

# Drainage development, neotectonics and base-level change in the Kalahari Desert, southern Africa

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## **Abstract**

The Kalahari Desert contains extensive networks of ephemeral and fossil drainage that are potential indicators of past and present neotectonic activity and climate-driven environmental change. An absence of topographic data has hindered our understanding of their development. We present long-profile information for twenty-nine valley networks derived from Shuttle Radar Topographic Mission (SRTM) digital elevation data. 8,354 km of valley talweg was measured for x, y and z information. Most valleys exhibit concave-up profiles. Fifty-five previously unknown knickpoints were identified. The majority coincide with lithological boundaries or fractures, but many developed in response to Neogene uplift and/or downwarping or occur where valleys cross palaeolake shorelines. The headwaters of four valleys cross the Kalahari-Limpopo drainage divide and predate the presumed Miocene uplift of the Kalahari-Zimbabwe axis, suggesting that they are of considerable antiquity.

## **Keywords**

Long-profile, drainage development, SRTM, neotectonics, Kalahari Desert

## **Introduction**

Analyses of the long term development of African drainage networks can provide valuable information about the connection between processes operating at the Earth's surface and its internal dynamics (Lithgow-Bertelloni and Silver, 1998; Moore *et al.*, 2009; Roberts and White, 2010). However, the lack of high resolution topographic information for much of the continent has, until recently, hindered attempts at detailed reconstruction. Identifying the location of African palaeodrainages has been assisted greatly by developments in the availability of remotely-sensed radar data (e.g. Griffin, 2006; Drake *et al.*, 2008), with three-dimensional reconstructions possible since the release of Shuttle Radar Topographic Mission (SRTM) digital elevation data for Africa in 2003. SRTM data have been used previously to examine the morphology of earth surface features ranging from aeolian dunes (Blumberg, 2006) to watersheds (e.g. Hancock *et al.*, 2006; Zhang *et al.*, 2006; Ba *et al.*, 2013; Gopinath *et al.*, 2014). However, with notable exceptions (e.g. Hayakawa *et al.*, 2010; Moore *et al.*, 2012; Telbisz *et al.*, 2014), such data are rarely applied to the investigation of drainage evolution.

In this paper, we utilise Shuttle Radar Topographic Mission (SRTM) data to construct, for the first time, the long-profiles of the major ephemeral and fossil drainage networks in the arid to semi-arid Kalahari Basin (Figure 1). The nature of these long-profiles is verified against available topographic survey data for selected drainage systems. Through such profiles, we examine the response of drainage systems at a sub-continental scale to Palaeogene-Quaternary neotectonic activity and base-level changes.

## **Kalahari drainage systems**

The Kalahari (Figure 1) is a large sedimentary basin that occupies much of central southern Africa. It formed following Late Cretaceous downwarping, and was filled subsequently by the terrestrial Kalahari Group sediments (Baillieu, 1975; Haddon and

McCarthy, 2005). The basin has experienced faulting and flexuring throughout the Cenozoic (du Toit, 1933; Thomas and Shaw, 1991; 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 periods during the Quaternary (Thomas and Shaw, 2002; Burrough and Thomas, 2008; Burrough et al., 2009a,b; but see Moore et al., 2012 for further discussion). This combination of climate change and neotectonics has produced the complex drainage networks and associated long-profiles that exist today.

Perennial rivers are absent from much of the Kalahari Basin, with the Orange, Okavango, Chobe and Zambezi systems providing the only permanent drainage. Drainage pattern analyses suggest that the development of these systems was influenced by Cretaceous-Cenozoic uplift along flexure axes (e.g. Thomas and Shaw, 1988; Nugent, 1990; Moore, 1999; Moore and Larkin, 2001; Haddon and McCarthy, 2005). Perennial rivers are not considered further, although the neotectonic drivers of drainage pattern change are relevant to the development of the systems discussed here. Ephemeral rivers which flow periodically during the austral summer occur around the basin periphery (Shaw, 1989). Many of these systems rise to the east of the Kalahari-Limpopo drainage divide and are marginal to the Kalahari drainage. Networks such as the Moseitse and Mosope, however, drain westwards into Sua Pan and are discussed here.

The most extensive components of the Kalahari drainage are networks of dry valleys (or *mekgacha*; Nash, 1996). The majority of valleys rise on basement bedrock types and traverse, and commonly terminate within, areas covered by Kalahari Group sediments (Boocock and van Straten, 1962). Two groups of valleys can be identified. The first includes the externally-draining Auob-Nossop and Molopo-Kuruman systems. These once connected to the Orange River, although floodwater has not reached the Orange-Molopo

confluence during the historical period (Nash, 1996; Nash and Endfield, 2002). Most externally-draining (and some internally-draining) systems are spring-fed and contain seasonal flow in their headwater sections (Nash *et al.*, 1994). The second group of valleys includes internally-draining fossil systems such as the Okwa and Xaudum which formerly drained into the Makgadikgadi Depression and Okavango Delta respectively. Surface flow within these networks is rare; the majority have not flowed since around 14 ka BP (Shaw *et al.*, 1992) and today only contain water in seasonal pools. One further system, the Serorome, is considered here. The Serorome is unusual in that it is externally-draining and grades 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.

## **Methodology**

Drainage long-profiles were constructed for the twenty-nine valley segments identified in Figure 1. These include all of the internally-draining valley systems in addition to those that drain externally via the Orange and Limpopo. Long-profiles were constructed using global SRTM3 data at a resolution of 3 arc-seconds (horizontal resolution of approximately 90m) covering 12000 x 12000 pixels or approximately 1.2 million km<sup>2</sup>. Absolute vertical accuracy for southern African SRTM data is estimated at 3-5m (Rodriguez *et al.*, 2005). SRTM data were chosen over ASTER data because of the low performance rating of the latter (Gonga-Saholiariliva *et al.*, 2011). The indistinct nature of the drainage divides between individual valley systems within the Kalahari (Boocock and van Straten, 1962) precludes the automated analysis of slope-area relationships. Instead, long-profiles were produced using a manual extraction technique, with each valley or tributary traced from its highest (most distant) headwater to its end-point or confluence. Digital height numbers were generated from a sample path along the valley talweg in an optimised grey shade

depiction of the valley floor. The extraction path in the SRTM data was validated against Landsat ETM imagery geocoded to the same coordinate system. Imagery obtained from the Global Land Cover Facility were displayed in Channels 7,3,2 (R,G,B), with the occurrence of riparian woodland, rock outcrops and changes in stream path used to optimise the extraction of height information. The resulting data profiles were filtered using a five-point moving average so as to eliminate noise and accentuate stream gradient anomalies. The extraction technique also produced horizontal pixel location values which were used to generate detailed vector lines of the less well mapped Kalahari drainage. In total, 8,354 km of valley were measured for x, y and z information, which produced data for 89,831 measurement points. Knickpoints and gradient reversals were identified visually from the full resolution long-profile data set at points where major changes in the stream gradient index,  $k$ , occurred. Stream gradient index values were calculated from:  $k = (H_i - H_j) / (\ln L_j - \ln L_i)$  where  $H$  is altitude and  $L$  the horizontal distance between two points  $i$  and  $j$  (Hack, 1973).

### **Characteristics of valley long-profiles**

SRTM-derived long-profiles for the twenty-nine valley systems are shown in Figures 2-4. The majority of valleys exhibit concave-up long-profiles for at least part of their course, 'graded' to local or regional base-levels. Exceptions are the Auob, Passarge, Mosope and Letlhakane which have linear long-profiles. Most profiles lack the pronounced concavity typical of temperate graded rivers (Hack, 1973), with stream gradient indices lower than expected in headwaters and higher in distal sections. 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 contrast with the marked convexities exhibited by some hyperarid systems (e.g. in the Namib; Goudie, 2002). The profiles differ from the flat or stepped longitudinal forms typical of systems generated by

groundwater sapping (Howard *et al.*, 1988), implying that seepage erosion may have played a less significant role in Kalahari valley development than has been suggested previously (Nash *et al.*, 1994).

### **Knickpoints and gradient reversals within valley long-profiles**

Twenty-five of the twenty-nine valley systems contain distinct knickpoints, the exceptions being the Auob, Passarge, Mosope and an unnamed Okwa tributary. Fifty-five knickpoints were identified, most of which occur as km-scale transitional zones of gradient change in the long-profile. A detailed comparison of knickpoint positions with geological maps indicates that the majority correspond with lithological boundaries. For example, the middle knickpoint on the Molopo (Figure 2) occurs where the valley passes from Kalahari Group sediments onto an inlier of more resistant Karoo Dwyka Group diamictites, siltstones and sandstones. The upper knickpoint on the Nossop is immediately south of the boundary between Nama Schwarzrand subgroup and more resistant Kuibis subgroup lithologies. The middle Okwa and lower Hanehai inflections (Figure 3) 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 knickpoints on the Nunga and Boteti appear from Landsat imagery to relate to outcrops of more resistant duricrusts within the Kalahari Group sediments. In general, knickpoints are steeper when valleys cross from less to more resistant lithologies, due to the greater potential for headward erosion into softer materials.

Other knickpoints occur where valleys intersect exposed or shallow faults (or lineaments in areas of greater sediment cover). For example, most knickpoints on systems draining towards the eastern Makgadikgadi Depression (Figure 4) occur where these valleys cross known or inferred faults or fractures, possibly linked to neotectonic movements within the basin. The majority of faults and fractures in the Kalahari are unclassified. As such, it is not

possible to determine the impact of normal vs. reverse or active vs. inactive faulting upon valley gradients.

Larger knickpoints are associated with areas where there is known evidence of base-level lowering and/or uplift along flexural axes. Most pronounced is the distal knickpoint on the Molopo (Figure 5), where the valley floor drops from 750 to 460m asl over a distance of 45km. The knickpoint developed in response to headward migration of Augrabies Falls past the Molopo-Orange confluence, presumably following subcontinental uplift between 75 and 65 Ma (McMillan, 2003; Bluck *et al.*, 2007). The lower knickpoint on the Serorome (Figure 4) appears to have been generated in response to incision along the Limpopo. The lower inflection on the Nossop (Figure 2) falls at the confluence of the Black and White Nossop rivers, whilst the upper Serorome knickpoint, middle Epukiro inflection and lower knickpoints on the Lememba and Xaudum (Figure 4) 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, 2007). Knickpoints on the Boteti and Deception occur where these valleys cross palaeolake shorelines in the Makgadikgadi Depression and may be controlled by former lake levels.

The courses of four headwaters of the Mmone/Quoxo drainage system straddle the Kalahari-Limpopo drainage divide (Figure 3). These include the main Mmone/Quoxo, which rises at an altitude of c.1205m and 'flows' uphill for 19km before crossing the Kalahari-Limpopo divide at 1286m. Three tributaries to this system (Dikgonnyane, Gaotlhabogwe and Letlhakeng Valley 2) also exhibit reversed gradients in their headwaters and can be traced for 2-5km before crossing the drainage divide at 1173, 1233 and 1252m respectively. Analyses of aerial photographs of the headwater sections of



each of these valleys (e.g. Figure 7) indicate that the drainage line was once continuous across the Kalahari-Limpopo divide but is now marked by a chain of small pans. Each of the valleys contain major knickpoints, the most pronounced occurring at 80km from the source of the Mmone/Quoxo where the valley falls from 1150 to 1080m over 11km.

### **Timing of knickpoint development and valley gradient reversal**

Constraining the timing of tectonically-driven knickpoint development and valley gradient reversal is difficult, due to the lack of a precise chronological framework for the tectonic evolution of southern Africa. However, the headwaters of the Mmone/Quoxo must have been established prior to uplift along the Kalahari-Zimbabwe axis (Figure 1) that broadly coincides with the Kalahari-Limpopo drainage divide. Geomorphological evidence suggests that there were two uplift episodes along this axis; a minor Miocene phase and 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 early Oligocene onwards (Walford *et al.*, 2005) and off the mouth of the Limpopo from the Miocene (Ilfie *et al.*, 1991). Increased sediment yields in the Zambezi Basin have been attributed to epeirogenic uplift and drainage capture, although a climate change contribution cannot be excluded (Walford *et al.*, 2005). Given the scale of the upper Mmone/Quoxo knickpoints, valley incision is most likely to have been initiated during the Pliocene uplift phase (du Toit, 1933; Haddon and McCarthy, 2005).

The history of knickpoint development in systems that terminate in the Makgadikgadi Depression can be interpreted in the context of known Quaternary hydrological changes. The middle knickpoint on the Deception, for example, falls where the valley dog-legs through a shoreline of Palaeolake Deception (McFarlane and Eckardt, 2008), the highest elevation (c. 980-990m) palaeolake identified in the Makgadikgadi region (Moore *et al.*, 2012). The Passarge terminates at, and therefore possibly predates, this shoreline. The

upper knickpoint on the Boteti River occurs immediately west of the Gidikwe Ridge, a 940-945m elevation shoreline of palaeolake Makgadikgadi that may have been an active lake margin until as recently as 35 ka BP (Cooke, 1984). Topographic evidence suggests that the Boteti entered the palaeolake some 50km to the northeast when the Gidikwe Ridge was forming (Gumbricht *et al.*, 2001), with the river shifting to its present course following neotectonic tilting. The elevation of the upper Boteti knickpoint implies that it may be related to the draining of either a 924m palaeolake that occupied the Makgadikgadi Depression possibly from 32-27 ka BP (Shaw *et al.*, 1997) or a 920m lake that existed from 15-12 ka BP (Shaw *et al.*, 1992). The lower Boteti and distal Nunga knickpoints occur where the valleys enter collapse features in the Makgadikgadi Depression. The initiation of the lower Deception knickpoint probably relates to the same period of tilting which caused the migration of the Boteti (Cooke and Verstappen, 1984). The absence of palaeolake-related knickpoints on valleys entering the eastern and southern Makgadikgadi Depression may be because these systems cross resistant basement lithologies and were less sensitive to short term lake level changes.

The timing of knickpoint formation in valleys entering the Okavango half-graben 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.

## **Conclusion**

In summary, Kalahari valley systems have been highly sensitive to tectonic and/or eustatic base level changes during their evolution, particularly where movements along tectonic flexure zones have resulted in either regional uplift or downwarping. Some systems may

have been established as early as the Miocene, suggesting that the drainage networks as a whole are of considerable antiquity. Having established the locations of knickpoints across twenty-nine drainage systems, further work is now needed to confirm their origin and constrain their time of development.

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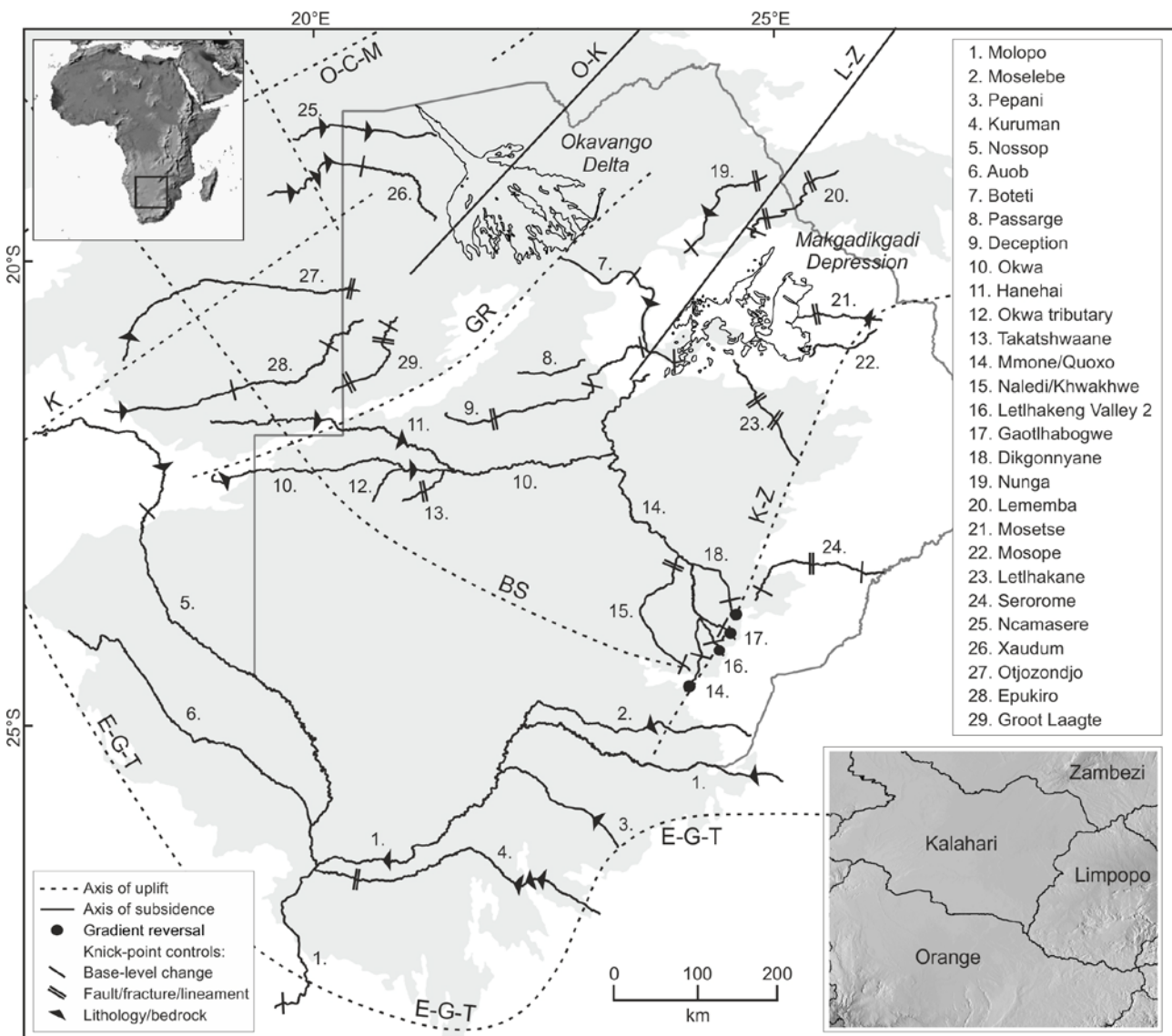
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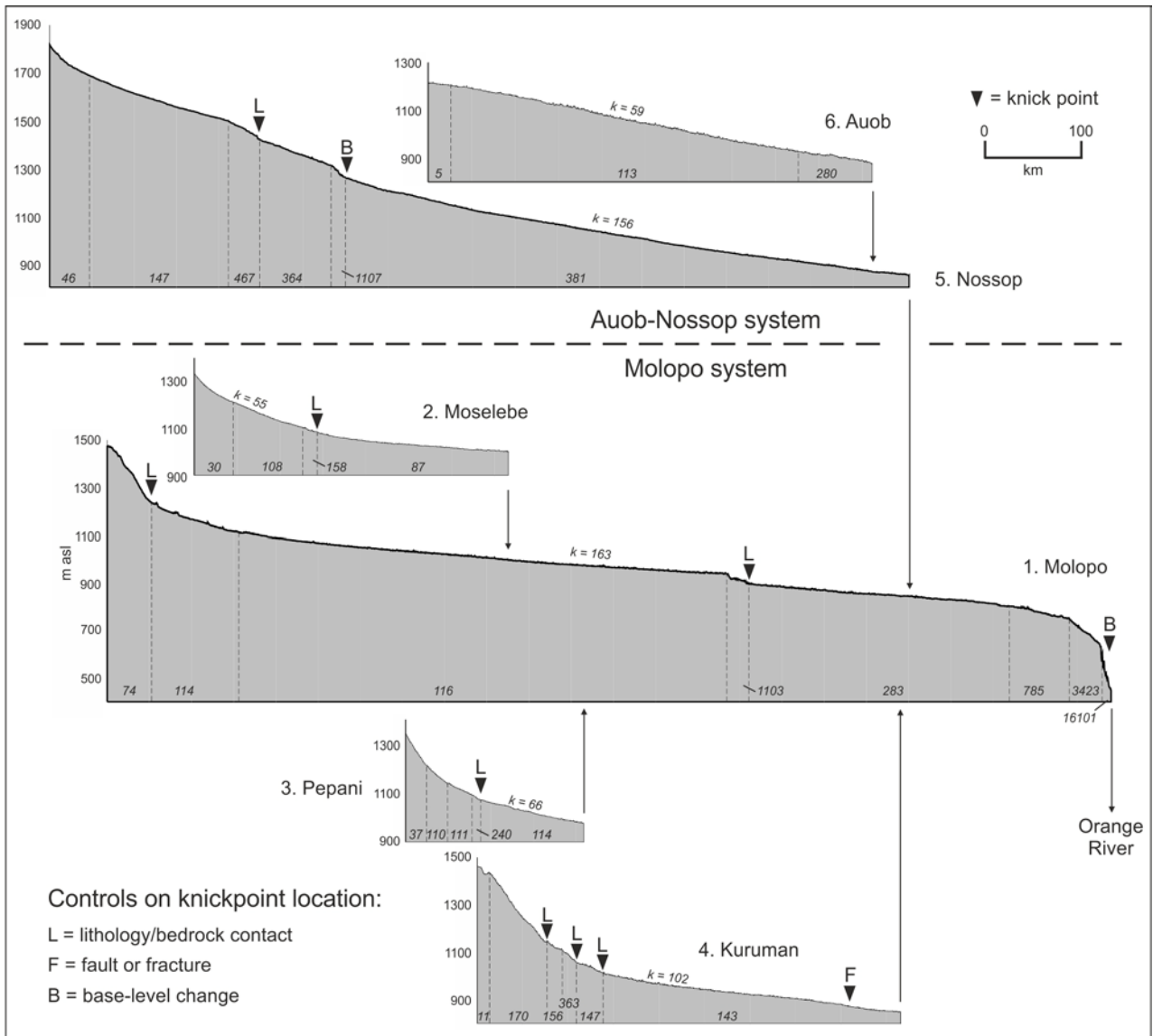


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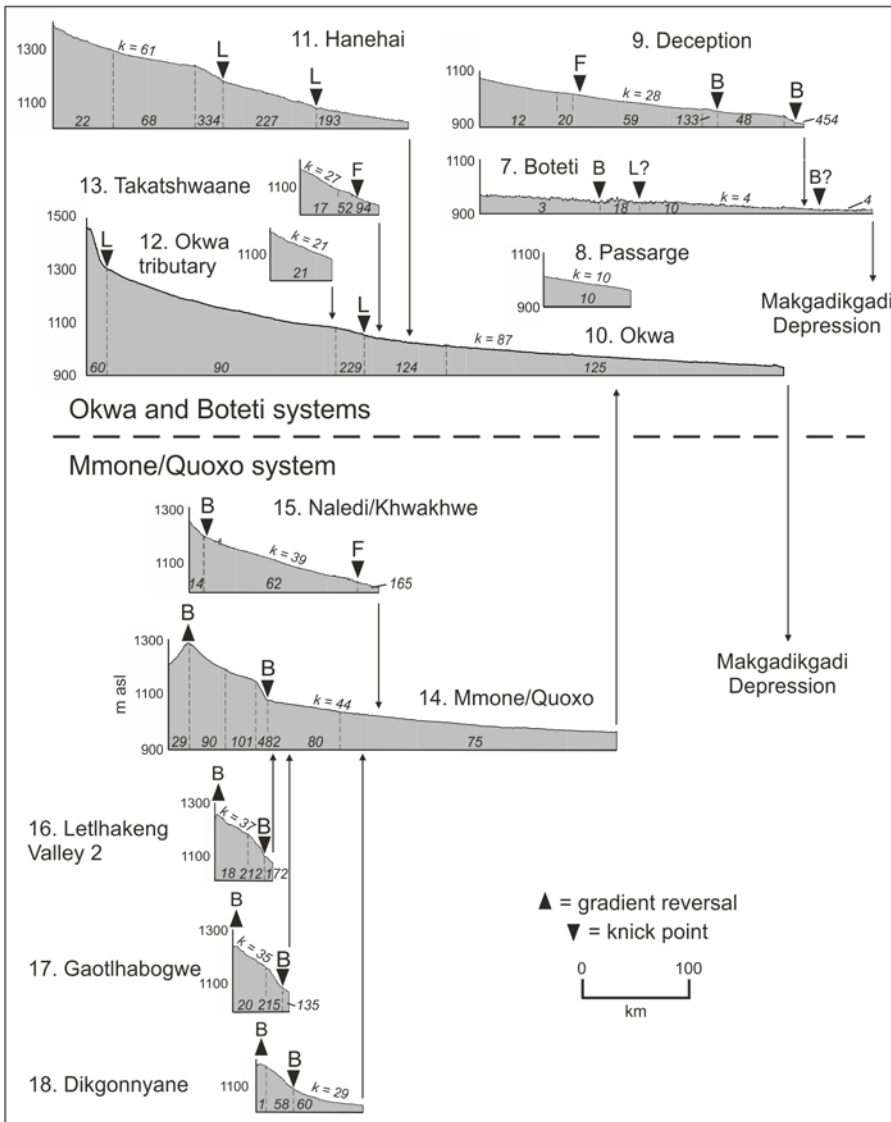
## Figures



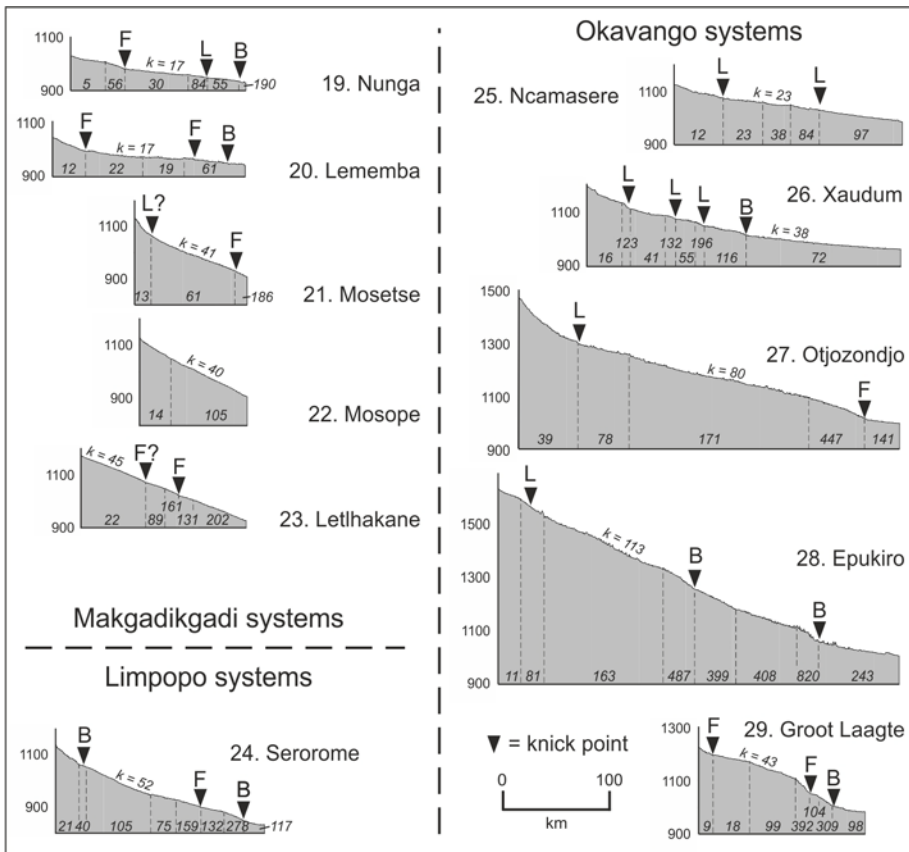
**Figure 1:** Sampled ephemeral and fossil drainage systems, with knickpoints and gradient reversals indicated. Knickpoints are distinguished according to their dominant control: base-level change; intersection with a fault, fracture or lineament; or differential rock resistance across a lithological boundary. The boundary of Botswana (pale grey), distribution of Kalahari Group sediments (shaded) and 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-Capriivi-Mweru axis; K, Khomas axis). The numbers shown against individual valley segments are used in subsequent figures. Inset maps (derived from SRTM30 digital terrain data at 1km resolution) indicate the location of the study area in southern Africa (top left) and the boundaries between the Okavango-Kalahari, Orange, Limpopo and Zambezi drainage basins (bottom right). The drainage basin map covers the same geographical area as the main figure.



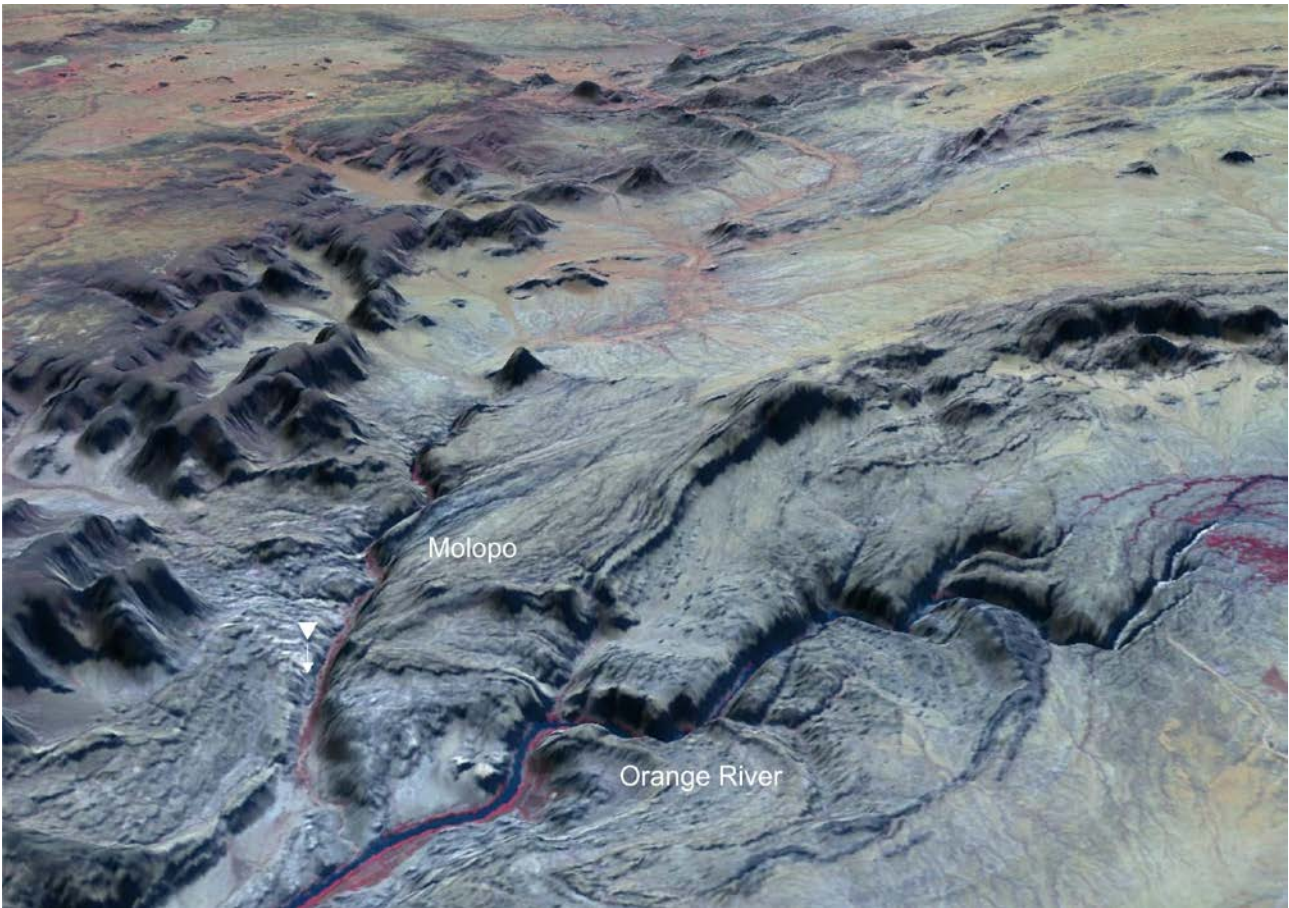
**Figure 2:** SRTM-derived long-profiles for the externally-draining Southern Kalahari drainage networks. Stream gradient index ( $k$ ) values are shown for comparative purposes for entire long-profiles and individual valley segments. Vertical arrows indicate confluence points between valley segments and the connection with the Orange River. Long-profiles are plotted at the same horizontal scale in Figures 2-4, with 250-times vertical exaggeration. See Figure 1 for locations of valley segments.



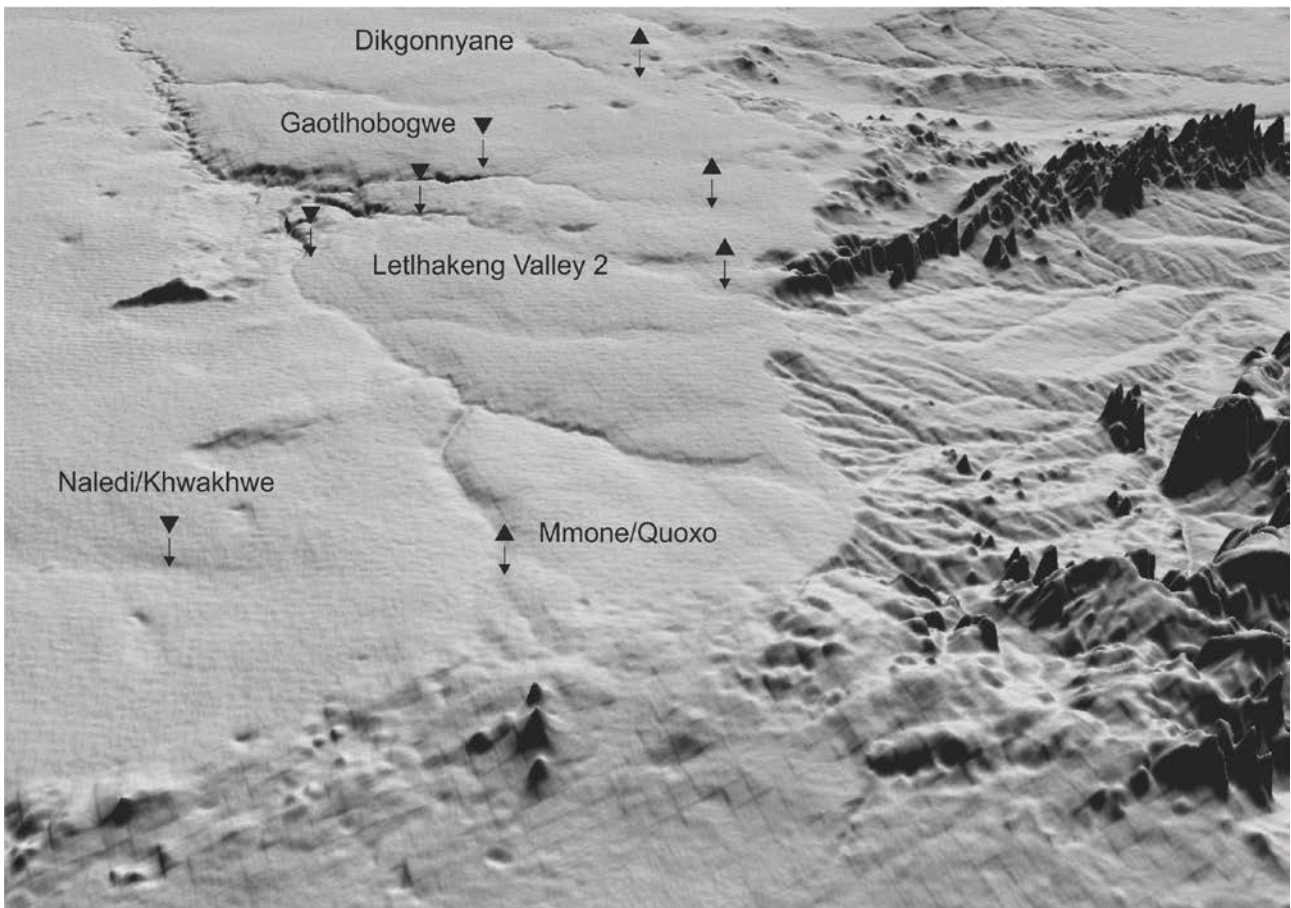
**Figure 3:** SRTM-derived long-profiles for the internally-draining Okwa, Boteti and Mmone/Quoxo drainage networks. See Figure 2 for further details.



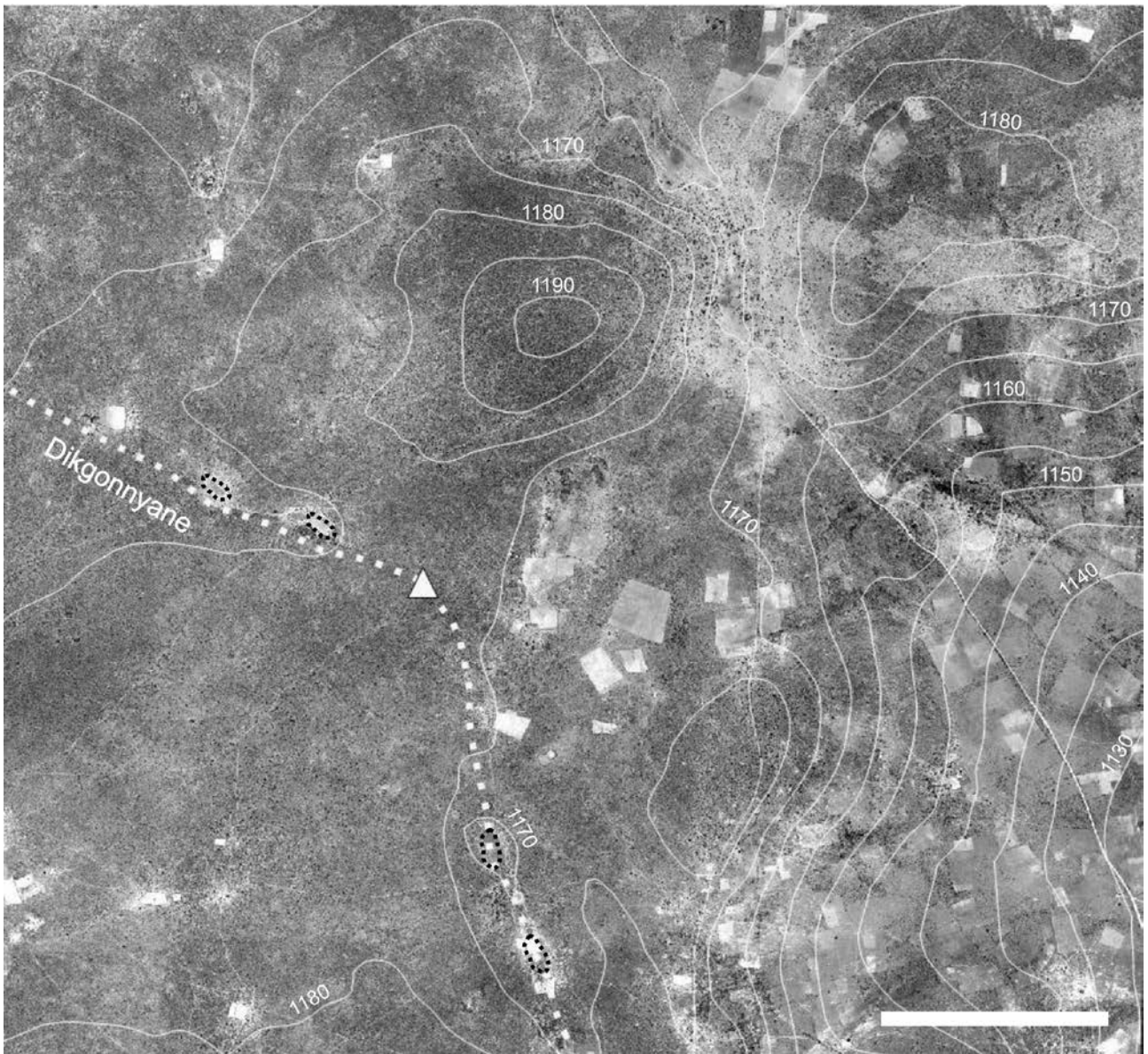
**Figure 4:** SRTM-derived long-profiles for the externally-draining Limpopo and internally-draining Okavango and Makgadikgadi drainage networks. See Figure 2 for further details.



**Figure 5:** Oblique SRTM-derived view of the knickpoint at the Molopo/Orange junction (looking N; field of view approximately 150 km) with Landsat ETM drape. Inverted white triangle indicates the approximate position of the southernmost knickpoint on the Molopo valley (see Figure 1).



**Figure 6:** 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). 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. Inverted black triangles indicate the position of the knickpoints in the Dikgonnyane, Gaotlhobogwe, Letlhakeng Valley 2, Mmone/Quoxo and Naledi/Khwakhwe systems shown in Figure 1. 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. An aerial photograph of the gradient reversal in the headwaters of the Dikgonnyane valley is shown in Figure 7.



**Figure 7:** Aerial photograph of the headwater section of the Dikgonnyane valley showing the valley talweg (white dotted line) and the approximate location of the gradient reversal (white triangle) indicated on Figures 1 and 6. Isolated pans within the valley floor are outlined with a black dotted line to distinguish them from arable fields. Topographic contours (at 5m intervals) are also shown. Scale bar 2km. Orthophoto and contour data courtesy of the Department of Surveys and Mapping, Government of Botswana.