SOURCE OF LUNETTE DUNE SEDIMENTS: A GEOMORPHIC TERRAIN ANALYSIS APPROACH IN ETOSHA NATIONAL PARK, NAMIBIA

With 5 figures

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Zusammenfasssung: Zur Herkunft von Lunettedünen-Sedimenten im Etoscha-Nationalpark, Namibia

Vorkommen von so genannten Lunette-Dünen am leeseitigen Rand von Pfannen in Nord-Namibia haben zu einer Diskussion über ihre Genese in Verbindung mit der Entstehung der zugehörigen flachen Becken geführt. Das Sediment der Lunette-Dünen ist überwiegend gröber als das der Pfannen, von denen das Sediment angeblich stammen soll, was gegen eine Auswehung von der Pfannenoberfläche spricht. Im Fall der Etoschapfanne ergibt sich ein weiterer Widerspruch aus der Tatsache, dass die Dünen am Nordwest- und Westrand der Pfanne liegen, die vorherrschenden heutigen Winde jedoch aus Nordost wehen. Ergänzende Daten wurden gemeinsam mit hochauflösenden Satellitenbilddaten in eine geomorphologische Reliefanalyse eingebunden. Alle Befunde weisen darauf hin, dass das Ekuma-Delta am Nordwestrand der Pfanne und nicht der Pfannenboden selbst die Quelle der Sedimente ist. Vermutlich stammen auch an anderen Pfanne die gröberen Leeseitensedimente aus fluvialem Eintrag und sind nicht, wie häufig angenommen, das korrelate Sediment einer durch Deflation entstandenen Pfanne.

Summary: The presence of so-called lunette dunes in the lee of pans in northern Namibia sprouted a discussion on the formation of the shallow basins related to them. These lunette dunes are made up of larger particles than those found in the pans, from which the sediments are thought to have originated. At Etosha Pan, this contradiction is compounded by the fact that the dunes are found on the northwestern and western side of the pan, whilst the prevailing dominant wind, believed to have played a formative role in their development, blows from the northeast. Ancillary data, in concert with high-resolution, multi-date satellite imagery were examined through the prism of geomorphic terrain analysis. The resultant indicators unequivocally point to the Ekuma delta, on the northwestern rim of the pan, in direct opposition to the pan floor proper, as the source of these dune sediments. It is therefore probable that coarser sediments found on the lee side of similar pans can be similarly explained as originating from former inlet deposition and not from wind excavation in the process of pan initiation as popularly held.

1 Introduction

One of the controversies surrounding the origin of pans is the common presence of lunette dunes on their downwind fringes. Often these dunes are mainly composed of coarser materials (GOUDIE a. THOMAS 1985) than the sediments found within the adjacent pan floor (SHAW 1988). A number of investigations, courting the concept of pans as deflational landforms (GILBERT 1895; ROGERS 1934), explained this phenomenon by asserting that the coarser sediments resulted from deflation of surface sands to make way for pan depressions (i.e. WAYLAND 1953; LANCASTER 1978a, b; BUCH et al. 1992). However, WOOD and OSTERKAMP (1987) for example, attempted to refute this argument, citing that the volume of sediments in the dunes is generally less than the volume removed from the depressions. Yet LANCASTER (1978b), working in the Kalahari, had previously observed a close relationship between the size and extent of the dune complexes and the depth and area of the neighbouring pans. In addition, deflated surface pan sediments are known to be transported well beyond the immediate pan margins (REEVES 1966; YOUNG a. EVANS 1986; GRAF 1988; SHAW a. THOMAS 1989; LIVINGSTONE a. WARREN 1996; EITEL a. BLÜMEL 1997). KEMPF (2000) investigated a number of pans close to watersheds in the Namibian highlands, identifying them as temporary lake basins in chemically much weathered country rock that do not have any lunette dunes at all. The purpose of this paper is therefore to present part of the results of ongoing research focusing on Etosha Pan, as an appraisal of the pan's conformity to the reigning view of lunette dunes and their source of sediments.

2 Contextual Characteristics of Pans and Lunette Dunes

Pans are shallow, circular centres of inward drainage systems with no surface outlets. They vary in size from a few square meters to over 10 km^2 and may be more than 30 m deep, generally occurring in levelled areas (PRITCHARD 1986). Pans are often dry, but after (good) rains, water may collect on their floors for several months. Many are covered with grass, while others are topped with a salt crust or clay (Boocock a. van Straaten 1962; Buckle 1978).

The morphology and composition of pan margin dunes in the regional context has been described by Lancaster (1978b) working in the southern part of the Kalahari. Commonly two distinct dune ridges, an outer and an inner one, occupy the leeward side of pans. The outer dune is frequently larger than the inner one, with what is interpreted as a dune corridor separating them. Dunes alignments are consistent with present-day wind regimes over the region, particularly during the dry winter months when winds are stronger and more constant. The outer dunes are often made up of polished, fine and moderately well sorted and rounded quartz sand. In contrast, the inner dunes are composed of poorly sorted sands, mixed with up to a quarter of silt- and clay-size materials.

3 Study Area

Etosha Pan is the core of Etosha National Park, located in northern Namibia (Fig. 1). The park is in a semi-arid environment, with summer rainfall increasing from 270 mm in the west to 430 mm in the east. At a surface area of 4,760 km^2 (Lindeque a. Archibald 1991) and maximum diagonals of 120 km and 80 km (Buch a. Zöller 1992), this virtually barren Etosha Pan is surrounded by various vegetation communities, ranging from very low savanna to high-tree savanna (Sannier et al., submitted). Its floor is described by Schwarz (1920) as being covered with slate-green clay, which turns to a yellowish green colour when its surface becomes wet. The edge of the pan is made up of white chalky clay, which he alleged to underlie the whole pan, except for its centre. There a crust of hard clay covering a "boggy ground", of which he reported that it suddenly gave way and engulfed the whole caravan, men, oxen, and wagon, of an expedition that attempted to cross the pan.

Three main ephemeral rivers, Ekuma, Oshigambo and Owambo, feed into the pan. The latter flows in from the east, whilst the former two, bringing in water via a series of shallow anastomosing channels called iishana (sing. oshana), enter from the north. A number of springs dot the pan's perimeter, mainly on its southern, eastern and western margins, and attract a diverse and magnificently large wildlife population.

Topographically, the pan occupies the lowest part of the Owambo Basin surface (Hedberg 1979). Etosha is situated at the southern fringe of the greater Ovambo Basin as a part of the Cenozoic Kalahari. The Ovambo Basin as such is a large tectonic depression filled with Kalahari sediments of unknown, probably middle Tertiary to Quaternary age (Kempf 2000). The upper part of the Kalahari sediments in Etosha and surrounding areas consists of a non-carbonatic, sandy to sandy-loamy unit with glauconitic clay concentrations and a considerable salt content (Andoni Formation). The glauconite imprint is indicative of a former reductive palaeo-environment, more specifically a shallow lake of greater extent than the recent Etosha Pan, the salt likely to originate from desiccation phases.

The age of the Andoni Formation, the youngest geological unit of the Kalahari Group (SACS 1980), is unknown. Buch (1996) assumes a Pre-Miocene, probably Oligocene age, but this is to be questioned as Sauer (1966) reports Struthio fossils from the underlying Beiseb Formation, which therefore cannot be older than Miocene and are most likely of Pliocene age. The age of the overlying Andoni Formation can therefore be assumed to be Pliocene to Early Quaternary.

The Andoni Formation is capped by thick massive calcrete layers, described by Buch (1996) as evaporitic "Etosha Limestone" of Miocene age. However, the so-called Etosha Limestone is identical with the top of the excessively wide-spread Kalahari calcrete, identified by Kempf (2000) to be of early to middle Quaternary age, based on prehistoric and fossil sites in equivalent calcrete of the western Kalahari of central Namibia. The calcareous top layer underlies Middle to Late Quaternary longitudinal dune systems in vast areas of the adjacent Oshana region.

Neotectonic structures and lineaments were mentioned in Kempf and Hipondoka (2003). The area shows evidence of slight eastward tilting, with the deepest parts of the pan lying in the east. A straight and very shallow water course on the pan floor follows a fault zone extending from the Okondeka springs to the west to Namutoni Bay in the east, called the "Okondeka channel" by the authors. Not far from the north-eastern rim of Etosha Pan a thermal spring is shown on the maps, penetrating the sediments of the Kalahari Group, which is more than 200 m thick at this point (Haddon 2000).

Wellington (1938) conceived Etosha Pan to be a desiccated palaeo-lake, resulting from the capture of the Kunene River by the proto-Kunene and its diversion to the Atlantic Ocean, an assumption supported by a number of investigators (i.e. Shaw 1988; Thomas a. Shaw 1991; Stuart-Williams 1992). The 'capture' of the upper Kunene as well as the formation of the Etosha-/Ovambo-palaeolake depression implies younger tectonic movement. It has be encountered, however, by the theory that Etosha Pan is an erosional landform, having evolved by scarp retreat in a manner similar to a cuesta landform. According to RUST (1984) Etosha Pan is a 'super pan' which originated from the fusion of several scarp retreat pans' whilst "its development is not related to the fluvial history of the Kunene river". However, RUST (1984) did not explain the origin of the base level of scarp retreat, as the pan itself is already the deepest part of the fluvial system. Without assuming karst processes to explain the export of material from the erosional base level the proposion of 'fluvial endorheic erosion processes' is misleading.

BUCH (1993 in BUCH 1997), BUCH and ZÖLLER (1992), and BUCH et al. (1992) endorsed and reinforced these sentiments by attributing the development of Etosha Pan to long-term erosional processes and their modification by deflation of chemically weathered residuals, which resulted in several independent shallow karst-like depressions. According to BUCH (1997),

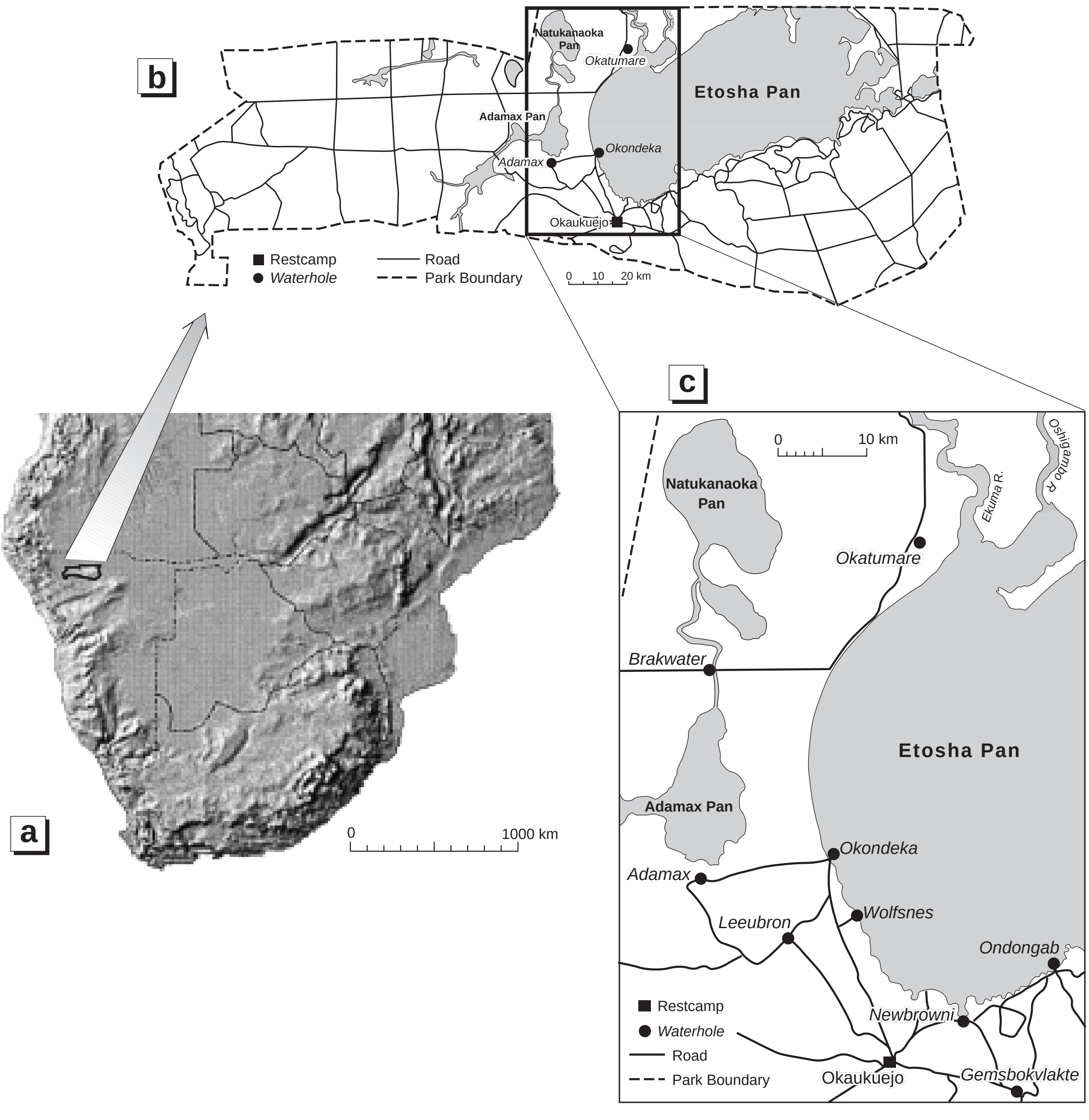

Fig. 1: Location of the study area: A) Southern Africa; B) Etosha National Park; C) Study Area.

Lage des Untersuchungsgebiets: A) Südliches Afrika; B) Etoscha Nationalpark; C) Untersuchungsgebiet these widened laterally, along with further momentum generated by the intensified removal of sediment by animals, salt accumulation and scarp retreat, thus collectively resulting in what is known today as Etosha Pan. The littoral terraces surrounding the pan are explained as former pan floors created by phases of deflational downwearing (Buch 1996).

4 Materials

Two Landsat TM images were available for this study. Taken five years apart (1992 and 1997), both images were captured in April, the end of the wet and hot season (Berry 1980). However, 1992 was an exceptionally dry year in the recorded history, the driest since 1965 and the third-driest since 1934 at Okaukuejo (ETOSHA ECOLOGICAL INSTITUTE, unpublished data). The dry conditions, resulting in a higher reflectance in the visible bands, are apparent in the 1992 image. A common georeference was created to facilitate a multi-data colour composite, using the ILWIS GIS (ITC, Enschede) program. A colour composite of bands 7–1992, 7–1997, 4–1997 in red, green and blue in that order, was digitally enhanced using the histogram equalisation stretch, following a radiometric correction.

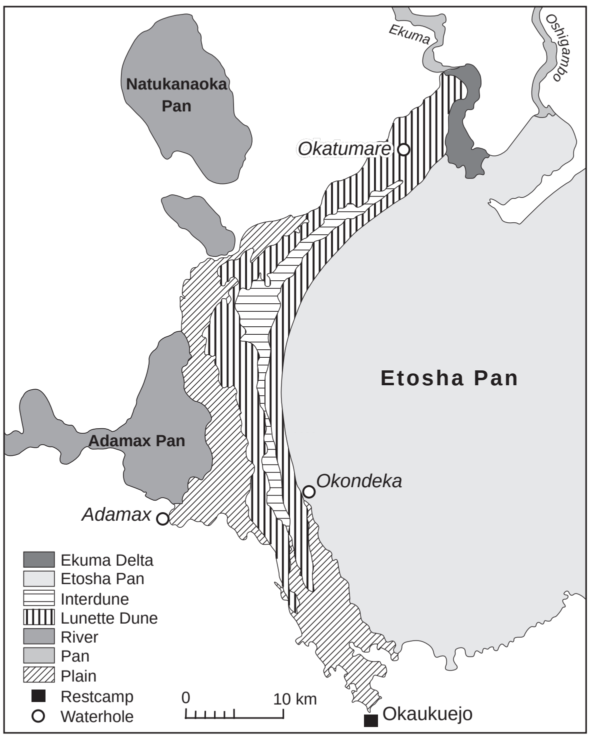

Fig. 2: Principal Geomorphological Units of the Study Area.
Geomorphologische Einteilung des Untersuchungsgebiets.

The unusual multi-data bands combination provided a far superior image contrast in comparison to a single data set. Major geomorphological terrain units were subsequently digitized on-screen, cognitive of the corresponding digital terrain model and spectral signature.

Fieldwork was carried out between April and June 2003. Six transects with a total of 21 samples from 15 profiles where taken at the Ekuma delta as well as from the inner and outer "lunette" dunes at a distance interval of 5, 20, 40, 45, and 50 km from the delta. A hand-held soil auger (10 cm diameter; EIJKELKAMP AGRISEARCH EQUIPMENT, The Netherlands) was used to take samples from down to around 120 cm below the surface, except at the delta and southern end of the dunes, where the soil and sediment depth was less. Treatments aimed at facilitating sedimentological analysis were carried out before applying the wet sieving method for sand and the sedimentation method for mud particles. The treatments included the removal of carbonate by hydrochloric acid, and the application of hydrogen peroxide for digesting organic material. Sodiumdiphosphate (0.4 n $Na_4P_2O_7$ x $10H_2O$) was used as a dispersing agent. The $CaCO_3$ content and the pH (1 m KCl) values were also determined in the laboratory. The results were analysed in a GIS environment and on a spreadsheet.

5 Results

Six distinct geomorphological terrain units, namely pan, river delta, river channel, lunette dune, interdune and plain, emerged from the spectral signatures of the colour composite (Fig. 2). Of relevance here is the spatial relationship between the river channels, river delta, pans and dunes.

The Ekuma River mouth, unlike that of the nearby Oshigambo, has a pronounced delta, bordering on the northern terminal of the lunette dune for a ground distance of just over 10 km. The delta is about 11 km long and 4.5 km wide at its broadest base. According to Wright's (1985) delta classification Ekuma is a fluvially-dominated bird-foot delta. The natural levees, tens to hundreds of centimetres high above the channels, are covered with grass, whereas the distributary channels are bare.

The lunette dunes stretch from Ekuma delta, curve along the western pan margin and taper off with decreasing distance to the south-western pan edge. The southernmost end of both dunes lies some 5 km north of the south-westernmost limit of the Etosha Pan rim. Near the delta, the dunes coalesce, forming a broad base, the interdune depression separating them only beginning approximately 4 km below the delta. As the dunes tail southwards, the distance between them and the pan edge widens, and then interfinger with and eventually give way to the flat Okaukuejo calcrete plain.

Sedimentological results show that the soil texture ranges from sand to sandy loam. The delta is characterized by sandy soil, mainly arenic Regosols, whereas the flanking dune field, west of the delta, fines to a loamy sand and sandy loam texture (cambic Arenosols). The texture of the outer dune progressively fines with increasing distance from the delta to silt loam at its southern tip. However, at the 45 km transect, a loamy sand texture was encountered.

Granulometric analysis shows that, on average, the sediments of the outer dune are moderately well-sorted, and poorly sorted in the inner dune. The ratios of sand, silt, and clay of the dunes and delta sediments are detailed in figure 3, while figure 4 summarizes the cumulative proportions of sand and silt particles plotted against the distance from the delta. Notable in these figures is a discernable fining pattern of sediments in the outer dune with increasing distance from the delta. However, a distinct spike appears at the 40 and 45 km transects (just north of Okondeka) of the inner and outer dune, respectively, where the sand-sized composition are elevated out of phase. These two sites are aligned in a northeast-southwest direction from each other. Moreover, the sampling site of the inner dune is located near a contact spring, Okondeka. The sand body of the inner dune at this locality is topographically higher than the adjacent parts of the same dune complex. Overall, the inner dune is made up of finer materials than the outer dune; but the inner dune has significantly less clay content than the outer one.

The pH value, with an average of 8.7 on both dunes, is comparable between and along the dunes. The carbonate content, however, shows a marked difference between the two dunes (Fig. 5). The inner dune has much higher values, peaking around the major axis of the pan. Towards the southern end of the dunes, massive concreted as well as nodular calcrete are found at or near the surface. Calcrete was also encountered at a depth of 120 cm, in an outer dune profile at the 20 km transect. By and large, the delta itself has a very low carbonate content, whereas that of the dunes increases with distance away from the delta, before it decreases again slightly at the southern end of the dunes.

6 Discussion

The spatial arrangement of the lunette dunes in relation to the neighbouring geomorphic terrain units and the dominant north-easterly wind regime do not agree with the current assumption that the dune sediments originated from the floor of Etosha Pan proper, although they have partly similar mineralogical compositions (e.g. Buch et al. 1992; Buch a. Rose 1996). Treading back into the past, within the limits of current understanding of this landscape-setting, may be a way to unveil the source of these dune sediments.

This sequence can be approached through and commenced with Wellington's presupposition (1938) of the broken relationship between Etosha Pan and the Kunene River. If indeed the Kunene once fed into the greater Etosha basin via the shallow, anastomosing channels, similar in many ways to the fluvial system of the Okavango today, then it is imperative that all or at least part of its sediment load should be accounted for. While the time when the 'capturing' of the Kunene took place is still guess-work, one may take recourse to the modern estimated sediment load of up to 2 million tonnes per annum as reported from Ruacana (Burmeister a. Partners 1997). Ruacana dam is located some 300 km upstream of the river's discharge into the Atlantic Ocean, about 70 km below the critical point where the most westward bend of the Kunene River occurs. There the main spillways into the Etaka channel have formed, leading into Etosha Pan (Kanthack 1921) via the Ekuma River. For comparison, the sediment load assumed is eight times less than that of the Orange River, with its catchment being about 10 times larger (Milliman a. Meade 1983). Although extrapolating today's river sediment discharge into the past should in principle be avoided, given different climates and erosional regimes of the past, it is still safe to assume that a formidable amount of sediment, left by the Kunene River before it was re-directed to the Atlantic Ocean, should feature in the vicinity of the Ekuma delta, being regarded as the Kunene's former river mouth.

With this in mind, the current proximity between the Ekuma delta and the lunette dunes calls for geomorphological attention. The inner dune and the delta share a common border for a distance of about 10 km, before the Etosha Pan spreads to separate them. In addition, the dune has a much broader northern end, differing in this respect from the typical crescentic form of a lunette that tails on both ends (Lancaster 1978b). At the opposite southern end, which is the most distal part of the sediment body, the tailing off of the dunes with increasing distance from the delta would suggest limited sediment availability for transport and deposition from the delta. There is also a lack of spatial coherence between Etosha Pan and the lunette dunes, as the dunes terminate at their southern end well before the corresponding extent of the pan rim.

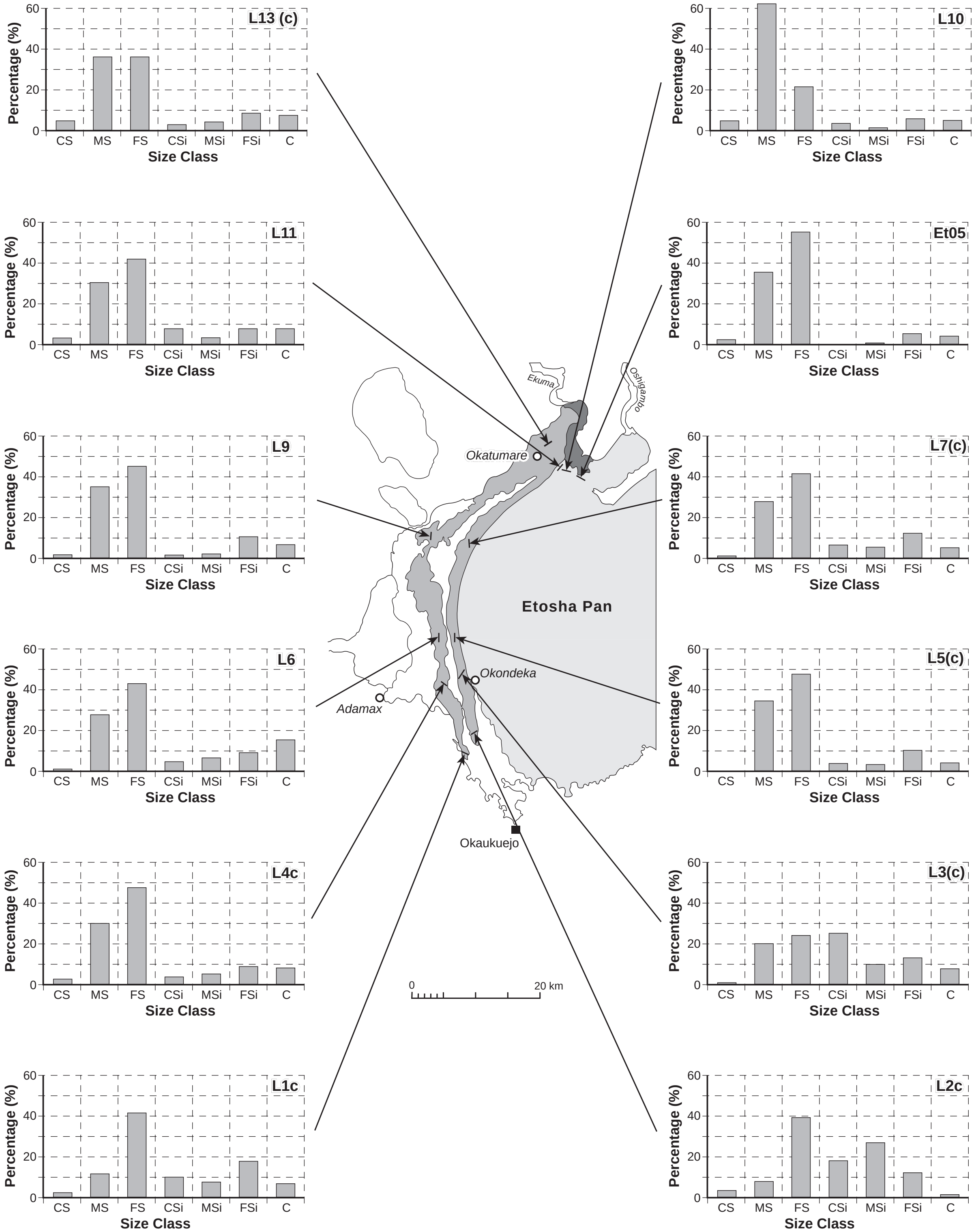

Fig. 3: Selected ratios of sand, silt, and clay along the dunes and at the Ekuma delta. Key: CS – coarse sand, MS – medium sand, FS – fine sand, CSi – coarse silt, MSi – medium silt, FSi – fine silt, C – clay.

Ausgewählte Lokalitäten für Texturproben im Dünenbereich und dem Ekuma-Delta. Bezeichnungen: CS = Grobsand, MS = Mittelsand, FS = Feinsand, CSi = Grobschluff, MSi = Mittelschluff, FSi = Feinschluff, C = Ton.

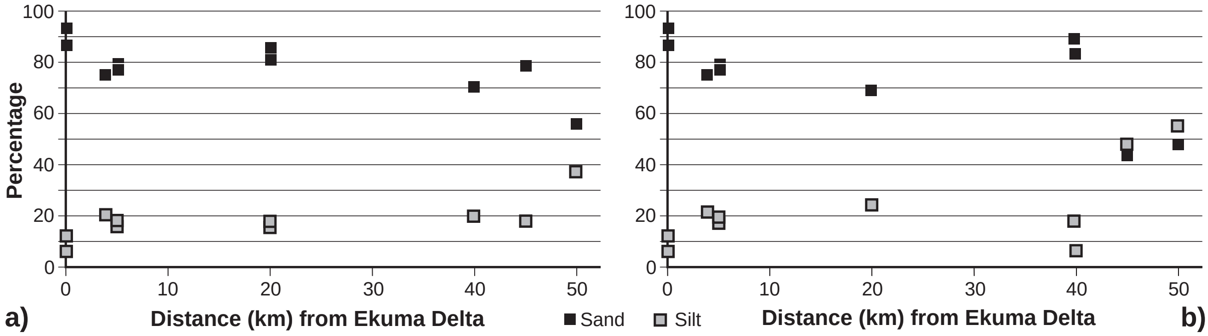

Fig. 4: Sand and silt grain composition along transects from the Ekuma delta. (a), outer dune, and (b), inner dune.
Sand- und Schluffanteile entlang Gradienten vom Ekuma-Delta nach Süden. (a) = äußere Dünen, (b) = innere Dünen.

This spatial arrangement should be considered in the light of the prevailing north-easterly wind regime, prominently declared by BUCH et al. (1992), BUCH and ZÖLLER (1992), BUCH and ROSE (1996) and BUCH (1996, 1997) as having been active for at least the last 140,000 years. The authors attribute the formation of these lunette dunes to the power and frequency of the north-easterly winds. As shown above, though, there is a clear disagreement between the position of the lunettes and the wind direction, as is also between the orientation of the pan, with its major axis extending straight eastward instead of northeast-southwest with the prevailing winds.

Sedimentological analysis reveals a southward fining of the dune sediments with increasing distance from the delta. One exception each for the inner and outer dune was encountered at the 40 km- and 45 km-transect, which is most likely the local effect of a palaeo-drainage line entering Etosha Pan from the west through Adamax Pan (cf. KEMPF a. HIPONDOKA 2003). This drainage line is surficially blocked by the Okondeka dune complex, with only percolating water feeding the Okondeka contact spring. A probable remnant of this palaeo-channel is the conspicuous "pre-historical channel" shown on the topographic maps. This, the above-mentioned west-east oriented Okondeka channel on the southern pan floor, has its origin near Okondeka. A further tributary to Okondeka channel originates at Wolfsnes, an episodic spring which has been dry for decades but as satellite image interpretation suggests, most likely also has a confluence from Adamax Pan.

It is significant that the dunes, in spite of their rather high clay content compared to regular sand dunes, contain much less clay than the almost 100% available for wind erosion at the pan surface itself. In addition, the small amount they contain, increases from the inner to the outer dune, with increasing distance from the pan. The clay content in general might be due to aeolian deposition, due to the frequent occurrence of dust storms coming from the Etosha Pan under various wind vectors, as satellite imagery testify (i.e. ETOSHA ECOLOGICAL INSTITUTE, unpublished data; MENDELSOHN et al. 2000). This post-depositional input could not, however, explain the difference in clay content between the inner and the outer dune. It is therefore assumed that it is more likely to be the secondary product of in-situ weathering, given that the outer dunes are known to be older than the inner ones (LAWSON a. THOMAS 2002). This and the southward fining of sediment from the delta speak against the pan floor as the primary source of the dune sediments.

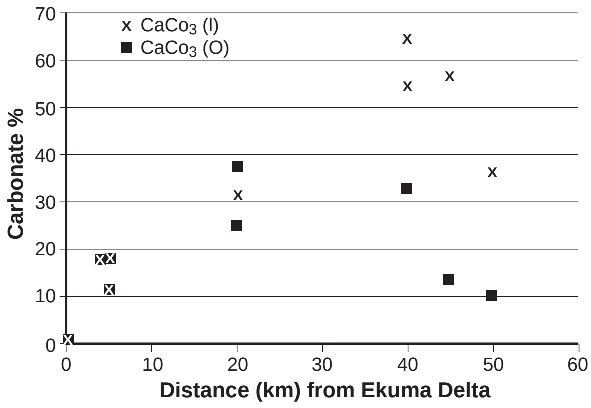

Fig. 5: Carbonate content of the inner and outer dune along transects from the delta. (I) – inner dune, (O) – outer dune.
Carbonatgehalte der inneren und äußeren Dünenkörper entlang der Transekte vom Ekuma-Delta nach Süden. (I) = innere Düne, (O) = äußere Düne.

Dating of lunette dune sediments in southern Africa (Buch a. Zöller 1992; Eitel a. Blümel 1997; Lawson a. Thomas 2002), has consistently shown that depositional activity in lunette-dune areas has been taking place episodically, and that the age estimates of the sediment increase in age with depth. Moreover, some of these investigators provided ages as young as from the period after the arrival of Europeans in South Africa for the phases of lunette dunes deposition, shedding light on the fact that they continue to develop, even under semi-arid conditions comparable to the present. Therefore, the successive phases of lunette dune deposition, viewed alongside the geomorphological findings of this paper at Etosha, and the fact that the lunette dune sediments are coarser than those found in the pans, all suggest that these dune sediments have originated well beyond the current extent of the pan margin and that pan formation preceded that of the lunette dunes.

It appears that at the origin of these lunette dune sediments there is river delta deposition. Subsequently, the ensuing aeolian processes, in collaboration with lakeshore wave action, reworked the delta sediments and moulded them into their current landform as sand dunes topping two beach barriers of a palaeo-lake within Etosha Pan, the outer body being older than the inner one.

7 Conclusion

Geomorphological terrain analysis, aided by high-resolution satellite imagery, provided a necessary platform for understanding the seemingly simple landscape setting of western Etosha Pan. The configuration and size of Etosha Pan, its relation to relevant geomorphological terrain units, and sedimentological analysis helped to determine the source of the lunette dune sediments. By examining the individual alignment and position of terrain units and associating them with each other, the sediments of the lunette dunes were traced to the Ekuma delta, from where significant quantities of unconsolidated materials are thought to have been injected into the aeolian system. This conclusion contrasts acutely with the assumption that these sediments came about as a result of wind erosion and deflation of the surficial Kalahari sand, the process formerly believed to have created Etosha Pan. Therefore the lunette dunes do not help explain the origin and evolution of the ubiquitous pans of northern Namibia, which have been subject to debate for over a century.

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