming more or less the same shape of the sand ramp as today, water would also have had to flow parallel to the contour lines. As there is also no dissection or depositional area downslope of the ridges that might be attributed to such an event, formation of the ridges by fluvial erosion has to be ruled out.

Aeolian erosion is are also difficult to argue for; the sediments of the present-day ridges would have had to be more wind-resistant than their surroundings, but there is no evidence for differentiated stabilization.

Weighing all the options, the ridges must have been deposited as true sand dunes, though by much stronger winds than today. The material properties suggest a very local source for at least the coarse sand.

As mentioned above, similar dunes are present in the immediate foreland of the ramp. For comparison, a pit 40 cm deep (AW 8) was dug in the crest of the highest dune, next to the riverbed fringing the sand ramp (cf. Fig. 86). These foreland dunes are similar in shape to those on the sand ramp. There are no sharp crests, but rounded tops; wind ripples indicate some present aeolian activity (Fig. 92). There is also some vegetation growth on them, with small bushes on the steeper south-western flank and tussock-like grasses (probably *Stipagrostis sabulicola* – dry and therefore difficult to identify) on the more gentle north-eastern slopes, with a transition to a smaller, but more closely spaced *Stipagrostis* variety in the interdune areas.

Fig. 92: Overview of the first dune next to the sand ramp (® NNW).

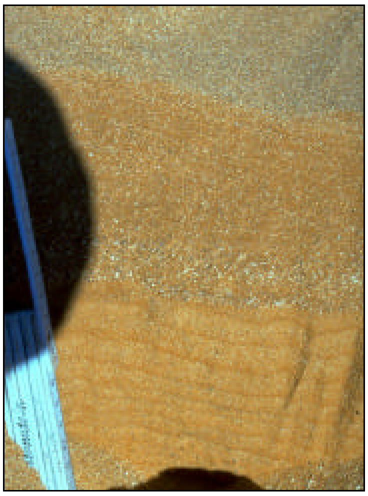


Fig. 93 (l.): Upper 20 cm of section AW 8 on top of the dune.
Fig. 94 (r.): 10 – 30 cm of section AW 8. Note the stability of the fine-grained layers.

Fig. 93 illustrates the upper 20 cm of section AW 8. The surface is deflated, with a pavement of coarser grains. Down to 10 cm (sample AW 8:1), weak aeolian layering is visible. The photograph clearly shows the high amount of mainly subrounded coarse sand (> 20%; for grain-size composition see Fig. 91); especially from 7 – 10 cm its content is noticeable. The uppermost centimetre is unconsolidated trickling sand; down to 10 cm the stability increases. At 10 cm there is an obvious break. The sand below (sample AW 8:2) is even more stable, consisting of medium- and fine-grained sand only, subangular to subrounded and better sorted than the medium sand fraction of AW 8:1, and there is no more bedding, but some banding. Its grain-size composition perfectly fits with the grain-size curve of a longitudinal dune sampled north in the study region (TL 22b, cf. App. II). The grains are partly coated by red iron oxide, especially preserved in small pits of their surface.

The banding within this horizon, at first glance to be mistaken for aeolian layering, deserves attention. Comparison with Fig. 67 (aeolian layering on Sandkop) reveals obvious differences. The layers are thicker and slightly more irregular than one would expect from a wind-blown layer, and the bands, of which there are about 25, are slightly more firm and more fine-grained (Fig. 94). For the whole banded horizon this translates into 2% of fines, as compared to 1% for the uppermost horizon. All this is evidence of a relict soil, resembling the weakly developed lower part of a banded grey-brown podsolic soil (*Bänderparabraunerde, cf.* AG BODEN 1994, p. 192), found in sandy substrates in Central Europe, but also described as a relict soil for the central Sahara (cf. BUSCHE 1998, p. 270). The fine-grained bands are more closely spaced downwards and can be identified down to a depth of 24 cm. Below 20 cm, layers of coarse sand appear again, but the sand between these layers is much finer and better sorted than in the uppermost 10 cm. Beneath the zone of banding, aeolian layering is visible again. It can no longer be determined whether there is an unconformity at 20 cm. If not, this would indicate that deposition of coarse sand ceased towards the end of the accumulation period.

For the uppermost 40 cm alone, the different layers indicate deposition under three different wind speeds from strong winds, corresponding to the sand below 20 cm, to moderate winds, responsible for the fine-grained and layered sediments at 10 – 20 cm, to very strong winds able to transport considerable amounts of coarse sand grains up to 2 mm. Prior to the last period of very strong winds, soil formation occurred, followed by erosion removing the A- and perhaps also part of the B-horizon of the soil profile.

Like on the dunes on the ramp, the upper 10 cm layer indicates extremely strong winds during its deposition. In both locations, there have been soil formation, reshaping of the dune cross profile and erosion of part of the profile. Different depths of removal or different locations within the soil catena may account for the different content of fines, 4 – 6% for the dune on the ramp as to merely 2% of the foreland dune. Varying pore sizes due to sorting and grain-size composition may also have contributed to the difference.

7.2 Sand ramp body sediments

The sediments of the Aus sand ramp underlying the dunes and forming the main body of the ramp are quite similar to those of the Jagpan Mts. and Sandkop. Four sections on the Aus sand ramp were analyzed in detail. Although there are certain differences in grain-size composition (Fig. 95), the variations are small enough to describe them as the same type of sediment. Everywhere a desert pavement of coarse sand and grus characterizes the surface of the ramp; and there is slope debris close to the bedrock slope, in particular where the ramp is still connected to the inselberg slope. Vegetation cover is also identical all over the ramp, dominantly comprising the grasses *Stipagrostis obtusa* and *S. ciliata*, but especially after winter rains also chamaephytes and herbs (mainly Asteraceae and Liliaceae), as well as small leaf-succulent plants (e.g. *Mesembryanthemum barclyi*). The ramp has largely been cut off from the bedrock slope, and where there still is contact, the line is well defined. Only in the northern part of the ramp, between the two stream cuts, the contact is overlain by recent and modern aeolian sands, creating a smooth transition between the sand ramp and the mountain.

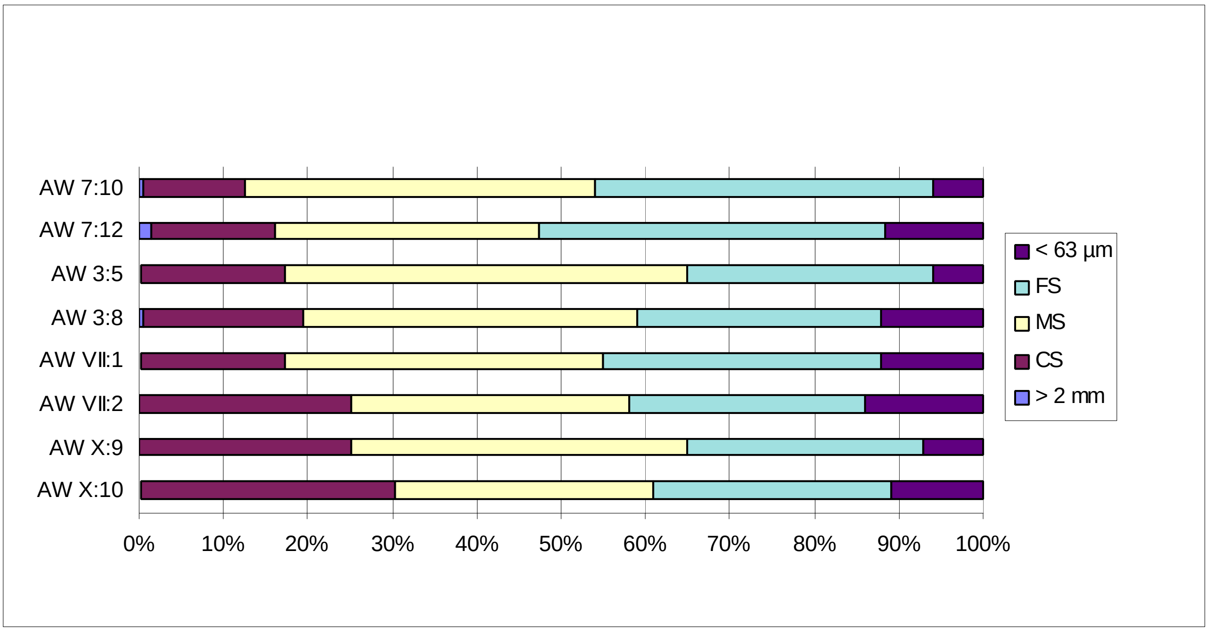


Fig. 95: Grain-size distribution for four sections in sediments of the main body of the Aus sand ramp. (Sample depths (cm): 7:10 1-5, 7:12 35-50; 3:5 1-5, 3:8 50-60; VII:1 10-20, VII:2 40-50; X:9 1-10, X:10 40-50.)

Fig. 96: Typical section of sand ramp sediments of the main body (site AW X). (Munsell chart 7.5YR for colour reference.)

Fig. 96 shows a typical section (AW X) of the sand ramp sediment. The walls of the pits dug for obtaining the sections are always stable; only the upper 5 – 10 cm may be somewhat less consolidated. The sediment is homogeneous, of a reddish yellow/yellowish red colour (7.5YR 5/6 /5YR 5/8; natural/artificial light) and well penetrated by fine roots. The content of clay and silt increases downwards from ~ 6 to ~ 12%, indicative of soil formation. Pedologically, the sediment is a weakly developed Regosol. The sand grains are coated by iron oxides, most intensely in small pits and cracks. The coarse sand fraction is mainly subrounded, the medium-sized from subangular to subrounded. Sorting is moderate in all.

Compared to the sand ramp sediments from Excelsior and Sandkop, there are some differences. The amount of fines is higher (a mean of 10.5 vs. 4.5%), as is that of medium-sized and coarse sand. The sediment is also less well sorted at Aus. As for coarseness this suggests stronger runoff, and the higher amount of fines may be due to more intensive soil formation. The almost complete absence of grus particles (> 2 mm) may be due to the fact that the prevailing aluminous gneiss at Aus only weathered to particles smaller than grus. For Sandkop, the low content of grus, as compared to the Jagpan Mts., has been attributed to the fact that the sand ramp extended high up the bedrock slope during certain deposition phases, leaving only a small area of mountain slope for supplying slope wash (cf. chap. 5.3). This explanation would not work for Aus, though, unless the original ramp had been almost twice as high as today, for which there is no evidence.

7.3 Basal sediments

As described in the introduction to this chapter, the sediments underlying the main body of the Excelsior/Sandkop-style sand ramp have been exposed by erosion in walls at the foot of the ramp and along stream cuts. They are of a different character and a more diverse nature than all sediments presented so far. They will be described from several sites in the following order: 1. Sites at or near the bedrock slopes (AW VI and VIII); 2. sites along the riverbed following the foot of the ramp (AW I, III, IV and AW IX in the "incomplete cut" (cf. introduction of this chap.)).

7.3.1 Sediments at or near the bedrock slopes

Site AW VI

The two stream cuts in the northern part of the sand ramp are a continuation of ravines separating the ramp from the mountain slopes. In the southern channel, at about 1,080 m a.s.l., fluvial erosion has exposed a near-vertical wall, oriented roughly parallel to the stream cut, 12 m high and of firmly cemented sand ramp sediments (AW VI, cf. Fig. 85). Fig. 97 gives an overview of this site, looking NNW. The bedrock slope is to the left, where the sand ramp is partly cut off, thus permitting direct access to the sediments of the "contact zone", as the ravine is not buried by younger aeolian sediments there. In Fig. 98, this ravine is seen from above, looking SSE, with the sand ramp to the left and the mountain slope to the right. (Site AW VI is "down the ravine and left around the corner", facing the same direction as the viewer.) This photo also clearly illustrates that the original extent of the sand ramp sediments must have been much larger, even if only the present top of the sediments is taken. Before all the erosion took place, they must have covered the entire part of the slope pictured. Remnants of consolidated sand ramp material are found at the inselberg slope, although dominantly in the lower part, where the ramp is cut off. The centre of the photo shows that fluvial erosion not only formed a simple stream-cut, but shaped the whole flank of the main ramp looked at. The dissection occurred in three phases, subsequently narrowing down from an initial broad riverbed about 200 m wide to the present box-shaped stream bed.

Fig. 97: Overview of site AW VI (® NNW).

Fig. 98: Ravine behind AW VI (® SSE).

In the contact zone at the "back" of site AW VI, sand ramp sediments and slope debris (up to boulder size) are intensively mixed and strongly consolidated. About the lowest metre is intensively calcified (Fig. 99). Both the debris and the neighbouring bedrock are laminated with $CaCO_3$ in most places. Higher up the wall, the sediments consist of a sandy to gritty matrix, tightly interspersed with layers of coarse slope debris (angular to subangular grus, gravel and stones up to a size of c. 15 cm) (Fig. 100). These layers are mostly irregular and are difficult to trace for more than half a metre. The top 20 cm contain a distinctly higher amount of larger debris than the underlying sediments, either indicating concentration of coarse material by selective removal of fines or a single(?) phase of strong slope wash towards the end of the deposition cycle.

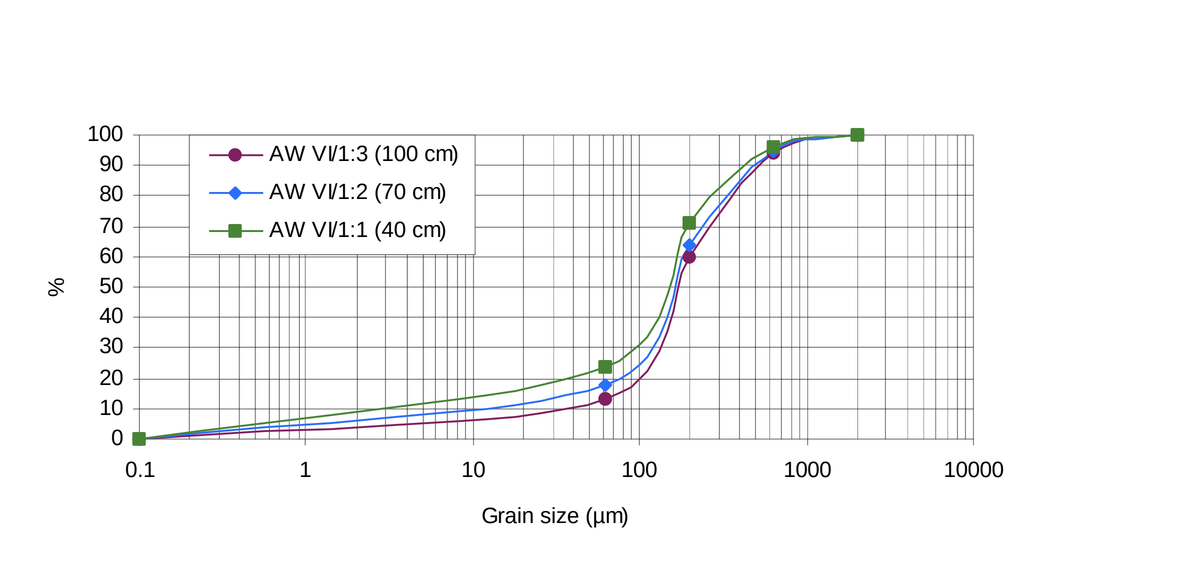
Fig. 99 (l.): Contact zone between sand ramp sediments and slope debris, $CaCO_3$-cemented.
Fig. 100 (r.): Coarse sediments in the ravine along the contact zone.

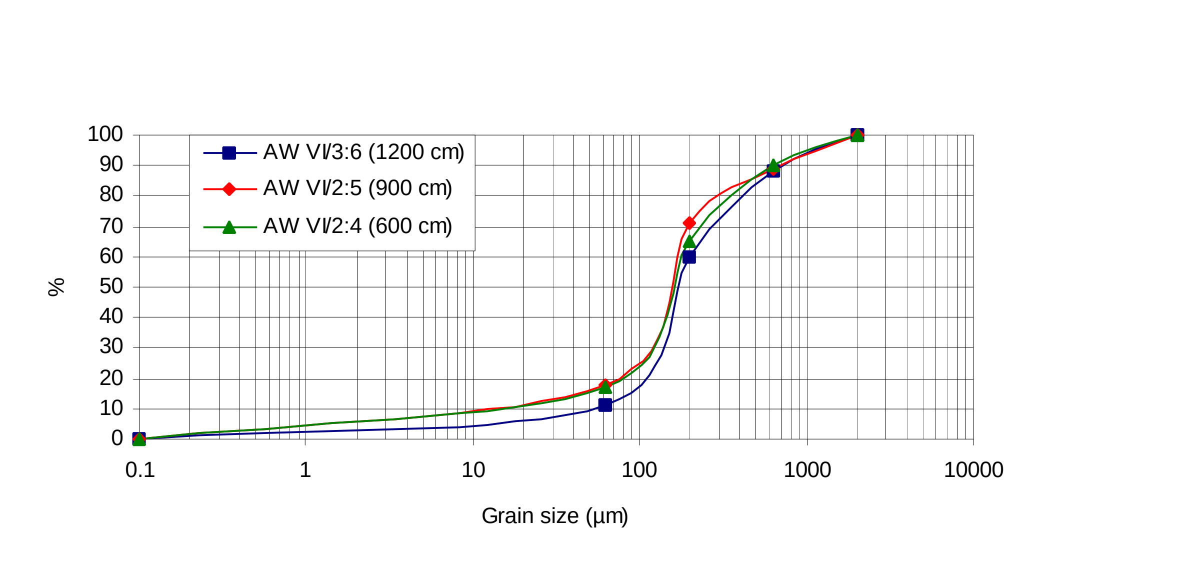
Fig. 101: Typical sand ramp material at site AW VI (at c. 600 cm).

Around the corner (90°) the aspect is quite different. Here, at site AW VI, there are much less large particles than in the sediment exposed in the ravine. The size of the coarse material ranges from grus to gravel, mostly not larger than 1 – 3 cm (Fig. 101 shows the typical, uniform, yellowish red (5YR 5/8 – 4/8) sand ramp material dominating the upper 6 to 8 m); only close to the mountain slope larger stones are incorporated. Generally, the layers of coarse material are much less distinct and can only be followed when viewed from a distance. Only in the upper part of the wall a single zone with markedly more slope debris can be outlined (AW VI 2:5, see below; cf. Fig. 97). The bedding is more or less horizontal; therefore the ramp must have been larger during the phase of accumulation than today. It must not only have been higher and have covered a larger part of the inselberg as described above, but it must also have spread considerably much farther to the north-east. Following the present 1,090 m-contour line marking the top of the sediment, the depositional area of these horizontally bedded sediments must have had its eastern limit at the west side of the Aus Mts. (c. 9 km to NE, cf. Fig. 4), and northwards at the Eureka Mts., roughly 12 km away. The former western rim of the deposit cannot be defined at all, as the plain gently slopes towards the coast, without any topographic barrier that might have limited the extent of the sediments. Huge amounts of sediment must thus have been removed at some time.

Six samples from site AW VI were taken for analysis, which suggests the existence of two sediment complexes: The one is represented by samples 1:1, 1:2 and 1:3 (at 40, 70 and 100 cm from below), the other one by 2:4, 2:5 and 3:6 (at 600, 900 and 1200 cm – the "free face" in Fig. 97). As the middle part of the wall is not vertically exposed, it cannot be definitely determined where and how the two sediment types meet.

The grain-size curves of Fig. 102 all show similar courses, which suggests similar morphodynamics during their formation. The difference between the upper and lower sediments primarily shows in the coarse fractions; the proportion of coarse sand and the amount of material > 2 mm are markedly higher in the upper sediment. Characteristic for the lower sediments is a distinct fining-downwards, less well developed in the upper sediment.





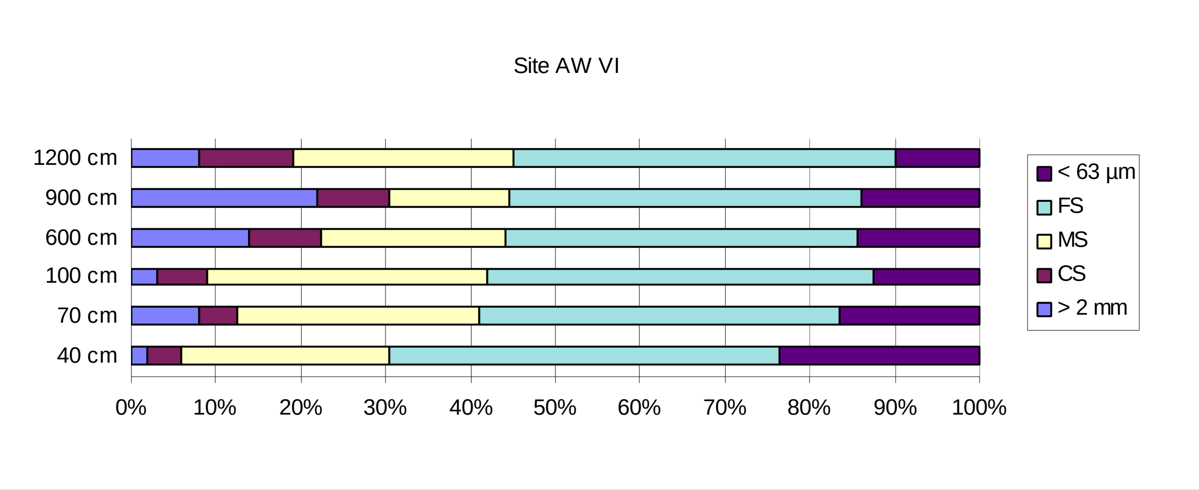


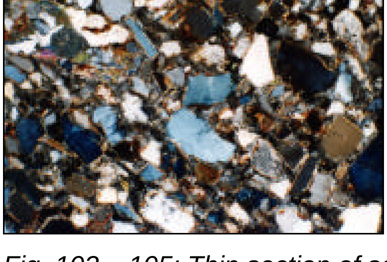
Fig. 102: Grain-size composition for site AW VI (depths from below).

In both sediment complexes there is a downward increase of organic matter as well as of calcium carbonate. $CaCO_3$ strongly cements all of the lower complex, whereas in the upper one cementation is present, but weaker and only visible in cracks and a low number of root casts (for microscopic analysis see below).

The grains of the coarse sand fraction throughout both sediments are very colourful, due to a mixed mineral composition of quartz, feldspar and other fragments, and angular to subangular in shape. The sorting is bad. The medium-sized sand varies in its characteristics between different samples. Generally, the fraction is moderately sorted and the grains are subangular; in sample AW VI/2:5 the sorting is bad and the shape angular to subangular. It also has the highest content of particles > 2 mm, suggesting higher fluvial activity during its deposition from a nearby source area. The grains in this layer are not coated, and neither is the medium-sized sand of the samples 1:1, 1:2 and 2:4. In sample 1:3 the grains show some coating, sample 3:6, near the surface, has the reddest particles, but even these are only partly covered by the iron oxide skins, dominantly preserved in pits.

Thin sections of the consolidated sediments reveal more about their inner structure. In samples 1:2, 1:3, 2:4 and 3:6 the grains are tightly packed and hardly any matrix is visible (Figs. 103 & 104). In sample 2:5 (the coarse one), the cementing agent clearly is $CaCO_3$, filling the pore spaces. The lowermost sample, 1:1, largely consists of calcium carbonate, which, during precipitation, displaced the host material and increased the distance between the particles (Fig. 105). The texture of the matrix is mainly micritic (very fine-grained, single crystals not to distinguish), especially so where in contact with the host particles, and partly microsparitic (small crystals visible). Quartz is the dominant mineral, but also feldspar, biotite, and some heavy minerals (e.g. garnet, zircon, hornblende, epidote) are present. A number of particles show signs of intensive weathering, such as irregular surfaces and fissures; in places, calcium carbonate filled the cracks, thereby further disintegrating the rock fragments or minerals. In contrast to the particles that were wet-sieved, about 50% of all grains in the thin sections are surrounded by thin iron oxide skins; for sample 1:2 and 1:3 the proportion is even higher. Partly, the oxides also colour the adjoining carbonatic matrix.

Although the sorting of the material of site AW VI generally appears as bad in the thin sections, it is still the best as compared to the other sites studied (see below); additionally, the sediments are the finest (for the fraction < 2 mm), except for the very large particles incorporated in layer 2:5.



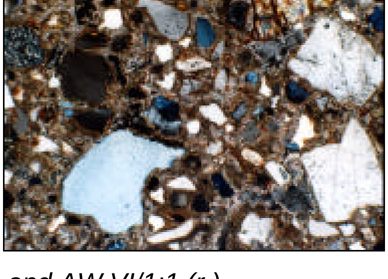


Fig. 103 – 105: Thin section of samples AW VI/1:3 (l.), AW VI/3:6 (m.) and AW VI/1:1 (r.).

Fig. 106 shows the lower sediment complex of site AW VI, and Fig. 107 is a close-up shot of the very basal part (= sample 1:1). Due to its high $CaCO_3$-content, this lowermost part is the most consolidated one. Its colour appears more pinkish, as compared to the yellowish red sediments above. The structure is almost columnar, with both vertical and horizontal cracks. Above 50 to 70 cm, however, the sediments seem to have a dip of ~ 25° to SSE, parallel to the present surface of the ramp-like erosional form. Most probably these structures are not original sediment structures, but can be compared to pressure relief planes which formed after the erosion of the main part of the lower sediment complex, only leaving this small ramp present today (the ramp-like form on Fig. 106, not the sand ramp!). The ramp may also be described as a "haldenhang" in the sense of LOUIS (1960).

Fig. 106 (l.): Lowermost part of site AW VI.
Fig. 107 (r.): Fine-grained, $CaCO_3$-cemented basal sediments, site AW VI (= sample 1:1).

Taking all observations together, a rather complex picture emerges: much slope debris close to the mountain slope at the "back" of site AW VI, fine-grained, highly calcified sediments constituting the base of AW VI, and somewhat coarser and less cemented sediments in the upper part. The basal sediments form a distinct unit, today probably of very limited extent.

The relation between the coarse sediments at the back, exposed in the ravine cutting off the sand ramp, and the fine-grained one around the corner at site AW VI, exposed by the stream cut dissecting the ramp, may be as follows: If the fine-grained sediments are older and were cut off from the bedrock slope at some time, the coarse sediments may have filled the ravine later on and have only been preserved to a very small extent during the incision of the present ravine. Rapid decrease in transport capacity might also be an explanation, but there are comparable deposits at least 100 m away from the bedrock slope in the northern part of the sand ramp with a similar slope angle and catchment area (site AW VIII, see below). During a younger phase of deposition slope debris was even transported as far as the toe of the sand ramp. This hypothesis may therefore be discarded.

A finding a few meters downstream of site AW VI supports the idea of a former dissection of the ramp (Fig. 108). A low wall, c. 120 cm high, of material comparable to the upper sediments of site AW VI shows sediment structures obviously formed by slumping and mud-sliding as typical for lateral stream erosion in unconsolidated, rather wet sediments. This wall cannot have been considerably higher during the formation of these sliding structures, which implies that the removal of the large amount of sediment touched on above must have occurred prior to incision and the deposition of the sediments rich in slope debris.

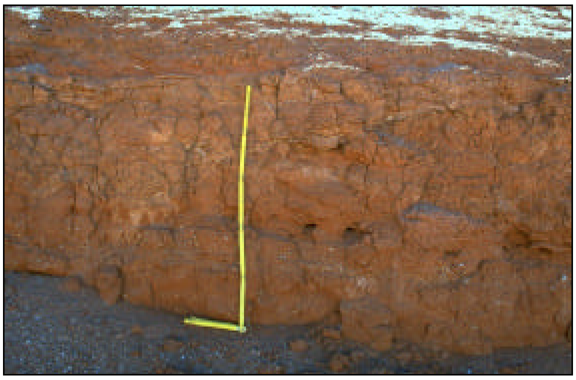


Fig. 108: Sediments downstream AW VI bearing witness to slumping and sliding.

Site AW VIII

Along the northern stream cut dissecting the sand ramp, close to the bedrock slope, a sediment body is exposed in a wall about 20 m long and up to 6 m high, at around 1,022 m a.s.l. The sediments resemble those of the rear side of site AW VI, except that the amount of slope debris in it is even higher (Fig. 109). There are beds of up to 90% of coarse particles > 2 mm, as compared to 50% for the rest of the sediment, which is about 45% medium-sized sand and only 13% fine sand, unlike AW VI where fine-grained sand is predominant. The coarse sand shows no sorting, and the colourful mixture of quartz, feldspar, biotite and diverse rock fragments is angular. The same range of material and high angularity are also found in the medium-sized sand. Thin sections reveal that iron oxides coat many particles, even larger rock fragments. Calcium carbonate of micritic and microsparitic texture forms the matrix.

Fig. 110 shows the slope of the sand ramp opposite site AW VIII, on the other side of the stream cut. The view is upstream, where the box-shaped stream valley changes into a ravine, separating the sand ramp to the south-east (left) from the bedrock mountain slope to the north-west (right). This photo clearly illustrates that deposition of slope debris onto the ramp (notice the large boulder at the flank!) must have occurred prior to incision. The same is true for the stabilization of the sediments: otherwise these steep slopes would not be stable. The gneiss block in the foreground is covered by calcium carbonate, and root casts, $CaCO_3$-coated stones and outcrops of sediment indurated by calcium carbonate are found all over the flank. Also because the induration is uniform from top to base, the calcification is thought to have occurred before incision (disregarding secondary dissolution and precipitation for the moment).

Fig. 109: Detail of site AW VIII.

Fig. 110: Opposite slope, covered by debris.

7.3.2 Sediments at the foot of the sand ramp

Site AW I

Site AW I is situated in the northern part of the sand ramp, north of the southern stream valley, at the delineating dry riverbed, c.1,025 m a.s.l. Over a length of about 100 m, facing ESE, about 8 m of the sediments are exposed in steps, which gives easy access to all layers (Fig. 111). 7 samples were taken (cf. Fig. 112). This is a generalized section, as lengthwise small-scale variations within the long outcrop are the rule with regard to layer thickness, debris content, colour, and intensity of calcification. The sediments throughout the wall are loamy sand with between 13 and 21% of fines (cf. Fig. 121 for grain-size composition). (Sample 7:5, from the lower calcrete, could not be sieved because of its induration. Dissolution of the calcium carbonate might have affected the host material and thus any comparison with the other samples. For the upper calcrete, a sample from the lower, less cemented part allowed analysis (2:1)). On the sand ramp surface at site AW I, Middle Stone Age artefacts were found (artefacts identified by D. NOLI).

Fig. 111: Overview of site AW I ® NNE.

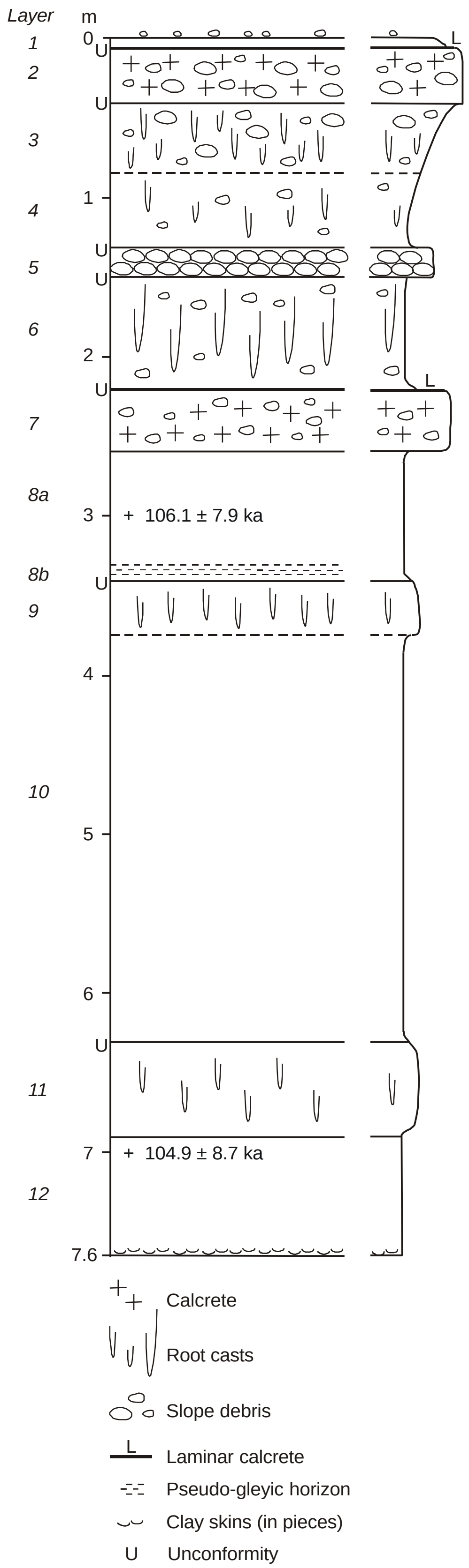


Fig. 112: Sediments exposed at site AW I.

Description of layers, site AW I

0 Angular slope debris, up to block size, partly $CaCO_3$-coated; Middle Stone Age artefacts.

1 Secondary colluvium: ang. to subang. debris, brownish matrix sandy to gritty; 6 cm thick (in this place).

2 Upper crust/calcrete: soil sediment/sand ramp material, intensively cemented by $CaCO_3$; several generations of calcification; coated by laminated crust (secondary); clasts strongly weathered; lots of ang. to subro. debris, coarser in the upper 10 cm; many root casts; scarp partly wind-scoured (from NE); 36 cm thick; sample AW I / 2:1 (c. 25 cm below surface).

3 Transition zone: calcification and debris decreasing downwards, strongly interspersed with roots; more porous; 43 cm thick.

4 Sand ramp material (sandy to gritty/gravelly): subro. to rounded clasts; weakly calcified; many and strong root casts, calcified rhizomes; organic material preserved; 45 cm thick; sample AW I / 4:2 (c. 110 cm).

5 Stoneline: coarse, up to > 20 cm, ang. to subang.; 20 cm thick.

6 Sands with lots of debris: coarse sand to grit/gravel; large root casts reaching from top to base; stronger calcified than 4, $CaCO_3$-content increasing downwards; brownish-reddish; 70 cm thick; sample AW I / 6:3 (c. 185 cm).

7 Crust/calcrete (palaeosurface): nodular concretions, several generations of calcification; coated by laminated crust (secondary, at least 1 cm, partly desiccation cracks), calcrete-"iced"; slope debris, esp. gravel and small stones, ± horizontally layered; windscoured in exposed positions; from here downwards structure somewhat columnar; 40 cm thick; sample AW I / 7:5.

8a Sand ramp material (sandy): few root casts, 5YR 6/8 to 5/6; 70 cm thick; sample AW I / 8:6 (c. 300 cm).

8b Pseudo-gleyic horizon(?): redder in colour (2.5YR 4/6 to 4/8) than 8a; no $CaCO_3$, no root casts; lateral extent c. 10 m, changing topography, sloping NNE.

Unconformity? Palaeosurface?

9 Root casts, stronger calcified than 8 & 10; 30 cm; sample AW I / 9:7 (c. 355 cm).

No sharp change, transition

10 Sand ramp material (red sands): no debris; calcification and rhizomes (often exposed by weathering) decreasing downwards, local $CaCO_3$-occurrence; 260 cm thick; sample AW I / 10:9 (c. 500 cm).

11 More root casts, stronger cemented by $CaCO_3$; 60 cm thick.

12 Sand ramp material (red sands): clay skin pieces, less $CaCO_3$; 70 cm thick.

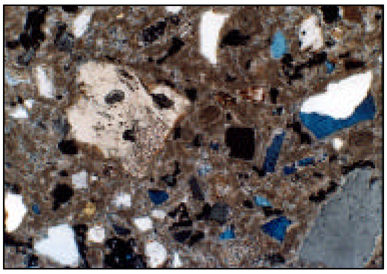
Riverbed

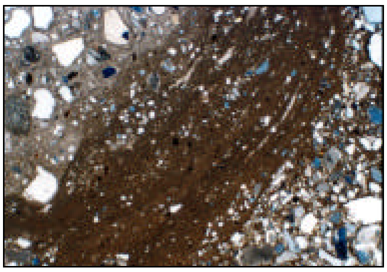
The most distinct characteristic of this section is the occurrence of two layers of compact calcrete, the one near the present surface (Fig. 113), the other one at about 250 cm. The upper crust (layer 2) is overlain by a secondary, brownish colluvium of laterally varying thickness (2 – 30 cm), which carries a desert pavement of particles ranging from coarse sand to slope debris, in places coated by calcium carbonate. Both calcretes are pink (7.5YR 8/4 – 7/4), obviously due to very finely distributed haematitic iron, and developed in a sandy to grussy soil sediment with 20 – 50% slope debris (increasing in size and amount upwards within each crust). The calcrete has the typical roundish, nodular form (Fig. 113), and shows several phases of precipitation and cementation.

Fig.113: Upper calcrete, site AW VI/2:1.

Fig.114: Laminar crust on upper calcrete.

Thin sections show minor differences (Figs. 115 – 117). The upper calcrete (sample 2:1) partly has a micritic matrix, partly a microsparitic. There are circular structures which may be cross sections of root casts. The host material consists of unsorted, subangular particles, rarely coated by iron oxide. In the lower crust (sample 7:5), there is slightly more coating of iron oxide, there are less large particles and much more fines, the sorting appears to be better, and a considerable number of grains is subrounded. Many particles are surrounded by radially grown calcium carbonate crystals. The matrix of the lower calcrete is partly micritic, especially where there has been much displacement of the host material, and partly microsparitic. In Fig. 116, a laminar pattern is visible.





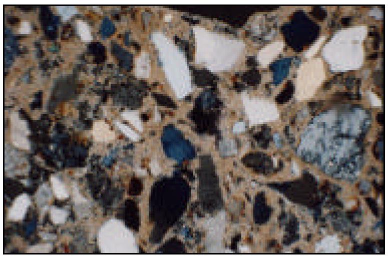


Fig. 115 (l.): Thin section of the upper calcrete, AW I/2:1.
Figs. 116 & 117: Thin section of the lower calcrete, AW I/7:5; overview (m.), detail (r.).

Both calcretes are topped by a laminar, multi-layered crust with desiccation(?) cracks, up to 1 cm thick (cf. Fig. 114). This is commonly interpreted as having been formed subaerially (e.g. BLÜMEL 1991), which would indicate that the calcretes represent former land surfaces. These two calcrete surfaces are differently inclined to the NNE; the lower one 1.5°, the upper one 4.0°, in this way merging with the lower crust at the level of the riverbed a few hundred meters away, near the bend in the river. The different inclination of the calcrete surfaces indicates that the morphology of the sand ramp has considerably varied in time. Both calcrete surfaces are somewhat irregular, at the cm-scale. They must have been developed in this way, as there is hardly any variation of thickness throughout the exposure.

Below the upper crust, the content of large slope debris decreases to about 10 – 20%, as does the content of calcium carbonate in the form of root casts, which become smaller and less densely spaced downwards. A thin section from sample AW I/4:2 still shows some calcification, but less intensively than in AW I/2:1. The matrix is mainly microsparitic, and only in places where the carbonate distinctly displaced particles it is micritic, indicative of rapid crystallization. In other parts the particles are packed very tightly, without a matrix visible. Remarkable are the intensive reddish iron oxide skins covering many grains, an observation only to be made in the thin section. Obviously they are easily destroyed during sieving, as grains examined after it only show slight coating, mostly in cracks and pits. Below layer 4 there is a distinct stone line of $CaCO_3$-coated slope debris, and in the sediment beneath very strong and long root casts have been formed (Fig. 119).



Figs. 118 (l.) & 119 (m.): Upper part of site AW I, hammer on stone line (middle).
Fig. 120 (r.): Detail view of the sediment with single root casts.

The sand fractions within the upper 220 cm occur in relatively equal proportions. The coarse sand fraction is generally mainly subrounded quartz with moderate sorting. The medium-sized sand fraction is rather subangular (to subrounded), and also of moderate sorting. The sediments are reddish yellow to yellowish red (5YR 6/6 – 5/8 respectively 5/6) (Fig. 118).

Below the second calcrete, the sediments are relatively monotonous. Root casts are concentrated in two layers (9 and 11), not always in their original position, as a horizontal or tilted orientation is common; the sediments in between the root cast layers at best show some slight local calcification (Fig. 120). In the transition zones below the root casts layers as well as below the second calcrete, calcium carbonate coatings are found in some cracks and fissures of most likely pedogenic origin. Immediately beneath the calcrete, the content of material > 2 mm is as low as 1.5%, increasing downwards to 10% (cf. Fig. 121). The size of the coarse fraction particles is much smaller than in the upper part of the wall; only grus and at most gravel-sized particles are dispersed within the fine-grained matrix, and there is no larger slope debris incorporated.

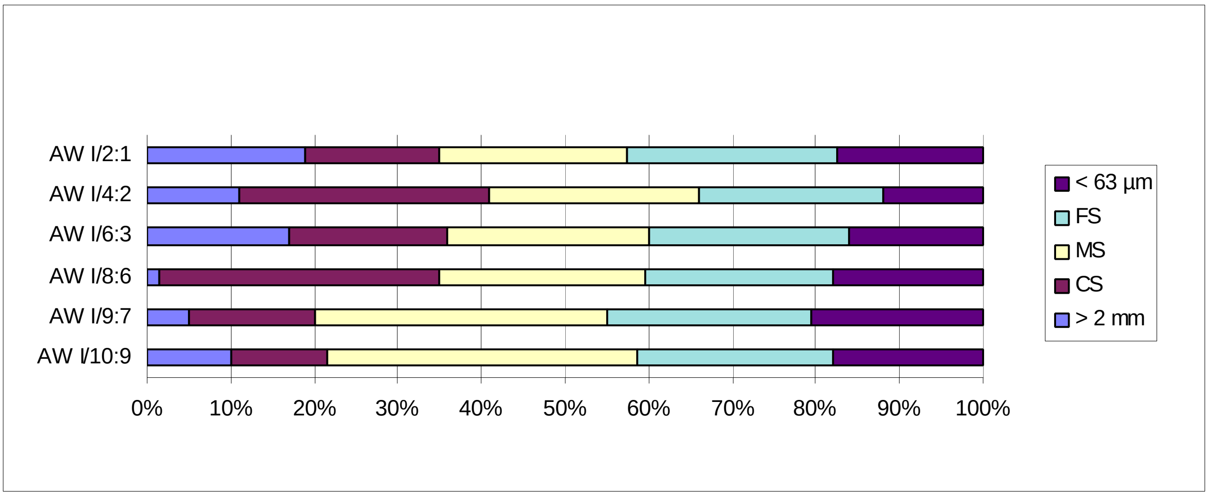


Fig. 121: Grain-size composition of the sediments at site AW I (the second calcrete, sample 7:5, would be placed in the middle).

The fines (< 2 mm) below the second calcrete do not differ markedly from the sediments above. The two lowest samples (9:7 and 10:9) are somewhat better sorted than the overlying sediments, mostly being medium-sized sand, with rather small grains making up the coarse sand fraction. A thin section of the more strongly calcified layer 9 shows that part of the particles is very tightly packed, the other parts having a micritic to microsparitic matrix. Fig. 122 illustrates the strong presence of reddish-brown coatings which have even coloured the surrounding carbonate. The colour of the lower sediments is similar to the layers above, reddish yellow to yellowish red (5YR 6/6 – 5/8). Sample 10:9 only is clearly yellowish red (5YR 5/6 – 4/8). There is an obvious dependence of colour on $CaCO_3$-content: the less carbonate, the more intensive the colour. The pH-value is around 8.6 throughout the sediments, which is distinctly higher than for the sediments at site AW IV, near the bedrock slope (pH around 7.7).

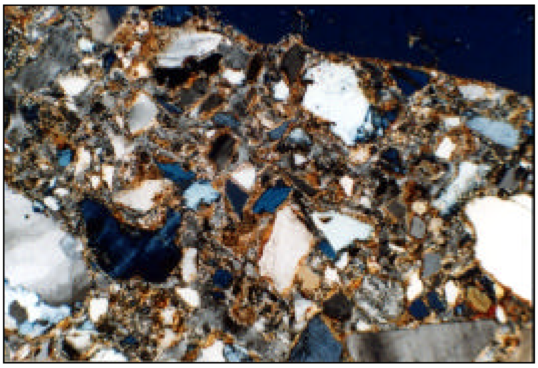


Fig. 122: Thin section AW I/9:7.

Site AW I – stages of development

The characteristics of the layers exposed at site AW I allow to draw conclusions about the morphodynamics during the formation of this part of the Aus sand ramp. For clarity, the stages of development are recounted in key words only. The description is from the oldest to the youngest; the numbers correspond to the layers in Fig. 112.

12, 11 Sedimentation – stabilization (environmental stability; soil formation), vegetation cover – root-cast formation at the time of decaying vegetation – denudation (as not the complete soil profile is preserved, but only the root casts, partly tilted or laying horizontally).

9, 10 Sedimentation – stabilization, vegetation cover – root-cast formation – denudation.

7, 8 Sedimentation, at first only fine-grained material (~ < 2 mm), later mixed with slope debris – concentration of slope debris particles on top by denudation – stabilization, vegetation cover – calcrete formation – subaerial exposure – lamination of calcrete.

6 Sedimentation (coarser sediments than before with a varying amount of slope debris, indicative of increased transport capacity) – stabilization, vegetation cover – root-cast formation, indicating by their size that at least shrubs, if not trees were present – denudation.

5 Sedimentation – formation of stone pavement by denudation.

3, 4 Sedimentation (material of varying characteristics, see above), again including slope debris – concentration of slope debris on top by denudation – stabilization, vegetation cover – root-cast formation – denudation.

2 Sedimentation, including slope debris – concentration of slope debris in the upper part by denudation – stabilization, vegetation cover – calcrete formation – subaerial exposure – lamination of calcrete.

1, 0 Sedimentation (secondary colluvium with slope debris) – stabilization, vegetation – development of desert pavement (denudation), particles partly coated by $CaCO_3$ (either incomplete coverage or partly eroded later on; wind-scoured).

Formation of a bluff due to fluvial undercutting.

Layers with a high amount of slope debris are regarded as having been concentrated and not reflecting a phase of exclusively slope debris deposition by the end of the sedimentation phase. Fluvial transport of debris from the bedrock slope over the sand ramp to its toe will unavoidably also have included the transport of sand, which was later washed out or possibly blown out from the sediment mixture. The particles of the stone pavement (5), appearing as a line in the section, must have been deposited after soil formation, root cast development in a B-horizon with a change of environmental conditions, and truncation of the upper part of the soil profile, as the large root casts begin below the stone line.

To summarize: The section at site AW I records (at least) eight phases of sedimentation, seven layers representing environmental stability by soil formation and vegetation growth indicated by root cast precipitation, eight phases of denudation, and ten former subaerial surfaces (the erosion surfaces and the tops of the two calcrete layers).

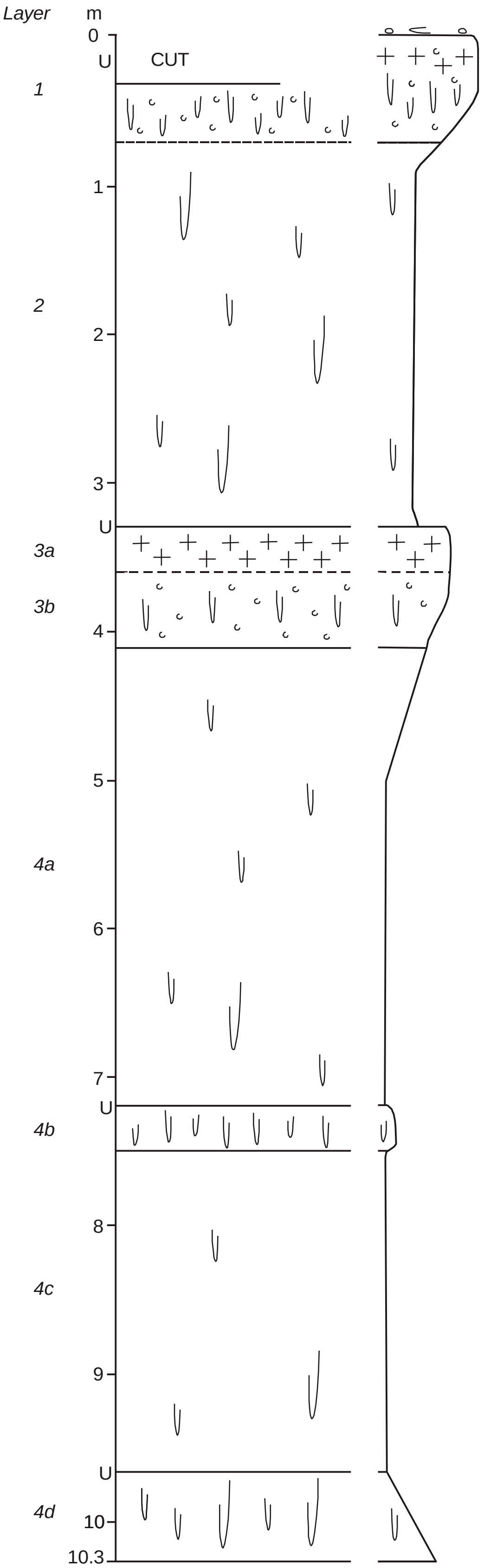
Two luminescence dates were obtained for the sediments below the lower calcrete layer, at 300 and 700 cm respectively. Both samples were deposited at about 105,500 years BP (at 300 cm: 106.1 ± 7.9 ka; at 700 cm: 104.9 ± 8.7 ka). For two more samples at 70 and 490 cm the palaeodose could not be determined, making the calculation of an age impossible (cf. chap. 4.2.3, App. I).

Site AW III

Site AW III is located about 1.5 km south of site AW I at the toe of the sand ramp, c. 35 m higher in elevation (1,060 m a.s.l.). River erosion exposed the sediments in an east-facing wall for over 50 m at a height of about 10 m (cf. Fig. 123). In general, the section is similar to the sediments at AW I, except that there is an almost complete absence of coarse slope debris: the largest particles are 1 cm in diameter.

Similar at both sites are two distinct pinkish calcrete layers and sandy to slightly gritty sediments in between, mostly medium-sized sand, and getting slightly coarser upwards. The grain-size curves below the lower calcretes at site AW III and AW I correlate very well, although the amount of fines is somewhat higher in AW I (20 and 21% vs. 15 and 18%). For the sediments above the lower calcrete, the curves for AW I/4:2 and AW III/1:1, as well as for AW I/6:3 and AW III/2:2 are very similar; at the same time, AW III/2:2 also correlates with AW I/2:1 (the upper calcrete). As the content of coarse material (> 2 mm) differs substantially, these correlations should not be regarded as crucial in any interpretation.

As at site AW I, root cast density varies, and the presence of calcium carbonate in the lower half of the wall seems to be confined to root casts. The lowest layer (4) is redder (7.5YR 7/4 – 6/4) than the rather brownish – pinkish (5YR 5/8) sediments between the two calcretes (layer 2) (Fig. 124). This may be due to the more confined occurrence of $CaCO_3$, a finding also supported by the lower pH-value of 7.9, as compared to 8.5 for the upper sediments, or to a more intensive soil formation (which is not supported by any markedly higher content of fines, though, as one would expect). The upper calcrete layer is about horizontal, while the lower one dips south into the riverbed (Fig. 125), indicating a different topography of the sand ramp at the time of its formation.



Description of layers, site AW III

0 ”Debris" on surface: root casts from the upper crust; desert pavement coarse sand gravel.

1 Hard surface, 0 to 30 cm partly truncated; sand ramp material incrusted by $CaCO_3$: ferralic Arenosol, calcic phase, on colluvium; relatively weakly indurated, "diggable"; root casts; $CaCO_3$-content decreasing downwards; pores $CaCO_3$-lined; matrix coarse sand to silt; 70 cm thick; sample <u>AW III / 1:1</u> (c. 55 cm).

No sharp boundary

2 Sand ramp material; slightly columnar structure; root casts rounder/smoother than further down; 260 cm thick; sample <u>AW III / 2:2</u> (c. 200 cm).

Hiatus

3a Strongly cemented by $CaCO_3$; 30 cm thick.

3b Pores lined with carbonate; 50 cm thick.

4a Sand ramp material: downward increase of calcification along the root casts, concentration of $CaCO_3$ to the roots = hard root casts; 310 cm thick; sample <u>AW III / 4:3</u> (c. 480 cm).

4b Rhizome casts horizon, somewhat harder; 30 cm thick.

4c Sandy; weakly cemented; single root casts; 230 cm thick; sample <u>AW III / 4:4</u> (c. 940 cm).

4d Rhizome casts more closely spaced; 50 cm thick.

Riverbed

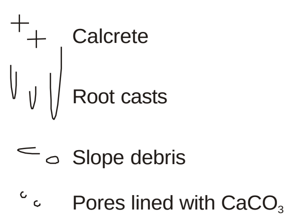


Fig. 123: Sediments exposed at site AW III.

Fig. 124: Site AW III, layers 2, 3, 4 (1 capped).

Fig. 125: Overview of site AW III with dipping lower calcrete.

The lack of coarse particles in a thin section of sample AW III/2:2 indicates slightly better sorting than in the comparative sediment of site AW I. The grains are somewhat better rounded and iron oxide coatings are comparably few. The amount of calcareous matrix is higher in AW III/2:2 than in AW I/4:2, but lower than in AW I/2:1 (the calcrete on top). The matrix is microsparitic, with quite large crystals.

Site AW IV

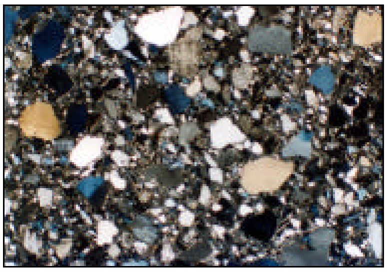
Site AW IV is situated in the southern part of the ramp, at ± 1,120 m a.s.l. Here, the sand ramp gradually slopes down to the level of the riverbed, as visible in the foreground of Fig. 126. Where walls have been formed, as at site AW IV, in the rear of the photograph, their height and length are limited, in this case to 3 and c. 10 m respectively. This site differs markedly from the two sites described above (AW I, AW III), characterizing the northern foot of the sand ramp. There are no distinct calcrete layers present, and there is basically no material > 2 mm (max. 0.3%).

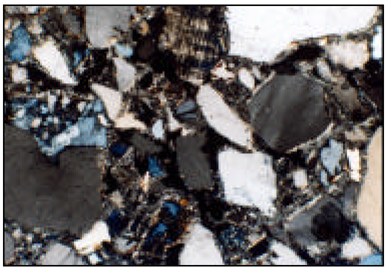
Fig. 126: Southern part of the Aus sand ramp, gently sloping to the riverbed. Site AW VI in the rear.

The reddish yellow to yellowish red (5YR 6/6 – 5/6) sediments are very strongly cemented, although at first sight calcium carbonate in the upper 1.5 m only seems to occur in cracks and fissures. Especially in the uppermost 20 cm, cracks are intensively coated by $CaCO_3$ and there are a few, but thick root casts. The grain-size distribution for the two samples taken (at 150 respectively 200 cm from below) is identical: loamy sand, with 21% fines and equal shares of the three sand fractions. With regard to grain size, the sediments are closest to layer AW III/2:2, although the content of fines there is only 16%. Compared to the lower sediments of site AW III (4:3 and 4:4) and of site AW I (9:7 and 10:9), the dominance of medium-sized sand found there (around 40%) is not present here (< 30%); instead, the sediments of site AW IV are richer in coarse sand (24% vs. ~15%).

Both the medium-sized and the coarse sand fraction show the best sorting of all sites studied, and the content of quartz grains is the highest of all. The coarse grains are subrounded, medium-sized sand is subangular to subrounded.

The thin sections show a rather coarse, but rather well sorted sediment. The particles are tightly packed, and there is only little, dark, and probably microsparitic matrix (Fig. 127). Lighter layers around some of the particles are interpreted as micritic matrix. At the thin section level, there is one obvious difference between the two samples: In the lower sample (AW IV:1) only very few iron oxide skins can be identified (Fig. 128), while in sample AW IV:2, 50 cm above, these coatings are more frequent.





Figs. 127 & 128: Thin section of sample AW IV:1; overview (l.), detail (r.).

Site AW IX

As mentioned at the beginning of this chapter, there is a discontinuous gully (the "incomplete cut") in about the middle part of the sand ramp, draining north-west, about 500 m long and up to 6 m deep. It is neither long nor deep enough to join the riverbed skirting the ramp, but terminates about 100 m before, with its floor running out one or two meters above the present main drain (Fig. 129).

Fig. 129 (l.): View from the riverbed towards the discontinuous gully.
Fig. 130 (r.): Calcrete at the rim.

The sediments exposed there are covered by a surficial calcrete 30 to 60 cm thick (Fig. 130), forming a little scarp at the rim of the stream cut. This white calcrete was precipitated in a sandy to grussy host material rich in slope debris; when the strongly cemented sediment became exposed at the surface, it was coated by a laminar crust up to 1 cm thick and then subjected to solution and wind polishing. From morphological evidence this calcrete correlates with the upper calcrete described for sites AW I and AW III. Subrounded pieces of disintegrated calcrete and weathered-out root casts litter the present surface, implying that there must have been an overlying layer of sediment, in which soil, root-cast and calcrete formation had occurred and which was largely removed later, here only to trace by the calcareous remnants.

In most places, the slope from the calcrete rim down to the stream floor is a gently inclined ramp, consisting of unsorted sandy to grussy sand ramp sediment intermixed with calcrete pieces and root casts. There are only few vertical walls; the highest of them (c. 130 cm) is site AW IX, situated in the upper quarter of the stream cut at c. 1,100 m a.s.l. (Fig. 131). The massive calcrete is found 150 cm above the wall; the sediments on the ramp between them are like that of the gently inclined slopes just referred to.

Fig. 131: Overview of site AW IX.

The description below is only of the vertical part of the section. The upper 10 cm of site AW IX are a strong brown (7.5YR 5/6) sediment with a platy structure, slightly calcified after deposition (AW IX:5). Its surface, with desiccation cracks partly lined with $CaCO_3$, is covered by black lichen. The grain-size analysis (Fig. 132) shows a very high content of coarse sand (40%) and a very low figure for the fine-grained sand (15%), with a large proportion of fines (18%). This sediment resembles the thin, brownish colluvium found on top of site AW I, which would imply that deposition of this sediment occurred after incision of the discontinuous channel.

Beneath this layer there are c. 30 cm of a red-brown sediment with root casts and calcification along vertical and horizontal joints (AW IX:6). Although the matrix is rather fine with only 1% grus, subangular stones are incorporated into this layer. Obviously this sediment was deposited onto an eroded surface, as it fills cracks in the underlying layer. This layer, 25 cm thick (AW IX:7), is a strongly calcified sediment of pink to reddish yellow colour (7.5YR 7/4 – 7/6). It is less inclined than the present surface, again indicative of a former different ramp morphology, in particular a greater extension to the north-east. In spite of the obvious unconformity separating the two layers, the grain-size distribution of IX:6 and IX:7 is very similar, comparable to the sediments of site AW IV and AW III/2:2 (disregarding the lower content of fines in III/2:2, as already discussed for site AW IV).

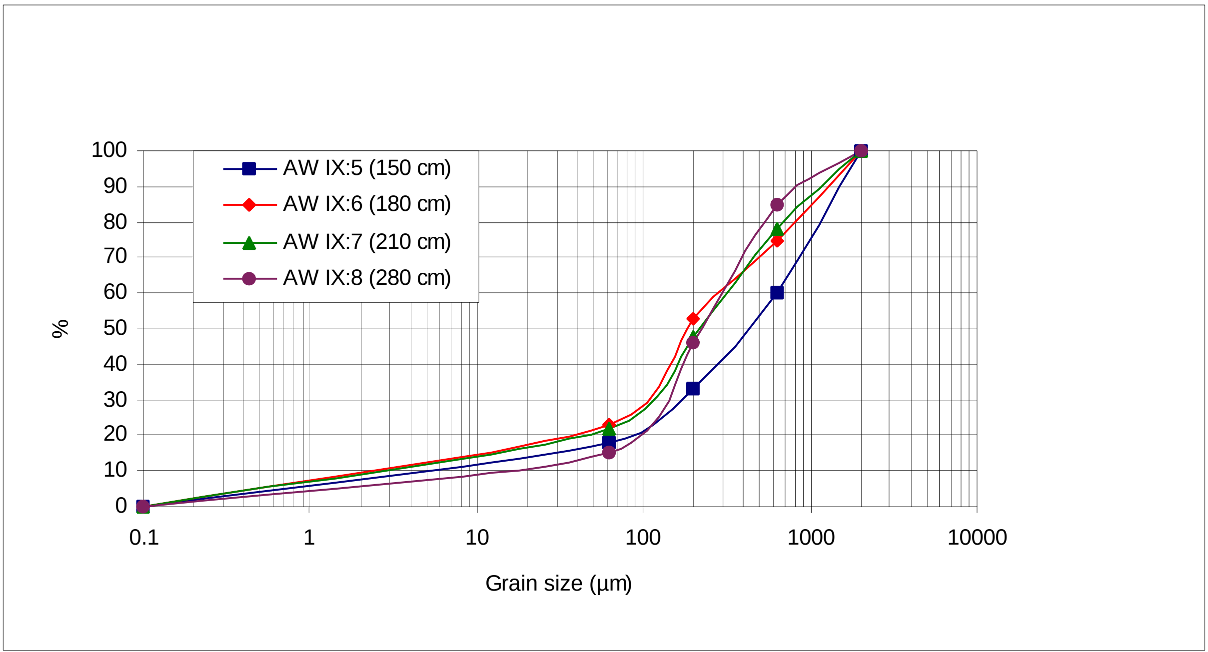
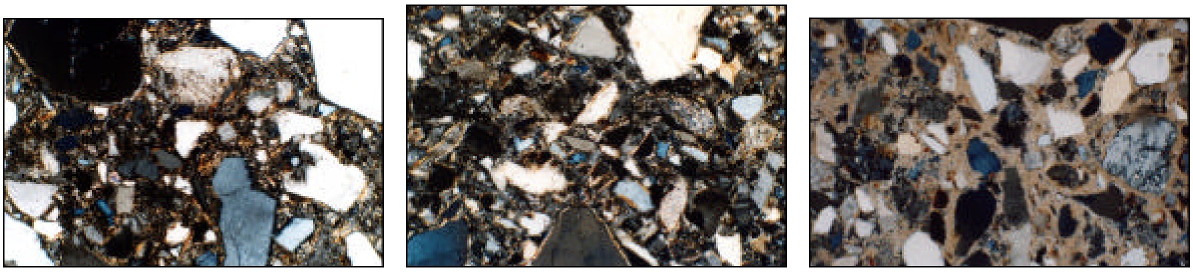


Fig. 132: Grain-size distribution of the sediments at site AW IX. Sampling depths below the calcrete surface.

Downwards from the calcified layer IX:7, field observations only suggested a gradual decrease in the $CaCO_3$-content, being confined to root casts and coatings on joints in the lower part of the wall, but the grain-size determination tells differently: Layer AW IX:8 differs from IX:7 in its lower amount of fines (15% vs. 23%), its better sorting, and a lower content of coarse sand (15%, which is the lowest within the wall). The grain-size composition of IX:8 is fully comparable with the lower sediments of both sites AW I (9:7 and 10:9) and AW III (4:3, 4:4). The strong calcification in layer AW IX:7 may thus be correlated with the formation of the lower calcrete at sites AW I and AW III.

Throughout the section iron-oxide coating has only been preserved in the pits of the sand grains. The sorting of the sand fractions is moderate, comparable to site AW III, i.e. they are better sorted than the sands of site AW I and worse than the ones of site AW IV.

In the thin sections a trend from rather subangular to more subrounded particles down the wall can be made out. AW IX:5 (Fig. 133) is characterized by the occurrence of only little and dark matrix, which inhibits the description of its texture. Iron oxide skins are present, but they are not confined to coating the particles but also colour the calcareous matrix. AW IX:6 shows even less matrix than IX:5 (Fig. 134). Mostly, the particles are packed very tightly, but where matrix is found it is microsparitic (even here the matrix is dark and difficult to classify). Some particles are surrounded by lighter zones, which may be a combination of small calcic crystals and iron oxide coatings. For AW IX:7 (Fig. 135) a microsparitic matrix, especially around the particles, is easy to identify. In accordance with the field investigations, this layer was obviously infiltrated by calcium carbonate, crystallized in its micritic form between the particles of the host material. Also here, the few iron oxide skins are not only confined to the grains, but colour the matrix as well.



Figs. 133 – 135: Thin section of layers AW IX:5 (l.), AW IX:6 (m.) and AW IX:7 (r.).

7.4 Correlation of the sedimentological evidence of the Aus sand ramp

Characteristics like grain-size distribution, content of slope debris, degree of calcification or distinctiveness of horizons express differences and similarities between the sediments of the Aus sand ramp. Fig. 136 schematically illustrates the distribution of the different sediment types. In this chapter, the sediments described from the various sections will be correlated in order to arrive at the geomorphic history and relative chronology of the Aus sand ramp, with additional sedimentological and morphological evidence.

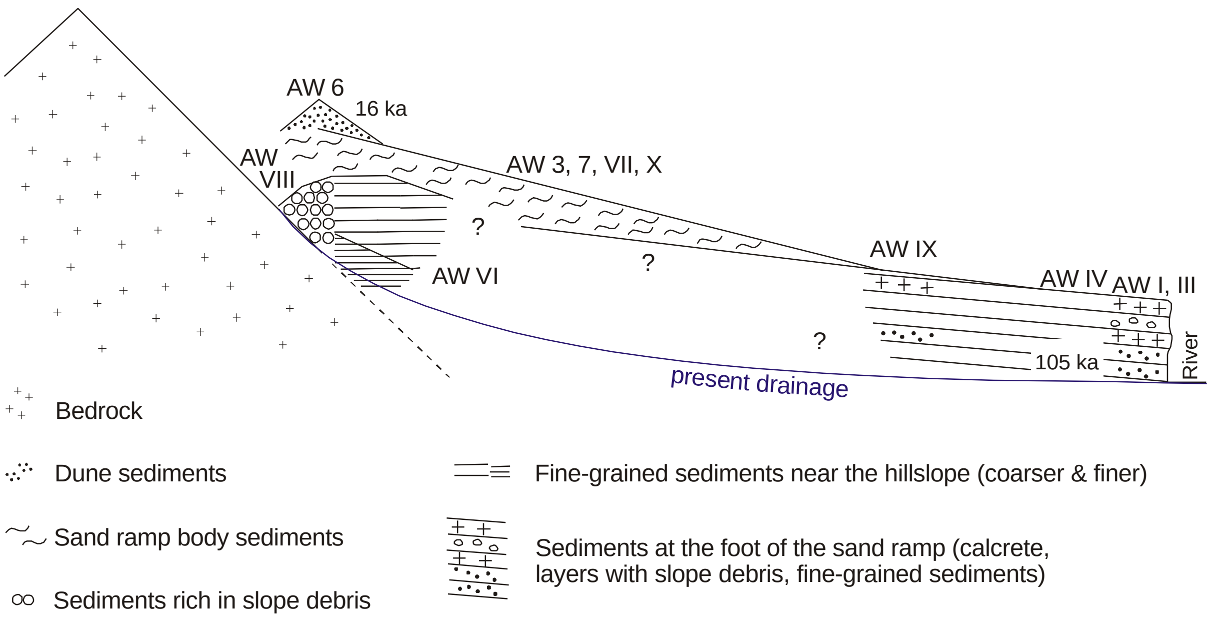


Fig. 136: Schematic view of the distribution of the sand ramp sediments.

The most distinct feature of the naturally exposed sediments studied is the occurrence of two calcrete layers present at the foot of the ramp at sites AW I and III, and at site AW IX in the discontinuous gully about 500 m from the sand ramp's rim. At all sites, below the lower of the calcretes, there is a relatively well-sorted and fine-grained sediment of predominantly medium-sized sand. Occurrences of calcium carbonate are confined to root casts and occasional coatings of joints. Because of their similarities these sediments are regarded to be of the same age and origin. They are very homogenous, without any marked horizontation either by grain-size, content of slope debris or colour. Two layers with a higher concentration of root casts at sites AW I and AW III are the only evidence that deposition must have occurred in at least three phases, interrupted by periods of stability allowing the growth of vegetation together with soil formation, and subsequent development of root casts and denudation of the upper part of the soil profile in times of decreasing environmental stability. The ensuing unconformities are not very distinct, in the field the most obvious one being above the root-cast horizon of layer 9, site AW I (cf. Fig. 112). At the other root cast locations the transition to the overlying sediment is more gradual. However, as only the lower parts of the soil profiles have been preserved, denudation needs to have occurred before the next phase of sedimentation. Thanks to the OSL dates obtained from the two samples at site AW I, the age of the sediments below the lower calcrete can be determined to about 105.5 ka.

The sediments between the two calcrete layers correlate less well in their grain-size distribution, both with regard to grains < 2 mm and the content of slope debris. This may reflect transport processes rapidly changing in location and time. Site AW I shows the most diverse development of horizons; the stages of development (multiple phases of sedimentation, stabilization with soil formation, vegetation growth, root-cast formation and denudation) have been described in detail above (cf. p. 87). The highest content of slope debris is at site AW I, with a decrease in amount and size towards AW IX and AW III, and a complete absence at site AW IV. This is explained by the position of the sites, depending on the distance from the mountain slopes and the slope angle of the ramp (cf. Fig. 85). AW I is situated about 800 m downslope of the outcropping bedrock. AW III is about 1,700 m away and consequently only contains particles up to 1 cm in size. AW IV is again closer to the mountain slope, but more to the south-west, whereas the main slope direction is north-east to east. Also, the slope angle is less than at the other sites, so that AW IV is in a position about 100 m higher than AW I. The deposition of slope debris in situations far away from its source, the bedrock mountain slopes, implies a higher transport capacity than during the time of deposition of the lower sediments. Debris production by weathering is assumed to have occurred prior to sand ramp formation. The uniform character of the sandy part of the ramp sediment does not indicate any interruptions of deposition that would unavoidably have occurred at hypothetical phases of rock disintegration.

The sediments exposed at the foot of the sand ramp (incl. AW IX) are suggested to have developed under about the same conditions as the younger sand ramps at Sandkop and the Jagpan Mts. (cf. chap. 6.1). The stages A (alternating fluvio-aeolian sedimentation under a dry, cold regime with rare, but high-intensity rainfalls) and B (environmental stability, low variability, soil formation and vegetation growth) simply occurred at least eight times (site AW I) instead of only once as at the other locations. Also, processes of the alternating stages seem to have been considerably more intensive. This is particularly obvious with regard to the high amount of slope debris incorporated during the later deposition phase at Aus, and the phases of soil formation must have been those of considerable geomorphological stability. Stage B each time ended by precipitation of calcium carbonate either forming root cast horizons or compact calcretes, indicating the transition from environmental conditions characteristic of few changes of $CaCO_3$-precipitation and solution to conditions supporting frequent changes of precipitation and solution (cf. KEMPF 2000). – Whether root casts or compact calcretes were formed probably depended on the length of the period favourable for $CaCO_3$-precipitation; the longer these conditions lasted, the more the vertical water flow was hindered, subsequently resulting in horizontal water movement, denudation processes and finally in the formation of a laminar crust at the surface.

Also the availability of calcium carbonate may have had an effect on root-cast or calcrete formation. As large parts of the sediments are carbonate-free, the input of calcium seems to have varied over time. In the region, there is no self-evident source of calcium like a large pan or the occurrence of limestone in the catchment area. Although aeolian input of calcareous dust is frequently regarded to be the main source of calcium carbonate for calcrete formation (e.g. EITEL 1995), the way of mobilization of this dust has not been explained sufficiently. It cannot be excluded that the calcium originated from the chemically weathered bedrock of the slopes adjacent to the sand ramp. This problem thus requires further attention; however, discussing its complexity in detail within this study would be taking things too far.

Denudation occurred after each period of stabilization, but the development of a desert pavement (stage C) can only be proved for the layers including slope debris (pavements of grus and coarse sand would have been difficult to preserve).

Although at least eight phases of soil formation could be identified, none of them is likely to have caused the reddish colour of the sediments. There are no red soil horizons within the various sections; colour basically only varies according to the content of calcium carbonate (the more, the paler). Therefore it has to be assumed that the sand grains had already been coated by soil formation at a different location prior to aeolian transport. This is suggested by the general observation that the iron oxide coating only occurs in pits of the sand-grain surfaces. At the more exposed parts of their surfaces the coating is likely to have been worn off during the innumerable grain-to-grain collisions during transport. Relics of such sandy soils that may have been the sources of the grains transported to the sand ramps were found, for instance, on farm Rooikam south-east of Aus.

Figs. 137 – 139: Terraces of fluvial sediment on farm Klein Aus (Fig. 137 (l.), rear: sand ramp).

Another possible source is a fluvial sediment only preserved as terrace remnants on the farms Klein Aus and Heinrichsfelde east of the sand ramp (Figs. 137 – 139). These terraces are found at least between 1,200 and 1,420 m a.s.l. The dissection and removal of this large amount of material is assumed to have occurred before the present sand ramp sediments were deposited, as such intensive fluvial erosion would also have had an impact on the sand ramp sediments; consequently, also the fluvial sediment needs to be older than the ramp. The erosion of the fluvial sediment also meant mobilization of material, so that deflation could provide aeolian sand for the sand ramp.

The sediments close to the hillslopes differ from the sediments at the foot of the ramp. There are no clear-cut/readily identifiable horizons. The sediments at site AW VI are strongly dominated by fine-grained sand (almost 50%) and contain much less coarse sand than the samples at the foot of the ramp (4 – 12% vs. about 24%), which may indicate lower wind speeds during their deposition. Another difference is that the content of calcium carbonate (both from field and thin section evidence) is lower and generally dispersed, i.e. there are no root casts; in agreement with this observation, the pH-value is lower (7.7 vs. an average of 8.3). The bedding is almost horizontal. Extrapolating this slope, the early sand ramp must have extended far more into the basin than the present form, covering an area of at least 50 km^2, but probably much larger, as the extent to the west cannot be determined (cf. p. 77). The removal of this huge amount of sediment must have required considerable fluvial activity. Neither in the satellite image, nor in the aerial photographies, any remnants can be identified. Field work was inhibited due to the location of any possible remnants within the Restricted Diamond Area.

Another different type of sediment adjacent to the bedrock slope has been described from the "back" of site AW VI and from AW VIII. Its very high amount of coarse slope debris indicates a strong fluvial input from the mountain slopes. Similar to the fine-grained sediment at site AW VI, the debris-rich body is also more or less horizontally layered, again indicating a much larger former size of the sand ramp (especially evident at site AW VIII). The relation between the sediments at the "back" and the "front" of site AW VI is best explained by assuming that a ravine was cut into the fine-grained sediment exposed at the front, which in turn became filled with coarse sediment, today exposed at the back by a younger cut-off (cf. p. 80 f.).

From their morphological position the sediments near the bedrock slopes must be older than the sediments at the foot of the ramp. The foot-sediments were deposited onto and next to the near-slope sediments; as the slope debris can only have originated from the bedrock slopes, the transport of material must have occurred over the near-slope sediments. A certain reworking of the older sediments near the bedrock slopes during slope wash processes cannot be excluded.

As indicated by Fig. 136, the basal sediments are covered by a younger sand ramp body of the Excelsior/Sandkop-type. Therefore it is difficult to determine the contact between the near-slope and the foot-sediments. The slopes of the ravines and stream cuts, where not buried by younger aeolian sand, provide some information. At one of those places, for instance in the upper part of the northern stream valley (Fig. 140, c. 1,110 m a.s.l.), sediments are exposed. The wall in the foreground of Fig. 140 contains a high amount of slope debris in a red-brown matrix, more intensively coloured in the upper half of the section (Fig. 141), thus indicating a palaeosoil. Most parts of the coarse layers are strongly cemented by calcium carbonate, while in the fine-grained sediments the $CaCO_3$ is confined to root casts and joint coatings. The high content of slope debris resembles the sediments found at site AW VIII and at the back of site AW VI.

Fig. 140: Downslope view into the northern stream valley with exposed sediments at the flank.

The sediments exposed further downstream (Fig. 140, middle) present a different picture (Fig. 142), although at about the same level. Slope debris is mainly found in a single coarse layer, intensively calcified. The sediments are also red-brown, though more pale below the coarse layer, and there are also root casts, not visible in the photograph. As the fine-grained matrix is similar to the one exposed further upstream, these two sediment bodies are suggested to be more or less the same, the downstream one simply indicating decreased debris transport. On the other hand, as site AW VIII, which is rich in slope debris, is located even further downstream, it may be concluded that small-scale variations often occurred during the deposition of coarse material.

Fig. 141 (l.): Sediments rich in slope debris, uppermost site in Fig. 140.
Fig. 142 (r.): Fine-grained sediments of the site in the middle of Fig. 140.

Fig. 140 also shows a low bluff at the surface that has been formed in the sand ramp material. The sediment is intensively calcified, rich in root casts and poor in coarse material. On top of it there are a few centimetres of a slightly consolidated brownish sediment with angular gravel and small stones, comparable to the colluvium found on top of sites AW I and IX. The calcareous surface layer truncates the more gently inclined sediments exposed at the flank of the ravine. This calcrete may be the one referred to at site AW IX (p. 93), where on the surface of the initially assumed uppermost calcrete layer root casts were found, indicating another phase of sedimentation, soil formation and $CaCO_3$-precipitation. This stream valley reveals that this calcrete layer follows the present form of the sand ramp. It is thus concluded that after the formation of the upper calcrete of the foot-sediments there was an additional phase of aeolian deposition with slope wash, followed by denudation processes forming a glacis d'érosion (cf. CAILLEUX 1950, COQUE 1956; Fig. 143). Soil formation and vegetation growth stabilized the glacis surface, subsequently again followed by root-cast precipitation and calcrete formation. Renewed denudation then exposed the calcrete, which since that time has preserved the original slope of the glacis.

Fig. 144 illustrates this calcrete layer at the present surface, near the toe of the sand ramp. The crust is very hard, greyish, and rich in slope debris, with particles partly weathering out. On the northern and middle part of the ramp fragments and scattered root casts from it can be traced at or near the surface, for at least 600, 700 m upslope of the foot of the ramp. 50 to 100 m upslope of site AW IX, for example, the sand ramp surface is strewn with white, grey, pink and redbrown root casts, before the younger sand ramp cover begins. Similarly, the southern part is littered with root casts and fragments, if only for a distance of c. 100 m from the rim upslope. This type of surface shows well in the Landsat image (Fig. 86, p. 68). The younger sand ramp body and the dunes are yellow, the calcrete-strewn surface of the outer part of the sand ramp bluish – turquoise coloured, visualizing the exposed part of the old sand ramp surface.

In correlation with the occurrence of this uppermost calcrete layer, the brownish colluvium found on top of sites AW I and IX and at the rim of the flank of the northern stream valley may constitute remnants of the soil which had formed on the glacis surface and which was redeposited by denudation processes during exposure of the calcrete.

Fig. 143 (l.): Glacis d'érosion surface preserved by calcrete; northern part of the ramp.
Fig. 144 (r.): Detail view of the glacis-preserving calcrete.

All exposures are unequivocal evidence that fluvial dissection of the ramp took place after all the phases of soil formation, calcrete induration and denudation described above, and also after formation of the younger sand ramp body, as slope wash from the bedrock slope would have been impossible otherwise. Dissection occurred prior to the accumulation of the dunes, though, as they are deposited at almost the same level as the riverbed delimitating the sand ramp. However, there must have been fluvial activity after the deposition of the dunes, as the riverward ends of the dunes are curved (cf. Fig. 86). There is no evidence that wind erosion could have played any significant part in the dissection of the sand ramp. The bedrock in places exposed on the valley floors shows signs of recent fluvial scour and a total absence of desert varnish (Fig. 145).

Fig. 145: View upstream the northern channel, where polished bedrock bears witness to fluvial erosion.

In none of the stream cuts is there any evidence for multiple phases of dissection; therefore the separation of the sand ramp body from the bedrock slopes must have taken place in a single event. The discontinuous channel (chap. 7.3.2, with site AW IX) may have been incised in the same event. Its incompleteness may be due to the fact that more rapid incision of the other two channels, with their larger drainage areas, may have cut if off from its water supply. Obviously the local rainfall on the sand ramp itself was and is insufficient for further downcutting.

Formation of the discontinuous channel is circumstantial evidence of the continuation of the calcrete-indurated surface of the older sand ramp generation beneath the younger sand ramp sediment. The channel begins where interflow from the bedrock slope through the younger sand ramp – blocked from further infiltration by the more or less impermeable layer – seeped out, concentrated on the old sand ramp surface and started downcutting for some time. This downcutting must have come to an end, as inferred above, when most of the runoff was shifted from infiltration into the younger sand ramp sands to the two incipient streams eventually separating most of the ramp from its bedrock contact. If this process was accompanied or even caused by increased fluvial activity, also the river delimiting the sand ramp may have incised more deeply, thereby changing the local base level of erosion.

Prior to or contemporarily with the incision of the delimitating riverbed, fluvial erosion reshaped parts of the toe of the sand ramp. Except for the high bluffs in the northern and central parts and the gentle transition of the ramp into the riverbed in the southern part as described above (e.g. p. 69), additional forms are found. Just south of site AW I, the ramp is terraced (Fig. 146). The surfaces of these two terraces are strewn with pieces of calcrete and roots casts and are thus assumed to have been formed on the two comparatively resistant calcrete layers typical for the foot-sediments. In another place, fluvial erosion has completely destroyed the horizontation of the foot-sediments, having left “red hills” of a brown to red sandy sediment full of pinkish root casts; the sediment itself is basically free of carbonate, surficial coating is only rarely found (Figs. 147 & 148).

Fig. 146 (l.): Lowered rim of sand ramp near site AW I. 2 terraces = 2 calcrete levels.
Fig. 147 (m.): "Red hills": Disturbed foot-sediments.
Fig. 148 (r.): Detail red hills with numerous root casts. Light spots = slope debris.

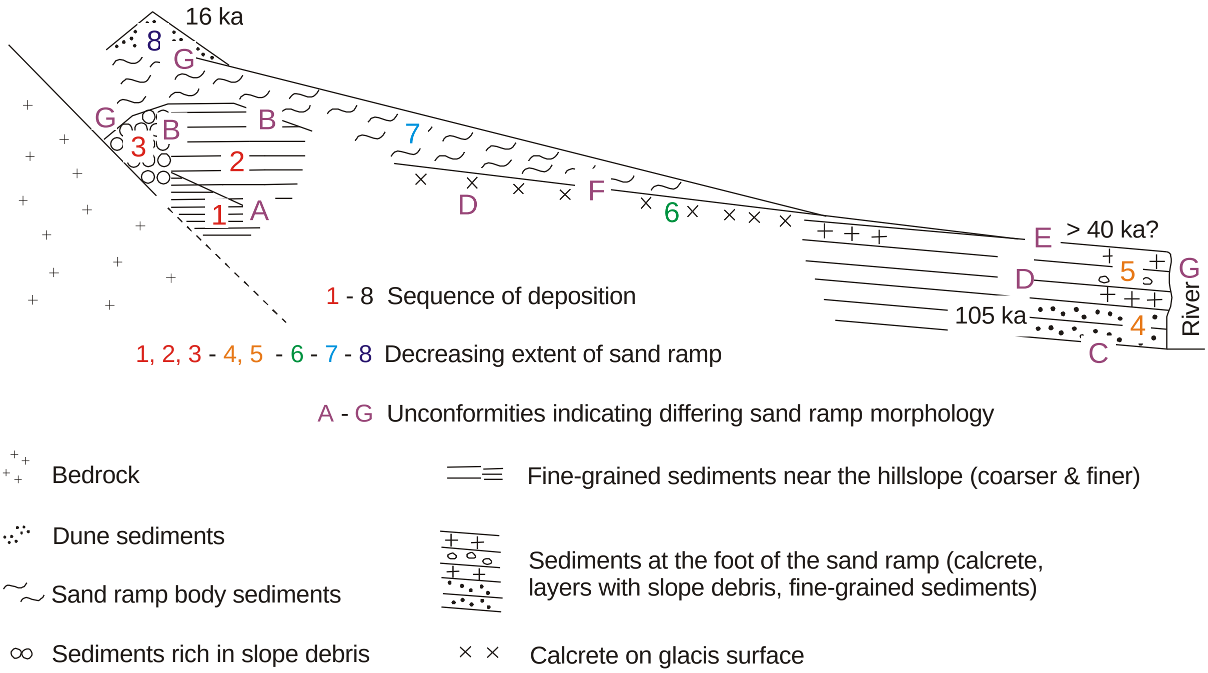


Fig. 149: Schematic view of the different sediments types of the Aus sand ramp, indicating relative age, former extent and change of sand ramp morphology.

In conclusion, Fig. 136 presented at the beginning of this chapter can now be completed by numbering the sequence of events that have led to the present aspect of the Aus sand ramp (Fig. 149). It shows the much higher complexity, and consequently longer history, of the older sand ramp than of the overlying younger one of the Excelsior/Sandkop-type. The lesser inclination of the strata within the lower body is also unequivocable evidence that the first sand ramp (1, 2, 3) covered a much larger area than the younger forms. Simply by extrapolating the inclination towards the floor of the adjacent basin, it must have ended at about 12 km from the bedrock contact (assuming the basin not being filled by, for instance, fluvial deposits), compared to the mere 600 m for the younger generation (7).

8 SEQUENCE OF PROCESSES

From the sedimentological and morphological characteristics of the sand ramps described in this study a general succession of processes can be deduced (Fig. 150). This listing does not claim to be complete, as not every change in morphodynamics may have been preserved to this day; still, the variety and variability of environmental changes that occurred in the time of sand ramp formation is impressive and emphasizes the importance of looking at the details even in a landscape where allegedly not much happened morphologically during the last few hundred thousand years ...

			Sequence of processes	Site[1]	Age
"Near-slope sediments"	1	*A*	Deposition, fine-grained sediment	AW VI base	
	2	*B*	Soil formation	"	
	3		$CaCO_3$-cementation	"	
	4	*C*	Denudation	"	
	5	*A*	Deposition, coarser sediment than 1	AW VI top	
	6	*B*	Soil formation	"	
	7		$CaCO_3$-precipitation	"	
	8	*C*	Denudation	"	
	9	*D*	Dissection, significant removal of sediment	AW VI	
	10	*A*	Deposition, sediment very rich in slope debris	AW VIII	
	11	*B*	Soil formation	"	
	12		$CaCO_3$-precipitation	"	
	13	*C*	Denudation	"	
Lower part of "foot sediments"	1	*A*	Aeolian deposition with slope wash, grus production	AW I *11, 12*	106.1 ka ± 8.7[2]
	2	*B*	Soil formation	"	
	3		Root-cast formation	AW I *11*	
	4	*C*	Denudation	"	
	5	*A*	Aeolian deposition with slope wash; grus production	AW I *9, 10*	
	6	*B*	Soil formation	"	
	7		Root-cast formation	AW I *9*	
	8	*C*	Denudation	"	
	9	*A*	Aeolian dep. with slope wash, incl. smaller sl. debris; grus prod.	AW I *7, 8*	104.9 ka ± 7.9[2]
	10	*C*	Denudation – concentration of slope debris	"	
	11	*B*	Soil formation, incl. pseudo-gleyic horizon	AW I *8b*	
	12		Root-cast formation, calcrete formation	AW III *3*	
	13	*C*	Denudation – exposure of calcrete at the surface	AW I *7*	
	14		Precipitation of laminated calcrete	"	
Upper part of "foot sediments"	15	*A*	Aeolian depos. with slope wash, incl. smaller sl. debris; grus prod.	AW I *6*	
	16	*B*	Soil formation	"	
	17		Root-cast formation (thick root casts)	"	
	18	*C*	Denudation	"	
	19	*A*	Aeolian depos. with slope wash, incl. larger slope debris; grus prod.	AW I *5*	
	20	*C*	Denudation – formation of stone pavement	"	
	21		$CaCO_3$-precipitation	"	
	22	*A*	Aeolian depos. with slope wash, incl. larger slope debris; grus prod.	AW I *3, 4*	
	23	*C*	Denudation – concentration of slope debris	"	
	24	*B*	Soil formation	"	
	25		Root-cast formation	AW I *3*	
	26	*C*	Denudation	"	
	27	*A*	Aeolian depos. with slope wash, incl. larger sl. debris; grus prod.	AW I *2*	

			Sequence of processes	Site[1]	Age
Upper part of "foot sediments"	28	*C*	Denudation – concentration of slope debris	"	
	29	*B*	Soil formation	"	
	30		Calcrete formation	"	
	31	*C*	Denudation – exposure of calcrete at the surface	"	
	32		Precipitation of laminated calcrete	"	
	33	*A*	Aeolian deposition, incl. slope debris		
	34	*C*	Formation of glacis d'erosion		
	35	*B*	Soil formation		
	36		Root-cast formation, calcrete formation	AW IX	
	37	*C*	Denudation		> 40,000 BP?[3]
Younger sand ramps	1	A	Aeolian deposition with slope wash; grus production	EX, SK	
	2		Aeolian deposition with slope wash, incl. slope debris	"	
	3	B	Soil formation	"	
	4	C	Formation of desert pavement	"	
	5	D	Dissection incl. cut off	"	
Recent sands	1	E	Aeolian deposition	AW 6	15.0 ka ± 1.1[2]
	2		Soil formation	AW 8	
	3		Fluvial activity	AW 8	
	4		Deflation	"	
Modern sands	1	E	Aeolian deposition and reworking	EX	
	2		Deflation, active aeolian forming	"	present

1, 2, 3 … Indication of the minimum number of environmental stages during each major period of sand ramp formation, adding up to 60 changes in morphodynamics.

A, B, C, D, E: Stages of sand ramp formation for the younger generation (cf. chap. 6.1)

A, B, C, D: Stages of sand ramp formation for the basal parts of the Aus sand ramp, following the stages of development for the young generation:

A: Equivalent to stage A of sand ramp formation. Aeolian deposition with slope wash, implying a highly dynamic climatic system, seasonal aridity and low-frequency, but high-intensity rainfall.

B: Equivalent to stage B of sand ramp formation. Soil formation, implying environmental stability, growth of vegetation and stabilization and consolidation of the sediments.

C: Equivalent to stage C of sand ramp formation: Denudation, implying decreasing environmental stability as compared to stage B.

D: Equivalent to stage D of sand ramp formation. Dissection, implying high-intensity rainfalls.

[1] Representative sites, [2] OSL-date, [3] Archaeological evidence.

Fig. 150: Sequence of processes of the Aus sand ramp.

9 SAND RAMPS IN THE CONTEXT OF LANDSCAPE EVOLUTION

The previous chapter has emphasized the large number of environmental changes recorded by the sand ramp sediments and their morphology. Luminescence dating has shown that the sand ramps came into existence during the Late Quaternary. The bulk of the sand ramp sediments falls into the Last Glacial; from stratigraphic evidence it can be concluded that the oldest sediments at Aus near the bedrock slopes were deposited well before 105,000 BP, which is the OSL date for the younger foot-sediments. Whether the near-slope sediments formed an extensive sand ramp only or were part of a much larger valley fill cannot be decided from the data available. The removal of the major part of these sediments is assumed to have occurred prior to the deposition of the foot-sediments (cf. chap. 7.3.1), as the morphology of the latter suggests a sand ramp of much smaller extent – but still somewhat larger than the present ramp.

Archaeological evidence suggests that the deposition of the basal sediments (including the formation of the glacis and its preservation) probably came to an end before at least 40,000 BP (cf. chap. 6.3). Formation of the younger sand ramp generation will thus have occurred well before the Last Glacial Maximum, when the overlying recent sands were deposited (16,000 BP). The final phase of stabilization of the sands is ascribed to the Holocene Climate Optimum, as there seems to be agreement about a more humid and warmer phase in southern Africa around 6000 BP (TYSON & PARTRIDGE 2000). From the Koichab River aquifer, formation of ground water 5,000 – 7,000 years ago has been reported (CHRISTELIS & STRUCKMEIER 2001). The purely wind-blown deposition of the modern sands, at least partly by remobilization of the older sands, may have been initiated during the Little Ice Age, which in southern Africa is thought to have been characterized by cooler and drier conditions (LEE-THORP et al. 2001). These modern sands are still mobile.

The Quaternary of southern Africa has been studied extensively and is characterized by repeated climatic changes of considerable amplitude, but as yet no consistent picture has emerged. Between 50,000 and 35,000 years ago, for instance, coastal upwelling off Namibia appears to have been at a maximum (KIRST et al. 1999) and thus hyper-arid conditions should have prevailed inland, at least close to the coast. For about the same period, from 51,000 – 43,000 BP (HOLMGREN et al. 1995), south-eastern Botswana, also situated near the present winter rainfall region, is thought to have experienced warm and humid conditions. Given the high degree of contemporary climatic complexity in southern Africa, it is not surprising, though, that there are regional variations in climate response (MEADOWS 2001). Cf. KEMPF (2000) for a synopsis of Early to Late Pleistocene and Holocene climate indicators from various localities in southern Africa.

Attempts to correlate the established stratigraphy of the sand ramps with other chronologies of climate change established by palaeoclimatic studies from different climatic regions in southern Africa is therefore involved with difficulties. Aside from the "general complexity" of climate patterns in southern Africa, there are some particularly complicating factors in the study region. Firstly, it lies at a desert margin and will thus be especially sensitive to environmental change – but in which direction? Geomorphological research in Namibia so far has concentrated either on the Namib Desert or on the hinterland; the desert margin has been out of focus, especially the southern part.

Secondly, the study region is located about 100 km from the west coast and thus probably strongly influenced by the Benguela Current – but to what degree? The Benguela upwelling system has been studied in great detail, and there is no doubt on the effect on both the local environmental conditions along the coast as well as on the atmospheric circulation at least of the subcontinent (and vice versa!). Still, the regional impact of this intricate ocean – climate relationship can only be unravelled by detailed studies in just the region studied here. As of now, no such correlation studies have been made, though.

Thirdly, the study region is presently influenced by both summer and winter precipitation. Thus, the region must have been highly sensitive to even small changes in the position of the boundary between the two regimes during the last glacial. Palaeoclimatic results obtained from regions with a more distinct climatic regime (typical summer *or* winter rainfall areas) can therefore only be applied with difficulty.

The thoroughly updated stratigraphy of the central and southern Namib Desert by PICKFORD & SENUT (1999) focuses on its development since the beginning of the Cenozoic, but the authors unfortunately end their detailed investigation in the Early Pleistocene. They name a number of studies of Pleistocene sediments in the Namib, but only conclude that "local climatic conditions varied appreciably throughout the Quaternary between extremes ranging from semi-arid to hyper-arid." As all of these studies were conducted in the central and northern Namib only – regions less or not influenced by winter rainfall during the last glacial period – they do not lend themselves to detailed analysis for the present study.

However, there is one general trend emerging from several studies which should be mentioned in this context: Around 20,000 – 25,000 BP a period of wetter conditions has been identified for the central and northern Namib (compilations by DEACON & LANCASTER 1988 and PICKFORD & SENUT 1999). RUST (1991) also reports higher precipitation for both the hinterland and the Namib for that time. Even for the Koichab Pan in the southern Namib evidence is available; calcified reed beds there are evidence of more humid conditions around 22,800 – 29,000 BP (LANCASTER 1984, VOGEL 1989). As the ages were obtained by radiocarbon dating of roots and calcic pedotubules (root casts in the terminology of this study), they have to be handled with caution. Nevertheless, evidence of wetter conditions is irrefutable. Correlated to the development of sand ramps, it is suggested that the stabilization of the younger ramps by vegetation and soil formation occurred during this time.

There is thus no detailed stratigraphy for the Late Pleistocene and Holocene for the region. For the southern Namib just the formation of a single aeolianite, the Annental sandstone, is ascribed to the Late Pleistocene (WARD & CORBETT 1990). WARD (1987) also places the Gobabeb Gravel Formation and the Homeb Silt Formation of the central Namib in this period, which suggests at least some fluvial activity. KEMPF (2000) has identified five landform generations following the Walvis transgression (~ Eem): Aeolian sedimentation, colluvial deposits, soil formation and formation of terraces, weak gravel reactivation and the Holocene processes of weak accumulation and dissection. The Namib is still largely considered to have been basically arid ever since the Miocene (e.g. BESLER 1991, WARD & CORBETT 1990 – in spite of the gravels and silts mentioned), and HEINE (1998) explicitly states that "the hyper-arid Namib Desert experienced no significant changes in precipitation during the Late Quaternary". In view of such statements the identification of Late Pleistocene and Holocene relief generations is remarkable, indeed. However, correlation with the detailed record from the sand ramps does not seem to serve a sensible purpose.

About the chronology of aeolian accumulation in the Namib as yet nothing is known (LANCASTER 2000), in contrast to the Kalahari. For the south-western part of the Kalahari intensive aeolian activity from 22 – 28 ka BP has been identified, probably reworking all older dune sediments (STOKES et al. 1997a). According to STOKES et al. 1997b, the last major phase of dune development occurred 17,000 – 10,000 years ago, which correlates well with the accumulation of the sand dunes overlying the sand ramps. The authors ascribe the dune building phases to arid conditions – which would be out of phase with the wet period in the Namib around 20 – 25 ka and would again emphasize the differential response of climate change between regions – it may be recalled, though, that dune emplacement requires the availability of mobile sand. In agreement with this line of reasoning, CLARKE & RENDELL (1998), for instance, showed for the dunes and sand ramps of the Mojave Desert that 94% of the sands were deposited at times when pluvial lakes filled the desert basins and floods occurred in the rivers. The controlling factor of sand dune accumulation was suggested to be the supply of sediment triggered by climate change. STOKES et al. (1997a) themselves state that presently aeolian activity in the south-western Kalahari is restricted by low wind energy conditions, implicitly accepting that it takes more than just aridity to explain a time of aeolian sand transport.

In conclusion, the detailed sequence of process changes established in the present study of some southern Namibian sand ramps cannot yet be tied in with other palaeoclimatic studies, because of insufficient regional and process change resolution. Nevertheless, a more generalized correlation for the main sand ramp elements is attempted below (Fig. 151).

Compared to the sand ramps of the Mojave Desert and of central Iran already referred to (cf. chaps. 1.2.1, 1.2.2), the sand ramps studied in south-western Namibia are likely to be older, and definitely so the basal sediments of the Aus sand ramp. For the Mojave Desert, depositional phases were identified for the periods 20 – 30 ka and 15 – 7 ka (RENDELL & SHEFFER 1996), a sand ramp studied in Iran was deposited during the period 20 – 25 ka (THOMAS et al. 1997). As absolute dates for the deposition of the young sand ramps in Namibia do not yet exist, it can only be assumed from circumstantial evidence that they also developed during the Late Pleistocene. Well aware of the problem of regional response to climatic change discussed above, it is nevertheless likely that the wetter period in the Namib around 25 ka has been responsible for the stabilization of the sand ramp by facilitating soil formation. The final dissection may then already indicate the change to increasingly unstable environmental conditions in approaching the LGM.

Field evidence	Period	Reference
Young mobile sands	Little Ice Age – modern	LEE-THORP et al. 2001
Stabilization	Holocene Climate Optimum	TYSON & PARTRIDGE 2000 CHRISTELIS & STRUCKMEIER 2001
Recent aeolian sands	Last Glacial Maximum 16 ka BP	STOKES et al. 1997a, b; OSL dates, this study
Desert Pavement / Dissection	</= 20 ka BP	
Stabilization	~ 20 – 30 ka BP	LANCASTER 1984 VOGEL 1989
Sand ramp deposition; younger generation (EX, SK, Aus main body)	~ 30 – 40 ka BP?	VOGELSANG 1998
Basal sediments, foot (Aus)	~ 50 – 105 ka BP	OSL dates, this study
Basal sediments, near slope (Aus)	> 105 ka BP	

Fig. 151: General correlation of sand ramp elements with periods of landscape evolution.

10 ESSENCE OF THE STUDY

This is the first study of sand ramps in Namibia. Sand ramps of different morpho-types and ages have been identified and their sediments and morphologies described. The processes that formed the sand ramps have been identified. Sand ramps have shown to be fossil forms, and thus a detailed record of palaeoenvironmental information could be deciphered.

There are two generations of sand ramps, the older one so far only identified at Aus, with some characteristics not found in the younger generation. The younger generation comprises three morphological types: In the windward position of inselbergs, i.e. on north- to east-facing slopes, voluminous ramps are found; in the leeward position, behind mountain passes, low-volume ramps occur, either as steep forms attached the mountain slopes, or as very gently inclined ramps at the footslopes.

The most distinct characteristic of the sand ramp sediments is that there has been a close interaction of fluvial and aeolian processes of sands blown upslope in dry weather and then washed downslope, intermingled with slope debris, during heavy rains. There is no evidence of separate aeolian and fluvial layers in the sedimentary record. This implies a highly dynamic climatic system with strong winds, seasonal aridity and low-frequency, but high-intensity rainfalls. The final deposition of sand ramp material, forming the entire generation of young sand ramps, has been dated to approximately younger than 40 ka BP. Following its deposition, a phase of environmental stability under more humid conditions supported vegetation growth, thus stabilization and soil formation on the ramps, around 25 ka BP. With a shift to more arid conditions again, a desert pavement formed in response to denudation, most likely under climatic conditions like today. The ramps were then cut off from the bedrock slopes at most places, implying a change towards environmental conditions of greater variability. As so far the last major process on the sand ramps, in two phases aeolian sands came to cover their upper parts. An OSL date for the older of the two sand bodies puts its deposition around 16 ka BP, close to the Last Glacial Maximum. Regarding the source of the sands, a local origin is proposed.

During formation of the old sand ramp at Aus, the basic cycle of initial deposition, stabilization with vegetation growth and soil development and eventually denudation, as identified for the younger sand ramp generation, repeated itself at least twelve times, including a phase of calcrete or calcareous root-cast formation in each of them. This adds up to about 60 changes in morphodynamics altogether. At least nine of these cycles took place between 105 ka BP and the LGM, thereby indicating that the general cooling trend during the Late Pleistocene was complicated by a high number of oscillations of environmental conditions not documented before for southern Namibia. Due to the high relative temporal resolution obtained by the study of sand ramp development, but also due to the very special situation of the study area at a desert margin, about 100 km away from the South Atlantic and situated in the transition zone between summer and winter rainfall, correlation with those stratigraphies (of mostly lower resolution) established for different places of southern Africa do not appear promising at the moment.

In conclusion, the sand ramps studied have been shown to be a valuable object for deciphering past morphodynamics and thereby palaeoenvironmental conditions in south-western Namibia. Due to their multi-process character they have recorded this information better than exclusively aeolian or fluvial deposits. They can thus be recommended for further research with comparable aims in other parts of Namibia, where first observations show a number of differences.

This study puts sand ramps on the Namibian map and sheds some more light on the Late Quaternary landscape evolution of south-western Namibia.

Still, there are a number of open questions: When exactly did the deposition of the young sand ramps occur? What is the source of the aeolian sand fraction of the sand ramps? What is the exact relationship to the erg? Where did the calcium carbonate for the calcrete and the root casts come from, and what was the manner of transport? Are the oldest sediments of the Aus sand ramp related to the remnants of an extensive valley fill in the basin of Aus? How old are these sediments and what palaeoecological information can be obtained from them complementary to that from the sand ramps? When, and under which climatic conditions, did the erosion and removal of this enormous amount of sediment occur, and where was it deposited? What is the nature of sand ramps in other, and climatologically different regions of southern Africa? …

Additional geomorphological and sedimentological analysis beyond the present study region, on farms that could not be entered during field work for this study, and within the Restricted Diamond Area in particular, combined with additional luminescence dating, may provide answers to some of the questions. But that would be a research project of its own.

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Maps

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Aerial photographs

SURVEYOR-GENERAL: 30.09.98 14/16; 07.10.98 11/22, 11/25.

Satellite image

Landsat 5 TM, 178-077 (Tsaris), 178-078 (Tiras), January 14th, 1987. Resolution 28.5 x 28.5 m.

APPENDIX I – Luminescence dose rates, palaeodoses and age determinations

Lab no.	**Sample site; depth**	**Grain size**	**Element concentration, NAA**	**Element concentration, Gamma-spectrometry MR; error 7%**
MR0126	AW I; 70 cm	100 – 200 µm		$^{235, 238}U$: 2.85 ± 0.20 ppm ^{232}Th: 25.58 ± 1.79 ppm ^{40}K: 2.25 ± 0.16 %
MR0124	AW I; 300 cm	100 – 200 µm		$^{235, 238}U$: 3.08 ± 0.22 ppm ^{232}Th: 27.96 ± 1.96 ppm ^{40}K: 2.26 ± 0.16 %
MR0125	AW I; 490 cm	100 – 200 µm		$^{235, 238}U$: 2.12 ± 0.15 ppm ^{232}Th: 19.32 ± 1.35 ppm ^{40}K: 2.54 ± 0.18 %
MR0127	AW I; 700 cm	100 – 200 µm		$^{235, 238}U$: 2.34 ± 0.16 ppm ^{232}Th: 19.61 ± 1.37 ppm ^{40}K: 3.78 ± 0.26 %
MR0128	AW 6; 280 cm	63 – 200 µm	$^{235, 238}U$: 1.87 ± 0.19 ppm ^{232}Th: 17.20 ± 1.72 ppm ^{40}K: 3.63 ± 0.36 %	insufficient amount of sediment

Sample site; depth	**Palaeodose (SAR QZ) (Gy)**	**Dose rate QZ (Gy/ka)**	**SAR QZ Age (ka)**	**Palaeodose (SAR FSP) (Gy)**	**Dose rate FSP (Gy/ka)**	**SAR FSP Age (ka)**
AW I; 70 cm	n.a.p.			712.61 ± 59.79	5.5 ± 0.4	130.2 ± 14.2 *
AW I; 300 cm	n.a.p.			608.12 ± 14.5	5.7 ± 0.4	**106.1 ± 7.9**
AW I; 490 cm	n.a.p.			n.a.p.		
AW I; 700 cm	n.a.p.			657.68 ± 26.66	6.3 ± 0.5	**104.9 ± 8.7**
AW 6; 280 cm	90.11 ± 4.57	5.3 ± 0.4	**16.8 ± 1.5**	90.02 ± 3.23	6.0 ± 0.4	**15.0 ± 1.1**

n.a.p. = No analysis possible due to saturation effects of the growth curve (high Th^{232}-contents).
* Only one subsample datable (out of five) → no reproducibility; excluded from interpretation.

APPENDIX II - Sedimentological properties	
Legend	
Place = Farm	
AW	Klein Aus/Ausweiche
DR	Dieprivier
EX	Excelsior
GB	Gunsbewys
SK	Sandkop
TL	Tirool
WK	Waaihoek
Type	
SR	sand ramp
SR-R	sand ramp reworked
S	sand
DS	dune sand
D	dune
F	fine material
B	soil-like
K	calcretic
Grain sizes	
cs	coarse sand (2 - 0.63 mm)
ms	medium sand (0.63 - 0.2 mm)
fs	fine sand (0.2 - 0.063 mm)
csi	coarse silt (0.063 - 0.02 mm)
msi	medium silt (0.02 - 0.0063 mm)
fsi	fine silt (0.0063 - 0.002 mm)
Abbreviations in Material properties/Comments	
acc.	accumulation
aggr.	aggregates
ang.	angular
cc	calcrete
ccn	calcrete nodules
ccp	pieces of calcrete
cem.	cemented
cm	coarse material (> 2 mm)
comp.	compacted
cov.	covered
fm	fine material (< 2 mm)
homog.	homogenous
mtrl	material
part.	particles
patin.	patinated
pavem.	pavement
prop.	proportion
qz	quartz
r.fr.	rock fragments
sf.	surface
sr	sand ramp
str.	strongly
subang.	subangular
subro.	subrounded
Others	
* Mean of two sievings. As a result, summary of grain size fraction might not be 100%.	
** Rise of temperature during measurements -> particles sinking faster	
1) Corrected for clay content (LOI minus 0.1% per percent clay (if clay content determined))	
2) bf: basically free of $CaCO_3$ (below 1% = limit of detection)	

Sedimentological properties, samples from Excelsior and Sandkop													
Location		**Sample**						**Grain size (weight %)**					
S	E	Date	Place	Point	No.	Depth (cm)	Type	> 2 mm	< 2 mm	CS	MS	FS	< 63µm
EXCELSIOR													
Steep sandramp in inselberg complex (A)													
Top/Pass, ripples													
~26°12.820'	016°27.150'	03.12.1999	EX	15	18	15 - 25	DS	7	93	6	49	42	3
Top, between stones and grus													
~26°12.820'	016°27.150'	03.12.1999	EX	16	19	15 - 25	DS	3	97	8	48	41	3
Middle slope													
~26°12.890'	016°27.160'	03.12.1999	EX	18	21	0 - 5	SR	0.3	99.7	8	59	31	2
~26°12.890'	016°27.160'	03.12.1999	EX	18	22	15 - 25	SR	0.5	99.5	11	57	29	3
Sand ramp with calcrete nodules (B2)													
Middle slope													
26°12.770'	016°26°175'	03.12.1999	EX	20	25	1 - 5	SR	9	91	* 29	16	48	7
26°12.770'	016°26°175'	03.12.1999	EX	20	27	50 - 60	SR	6	94	* 21	15	55	9
Big sand ramp with triangular sand ramp (C)													
Upper slope - steep ramp													
~26°13.560'	016°27.550'	15.02.2000	EX	36	3	5 - 15	SR	0	100	7	57	33	3
~26°13.560'	016°27.550'	15.02.2000	EX	36	4	45 - 55	SR	0	100	5	58	33	4
Lower slope - flat ramp													
~26°13.755'	016°27.755'	15.02.2000	EX	37	5	5 - 15	SR	5	95	7	42	47	4
~26°13.755'	016°27.755'	15.02.2000	EX	37	6	45 - 55	SR	3	97	5	48	43	4
Lower slope - flat ramp													
~26°13.700'	016°27.580'	15.02.2000	EX	38	7	5 - 15	SR	4	96	10	35	51	4
~26°13.700'	016°27.580'	15.02.2000	EX	38	8	45 - 55	SR	4	96	8	38	50	4
Triangular sand ramp													
~26°13.680'	016°27.455'	15.02.2000	EX	35	1	5 - 15	SR	3	97	0.5	12	83	4.5
~26°13.680'	016°27.455'	15.02.2000	EX	35	2	45 - 55	SR	2	98	1	14	81	4
Sand ramp in Tierkloof													
Upper slope													
~26°08.340'	016°27.640'	05.02.2000	EX	31	1	5 - 15	SR	0	100	0.5	53	43	3.5
Lower slope													
~26°08.365'	016°27.800'	05.02.2000	EX	32	2	5 - 15	SR	7	93	22	29	43	6
"Debris ridge" near barrier dune													
~26°12.930'	016°26.640'	03.12.1999	EX	19	23	5 - 15	DS/F/B	33	67	10	24	58	8
River terrace													
~26°13.650'	016°25.210'	30.11.1999	EX	7	8	2 - 10	F/B/P	2	98	* 3	3	46	48
SANDKOP													
Sand ramp Sandkop													
Upper slope - drilling core													
26°27.160'	016°31.545'	15.10.1999	SK	8	1	50 - 60	SR	0	100	* 14	32	49	5
26°27.160'	016°31.545'	15.10.1999	SK	8	4	135 - 150	SR	0	100	* 15	39	43	3
Transition sand ramp - surrounding (N)													
26°26.709'	016°32.362'	01.11.1999	SK	3	6	0 - 8	S/B	3	97	17	22	56	5
26°26.709'	016°32.362'	01.11.1999	SK	3	7	10 - 20	S/B	2	98	14	18	60	8
26°26.709'	016°32.362'	01.11.1999	SK	3	8	25 - 35	S/B	3	97	21	23	49	7
Transition sand ramp - surrounding (S)													
26° 28.313'	016° 32.310'	13.02.2000	SK	51	1	5 - 15	S/B	3	97	12	26	54	8
26° 28.313'	016° 32.310'	13.02.2000	SK	51	2	25 - 35	S/B	4	96	17	33	41	9
Sand over calcrete													
26°24.226'	016°31.780'	31.10.1999	SK	3	5	5 - 15	S/B	2	98	33	15	44	7
Deepest point in basin													
26°26.870'	016°33.467'	01.11.1999	SK	2	4	3 - 15	F/B	22	78	23	15	47	15
26°26.870'	016°33.467'	01.11.1999	SK	2	5	15 - 30	F/B	21	79	22	18	40	20

Sedimentological properties, samples from Excelsior and Sandkop

Sample			Grain size (w. %)				Soil	LOI (%)	pH	CaCO3 (%)		Munsell Colours	
Place	Point	No.	CSi	MSi	FSi	Clay	texture class	1)	in KCl	Titration	Scheibler	Code	Soil Colour Names
EX	15	18					(sand)	0.5	7				
EX	16	19					(sand)	0.5	7	0		5YR 5/8 - 4/8	yellowish red
EX	18	21					(sand)	0.4	6.1				
EX	18	22					(sand)	0.4	7	0		5YR 5/8	yellowish red
EX	20	25	4	0.5**	7	0.4	sand	0.6	8.1	0.1	bf	5YR 5/6 - 4/8	yellowish red
EX	20	27	3	0.5	7	4	sand	0.8	8.1	0.3	bf	5YR 5/6 - 4/8	yellowish red
EX	36	3					(sand)	0.5	6.5				
EX	36	4					(sand)	0.5	6.4	0		5YR 5/6 - 4/8	yellowish red
EX	37	5					(sand)	0.6	6.6				
EX	37	6					(sand)	0.5	6.6	0		5YR 5/8 - 4/8	yellowish red
EX	38	7					(sand)	0.7	6.5				
EX	38	8					(sand)	0.5	7.4				
EX	35	1					(sand)	0.6	6.8	0		5YR 5/8 - 4/8	yellowish red
EX	35	2					(sand)	0.6	6.6	0		5YR 5/8	yellowish red
EX	31	1					(sand)	0.5	5.2	0		5 YR 4/8	yellowish red
EX	32	2					(sand)	0.7	5.6	0		5 YR 4/8	yellowish red
EX	19	23					(sand)	0.7	5.9	0		5YR 5/8 - 4/8	yellowish red
EX	7	8	17	15	14	3	sandy loam	2.7	7.7	4	4	10YR 7/3	very pale brown -
												- 6/3	pale brown
SK	8	1	2	0.3 **	6	1	sand	0.8	6.5	0	bf	5YR 5/6 - 5/8	yellowish red
SK	8	4	0.5	0	7	0.3	sand	0.5	7.2	0	bf	5YR 5/6	yellowish red
SK	3	6					(sand)	0.8	5.7	0		5YR 4/8	yellowish red
SK	3	7					(sand)	0.8	5.8	0		5YR 4/8	yellowish red
SK	3	8					(sand)	0.9	6.1	0		5YR 4/8	yellowish red
SK	51	1					(sand)	0.8	6.3	0		5YR 4/8	yellowish red
SK	51	2					(sand)	0.9	7.3	0		5YR 5/8 - 4/8	yellowish red
SK	3	5					(sand)	0.8	7	0		5YR 5/6 - 4/8	yellowish red
SK	2	4					(sand)	1.8	7.8	0.7		7.5YR 5/6	strong brown
SK	2	5					(sand)	2.0	7.8	2		5YR 5/6	yellowish red

Sedimentological properties, samples from Excelsior and Sandkop				
Sample			**Material properties**	**Comments**
Pl.	Pnt.	No.		
EX	15	18	very ang. grus & gravel	Pass; sf: cs ripples, ms in betw., aeolian activ.; > 30 cm stones, rock
EX	16	19	very ang.	concavity: stones + gravel at sf; > 45cm stones, rock
				17: convex sand acc., very steep; sand not comp., loose, but stable sf.
EX	18	21	few small ang. grus part.	0-6 cm layered; steep; grasses + herbs
EX	18	22	few small subang. grus part.	many very fine rootlets
EX	20	25	ro. qz, subr. grus, some ccn	ccn on sf.; profile homogenous
EX	20	27	ro. qz, subr. grus, without ccn	
EX	36	3	few grus part.; homog.	upper slope with some aeolian activ., but above even steeper;
EX	36	4	few grus part.; profile stable	sf: few grus part.; micro relief; root coatings
EX	37	5	homog.; diff. to dig	eastern part of sr, betw. 2 dissections/lower parts;
EX	37	6		sf: dense pavem. grus + gravel, "fresh"
EX	38	7		on main sr. betw. "ridge" + car; compare with EX 37
EX	38	8	small stones within profile	
EX	35	1	homog.	sf: pavem. grus + gravel, no patina, ang.; sand weakly comp.,
EX	35	2		but profile stable
EX	31	1	layered; slightly comp.	uppermost part of sr with recent/modern aeolian activ.
EX	32	2	slightly comp.	mtrl clearly much coarser, cs, grus, gravel, ang. - subang.; partly patina
			further downslope: harder, comp., no sandy character, gravelly pavem.	
EX	19	23	diff. to dig	debris ang. - subang., cov. by fm; sf: cm, "dirty" (= silty);
				many stones in profile, diff. to dig; 1 block 4 cm apart
EX	7	8	greyish; very hard aggr. (silty)	> 13cm very hard
SK	8	1	7 grus part., subang.	
SK	8	4	14 grus part., subang.	
SK	3	6	loose mtrl	sf. grus - sand, but micro-relief (ripples), soft; *Stipagrostis obtusa*
SK	3	7	aggr.; fm comp.	
SK	3	8	even more aggr.; fm comp.	
SK	51	1	0.5 cm loose sand and grus	sf. not vegetated
SK	51	2	colourful grus + fine gravel, slightly patin.; smaller part. subang., larger ones subang.-ang.	
SK	3	5	calcrete part., ro. qz	
SK	2	4	no aggr.; ro. qz; higher prop. of smaller part.	
SK	2	5		

Sedimentological properties, samples from Gunsbewys, Waaihoek and Tirool

Location		Sample						Grain size (weight %)					
S	E	Date	Place	Point	No.	Depth (cm)	Type	> 2 mm	< 2 mm	CS	MS	FS	< 63µm
GUNSBEWYS													
Sand ramp Gunsbewys													
Upper slope													
26° 08.601'	016° 23.350'	09.03.2000	GB	13	2	5 - 15	SR	7	93	* 24	21	49	6
26° 08.601'	016° 23.350'	09.03.2000	GB	13	4	70 - 80	SR	9	91	* 33	19	41	7
Lower slope													
~26°08.620'	016°23.520'	09.03.2000	GB	14	6	5 - 15	SR/F/B	32	68	* 15	19	55	11
~26°08.620'	016°23.520'	09.03.2000	GB	14	8	> 50	SR/F/B	58	42	* 18	16	45	21
Ridge near dunes													
26° 11.111'	016° 21.240'	03.03.2000	GB	10	1	5 - 15	D/SR	1	99	* 14	31	51	4
26° 11.111'	016° 21.240'	03.03.2000	GB	10	2	50 - 65	D/SR	3	97	9	29	55	7
26° 11.111'	016° 21.240'	03.03.2000	GB	10	6	175 - 190	D/SR	5	95	* 21	14	55	10
26° 11.111'	016° 21.240'	04.03.2000	GB	10	11	380 - 395	D/SR	5	95	29	13	43	15
26° 11.111'	016° 21.240'	06.03.2000	GB	10	15	590 - 600	D/SR	4	96	* 21	12	54	13
Modern dune sand													
~26°10.850'	016°21.240'	19.02.2000	GB	3	1	30 - 40	DS	0	100	0	23	76	1
~26°10.850'	016°21.240'	19.02.2000	GB	3	2	30 - 40	DS	0	100	0	19	78	3
~26°10.850'	016°21.240'	19.02.2000	GB	3	3	25 - 30	DS	0	100	0	34	65	1
WAAIHOEK													
Sand ramp Waaihoek													
Upper slope													
26°16.450'	016°30.451'	05.11.1999	WK	7	7	5 - 15	SR	0	100	* 10	44	41	5
26°16.450'	016°30.451'	05.11.1999	WK	7	8	30 - 40	SR	0.5	99.5	19	35	42	4
Middle slope													
~26°16.430'	016°30.520'	05.11.1999	WK	8	10	30 - 40	SR	6	94	19	21	53	7
Lower slope													
26°16.484'	016°30.523'	05.11.1999	WK	9	12	5 - 15	SR	7	93	* 21	19	51	9
26°16.484'	016°30.523'	05.11.1999	WK	9	14	55 - 65	SR	10	90	* 15	19	56	10
Erg													
3rd interdune													
26°16.480'	016°26.270'	22.11.1999	WK	12	3	10 - 20	DS	0.3	99.7	* 12	28	50	10
26°16.480'	016°26.270'	22.11.1999	WK	12	5	40 - 60	DS	0.5	99.5	* 11	24	58	7
Dune crest													
~26°16.270'	016°26.310'	22.11.1999	WK	14	8	0-5	DS	0	100	0	67	32	1
TIROOL													
Longitudinal dune													
Between 2 crests													
26° 24.279'	016° 29.148'	26.11.1999	TL	22c	5	7 - 14	DS	0	100	0.1	55	44	1
26° 24.279'	016° 29.148'	26.11.1999	TL	22c	8	> 40	DS	0	100	0.1	39	60	0.5
Dune crest													
26° 24.279'	016° 29.148'	26.11.1999	TL	22b	10	1 - 5	DS	0	100	0	54	45	1
Dune base													
26° 24.279'	016° 29.148'	26.11.1999	TL	22a	12	5 - 10	DS	0	100	3	33	61	3
26° 24.279'	016° 29.148'	26.11.1999	TL	22a	15	50 - 60	DS	0	100	2	38	59	1
Terrace cemented by calcrete, near dunes													
26° 23.812'	016° 25.526'	26.11.1999	TL	23c	17	5 - 15	F/B/K	2	98	3	42	48	7
26° 23.812'	016° 25.526'	26.11.1999	TL	23b	19	10 - 20	F/B/K	51	49	21	21	46	12
26° 23.812'	016° 25.526'	26.11.1999	TL	23b	20	30 - 40	F/B/K	5	95	25	22	39	14

Sedimentological properties, samples from Gunsbewys, Waaihoek and Tirool

Sample			Grain size (w. %)				Soil	LOI (%)	pH	CaCO3 (%)		Munsell Colours	
Place	Point	No.	CSi	MSi	FSi	Clay	texture class	1)	in KCl	Titration	Scheibler	Code	Soil Colour Names
GB	13	2	2	1.7	6	3	sand	0.6	6.3	0	bf	5YR 5/6 - 4/8	yellowish red
GB	13	4	2	0.2	7	1	sand	0.6	6.8	0	bf	5YR 4/8	yellowish red
GB	14	6	6	1.5	6	1	sand	1.0	6.1	0	bf	5YR 4/8	yellowish red
GB	14	8	4	3	7	13	loamy sand	1.8	7.8	0.1	bf	5YR 6/6 - 5/6	reddish yellow
													- yellowish red
GB	10	1	2	1	6	0.1	sand	0.6	6.3	0	bf	5YR 4/8	yellowish red
GB	10	2					(sand)	0.8	6.7	0			
GB	10	6	4	1	7	2	sand	1.0	8.1	0.1	bf	5YR 4/8	yellowish red
GB	10	11					(sand)	1.1	8.3	0.4		5YR 4/8	yellowish red
GB	10	15	4	2	9	6	sand	1.2	8.3	0.9	bf	5YR 5/6	yellowish red
GB	3	1					(sand)	0.5	6.2				
GB	3	2					(sand)	0.6	6.0				
GB	3	3					(sand)	0.5	6.2				
WK	7	7	2	2	6	0.0	sand	0.5	6.4	0	bf	7.5YR 5/6 - 5/8	strong brown
WK	7	8					(sand)	0.5	6.6	0		7.5YR 5/6 - 5/8	strong brown
WK	8	10					(sand)	0.7	7	0		7.5YR 5/6 - 5/8	strong brown
													(-yellowish red)
WK	9	12	3	0.5	8	0.0	sand	0.7	6.5	0	bf	5YR 5/6 - 4/8	yellowish red
WK	9	14	5	0.1	7	4	sand	0.7	7.2	0	bf	5YR 5/8 - 4/8	yellowish red
WK	12	3	6	1	7	1.5	sand	0.8	8	0.2	bf	5YR 5/6	yellowish red
WK	12	5	3	1	7	3	sand	1.3	8.3	2	2	5YR 6/6 - 5/6	reddish yellow
													- yellowish red
WK	14	8					(sand)	0.4	6	0		5YR 5/8	yellowish red
TL	22c	5					(sand)	0.4	6.3	0		7.5YR 5/8	strong brown (-y.r.)
TL	22c	8					(sand)	0.4	6.4	0		7.5YR 5/8	strong brown
													(-yellowish red)
TL	22b	10					(sand)						
TL	22a	12					(sand)	0.5	6.8				
TL	22a	15					(sand)	0.5	6.8				
TL	23c	17					(sand)	0.7	8.4	0		5YR 5/8	yellowish red
TL	23b	19					(sand)	1.3	8.4	5		5YR 6/6	reddish yellow
TL	23b	20					(sand)	1.6	8.4	5		5YR 6/6	reddish yellow

Sedimentological properties, samples from Gunsbewys, Waaihoek and Tirool				
Sample			Material properties	Comments
Place	Point	No.		
GB	13	2	ang. - subang.	
GB	13	4	ang. - subang. (without large part.)	
GB	14	6		rel. many + strong roots
GB	14	8		
GB	10	1		
GB	10	2	roundish, slightly comp. aggr.	
GB	10	6	more silt, lighter	
GB	10	11		
GB	10	15		
GB	3	1	no mtrl > 2 mm	dune crest, dry; sand flows through sieve
GB	3	2	no mtrl > 2 mm	wet
GB	3	3	no mtrl > 2 mm	above 3:1, wet
WK	7	7		
WK	7	8	main part. subang., partly subro., partly ang.	
WK	8	10	> 2 mm as sample 9	
WK	9	12		
WK	9	14	> 2 mm as sample 12	
WK	12	3	c. 25 grus part., subro., not pat.	sand flows through sieve (sample 5 too)
WK	12	5	2 ccn, c. 20 grus part., subro., not pat.	
WK	14	8		sand flows through sieve
TL	22c	5	clearly layered; no mtrl > 2 mm	sf. mtrl very well sorted; no roots; at 14 cm 5 mm coarser, loose mtrl
TL	22c	8	slightly layered; no mtrl > 2 mm	no roots
TL	22b	10		
TL	22a	12	few ro. aggr., 3 subang. qz. grains	less well sorted; sf: very coarse sand
TL	22a	15	1 qz. grain, subang.; no aeol. layers	profile stable
TL	23c	17	aeol. layers, no aggr., ro. qz., single ccn	
TL	23b	19	many ccn!, some ro. qz. grains	
TL	23b	20	greyish appearance; homog.	

Sedimentological properties, samples from Klein Aus/Ausweiche										
Location		Sample							Grain size (w. %)	
S	E	Date	Place	Point	Stratum	No.	Depth (cm)	Type	> 2 mm	< 2 mm
KLEIN AUS/AUSWEICHE										
Sand ramp Aus										
Sections naturally exposed										
AW I, foot of sand ramp, N (A - E)							samples from:			
26°39.780'	016°06.249'	15.08.2001	AW	I	AW I / 2	1	6 - 42	SR-R	19	81
26°39.780'	016°06.249'	15.08.2001	AW	I	AW I / 4	2	85 - 130	SR-R	11	89
26°39.780'	016°06.249'	15.08.2001	AW	I	AW I / 6	3	150 - 220	SR-R	17	83
26°39.780'	016°06.249'	15.08.2001	AW	I	AW I / 8	6	260 - 330	SR-R	1.5	98.5
26°39.780'	016°06.249'	15.08.2001	AW	I	AW I / 9	7	340 - 370	SR-R	5	95
26°39.780'	016°06.249'	15.08.2001	AW	I	AW I / 10	9	370 - 630	SR-R	10	90
AW III, foot of sand ramp, middle (Chamaeleon)							samples from:			
26°40.458'	016°06.472'	16.08.2001	AW	III	AW III / 1	1	40 - 70	SR-R	0.2	99.8
26°40.458'	016°06.472'	16.08.2001	AW	III	AW III / 2	2	70 - 330	SR-R	2	98
26°40.458'	016°06.472'	16.08.2001	AW	III	AW III / 4	3	470 - 490	SR-R	14	86
26°40.458'	016°06.472'	16.08.2001	AW	III	AW III / 4	4	930 - 950	SR-R	2	98
AW IV, foot of sand ramp, S (kraal)							from below:			
26°41.397'	016°05.935'	15.08.2001	AW	IV	AW IV / 1		150	SR-R	0.3	99.7
26°41.397'	016°05.935'	15.08.2001	AW	IV	AW IV / 2		200	SR-R	0.1	99.9
AW VIII, foot of sand ramp, near NW fence							from below:			
26°39.554'	016°06.011'	17.08.2001	AW	VIII		3	250	SR-R	50	50
26°39.554'	016°06.011'	17.08.2001	AW	VIII		4	220	SR-R	93	7
AW VI, at hillslope							from below:			
26° 40.019'	016° 05.802'	16.08.2001	AW	VI	AW VI / 3	6	1200	SR-R	8	92
26° 40.019'	016° 05.802'	16.08.2001	AW	VI	AW VI / 2	5	900	SR-R	22	78
26° 40.019'	016° 05.802'	16.08.2001	AW	VI	AW VI / 2	4	600	SR-R	14	86
26° 40.019'	016° 05.802'	16.08.2001	AW	VI	AW VI / 1	3	100	SR-R	3	97
26° 40.019'	016° 05.802'	16.08.2001	AW	VI	AW VI / 1	2	70	SR-R	8	92
26° 40.019'	016° 05.802'	16.08.2001	AW	VI	AW VI / 1	1	40	SR-R	2	98
AW IX, discontinuous valley										
26°40.380'	016°06.194'	17.08.2001	AW	IX		5	150-160	SR-R		
26°40.380'	016°06.194'	17.08.2001	AW	IX		6	175-190	SR-R	1	99
26°40.380'	016°06.194'	17.08.2001	AW	IX		7	200-220	SR-R	3	97
26°40.380'	016°06.194'	17.08.2001	AW	IX		8	280	SR-R	0.1	99.9
Sections dug										
AW 3, main body										
26° 40.295'	016° 05.621'	04.05.2000	AW	3		5	1 - 5	SR	0.3	99.7
26° 40.295'	016° 05.621'	04.05.2000	AW	3		8	50 - 60	SR	0.5	99.5
AW VII, main body near IV										
26°41.265'	016°05.861'	17.08.2001	AW	VII		1	10 - 20	SR	0.3	99.7
26°41.265'	016°05.861'	17.08.2001	AW	VII		2	40 - 50	SR	0	100
AW X, main body even higher up										
26°40.424'	016°05.966'	17.08.2001	AW	X		9	1 - 10	SR	0	100
26°40.424'	016°05.966'	17.08.2001	AW	X		10	40 - 50	SR	0.3	99.7
AW 7, between two longitudinal dunes on top of sand ramp										
26° 40.524'	016° 05.460'	09.05.2000	AW	7		10	1 - 5	SR	0.5	99.5
26° 40.524'	016° 05.460'	09.05.2000	AW	7		12	35 - 50	SR	1.5	98.5
AW 6, longtitudinal dune on top of sand ramp										
26° 40.508'	016° 05.531'	09.05.2000	AW	6		2	1 - 5	DS/SR	0	100
26° 40.508'	016° 05.531'	09.05.2000	AW	6		5	75 - 90	DS/SR	0.5	99.5
26° 40.508'	016° 05.531'	09.05.2000	AW	6		8	225 - 235	DS/SR	0	100
AW V, dune at cut-off part										
26°40.599'	016°05.424'	16.08.2001	AW	V	AW V / 1		15 - 30	DS/SR	2	98
AW 8, longitudinal dune next to sand ramp										
~26°40.140'	016°06.580'	11.05.2000	AW	8		1	0 - 10	DS	0.5	99.5
~26°40.140'	016°06.580'	11.05.2000	AW	8		2	10 - 20	DS	0	100
DIEPRIVIER										
Tsondab Sandstone, soil formation										
24°06.814'	015°53.671'	19.08.2001	DR	I					0	100

Sedimentological properties, samples from Klein Aus/Ausweiche														
Sample		**Grain size (weight %)**								Soil	**LOI (%)**	**pH**	**CaCO3 (%)**	
Stratum	No.	CS	MS	FS	< 63µm	CSi	MSi	FSi	Clay	texture class	1)	in KCl	Titration	Scheibler
AW I / 2	1	* 20	28	31	21	5	2	11	8	loamy sand	2.9	8.3	10	17
AW I / 4	2	* 34	28	25	13	5	0	6	6	loamy sand	2.0	8.9	3	3
AW I / 6	3	23	29	29	18					(loamy sand)	2.6	8.7	0.4	
AW I / 8	6	* 34	25	23	18	6	4	10	4	loamy sand	1.5	8.6	0.3	2
AW I / 9	7	16	37	26	21					(loamy sand)	1.5	8.3	2	
AW I / 10	9	* 13	41	26	20	14	0 **	8	9	loamy sand	1.6	8.5	0.2	1
AW III / 1	1	36	23	26	15					(loamy sand)	1.2	8.5	2	
AW III / 2	2	24	31	29	16					(loamy sand)	1.2	8.5	10	
AW III / 4	3	14	41	27	18					(loamy sand)	1.5	7.9	0.1	
AW III / 4	4	15	44	26	15					(loamy sand)	1.3	7.9	0.2	
AW IV / 1		23	27	28	22					(loamy sand)	1.8	8.1	0.2	
AW IV / 2		* 24	28	27	21	7	4	8	5	loamy sand	2.7	8.1	0	bf 2)
										/sandy loam				
AW VIII	3	24	47	16	13					(sand)	1.2	8.2	2	
AW VIII	4	27	40	19	14					(sand)	1.5	8.7	2	
AW VI / 3	6	* 12	28	49	11	3	0	7	1.5	sand	1.1	7.8	0.1	bf
AW VI / 2	5	11	18	53	18					(loamy sand)	1.7	7.7	0.3	
AW VI / 2	4	* 10	25	48	17	7	1.5	8	3	loamy sand	1.8	7.9	1	
AW VI / 1	3	* 6	34	47	13	4	3	7	0.5	loamy sand	1.2	7.4	0.1	bf
AW VI / 1	2	5	31	46	18					(loamy sand)	2.2	7.7	0.2	
AW VI / 1	1	* 4	25	47	24	12	5	9	9	loamy sand/	3.0	7.7	3	17
AW IX	5	* 40	27	15	18	4	4	10	4	loamy sand	1.3	8	0.5	bf
AW IX	6	25	22	30	23					(loamy sand)	1.8	8.1	0.5	
AW IX	7	* 22	30	26	22	7	4	9	5	loamy sand	2.1	8.4	3	6
AW IX	8	15	39	31	15					(loamy sand)	1.3	8.2	0.2	
AW 3	5	* 17	48	29	6	4	0.5 **	7	1	sand	0.7	7.5	0	bf
AW 3	8	* 19	40	29	12	5	1.5	8	4	sand	1.2	7.9	1	1
AW VII	1	17	38	33	12					(sand)	0.7	6.6	0.1	
AW VII	2	25	33	28	14					(sand)	0.9	6.9	0	
AW X	9	25	40	28	7					(sand)	0.6	7.3	0	
AW X	10	* 30	31	28	11	6	1	7	3	sand	0.6	7.2	0.1	bf
AW 7	10	12	42	40	6					(sand)	0.9	6.3	0	
AW 7	12	15	32	42	11					(sand)	0.9	7	0	
AW 6	2	* 18	46	31	5	1.5	0	7	1.5	sand	0.6	6.3	0	0
AW 6	5	24	41	29	6					(sand)	0.6	6.6	0	
AW 6	8	* 12	54	30	4	1.5	0	6	1	sand	0.5	6.8	0	0
AW V / 1		*21	40	29	10					(sand)	0.9	7.1	0	bf
AW 8	1	23	55	21	1					(sand)	0.4	6.3	0	
AW 8	2	0.2	52	46	2					(sand)	0.6	6.5	0	
DR I		* 0	17	64	18	8	8	5	1.5	loamy sand		7.9	2.4	

Sedimentological properties, samples from Klein Aus/Ausweiche

Sample		**Munsell Colours**	
Stratum	No.	Code	Soil Colour Names
AW I / 2	1	7.5YR 8/4 - 7/4	pink
AW I / 4	2	5YR 6/6 - 5/8	reddish yellow - yellowish red
AW I / 6	3	5YR 6/6 - 5/6	reddish yellow - yellowish red
AW I / 8	6	5YR 6/6 - 5/6	reddish yellow - yellowish red
AW I / 9	7	5YR 5/6 - 5/8	reddish yellow - yellowish red
AW I / 10	9	5YR 5/6 - 4/8	yellowish red
AW III / 1	1	7.5YR 7/4 - 6/4	pink-light brown
AW III / 2	2	7.5YR 7/4 - 6/4	pink-light brown
AW III / 4	3	5YR 5/6 - 5/8	yellowish red
AW III / 4	4	5YR 5/8	yellowish red
AW IV / 1		5YR 6/6	reddish yellow
AW IV / 2		5YR 6/6 - 5/6	reddish yellow - yellowish red
AW VIII	3	7.5YR 5/6 - 5/8	strong brown
AW VIII	4	7.5YR 6/6 - 5/6	reddish yellow - strong brown
AW VI / 3	6	5 - 7.5YR 5/8	yellowish red - strong brown
AW VI / 2	5	5YR 5/6 - 4/8	yellowish red
AW VI / 2	4	5YR 5/8 - 4/8	yellowish red
AW VI / 1	3	5YR 5/8 - 4/8	yellowish red
AW VI / 1	2	5YR 5/6	yellowish red
AW VI / 1	1	5YR 6/6 - 5/6	reddish yellow - yellowish red
		- 7.5YR 5/8	
AW IX	5	7.5YR 5/6	strong brown
AW IX	6	7.5YR 5/6 - 5/8	strong brown
AW IX	7	7.5YR 7/4 - 7/6	pink-reddish yellow
AW IX	8	5 - 7.5YR 5/8	yellowish red - strong brown
AW 3	5	5 - 7.5YR 5/6	yellowish red - strong brown
AW 3	8	7.5YR 6/6 - 5/6	reddish yellow - strong brown
AW VII	1	5YR 5/6 - 5/8	yellowish red
AW VII	2	5YR 5/8 - 4/8	yellowish red
AW X	9	5YR 5/6 - 5/8	yellowish red
AW X	10	5YR 5/8	yellowish red
AW 7	10	5YR 5/8	yellowish red
AW 7	12	5YR 5/8	yellowish red
AW 6	2	5YR 5/8	yellowish red
AW 6	5	5YR 5/8	yellowish red (- strong brown)
AW 6	8	5YR 5/8	yellowish red
AW V / 1		5YR 5/8 - 4/8	yellowish red
AW 8	1	7.5YR 6/8 - 5/8	reddish yellow - strong brown
AW 8	2	7.5YR 6/8 - 5/8	reddish yellow - strong brown
DR I		5YR 6/6 - 5/6	reddish yellow - yellowish red

Sedimentological properties, samples from Klein Aus/Ausweiche

Sample		**Material properties**
<u>Stratum</u>	<u>No.</u>	
AW I / 2	1	cm: many ccp, sample very light = $CaCO_3$; grus (qz, r.fr.)-small stones, ang.-subang.
AW I / 4	2	cm: ccn, grus (qz, r.fr.), ang.-subang.
AW I / 6	3	str. cem., very hard, $CaCO_3$!; many ccp; grus even qz, r.fr., ang.-subang.
AW I / 8	6	cem., partly str. cem., $CaCO_3$, cm: few, small ccp; grus: ccp, qz, r.fr., ang.-subang.
AW I / 9	7	str. cem. ($CaCO_3$?); cm: grus - gravel, ccp, few grus part., qz, r.fr., ang.-subang.
AW I / 10	9	cm: ccp, rather ang., 1 - 2 cm, few grus part., qz, r.fr., ang.-subang.
AW III / 1	1	cem.; 2 grus part., qz, r.fr., ang.-subang.; light colour
AW III / 2	2	str. cem.; cm: 1 ccp, 1 cm; 3 grus part., qz, r.fr., ang.-subang.
AW III / 4	3	cem.; red; cm: hard ccp (fm comp.); few grus part., qz, feldspar, r.fr., ang.-subang.
AW III / 4	4	cem.; cm: ang. ccp; grus: qz, r.fr., ang.-subang., red patina
AW IV / 1		str. cem., root casts; 1 grus part.: ccn
AW IV / 2		str. cem., hard; 1 grus part.: qz, ang.-subang.
AW VIII	3	str. cem., $CaCO_3$; cm: up to gravel, ang.-subang., variating composition, partly ccp
AW VIII	4	cm: up to large stones, slightly patin., slightly clay layered, ang.-subang., var. compos.
		hard ccp as stones, stones often weak, fall apart under pressure; few aggr.
AW VI / 3	6	str. cem.; grus - gravel, qz, r.fr., ang.-subang.
AW VI / 2	5	str. cem.; red-brown; cm: grus - small stones, all light r.fr., max. subang.
AW VI / 2	4	str. cem.; grus - gravel, ccp, feldspar, qz, r.fr., ang.-subang.
AW VI / 1	3	str. cem.; grus - gravel, feldspar, qz, r.fr., ang.-subang.
AW VI / 1	2	str. cem., hard; cm: ang.!, small stones, grus partly subang., mostly r.fr.; garnets?
AW VI / 1	1	str. cem., hard ($CaCO_3$); cm: ang., comparable to sample 2, bit less and smaller
AW IX	5	
AW IX	6	str. cem.; cm: grus part., qz, feldspar, r.fr., subang.
AW IX	7	cem.; cm: ccp, 3 grus part., qz, feldspar, ang.-subang.
AW IX	8	cem.; 1 grus part., feldspar, ang.-subang.
AW 3	5	little cm, fine gravel, subang.-subro. qz and feldspar
AW 3	8	little cm, fine gravel, subang.-subro. qz and feldspar
AW VII	1	4 grus part. qz, subang.-subro., slightly pitted; 1 r.fr. ang., 1 feldspar
AW VII	2	1 grus part. qz, subang.-subro., slightly pitted; homog.
AW X	9	homog.
AW X	10	2 grus part., subro.
AW 7	10	coarse grus and coarser, subang., small weak aggr.
AW 7	12	coarse grus and coarser, subang., more aggr.
AW 6	2	grus slightly > 2 mm, subro. qz
AW 6	5	grus slightly > 2 mm, subro. qz; clearly more cm
AW 6	8	1 grus part.
AW V / 1		loose; grus-fine gravel, r.fr., qz, feldspar, ang.-subang., slightly orange patin.
AW 8	1	little cm, only grus, qz, feldspar, subang.-subro.; much cs, esp. 7 - 10 cm; aeol. layers clear!
AW 8	2	no cm; very fine mtrl, silt layers; stable profile; very well sorted

Sedimentological properties, samples from Klein Aus/Ausweiche

Sample		Comments
Stratum	No.	
AW I / 2	1	upper crust, soil sediment str. CaCO3-cem., slope debris, root casts
AW I / 4	2	sandy - grusy/gravelly, slightly carbonated; strong and many root casts
AW I / 6	3	washed-down sands with lots of slope debris; big root casts, stronger cem. than 4
AW I / 8	6	sandy, few root casts
AW I / 9	7	root casts, more CaCO3
AW I / 10	9	red sands, no cm, CaCO3-content and root penetration decreasing downwards; regional CaCO3
AW III / 1	1	carbonated sr-mtrl, diggable, cs-silt, root casts
AW III / 2	2	sr-mtrl
AW III / 4	3	downwards increasing carbonatization along the roots, hard root casts
AW III / 4	4	loose, sandy, slightly comp., single root casts
AW IV / 1		str. cem. by CaCO3 up to 160 cm
AW IV / 2		on sf.: less carbonate, but behind same as sample 1
AW VIII	3	without stoneline
AW VIII	4	only stoneline
AW VI / 3	6	top of profile
AW VI / 2	5	
AW VI / 2	4	less cem. than below; upper, vertical part
AW VI / 1	3	
AW VI / 1	2	
AW VI / 1	1	AW VI: pinkish mtrl on hillslope, carbonated, reminds of AW IV
AW IX	5	brown sediment, sheet structure, CaCO3-cem. after deposition
AW IX	6	red-brown soil sediment, CaCO3-cem. after deposition
AW IX	7	str. cem. (CaCO3) soil sediment
AW IX	8	decrease in CaCO3-content downwards; root casts
AW 3	5	sf. deflation pavement grus - cs, esp. ro. qz, less feldspar (ro.); first cm very loose sand
AW 3	8	> 10 cm stable
AW VII	1	typ. sr-mtrl, slightly convex; pavement cs/grus; some veg., many roots; "good soil"
AW VII	2	slope angle c. 4.5 - 5.0°
AW X	9	very weak Regosol; cs/grus pavement thicker than AW VIII
AW X	10	
AW 7	10	stable sf., almost deflated, subang. grus on sf.
AW 7	12	> 5 cm stable, > 10 cm very stable
AW 6	2	drilling; active aeolian sf., spottiness of tussock-like grasses
AW 6	5	1 - 10 cm slightly layered; sample 4+5 slightly wet
AW 6	8	better sorted, better rounded than AW 7
AW V / 1		typ. sr-mtrl
AW 8	1	dune crest, SW-side steeper, with shrubs, NE *Stipagrostis* ; well layered
AW 8	2	dune crest; much more stable, finer, well sorted; > 20 cm fine sand with coarse layers,
		more fine-grained and better sorted than 0 - 10 cm