11 Dry Valleys (*Mekgacha*)

David J. Nash

Abstract

Conventional rivers are absent from much of Botswana, with only the Okavango, Chobe and Zambezi systems in the extreme north containing perennial flowing water. Ephemeral rivers occur in the eastern hardveld, but the most extensive components of the surface drainage are the networks of fossil or dry valleys (termed *mekgacha* in Setswana and *dum* in various San languages) that cross the sandveld. This chapter presents the first holistic review of current knowledge about these enigmatic landforms. It does so using a range of evidence types, from radar remote-sensing to the analysis of historical documents written by missionaries and explorers. The chapter considers dry valley distribution, morphology and contemporary and historical hydrology before discussing valley evolution over longer timescales. It concludes with a synthesis of the main arguments concerning how dry valley systems may have formed, including the balance between conventional fluvial incision and processes such as groundwater seepage erosion.

Keywords

Dry valley • Ephemeral river • Kalahari desert • Long-profile • Drainage evolution

11.1 Introduction

Perennial rivers are absent from much of Botswana, with the Okavango, Chobe and Zambezi systems in the extreme north of the country providing the only permanent drainage (see Chap. 7). Ephemeral rivers occur at the periphery of the Kalahari Basin in the east of the country and flow periodically during the summer rainy season (Shaw 1989). Most of these systems rise to the east of the Kalahari-Limpopo drainage divide and cross into South Africa, although some drain westwards towards the Makgadikgadi Basin and provide fluvial input to Sua Pan (see Fig. 11.1). The most extensive components of the drainage within Botswana, however, are the networks of dry valleys that form the focus of this chapter. These are termed *mokgacha* (singular; or *mekgacha*, plural) in Setswana, *dum* in various San languages, *omuramba* (singular; or *omiramba*, plural) in Otjiherero and *laagte* in Afrikaans.

The Kalahari Basin has experienced faulting and flexuring throughout the Cenozoic (e.g. du Toit 1933; Thomas and Shaw 1991; Haddon and McCarthy 2005; de Wit 2007; Moore et al. 2009, 2012), notably associated with the extension of the East African Rift System. There is also evidence for longer term climatic fluctuations about the present-day semi-arid mean, with parts of the Kalahari occupied by palaeolakes or covered by active linear dune systems at various periods during the Quaternary (Chaps. 5, 8and9). This combination of climate change and neotectonics has produced the complex drainage networks that exist today.

The aim of this chapter is to summarise the major characteristics of the Kalahari dry valley networks within Botswana, including their geomorphology, contemporary and past hydrology and the various theories surrounding their (still enigmatic) age and origins. Many dry valley systems are transboundary, rising either in South Africa or Namibia before crossing into Botswana (or, in the case of the Serorome, rising in eastern Botswana and crossing into South

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D. J. Nash (✉)
School of Applied Sciences, University of Brighton, Brighton, UK
e-mail: D.J.Nash@brighton.ac.uk

D. J. Nash
School of Geography, Archaeology and Environmental Studies, University of the Witwatersrand, Johannesburg, South Africa

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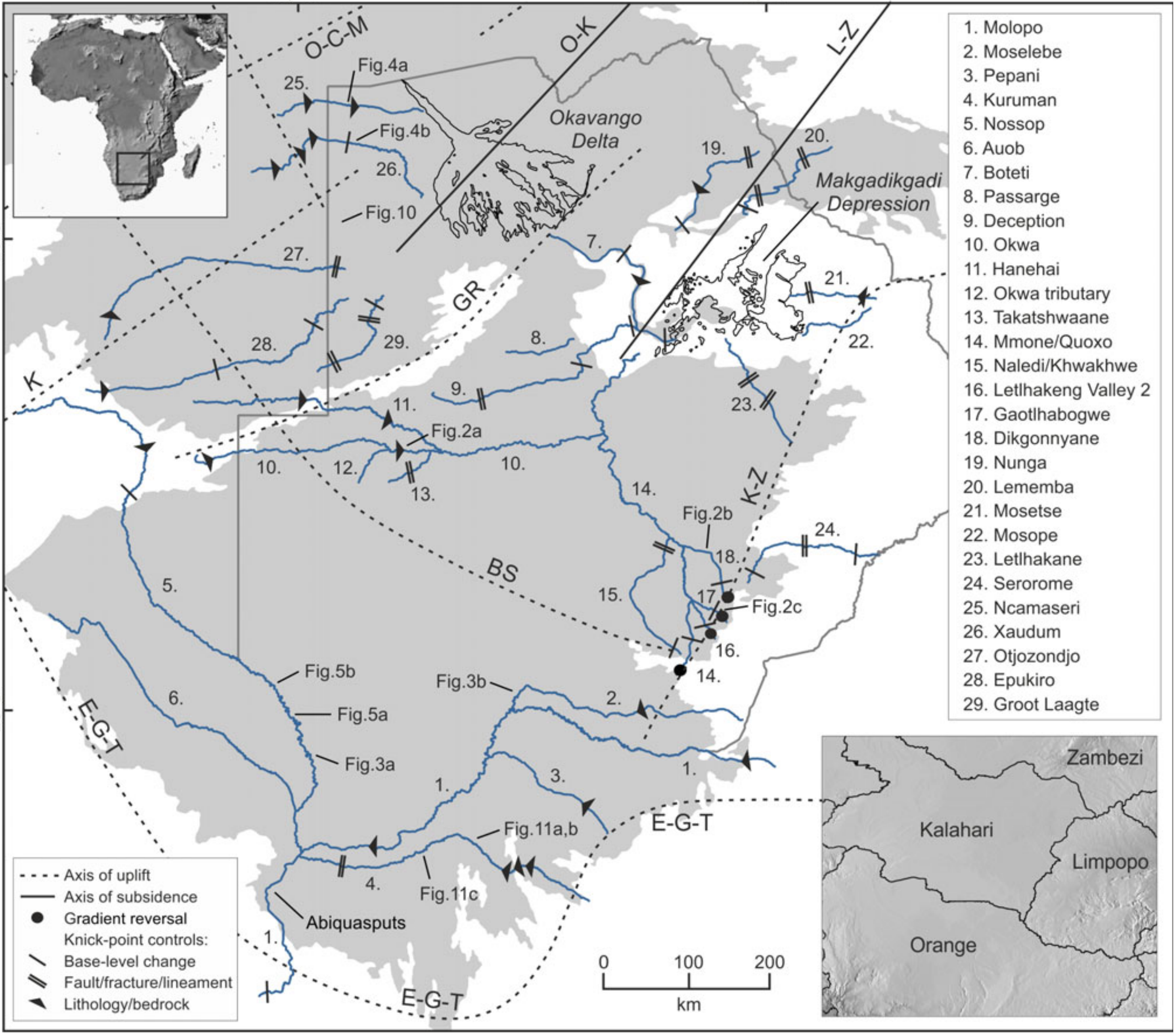

Fig. 11.1 Major dry valley and ephemeral river systems in Botswana and the wider Kalahari Basin (after Nash and Eckardt 2016). The Botswana border is delimited by a grey line and the area covered by Kalahari Group sediments shaded pale grey. Knickpoints and sections of valleys that exhibit gradient reversals are indicated. Knickpoints are distinguished according to their dominant control: base-level change; intersection with a fault, fracture or lineament; or differential rock resistance across a lithological boundary. The location of major flexural axes (after Haddon and McCarthy 2005) are also shown (BS, Bakalahari Schwelle; E–G–T, Etosha-Griqualand-Transvaal axis; GR, Ghanzi Ridge; K-Z, Kalahari-Zimbabwe axis; L-Z, Luangwa-Zambezi axis; O-K, Okavango-Kafue axis; O-C-M, Otavi-Caprivi-Mweru axis; K, Khomas axis). The numbers shown against individual valley segments are used in Figs. 11.6, 11.7 and 11.8. Inset maps (derived from SRTM30 digital terrain data at 1 km resolution) indicate the area covered by the main figure in relation to Africa (top left) and the boundaries between the Okavango-Kalahari, Orange, Limpopo and Zambezi drainage basins (bottom right; note that this map covers the same geographical area as the main figure)

Africa). Rather than focus only on the parts of these systems that fall within Botswana, characteristics of whole dry valley networks are considered where appropriate.

11.2 Major Dry Valley Systems

The main dry valley networks of the Kalahari are shown in Fig. 11.1 (after Nash and Eckardt 2016). Most systems rise in areas of exposed basement bedrock and traverse, and commonly terminate within, areas covered by Kalahari

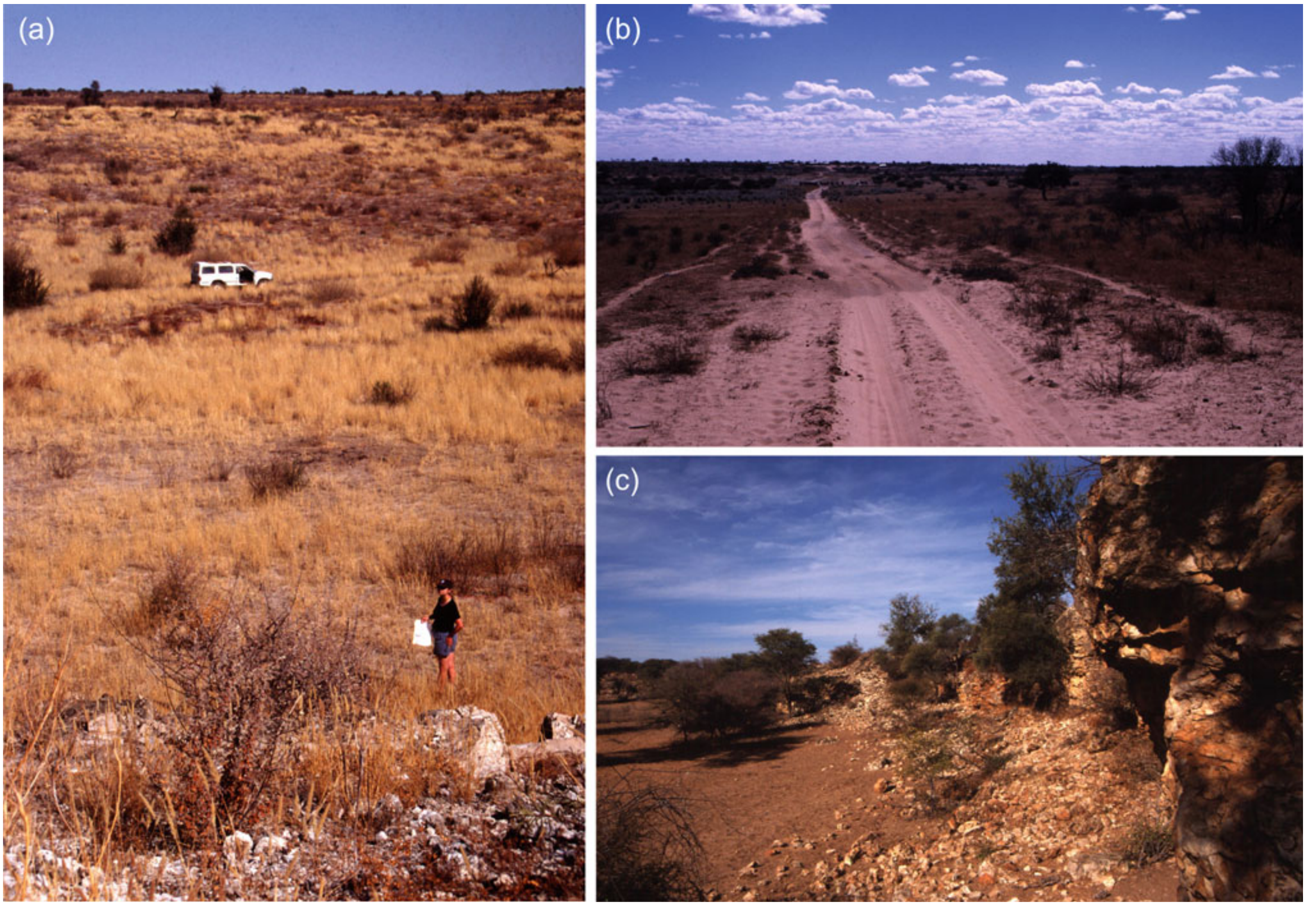

Fig. 11.2 Views of internally-draining (endoreic) dry valleys in Botswana: **a** Okwa valley immediately west of Tswaane borehole; **b** Dikgonnyane valley; **c** Gaotlhobogwe valley immediately downstream of the major knickpoint ~60 km from the valley headwater area (see Figs. 11.1 and 11.7) with exposures of silcrete (photographs: David Nash)

Group sediments. Two groups of valleys can be identified, separated by the broad, featureless *Bakalahari Schwelle* interfluve in central Botswana at 1000–1100 m asl (Passarge 1904; Thomas and Shaw 1991; Nash et al. 1994b). The first includes internally draining (or endorheic) fossil systems such as the Okwa-Mmone/Quoxo, Deception, Letlhakane, Nunga and Lememba that formerly fed into the Makgadikgadi Depression, and the Ncamaseri, Xaudum, Epukiro, Groot Laagte and other smaller systems that drain eastwards from Namibia towards the Okavango Delta (Fig. 11.2). These drain the shield and platform desert areas of the eastern and northern Kalahari. The largest of these systems, the Okwa-Mmone, has a catchment area in excess of 90,000 km^2 (Thomas and Shaw 1991). Some of these systems, most notably those that cross northwest Botswana, rise at headwater springs. Many endoreic valleys contain ponded water during the rainy season; however, evidence for surface flow is scarce (see Sect. 11.4). One further valley, the Serorome in eastern Botswana, is considered here alongside the various endoreic systems. The Serorome is unusual in that it is externally draining and swings eastwards into the Notwane, a headwater of the Limpopo. However, it rises in an area of Kalahari Group sediments and is geomorphologically similar to other internally draining valley networks.

The second group of dry valleys includes the externally draining (or exoreic) Southern Kalahari networks—the Auob-Nossop, Molopo-Kuruman and their tributaries (Fig. 11.3). The Auob and Nossop rivers both rise in the Khomas Highlands east of Windhoek, Namibia, at ~1200 m and ~1800 m asl, respectively, and flow in a broadly northwest-southeast direction before joining in the Kgalagadi Transfrontier Park. The east–west flowing Molopo and Kuruman rivers both rise at ~1500 m asl in South Africa near to the towns of Mafikeng (Northwest Province) and Kuruman (Northern Cape), respectively. The Molopo demarcates the border between southern Botswana and South Africa, while the Nossop forms the border between the two countries in the Kgalagadi Transfrontier Park. Most of the Southern Kalahari systems originate in areas of basement bedrock beyond the margin of the Kalahari Group sediments (Boocock and van Straten 1962), although some tributary systems—including the Moselebe

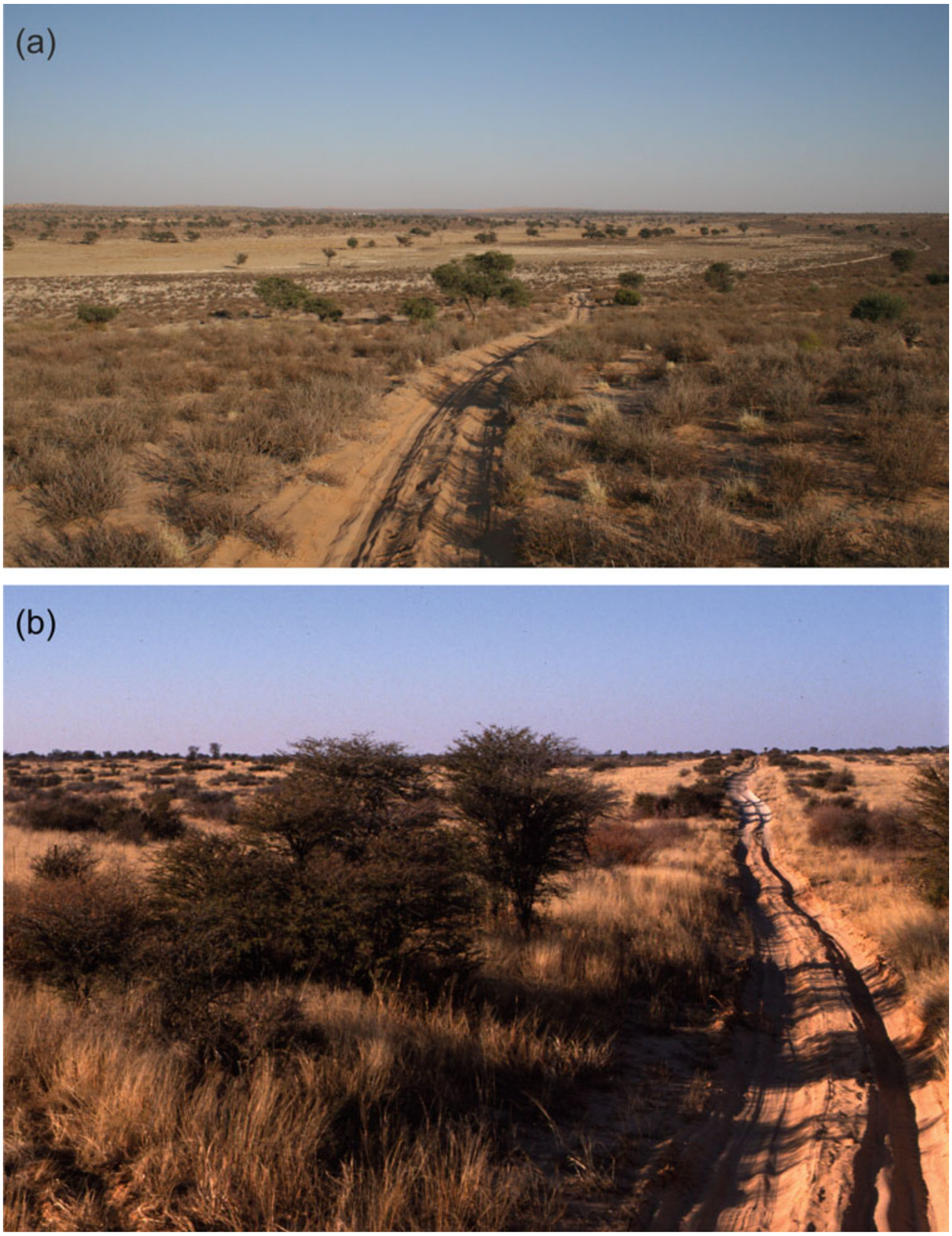

Fig. 11.3 Views of externally-draining (exoreic) dry valleys: **a** the Nossop valley within the Kgalagadi Transfrontier Park (photograph courtesy of Philip Raggett); **b** the Moselebe valley north of its confluence with the Molopo (photograph: David Nash)

valley, a feeder to the Molopo in Botswana—originate in areas with a Kalahari sand cover (the uppermost unconsolidated component of the Kalahari Group). All four main systems converge in the southwest Kalahari and ultimately connect to the Orange River (and hence the Atlantic) downstream of Aughrabies National Park via a long-dry section of the Molopo. As discussed in Sect. 11.4, the Southern Kalahari valleys have flooded on a number of occasions within the past 150 years; as such, they may represent a transitional state between the endoreic Middle Kalahari systems and the ephemeral rivers of the semi-arid hardveld (Shaw 1989; Shaw et al. 1992).

11.3 Dry Valley Morphology

Until recently, the basic morphological characteristics of Kalahari dry valley systems, including fundamental properties such as their long-profile shape, were poorly understood. This was due primarily to a lack of topographic survey data for areas of Botswana away from the more densely populated eastern hardveld. This section considers the morphology of the dry valley systems, with processes of formation discussed in Sect. 11.6.

11.3.1 Older Accounts of Dry Valley Morphology

Many of the earliest accounts of the morphology of dry valleys were based on analyses of aerial photography—as such, they were relatively detailed in terms of the planform of many systems but provided limited information about topographic variability. The seminal study of Boocock and van Straten (1962) suggested that it was possible to identify three broad morphological stages within the internally draining *mekgacha* in Botswana. Headwater regions of systems (away from areas of outcropping basement bedrock) were noted as being typically flat, shallow, clay-floored and channel-less, sometimes with a dambo-like lobate morphology (Boocock and van Straten 1962; Cooke 1984). This generalisation is particularly true of the upper sections of the Mmone/Quoxo system south of Letlhakeng in southeast Botswana. This gentle form gives way, often abruptly, to an incised 'gorge-like' middle section with a rectilinear flat-bottomed form (Shaw and de Vries 1988; Shaw et al. 1992). Rarely, this middle section may contain evidence of abandoned meander channels (Fig. 11.4) but valley-floor sediments are hardly ever exposed. Note that the term 'gorge-like' is used here relative to the otherwise relentlessly flat Kalahari topography—endoreic dry valleys in Botswana are seldom incised more than 40 m into the surrounding landscape. The deeper sections of valleys often expose outcropping silcrete, calcrete and intergrade duricrusts such as cal-silcrete and sil-calcrete (Shaw and de Vries, 1988; Nash et al. 1994a; Kampunzu et al. 2007)—see Chap. 13. Many valleys eventually dwindle to a further broad and flat stage, often becoming completely sand-choked by wind-blown sediment in their lower reaches.

Investigations by Nash et al. (1994b), Bullard and Nash (1998) and Nash (2015) include further detail about the exoreic Auob, Nossop, Kuruman and Molopo valleys. The cross-sectional shape of these systems varies considerably, ranging from gently sloping convex/concave forms to steep-sided more incised sections (up to 30 m deep) where the valleys cut through the southwest Kalahari calcrete plateau (see also Chap. 13). Variability occurs not only between the different systems but also along the lengths of individual valleys. The Auob valley, for example, is narrow and barely distinguishable in its headwater sections but reaches a maximum width of 1.8 km south of Stampriet in Namibia before narrowing to around 0.5 km within the Kgalagadi Transfrontier Park (Bullard and Nash 1998). Wider sections of the Nossop also contain numerous abandoned channels and meander systems (Fig. 11.5), including where the valley forms the border between Botswana and South Africa (Nash et al. 1994b; Nash 2015).

11.3.2 Advances Since the Advent of Radar Remote Sensing

The release of Shuttle Radar Topographic Mission (SRTM) digital elevation data for Africa in 2003 made it possible to reconstruct the morphology of entire Kalahari drainage systems with an absolute vertical accuracy estimated at 3–5 m (Rodriguez et al. 2005). Using SRTM data, Nash and Eckardt (2016) produced the first spatially accurate location map of 29 exoreic and endorheic dry valley courses (see Fig. 11.1) and reconstructed their long profiles (Figs. 11.6, 11.7 and 11.8). Like river systems in other parts of the world, the majority of Kalahari dry valleys exhibit concave-up long profiles for at least part of their course, graded to local or regional base levels. Exceptions to this generalisation include the Auob, Passarge, Mosope and Letlhakane, which have broadly linear long profiles. Most dry valleys lack the pronounced concavity typical of temperate graded rivers (Hack 1973), with stream gradient indices lower than expected in headwaters and higher in downstream sections. Kalahari dry valley long profiles are similar to those of ephemeral rivers in Australia, Israel, Kenya and the southwest USA (e.g. Leopold and Miller 1956; Frostick and Reid 1989; Tooth 2000) but do not exhibit the marked convexities seen in some hyperarid systems, such as those in the Namib Desert (Goudie 2002).

Nash and Eckardt (2016) demonstrated that 25 of the 29 dry valley systems contain distinct knickpoints—locations where major changes in valley gradient occur—exceptions being the Auob, Passarge, Mosope and an unnamed tributary of the Okwa. A total of 55 knickpoints were identified, most of which occur as kilometre-scale transitional zones of gradient change in the valley long-profile. A detailed comparison of the knickpoint positions shown in Figs. 11.6, 11.7 and 11.8 with geological maps for Botswana and Namibia indicated that the majority of knickpoints occur at lithological boundaries. For example, the middle knickpoint on the Molopo (Fig. 11.6) is located where the valley passes from Kalahari Group sediments onto an inlier of more resistant Karoo Dwyka Group diamictites, siltstones and sandstones. The knickpoints on the middle Okwa and lower Hanehai (Fig. 11.7) coincide with locations where the valleys cross from inliers of more resistant Okwa Basement Complex and Ghanzi Group lithologies, respectively, onto Kalahari Group sediments. The middle knickpoint on the Nunga appears to be related to an outcrop of more resistant duricrusts within the Kalahari Group sediments. In general, Nash and Eckardt (2016) identified that knickpoints were steeper where valleys cross from less to more resistant lithologies, primarily due to the greater potential for headward erosion into softer materials. SRTM data reveal other knickpoints where valleys intersect exposed or shallow faults. For example, most

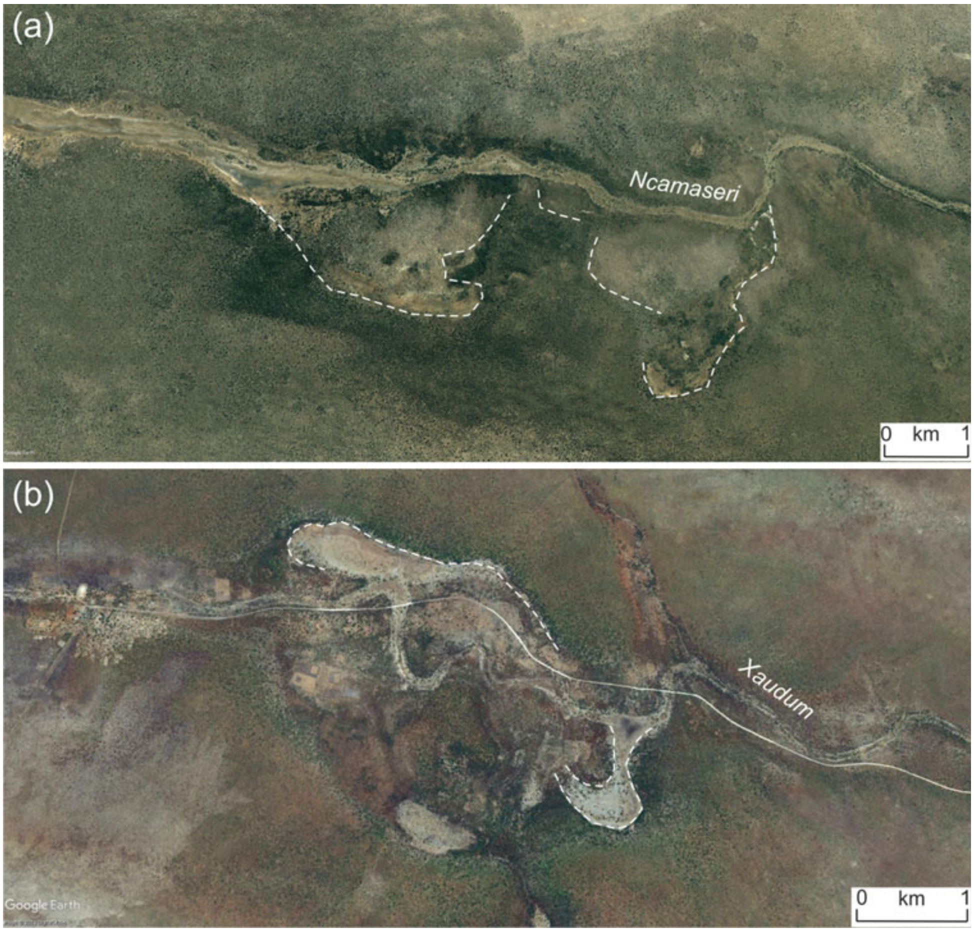

Fig. 11.4 Abandoned meanders (dashed line) along the course of the **a** Ncamaseri and **b** Xaudum dry valleys in northwest Botswana. See Fig. 11.1 for locations of images. Images courtesy of Google Earth, dated (**a**) 6 July 2008, (**b**) 19 October 2014

knickpoints on systems draining towards the eastern Makgadikgadi Depression (Fig. 11.8) occur where these valleys cross known or inferred faults or fractures, possibly linked to neotectonic movement within the basin.

The larger knickpoints within dry valley systems tend to be associated with areas where there is known evidence of base-level lowering and/or uplift along neotectonic flexural axes. Most pronounced is the distal knickpoint on the Molopo in South Africa (Fig. 11.6), where the valley floor drops from 750 to 460 m asl over a distance of 45 km. Nash and Eckardt (2016) argue that the knickpoint developed in response to headward migration of the Augrabies Falls on the Orange River past the lower Molopo-Orange confluence, presumably following subcontinental uplift between 75 and 65 Ma (McMillan 2003; Bluck et al. 2007). The lower knickpoint on the Serorome (Fig. 11.8) appears to have been generated in response to an incision along the Limpopo River. In contrast, the upper Serorome and middle Epukiro knickpoints and the lower knickpoints on the Lememba and Xaudum (Fig. 11.8) all fall at confluences with incised tributaries. The distal Otjozondjo, Epukiro and Groot Laagte knickpoints occur immediately up-valley of where these systems enter the half-graben occupied by the Okavango Delta and are most likely a product of tectonic base-level lowering. In the Otjozondjo, the distal knickpoint coincides with the Gumare fault, which has a 17 m southeast throw here (Kinabo et al. 2007; McFarlane and Eckardt 2008). The knickpoints on the Deception occur where the valley crosses palaeolake shorelines in the Makgadikgadi Depression and may be controlled by former lake levels.

The courses of four headwaters of the Mmone/Quoxo valley system straddle the Kalahari-Limpopo drainage divide (Fig. 11.7). These include the main Mmone/Quoxo, which rises at an altitude of c.1205 m asl and ‘flows’ uphill for 19 km before crossing the divide at 1286 m. Three tributaries to this system (the Dikgonnyane, Gaotlhabogwe and ‘Letlhakeng Valley 2’) also exhibit reversed gradients in their headwaters and can be traced for 2–5 km before crossing the drainage divide at 1173, 1233 and 1252 m, respectively (see Fig. 11.9). Analyses of aerial photographs of the headwater sections of each of these valleys by Nash and Eckardt (2016) indicate that the drainage lines were once continuous across the Kalahari-Limpopo divide but are now marked by a chain of small pans. Each of these valleys also

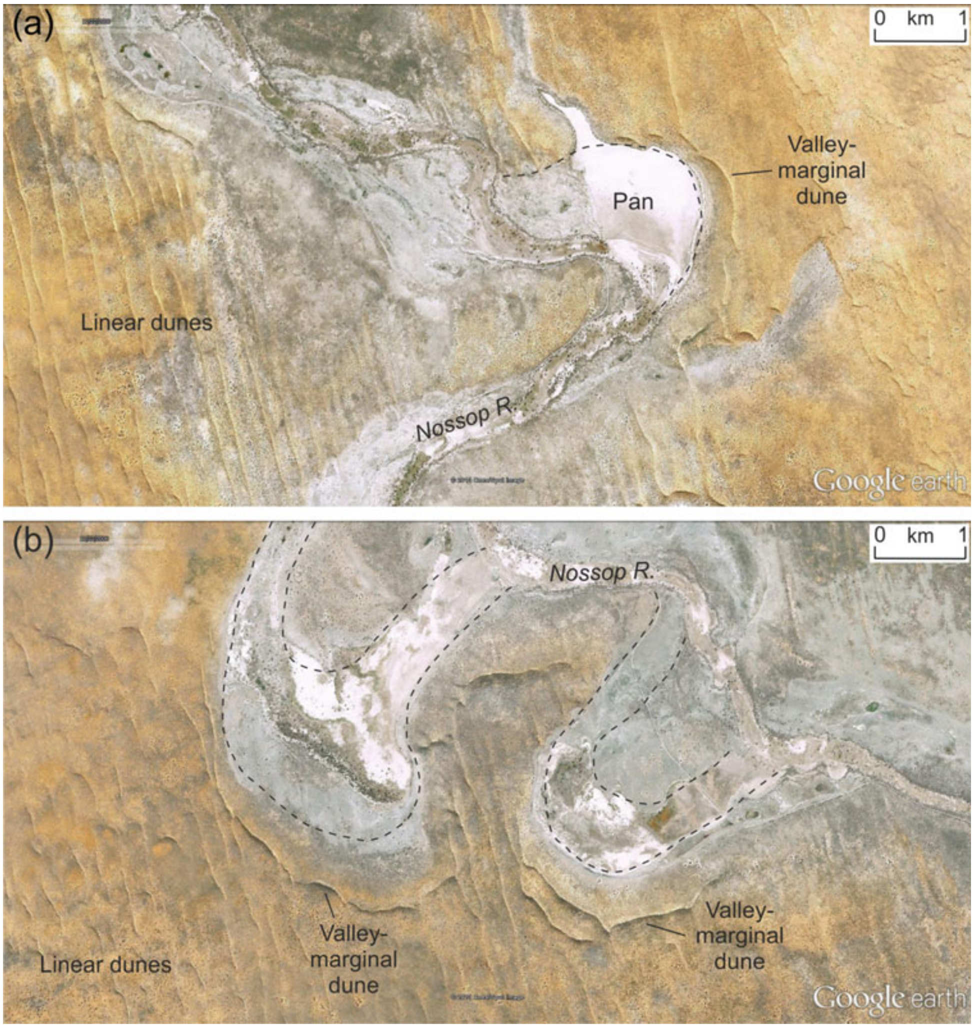

Fig. 11.5 Abandoned meanders (dashed line) and valley floor pans along the course of the Nossop River where it forms the boundary between Botswana and South Africa. Linear dunes and valley-marginal dunes (see Bullard and Nash 2000) are also indicated. See Fig. 11.1 for locations of images (a) and (b). Images courtesy of Google Earth (date of images, 22 November 2006)

contains major knickpoints (Fig. 11.7), the most pronounced occurring at 80 km from the source of the Mmone/Quoxo where the valley falls from 1150 to 1080 m over 11 km and extensive exposures of silcrete, calcrete and intergrade duricrusts occur (Shaw and de Vries 1988; Nash et al. 1994a; Kampunzu et al. 2007).

11.4 Hydrology and Palaeohydrology

11.4.1 Contemporary and Historical Hydrology—Endorheic Valleys

Surface flows have only been recorded within endorheic dry valley systems in Botswana on a handful of occasions, each time triggered by high-intensity summer rainfall events associated with the passage of convectional storms or tropical lows off the Indian Ocean (see Preston-Whyte and Tyson 1993). The Letlhakane has experienced the greatest number of documented flood events. Surface flow is known to have occurred over a section of the valley in 1969 in response to intense precipitation (Mazor et al. 1977). Short-lived flooding was also reported in January 2013 (Morrison and Morrison 2013) and February 2018 (Motlhabani 2018), with the former event triggered by ~100 mm precipitation falling near Letlhakane village in a single day (Morrison and Morrison 2013). Flooding has also been known to occur during the twentieth century in the Groot Laagte and Epukiro valleys (Nash 1996). The headwaters of valleys that rise at springs in the Aha Hills along the Namibia-Botswana border occasionally contain standing or gently flowing water (Fig. 11.10), but the flow is limited to bedrock sections of these valleys (Yellen and Lee 1976; Helgren and Brooks 1983).

Rather than transmitting surface flow, most endorheic valley systems normally remain dry throughout the year—the only exception being the occurrence of ephemeral pools in valley floor depressions in some systems during the summer rainy season. This is unsurprising, given the extent of unconsolidated sediments within valley floors and the lack of any significant valley gradient to create a slope that

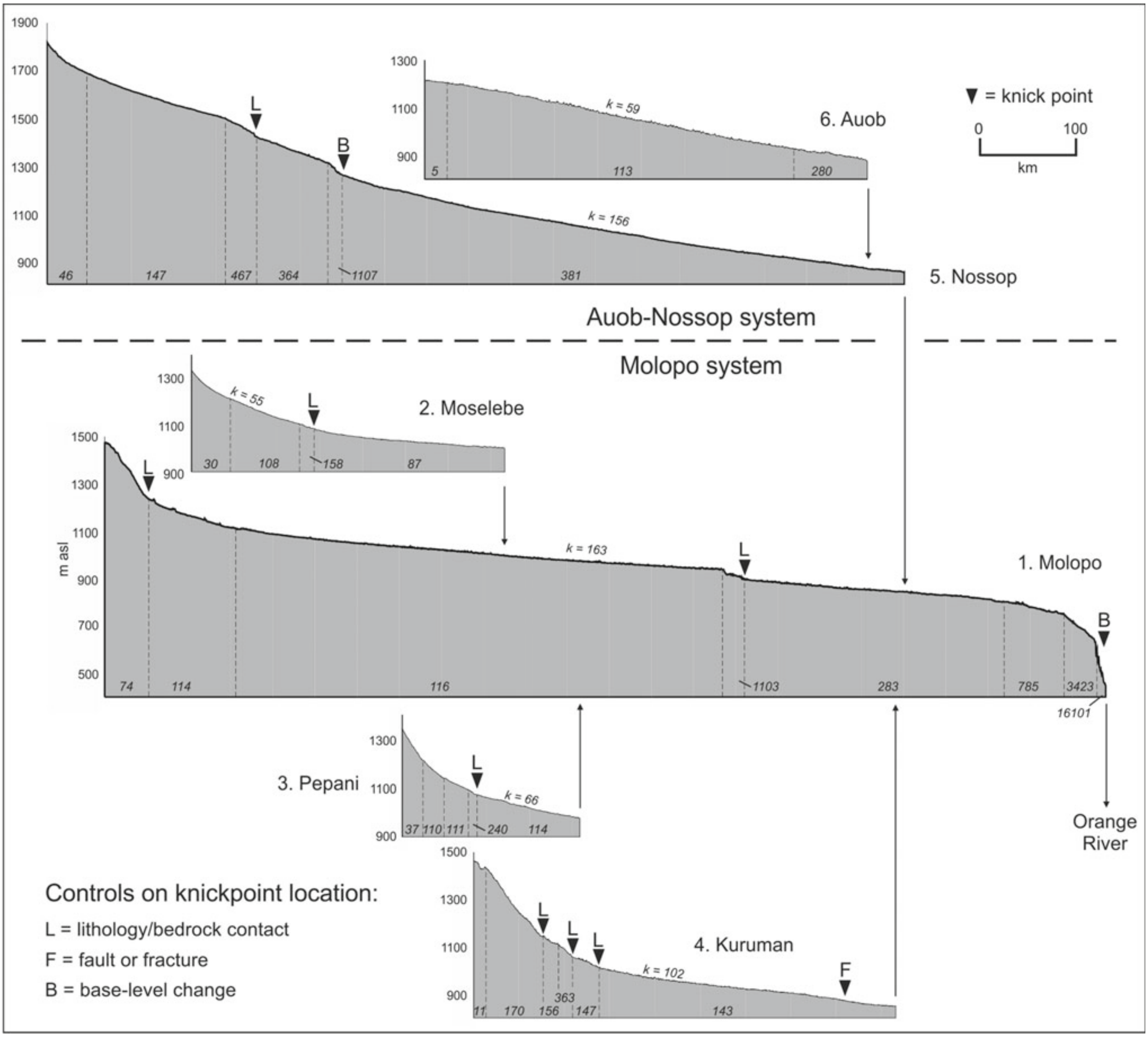

Fig. 11.6 SRTM-derived long-profiles for the externally-draining Southern Kalahari dry valley networks (after Nash and Eckardt 2016). Stream gradient index (k) values are shown for comparative purposes for entire long-profiles and individual valley segments. Stream gradient indices were calculated using the equation: $k = (H_i – H_j) / (\ln L_j – \ln L_i)$ where *H* is altitude and *L* the horizontal distance between two points *i* and *j* (after Hack, 1973). Vertical arrows indicate confluence points between valley segments and the connection with the Orange River. Long-profiles are plotted at the same horizontal scale in Figs. 11.5, 11.6 and 11.7, with 250-times vertical exaggeration. See Fig. 11.1 for locations of valley segments

would allow floodwater to flow faster and further. On the rare occasions that rainfall levels are sufficient to saturate valley-floor sediments, valleys may act as conduits for groundwater recharge (Farr et al. 1981; de Vries et al. 2000).

The general lack of surface hydrological activity within endorheic valley systems has persisted since at least the early nineteenth century when written descriptions of the Kalahari landscape first become available. There is, however, evidence that some valleys may have become drier over the past 150 years. Until the late nineteenth century, semi-permanent standing pools associated with near-surface water tables were common in many valley floors, only disappearing once human settlement and associated cattle spread throughout the region (Shaw et al. 1992). This mirrors the drying up of several perennial spring sites in Botswana during the nineteenth century evidenced by authors including David Livingstone (1857), Charles Andersson (1856) and Andrew Bain (Lister 1949). Bain indicated that Kang may once have had a spring (Campbell and Child 1971), whilst Andersson (1856) described a number of wells between Lake Ngami

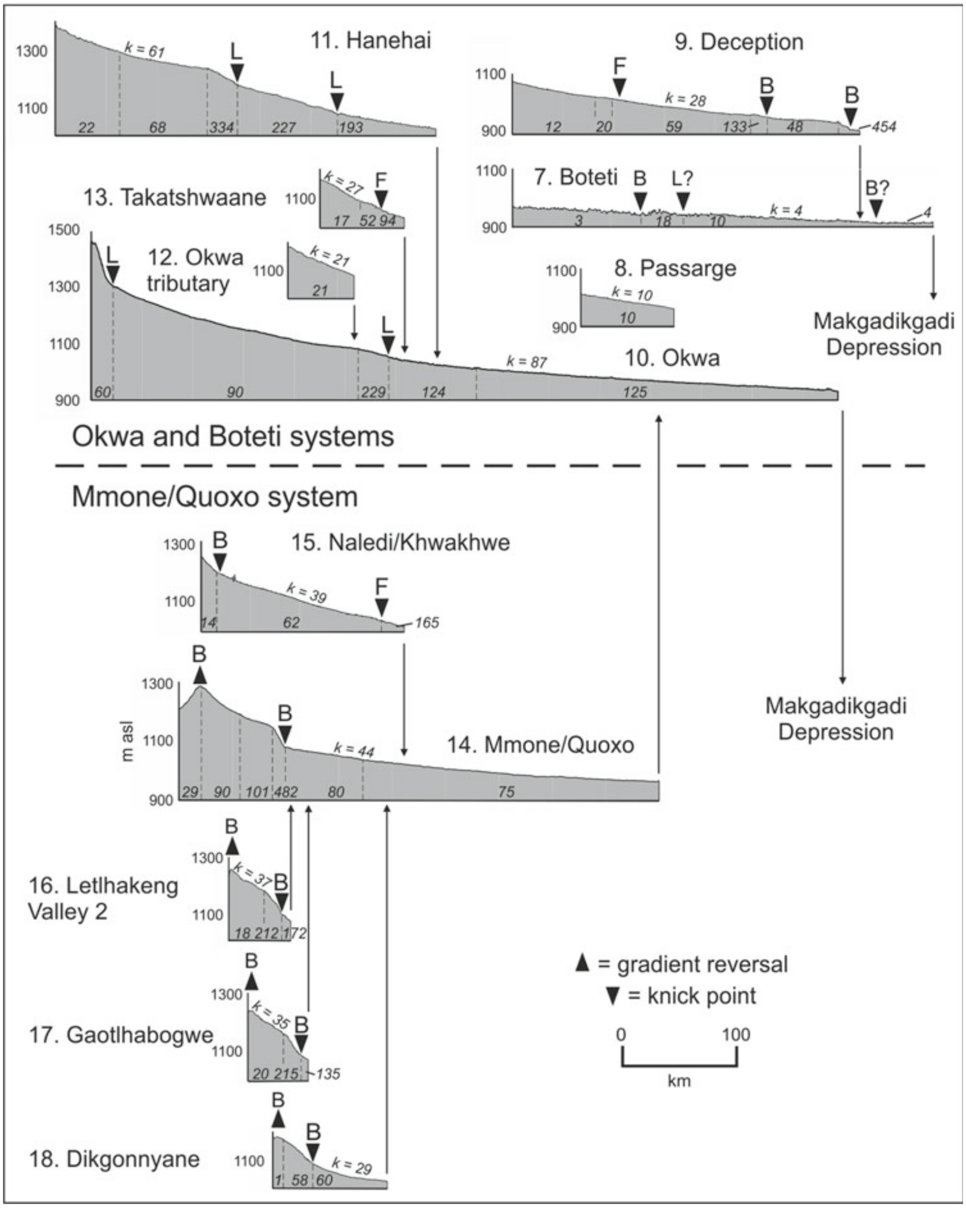

Fig. 11.7 SRTM-derived long-profiles for the internally-draining Okwa and Mmone/Quoxo dry valley networks (after Nash and Eckardt 2016). The profile for the ephemeral Boteti River is shown for comparison. See Fig. 11.6 for further details

and Ghanzi and strong spring-flow near to Mamuno. All these springs are now dry, although a map compiled by Stigand (1923) records spring sites near Ghanzi. It is also significant to note that many settlements in presently dry valleys (e.g. Letlhakeng and Letlhakane) have names meaning ``place of reeds' in Setswana but lack swampy conditions today (Campbell and Child 1971). Whether this apparent regional lowering of water tables is a result of the over-consumption of groundwater (see Thomas and Shaw 1991) and/or reflects long-term drying trends over the southern African interior (see Neukom et al. 2014; Nash et al. 2016) is not known.

Only two accounts from the nineteenth century include direct descriptions of either standing or flowing water within an endorheic dry valley (see Nash and Endfield 2002). The most important of these is a flood reported in the Letlhakane to the south of the Makgadikgadi Depression in 1851. The flood is described within the unpublished and unedited version of David Livingstone's *Bechuanaland Journal* held in the Council for World Mission Archive (School of Oriental and African Studies, London). In this journal, Livingstone described his journey from the Chobe and Linyanti rivers to the Kuruman mission station in September 1851, immediately after crossing Ntwetwe Pan:

> While at Letlehan [Letlhakane] we had three days rain. This made the [valley] assume the appearance of a large river flowing

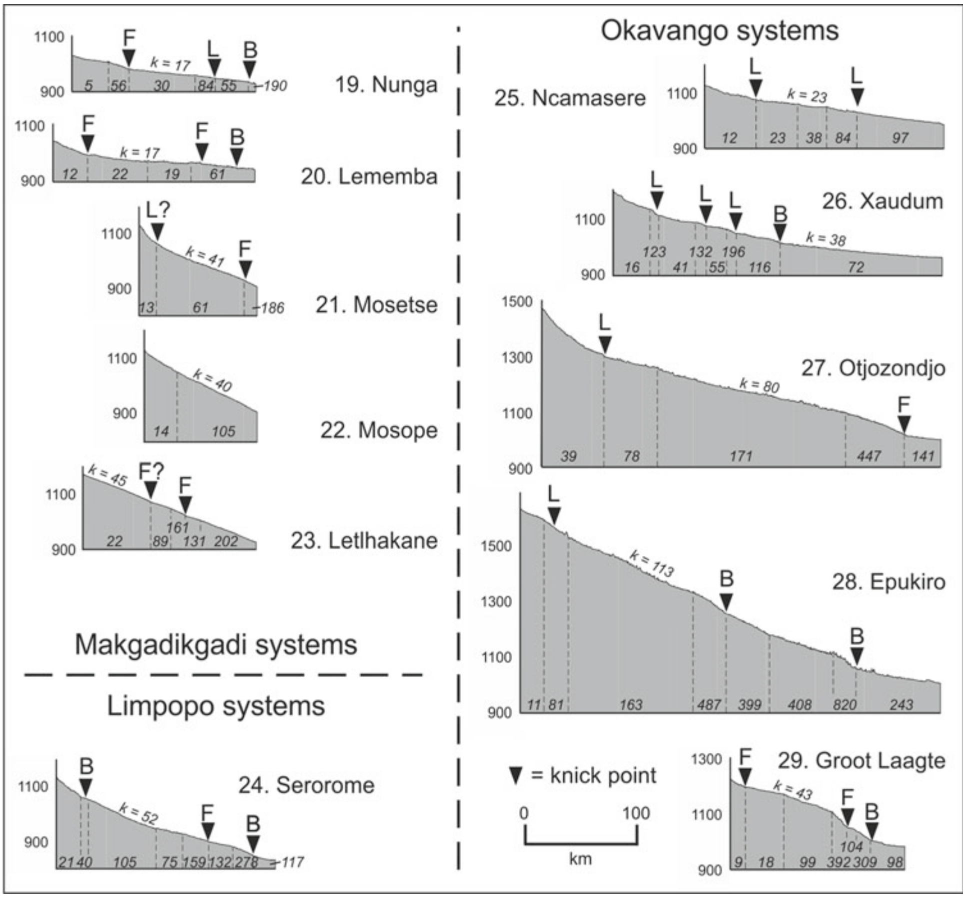

Fig. 11.8 SRTM-derived long-profiles for the externally-draining Limpopo and internally-draining Okavango and Makgadikgadi dry valley networks (after Nash and Eckardt, 2016). See Fig. 11.6 for further details

> northwards. The old people remember the time when it flowed as through the whole year…[1]

The other account is provided in an unpublished letter written from Shoshong to the London Missionary Society headquarters in London in 1880 by the missionary Rev. James D. Hepburn (Nash and Endfield 2002). This letter includes a second-hand report of an itinerating journey in 1879 by the Motswana missionaries Khukwe and Diphukwe from Lake Ngami to the north of Shakawe via the western side of the Okavango Delta. The journey followed the presently dry Thaoge river and then crossed a number of fossil valleys including the Xaudum, with Hepburn noting:

> In June they got to another river called Cadom. It has large pools of water all along its course in the dry season. They stayed here again for two weeks… Two treks from this river brought them to another lot of large pools in the riverbed and another trek brought them to a beautiful water called the waters of the Bakgalagadi. These are beautiful springs and a nice strip of ground lying below them. Again, they went on to another river called Kaudom. At Kaudom there is deep water in the riverbed all the way down, but it is under the surface and is very deceptive to anyone unacquainted with that fact. From what I can make out it must be almost like a quicksand for Khukwe says a man might easily drowned at this place. There is a place where it can be crossed by the wagon for all that…[2]

Khukwe and Diphukwe subsequently travelled to just north of Shakawe and then returned to Lake Ngami via the same route. Hepburn's letter noted that they travelled from:

> …Kaudom and from Kaudom to Chadom. They taught at these places Boers, Masarwa, Bechuana hunters and others gathered together at the waters[2]

These descriptions of water within presently dry valleys are potentially significant. It is, however, difficult to identify from Hepburn's account exactly which systems were crossed by Khukwe and Diphukwe's party, as several valleys in northwest Botswana are referred to by similar names in regional languages. It would appear likely from the accounts of distances travelled that the Cadom (or Chadom) is the present-day Xaudum whilst the Kaudum is the Ncamaseri (known as the Xeidum in westernmost Botswana and the Xaudum or Khaudum in Namibia). Regardless, that both

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[1] Council for World Mission Archive, London Missionary Society, David Livingstone's Bechuana Journal p.151, September 1851.

[2] Council for World Mission Archive, London Missionary Society, South Africa Correspondence Box 40, Folder 3, Jacket C, Rev. J.D. Hepburn, Shoshong, June 1880.

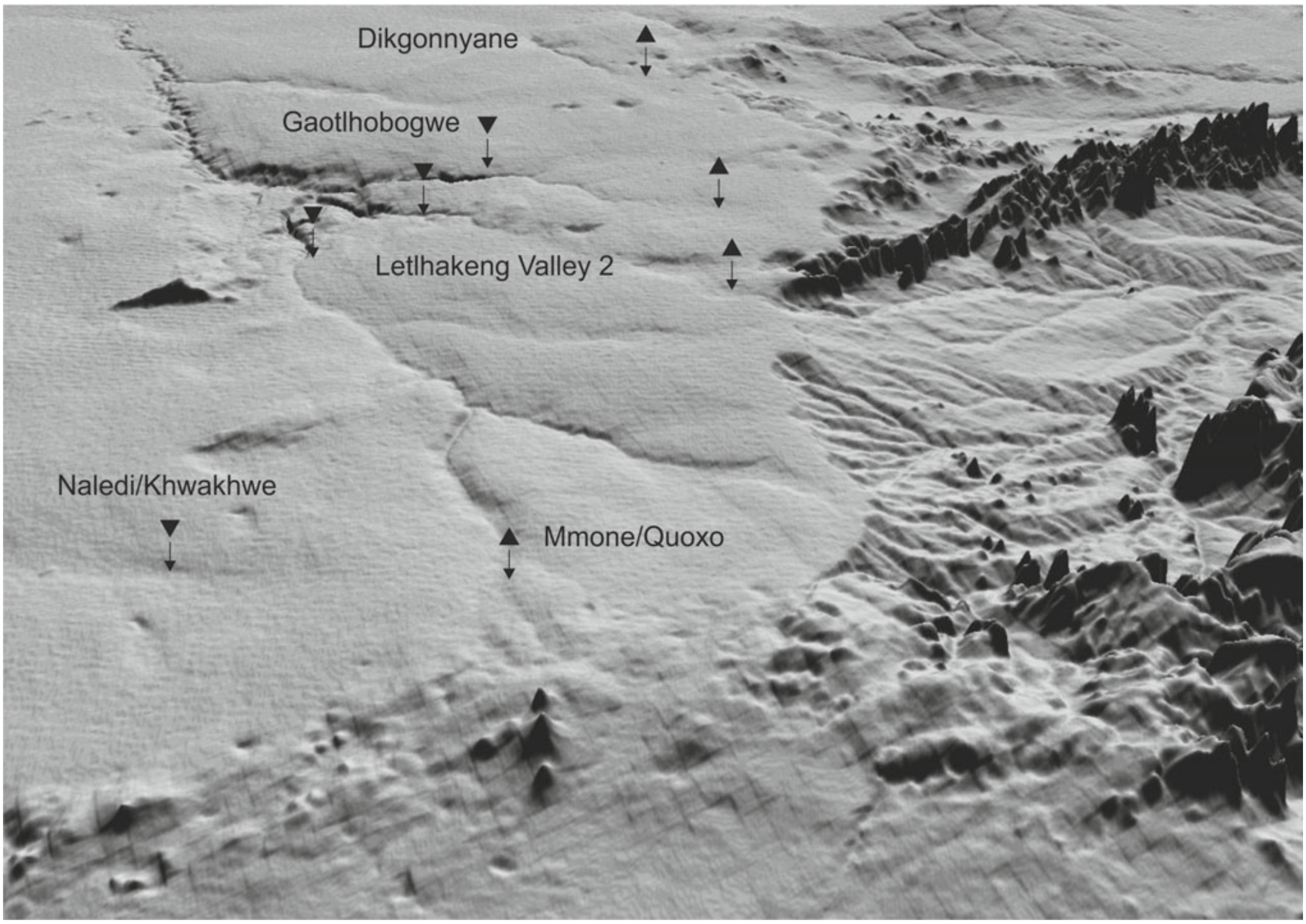

Fig. 11.9 Oblique SRTM-derived view of the headwaters of the Mmone/Quoxo system, showing areas of gradient reversal and major knickpoints (looking NNE; field of view approximately 70 km wide) (after Nash and Eckardt, 2016). Inverted black triangles indicate the position of the knickpoints in the Dikgonnyane, Gaotlhobogwe, Letlhakeng Valley 2, Mmone/Quoxo and Naledi/Khwakhwe systems shown in Figs. 11.1 and 11.7. Upright black triangles mark the approximate positions of the gradient reversals in the headwater sections of the Dikgonnyane, Gaotlhobogwe, Letlhakeng Valley 2, and Mmone/Quoxo systems. The smooth terrain on the left of the image is blanketed with Kalahari Group sediments, whilst the more dissected terrain to the right marks the western edge of the Limpopo catchment. The image demonstrates the indistinct nature of the drainage divides between Kalahari valley systems

valleys contained surface pools or shallow sub-surface water in 1879 is in marked contrast to the present day. Caution is needed, however, as it is possible that the sites described were adjacent to the Okavango Delta where relatively shallow groundwater occurs today beneath the floors of dry valleys where they join the Delta floodplain (Nash and Endfield 2002; Nash et al. 2006).

Wetter conditions in the Ncamaseri during the late nineteenth century may be corroborated in oral histories reported by Robbins et al. (1994). Samuchau, a Mumbukushu elder living at Tsodilo Hills, 7 km south of the Ncamaseri, described what he had been told by his grandparents sometime around 1930:

> Long ago during heavy rains, the Xeidum flowed from the west. When the big floods built up in the Okavango, water backed up in the Ncamaseri creating a continuous stretch from the Okavango to a place west of Tsodilo”. Samuchau’s ancestors could “…paddle or pole their mekoro [dugout canoes] from the Okavango up the Ncamaseri until it became the Xeidum where they hunted and fished (Robbins et al.1994, p.262).

Other nineteenth-century accounts provide more general descriptions of endorheic dry valleys, including both primary and second-hand references to the presence of water. The earliest of these is by the trader Joseph McCabe (as an appendix to Holden 1855), who crossed what is likely from his route description to be the Okwa and Hanehai valleys in July 1852 whilst travelling from Kang to LakeNgami. In his journal McCabe described crossing the Okwa:

> On the 8th July I reached a large and rather deep valley, called... Mugube Magoolo. This was the first appearance of a valley we had met since we left Sentuhe's [in Kolobeng]. This valley stretches from N.W. to N.E. and in many seasons holds water. On the south side it is lined with heavy sand hills (Holden 1855, p.419).

Fig. 11.10 Spring-fed waters ponded within an area of massively bedded calcrete at the head of the Gcwihabe valley, east of Xai-Xai, northwest Botswana (photograph: David Nash)

References to the Hanehai include that of Charles Andersson who travelled along the ``sandy and dry water course' of the ``Otjiombinde' on 15 May 1853 noting:

> The soil consisted of fine, white sand, reflecting a light dazzling and painful to the eyes... the grass was still green and plentiful, and the vegetation, in general, was rank. We passed several vleys containing small quantities of muddy water, alive with loathsome reptiles (Andersson 1856, p. 379).

Thomas Baines also followed the course of the Hanehai, noting that:

> ... it's breadth was from 100 to 150 yards, with low banks and ridges of sandstone here and there; and the grass in it was as dry, white and feathery as if water had never flowed there, and never could (Baines 1864, p.119).

Along with McCabe, Arnold Hodson was one of the few trans-Kalahari travellers who recorded detailed landscape information. Whilst crossing the Mmone/Quoxo valley near to the present-day village of Khudumalapye in January 1905 he noted:

> The last place of interest we passed was a dry river bed... whence we could obtain beautiful water at any point by digging. My own theory is that this place, like many similar dry river beds in the Kalahari has an underground river, otherwise it would be difficult to account for the presence of water so close to the surface (Hodson 1912, pp.79-80).

Other information about endorheic valleys is less detailed, with, for example, Hodson crossing the Okwa to the south of Kalkfontein in late May or early June 1905 describing it as ``a river only in name as it was quite dry' (Hodson 1912, p.96). The Groot Laagte in northwest Botswana is mentioned by Passarge (1899, p. 312) who crossed the valley at a point where it was 3 km wide and contained a channel over 400 m wide, leading him to suggest that it must have once carried a body of water comparable to that of the Okavango River.

The only other endorheic dry valley mentioned explicitly in historical sources is the Serorome. The village of Boatlaname within the valley was a staging point on the Missionary Road from Kuruman (South Africa) northwards through eastern Botswana and is mentioned on a number of occasions by David Livingstone (1857) and Leyland (1866). Livingstone described Boatlaname as:

> ... a lovely spot in the otherwise dry region. The wells from which we had to lift out the water for our cattle are deep, but they were well filled (Livingstone, 1857*, p.54).*

However, he also noted (p. 54) that wells in the village of Lephephe provided:

> another proof of the desiccation of the country. The first time I passed it, Lopepe was a large pool with a stream flowing out of it to the south; now it was with difficulty we could get our cattle watered,

an observation that Leyland echoed when visiting Boatlaname on 16th April 1851, finding:

> several wells sixteen to seventeen feet deep, but not sufficient water for half the oxen (Leyland 1866*, p.140).*

William Finnaughty Tabler (1916), Chapman (1886) and Anderson (1887) also crossed the Serorome, with the latter noting water within calcrete pits at Boatlaname (Anderson 1887, p. 206).

11.4.2 Contemporary and Historical Hydrology – Exoreic Valleys

Surface flow is much more common in the externally draining Auob-Nossop and Molopo-Kuruman systems. The Auob and Nossop both rise in the highlands of central Namibia and have a flashy regime. Flow in the Nossop regularly reaches as far as Aranos, upstream of the Kgalagadi Transfrontier Park (Leistner 1967), and Gochas for the Auob (Range 1912), but may extend further following heavy rainfall. The main Kuruman and Molopo valleys both rise at spring sites, with surface flows and occasional floods triggered by the effects of either heavier precipitation over higher elevation areas or groundwater discharge (Nash et al. 1994b; Nash 1996). The Kuruman (Fig. 11.11) has the most regular flow of all Southern Kalahari networks and is effectively a permanent river over the first 10 km of its course due to the 750 m^3 of water per hour supplied by its main spring, the ``Eye' at Kuruman; it is also more responsive to precipitation than other rivers in the network (Shaw et al. 1992). The Molopo only rarely contains water as far west as Bray on the Botswana border (Grove 1969) with the furthest recorded historical flow being at Watersend Farm (Shaw et al. 1992). Present-day flow conditions in all four systems have been greatly influenced by groundwater extraction. The waters of the Kuruman, for example, are used for irrigation and public supply, with the “Eye” and other springs being exploited since at least the 1820s (Livingstone, 1857 p. 8).

Floodwater has not reached the Orange-Molopo confluence during the historical period (Nash 1996; Nash and Endfield 2002). However, large-scale flood events are known to have occurred in all major Southern Kalahari systems. The Kuruman, for example, experienced extensive flooding in 1817–18, 1819–20, 1891–92, 1894, 1896, 1915, 1917–18, 1920, 1933–34, 1974–77, 1988–89 and 2021 (when floodwater reached to within a few kilometres of its confluence with the Molopo). Floods occurred in the Molopo in 1871, 1891–92, 1896, 1915, 1917, 1933–34, 1988, 1999–2000, 2014 and, most recently, 2017 in the aftermath of tropical cyclone Dineo (Clement 1967; Verhagen 1983; Thomas and Shaw 1991; Nash 1996; Nash and Endfield 2002). Records for the Auob and Nossop are more scarce, but the former is known to have flooded in 1933–34, 1973–74 and 2012 and the latter in 1806, 1933–34, 1963–64, 1987 and 2012 (Clement 1967; Verhagen 1983; Thomas and Shaw 1991; Nash 1996).

With a few notable exceptions, most historical floods appear to have had only limited long-term effects upon valley geomorphology. For example, the Molopo broke its banks in the section of its valley below the Kuruman-Molopo confluence in 1894 because of flooding in the Kuruman. Floodwaters were unable to follow the main course of the Molopo as it was partially blocked by sediment, and instead formed a large lake at Abiquasputs (Range 1912) (Fig. 11.1). Nash and Endfield (2002) detail a letter suggesting that flooding may have extended south of this lake, possibly as far as the confluence with the Orange River, although corroboration is required to confirm this. The lake was refilled in 1934 as a result of widespread flooding that affected all four Southern Kalahari drainage systems, and is reported to have had a surface area of over 12,000 ha (Barrow 1974). On this occasion, floodwater extended as far as Noenieput, approximately 27 km south of Abiquasputs, whilst in 1976 flooding reached Springbok Vlei, 15 km north of Abiquasputs.

Other evidence for the historical hydrology of the exoreic dry valleys comes from the writings of early missionaries and explorers. Although hunters and traders are known to have penetrated the southern Kalahari by the end of the eighteenth century (Campbell and Child 1971), descriptions of the Molopo and Kuruman only date from the early nineteenth century (Nash 1996; Nash and Endfield 2002). The first recorded accounts of the valleys are given by William Burchell who visited one of the minor sources of the Kuruman on 28 June 1812 noting that:

> the spring was in its lowest state, as its waters were too weak to run more than two hundred yards from the spot where they rose out of the ground (Burchell 1824, Vol. 2, p.209).

However, he also described crossing the main river on 29 June 1812 at an unknown point downstream where it was:

> a beautiful little river running in a plentiful stream of the clearest water. At this point of its course it was fifteen feet broad and abounded in tall reeds (urchell 1824, Vol. 2, p.214).

Burchell also provided accounts of other valleys within the Kuruman system. For example, he noted that the Matlhwaring was:

> merely a ditch about twenty feet broad, without a tree, or even reeds, to mark its course... There was an abundance of water in the deeper hollows of its bed; and at two or three hundred yards below our station, it ran in a plentiful stream (Burchell 1824, Vol. 2, p. 222)

and that the bed of the Moshaweng (at a point approximately 10 km down valley from Lobotsane) was:

> ...but a few yards wide, and of this the water occupied but a small part; yet as it flows constantly during the whole year, it is regarded... as a considerable stream (Burchell 1824, Vol. 2, p. 253).

Fig. 11.11 The Kuruman River in flood January/February 2021: **a–b** at Thota Lodge, 60 km northwest of Hotazel (photograph [a] courtesy of Marelise Theart and [b] Melissa Delport, Thota Lodge); **c** 30 km from Van Zylsrus (photograph courtesy of Nicholas Pattinson, University of Cape Town). See Fig. 11.1 for locations of images

The Rev. John Campbell described crossing the Molopo river in its headwater section on 2 May 1820, at the start of the dry season, noting that it:

> ... was about ten yards wide and in some parts two feet deep; the bottom was stony, but the water clear and well tasted. No trees grew on either side nearer than 500 yards but reeds were in great abundance (Campbell 1822, Vol. 1, p.208).

On the return leg of his journey, Campbell crossed the Kuruman on 21 June 1820, describing it as ``a considerable stream'. Later the same day, having passed the confluence of the Kuruman and Matlhwaring at approximately 55 km down-valley from Kuruman, he noted:

> At three p.m. came to the bed of the Krooman River, which was dry, the stream having sunk into the sand nearly opposite Letakka (Campbell 1822, Vol. 2, p.87).

This suggests that water extended beyond the Kuruman-Matlhwaring confluence in this year, some 45 km further than usual.

The LMS missionary Robert Moffat crossed the Molopo at a point approximately three days journey west of Pitsane on 22 July 1824 and described it at as being ``as dry as the neighbouring plains' (Schapera 1951, p.127). In a separate account of the same journey, Moffat noted finding water in the river bed approximately 20 km west of Pitsane (Moffat 1842, p. 387). Andrew Bain crossed the Molopo on 12

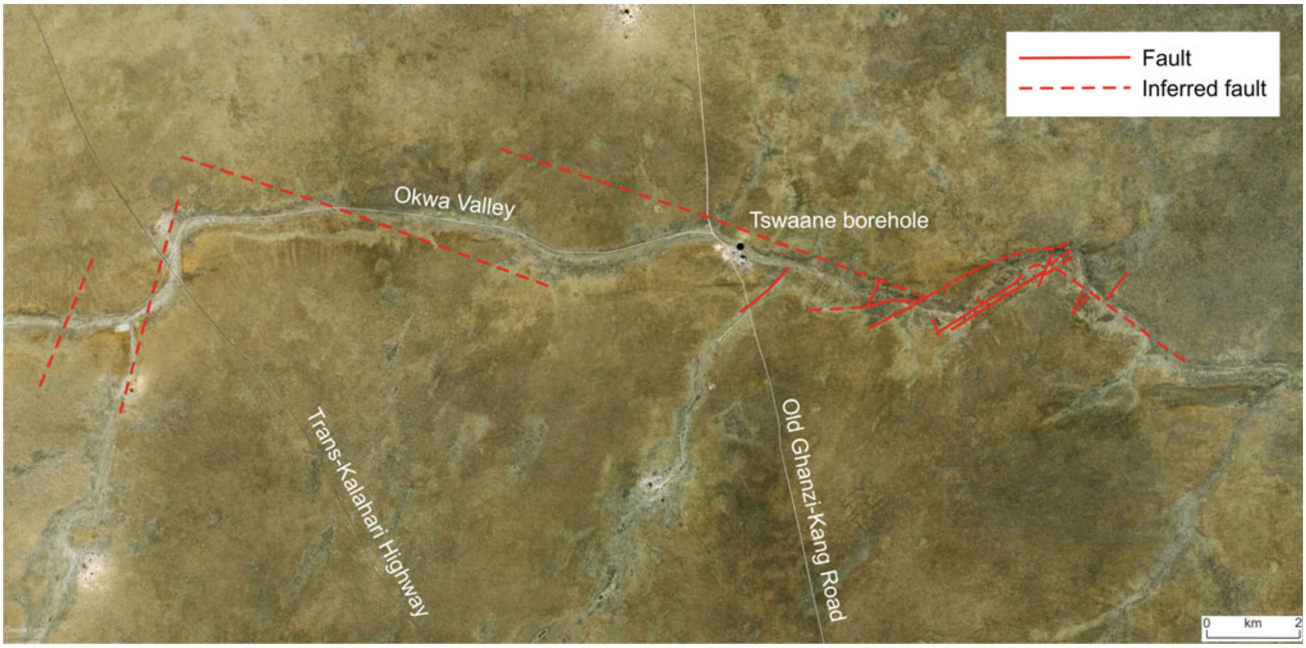

Fig. 11.12 Fault-controlled section of the Okwa Valley close to Tswaane borehole. Approximate positions of faults shown as red lines, dashed when inferred. Fault patterns redrawn after Aldiss and Carney (1992) and Ramokate et al. (2000)

August 1826 (Lister 1949) approximately 20 km east of Bray, describing it as having the appearance of a vlei and being dry except for a few muddy pools. He noted, however, that further upstream the Molopo was described by local inhabitants as being a ``fine running stream' with herds of hippo. Bain also crossed three valleys of the Moselebe system, describing deep wells in the main Moselebe at Lorolwane village, two small lakes in the Sekhutlane and springs within the Selokolela.

A number of travellers provide information about the Molopo and Kuruman between 1835 and 1836. Amongst these are Andrew Smith, who crossed the Molopo river near Pitsane twice, once at the start of the dry season and again prior to the onset of seasonal rains. Following the first crossing on 18 May 1835, Smith noted that there were three or four permanent springs near the fording point and further that:

> for several years the strength of these springs have undergone little change though, previously, they were much stronger, when the stream was also larger and flowed to a greater distance westward than it does at present (Lye 1975, p.212).

When Smith crossed the Molopo again on 7 October 1835, he recorded ``no difference in the quantity of water since we passed' (Kirby 1940, p. 257), which suggests constant spring outflow in the headwater regions. Smith also described travelling along the Kuruman in 1835 noting that ``both water and grass were scanty… and, where water occurred, it was found in holes dug… in the bed of the river' (Lye 1975, p.178). He also noted reaching a ``fine spring' in the form of a 6 m deep well in the river bed at the junction of the Kuruman and Matlhwaring. This spring was considered by Smith to be of importance to local inhabitants ``since the drying up of the two streams' (Lye 1975, p. 178). Given Campbell's earlier description of water sinking into the river bed well beyond the Kuruman-Matlhwaring confluence, it can be assumed that the extent of water within the channel had diminished between 1820 and 1835.

Captain Sir William Cornwallis Harris crossed the Molopo near its headwaters sometime after 14 October 1836, noting that:

> ...this river... exhibits a broad shallow bed, covered with turf, traversed by a deep stream about ten yards wide, completely overgrown with high reeds (Cornwallis-Harris 1852, p.66).

Gordon-Cumming also crossed the Molopo some 7 years later in 1843 recording that the:

> darling little river is here completely concealed by lofty reeds and long grass which clothe its margins to a distance of at least a hundred yards (Gordon-Cumming 1909).

In comparison with the Molopo and Kuruman, the Auob rarely features in historical documents despite being one of the major travel routes between Upington and Windhoek in the late nineteenth and early twentieth centuries (du Toit 1926; Weinberg 1975). Sir James Alexander (1838, pp. 159–160) described stopping to shoot elephant in the Nossop River in 1837, noting that the river bed contained many holes dug by elephants to gain access to shallow groundwater. Charles Andersson (1856) documented permanent springs in the headwaters of the Nossop and suggested, based on common fish species, that it was once linked to the Orange. Thomas Baines (1864) and James Chapman (1886) both described crossing the Olifants and Nossop valleys, with Baines depicting the Olifants as being "three or four times as broad as a turnpike road" (Baines 1864, p. 64). William Leonard Hunt (known as Farini) travelled up the Nossop to at least as far as the confluence with the Auob in 1885, where he described a 30 m deep well in the valley floor (Farini 1886). Other references to the Nossop include that of Lieutenant Arnold Hodson in November 1904 who described the valley to the north of Union's End as:

> ...very broad and quite dry; in fact there were a number of trees growing in the middle of it. The Hottentots had dug a fairly deep pit here, but they had not succeeded in getting any water (Hodson 1912, pp. 58-59).

In contrast, Herbst (1908) noted from studies of wells in the floor of the Nossop and Molopo near their confluence that:

> their beds have... been raised considerably, for in those wells that have been sunk therein the white shingle, beautifully smooth and rounded by running water in time past, is found fifty feet below the present surface. Below this shingle... water is found (Herbst 1908, pp. 207-208).

11.4.3 Pleistocene and Holocene Fluvial Activity

Relatively little is known about the Quaternary history of the endorheic Kalahari dry valleys within Botswana. This is primarily because they contain limited sedimentary or geomorphological evidence for past fluvial activity—although conventional wisdom suggests they must have contained water at various times in the past (Shaw et al. 1992). A small number of studies provide evidence to suggest former standing or flowing water. Jack (1980), for example, reported undated shell beds and lignite deposits to a depth of 55 m against a faultline beneath the floor of the Xaudum, whilst Brook (1995) suggested that the upper Ncamaseri contained sufficient water during the late Holocene to allow the accumulation of peat deposits. Extensive delta features are also present at the distal ends of both the Okwa valley (Cooke and Verstappen 1984) and Groot Laagte (Thomas and Shaw 1991).

To date, only three studies have provided age estimates for late Quaternary fluvial activity in endorheic systems. The first two of these focussed on the evolution of landforms and sediments in the Gcwihabe Hills in northwest Botswana, through analyses of calcretes in the Gcwihabe valley and speleothems and flowstones within the adjacent Gcwihabe (Drotsky's) Cave. Cooke and Verhagen (1977) used radiocarbon dating of cave deposits to identify that vadose conditions occurred within Gcwihabe Cave from 45,000–37,000, 34,000–29,000 and 16,000–13,000 yr BP, with Holocene sinter formation at ~2000 and ~750 yr BP (all uncalibrated ages). Radiocarbon ages from calcretised sands and gravels within the Gcwihabe valley interpreted by Cooke (1984) as representing ephemeral river flow under sub-humid/semi-arid conditions—fall at 34,700 ± 2000 and 22,700 ± 500 yr BP, with four dates clustering between 11,000 ± 100 and 9800 ± 200 yr BP. Given that the major passages within Gcwihabe Cave have a mean elevation of 12–15 m above the valley floor, Cooke (1984) postulated that the water table would have been at a similar height during periods when vadose conditions existed in the cave. During two of these vadose phases (~30,000 and 16,000–13,000 yr BP), he suggested "the Kwihabe river must have flowed in a valley about 25 m above the present level" (Cooke 1984, p. 272).

The third study of Pleistocene fluvial activity in an endorheic dry valley (Shaw et al. 1992) dated shell material and calcified sediments from sites in the Xaudum, middle Okwa (close to where the Trans-Kalahari Highway crosses the valley) and distal Okwa (where the valley cuts through the Gidikwe palaeoshoreline before entering the southwest Makgadikgadi Depression). The sites in the Xaudum and middle Okwa were similar in context, comprising exposures through low (1.0–1.5 m) calcrete-cemented terraces occupying the valley floors. In both cases, the calcrete consisted of cemented silty alluvium, with the near-surface section of each terrace containing intact and comminuted shells of the freshwater snail *Lymnaea natalensis*. Shaw et al. (1992) inferred still, near-permanent water during the later stages of terrace sediment accumulation from the presence of this species. A sample of combined calcrete and shell material from the Xaudum terrace yielded an uncalibrated radiocarbon age of 14,570 ± 160 yr BP, with an equivalent sample from the middle Okwa terrace dated to 11,890 ± 60 yr BP. In the distal Okwa, two shell-bearing samples were taken for dating from a depth of 80 cm within the floor of the valley (radiocarbon age estimate 14,490 ± 150 yr BP) and at 70 cm depth on the eastern face of the nearby Gidikwe Ridge (14,070 ± 150 yr BP). Shells in these samples included the gastropod *Melanoides tuberculata* and the bivalve *Corbicula africana*, with isolated specimens of *Bulinus* and *Lymnaea* spp also identified. Calcified reed stems (casts of algal growth on former reeds) were also sampled within the floor of the Okwa where it cuts the Gidikwe Ridge—these were radiocarbon dated to 11,980 ± 130 yr BP. The combined dates from the Xaudum and Okwa all fall within the range 14,570–11,890 yr BP, and are interpreted by Shaw et al. (1992) as evidence for a prolonged episode of greater moisture availability in the period 16,000–13,000 ka followed by a lowering of water tables and calcrete formation at 12,000–11,000 ka.

Given the large number of flood events documented within exoreic Southern Kalahari systems during the historical period, equivalent floods or periods of more permanent flow are highly likely to have occurred in prehistory. Certainly, oral histories reported by Campbell (1822) and corroborated by Andrew Smith (see Lye 1975) suggest that the Kuruman was a stronger-flowing river during the mid- to late-eighteenth century. Wider sections of the Nossop within the Kgalagadi Transfrontier Park, for example, contain abandoned channels and meander bends (see Fig. 11.5) that appear to have been cut off by floodwaters to form now-dry 'oxbow lakes' (Nash et al. 1994b; Bullard and Nash 1998; Nash 2015).

A provisional framework for the late Quaternary fluvial history of the Molopo system has been put forward by Heine (1982) through analyses of sediments within valley floors in the southwest Kalahari. This has been criticised by Thomas and Shaw (1991) as it confuses terrace levels and, in part, interprets radiocarbon dates derived from the land snail *Xeroceratus* as humid indicators. However, those dates conducted on *Unio*, *Corbicula* and *Bulinus* shells—indicative of perennial or semi-perennial flow—suggest wetter conditions in the dated range 16,600–12,500 yr BP. Several episodes of Holocene flooding have been dated in the Kuruman. Shaw et al. (1992) identified two terrace levels along the Kuruman from the vicinity of Hotazel to its confluence with the Molopo. At Groot Drink, the uppermost terrace, at a height of ~8 m above the riverbed, is presumed to predate Middle Stone Age artefacts found upon it. *Ceratophallus*, *Lymnaea* and *Burnupia* shells found within the top 30 cm of the lower (~3 m) terrace were radiocarbon dated to 320 ± 150 yr BP. Two sites downstream of the confluence with the Moshaweng River provide good vertical exposures of these lower deposits, with at least six cycles of deposition represented. Charcoal from a layer at 1.4 m height within one exposure at Aansluit farm was radiocarbon dated to 1780 ± 60 yr BP, while ostrich eggshell fragments from heights of 3.4 m and 4.8 m within an equivalent sequence at nearby Bella Vista farm were dated to 2840 ± 110 yr BP and 540 ± 30 yr BP respectively.

11.5 Ages of Dry Valley Networks

Elements of many Kalahari dry valleys are of considerable antiquity (Thomas and Shaw 1991) and, in some cases, may pre-date the deposition of the Jurassic to Recent Kalahari Group sediments; sections of the Black Nossop may even pre-date the Permo-Carboniferous Dwyka glaciation (Nash et al. 1994b). However, constraining the precise ages of networks is not straightforward. Neither is it easy to contextualise valley formation in terms of past climate since, with the exception of records from the Zambezi Delta (e.g. Walford et al. 2005; Ponte et al. 2019) and the mouth of the Limpopo (e.g. Iliffe et al. 1991), regional palaeoenvironmental information extending back to the Neogene and Paleogene is limited.

It may be possible to estimate the relative ages of some valleys and their associated knickpoints (see Sect. 11.3) in relation to known episodes of tectonic flexuring within southern Africa—with the obvious caveat that the timing of key tectonic events is itself not precisely constrained. The headwaters of the Mmone/Quoxo, for example, must pre-date the uplift along the Kalahari-Zimbabwe axis (broadly coincident with the Kalahari-Limpopo drainage divide; Fig. 11.1) that led to the valley gradient reversals shown in Figs. 11.7 and 11.9. Geomorphological evidence suggests that there were two uplift episodes along the Kalahari-Zimbabwe axis; a minor Miocene phase and a more significant uplift in the Pliocene (du Toit 1933; Partridge and Maud 2000). These phases coincide with evidence for increased sedimentation in the Zambezi Delta from the Oligocene onwards (Walford et al. 2005) and off the mouth of the Limpopo from the Miocene (Iliffe et al. 1991), likely assisted by wetter conditions during the Late Oligocene and Late Miocene (Ponte et al. 2019). Pollen evidence from the Zambezi Delta, for example, suggests that rainfall over the Zambezi catchment may have reached 2000 mm per annum during the Late Oligocene (Ponte et al. 2019). Given the scale of the upper Mmone/Quoxo knickpoints, Nash and Eckardt (2016) suggested that valley incision was most likely to have been initiated during the Pliocene uplift phase (du Toit 1933; Haddon and McCarthy 2005), which coincides with evidence from the Zambezi Delta of wetter conditions during the Zanclean and Piacenzian (Ponte et al. 2019).

For the dry valley systems that terminate in the Makgadikgadi Depression, the history of knickpoint development (and hence valley evolution) can be interpreted in the context of known Quaternary hydrological changes that led to the rise and fall of various palaeolake phases within the basin (Nash and Eckardt 2016). The middle knickpoint on the Deception, for example, falls where the valley dog-legs through a former shoreline of Palaeolake Deception (McFarlane and Eckardt 2008), the highest elevation (~980–990 m asl) palaeolake identified in the Makgadikgadi region (Moore et al. 2012). The Passarge Valley terminates at, and therefore possibly predates, this shoreline. The initiation of the knickpoint on the lower Deception probably relates to a period of neotectonic tilting during the latest Pleistocene that also caused the southerly migration of the Boteti River to its present course (Cooke and Verstappen 1984). The absence of palaeolake-related knickpoints on valleys entering the eastern and southern Makgadikgadi may be because these systems cross more resistant basement lithologies and were therefore less sensitive to short term lake level changes.

The timing of knickpoint formation in dry valleys entering the Okavango half-graben in northwest Botswana is less clear. However, given the contemporary levels of tectonic activity associated with the half-graben (Gumbricht et al. 2001), and evidence that movement along the Gumare fault has truncated Pleistocene dune sequences to the west of the Okavango Delta (McFarlane and Eckardt 2007), tectonically driven base-level lowering and valley incision has probably been ongoing throughout the Quaternary (Nash and Eckardt 2016).

11.6 Theories About the Origins of Dry Valley Systems

Conventional wisdom suggests that the various dry valley networks were formed by fluvial erosion during periods of wetter climate and are therefore inherited landscape features. Certainly, the deltaic landforms, abandoned channels, fluvial terraces, and lignite, peat and freshwater shell deposits described in Sect. 11.3.2 indicate increased river flow in the past. The concave-upward long-profiles common to most dry valleys (Figs. 11.6, 11.7 and 11.8) and localised adjustments in valley gradient to lithological variations and base-level changes are also typical of drainage features formed by fluvial erosion elsewhere. Based on a simple comparison of long-profile shape, it is most probable that valley systems were the product of episodic fluvial erosion over protracted periods of time. However, even the most active valley systems today are not hydrologically connected along their full length, and it is likely that most have been in this disconnected state for hundreds if not thousands of years.

While fluvial erosion has clearly played a major role in shaping Kalahari dry valley systems, it cannot alone explain the morphology of some systems in their middle ‘gorge-like’ sections (Thomas and Shaw 1991). The low bifurcation ratios of tributaries, increases in valley width over relatively short distances, and lack of channels in many valley floors are not typical of conventional river systems. Instead, various authors have suggested that processes such as deep weathering along fracture zones and groundwater seepage erosion may have played a role in valley formation and evolution. Sections of many valleys systems—including the Okwa (Nash 1995), Deception (Coates et al. 1979), Xaudum (Wright 1978), and various tributaries to the Mmone/Quoxo (Mallick et al. 1981; Nash 1995)—are aligned with faults and other geological lineaments (Fig. 11.12). The relationship reaches an extreme in the Serorome, which is oriented west and north before being diverted eastwards by the Zoetfontein Fault to join the Limpopo system (Thomas and Shaw 1991). There has also been a long association between Kalahari dry valleys and groundwater availability (Chapman 1886) with, as noted in Sect. 11.4.1, *mekgacha* acting as important foci for groundwater recharge (Farr et al. 1981; de Vries et al. 2000). Nash (1995) has suggested that deep weathering (as groundwater moves vertically and laterally along subsurface faults and fracture zones) may have permitted rock weakening, preferential erosion and surface lowering to form linear depressions. The significance of this process for valley development is that surface lowering can occur in the absence of surface fluvial activity and does not necessarily require seasonal recharge. It is likely that surface lowering would proceed more rapidly if there was an alternation between periods of dominant deep weathering and dominant fluvial activity. However, as Nash (2011) argues, there still remains the unresolved ‘chicken and egg’ question of what came first, the valley or the deep weathering.

Arguments that groundwater sapping or seepage erosion played a significant role within Kalahari valley development put forward by Shaw and de Vries (1988), Nash et al. (1994b) and Nash (1995) seem less likely in light of the new evidence provided by SRTM data (see Sect. 11.3.2). The valley long-profiles shown in Figs. 11.6, 11.7 and 11.8 differ from the flat or stepped longitudinal forms typical of systems generated by groundwater sapping (see Higgins 1984; Howard et al. 1988; Nash 2011); indeed, only four valley networks (the Auob, Passarge, Mosope and Letlhakane) exhibit predominantly flat/linear longitudinal profiles. Instead, it now appears most likely that the pronounced steps in the long profiles of valley systems such as the Mmone/Quoxo and its headwater tributaries are relict knickpoints resulting from the response of the fluvial system to regional uplift.

In addition to their scientific interest, the origins of the dry valleys of the Kalahari also feature in traditional knowledge. The G/wi San of central Botswana, for example, have a belief that the Okwa Valley was formed by a supernatural shape-shifting being named G//awama (Silberbauer 1981; Main 1987). Oral traditions suggest that, while hunting one day to the west of the Kalahari near Gobabis (in eastern Namibia), G//awama was bitten on the leg by a python. The bite was a bad one, and G//awama soon became feverish and very thirsty, so he headed east towards the Boteti River in search of water. As he walked, he dragged his injured leg and his trailing foot gouged out the course of the Okwa Valley. Wild animals harassed him *en route*, taking advantage of his weakness; this caused his course to waver, creating the meanders present in central sections of the valley. The fever induced by the python bite made him nauseous and he vomited frequently, with the dried vomit forming the calcrete- and diatomite-floored tributary valleys to the Okwa. As G//awama neared the waters of the Boteti he found new strength and increased his walking speed, thus dragging his leg less heavily. He was eventually able to walk almost upright, dragging his leg only slightly. To the G/wi San, this explains why the course of the Okwa almost disappears as it nears the Makgadikgadi Depression and the Boteti River. Geomorphological explanations would instead attribute the disappearance of the Okwa to a lack of hydrological connectivity with its headwaters in Namibia since the late Pleistocene and a resultant progressive infilling by aeolian sediments over time in its distal sections.

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David J. Nash is Professor of Physical Geography at the University of Brighton and Honorary Research Fellow at the University of the Witwatersrand (South Africa). He has worked on the geomorphology of Botswana since 1989, when he arrived in Gaborone for the first field season of his PhD research on the fossil valleys of the Kalahari. In the intervening years he has published over 100 articles on silcrete, calcrete and Holocene-to-recent environmental change, mostly with reference to southern Africa. His present research focusses on the use of geochemical data to determine the provenance of silcrete stone tools at archaeological sites in the Kalahari.