8 Dunes of the Southern Kalahari

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Abstract

The dunes of the southern Kalahari are amongst the most studied in the world. Occurring in a region embracing arid and semiarid conditions, and dunes that are both marginally dynamic as well as more stabilised, research has focussed both on the processes operating on partially and variably vegetated surfaces, and the palaeoenvironmental histories of dunefield accumulation. Whilst commonly classified as linear dunes, this chapter examines the range and variability of forms in southern Botswana and contiguous areas, their temporally variable dynamics, and the developing chronometric histories of their development during the late Quaternary period.

Keywords

Linear dunes • Partial vegetation cover • Disturbance • Holocene

8.1 Introduction

The Kalahari is a predominantly sandy dryland region, and dunes are an important part of southern African landscapes as a whole (Thomas and Wiggs 2012). Despite this, the Kalahari does not totally fulfil common conceptions of deserts in terms of the degree of aridity or the occurrence of sand dunes, which are absent from large tracts, especially in Botswana. It is in the southern and northern-most regions of the country that dunes dominate the landscape, but in very contrasting ways. In the driest southwestern part of Botswana, westwards from Tshabong, an extensive region of relatively low but pronounced linear dunes dominates a landscape that also includes distinctive pans (Chaps. 5 and 10) and river valleys (Chap. 11). North of around latitude 23°S, more degraded dune forms are found in a number of contrasting systems juxtaposed with the major lacustrine and fluvial systems of Makgadikgadi, Okavango and Zambezi. The northern dunes are analysed in the next Chap. 9; here we focus on the dunes of southern Botswana and neighbouring territories.

The southern Kalahari dunefield extends into the Northern Cape of South Africa and southeastern Namibia (Fig. 1.6), with the dunefield as a whole spanning latitudes 23°S (where the northern limit is met, in Namibia) to 28°20′S in the Northern Cape, with the Orange River providing the southerly limit to the main system, though some pockets of dunes are found south of the river. The system may have its origins at the Plio-Pleistocene transition (Miller 2014) with subsequent reworking of sediments represented by today's dune bodies, which record both evidence of episodic accumulation (Thomas and Burrough 2016) and contemporary activation (Wiggs et al. 1995).

From west to east the system extends from 18°E to 22°30′E longitude (Thomas and Shaw 1991). Most of this dunefield, which covers an area of around 100,000 km^2 (Fryberger and Goudie 1981), is in fact found outside Botswana, although the driest area, which has the most active dune surfaces under modern climate conditions, is in the southwest of the country, centred on Bokspits in the area traversed by the Nossop and Molopo river valleys, which mark the border between Botswana and South Africa (Fig. 8.1). On average, mean annual rainfall in the part of the summer precipitation zone of southern Africa that the southern dunefield occupies is 150–300 mm, but in any year can be significantly less or significantly more, with inter-annual rainfall variability as high as 50%. There is enough moisture in the system to support, under natural conditions in non-drought periods, a partial vegetation cover on the dunes which are dominated by, but not confined to, linear forms (Fig. 8.1), with vegetation including grasses, shrubs and

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trees (Fig. 8.2). Vegetation limits the ability of the wind to mobilise sand, with the operation of aeolian processes today commonly restricted to the upper slopes and crests of dunes (Wiggs et al. 1994), but both drought periods and grazing pressures (Perkins 2018) can result in more extensive sand mobilisation in the southern Kalahari (Thomas and Leason 2005, Fig. 8.3).

8.1.1 Early Work

Early twentieth century descriptions of the southern Kalahari dune landscape were limited to observations made by travelers. Arnold Hodson, the first British policeman in Bechuanaland, perceptively described the southwest of the country as 'not quite an ordinary desert… it is made up of a sea of sand hills' (Hodson 1912:21) going on to note that it 'constitutes by far the most dreary and depressing part of the desert' (ibid). In Namibia, Korn and Martin (1937) noted how the dunes that form the northwestern part of the system are cut by river valleys, suggesting formation prior to valley incision. Lewis (1936) provided the first scientific descriptions focussed on the dunes, with his field observations confined to the South African part of the dune system and conducted as part of a systematic topographic survey of the Union (Fig. 8.4) that also made use of discontinuous air photograph coverage flown in 1934.

It is worth considering some of the information in these first scientific reports, as they frame and provide context for more recent research. Amongst Lewis's pertinent observations was the parallelism and generally uniform size and spacing of the dune ridges, which at the large scale arced from c. 20° to 40° from north. He also noted that in some areas, such as north of the confluence of the Nossob and Auob rivers, dune patterns were less regular, whilst in other areas dunes branched one from another, with branches often terminating abruptly. Lewis also noted that the dunes were on average 27 feet (8.2 m) high with a mean crest to crest wavelength of 250 yards (228.6 m), had broad flat crests up to 30 feet (9.1 m) wide, with the crests being the only parts

Fig. 8.1 Google Earth image of part of the southern Kalahari dune system at the intersection of Botswana and South Africa. Three (usually) dry valleys cut through the linear dunes, in some places leading to dune-end deflections on the upwind (NW) side of valleys and in other places sourcing sediment for smaller downwind dunes. Pan depressions interact with dunes in various ways: sourcing downwind lunette dunes, which in turn may source linear forms, or seemingly deflecting airflow and dunes around their margins

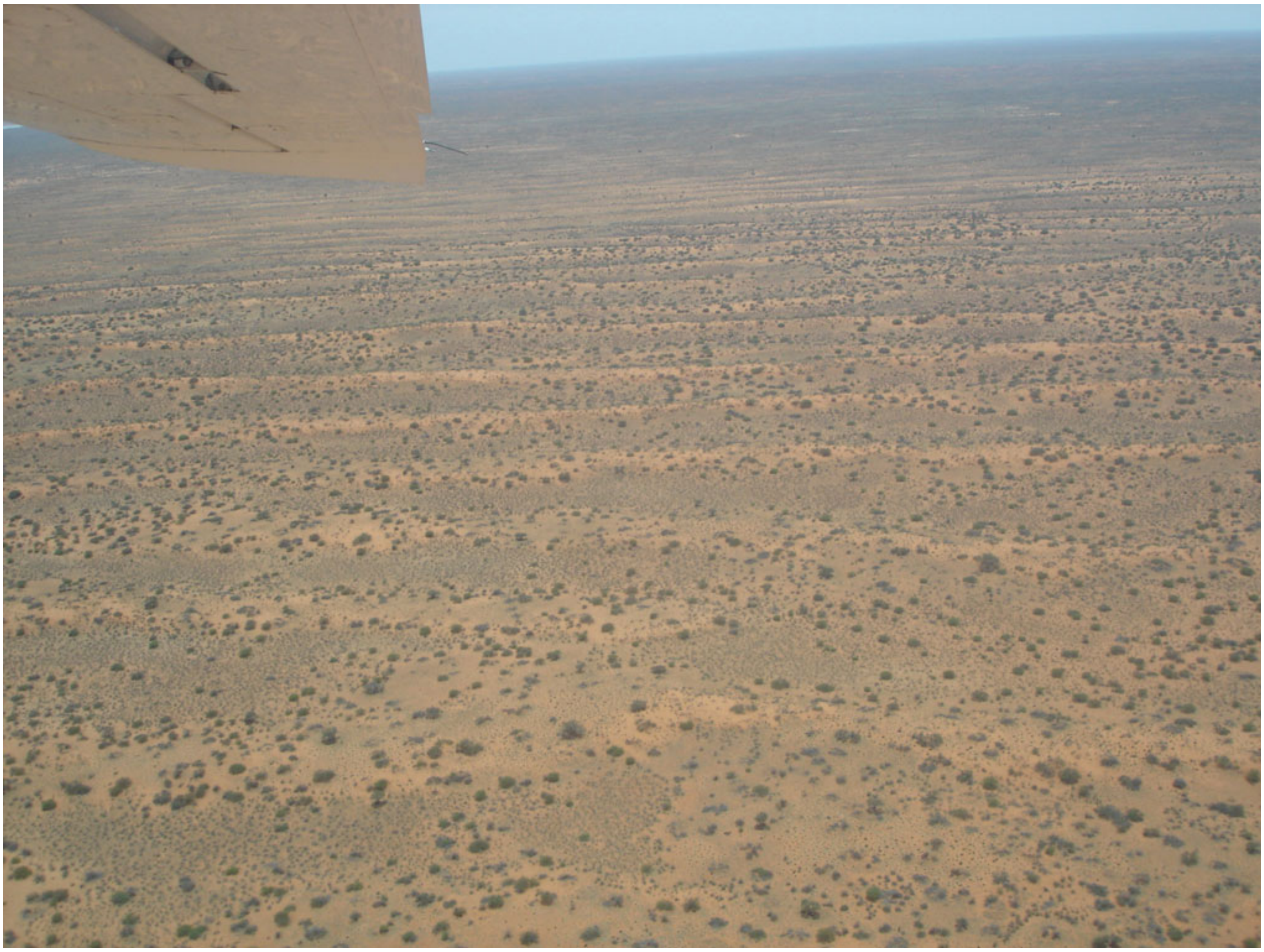

Fig. 8.2 Partially vegetated linear dunes near the Aoub valley, supporting a mixed vegetation cover. Inter-dunes are commonly well vegetated with grass species. Photograph taken in 2011. *Credit* David Thomas

of the dunes where the wind appeared to move sand. Photographs in Lewis's (1936) paper actually illustrate dune sites with very different vegetation covers, with some showing dunes and interdune areas devoid of vegetation except for widely spaced small trees. Based on the estimated age of one tree stump, 'a kameel-doorn tree said to be 400 years old' (p. 29) Lewis considered the dunes to be older than this and younger than the underlying but unspecified Kalahari limestone. He also regarded the features as transverse dunes, formed under the influence of easterly winds.

It was the aerial and field-based descriptions and analyses of Grove (1969) and Goudie (1969, 1970) that marked the beginning of a more systematic approach to dune science in the Kalahari. Grove's study drew on complete air photograph coverage of Botswana, with limited extension into South Africa, and six weeks of field reconnaissance to provide detailed morphological data and descriptions of landforms (Fig. 1.6). Building on Lewis's (1936) paper, much of Grove's description of the southern dunes mirrored these earlier observations but with some key differences and additions. First, Grove recorded the spatially systematic nature of dune system vegetation, with sparse grasses on crests, grasses, shrubs and small trees on flanks and taller (up to 5 m high) acacia trees in the grassed interdune areas. East–west variations in vegetation densities reflected the regional rainfall gradient. Second, Grove (1969) correctly ascribed the dominant forms as linear (rather than transverse) dunes, with formative sand transporting winds from the north-northwest over much of the curved dune system. He also reported that most dune 'Y junctions' occurred with the stems pointing downwind. Rather than branching—that is dunes splitting into two ridges—convergence has dominated, with adjacent ridges merging downwind, a point picked up in a statistical analyses of the ridge patterns by Goudie (1969) and Thomas (1985).

Third, over and above the occurrence of Y junctions within the dunefield morphometry, Grove recognised the

Fig. 8.3 Grazing pressures, especially close to water points, and droughts, can contribute to dune surface de-vegetation that in turn facilitates surface sediment mobilization by the wind. Photograph near Bokspits, 2008. *Credit* David Thomas

considerable complexity of dune patterns and forms in the southern Kalahari. This was reflected in his map of the system that included transverse ridges between 25°S and 25.8°S, particularly on the Botswana side of the border with South Africa (Fig. 1.6), as well as faint ridges ('furrow patterns') over an extensive area of central and eastern southern Botswana. Other than in Mallick et al. (1981), there has been little reference to these features since, though they might represent remnants of a southwest-northeast curvature of the main southern dune system (Thomas and Shaw 1991). Fourth, Grove also reflected on the ways in which the linear ridges interacted with other landscape features in the region. This included the downwind development of linear ridges from localised transverse (lunette) dunes on the margins of pan depressions (see Chap. 5) and interactions with dry river valleys that were subsequently analysed in-depth by Bullard and Nash (1998, 2000). Figure 8.1 shows examples of these contexts.

8.2 Dune Sediments

Aeolian processes are size selective, so that the sands that form desert dunes tend to be comprised of grains that have an upper size (relating to grain diameter) of c. 2 mm (2000 µm). Grains with a diameter less than 0.63 µm are classed as silt and clay, the silt fraction forming the main component of aeolian dust.

The sands of southern Kalahari linear dunes generally comprise over 90% quartz (Lewis 1936), the remainder comprising feldspars, zircon, garnet and other accessory minerals. Reddish-yellow hues are common (Thomas and Martin 1987), though sands may be paler and greyer downwind of valleys and pans (Stone and Thomas 2008). The redness of the dune sand is a result of thin iron coatings on grain surfaces (Lewis 1936). Sands are relatively coarse compared to those in many desert dunefields (Thomas and

Fig. 8.4 Lewis's (1936) map of southern Kalahari dunes, largely confined to the south African sector

Shaw 1991) although sediments generally become finer in a south-easterly direction in the system as a whole (Lancaster 1986). From the analysis of almost 50 samples from dune sediment cores from eastern Namibia, well-sorted medium sands dominated with the mean grain size commonly in the 250–300 µm range (Stone and Thomas 2008). Around 350 km further east in the Northern Cape, sands fall in the fine-medium size range. Cross-profile sediment sorting trends have also been reported, with dune crests generally being better sorted and comprising coarser sand than that found on the lower flanks (Lancaster 1986; Livingstone et al. 1999).

Silt particles are relatively rare in the sands of active dunes, because the saltation process that mobilises sand grains commonly liberates finer particles into the atmosphere where they can often be transported over longer distances by suspension. In most of the dune sand samples analysed by Stone and Thomas (2008) and Telfer (2011), less than 5% comprised silt or finer clay-sized material. An analysis of sediments from bare and partially vegetated dunes at Struizendam and Bokspits, on the Botswana side of the Nossop valley, reported less than 2% silt and clay in dune surface sediments (Bhattachan et al. 2013).

The interdune areas (or 'straats') between dune ridges are commonly sand covered, with sands generally having a higher silt and clay content than the dunes and also a greyer or whiter colouration (Thomas and Martin 1987). The thickness of these deposits is highly variable, being thinnest in western and southern parts of the system (Bullard and Nash 1998). The system as a whole is located on what was described as a limestone plateau by Mabbutt (1957) but is actually a partially silicified calcrete duricrust (Chap. 13) that is exposed in the flanks of the valleys that dissect the dunefield (Bullard and Nash 1998) or in pan margins (Lancaster 1986).

8.3 Technological Developments: The Advent of Systematic Research on Southern Kalahari Dunes

Despite only a small number of studies or descriptions of the southern Kalahari dunes being published in the first 70 years of the twentieth century, those considered above set the scene for the in-depth analyses of dune forms, histories and processes that have followed. From the 1970s onwards significant technical advances in the geosciences have also facilitated both observation of and research in the southern dunefield. Satellite imagery (e.g. Fig. 8.4), first available with global coverage from 1972 when the Landsat programme commenced, generated the ability for high resolution analysis of dunefield-wide patterns, morphometric analyses, and change analysis over time. For the southern Kalahari, this commenced with the work of Breed et al. (1979) within E. D. McKee's seminal edited volume *A study of global sand seas*. Luminescence dating was first applied to dune sediments in the Thar Desert, India, by Singhvi et al. (1982) with subsequent applications leading to the Kalahari becoming one of the best-dated dune systems on earth (Lancaster et al. 2016). This has allowed dune formation and accumulation histories to be produced, whilst questions surrounding aeolian sediment movement on partially vegetated dunes has benefited from the evolution and application of a range of field measurement and monitoring methodologies that allow sediment transport and surface changes to be recorded (Thomas and Wiggs 2008).

It is easy to ignore one further simple development that has changed our ability to investigate Kalahari dunes. Until the twenty-first century, access to the dunefield was largely restricted to sand tracks and dirt roads. Travel by horse, camel (a police camel breeding station was situated in the dunes near Bokspits and Askham on the South African side of the Molopo valley) or early motor vehicles at best made reconnaissance and research a slow process. Grove's (1969) paper, for example, was contingent on a slow six-week traverse of Botswana that barely entered the southern dunefield, getting only as far as Khuis on the northern side of the Molopo valley. Now tar roads allow the heart of the dunefield to be reached in a matter of hours from Upington in South Africa or Tsabong in Botswana, whilst Google Earth allows the full dune system to be explored and analysed from a desk.

The following sections pursue in detail the three themes considered above—dunefield morphology, dunefield accumulation and dune surface processes and activity in the southern Kalahari, focussing primarily on the principal linear and linear-like dune forms, before consideration of other, often under analysed forms found within the system.

8.4 Southern Kalahari Linear Dune Morphology and Morphometry

Linear dunes are the most common desert dune type on earth, and broadly speaking linear forms develop in wind environments dominated by a bimodal sand transport direction (Lancaster 1982; Thomas 2013), with dunes forming largely by extension in the resultant downwind direction (Thomas 1988; Telfer 2011). When the southern Kalahari dune system is considered as a whole, the pattern forms a 'wheelround' (Shaw 1997), or semi-circular arc (Lancaster 1981) that reflects the winds that blow anticlockwise around the semi-stable southern African anticyclone (Tyson 1986). Seasonal movements in the position of this atmospheric circulation feature mean that fluctuations in mean wind direction can occur throughout the year. Breed and Grow (1979), Lancaster (1981) and Thomas (1984) all used the 'Fryberger method' (Fryberger 1979) to calculate modern potential (not absolute as other factors such as ground cover and soil moisture determine whether sand actually moves) sand transport in the Kalahari dune systems. Lancaster (1981) noted that sand movement potentials were generally simple (unimodal), and only in the west of the dune system, around Keetmanshoop in Namibia, are potential sand transporting wind regimes truly directionally bimodal.

Imbalances between components of the wind regime that shape the ridges can lead to asymmetry in dune cross-profiles, which is a characteristic of these landforms recorded for example in Australia (Mabbutt and Wooding 1983) as well as in the Kalahari (Lewis 1936; Bullard et al. 1995). It can also lead to some lateral migration of ridges over time, recorded in linear ridge studies from Namibia and China (Bristow et al. 2005; Rubin et al. 2008). The occurrence of Y junctions, which have fascinated researchers in the southern Kalahari from Lewis (1936) through to Grove (1969), Goudie (1969) and Thomas (1988), may relate to complexities in the wind regime and sand transport over time leading to the deflection of ridge ends and their merging with adjacent forms (Breed and Grow 1979). Where ridges are spaced further apart, the opportunities for merging are fewer compared to situations where dunes are more closely spaced. The controls on dune patterns were subsequently investigated in modelling studies during the 1990s by for example Werner (1995) and Werner and Kucurek (1999).

Lancaster (1987) estimated that around a third to a half of the dunes in the southern Kalahari were simple linear ridges, simple dunes being those that do not have contact with neighbouring dunes (McKee 1979). These equate to the parallel/near-parallel forms recognised by Lewis (1936) in the South African sector and the extremely straight and continuous ridges that are particularly prevalent in the northern parts of the system, especially to the east of Mariental and around Stampriet in Namibia (Stone and Thomas 2008; White et al. 2015). Here Y junctions are rare and dunes are respectively c. 9 m high and 500–1000 m apart, trending NNW-SSE, and 16 m and 1–2 km apart, trending NW–SE. Individual ridges may be tens of kilometres long without converging on adjacent dunes. Through the system as a whole, the ridges are generally higher where ridge spacing becomes greater (Thomas 1988).

Factors affecting dune spacing and dune height are potentially complex and controversial, but certainly the volume of available sediment is one factor that limits or facilitates the number of ridges that can form in a given area and the heights that they can attain (Wasson and Hyde 1983). Wind regime, and changes therein over time, and the frequency of dune building episodes, both potentially linked to long term climate changes (Livingstone and Thomas 1993; Stokes et al. 1997; Bailey and Thomas 2014) are further elements that contribute to the complexities that have influenced dunefield patterns and morphologies in the southern Kalahari.

The mostly parallel and continuous forms apart, the remaining half- to two-thirds of the system possesses more complex dune patterns, where interactions between individual forms are more common and the identification of specific continuous ridges is more difficult. According to McKee (1979), these types of dunes are either compound, when dunes of the same type merge (i.e. in the Kalahari at Y junctions) or complex, where dunes of different forms interact, for example where linear forms emerge from pan margin dunes, as shown in Fig. 8.4. In parts of the southern Kalahari, the complexity of the patterns of dunes generates forms that are more akin to networks of dunes rather than strict linear forms.

Bullard et al. (1995) used detailed aerial photograph analysis and digital elevation models to investigate the variations in dune morphology and morphometry in a 4000 km^2 area of the dune field regarded as containing representative examples of the forms found throughout the system. This investigation led to a statistically rigorous five-fold classification of dune plan forms and morphologies that was then applied to an analysis of the system as a whole (Fig. 8.5). Dune classes embrace discontinuous ridges (class 1), through to simple continuous ridges (class 2) and network-like forms (class 5). With the formation of the dunefield associated with winds broadly from the northwest to westerly sector, and therefore with sediment transport occurring from a similar direction, it was shown that dune patterns become more complicated in a south-easterly direction (Lancaster 1988; Bullard et al. 1995) with an associated increase in Y junction occurrence. A possible secondary trend may relate to the regional aridity gradient (Bullard et al. 1995). With conditions becoming wetter towards the northeast (Thomas and Shaw 1991), the overall temporal opportunities for dune building and organisation, either in terms of long term periods of aridity or shorter aridity/drought phases, may have been less than in drier parts of the system.

The morphology and pattern of dunes can be affected by interactions with other landforms in the system, particularly river valleys and pans (Fig. 8.4), with changes in airflow (Eitel and Blummel 1997; Bullard and Nash 2000) and sediment availability (Thomas et al. 1993) being causal factors. Bullard and Nash (1997) recognised four types of dune valley contexts in the southern Kalahari: where dune patterns and orientations are the same on both up- and downwind sides of a valley (for example at the lower Nossop valley at 26°39'S 20°38'E); where dunes adjoin a valley on the upwind side and the pattern adjacent to the valley is altered (for example on the Nossop valley at 26°24'S 20°43′

	General Description	Example Location
1	Dunes parallel/sub-parallel, discontinuous occuring as short lengths (< 2km). Y-junctions uncommon and there are no transverse elements.	26° 49'S 21° 00'E
2	Dunes parallel/sub-parallel and continuous for several km, few Y-junctions and no (or very rare) transverse elements. Those Y-junctions which do occur tend to form at the junction of two long dunes rather than as short spurs at the side of a dune. Occasional slip faces on crests but < $2m^2$.	26° 42.57'S 20° 42.15'E
3	Dunes parallel/sub-parallel and continuous for several km. Y-junctions common,both as parallel dunes merge and as short spurs < 600m on either side of dune. No slip faces on undisturbed dunes but may be common where grazing occurs.	26° 33.01'S 20° 31.42'E
4	Linear dune network comprising large steep dunes and smaller gently sloping dunes. Larger dunes have broadly linear trend but are very sinuous. Small dunes tend to be orientated perpendicular to this trend. Small pans occur in deep interdune areas. Both types of Y-junction occur, Y-junctions and termini are common.	26° 26.84'S 20° 48.35'E
5	No obvious linear trend and a chaotic hummocky appearance. Dune slopes shallow with very rounded crests. Dunes have low relief but occasional dunes up to 7 - 8m high. Very little interaction between dunes.	26° 08.74'S 20° 36.37'E

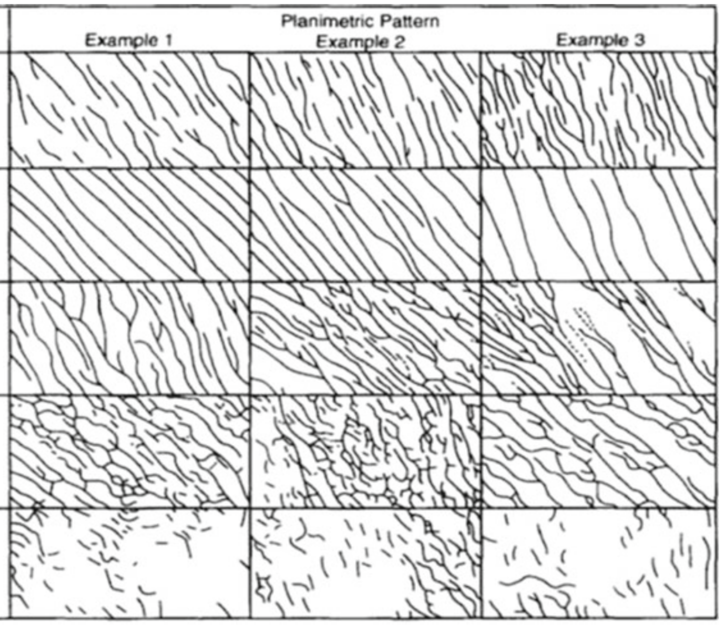

Fig. 8.5 Dune pattern and morphology variations in the southern Kalahari derived from aerial photograph and statistical analyses (Bullard et al. 1995). Reproduced with the permission of John Wiley and Sons

E); where dunes adjoin a valley on the upwind side but are absent on the downwind flank (i.e. the dunes terminate at the valley, or recommence several kilometres downwind of the valley, for example at 26°52'S 20°47'E on the Molopo valley); and where dune-free zones occur on both valley sides (for example along the Aoub valley at 24°46'S 18° 44'E). The type of association appears to be dependent on the topography and relative orientation of a valley at the point of contact with the dunes (Bullard and Nash 1998). Where dune patterns appear unaltered despite being traversed by a valley, a further explanation is that a once-continuous dune pattern has been disrupted by later channel flow (Thomas et al. 1998).

Some of the interactions between linear dunes and pan depressions are not dissimilar to those found between dunes and valleys, though other relationships also occur. In some contexts linear dune orientations clearly deflect around the margins of pans, which may be incised over 50 m into underlying sediments, presumably resulting in localised airflow deflection that has influenced net sediment transport direction on the linear ridges. In other contexts pans occur in broad, duneless corridors, but linear dunes extend downwind from the pan margin lunette. This is very evident, for example, at Koopan and other pans near the confluence of the Kuruman and Molopo valleys (Fig. 8.4), at Witpan (Thomas et al. 1993) and at numerous pans in southwest Botswana (Lancaster 1986).

8.4.1 Other Dune Forms in the Southern Kalahari and Their Significance

Aside from the patterns of linear and linear-like dune forms that dominate the southern Kalahari, other dune forms are an important if more localised part of the landscape too. Surface vegetation disturbances, often caused by fire, drought or grazing, can cause localised sand movement at sites often called 'blow outs'. In places, significant patches of superimposed secondary dune development can result where sand is moved downwind from disturbed patches, resulting in a parabolic-shaped dune front with trailing arms. Nested patches of parabolic dunes, up to 1 km long, are found in several locations in the dunefield (Eriksson et al. 1989; Thomas and Shaw 1991; Fig. 8.6). Other localised forms also occur, such as small barchan dunes developed from valley floor sediments in the Molopo (Lewis 1936; Bullard and Nash 1998), and narrow arcuate forms associated with valleys that Bullard and Nash (2000) term valley-marginal dunes.

Over 110 pan depressions in the southern Kalahari (Mallick et al. 1981), both within (Grove 1969) and beyond (Lancaster 1978a) the main dunefield, possess fringing dunes on their downwind margins (Fig. 8.7). Often described as lunettes (Hills 1940) due to their distinctive planform, these dunes (Telfer and Thomas 2006) are commonly regarded as developing from sediment deflated from the pan

Fig. 8.6 Patches of parabolic dunes are found at several locations in the dunefield, including here centred on 25.973°S 20.631°E in the Kalahari Transfrontier Park. Google Earth image, July 2013

floor, either directly during dry conditions when pans are excavated (Lancaster 1978b), from sediments initially transported to the downwind margin by wave action during wetter conditions (Bowler 1986), or from sediment that has washed or blown into the basin from the margins (Thomas et al. 1993).

Most lunette dunes in the southern Kalahari are vegetated and do not appear to be accumulating significant sediment under present conditions (Goudie and Thomas 1986). A notable exception is at Witpan (20.17°E 26.67°S) in the Northern Cape, where the western sector of a large fringing lunette has a distinctive bare and active lunette crest with a slip face (Thomas et al. 1993). The pan-facing plinth of the lunette is indurated with clay facilitating runoff and gullying during rainfall events that return sediment to the pan floor that is subsequently recycled back to the dune by the wind during drier conditions.

Grove (1969) noted that pans may have more than one downwind lunette dune, with differences in orientation, which can be particularly distinct in central southern Botswana reflecting changes in net sediment transport direction (Lancaster 1978b). Lawson and Thomas (2002) applied luminescence dating to a series of lunette sequences from pans within the main dunefield to the west of the Molopo valley, whilst the large 9 m high lunette at Witpan was subject to intensive full-profile luminescence dating by Telfer and Thomas (2007). Both studies found lunette age records dominated by Holocene ages, including accumulation in the last few centuries on inner lunettes and the upper sediments at Witpan.

8.5 Late Quaternary Linear Dune Accumulation in the Southern Kalahari

The partial vegetation cover that southern Kalahari dunes support is a significant characteristic that might relate to dune development and behaviour in two ways. It likely indicates that the main dune bodies formed in the past, and are now largely stabilised, and it may represent the generally static, and extending, nature of linear dunes being conducive to vegetation colonisation (Thomas 1992). These two

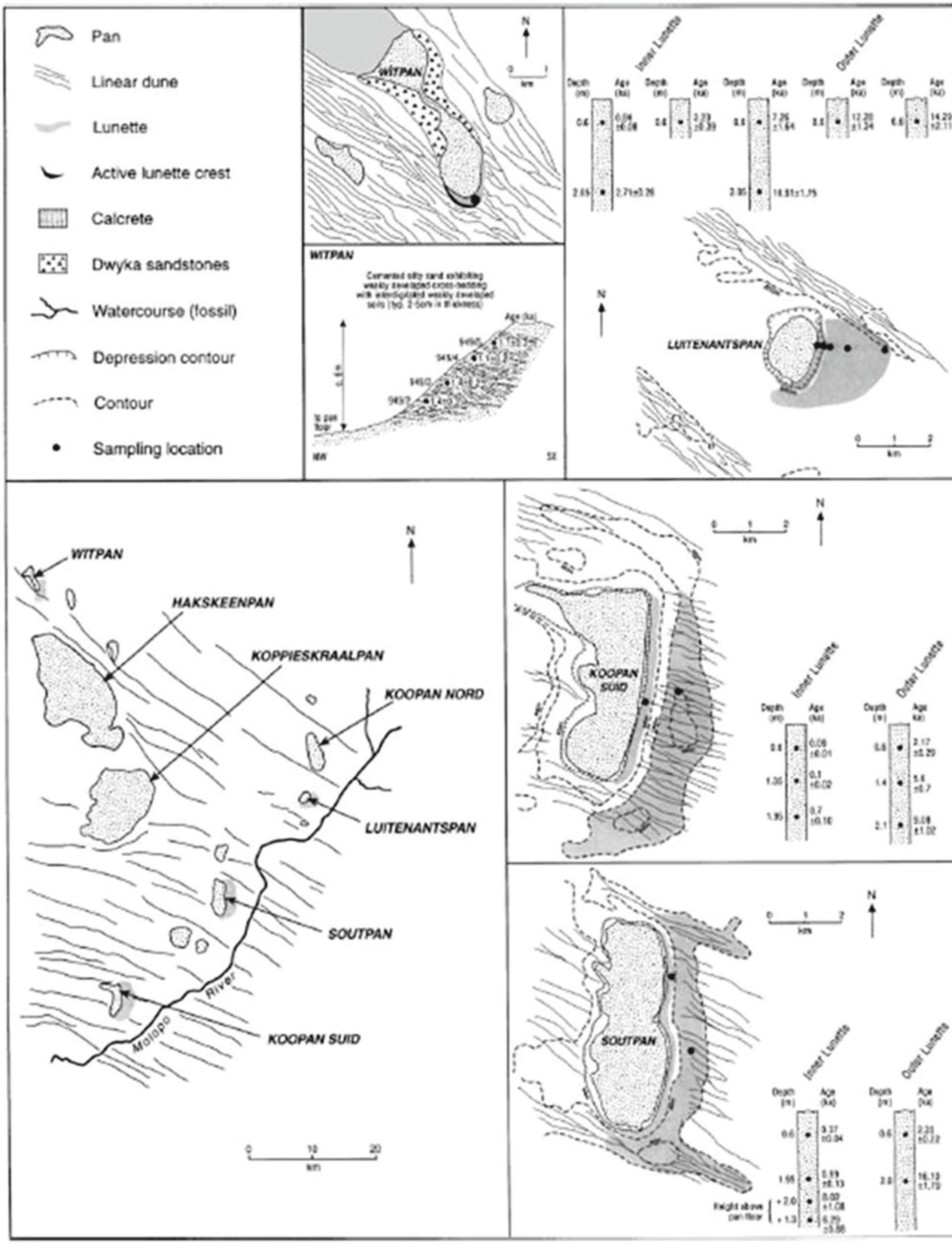

Fig. 8.7 Variations in lunette dune forms and associated dune ages from pans west of the Molopo valley (Lawson and Thomas 2002). Reproduced with the permission of Elsevier publishers

explanations are not, of course, mutually exclusive, especially in environments such as the southern Kalahari where rainfall is both seasonal and highly variable from year to year. Vegetation cover, and the sand on dune surfaces, is not immutable to change even at the relatively short timescales of years to decades (Livingstone and Thomas 1993). Knowing when the dunes were formed is therefore an important facet of understanding their status in the modern landscape.

Deacon and Lancaster (1988: 62) regarded the extensive Kalahari dune systems as ‘one of the most impressive pieces of evidence for the nature of late Quaternary climatic change in the Kalahari’. Lancaster (1981) compared the orientation of dunes with the modern sand transport vectors from wind data analysis, to infer subtle changes in the position of the southern African anticyclone between the time when dunes formed and the present day. He went on to develop a dune mobility index (*MI*) integrating both wind data and effective moisture data (annual precipitation minus potential evapotranspiration) (Lancaster 1988; Fig. 8.8), that was used to infer how climate conditions had changed in the region since the dunes were constructed. The interpretation of *MI* values depended on calibrating the index to a range of modern dune states, and the assumption that when mean annual precipitation exceeded 150 mm, there is too much moisture and vegetation in the environment for sufficient aeolian sand transport for dune bodies to accumulate.

From the 1990s onwards, luminescence dating, which measures the time that has elapsed since sediment was buried (i.e. since it was last transported on the surface of a dune and exposed to sunlight), and studies of sediment transport and environmental conditions affecting these dunes, considered in the next section, have gone a long way to explaining the history and behaviour of these features, and understanding the potential relationships, and differences, between dune building and surface sediment movement.

Luminescence dating was first applied to Kalahari linear dune sands by Stokes et al. (1997), since which 270 ages have been produced from sediments in the southern Kalahari dunefield out of 600 ages from dune features in southern Africa as a whole (Thomas and Burrough 2016, Fig. 8.9a). In the southern Kalahari 194 ages are from the linear ridges and associated features of the main dune system with most of the remainder from the lunette dunes on the margins of pan depressions. Thomas and Burrough (2016) divide the southern Kalahari linear dunes as a whole into the western system, which comprises the long, quasi-straight ridges of Namibia, and the southern system, which includes the more complex forms in the Northern Cape and in Botswana.

In some respects, the chronologies of dune emplacement and accumulation have proved difficult to interpret, especially as more age data have been published (Fig. 8.9b). With the notable exception of one full dune profile that was exposed and sampled, above underlying calcrete, in a road pit near Twee Rivieren on the South Africa – Botswana border (at 26°31’S, 20°36′E), the earliest ages were derived from a small number of samples primarily collected from hand-dug pits in the crests of ridges (Stokes et al. 1997). From this, a relatively simple picture of discrete episodes of late Quaternary dune building emerged for the southern Kalahari. Stokes et al. (1997) suggested that the linear dunefield was primarily constructed in phases at 6–10 ka and 22–16 ka ago, with the deepest basal age from the pit of 28 ± 8 ka.

As the sampling of dune ridge sediments progressed through the use of augering methods that allowed samples suitable for luminescence dating to be extracted from the full depth of dune sediments, new insights occurred. These included the identification of dune basal ages as old as 104 ± 8.3 ka near Witpan (Telfer and Thomas 2007) and in excess of 180 ka from the long straight ridges near Stampriet (Stone and Thomas 2008).

New questions and challenges also emerged regarding the interpretation of dune age records, reviewed by Telfer and Hesse (2013), and Thomas and Burrough (2016). Amongst these, emerging from work in the southern Kalahari, Stone and Thomas (2008) showed how the depth of sampling, and the sampling intervals used, affected interpretation of age records. Other imperfections in dune luminescence age chronologies from the region (Chase 2009), including the gaps in records and the relatively high statistical errors on ages, have also made interpretation challenging, compounded by uncertainties surrounding the climatic drivers of linear dune dynamics. Further, when age statistical errors are considered, the identification of distinct periods of dune building often becomes blurred through the overlapping of the one sigma statistical errors that age calculations produce (Thomas and Burrough 2016, Fig. 8.9b).

In some respects, these issues limit the contribution that dune age studies have been able to make to understanding the landscape history of the southern Kalahari region during the Quaternary period (Chase 2009; Chase and Brewer 2009). Part of the difficulty has derived from the ages themselves being used as the proxy record of past environmental conditions, without evidence of an association with a particular environmental process. To address this problem, Thomas and Bailey (2017) developed a methodology to quantify dune sediment accumulation associated with sequences of luminescence ages derived from dune bodies. This approach was built on Bailey and Thomas’s (2014) numerical model of linear dune accumulation that incorporated the climatic factors that drive dune surface activity and sediment accumulation. The model also recognised, and factored in, the potential effects of post-depositional reworking of older dune sediments on preserved records and the impacts of sampling and analytical processes on the

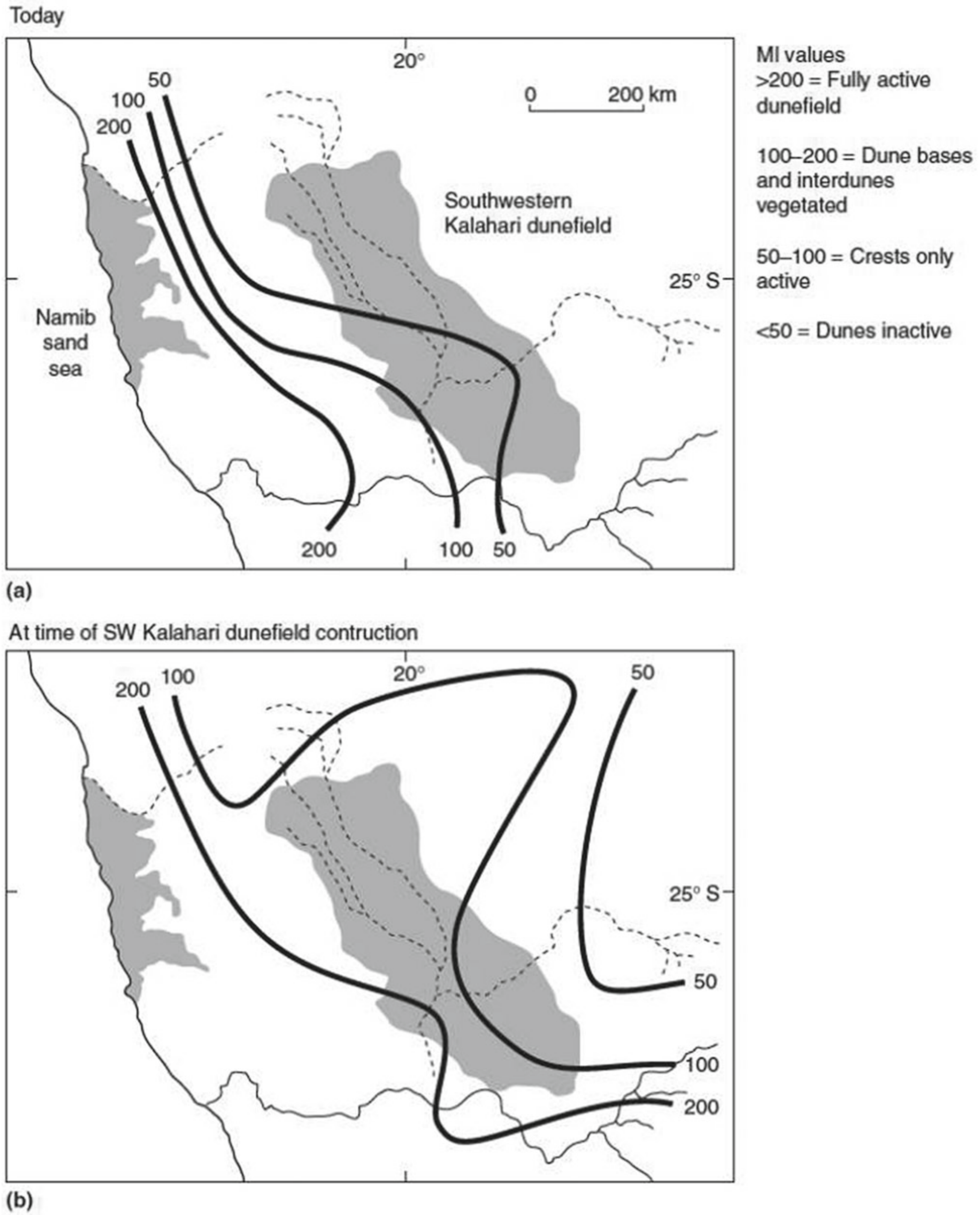

Fig. 8.8 Mobility Index values for the southern dunefield **a** today and **b** inferred for the time of dune accumulation. Index values are: 200 = fully active dunes; 100–200 = interdunes and lower dune slopes vegetated; 50–100 = only dune crests active and unvegetated; < 50 = dunes wholly inactive and vegetated. From Lancaster (1988). Reproduced with the permission of Elsevier publishers

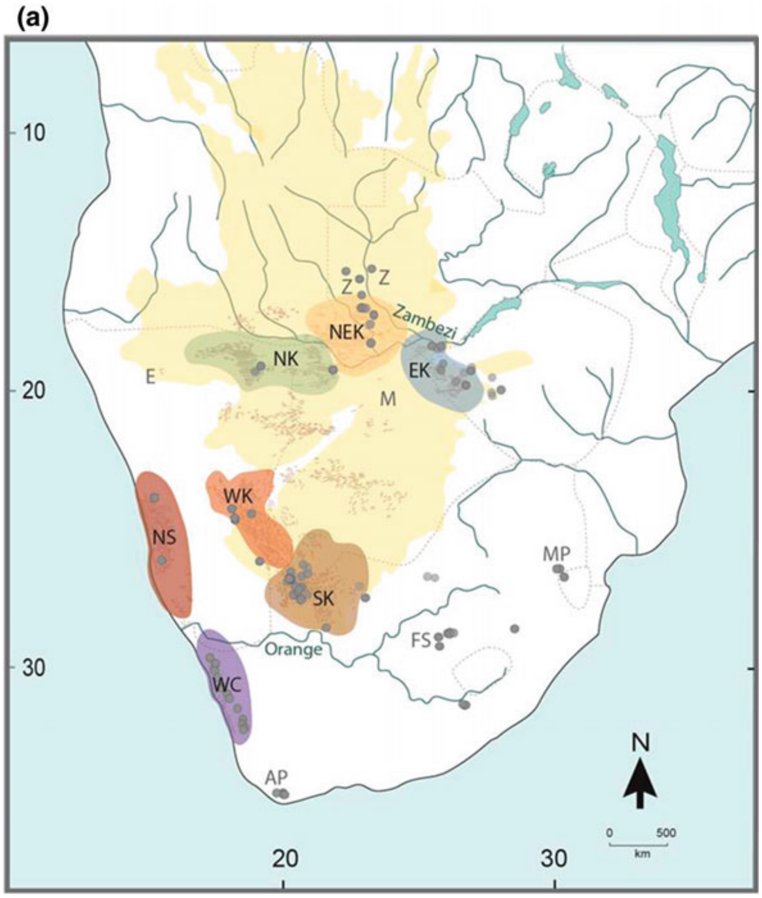

Fig. 8.9 **a** Locations of luminescence dated dune systems in southern Africa as a whole, showing also the distinction between the western and southern components of the wider Southern Kalahari dune system (after Thomas and Burrough 2016). Major dunefield areas are shaded: SK = southern Kalahari; WK = western Kalahari; EK = eastern Kalahari; NK = northern Kalahari; NEK = northeastern Kalahari; NS = Namib Sand Sea; WC = West Coast dunefield. Smaller dune areas or regions where dunes occur but are scattered rather than landscape-covering features are shown by letters: AP = Agulhas Plain; FS = Free State; MP = Mpumalanga; Z = Zambia east of the Zambezi River. E = Etosha Pan, M = the Makgadikgadi basin. Some of these systems are considered further in Chap. 9. Reproduced with the permission of Elsevier publishers. **b** Plots of southern Kalahari linear dunefield age data, showing how the overall record has evolved as new data have appeared. Data are shown for three time periods relating t the publication of information: 1997–2002; 2003–2007; and 2008–2013. The black histogram bars show the central ages plotted in 5 ka groups, while individual ages plotted with the central ages and statistical errors (horizontal lines associated with each age show an apparent record with indistinguishable phases of accumulation due to the age errors overlapping. The broad pale horizontal bars show the 9–16 ka and 20–26 ka periods of dune building that was proposed in the initial age study in the region by Stokes et al. (1997). Reproduced with the permission of Elsevier publishers

resultant data. The model was then developed to interpret dune luminescence age datasets (Thomas and Bailey 2017), quantifying the records of sediment accumulation that exists within stacked dune age records, examining the varying thicknesses of accumulation intervals between successive dated sediment units, and integrating the records for whole dunefields.

This approach was first applied to the total dunefield age and sediment dataset from the Kalahari, producing continuous records of variations in dune building (called accumulation intensity, or *AI*) through time (Thomas and Bailey 2017). Figure 8.10 shows the *AI* curves for the linear dunes of the southern and western Kalahari for the last 50 ka, alongside the record of water accumulation in the Stampriet aquifer (Stute and Talma 1998). This substantial aquifer underlies the southern dunefield (Chap. 12) and its recharge record, derived from ^{13}C dating of waters, is regarded as a proxy for regional rainfall changes. It can be seen that the linear dunes presently found in the southern and western parts of the system accumulated most intensively during the early Holocene period, around 13–9 ka, prior to significant aquifer recharge in the mid-Holocene. This represents a period of increased rainfall compared to today’s conditions that may have generated sufficient vegetation on dune

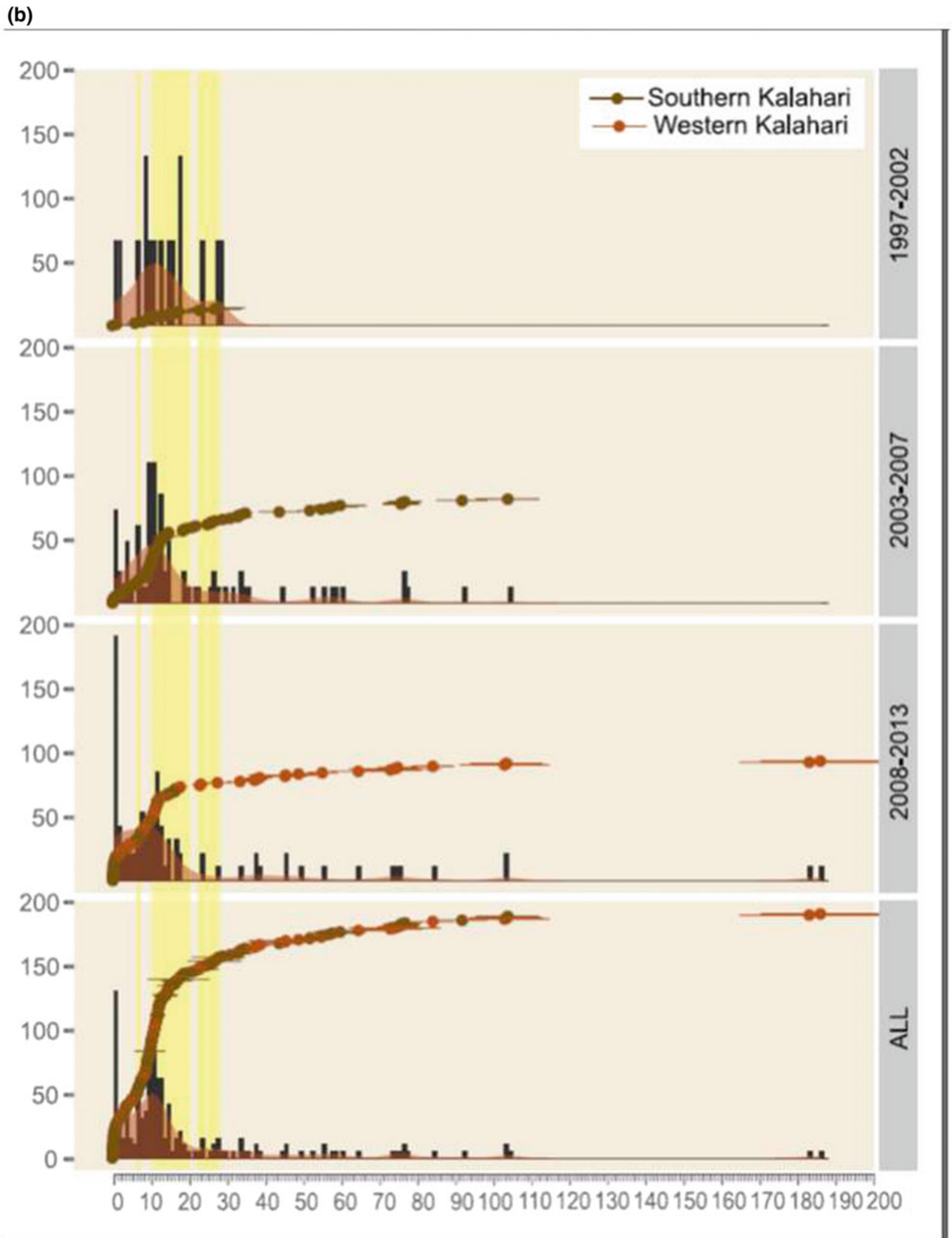

Fig. 8.9 (continued)

surfaces to inhibit dune activity. The last ~2 ka have also seen dune accumulation in the drier southern part of the system, as noted by Telfer and Thomas (2007).

In parts of the southern Kalahari, linear dunes encroach onto the upwind surface of pan depressions (e.g. Eitel and Blumel 1997; Telfer and Thomas 2007). The systematic and extensive application of luminescence dating to one of these, at Bettenstadtpan (27°25'S, 20°33'E) was used by Telfer (2011) to examine the assumption that linear dunes develop through downwind extension. 42 luminescence ages, derived from seven augered full-dune profiles at 100 m intervals along the downwind end of the dune, showed that basal ages increased from 7.5 ± 0.6 ka at the southeastern-most tip of the dune on the pan floor to 17.6 ± 1.3 ka 600 m upwind in a northwesterly direction. Whilst ages from the upper 2–3 m of the 8 m high ridge preserved evidence of reworking in recent centuries, sediments from the core of the dune also recorded a general trend of ages getting younger in a downwind direction, evidencing the role of dune extension in the accumulation histories of these forms.

In summary, it can be seen that there have been significant advances in the interpretation of longer-term southern Kalahari linear dunefield development, facilitated through the application of luminescence dating. It is likely that environmental conditions during the major early Holocene period of dune accumulation recorded in the sedimentary record were generally drier than those prevailing today and certainly drier than the wetter mid-Holocene period recorded in the Stampriet aquifer record. Luminescence dating also records significant sediment reworking and accumulation within the dune system in the late Holocene up to the present day, such that a full understanding of dune behaviour and dynamics requires consideration of surface activity under the partially vegetated conditions that prevail today.

8.6 Dune Surface Processes and Dynamics

The partial vegetation cover (Figs. 8.1 and 8.2) evident on the dunes of the Kalahari has led to them being described as fixed, stable or relic features (Grove 1969; Goudie 1970; Lancaster 1981) in contrast to the far-more active and dynamic dunes of the Namib Desert. This suggests that the dunes formed and developed in drier and/or windier conditions in the past partly stimulated the use of OSL dating on the dunes (as described above, Sect. 8.5), with the expectation that dated episodes of Kalahari dune-building could be utilised for palaeo-environmental interpretation in a relatively straightforward manner (e.g. Stokes et al. 1997). Whilst we now have a far better understanding of the sophistication required for collecting and interpreting OSL data (Telfer and Hesse 2013; Thomas and Burrough 2016), we also have a more highly-developed appreciation of the non-binary (i.e. not active vs inactive) nature of sand dune mobility and dynamics.

Livingstone and Thomas (1993) first discussed the extent to which the dunes of the southern Kalahari could be considered geomorphologically inactive features on account of their vegetation cover. Noting that there was no direct or indirect evidence for the Kalahari dunes having ever existed in a state of complete denudation, in contrast to the Namib dunes, they recognised that the relationship between dune

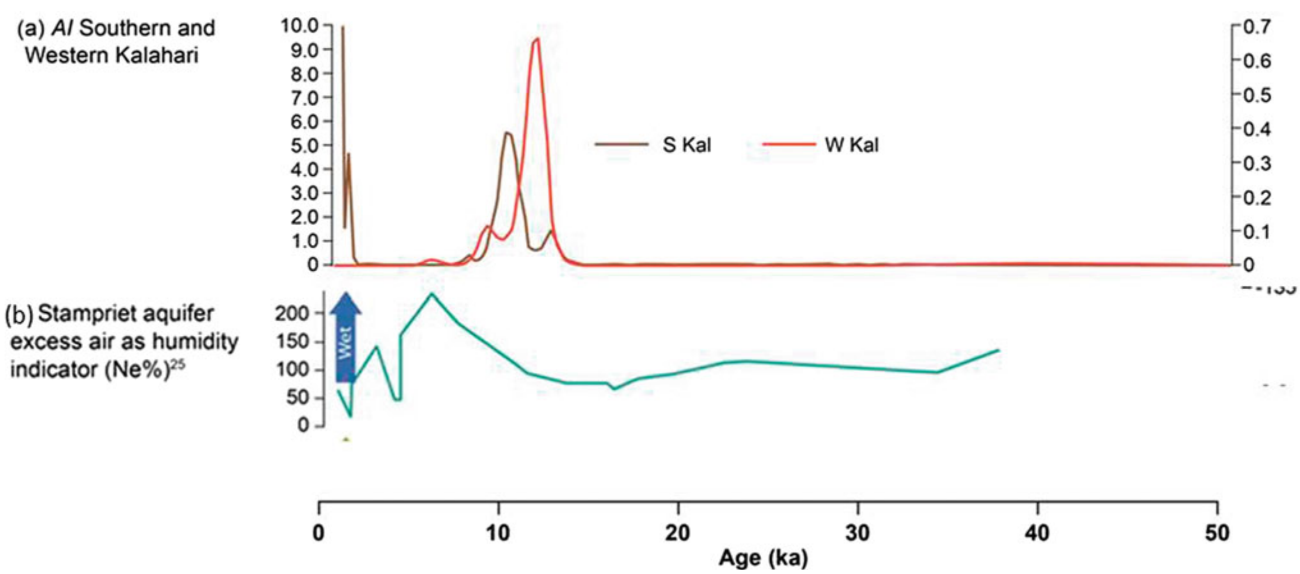

Fig. 8.10 Dune accumulation intensity (*AI*) curves for the southern and western linear dunes over the last 50 ka (Thomas and Bailey 2016), compared to the precipitation record derived from the Stampriet Aquifer (Stuut and Talma 1998). Reproduced with the permission of John Wiley and Sons

activity, vegetation cover, and environmental variability might be more nuanced and subtle than a simple dry/active and wet/inactive narrative. Rather, they considered that the presence of vegetation on a dune might not necessarily indicate dune inactivity, but rather represent a mobility dynamic existing as part of an environmental continuum. In this way, they considered that dune activity in the Kalahari could be both episodic, responding to changes in vegetation cover driven by the considerable rainfall variability in the semi-arid environment, and also as a more subtle and continual gradation in landscape change, rather than a hard threshold delineating dune activity.

Taking these ideas as a starting point, Bullard et al. (1996, 1997) undertook a meteorological analysis of the southern Kalahari dunefield between the years 1960 and 1992. In an attempt to identify the potential activity (*PA*) of the dunes in response to changing rainfall, wind, and vegetation cover, they applied Lancaster's (1988) Mobility Index, *MI*:

$$MI = W/(P/PE)$$

Where W is the amount of time wind blows above a threshold for sand entrainment, and P/PE encompasses the effectiveness of rainfall (P) accounting for potential evapotranspiration (PE). In this way, the index balances wind energy available for erosion against the resistance to erosion provided by a vegetation cover responding to moisture availability. As discussed above Lancaster (1988) had designed the Mobility Index to investigate the paleoenvironmental development of the Kalahari dunes. Extending the analysis to more recent times and at shorter temporal scales, Bullard et al. (1997) were able to identify high variability in the potential activity of the dunes on a year-to-year basis. As shown in Fig. 8.11 their analysis recognised the potential for partial sediment transport activity on the dune surfaces for much of the study period, and specifically identified the mid- and late- 1980s, a period of significant drought in southern Africa, as having the potential for active dune crests and fully active dunes.

The research of Bullard et al. (1996, 1997) showed that the key drivers for enhanced dune activity varied at sub-decadal timescales, intimating that some dune activity was possible in the Kalahari today despite a partial vegetation cover. Importantly, this study also showed the potential for a strong dynamic in dune mobility in response to periods of drought, where they found a correlation between decreased rainfall and increased wind energy. These findings pointed to the capacity for the dunes of the Kalahari to show both a muted, gradual mobility dynamic under a partial vegetation cover, and a stronger, episodic response to more intense environmental extremes, as indicated by Livingstone and Thomas (1993).

Bullard et al. (1996, 1997) showed the *potential* for landscape-scale mobility in the dunes of the southern Kalahari in response to changing environmental variables over annual temporal scales. Smaller, dune-scale studies of *actual* dune activity as a result of variability in vegetation cover were provided by Wiggs et al. (1994, 1995, 1996). Field-based measurements of airflow over de-vegetated and partially vegetated dunes in the south-west Kalahari allowed Wiggs et al. (1994, 1996) to quantify the acceleration of near-surface wind velocity evident with the removal of the vegetation canopy, and the consequent increase in erosion and deposition (total surface change) manifest on the respective dune surfaces (Fig. 8.12).

From Fig. 8.12 Wiggs et al. (1994) recognised that the impact of a reduction in the surface vegetation cover on the Kalahari dunes, provided by a natural burn event in this case, was most acutely experienced on the upper slopes and crests of the dunes. In these upper portions of the dunes sediment transport activity leading to erosion and deposition was enhanced in comparison to the far less active lower dune slopes and interdune areas. This was explained as a response of the windflow to the topography of the dunes, with airflow acceleration on the windward slopes leading to enhanced erosive stresses on the upper slopes and crests in the absence of vegetation (Wiggs et al. 1996). In this way, the much more dynamic crests of the non-vegetated dunes display a sharper crestal shape, as a result of the development of an avalanche slope, in contrast to the more rounded and flat crestal shapes of the partially vegetated dunes typical of the Kalahari environment (see Sect. 2.1.1).

Field measurements led Wiggs et al. (1994) to conclude that changes in airflow patterns as a result of vegetation removal on the Kalahari dunes resulted in an increase in dune surface activity (erosion and/or deposition) by up to 200%. This suggested that the dynamics of the Kalahari dunes were a function of variability in wind velocity but also vegetation dynamics (i.e. the frequency, scale, and duration of vegetation cover decline and growth). This sensitivity of Kalahari dune activity to vegetation cover change was explored more widely by Wiggs et al. (1995). Monitoring erosion and deposition activity on seven dunes with varying degrees of vegetation cover (from 10 to 29% lateral cover) over a period of 10 weeks, they noted the strong influence that vegetation cover has on dynamics at the dune-scale (Fig. 8.13).

Wiggs et al. (1995) recognised that whilst the dunes supporting a relatively substantial vegetation cover (ranging from 15 to 29% lateral cover) demonstrated some erosion and deposition activity on their surfaces, those dunes supporting a vegetation cover below around 14% exhibited a substantial increase in geomorphic activity, by up to an order

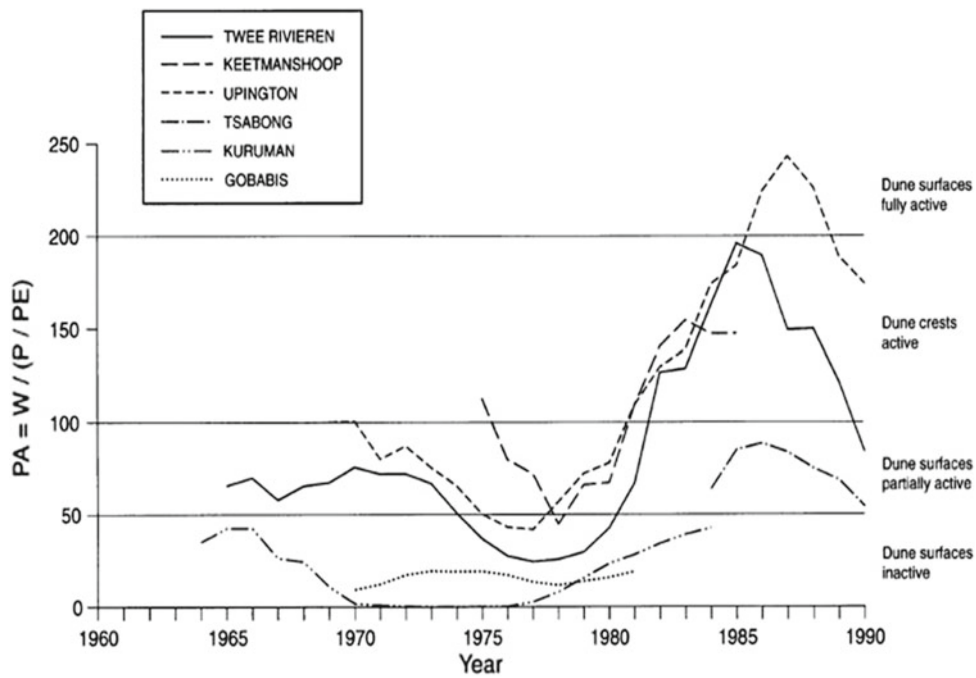

Fig. 8.11 Potential Activity (*PA*, 5-year running mean) of the Kalahari dunes as calculated from meteorological analysis by Bullard et al. (1997) using data from six weather stations in the southwest Kalahari. The thresholds for different stages of dune activity were determined by Lancaster (1988). Reproduced with the permission of John Wiley and Sons

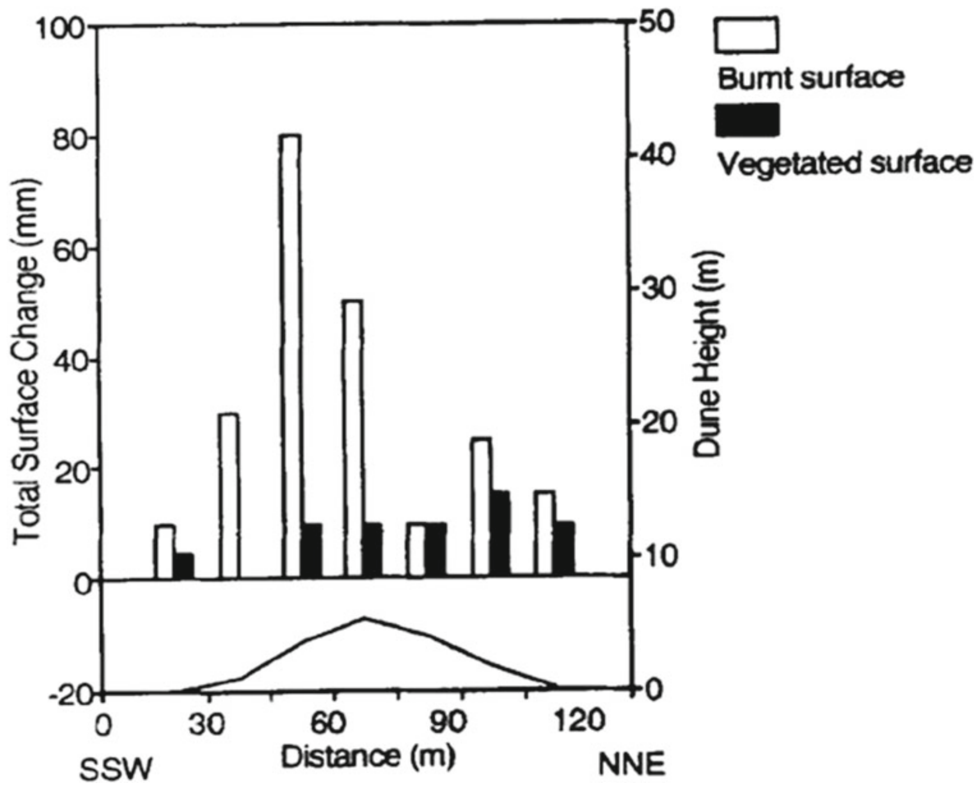

Fig. 8.12 Comparison of surface erosion/deposition activity (total surface change) between a naturally vegetated dune (vegetated surface) and a dune which was denuded of vegetation due to fire (burnt). Measurements taken over a period of 10 weeks by Wiggs et al. (1994). Bars represent surface change (left axis), line represents dune topography (right axis). Reproduced with the permission of John Wiley and Sons

of magnitude. Using the data shown in Fig. 8.12 Wiggs et al. (1995) tentatively identified a threshold lateral vegetation cover of around 14% which, in the Kalahari environment, appeared to differentiate between enhanced and subdued dune mobility.

This field-based evidence offered support to the conceptual arguments of Livingstone and Thomas (1993) against the notion of the partially vegetated Kalahari dune system as an inactive relic. Rather, the dunefield analysis of Bullard et al. (1995, 1996, 1997) and dune-scale field data of Wiggs

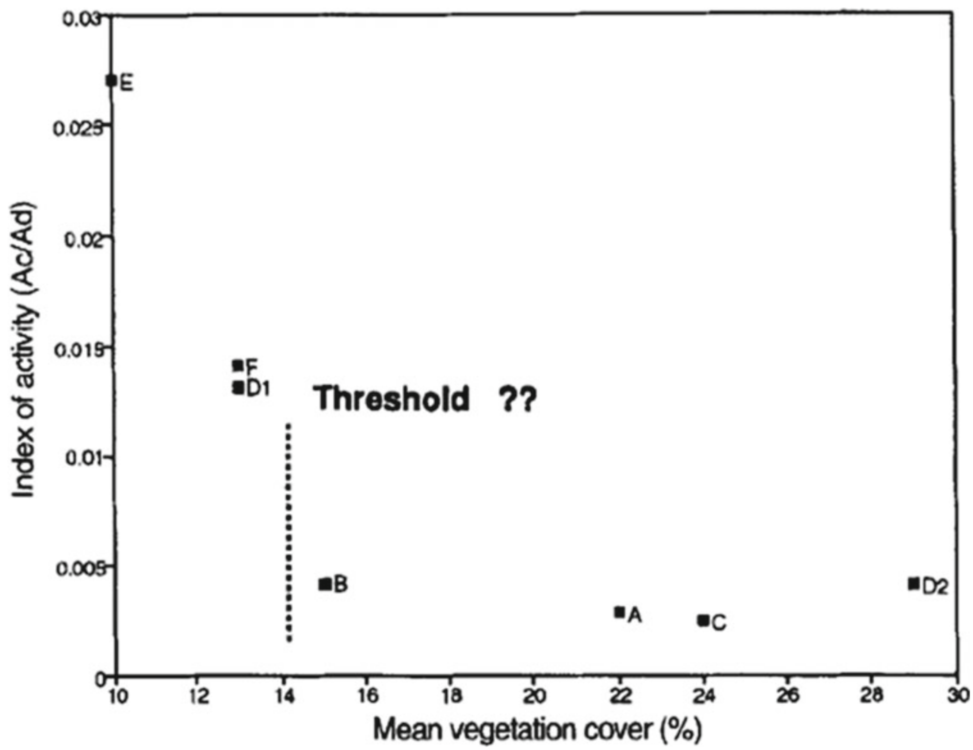

Fig. 8.13 Erosion and deposition activity (index of activity) measured on the surfaces of seven dunes of varying mean vegetation cover. Reproduced with the permission of John Wiley and Sons

et al. (1994, 1995, 1996) suggested that the dunes displayed a muted dynamic under a partial vegetation cover, with their upper slopes and crests exhibiting surface activity that varied in response to climatologically driven cycles of moisture availability and vegetation growth. However, the dunes demonstrated a much more intense geomorphological dynamic, with increased activity across whole dunes, when and where the vegetation cover dropped below about 14%. Hence the partially vegetated dunes of the Kalahari have the potential to display very significant episodic activity, in both time and space, in response to environmental drivers that impose vegetation reduction, such as drought, grazing, and fire.

8.7 Dune Landscape Response to Environmental Change

Research on the geomorphological dynamics of the south-west Kalahari dunefield in response to temporal and spatial variability in vegetation cover raises questions as to how the Kalahari environment might respond to large-scale pressures, such as predicted future global warming. Dintwe et al. (2015) report that in the twenty-first-century soil organic carbon in the Kalahari could reduce by as much as 14% due to declining values in mean annual precipitation and a drying of the soil (IPCC, 2013). This would have severe deleterious impacts on the ecological system. Research on the likely influence of such environmental changes on the Kalahari dune landscape has focussed on two issues; the potential for enhanced dune mobilisation, and the prospect of the dunes of the Kalahari becoming a significant emitter of aeolian dust.

8.7.1 Enhanced Sand Dune Mobilisation

The response of the dunefield vegetation to significant climatic shifts was established by Thomas and Leason (2005). Using Landsat TM data from a drought year (1984) and a wet year (1993) they monitored the changing extent of the dunefield comprising a vegetation cover <14%, the threshold recognised by Wiggs et al. (1995) below which enhanced dune activity might be expected. They analysed their data to determine maps for aeolian hazards, noting an increase of around 300% in the area with < 14% vegetation cover, and so potentially at risk of enhanced sand dune activity, in drought years (Fig. 8.14).

This recognition that large-scale climatic variability in the Kalahari Desert could lead to rapid and intense sand dune activity at the dunefield and sub-dunefield scales led Knight et al. (2004) to develop strategies by which outputs from Global Circulation Models (GCMs) could be best applied to driving indices of sand dune mobility. This allowed for the integration of climate model outputs relevant to vegetation growth and dune movement (such as precipitation, potential

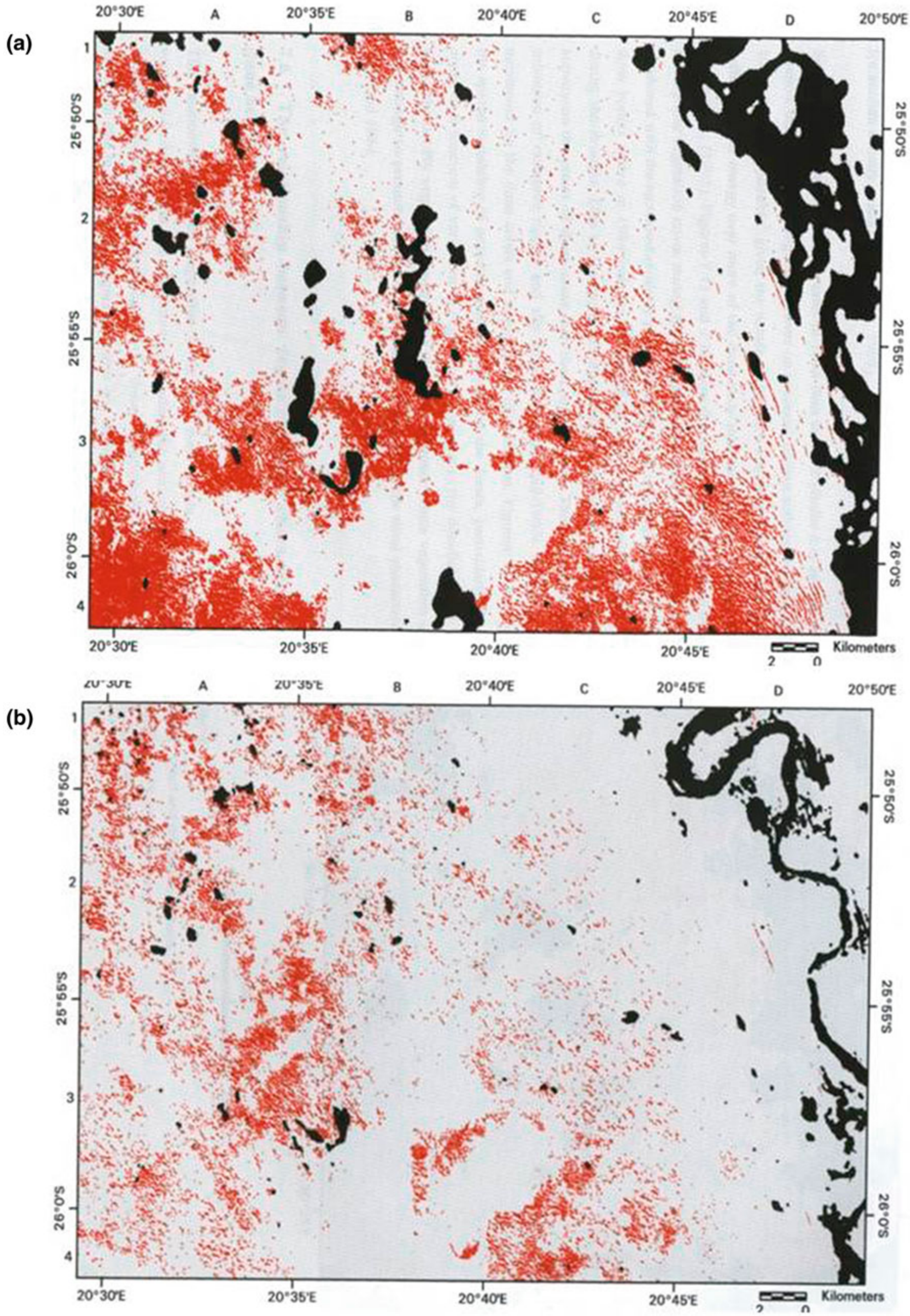

Fig. 8.14 Aeolian hazard maps determined by Thomas and Leason (2005) using Landsat TM imagery for **a** a dry year (1984) and **b** a wet year (1993). Red areas denote those with < 14% vegetation cover and are considered hazardous for increased aeolian activity. White areas have > 14% vegetation cover. Black areas are cloud cover, pan and river valley areas. Reproduced with the permission of Elsevier publishers

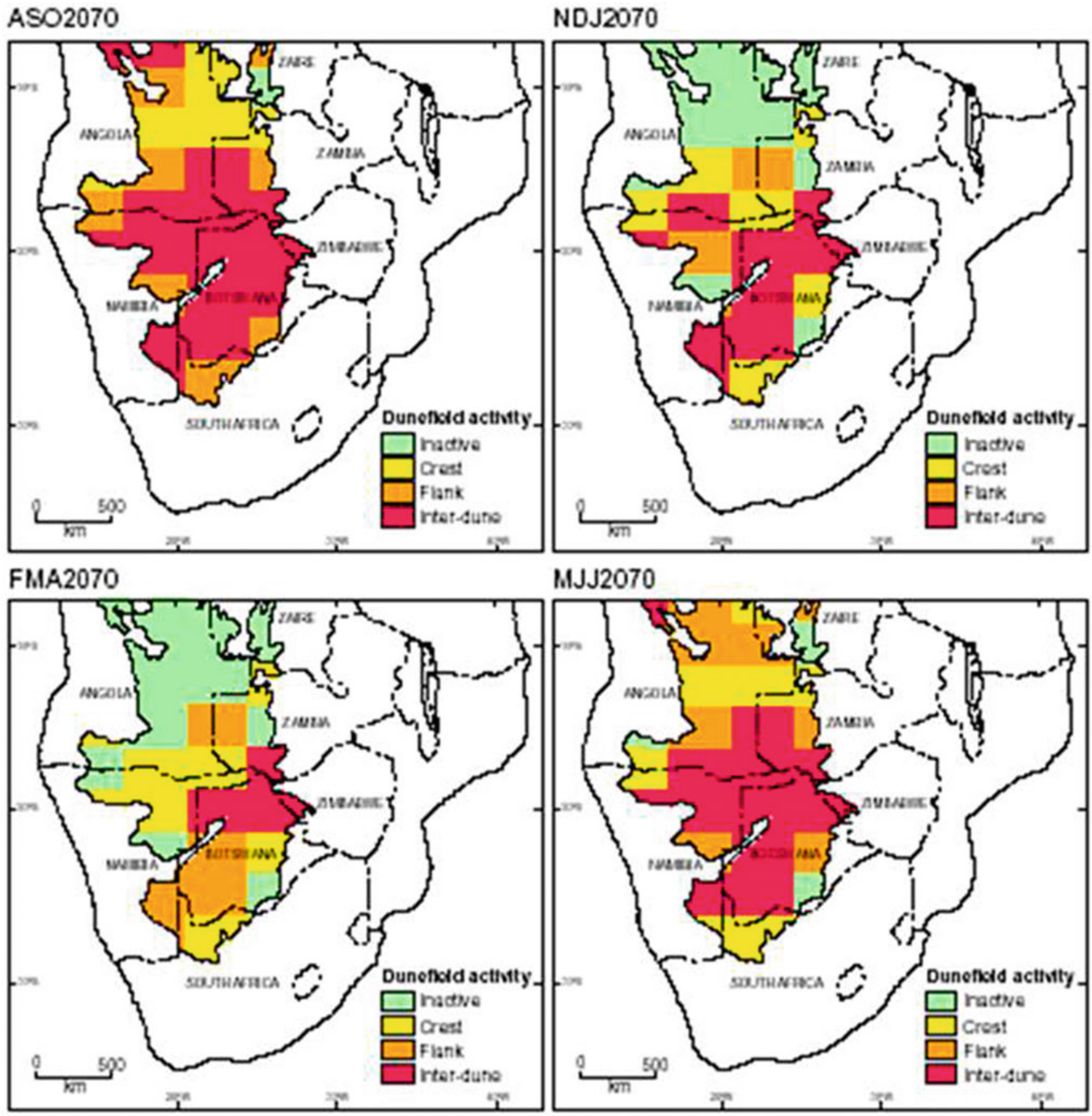

Fig. 8.15 Predicted dunefield activity in different 3-month blocks after 2070 (Thomas et al. 2005). Reproduced with permission of Springer Nature BV

evaporation, and wind velocity) with dune mobility indices to calculate sand dune activity with predicted changing future climate. There have since been a number of attempts to accomplish such predictions of dune mobility in the southwest Kalahari. Thomas et al. (2005) used an adaptation of the Lancaster (1988) Mobility Index incorporating mean windspeed and a weighted measure for net rainfall to account for the lag in response of vegetation to changing moisture status. Applying outputs from three GCMs and a range of emissions scenarios Thomas et al. (2005) found that all modelled outputs predicted marked increases in dune activity throughout the twenty-first century. Particularly intense activity was predicted for the dunes in the southwest Kalahari with a fully active dunefield anticipated by the year 2070 (Fig. 8.15), resulting in likely considerable impacts on both the landscape and agricultural potential of the dunefield.

The method used by Thomas et al. (2005) stimulated discussion as to the difficulties and challenges for predicting sand dune mobility under future climate scenarios in the Kalahari and elsewhere (Ashkenazy et al. 2012) and this led Mayaud et al. (2017) to attempt an alternative approach. Mayaud et al. (2017a, b) employed a cellular automaton model (ViSTA, Mayaud et al. 2017b) to simulate known and quantitative feedbacks between vegetation growth, wind flow dynamics, and sediment flux (Mayaud et al. 2016). The model was driven using projected climatic changes resulting from two principal emissions scenarios from the IPCC with outputs modelled at three sites in the Kalahari. Similar to the study of Ashkenazy et al. (2012), the Mayaud et al. (2017a) model did not predict the same degree of dunefield activity in response to twenty-first-century climate change as the study of Thomas et al. (2005). However, an appealing element of the Mayaud et al. (2017a) study was the inclusion of the potential impacts of changes in fire frequency and grazing dynamics. Here, Mayaud et al. (2017a) found that fire frequency (both anthropogenic and natural in origin) had a primary impact on vegetation cover in the Kalahari and, together with grazing pressure, dictated the intensity of sediment mobility. Mayaud et al. (2017a) therefore concluded that human activities could shape future Kalahari aeolian and dune landscapes to an extent at least equivalent to climate change impacts.

The potential degradational impact of human activity through increased grazing pressure was also the focus of the field observations and seedbank experiments of Bhattachan et al. (2014). Concentrating on the resilience and potential recovery of the vegetated dune surfaces after periods of intense grazing, Bhattachan et al. (2014) noted that whilst the seedbank of perennial grasses on the Kalahari dunes was depleted by grazing pressure, the impact of grazing on soil nutrient concentrations was relatively small. This meant that, in the absence of larger scale environmental pressures, vegetation could re-establish on the dunes fairly rapidly once grazing pressure had been removed. The implication from this finding, together with the findings of Mayaud et al. (2017a, b) and Thomas et al. (2005), is that the stability of the Kalahari dune system, provided by the existence of a partial surface vegetation cover, is at risk from both climatic variability and from any increasing intensity in human activity, including grazing pressure and burning. These changing environmental and human pressures may combine and result in severe degradation to the vegetation on dunes, resulting in considerable risk of dune activity and mobilisation.

8.7.2 Dunes as Emitters of Aeolian Dust

Emissions of aeolian dust in southern Africa are generally focused around topographic depressions (Thomas and Wiggs 2012). Here, silt-sized material is concentrated by the action of water, dried-out in the semi-arid climate, and subsequently eroded by winds. Source areas in southern Africa consisting of dry lake beds, inland pans, and dry river valleys can readily be identified (Vickery et al. 2013). Globally, dune systems are thought to have low potential as dust sources because of the absence of fine particles. However, evidence from the semi-vegetated Australian dune systems (e.g. Bullard et al. 2008) suggests that stable dunefields can accrue fine material primarily through weathering and abrasion. Where the surface vegetation becomes degraded due to human or environmental stresses, winds may then have the capacity to erode the fine material. There is therefore the potential for semi-vegetated dune systems to become sources of aeolian dust. In the Kalahari dunefield this potential has been explored by Bhattachan et al. (2012, 2013).

Using a dust impact generator to evaluate the relative potential of Kalahari dune sands to produce dust-sized material, Bhattachan et al. (2012) found that sediments in currently vegetated interdunes contained a ready supply of fine dust material that is also rich in nutrients (Bhattachan et al. 2013). The authors therefore suggest that the removal of vegetation in these areas, due to a more arid climate and/or increased grazing pressure, may allow the erosion of this fine material into the atmosphere. Bhattachan et al. (2012) note that any potential dust emissions from the dune sands would likely be unsustainable in the long term because, once de-stabilised and exhausted of dust-sized material, there would be no mechanism to re-supply fine material into the dune surface sediments. However, whilst the loss of nutrients from the dune sands due to erosion would be severe (Bhattachan et al. 2013), the authors also note that the emittance of dust from the Kalahari could potentially result in a very significant pulse of iron-enriched (and nutrifying) sediment into the Southern Ocean.

8.8 Conclusion

The dunes of southwestern Botswana and contiguous areas of Namibia and South Africa have been the subject of scientific investigations since the 1930s, with earlier non-scientific accounts providing important insights to this still-often remote landscape. We now know, from chronometric analyses, that the current dunes have formed over both a long period of time and in multiple periods of construction.

The partial vegetation cover on the Kalahari dune system today results in a muted response of the dunes to erosive forces, with activity generally limited to the upper flanks and crests of the dunes. However, periods of drought and intense human activity, reducing vegetation cover below a stability threshold, can result in episodic dune activity limited in spatial extent (with respect to human activity) and/or temporal extent (with regards to the longevity of periods of drought). Further, the dynamics of the Kalahari dune system is sensitive to these destabilising pressures such that there is evidence for increasing climatic and human pressures through the twenty-first century to induce a widespread increase in dune activity and mobility, and also in dust emission potential.

The southern Kalahari dune system represents a landscape oscillating around the threshold between stability and dynamism. The response of the dunes to changing environmental and climatic drivers is beginning to be understood and documented. Without careful management, the enduring susceptibility and sensitivity of the dune landscape to climate change and human activity is likely to become apparent in the century ahead.

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