Palaeodune morphology associated with the Gumare fault of the Okavango graben in the Botswana/Namibia borderland: a new model of tectonic influence

M.J. McFarlane
Bosele Investments (Pty) Limited, Box 66, Maun, Botswana.
Corresponding author. e-mail: mcf@dynabyte.bw

F.D. Eckardt
Environmental and Geographical Science Department, University of Cape Town, Rondebosch 7701, Cape Town, South Africa.
e-mail: eckardt@science.uct.ac.za

ABSTRACT

The degraded linear dunefield of north west Ngamiland, Botswana occurs in a seismically active area, lying to the northwest of the Okavango graben, widely considered to be the tail end of the East African Rift system. To assess the effects of neotectonism on the dunes, an area was selected for examination close to the Gumare fault, which bounds the graben on the northwest side. Digital SRTM data were converted to light shaded representation of the topography. It was found that dune forms only occur along the margin of the rift and on both sides of incising valleys, graded to the graben floor. A selection of long profiles showed dune crests standing some 25 m above the *straats* at the edge of the rift. The relative relief pinches out away from the fault, towards interfluves that do not depict dune morphology. Landsat satellite imagery shows linear features continuous across the flat interfluves, inviting the incorrect inference from the vegetation that the linear dune forms occur there. A model is proposed that an original linear dune field formed under arid conditions, was entirely flattened under wetter conditions, crest material being washed into the *straats,* thus obliterating the original dune morphology. Upon rifting and stream incision, these forms are being replicated, an example of equifinality. Replication is suggested to be by the action of infiltrating water, controlled by the groundwater gradients. These observations suggest that the active dunefield significantly predates the tectonic processes. With the additional time required for degradation and replication it would suggest that the dunes are of considerable antiquity. It has already been recognised that the dunefield has a complex history of construction and destruction, to which must now be added a process of base level-controlled replication.

Background

The landscape of northern Botswana is home to abundant proxy-evidence for major episodes during which the climate differed significantly from that of today (Cooke, 1984). Wetter conditions are evident from substantial fossil river systems in the Kalahari (Thomas and Shaw, 1991, Nash *et al.,* 1994a) and from extensive palaeolake systems, now reduced to dry or intermittently inundated basins such as the Makgadikgadi Pans (Cooke, 1979). Formerly much drier conditions are shown by the systems of linear dunes (Lancaster, 1989), much degraded today but still evident as subtle topographic features. The pattern of dunes and *straats* (inter-dune swales) is particularly evident on satellite images through contrasting spectral responses from vegetation on crests and *straats*. Typically, the open woodland of the dunes, with denser stands along the margins, gives way to herbaceous vegetation within the *straats*.

Recent research in northwest Ngamiland (Figure 1) has considered the nature and extent of the degradation of the linear dune system (McFarlane *et al.*, 2005). The degradation is the result of wetter conditions since dune formation and takes several forms. Although the original height of the dunes may be speculative, it is clear that the crests have been substantially reduced, judging from the extent to which the intervening *straats* have been infilled with sand brought down from the dunes, by splash or surface runoff. In some cases the infill has pinched out the once continuous *straats* to form a string of disconnected elongated segments. In other cases the *straats* are no longer recognisable as features on the ground, so substantial is the translocation of material from the crests to the interdune swales by water action. Degradation by water action in another form is also recognisable. Particularly around the Aha Hills and along the western flank of the Okavango Panhandle, the dunes have been degraded by waterlogging during a period which was evidently very much wetter than today. Dune morphology has also been modified by infiltrating water resulting in linear collapse features which transect the dunes. Where these structurally- and lithologically-controlled linear depressions intersect and infiltration is particularly facilitated, pans have formed. A further modification prompted by wetter conditions is overturning of the dune sands and immediately underlying strata by biological activity. This presents problems for luminescence dating, the implication being that the linear dunes may be significantly older than the late Quaternary, as has been suggested by absolute dating (Thomas *et al.,* 2000). The proposed greater

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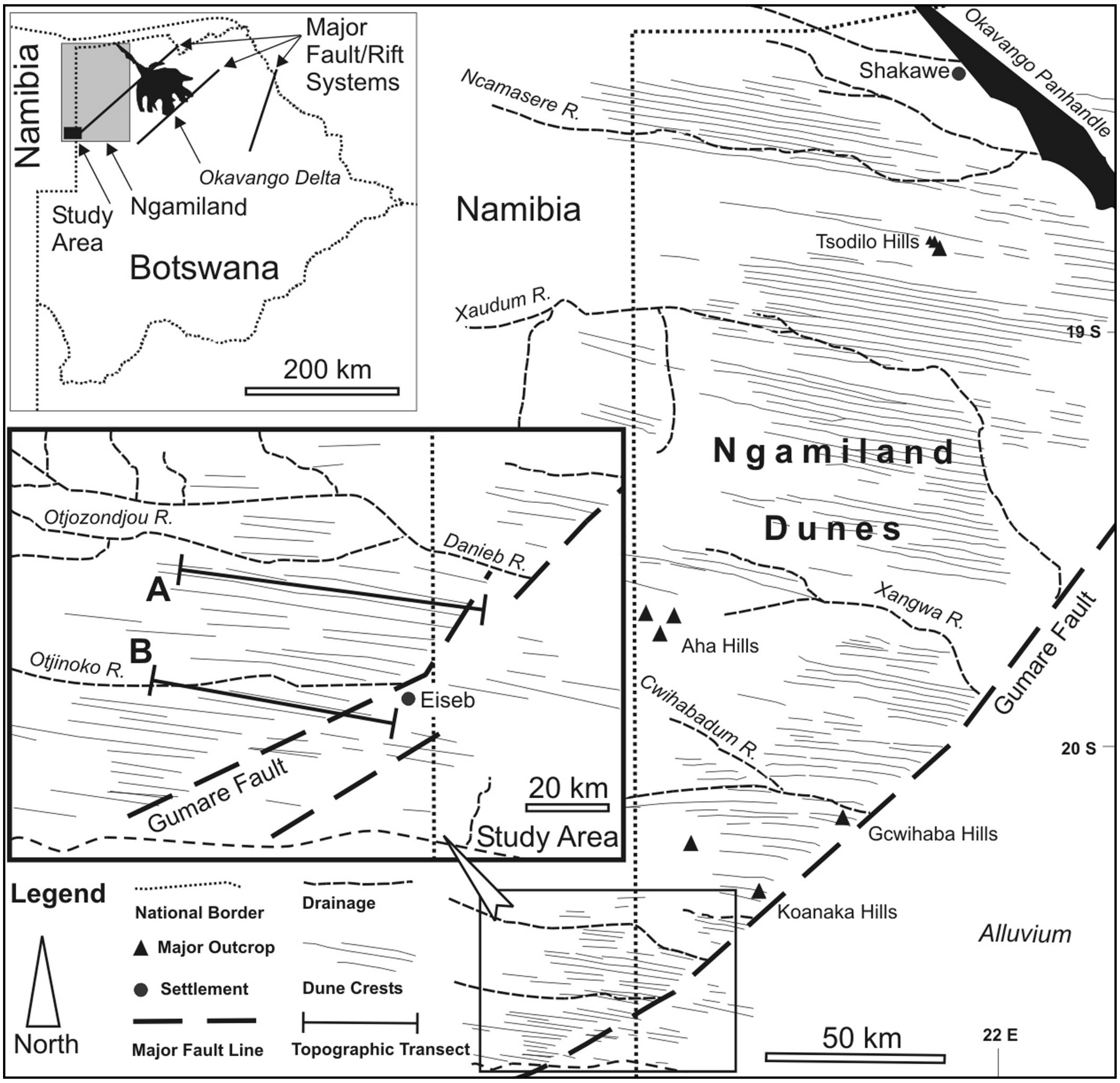

Figure 1. Location of the study area.

antiquity of the construction period is supported by the surfaces of the sand grains. These have structurally-controlled etching which has overprinted aeolian impact features to such an extent that they cannot be recognised (McFarlane *et al.,* 2005).

While the modifications of dune morphology by water action have become increasingly recognised, modifications induced by tectonic activity in this seismically active area (Scholz *et al.* 1976; Kumar *et al.*, 1998) are less well captured in the literature. Northwest Ngamiland lies to the west of the Okavango graben. This is widely considered to be the tail end of the East African Rift system (Mallick *et al.*, 1981; McCarthy *et al.*, 1991, Modisi, 2000; Modisi *et al.*, 2000) but this view has been recently reconsidered (Gumbricht *et al.,* 2001). The recency of the tectonic activity appeared to be indicated by the linear depressions across the dunes. However, the recognition that similar linear depressions can form along old lineaments, which are opened up by infiltration of water (GoB, 2003) introduces uncertainty regarding which are old features being opened up in this way and which are the result of relatively young, post-dune fault movements. In order to consider the effects of recent tectonic activity on the dunes, we selected a study area closely associated with the Gumare Fault, which bounds the graben on its northwest side.

Location of study area

On the southwest side of the Okavango delta, the linear dunes terminate abruptly at the northeast – southwest trending Gumare fault (Figure 1). Below the fault scarp, on the southeast side, lies an area of very low relief, blanketed by fluviatile and lacustrine sediments, relics of

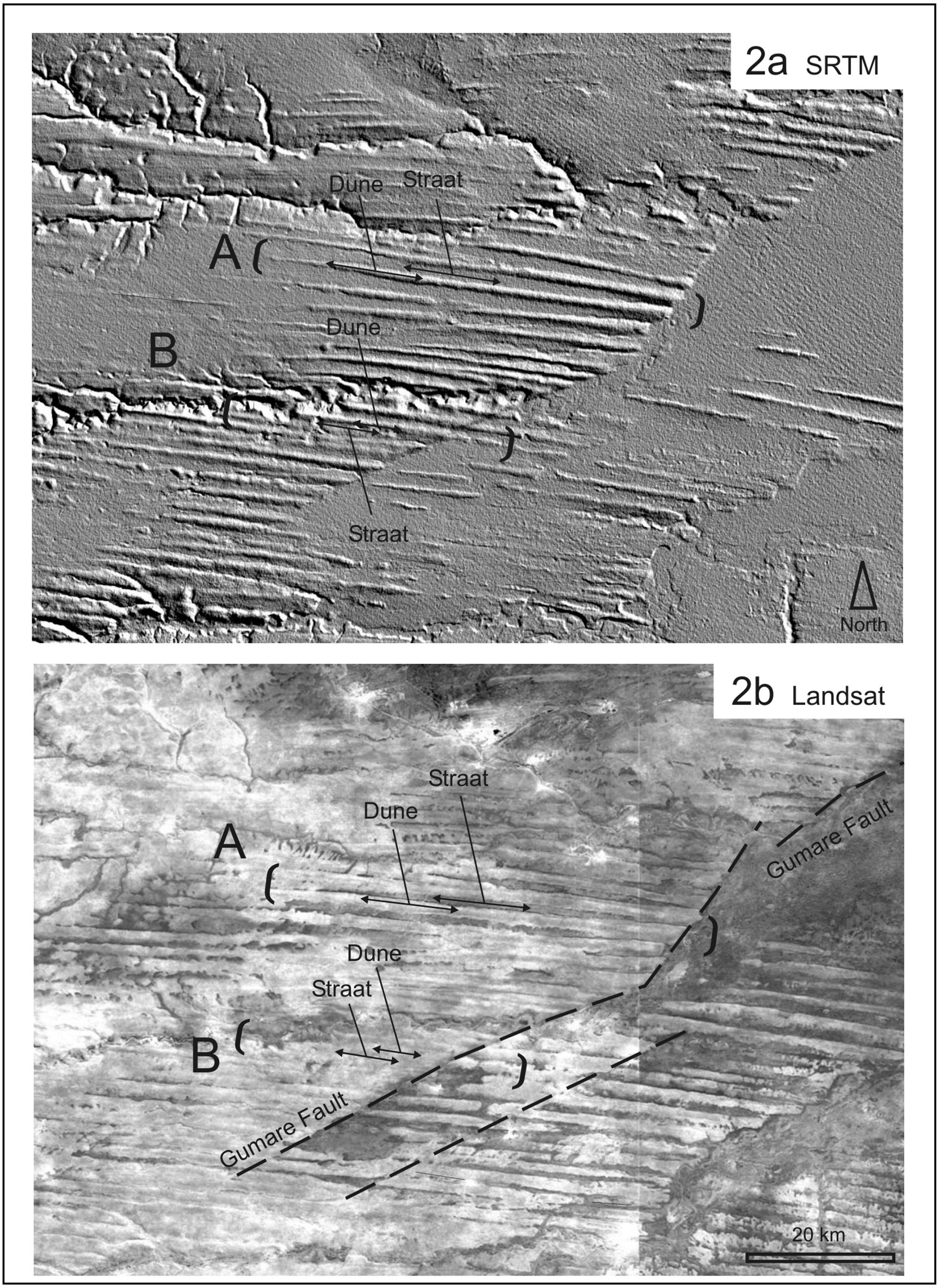

Figure 2. (**a**) satellite image. (**b**) Side-shaded relief. These are of the same area and show that the morphology cannot be inferred from the vegetation patterns. Dune morphology is best developed at the edge of the Gumare Fault and along the incising streams. Interfluve areas are flat.

times when the graben was flooded (Mallick *et al.,*1981). The deltaic sediment floor of the graben rises gently in a southwest direction, towards the Namibian border, the slope resulting from deposition of deltaic sediments from Namibia (Thomas and Shaw,1991).

The location of the study area in relation to the graben and dunefield is shown in Figure 1. The dunes lie on terrain which slopes gently south eastwards towards the graben. The land is incised by stream valleys which are now dry except intermittently in their upper reaches. The study area lies on the flank of the graben close to the most southerly recognised limits of the faulting, in the region of the Botswana/Namibian border. Since the faulting is considered to become generally younger along the length of the East African Rift (Kampunzu *et al.,*1998), it was thought that here the effects of the most recent neotectonic activity would be most pronounced and could most readily be assessed.

Methods

We used Shuttle Radar Topography Mission (SRTM) data at a near global resolution of 3 arc-seconds (SRTM3) which is a horizontal resolution of approximately 90 m. The total data set consists of 14,000 one degree by one degree raster tiles (ftp://e0srp0u.ecs.nasa.gov/srtm) referenced to WGS84. Data from Ngamiland were downloaded in 1 degree tiles, geocoded and assembled. Results depict landforms in unprecedented detail for some of the most remote and least mapped areas of the globe. Absolute vertical accuracy for southern Africa is estimated to be at least 3 to 5 m (Rodriguez *et al.,* 2005) and is supported by DGPS (Differential Global Positioning Data) for other parts of the Kalahari.

Results are presented in 3 formats. The shade product (Figure 2a) generates an artificially illuminated surface with controlled parameters such as illumination angle, azimuth and vertical terrain exaggeration. We used light coming from 60 degrees, at an angle of 45 degrees. Topography was exaggerated by a factor of 40. As a result, dunes, *straats* and faults are clearly depicted in the SRTM shade view. This procedure has the advantage that it shows *only* the relief, unlike the second format, the satellite imagery (Figure 2b), which was generated using Band 5 (MIR) of Landsat ETM image. This image accentuates the soil, vegetation and moisture contrasts with minimal atmospheric attenuation.

The third format depicts cross-sections along transects that extract digital heights from the SRTM data (Figure 3). Several transects were taken from dune and *straat* pairs in the study area to explore topographic relationships close to the influence of the Gumare fault. Two sets of transects were selected to illustrate the findings.

Results

Figure 2a shows the relief of the selected area. It is immediately apparent that the dune forms are by no means of uniform clarity. They are most clearly expressed in two situations. Directly at the edge of the graben, above the fault, they are very distinct, becoming increasingly subdued as relief features further from the edge, until, at a distance of some 40 km, they are entirely lost. The second situation in which the linear dunes have clear relief expression is along the flanks of the incised valleys, which today only carry occasional flow after extreme rainfall events. On both sides of the valleys, the dune forms are clear, becoming more subdued with increasing distance from the valleys. In interfluve situations, they have no relief expression.

Two pairs of long profiles are shown in Figure 3, with locations given in Figure 2. Figure 3A shows a profile along a dune crest from the interior towards the edge of the graben and also the corresponding profile along the adjacent *straat*. This is the more northerly pair, uninterrupted by the incising streams. A similar pair of profiles is shown in Figure 3B, lying further to the south and crossing one of the incised streams.

In the more northerly pair (Figure 3A), the crest of the dune follows the regional slope, gently down towards the graben, dropping about 90 m over a distance of 70 km. The floor of the *straat* slopes more steeply, dropping some 120 m over the same distance. The altitudinal gap between crest and *straat* is at a maximum immediately at the edge of the graben, reaching some 25 m, gradually pinching out with progressive distance from the fault until there is no dune/*straat* morphology and the terrain is completely flat. At the escarpment, the floor of the *straat* 'hangs' some 10 m above the graben floor.

In the more southerly transect, the *straat* floor 'hangs' about 20 m above the graben floor. There is a correspondence of irregular depressions on the dune crest and on the *straat* floor, particularly approaching the Otjinoko river where the height difference between dune crest and *straat* also increases.

Representation of the dunefield on satellite images is remarkably clear (Figure 2b). The occurrence of dune forms as topographic features cannot, however, be safely inferred from the images, as seen from comparison of Figures 2a and b. For example, the satellite image of the interfluve area on the west side of the frame, between the two transects, shows clearly linear tonal patterns, expressing vegetation variations. However, the inference that the vegetation pattern is responding to the morphology is incorrect, as seen from 2a . Clearly, dune forms existed in the past and these forms have been totally flattened, crest material entirely filling the *straats*. The response of the vegetation is to differences in edaphic conditions or moisture status rather than directly to the topography.

Discussion

Dune forms were, in the past, inferred from the vegetation patterns on satellite imagery. Thomas and Shaw (1991), for example, followed Mallick *et al.* (1981) in this respect. It has become clear, however, that this

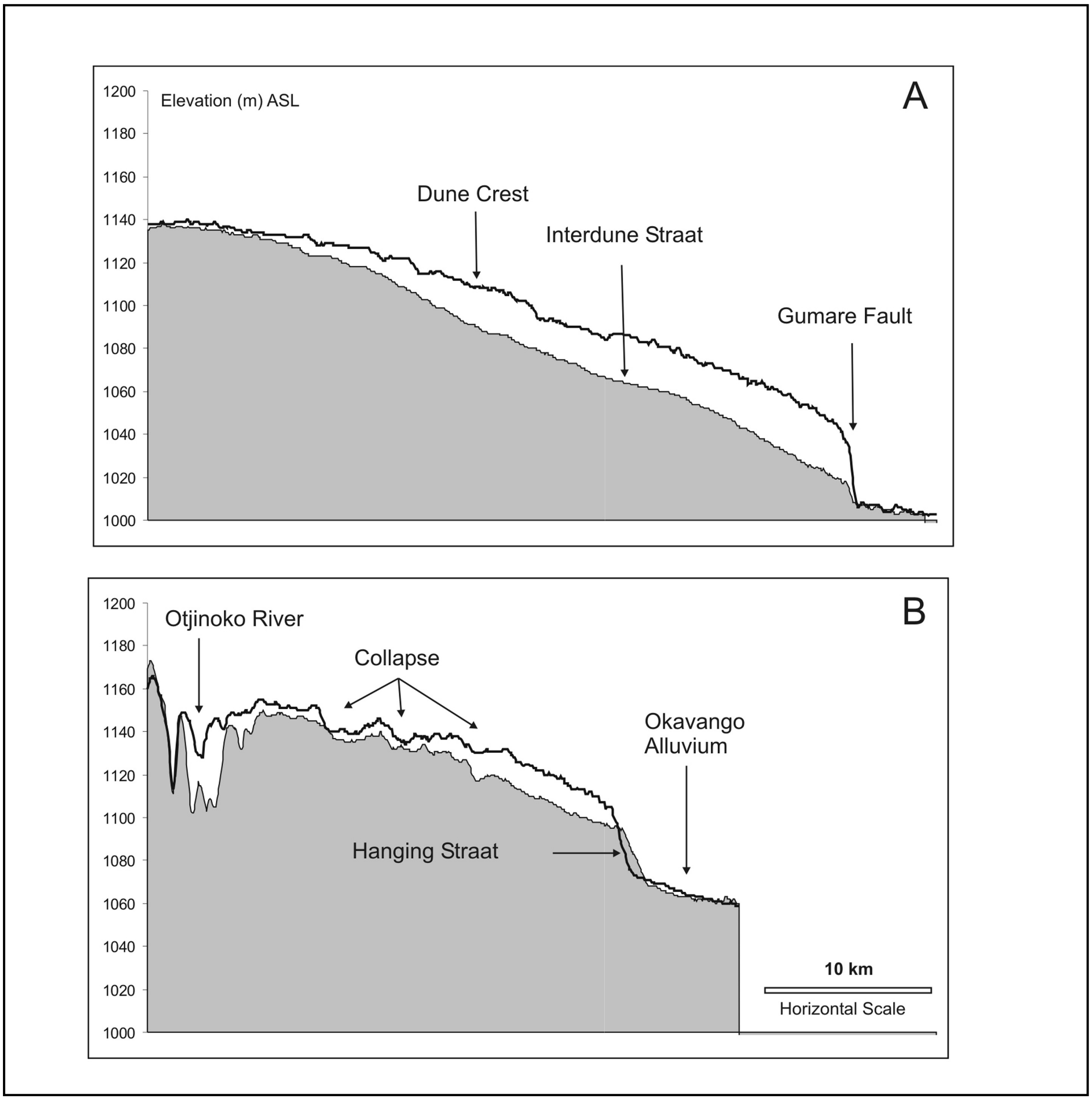

Figure 3. Selected transects along dune crests and adjacent *straats*. Locations are given in Figure 2. The relative relief of the dune/*straat* features increases towards the Gumare Fault and adjacent to stream incision.

procedure is insecure because the vegetation continues to reflect the dune and *straat* patterns even afer the dunes are no longer there as topographic features.

It could be argued that the more pronounced dune forms, close to the edge of the graben and along the incising valleys are the result of constructional processes, attributable to proximity to a supply of appropriately fine materials in the graben. Such a "source bordering" origin (Wasson 1983) was considered by Bullard *et al.* (1995) in southwestern Botswana where dune forms are pronounced at the margins of incising drainage lines, the fluviatile sediments appearing to offer a favourable source of material for dune building. As the dune forms there are on both sides of the drainage lines, as in our area, explanation in terms of a "source bordering" origin was not favoured and some form of wind turbulence resulting from the existence of the valley was suggested. There are strong arguments against both explanations in our study area. The bluntness of the dune faces at the scarp edge appears more consistent with truncation at the fault rather than initiation of development of dunes. The satellite image shows linear features below the graben sediments, fading out northwards into the area of thicker sedimentation, indicating that the linear features predate rifting. Since the development of the dune forms is on *both* sides of the incising valleys, aeolian constructional activity would seem highly unlikely as this would appear to require formation by two directly opposed wind directions. The development of the topographic features is directly related to the downfaulted graben and to the incising streams which are responding to the lowered base level. The floors of the *straats* are becoming graded to this base level. Thus, the action of water, not aeolian activity, is the key to the development of the current linear duneforms.

Although in the flat interfluve areas there is no sign of linear dunes as relief features, from the vegetation it can be deduced that the dune system existed there and that it is being *replicated* by the action of water. A model is therefore proposed, with three stages of development of the present linear dune relief in this area. In stage 1 linear dunes form by aeolian activity. In stage (or stages) 2 the dunes are entirely flattened largely by water action, that is direct surface run-off and splash. In stage 3 the faulting and graben development provide a lowered base level for water activity and the dune forms are replicated either by direct surface runoff, suffosion (subsurface erosion) and/or dissolution of substrate.

Fossil dunes that have been flattened to the extent that their morphology has been obliterated require a term to differentiate them from fossil dunes which, although inactive and variously modified, can be topographically recognised as old dunes. In northern Australia pans, silicate karst depressions, called 'lagoons' there, are abundant (McFarlane *et al.,* 1995). In some cases the formation process no longer operates and the pans are entirely infilled so that they are no longer recognisable as topographic features. Termed 'ghost' pans (or 'lagoons'), they are identifiable on the satellite images, on air photographs and in the field by the associated vegetation patterns. It is proposed that the flattened linear dunes here, only recognisable from the vegetation patterns, be called '*ghost dunes'*.

Direct surface runoff appears to have much to recommend it as the process of dune flattening. Degradation of dune forms has long been recognised, for example in Zimbabwe (Flint and Bond, 1968), where a strong case was made for relief reduction by sheetwash. Although some deposition in *straats* can be by aeolian activity at the end of the dune construction phase (Kocurek, 1998), when the sand supply wanes in response to weakening winds associated with increasing vegetation cover and decreasing aridity, the infilling appears best explained by direct surface runoff during wetter times.

The dune forms here described along the fault could, in a sense, be regarded as exhumed. However, exhumation implies that they have been buried, followed by removal of the burial material and re-exposure in their original forms. Here, only the *straats* have been buried, by material translocated from the crests which have never been buried. Also the depths to which the *straats* are excavated varies so that their floors are not necessarily at the same levels as the original floors. Close to the fault it may be that the present floors are even lower than their original position and in effect the forms are replicated at lower elevation; both dune crests and inter-dune floors are lower than the originals. Nash *et al.* (1994b), for example, noted that many dunefield valleys possess a distinctive duricrust terrace on both sides. It may be that the duricrust is the original *straat* floor, now incised by the exhumation process. The term '*replicated*' is therefore preferred to 'exhumed', meaning 'copied' or 'imitated', that is producing a 'likeness' or 'counterfeit'.

Direct surface runoff as the formative process of replicate dunes appears to have little to commend it. On the images and in the field there is no evidence of integrated channel flow or sheet wash towards the fault. There is, however, considerable evidence for the action of infiltating water. In detail, the *straat* floors are typically irregular, periodically dimpled along their courses by small pans. Such pans are often rimmed by termite mounds indicating small bodies of recharged fresh water within an area of generally deeper saline water (GoB, 2005). It has long been known that the development of weathering within the profiles of the African surface is both deep and advanced to the extent that congruent dissolution of secondary minerals by infiltrating water in the upper parts of the profiles creates voids. This causes the saprolite to collapse, resulting in the formation of residual mantles of resistates. Thomas (1994) has reviewed the vast literature body on this theme. The process is facilitated where infiltration is favoured, particularly along faults. There the collapse is maximised to the extent that there is topographic expression of the faults in the form of lines of pans and linear or dog-legging pan forms (*e.g.* McFarlane *et al.,* 1995). Such silicate karst collapse features can be spectacular, constituting hazards, as in the case of those occurring in the Sturt plateau area of Australia (McFarlane and Twidale, 1987). In the Kalahari of Botswana substantial void development within weathering profiles has also been recognised (Nash, 1995; GoB, 2003), as has a structural control on pan formation (Farr *et al.,* 1982; Wormald *et al.*, 2003). In northwest Ngamiland small pans in the *straats* between the dunes are linked by linear depressions on the dune crests, from which collapse of underlying saprolite is inferred along faults where infiltration of water is facilitated (McFarlane *et al.,* 2005). The structural control on dry valley systems in the Kalahari (Nash *et al.,* 1994a, 1995) has been explained by a proposed process of lowering of the ground surface by dissolution of the underlying bedrock. The importance of subsurface processes in the development of surface morphology, long recognised elsewhere (Thomas, 1994), is becoming evident in Botswana.

Although the topographic signatures of saprolite collapse occur, an objection to this proposed process appears to lie with the often very substantial thickness of fluviatile and other Kalahari sediments believed to intervene between the linear dune cover and bedrock (Haddon, 1999; 2000; Haddon and McCarthy, 2005). Nash (1995) suggested that the thicknesses of Kalahari Group sediments west of the Okavango delta, mapped by Thomas (1988) as 51-200 m, appear to be an overestimate. He also recorded the occurrence of a large void development within a weathering profile.

Since then, the view that the Kalahari sediment thickness has been overestimated has been supported by growing evidence that extremely weathered Damaran metasediments below the dunes have been misidentified as young sediments. For example, satellite imagery shows what appear to be Damara facies and structures on the surface of the dune system (McFarlane and Eckardt, 2004; McFarlane *et al.,* 2005). This led to the proposition that biological overturning has brought Damara saprolite, directly underlying the dunes, to the surface. Scanning electron microscope study of what was regarded as the basal member of the Kalahari sedimentary succession in northwest Ngamiland showed that the rounding of the contained quartz grains is not the result of physical transport but is produced by *in situ* weathering (McFarlane *et al.,* in press), which yields a predominantly sandy residuum. If it is correct that saprolite has been misinterpreted as transported sediment, this removes the objection to the identification of silicate karst topographic features. In our study area the depressions in the *straat* in Figure 3B and the corresponding depressions on the adjacent dune crest are attributed to silicate karstification, which would be consistnt with a proposed role for infiltrating water and shallow throughflow in the process of dune replication along the Gumare fault. It would appear, therefore, that the grading of the *straats* is controlled by the gradient of the groundwater level, towards the graben, that is the piezometric gradient.

It has already been suggested (McFarlane *et al.,* 2005), on the basis of the degradation of the linear dunes by water activity in northwest Ngamiland, that the dune system may be of greater antiquity than previously suspected. The sequence of events here proposed places both the formation of the original dune system by aeolian action and dune flattening by water activity in a time frame which pre-dates the formation of the existing fault scarp flanking the Okavango graben. This study supports the conclusion that the security of luminescence dating here requires very close scrutiny of precisely what is being dated. Having recognised the process of replication of dune forms following incision, we do not know, for example, if the degradation processes of the dune forms described recently (McFarlane *et al*., 2005) are acting upon entirely aeolian constructional features or if they are acting upon replicate forms.

If *straat* lowering, in response to base level lowering, results in not merely exhumation but also lowering of the floors into the substrate below the original dune system, then the relative relief of the forms, that is the height difference between crests and floors may be greater than that of the original aeolian features. To some extent the forms here described provide an example of equifinality, that is the achievement of similar forms by different processes. However in this case the height difference between the crests and the floors is controlled by the extent to which the base level is lowered, the level to which the *straats* are grading, and the time which has been available for the grading process. The formation of the Ngamiland dunes by wind and replication by water produce similar forms. Recognition of this underlines the suggestion that the original features are of very considerable antiquity. How old the original forms are is not known, but if it is correct that an African Surface saprolitic profile directly underlies the dunes, then the entire period between the Cretaceous and the uplift of the Kalahari-Zimbabwe axis, which resulted in the endorheic flooding of the Makgadikgadi basin, should be considered. The inferred age of this uplift is poorly constrained (Du Toit, 1933; Moore, 1999).

Conclusions

Tectonic activity plays an important role in the evolution of linear dune forms in northwest Ngamiland. Study of the forms in the vicinity of the Gumare fault, which bounds the Okavango graben on the northwest side, has shown that an ancient linear dune system was entirely flattened before the faulting. The dune forms are now being replicated along the fault scarp and on both sides of drainage lines that are incised and graded to the lowered base level of the graben. Replication results in dune/*straat* relative relief of some 25 m at the scarp. With increasing distance from the fault this decreases until, in the interfluve areas, the terrain is flat. The continuity of dune forms, inferred from satellite imagery, across the now flat interfluve areas attests to an ancient aeolian construction phase. Flattening by water activity followed this, prior to the rifting that has facilitated the replication of the forms. The complexity of the constructional and destructive periods of dune morphological evolution, pertaining to changing climates and changes of base level requires further scrutiny to facilitate reassessment of the interpretation of luminescence dating of former periods of aridity.

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