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Late Quaternary environmental change in central southern Africa: new data, synthesis, issues and prospects

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Abstract

Much of the interior of central southern Africa is a sand sea, within which aeolian and lacustrine landforms and sediments of local and regional extent are preserved. Closed cave sites are restricted to very few locations, while fluvial systems traverse the margins of the interior. Until the early 1990s, chronologies of late Quaternary environmental and climatic changes developed for this region were based on only a limited number of proxy data sets, derived largely from lacustrine deposits and precipitates. In particular, directly determined ages from aeolian deposits, the most extensive suite of features in the region, were absent. The application of luminescence-dating techniques to dune sediments, and the development of further detailed chronologies from cave precipitates, is now providing a more comprehensive record for the last 50 ka, with some chronologies extending back a further 100 ka. We present and review these data, assess their contribution to enhanced understanding of late Quaternary environmental changes in the region, and for the first time assess them against corrected radiocarbon ages from lacustrine sites. It is concluded that there is now an enhanced understanding of the spatial and temporal complexity of climate changes affecting the region in the last glacial cycle, including a complex record of punctuated aridity, but that many issues, including data-set integration and forcing mechanism controls, are imperfectly understood. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction and background

Palaeoenvironmental investigations in the interior of central southern Africa have been hampered by issues of access, the paucity of closed sites, and geochronological difficulties associated with establishing the timing of development of extensive geomorphic features. The pace of investigation has, however, increased substantially during the 1980s and 1990s, both through improved mapping and field investigation of landforms and the application of enhanced dating methods. Since 1969, geomorphological and palaeoenvironmental studies have yielded approximately 300 ^{14}C, 80 Th/U and 150 luminescence ages, whose spatial distribution is shown in Fig. 1. Here we concentrate on advances made since 1992 (Shaw and Thomas, 1996), notably the growing luminescence-dating based chronology of aeolian deposition events, detailed cave speleothem studies and a calibration of existing key radiocarbon ages.

The sediments and landforms of the 2.5 million square kilometres Kalahari sedimentary basin have long been widely recognised as a proxy record of climatic change (Livingstone, 1858; Passarge, 1904; Grove, 1969; Deacon and Lancaster, 1988). In the presently dry-subhumid to semi-arid middle Kalahari (latitudes 19–22°), river terrace sites around the eastern margins were investigated in detail over 50 yr ago and palaeoclimatic changes, associated with contemporary archaeological chronologies, were inferred (e.g. Jones, 1944, 1948). Lacustrine deposits in northern Botswana, including the Makgadikgadi Basin, and associated fluvial systems including the Okavango Delta, were subject to systematic palaeoenvironmental investigations 25 yr ago (e.g. Cooke, 1976), with provisional chronologies of environmental change determined by the application of ^{14}C to calcretes in fluvial and lacustrine terraces. The potential of cave sediments, found in the few isolated hills that dot an otherwise flat landscape, was also recognised at this time by Cooke (1975a). Degraded, inactive sand dunes in western Zimbabwe were considered by Flint and

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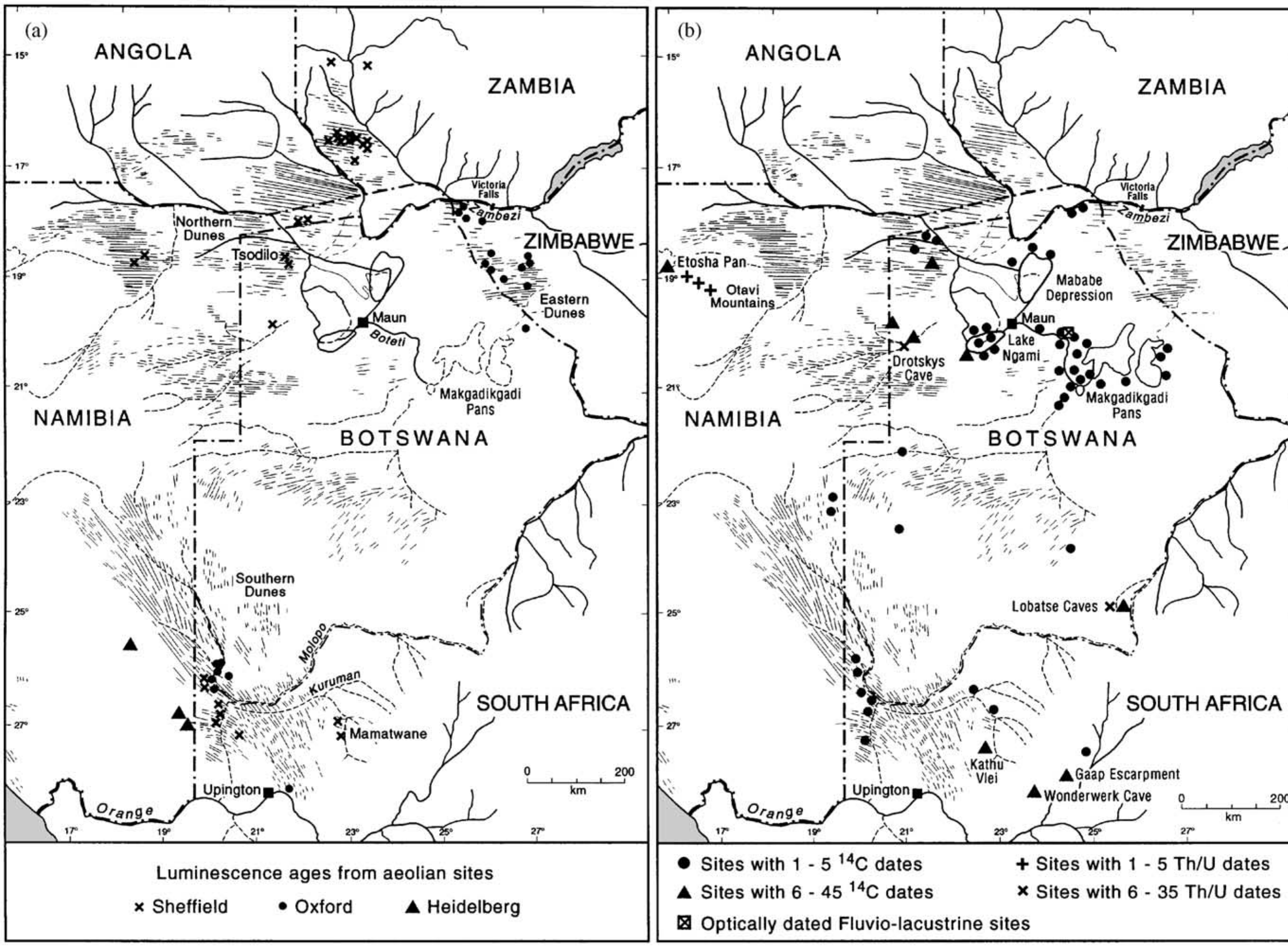

Fig. 1. Distribution of numerically dated sites in the Kalahari. (a) Luminescence-dated aeolian deposits. Samples dated in the Oxford and Sheffield laboratories are primarily optical ages, those from Heidelberg are TL ages. The majority of locations have at least two age determinations from a vertical sequence (see also Fig. 3). (b) Lacustrine, fluvial and cave sites that have yielded radiocarbon, Th/U and optical ages. For sources see Fig. 4.

Bond (1968) to provide evidence of two arid phases during the Pleistocene.

From 22°S to the Orange River at 29°S, the southern Kalahari becomes progressively more arid in a southwesterly direction. Lewis (1936) described the extensive partially vegetated dunes found in western areas, which he interpreted as evidence of even drier climates in the past. Lancaster (1976) generated the first systematic study and palaeoclimatic interpretation of the numerous pan depressions, many with fringing lunette dunes, that are found in the southwest. The dry valley systems of the Molopo River and its tributaries, with their ephemeral regimes, yielded shells and calcretes from which Heine (1978) derived a chronology of flow changes, and Cooke (1975b) highlighted the potential of cave speleothems at Lobatse, on the eastern edge of the southern Kalahari. It was, however, the spring and tufa deposits developed on the Gaap Escarpment, the southeastern margin of the Kalahari, that provided the first comprehensive and long (Tertiary to Quaternary) record of moisture and temperature changes in the region (Butzer et al., 1978). The northern Kalahari (north of latitude 19°S) has, by comparison, received little palaeoclimatic investigation. The terraces of the middle Zambezi River, above and below Victoria Falls, were investigated in early archaeological and geological studies (e.g. Maufe, 1939), but the degraded linear dunes and pans of western Zambia, described by Williams (1986), and related features in Angola, have until recently received no attention. Although a number of overviews have been published, up to the mid-1990s, of palaeoenvironmental investigations in the region, progress in recent years warrants an assessment of significant developments that includes a reappraisal of earlier radiocarbon-based chronologies and an integration of key outcomes with the findings of ongoing dune- and cave-based research.

2. The aeolian record

Dunes in central southern Africa are dominated by linear forms which are found across the modern

SW–NE rainfall gradient in areas with mean annual precipitation values ranging from 150 mm to over 1200 mm. The dunes today naturally possess a vegetation cover which ranges from sparse grasses in southern areas, where the features are morphologically recognisable as dunes, to dense deciduous woodland on degraded ridges in northern areas. A range of criteria allow the linear ridges to be diagnosed as relict forms (Heine, 1981; Lancaster, 1988; Livingstone and Thomas, 1993) though not all criteria apply at all locations. In northern and eastern areas, the dense plant cover, degraded ridge morphologies and sediment characteristics are all indicative of dune stability. In the semi-arid to arid south, aeolian sediment transport occurs today on the crests of sparsely grassed dunes. Dune process studies (Wiggs et al., 1995, 1996) and assessment of decadal scale potential dune activity (Bullard et al., 1996, 1997) indicate that while these dunes can experience episodic surface activity today, the interaction of low sand transport energy and the vegetation cover are not presently conducive to dune construction. These dunes too can therefore be regarded as palaeoforms.

In the past, each of three separate linear-dune systems developed in the Kalahari sand has been distinguished on the grounds of overall orientation, and attributed to a distinct period of formation (Lancaster, 1981; Thomas, 1984). Lancaster (1989) subsequently attributed the northern dune system (Namibia, Zambia and Angola) to formation prior to 32 kyr BP, the eastern (Zimbabwe) to the Last Glacial Maximum (LGM), 19–17 kyr BP, and the southern (SW Kalahari) to 10–6 kyr BP with localised activity at 4–3 kyr BP. These periods were determined partially from a few isolated ^{14}C dates from materials within or under aeolian sediments, and from gaps within the humid chronology.

A systematic UK-based programme of optical dating (e.g. Stokes et al., 1997a, b, 1998; Thomas et al., 1997; Lawson, 1998; O'Connor and Thomas, 1999), supplemented by additional independent investigations by other researchers, is permitting a geochronometric reassessment of Kalahari aeolian landforms and sediments. Since linear dunes, the dominant dune type throughout the interior, are extending rather than migratory forms, they possess the potential to accumulate and store aeolian sediment that preserves a record of successive phases of dune construction and aridity (Thomas and Shaw, 1991b). To date, 111 optical luminescence age determinations from aeolian features and sediments have been published of which 69 are from linear-dune sites in the southwestern (Stokes et al., 1997b; Thomas et al., 1997), eastern (Stokes et al., 1998) and northern (O'Connor and Thomas, 1999; Thomas et al., 2000) Kalahari. A further four thermoluminescence (TL) ages have been published from linear dunes in the southwestern Kalahari (Eitel and Blumel, 1998). Forty-two optical ages from pan-margin lunettes and minor dune forms in the southwestern and eastern Kalahari have been presented by Lawson (1998), Lawson and Thomas (2002), Stokes et al. (1997b) and Thomas et al. (1998), with TL ages from minor dune forms in the Etosha basin of northern Namibia presented by Buch et al. (1992). A further suite of age determinations from sand sheet and lunette-dune sites in the southern interior and from lunette dunes in western Zambia are being prepared, with reference being made in this paper to those which are currently available.

2.1. The southern interior

A number of morphological and sedimentological contexts within the main area of linear dunes have been embraced in optical-dating programmes in this area (Stokes et al., 1997a, b; Thomas et al., 1997, 1998) including ancillary forms that have developed on the principal linear features. Eitel and Blumel (1998) provide TL ages from three single linear ridges that traverse large deflation basins between Mariental and Aroab (25–27°S, 18–20°E) in southern Namibia, which extends the western limit of age data. To the east of the main dunefield, aeolian deposits are represented by an extensive, flat, sand sheet that extends to the eastern limit of Kalahari Group deposits. The sand sheet has been sampled (Thomas and Bateman) at Mamatswane for optical dating. Fig. 1 shows that more northerly locations in the southern linear dunefield have not yet been dated, while Fig. 3 identifies the optical ages and their locations from linear dunes in the southern and central parts of the dunefield, where secondary dune features have also been investigated. Thomas et al. (1998) dated the aeolian sediments exposed in the extensively gullied 6 m high lunette dune at Witpan, close to the South Africa–Namibia border. Lawson and Thomas (2002) present new ages from a detailed investigation of lunette-dune sediments in the vicinity of the Molopo valley in the southern Kalahari. Previously unpublished eastern sand sheet optical ages of 60.2±2.5 and 58.6±2.3 ka (samples CT96/11/1 and 11/2; Thomas and Bateman, pers. comm.) from the 3 m deep lower limit of yellow-red Kalahari sand exposed in the Mamatwane mine (27°22′S, 22°58′E; Fig. 2), represent *t* the earliest aeolian sand age determinations obtained so far within the southern Kalahari. All other ages fall within the last 30 ka, including those obtained from basal dune sands directly overlying non-aeolian beds in the main dunefield (Stokes et al., 1997a, b; Thomas et al., 1997). The suite of linear-dune ages suggests two significant phases of dune construction, at 30–23 and 16–10 ka. The Eitel and Blumel (1998) Namibian linear-dune ages range from 8 to 17.5 ka, and are compatible with this grouping, possibly

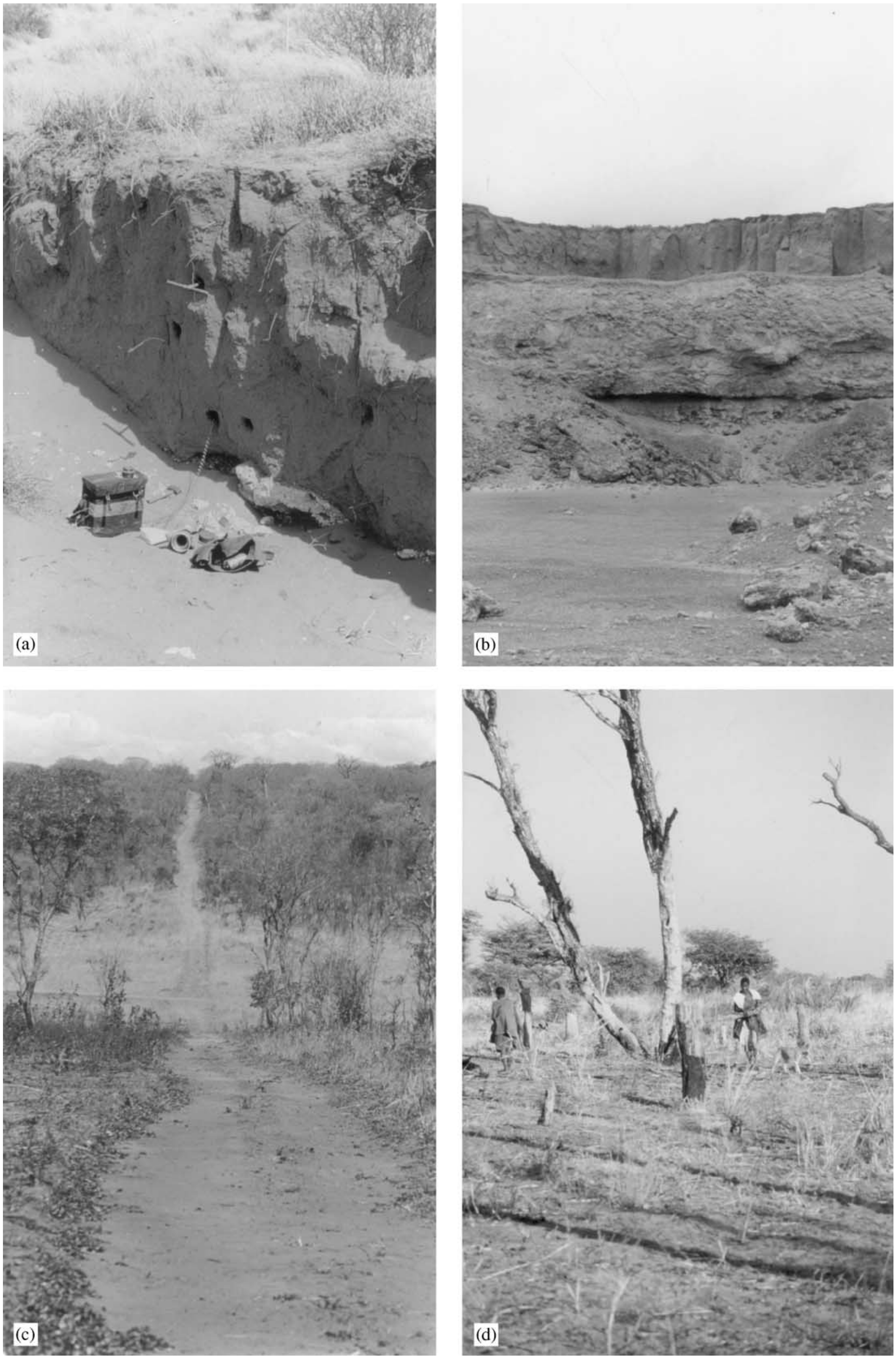

Fig. 2. Examples of dune and other aeolian sites that have yielded optical ages. (a) Site 948 at 26°31′S, 20°36′E in the main linear dunefield in the southwest Kalahari, showing cross section through the linear dune and underlying calcrete. (b) The 3 m thick upper sand sheet deposit exposed at Mamatwane mine, 27°22′S, 22°59′E; overlying duricrusts and Plio-Pleistocene age fluvial deposits. (c) Linear dune immediately south of Victoria Falls town, west of location in which site 896, at 18°00′S, 25°50′E was excavated. (d) Low linear-dune ridge, marked by the line of trees, in western Zambia; close to site am 95/24 at 16°28′S, 22°51′E. (a) is discussed in detail in Thomas et al. (1997); (c) in Stokes et al. (1998), and (d) in O'Connor and Thomas (1999).

indicating a more extended dune-construction period in a westerly, drier, location.

The absence from linear-dune sediments of ages older that 30 ka requires consideration. Dune construction in this area might not have occurred prior to this time, though this is unlikely, given both the sand sheet ages and since this driest location on the SW–NE rainfall gradient will have been the first area to experience externally forced regional aridity (Stokes et al., 1997a). Two possible explanations exist. First, despite sampling to the base of two dune bodies, older dune sediments preserved in isolated pockets (cf. Nanson et al. (1992a) in the Simpson Desert, Australia) have been missed. Second, this is a sand-starved environment with few sources of sediment for dune construction. It can be noted that dunes in the region are on average <12 m high, frequently rising <6 m above interdunes. Consequently, dune-building episodes in the Quaternary may have resulted in the reworking of older dune forms, resetting luminescence signals and erasing proxy evidence of earlier arid phases (Stokes et al., 1997b). The potential for the preservation of a long dune-construction record is therefore not simply a function of the appropriate climatic conditions having prevailed, but also the existence of a sediment supply allowing a stacked record to accumulate.

Lunette dunes in the southwest Kalahari have been optically dated at Witpan (Thomas et al., 1998), Luitenantspan, Soutpan and Koopan Sud (Lawson, 1998). Fourteen of the 18 dates presented in Lawson (1998) are of Holocene age, and the three Witpan section ages all at 1.1–1.5 ka. Lawson (1998) presents four ages between 17 and 11 ka, all derived from outer lunettes where pans possess more than one fringing transverse dune. Minor dune forms within the southwest linear dunefield, including crossing dune forms and hummocky dune patches, all generate mid- to recent-Holocene ages (Thomas et al., 1997). It would appear that since the end of the last major linear-dune construction period at 8–10 ka, opportunities for dune building have been localised rather than region-wide, as recorded in the lunette record and the hummocky dune patch at 26°27′S, 21°48′E superimposed on, and reworked from, linear-dune sediments. The total data set may, however, support the occurrence of a mid-Holocene dry event, witnessed in crossing-dune development at site 946 of Thomas et al. (1997). Both late Pleistocene and mid-Holocene dry periods have been independently identified from the cave sediment record at Wonderwerk, northern Cape Province, by Beaumont et al. (1984) and Thackeray and Lee Thorp (1992).

2.2. The central and northern interior

Optical-dating studies in western Zimbabwe (Stokes et al., 1997a, 1998) and western Zambia (O'Connor and Thomas, 1999) have focused on heavily degraded and well-vegetated linear-dune forms, with a total of 52 ages contributing to chronological assessments (Fig. 2). A further 19 linear-dune optical ages have been derived from linear dunes in northern Namibia (Thomas et al., 2000).

The record from western Zimbabwe includes two long linear-dune sequences (Stokes et al., 1998; Fig. 3). Site 952 located close to the middle Zambezi River above Victoria Falls at 17°55′S, 25°28′E provides a 4.5 m deep record from which three ages have been determined from the lower 2.5 m of the section, while 12 ages come from the 6 m long record excavated in a dune at 19°23′S, 26°45′E (site 1004) in Hwange National Park. Aeolian deposition is recorded at 52 ± 8, 77 ± 12 and 164 ± 32 ka at site 952. The length of recorded deposition, in contrast to the situation in the southern sites, is thought to be a function of greater sediment supply in this region when compared to the southern Kalahari. The chronology at site 1004 spans 18–112 ka (Fig. 3) without obvious depositional breaks in the record. This potentially generates interpretive problems, since continuous deposition might be inferred throughout the last glacial cycle; analysis of the data set by Stokes et al. (1997a) and independently by Singhvi and Wintle (1999), indicates that deposition, and therefore conditions conducive to the effective operation of aeolian processes, was punctuated (see below). The absence of stratigraphic breaks in the record can be considered by recourse to an understanding of the processes of linear-dune construction and to models of sediment supply in successive arid–humid phases. The onset of an arid phase leading to aeolian activity probably results in initial wind erosion of upper dune surfaces (including weak soils) at the onset of each new aeolian episode (cf. Kocurek, 1998) which would erase stratigraphic breaks. This view is endorsed by the extremely weak and shallow pedogenesis that has affected the modern surfaces of the western Zimbabwe dunes that have not experienced aeolian construction for over 10 ka (see Stokes et al., 1998). Stokes et al. (1997a, 1998) propose three main dune-building phases from the overall Zimbabwe record, at 115–95, 46–41 and 26–20 ka.

The western Zambian record (O'Connor and Thomas, 1999) presents some notable contrasts. South of the Mulonga Plain, to the west of the upper Zambezi River, dunes are no higher than 4–6 m (Fig. 2d), but are nonetheless very distinct because of clear vegetation contrasts with the interdune areas. Dune construction is identified at 32–27, 16–13 and 10–8 ka. The northern Namibian dunes (Thomas et al., 2000) are very pronounced compared to those in western Zambia, individually extending for up to 100 km and rising up to 25 m above interdune areas. Although these E–W orientated dunes are thought to be originally sourced with sediment from fluvial systems that traverse

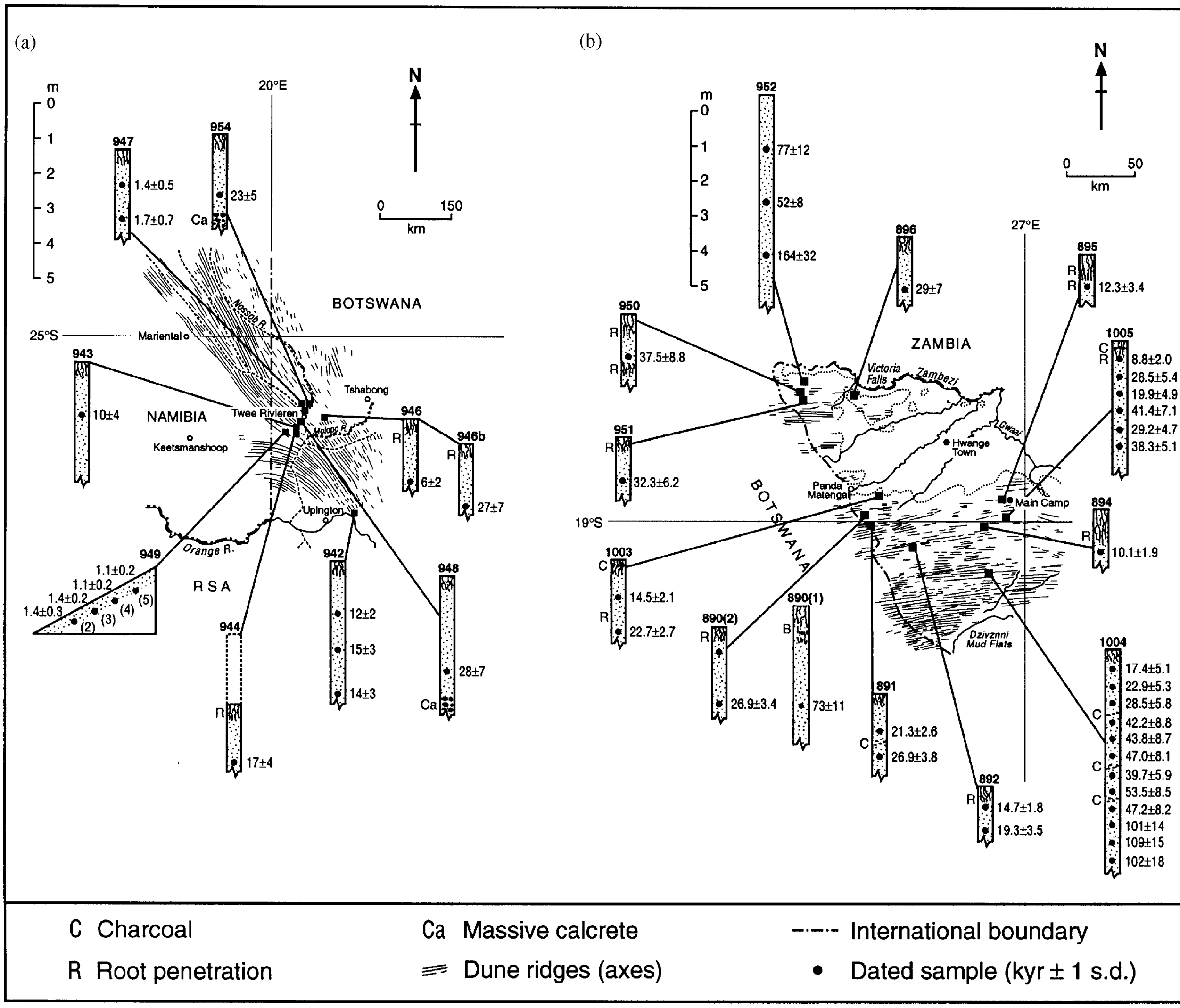

Fig. 3. Samples sites and optical ages from linear-dune sites in (a) the southern and (b) the middle Kalahari (modified after Stokes et al., 1997a).

northern Namibia from north to south, just as the Zambian ridges appear to have been deflated from sediment in the Zambezi system, their great length indicates that they are not simply the result of local, seasonal deflation but have developed from aeolian transport under arid conditions. Thirteen optical ages have been derived from the upper 2 m of dune sediments, with none more recent than 21 ± 2 ka, from sample Nam 95/43/3 at 18°53′S, 18°51′E. Dune construction is suggested at 48–41, 36–29 and 23–21 ka, while in both Zambia and Namibia, earlier phases of dune construction can be expected to be recorded in the, as yet, unsampled sediments below 2 m.

3. The lacustrine and cave record

Investigations have concentrated on palaeolakes, pans, dry valleys and cave sites, with reliance upon an uncorrected ^{14}C chronology of which nearly half the dates were derived from calcretes. In the middle Kalahari, two high stages of the massive palaeolake linking the Ngami, Mababe and Makgadikgadi Basins with the Okavango Delta and Zambezi system (Shaw, 1988) have been identified, the lower 936 m level dated to 17–13 and 2.5–2 ka BP. Although this may be attributed to greater inflow from the Angolan Highlands through the Okavango an equivalent local increase in precipitation from 17 to 12 ka BP has been indicated by shell deposits in the dry valleys such as the Okwa and Xaudum (Shaw et al., 1992). Initial work on Drotsky's (Gcwihaba) Cave suggested enhanced local rainfall at 45–37, 34–9 and 16–13 ka BP, with shorter Holocene episodes at 6–5, 4 and 2 ka BP. The high proportion of calcrete dates falling into the 12–10 ka BP bracket suggests that the widely evident late glacial wet period was followed by a regional decline in groundwater tables.

In the southern Kalahari, the long-term Gaap Escarpment tufa record (Butzer et al., 1978) has been supplemented by fragmentary and frequently conflicting evidence from Equus, Wonderwork and Lobatse Caves (Beaumont et al., 1984; Butzer, 1984; Shaw and Cooke, 1986), suggesting a moist, cold climate from 30 to 26 and 13 to 11 ka BP. In the Holocene initial cool, dry conditions were replaced by a warm, moist optimum between 8 and 5 ka BP, gradually drying to 2.7 ka BP. Lancaster's (1979) study of Urwi Pan suggested a lacustrine phase at 17–15 ka BP, whilst Heine (1981, 1982) proposed perennial or semi-perennial flow in the Molopo network from 16 to 12.5 ka BP. Overall, there is consistent evidence of late glacial humidity throughout the region, but discrepancies between individual sites, particularly in the southern Kalahari.

Recent work has sought to reevaluate the radiocarbon chronology, including recalibration following the method of Bard et al. (1990), to provide compatability with other chronological methods, establish longer records for cave speleothems using Th/U dating and evaluate the use of luminescence techniques on lacustrine sites, with the eventual aim of establishing an optical chronology. Some syntheses have been published (e.g. Brook et al., 1996, 1997, 1998) which combine the first two approaches. Research has also been initiated on new environments, such as pan sediments (Holmgren and Shaw, 1997) and the Okavango floodplain (Nash et al., 1997) using traditional ^{14}C methods.

Brook et al. (1996, 1997, 1998) have dated speleothems from Lobatse I, Drotsky's and Bone Caves and submerged speleothem material from five cenotes in the Otavi Mountain Land, east of the Etosha Basin. Additional analyses of incorporated clastic and organic sediments from stalagmite DC87 in Drotsky's Cave (Burney et al., 1994) have improved the Holocene record. In synthesis, these indicate wetter conditions, suitable for stalagmite growth, at 200–186, 133–131, 111–103, 93–83, 77–69, 50–43, 38–35, 31–29, 26–21, 19–14, 12.5–11, 8.2–7.9, 6.9–2.6 and 1.6–0.5 ka. The Otavi stalagmites, conversely, are considered to have formed subaerially at times of low groundwater tables and therefore suggest comparative aridity in eastern Namibia at 130–111, 103–93, 83–77, 69–50, 35–31, 30–27, 10–6–8.5 and at 7.5 ka. Potential sources of error in these age brackets include, first, the use of spot samples from unrelated speleothems and sinters and, second, bracketing using only two dates.

Detailed analysis of a single stalagmite, LII4, from Lobatse II Cave (Holmgren et al., 1994, 1995), using parallel Th/U and ^{14}C dating alongside 400 ^{13}C and ^{18}O isotope measurements, has addressed these sampling problems. LII4 accumulated in a warm, humid period from 51 to 43 ka, associated with C_3 ground vegetation, and between 27 and 21 ka, during which temperatures fell by an estimated 2°C and C_4 plants became dominant. A depositional hiatus between 43 and 27 ka is ascribed to dry conditions, whilst the stalagmite ceased to grow after 21 ka. Although comprehensive stalagmite analysis is preferable to selective sampling, it does raise the issue that the value of the analysis is ultimately controlled by the characteristics and environment of the stalagmite selected. For example, a core analysis of a large stalagmite, LII2, from the same cave, involving 17 U-series alpha spectrometry age determinations and 225 stable isotope measurements has indicated rapid stalagmite growth between 26 and 22 ka (Holmgren and Shaw, 1998–1999).

The chronology of lake fluctuation has, as already noted, been heavily dependent on radiometric dating of shoreline and lake bed calcretes, which are ambiguous in both the dates they yield and in their environmental interpretation. However, more reliable ages of high stands have been obtained from the dating of shoreline mollusc assemblages and these, when paired against their calcrete matrices, have indicated that the calcrete is 15–25% younger over the late glacial range (Shaw and Thomas, 1992). Organic materials are scarce, though, and refinement of the chronology will come from the application of luminescence techniques to the highly bleached sand of the Okavango Delta and its associated palaeolakes. An initial investigation into the age and provenance of the 250 cm diatom bed at Moremaoto, on the Boteti River (Shaw et al., 1997), using optical dating, indicates shallow lacustrine conditions resulting from the ponding back of neutral to slightly alkaline waters in a meander loop inside the Gidikwe Ridge, upstream of the Makgadikgadi Basin, in two phases between 32 and 27 ka. These dates are older than, and consistent with, available ^{14}C dates for calcretes on the Boteti terraces and confirm the existence of a lake in the Makagadikgadi basin at this time. The research has also confirmed the applicability of the optical method to lacustrine sediments, for which a major programme of dating has now been initiated.

4. Synthesis and dating constraints

A synthesis of Quaternary data for the region is presented graphically in Fig. 4. Fig. 5 provides time-slice maps of the provisionally determined distribution of drier and wetter conditions from 50 to 10 ka. Whereas earlier syntheses (e.g. Thomas and Shaw, 1991a, b) underlined the lack of data available for the timing of phases of enhanced aridity, here we place emphasis on the recently derived aeolian chronology. Evidence for more humid conditions derives from the more reliable sectors of the ^{14}C corpus, together with the results of recent cave and lake studies. All ^{14}C dates have been calibrated by the method of Bard et al. (1990). Discussion of dating constraints is limited here to the

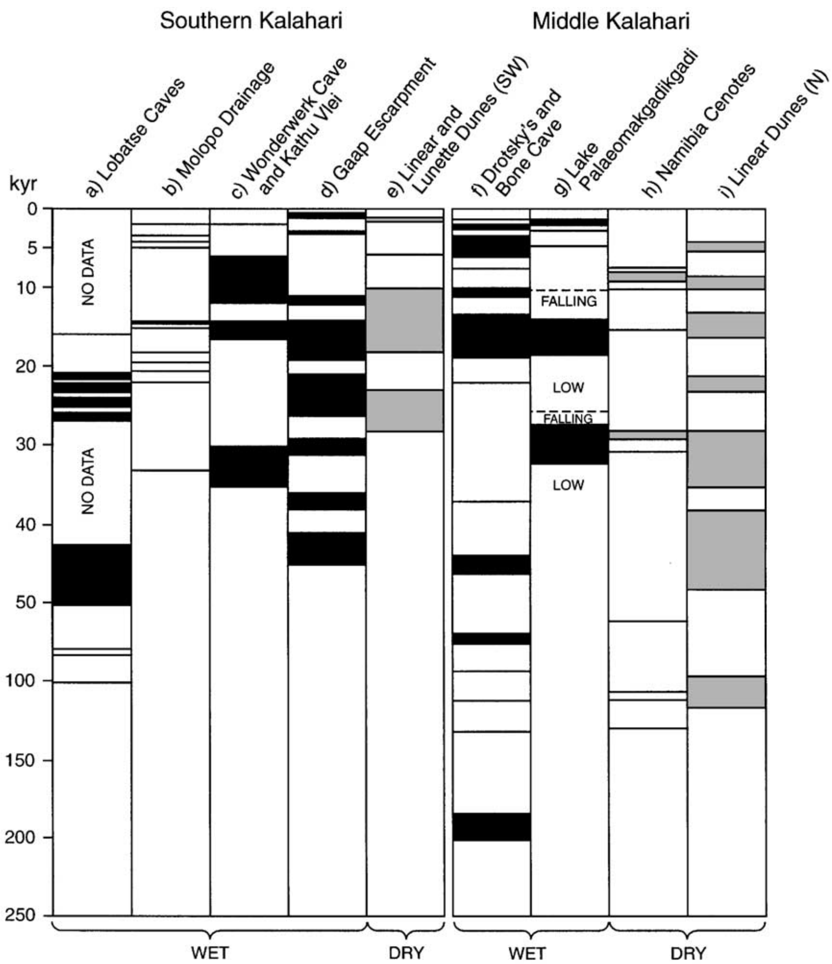

Fig. 4. Summary of wet and dry chronologies from the middle and southern Kalahari from 200 ka to present. Note the break in scale at 50 ka. Sources: (a) Shaw and Cooke (1986), Holmgren et al. (1994, 1995), Holmgren and Shaw (1998–1999), Brook et al., 1998; (b) Heine (1982), Shaw et al. (1992); (c) Beaumont et al. (1984), Butzer (1984), Johnson et al. (1997); (d) Butzer et al. (1978); (e) Thomas et al. (1997), Stokes et al. (1997a, b), Thomas et al. (1998); (f) Cooke and Verhagen (1977), Cooke (1984), Shaw and Cooke (1986), Thomas and Shaw (1991a), Burney et al. (1994), Railsback et al. (1994), Brook et al. (1996, 1998); (g) Cooke (1984), Cooke and Verstappen (1984); Shaw (1985), Shaw and Cooke (1986), Shaw and Thomas (1988), Thomas and Shaw (1991a), Shaw et al. (1992), Nash et al. (1997); Shaw et al. (1997), (h) Brook et al. (1996, 1997) and (i) Stokes et al. (1997b, 1998), O'Connor and Thomas (1999), Thomas et al. (2000).

aeolian programme, as the limitations of the humid landforms and their dating methods are covered elsewhere (e.g. Shaw and Thomas, 1996).

The suite of luminescence ages derived from dune sediments is enhancing understanding of the timing of aridity and dune development in the region, but a number of difficulties, in sampling and the interpretation of results, exist. The extensive nature of aeolian deposits can cause sampling problems, with the precise locations chosen in some cases determined by specific research questions or the occurrence of exposures. In many cases it is determined by the desire to achieve good lateral and vertical coverage, tempered by issues of access and the practicalities of achieving a good sampling depth. When a set of luminescence ages is analysed to provide a proxy record of dune activity, it is necessary to recognise the inherent limitations that might exist within a data set. For luminescence dating it is necessary to avoid sampling the upper 30–50 cm of a sediment body and to exclude sediments that have experienced either disturbance or excessive levels of cosmic radiation. Sediments below c 2 m depth can prove difficult to sample when natural or artificial sections or cuttings are absent. Some researchers have drilled or augered below this depth, but in turn this generates other difficulties, including problems of sample contamination during auger or drill extraction.

The luminescence age determinations from dune sediments can be used to investigate the temporal and spatial distribution of aeolian activity and aridity in the region during the last glacial cycle. Nanson et al. (1992b) used frequency histograms to group TL and others ages suites in an analysis of long-term (300 ka) aridity–humidity shifts in central and eastern Australia. To

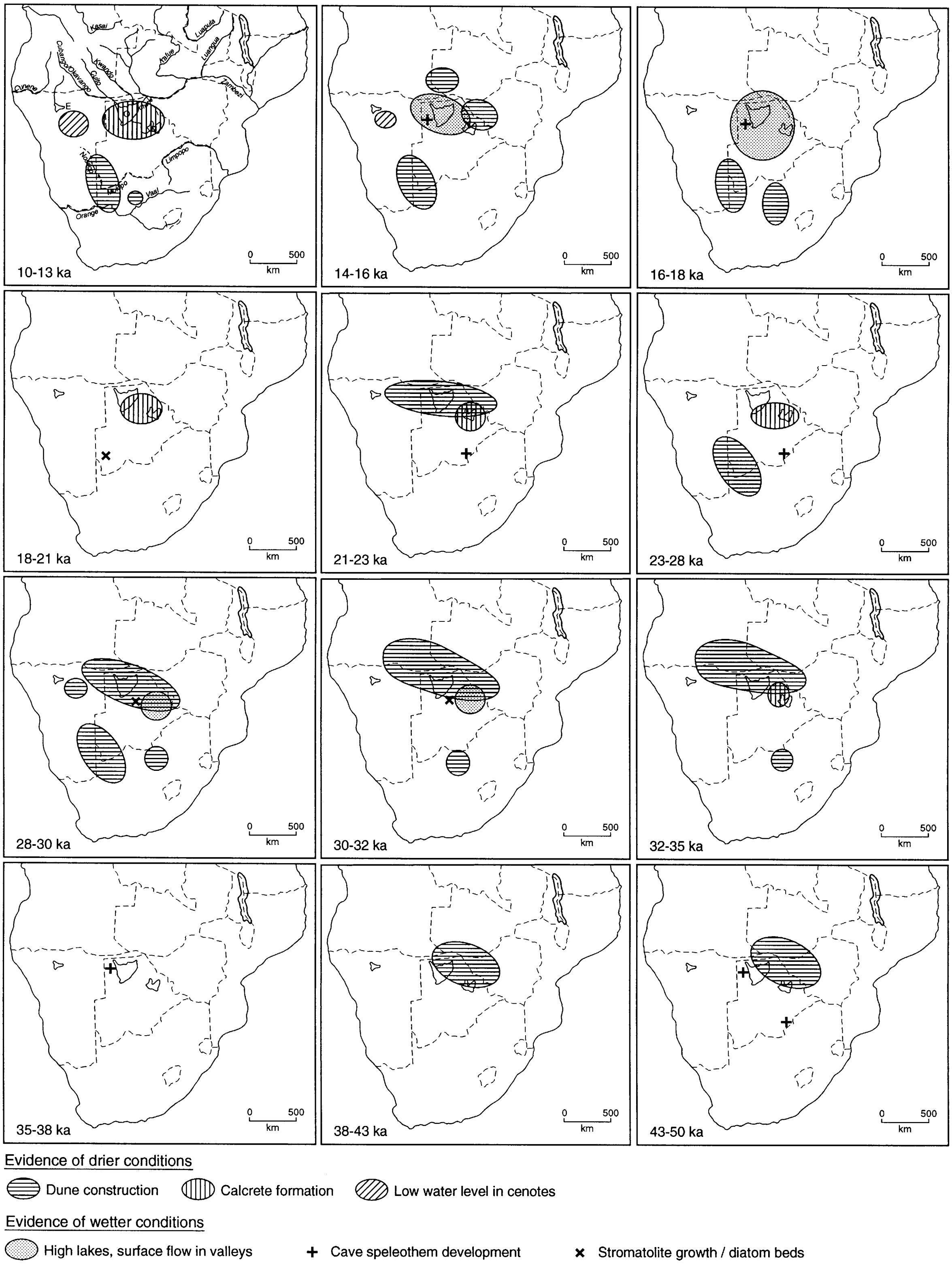

Fig. 5. Summary maps of major dated geomorphic and sedimentary evidence of late Pleistocene environmental changes in the Kalahari 50–10 ka. Information is based on evidence described in the text and on the geographical extent of dated contiguous landforms. Palaeoclimates have not been extrapolated from the data in the construction of maps—it can be seen, for example, for the period 14–16 ka in the middle Kalahari, that there are potential conflicts within evidence that may be interpreted as representing both arid and humid conditions.

some extent, this overcame problems associated with a data base where *n* was small, (20 TL ages in total from dune sands) but the 10 ka time intervals used to group frequencies would mask the subtleties of environmental change which the southern African interior record provides. Fig. 6 shows the frequency groupings of dune luminescence ages (taking age mid-points) by region in this paper, with a 1 ka frequency up to 30 ka, 5 ka frequency from 31 to 60 and 40 ka, thereafter. It demonstrates a propensity for older ages to be derived from middle and northern Kalahari locations, and younger ages from the southwest of the region.

An alternative approach, used by Stokes et al. (1997a), has been to group overlapping, statistically indistinguishable ages, and calculate mean weighted values for the ensuing groups. This approach can be applied to the total, region-wide, data set, but more logically, given the spatial variability in present day environmental and climatic conditions in the southern African interior, should take account of the regional locations of sampling sites. Singhvi and Wintle (1999) have now provided an independent analysis of the data set of Stokes et al. (1997a), using a Gaussian probability analysis, which confirms the punctuated nature of dune construction through the identification of several peaks in the record of aeolian sediment deposition. When the dated records from western Zambia, western Zimbabwe and northern Namibia are considered together, a number of disparities are presently identified in the overall record of dune construction in the period c 48–20 ka, which may be resolved by further field investigations or which may represent real spatial difference in the timing of dune construction.

The dated record preserved in the southwest Kalahari identifies two post-30 ka periods of linear-dune construction, with isolated older ages from sand sheet deposits. The propagation of aridity, favouring the operation of dune construction if both conditions of

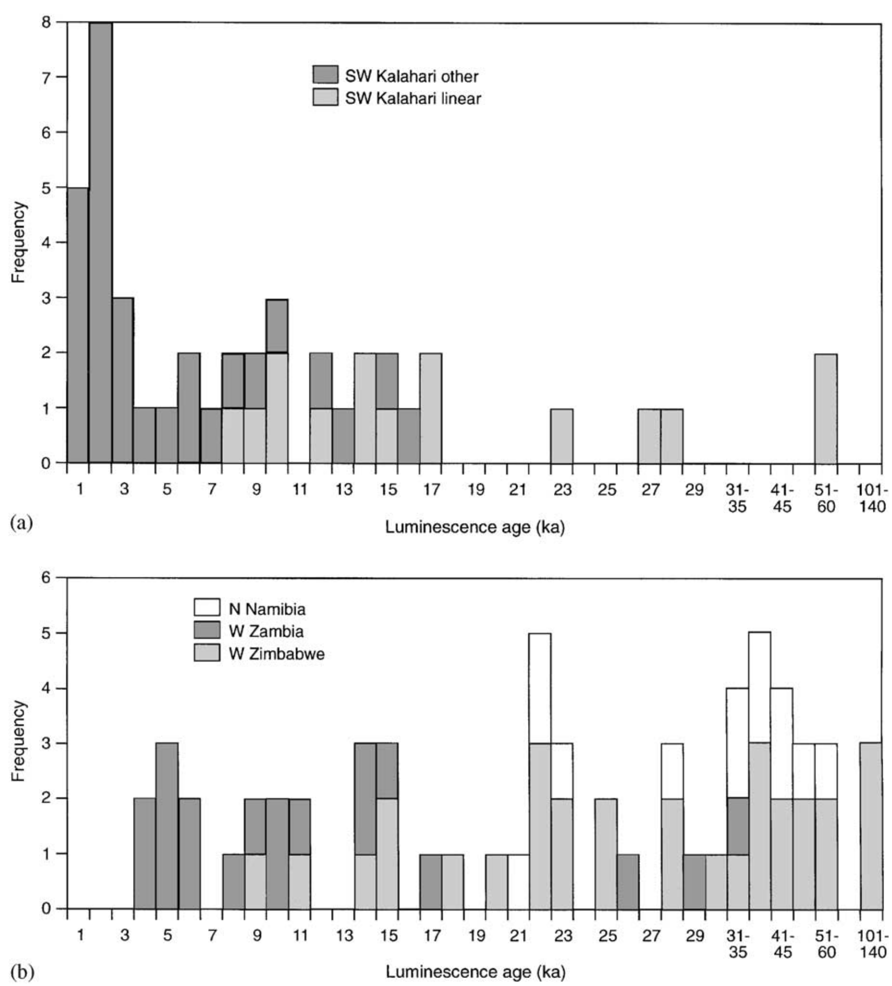

Fig. 6. Histograms of dune and aeolian sediment luminescence ages derived from (a) the southern Kalahari and (b) the middle and northern Kalahari. Central points on ages are plotted without the inclusion of 1 sigma deviations. The latter have been used by, for example, Stokes et al. (1997a) to assess age clusterings and also by Singhvi and Wintle (1999) to assess the probability of peaks of aeolian deposition within the record (see text).

sufficient windiness and sediment supply are satisfied, across the interior of southern Africa, has been proposed by Stokes et al. (1997a) to explain the general distribution of dune sand ages. The identification of extensive early Holocene age linear dunes in western Zambia (O'Connor and Thomas, 1999) requires further explanation if this model is correct.

The humid chronology is still constrained by the incompatibility of the different lines of evidence, and the limitations of available dating techniques. In particular, doubts must be raised about widely quoted records which have low environmental resolution, such as the springs of the Gaap Escarpment (Butzer et al., 1978, Fig. 4, column (d)) or ambiguous climatic interpretations, such as the river-bed deposits of the Molopo (Heine, 1978, Fig. 4, column (b)). Long-term detailed speleothem records appear to offer great potential, with a caveat concerning the individuality of single stalagmites, but have so far proved difficult to integrate into regional scenarios (Fig. 4, columns (a) and (e)). In particular, the speleothem records proposed for 200–50 ka are based on few dated samples (Brook et al., 1998), and must be regarded as a preliminary attempt to establish a chronology.

Within the last 50 ka, the high levels in the Boteti River and Makgadikgadi at 32–28 ka, preceded and followed by episodes of lake-bed calcretisation (Shaw et al., 1997) are now at variance with aeolian and cenote evidence for aridity, and will require further research. There is widespread evidence for a cool, dry, LGM in the Kalahari, followed by wetter conditions in lakes and valleys throughout the Kalahari from 18 to 14 ka, in turn superseded by drier conditions in which calcretes formed by falling groundwater tables from 13 to 10 ka. The overlap between wet and dry evidence in the middle Kalahari at around 14 ka is most probably due to lack of resolution in the current data set.

The body of evidence for Holocene palaeoclimates, summarised in Fig. 7, has not grown much in recent years and a number of conflicts remain between sites. Most indicate an increase in temperature and precipitation from 10 ka to the Holocene Optimum around 7 ka, although the conditions at that time were probably

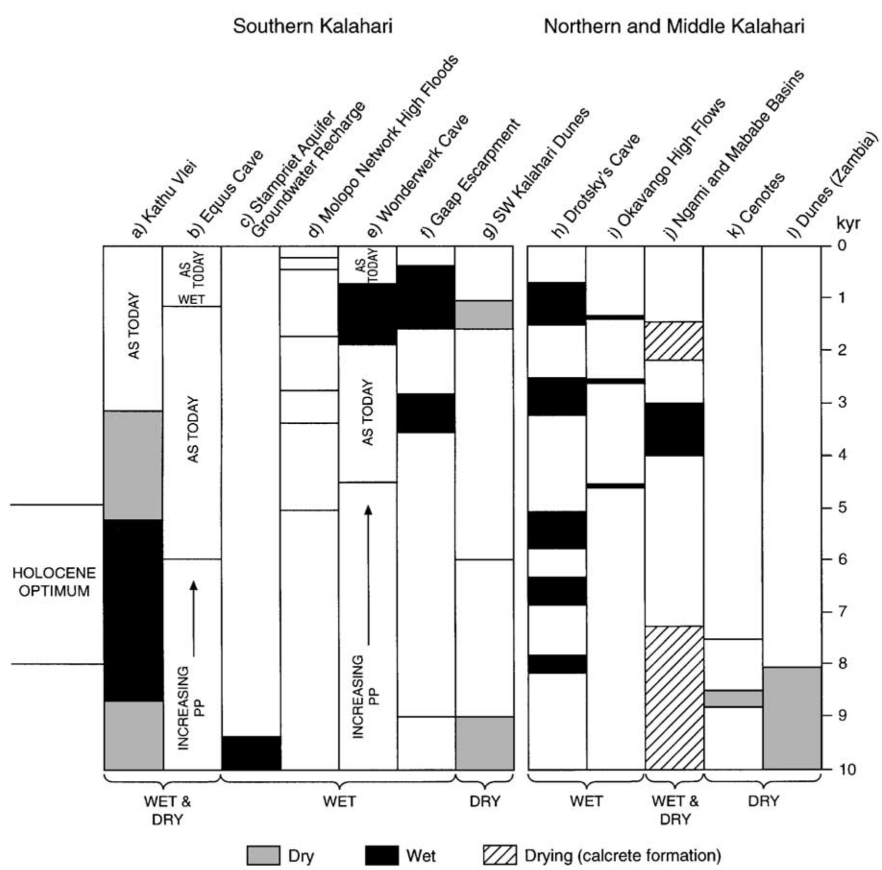

Fig. 7. Summary of wet and dry chronologies from the middle and southern Kalahari for the Holocene. Sources: (a) Beaumont et al. (1984); (b) Johnson et al. (1997); (c) Heaton et al. (1983); (d) Heine (1982), [64]Shaw et al. (1992); (e) Butzer (1984); (f) Butzer et al. (1978); (g) Thomas et al., 1997; (h) Brook et al. (1996, 1998); (i) Shaw and Thomas (1988), [50]Nash et al. (1997); (j) Shaw (1985), Robbins et al. (1998); (k) Brook et al. (1996, 1998) and (l) O'Connor and Thomas (1999).

similar to the present, rather than the 10–20% increase in rainfall hypothesised by Partridge et al. (1999). Short-term increases in precipitation in the middle Kalahari are suggested from speleothems and Okavango channel sediments (Nash et al., 1997) at 3–2.5 ka and c 1.4 ka. In the southern Kalahari, similar conditions appeared between 1.8 and 1.2 ka. A recently published high-resolution speleothem record (Holmgren et al., 1999) from Cold Air Cave, Northern Province, South Africa, confirms that a warm, wet period was widespread throughout the summer rainfall zone at 2–1.6 ka. Although the optical-dating programme has yielded a large number of dates for the SW Kalahari (Fig. 6), these are mostly related to pan lunette dunes, suggesting that once linear-dune mobility ceased around 9 ka, subsequent aeolian activity was localised to minor dune forms.

5. Forcing mechanisms of change

Dune construction in central southern Africa is inhibited today by both effective precipitation amounts (the climate is too wet) and wind strengths (conditions offer insufficient aeolian transport potential). Effective channel flow does not occur today either, except in the northern Kalahari where perennial rivers originate from wet tropical locations. Lakes are therefore dry too. Present day conditions would therefore appear to be 'sedimentation neutral' over much of the Kalahari summer rainfall zone. Aridity leading to dune building in the northern Kalahari requires a reduction in effective rainfall equivalent to a c 500–600 mm decrease from present day annual precipitation values. This could be achieved by a fall in absolute precipitation levels, an increase in potential evapotranspiration, or a combination of both. To replenish the Ngami and Mababe lakes to the 936 m a.s.l. Lake Thamalakane level would likewise require a 100% increase in regional precipitation, taking into account the amplifying effect of the Okavango swamps (Shaw, 1988). The southern Kalahari would require a significantly lower reduction in rainfall (or increase in evaporation) for dune construction to occur, but present wind energy levels are insufficient for dune building even if precipitation levels were sufficiently reduced (Lancaster, 1988; Bullard et al., 1997). What factors are likely to control windiness, precipitation or evaporation values in the southern African interior, which would appear to be the major controls on sedimentation in the region?

At deca-millennial Quaternary timescales, key debates presently revolve around the relative roles and impacts of high-latitude ice volume and direct orbital procession, solar insolation, and forcing of African tropical and subtropical climates. If ice volume changes are a key driving mechanism, then northern- and southern-hemispheric covariance in key climatic parameters, as recorded by proxy indicators of climate change, would be expected. If direct solar insolation is most important as a climate driver, then antiphase changes in key climate indicators may be expected between the two hemispheres.

Following a complex analysis of sedimentary data from Pretoria Salt Pan, located c 200 km to the southeast of the Kalahari periphery, Partridge et al. (1997) proposed antiphase variations in monsoon peaks (rainfall maxima) between the African north and southern hemispheres, over the last 200 ka. Through a process of 'phase locking', the same authors linked the Pretoria Salt Pan rainfall maxima to 23 ka-cyclicity summer insolation peaks, with a 15% increase in summer insolation at 30°S correlating with a 68% increase in precipitation. Partridge et al. (1997) therefore propose direct solar insolation variations as a primary mechanism for late Quaternary rainfall changes and ensuing changes in ecological, geomorphological and sedimentological processes, in central southern Africa. It should be noted, though, that the relationship breaks down for the c 20 ka ago summer insolation maxima, which coincided with (LGM) low-precipitation levels.

In contrast, analysis by Little et al. (1997a,b) of microfaunal remains in southeastern Atlantic sediment cores from 19°34′S, 11°11′E and 23°19′S, 12°23′E has proposed a direct link between northern hemisphere ice volume changes and atmospheric circulation in the region. Precipitation in the summer rainfall zone of central southern Africa is closely linked to the seasonal movements of the intertropical convergence zone and the expansion of moist air bodies, derived from the Indian Ocean, over the subcontinent. It has also been shown by Tyson and co-workers (e.g Tyson, 1986; Tyson and Lindesay, 1992), that present day dry phases/droughts are closely linked to strengthened and expanded westerly circulation, associated with intensified blocking anticyclone conditions over southern Africa. This both inhibits the penetration of moist easterly airflows of the Indian Ocean and gives a relative increase in the westerly (Atlantic) moisture sources. This may provide an analogue for situations where aridity is enhanced in eastern areas at times when moisture increases occur in the west.

Sea surface temperature (SST) changes are a key factor linked to the circulation changes considered above, which Cohen and Tyson (1995) have modelled for the Holocene and which appear to correlate with proxy records of coastal conditions around the southern African coast. Warm SST anomalies off the south/southeast coast of South Africa are related to dry interior conditions and low SSTs with warm, wet periods.

Off the southwest coast, Little et al. (1997b) have produced a long (140 ka) record of SST changes related to changes in the upwelling of the Benguela current. Enhanced upwelling (lower SSTs) events are associated with stronger and more zonal trade winds, and are teleconnected to North Atlantic Heinrich events and Greenland ice cap Dansgaard–Oeschger cycles. These changes in the strength of the Benguela current upwelling appear to correlate with late Pleistocene arid events in the interior (Stokes et al., 1997a), determined from the dune-construction chronology. The role of teleconnections in explaining climate change processes in southern Africa has now been explored in consideration of windspeed changes across the region. Wind speed maxima in the southern Kalahari have been linked to Asian monsoon minima (Prell and Van Campo, 1986; Stokes et al., 1999) both in modelled variations in the late Quaternary and observed variations during the last century. This is due to the development of ridged anticyclonic conditions in the southern Indian Ocean when the monsoon is weak.

The record of dune construction for the Kalahari based on luminescence dating shows a complex spatial and temporal record of aeolian construction during the last glacial cycle, that presently does not readily correspond to the predictions of low-latitude insolation or high-latitude ice forcing mechanism models. The reliable elements of the current humid proxy record from the Kalahari afford a further level of complexity in attempting to identify the forcing mechanisms of environmental change in the region. Whether climate changes in the southern African interior are driven by direct insolation variations or SST variations, linked to events in high latitudes, or whether the relative importance of these two possible mechanisms varies through time, establishing the climatic forcing mechanisms responsible for directly recorded environmental changes is presently complicated by limitations and uncertainties within the proxy record and difficulties in linking the millennia timescales of the records of environmental changes in the interior and the century or less scales of some of the climatic change mechanisms that are being proposed.

6. Conclusion

Regional palaeoenvironmental data bases have recently been employed by Jolly et al. (1998) and Partridge et al. (1999) to evaluate the nature of southern African climate at the LGM and mid-Holocene, and as comparators against modelled climates. The interior of southern Africa is poorly represented in these assessments, largely due to the absence of the long sedimentary cores and palynological evidence found elsewhere. Palaeogeomorphic and sedimentary evidence, along with isolated cave records, therefore remain the principal sources of data that are available for reconstruction in the Kalahari. In the last decade, notable developments have occurred in deriving chronologically controlled records of regional-scale dry events and higher-resolution records of precipitation events. Appropriate scaling, and gaining an improved understanding of the nature and controls of subregional climatic variations and the millennia scale, are amongst key issues that require continued investigation.

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