

Sand ramps as palaeoenvironmental archives: Integrating general principles and regional contexts through reanalysis of the Klipkraal Sands, South Africa

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ABSTRACT

Sand ramps occur on a continuum of topographically-controlled landforms ranging from purely aeolian features (climbing/falling dunes) to talus cones and alluvial fans. Sand ramps have been identified as potentially important palaeoenvironmental archive in dryland regions that possess relatively few Quaternary proxy records. Their utility however requires not only good age control of depositional phases but clear identification of process regimes, determined through morphological and sedimentological analyses, with several recent studies indicating the complexities of palaeoenvironmental interpretations and the controls of ramp development (Bateman et al., 2012; Rowell et al., 2018).

Klipkraal Sands is a sand ramp on the north-eastern margin of the semi-arid Karoo that has been important for inferences of the extent of southern African Late Quaternary aeolian activity (Thomas et al. (2002). We reanalyse this feature, in the light of both its significance and other recent studies that have inferred extensive southern African LGM aeolian activity (Telfer et al., 2012, 2014). New sedimentological data and twelve OSL dates indicate the Klipkraal Sands formed episodically between ~100-0.14 ka, rather than accumulating rapidly, while sedimentological data question the aeolian affinities of the bulk of the feature. Therefore, Klipkraal is reinterpreted as showing no particular affinity to the LGM, with sediments locally sourced with a significant colluvial component. Only the upper historical sediments can be clearly interpreted as aeolian deposits. A complex interplay of processes is suggested, for which a meaningful palaeoenvironmental interpretation cannot be easily defined. This implies that the local geomorphic processes and controls operating on sand ramps need to be established before they can be fully utilised as palaeoenvironmental archives, with implications for their interpretation worldwide.

Keywords

Sand ramp Aeolian processes Colluvium Late Quaternary

1. INTROUCTION

Located at the interface between dryland flats and topographic obstacles, and integrating slope, fluvial and aeolian deposits (Lancaster and Tchakarian 1996), sand ramps are increasingly recognised as a source of geoproxy data in environments often deficient in other archives of Quaternary environmental changes (e.g. Rendell and Seffer 1996, Thomas et al., 1997; Bateman et al., 2012; Kumar et al., 2017). Sand ramps lie on a continuum of landforms ranging from purely aeolian features (climbing/falling dunes) at one end to talus cones and alluvial fans at the other (Fig. 1). If ramp formation processes and controls can be identified and understood, and accumulation chronologies can be generated, sand ramps have the potential to provide valuable, dateable records of Late Quaternary environmental conditions. They have been investigated in this manner from around the world: for example

in North America (Pease and Tchakarian, 2003), Europe (Clemmensen et al., 1997), Middle East (Thomas et al., 1997), India (Kumar et al., 2017), and northern (Berking and Schutt, 2011) and southern Africa (Telfer et al 2012).

Sand ramps can however display a diversity of forms and sedimentary records that reflect a range of factors in addition to environmental changes, including accumulation space and sediment supply (Rowell et al. 2018). Convergence of sedimentary properties within ramps can potentially lead to difficulties in ascribing process domains to different units, confounding palaeoenvironmental interpretations (e.g. Telfer et al., 2014), while some features now interpreted as sand ramps were initially described simply as climbing dunes (e.g. Marker and Holmes, 1993; Clemmensen et al., 1997). Within-ramp spatial variations in sedimentary facies and stratigraphies can also be marked (see e.g. Bateman et al., 2012 and Telfer et al., 2012), such that chronometric reconstructions of ramp histories, commonly based on OSL dating, may be affected by issues such as the spatial resolution of sampling for dating.

Given these complexities, which have emerged from recent sand ramp investigations (i.e.

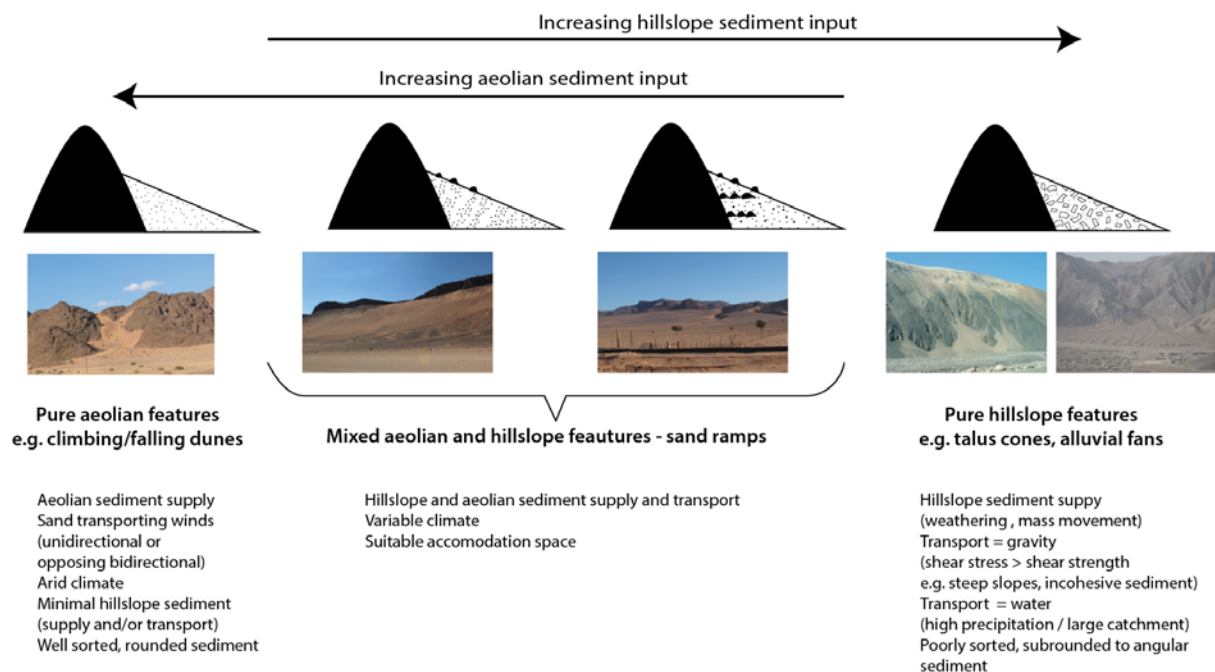


Figure 1 . Processes operating on sand ramps. From Rowell et al. (2018). Sand ramps form when aeolian sand and hillslope deposits (both colluvial and fluvial) accumulate against a topographic barrier. They occupy the continuum between purely aeolian climbing/falling dune and purely hillslope features and contain varying proportions of sediments derived from these processes.

Bateman et al 2012, Telfer et al. 2012, 2014, Rowell et al. 2018), and the potential value of ramp records for Quaternary studies in proxy-poor dryland environments, it is important to revisit earlier studies and the environmental conclusions that were drawn from them. This has occurred for the Soldier Mountain sand ramp in the Mohave Desert, where Bateman et al. (2012), employing new sedimentary analyses and applying new luminescence dating protocols, significantly revised earlier conclusions on the timing and accumulation context of this Late Quaternary feature. In this study, we reinvestigate the first sand ramp to be studied in southern Africa, Klipkraal Sands (Marker and Holmes, 1993; Thomas et al., 2002), focussing on issues of sediment origins and chronometric control, with a view to better understanding the evolution of this feature, relevant both to regional palaeoenvironmental reconstructions and the interpretation of sand ramp records in general. This ramp has been important for interpretations of the extent and timing of the occurrence of aeolian activity during the last Glacial cycle.

2. STUDY SITE AND METHODS

Klipkraal (31°23'35.10"S, 26°41'24.40"E, Fig. 2) is located within the Eastern Cape Province on the north eastern margin of the Karoo biome, South Africa, at considerable distance from dryland areas, such as the Kalahari and Free State, where aeolian sediments are more commonly found (e.g. Telfer and Thomas, 2007; Holmes et al., 2008). The ramp is situated at 1800 m a.s.l. on the north western flank of a ridge within the Stormberg Mountain range. The ridge and surrounding mountains are composed of Elliot Formation mudstones capped with resistant outliers of Clarens Formation sandstone (Marker and Holmes, 1993). Presently the site sits within the southern African summer rainfall zone with >50% of mean annual precipitation derived from the Indian Ocean monsoon. Occasional winter rainfall originates from the passing of cold fronts associated with mid-latitude cyclones (Tyson and Preston-Whyte, 2000) and brief but heavy snowfalls are not uncommon. MAP is 400-600mm with 25-35% annual variability and relative humidity typically above 40%. Sub-freezing temperatures are frequently experienced throughout winter, with nearby Buffelsfontein farm arguably the coldest place in South Africa (News24, 2010) whilst mean summer

temperatures are 22-28°C (Schulze et al., 1997). Regional wind regimes are bimodal, prevailing from the NW and SE (WASA, 2014).

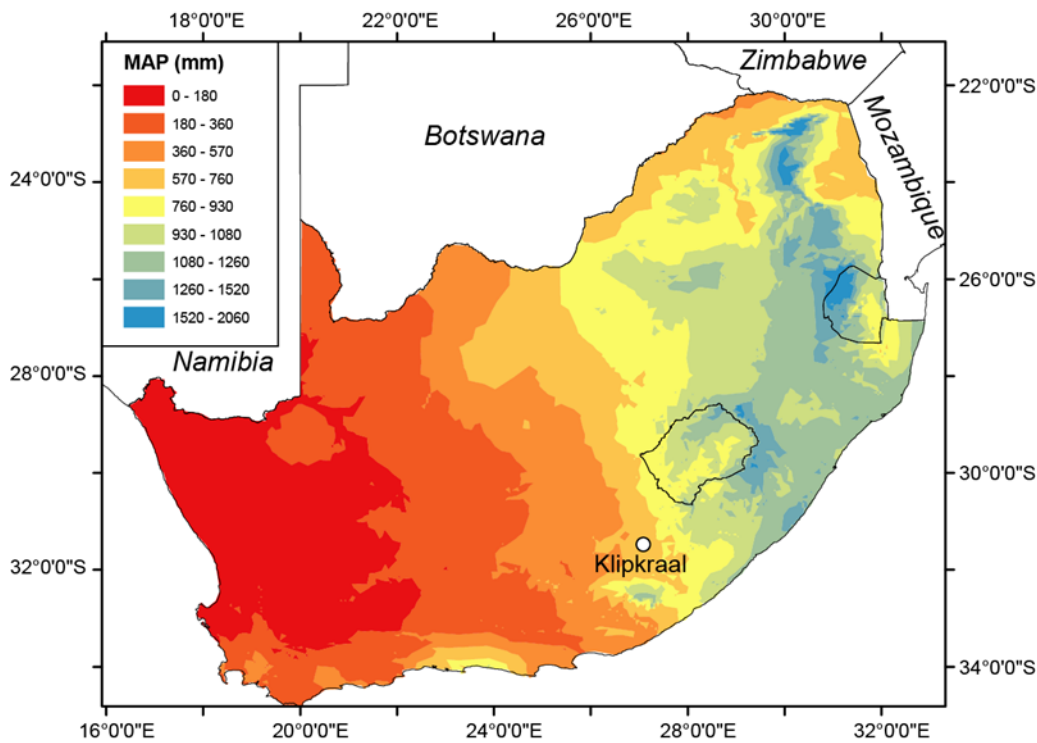


Figure 2. Mean annual precipitation in South Africa (1950-2000) (Hijmans et al., 2005). The location of Klipkraal is indicated.

2.1. PREVIOUS INVESTIGATIONS

The Klipkraal sand ramp, initially reported as a climbing dune (Marker and Holmes, 1993; Thomas et al., 2002), was interpreted as a unique aeolian landform in a region otherwise dominated by hillslope processes and given as evidence of reduced vegetation cover, strong anti-cyclonic conditions over the LGM and early Holocene, and long-distance aeolian sediment transport (Thomas et al., 2002). Recently, Telfer et al. (2012, 2014) have examined features similar to the Klipkraal Sands in the Drakensberg mountains, also in south eastern South Africa. Like the feature at Klipkraal, the Drakensberg ramps have been interpreted as primarily aeolian in origin (Telfer et al., 2012, 2014), but with wind-blown sediments derived from local sources. However, both the Klipkraal Sands and the Drakensberg features share

sedimentary and morphological characteristics with a Quaternary colluvial unit; formalised as the Masotcheni Formation to the east of the Great Escarpment, and widespread in eastern, central southern Africa (Botha, 1996; Clarke et al., 2003; Temme et al., 2008; Watson et al., 1984). This casts uncertainty on the previous interpretation of the Klipkraal Sands and suggests reanalysis may provide valuable information on the controls and nature of sand ramp formation.

2.2. FIELD SAMPLING

Klipkraal Sands were visited in 2013 to conduct a reinvestigation including new sampling for sedimentary and age analyses. Sand ramp sedimentology and morphology were logged in the field which guided the selection of four sections, exposed in gullies, as representative of wider sedimentary units within the feature. From these sections, 12 samples were taken that embraced the three main sedimentological units in multiple locations (Fig. 3). Samples for OSL dating and sedimentological analysis were obtained by hammering opaque black plastic tubes into cleaned exposures (Fig. 4). The light-exposed ends were removed in the laboratory and used for particle-size analysis and loss-on-ignition (LOI).

2.3. SEDIMENTOLOGY

Particle size analysis of the <2mm size fraction was conducted using a Malvern Laser Granulometer Hydro Mu 2000 with wet dispersion. Statistics were calculated using the Folk and Ward, (1957) formula and the GRADISTAT™ program (Blott and Pye, 2001). Organic and carbonate content were determined using sequential loss on ignition at 550°C and 950°C (Heiri et al., 2001) with organic content (%) proportional to loss at 550°C and carbonate content (%) calculated by the loss at 950°C multiplied by 1.36 (Bengtsson and Enell, 1986) and expressed as a percentage of the sample weight.

2.4. OSL DATING: SAMPLE PREPARATION

Samples for dating were prepared by isolating pure quartz through treatment in HCl, H₂O₂, wet sieving to the modal size-fraction, density separation using sodium polytungstate to 2.58 - 2.72 g/cm⁻³ and a 60 minute etch in 40% HF followed by treatment in HCl. Fully

prepared dry material was mounted as a 2mm monolayer onto aluminium discs using Silkospray™. All laboratory work was conducted under subdued orange light (~585nm).

All luminescence measurements were conducted using one of two Risø TL/OSL-DA-15 automated readers (Bøtter-Jensen et al., 2003), fitted with a blue (470 nm) LED array emitting at either 16 mW/cm² or 28 mW/cm². Infra-red (IR) simulation was conducted using a 870 nm laser diode array. Luminescence was measured using a EMI9235QA photomultiplier fitted with 7.5mm of Hoya U-340 filters. Beta irradiation was administered using ⁹⁰Sr/⁹⁰Y beta sources calibrated relative to the National Physical Laboratory, Teddington Hotspot 800 60Co γ-source (Armitage and Bailey, 2005).

2.5. OSL DATING: EQUIVALENT DOSE DETERMINATION

Typically, 24 small aliquots of ~200-500 grains (Duller, 2008) were measured for each sample using a modified Single Aliquot Regeneration (SAR) protocol with a 280°C optical bleach for 40s after the measurement of each test dose (T_x) (Murray and Wintle, 2000, 2003; Wintle and Murray, 2006). OSL was measured at 130°C for 40s. Sensitivity change and feldspar contamination were monitored using a repeated dose (Recycling Ratio; RR point) and an IR-depletion ratio point (Duller, 2003) respectively. Recuperation was monitored using a zero point. Samples were rejected if repeat RR or IR points were >10% of unity, recuperation was >5% of the natural or samples had a fast ratio <20 (Durcan and Duller, 2011). Dose recovery tests (DRTs) were performed on a subset of samples. Before irradiation discs were twice bleached for 1000s at 20°C separated by a 10,000s pause.

Preheat temperatures (PH) were determined following preheat plateau tests on recovered doses from a sub-set of samples (see Supplementary Information.1). Samples from Unit 3 (Fig. 3, Fig. 4) could recover the given dose within 10% of unity between 220-280°C (Supplementary Information. 1). However, at and above 260°C the samples increasingly failed recycling ratios and dose response curves (DRC), and could not be fitted with a single saturating exponential (SSE), a saturating exponential plus linear (SEPL) or a double saturating exponential (DSE) function. Therefore, a PH 1 temperature of 240°C and PH2 of

220°C for 10s were used for D_e determination. The applicability of these conditions was confirmed by DRTs (Supplementary Information 2). Samples from Unit 2 underestimated given doses by c.25% when a PH1 of 240°C was administered. However, samples recovered the given dose to between 5-12% of unity when a PH 1 of 260°C was used. Therefore, samples from Unit 2 were measured using a PH 1 temperature of 260°C and PH2 of 220°C for 10s. Preliminary tests indicated samples from Unit 1 were young with low sensitivity. Pre-heat tests were conducted between 120-240°C to monitor the increased likelihood of significant thermal transfer. Samples recovered doses within 10% of unity at all pre-heat temperatures (Sup. Info. 1) and PH 1 & 2 of 200°C for 10s were chosen for analysis to minimise the likelihood of any thermal transfer.

Individual aliquot D_e estimates were derived by interpolating the natural signal onto DRCs fitted with the most appropriate curve function (SSE, SEPL or DSE). Uncertainties were calculated using 1000 Monte Carlo fits of the curve and propagated with a 2% measurement error. Sample D_e s were calculated using the Central Age Model (CAM) (Galbraith, 1999).

2.6. OSL DATING: DOSE RATE DETERMINATION

Radionuclide (^{232}Th , ^{238}U and ^{40}K) concentrations of all samples were measured using ICP-MS (^{232}Th and ^{238}U) and ICP-OES (^{40}K). Where available, gamma spectrometry was used to determine the gamma contribution. Radionuclide concentrations were calculated using the window method of Aitken (1985) and radioactivity was calculated using the Liritzis et al., (2013) conversion factors. Based on reconstructions of fluctuating but typically dry conditions over the past 45 ka (Chevalier and Chase, 2015, 2016) and the position of the sediments on a free draining hillslope, a water content of $5\% \pm 5\%$ was used for all samples. Beta attenuation was corrected for using Guérin et al. (2012) and the etch depth values of Bell (1979). Cosmic dose was calculated using the formula of Prescott and Hutton (1994). Total dose rates were calculated using DRAC (Durcan et al., 2015).

187 3.1 SEDIMENTOLOGY

188 The sediments at Klipkraal are more complex than described by Thomas et al. (2002),
189 although Holmes and Marker (1993) noted internal variations within the overall exposures
190 of sediment. Upslope from the toe of the landform, which was quarried prior to the 1990s
191 providing clear sedimentary faces, exposures in gullies show that the feature comprises
192 three distinct sedimentary units (Table 1, Fig. 3).

193 Unit 1 contains moderate- to poorly- sorted fine sands with no clay and minimal silt. The
194 unit is predominantly massive but with some faint cross bedding. The contact with the
195 underlying unit is abrupt. Unit 2 is a dark brown palaeosol predominantly containing poorly
196 sorted fine sands and silts. Angular clasts with long axes up to 7cm are common. This unit is
197 wedge shaped, up to 5m thick upslope but thinning towards the base of the sand ramp and
198 not present in the toe sediments. The contact with the underlying unit is gradational. Unit 3
199 is the thickest, representing ~70% of the total landform. Sediments are primarily poorly
200 sorted medium sands to silts. Sedimentary characteristics vary through the unit with lenses
201 of consolidated fine sands and silts amid loose massive fine to medium sands, sections of
202 horizontal sand laminations and some gravel lenses are also present. Angular clasts are rare
203 but are found sporadically throughout the unit. Subsequent sampling for analyses and
204 dating embraced these three units, which are included in the results discussed below.

Table 1 Sedimentological properties of the main units. Grain-size, sorting, skew, kurtosis, organic and carbonate contents are expressed as averages of the samples from these units +/- one standard deviation. Folk and Ward (1957) descriptions are based on average values. See online Supplementary Information. for sedimentary properties of individual samples.

Unit	Thickness (m)	Description	Grain-size (μm)	Sorting (ϕ)	Skew (μm)	Kurtosis (μm)	Organic content (%)	Carbonate content (%)	Munsell colour
1	c. 0.5	Moderately to poorly sorted fine sand with sub-angular to rounded grains.	182 \pm 0.5	1.0 \pm 0.2 Moderately/ poorly sorted	-0.17 \pm 0.07 fine skewed	1.1 \pm 0.1 Leptokurtic	0.9 \pm 0.02	0.5 \pm 0.01	7.5YR 4/4 brown
2	0.2-5.0	Sandy soil of poorly sorted silts and fine sands. Individual grains show evidence of chemical dissolution. Frequent angular sandstone clasts up to 7cm	75 \pm 31	1.7 \pm 0.2 poorly sorted	-0.25 \pm 0.02 fine skewed	1.3 \pm 0.1 Leptokurtic	2.3 \pm 1.0	0.9 \pm 0.3	7.5YR 3/2 dark brown
3	0-7.0	Predominantly poorly sorted sub-angular to sub-rounded fine sands with sporadic angular sandstone clast <5mm. Intermittent sections of bedding and lamination. Some evidence of palaeosol development.	120 \pm 36	1.7 \pm 0.3 poorly sorted	-0.21 \pm 0.07 fine skewed	1.2 \pm 0.2 Leptokurtic	1.1 \pm 0.5	0.8 \pm 0.3	5YR 4/6 Yellowish red, 7.5YR 4/6 Strong brown, 10YR 6/3 Pale brown

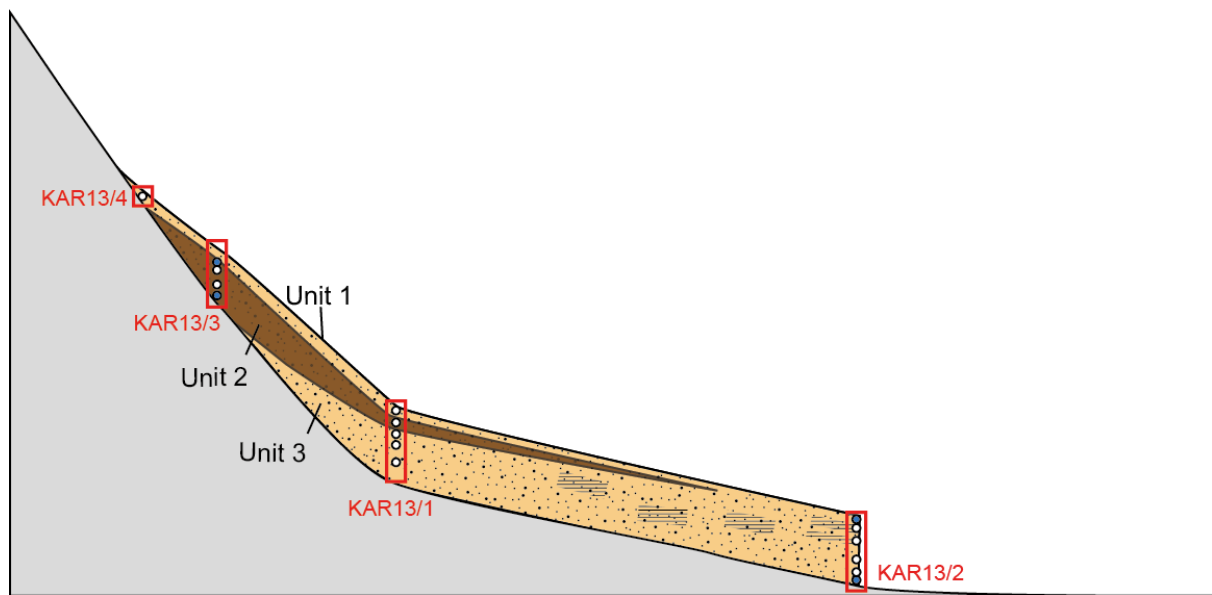


Figure 3. Schematic cross section of the Klipkraal sand ramp sediments. Sampling locations in this study are marked by white circles. Red boxes indicate sampling profiles (displayed in detail in Figure 4). Blue circles represent the approximate location of samples studied by Thomas et al (2002). For detail on sedimentology of the different units see Table 1 & Figure 5.

3.2 CHRONOLOGY

OSL data are provided in Table 2, while Fig. 5 shows the final ages in their stratigraphic and sedimentological contexts, and Fig. 6 the locations of the studied sections. The upper Unit 1 dates to between c.140-160 years ago (c.1853-1873AD). Unit 2 is of Holocene age, accumulating between 3.5 ± 0.3 and 12.4 ± 1.0 ka. Unit 3 accumulated primarily during the Last Glacial, with at least two periods of significant deposition; one at 29.8 ± 3.1 ka to 35.2 ± 2.6 ka and another 86.8 ± 5.3 ka to 95.1 ± 5.3 ka and 101 ± 9 ka. Sediments from both these phases display apparent age reversals, but these are within 1 sigma errors. If ages and uncertainties are assumed correct, stratigraphic relationships suggest deposition in these two phases occurred in time periods with maximum durations of 32.9 to 32.6 ka and 101 ± 9 to 89.8 ka respectively. Deposition of Unit 3 is also recorded at 14.8 ± 0.9 ka (KAR13/1/4) while sample KAR13/1/3, taken from the diffuse boundary between Unit 2 and Unit 3, dates to $8.7 \text{ ka} \pm 0.5 \text{ ka}$.

Table 2 Luminescence properties of samples. *n.* is the number of accepted aliquots *D_e* estimates were calculated using CAM (Galbraith et al., 1999). Dose rates were calculated using DRAC (Durcan et al., 2015).

Sample	Depth (m)	Dated modal size fraction (μm)	n.	De	Over-dispersion (%)	ICP-MS			Gamma Spectrometry			Beta dose (Gy/ka)	Gamma dose (Gy/ka)	Cosmic dose (Gy/ka)	Dose rate (Gy/ka)	Age (ka)
						U (ppm)	Th (ppm)	K (%)	U (ppm)	Th (ppm)	K (%)					
KAR13/1/1	0.3	180-210	17	0.19 ± 0.01	15 ± 1	1.25 ± 0.19	7.22 ± 1.44	0.34 ± 0.03	1.58 ± 0.23	8.39 ± 0.64	0.72 ± 0.07	0.51 ± 0.05	0.54 ± 0.07	0.31 ± 0.03	1.37 ± 0.09	0.14 ± 0.01
KAR13/1/2	0.6	180-210	19	6.1 ± 0.4	30 ± 2	1.66 ± 0.26	9.24 ± 1.85	0.56 ± 0.05	n/a	n/a	n/a	0.75 ± 0.06	0.72 ± 0.05	0.28 ± 0.03	1.75 ± 0.08	3.48 ± 0.26
KAR13/1/3	1.1	125-150	14	13.1 ± 0.6	21 ± 2	1.43 ± 0.01	8.24 ± 0.12	0.44 ± 0.03	n/a	n/a	n/a	0.64 ± 0.03	0.63 ± 0.02	0.25 ± 0.03	1.52 ± 0.05	8.65 ± 0.47
KAR13/1/4	1.6	125-150	12	25.5 ± 0.9	11 ± 1	1.45 ± 0.22	8.49 ± 1.70	0.57 ± 0.05	1.64 ± 0.24	8.76 ± 0.67	0.78 ± 0.07	0.74 ± 0.06	0.76 ± 0.05	0.24 ± 0.02	1.73 ± 0.08	14.76 ± 0.88
KAR13/1/5	3.2	125-180	19	180.2 ± 11.1	25 ± 2	1.54 ± 0.24	8.98 ± 1.80	0.72 ± 0.06	n/a	n/a	n/a	0.87 ± 0.07	0.74 ± 0.09	0.19 ± 0.02	1.80 ± 0.12	99.95 ± 8.95
KAR13/2/1	2.4	125-150	20	48.2 ± 1.7	15 ± 1	1.30 ± 0.20	6.89 ± 1.38	0.44 ± 0.04	n/a	n/a	n/a	0.60 ± 0.05	0.56 ± 0.07	0.21 ± 0.02	1.37 ± 0.09	35.21 ± 2.62
KAR13/2/2	3.5	125-180	19	41.8 ± 3.2	33 ± 3	1.22 ± 0.19	8.09 ± 1.62	0.46 ± 0.04	n/a	n/a	n/a	0.61 ± 0.05	0.60 ± 0.08	0.19 ± 0.02	1.40 ± 0.10	29.79 ± 3.09
KAR13/2/3	4.7	180-210	19	121.5 ± 5.9	20 ± 2	1.30 ± 0.04	6.74 ± 0.19	0.42 ± 0.01	n/a	n/a	n/a	0.57 ± 0.02	0.54 ± 0.02	0.16 ± 0.02	1.28 ± 0.03	95.14 ± 5.26
KAR13/2/4	5.5	180-210	16	151.7 ± 11.6	28 ± 3	1.52 ± 0.52	8.95 ± 1.79	0.72 ± 0.07	n/a	n/a	n/a	0.86 ± 0.07	0.74 ± 0.09	0.15 ± 0.02	1.75 ± 0.12	86.82 ± 8.80
KAR13/3/1	1	180-210	23	14.2 ± 0.2	7 ± 1	1.76 ± 0.27	9.77 ± 1.95	1.17 ± 0.11	n/a	n/a	n/a	1.23 ± 0.10	0.91 ± 0.10	0.24 ± 0.02	2.37 ± 0.15	5.99 ± 0.38
KAR13/3/2	3	125-180	24	23.3 ± 0.8	16 ± 1	1.72 ± 0.27	10.53 ± 2.11	0.64 ± 0.06	n/a	n/a	n/a	0.88 ± 0.08	0.81 ± 0.10	0.20 ± 0.02	1.89 ± 0.13	12.35 ± 0.95
KAR13/4/1	0.5	90-125	17	0.19 ± 0.02	34 ± 4	0.98 ± 0.15	5.11 ± 1.02	0.39 ± 0.04	n/a	n/a	n/a	0.48 ± 0.04	0.43 ± 0.05	0.29 ± 0.02	1.20 ± 0.07	0.16 ± 0.02

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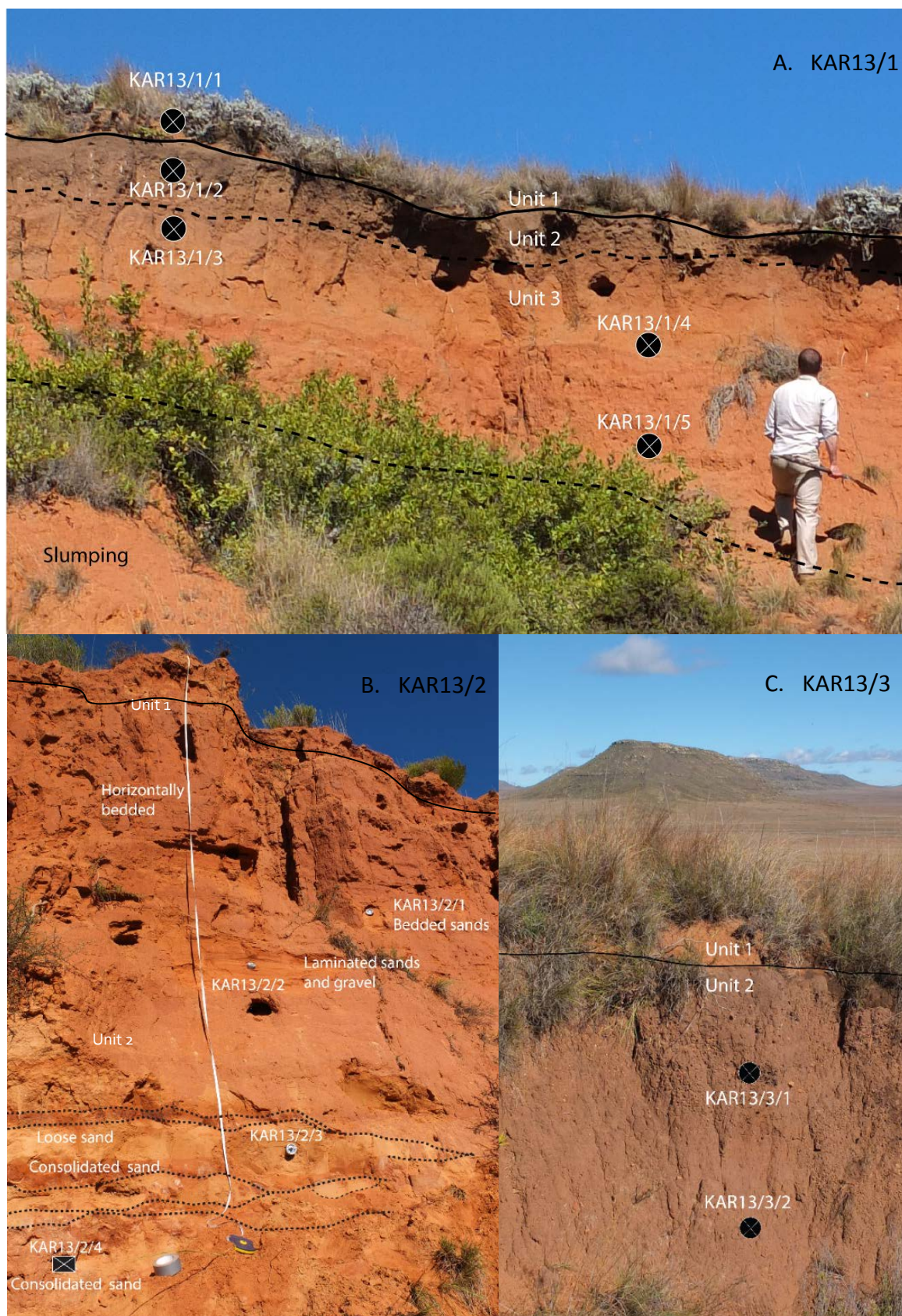
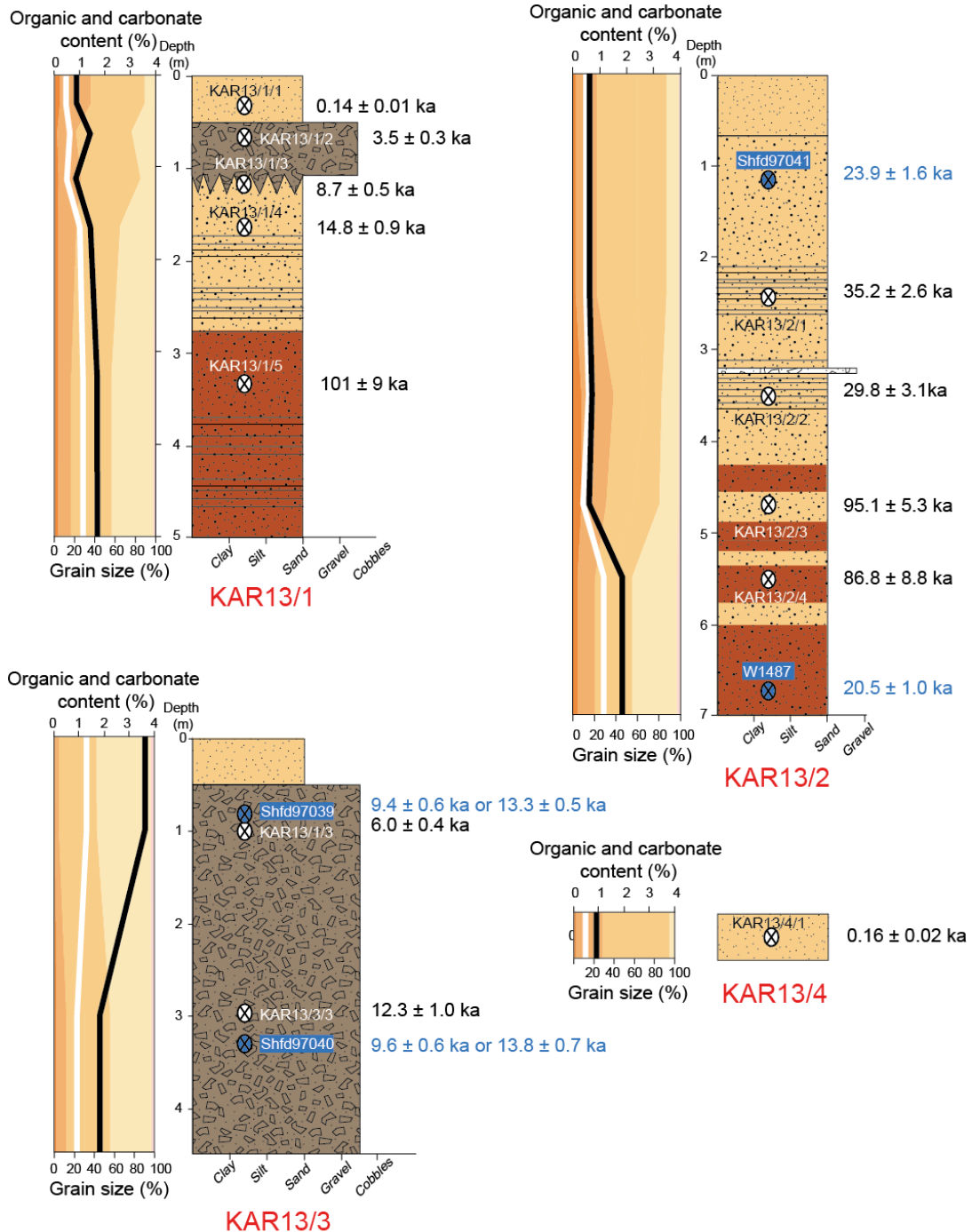


Figure 4. Sampling sections of the Klipkraal Sands. A). KAR13/1 B). KAR13/2 C). KAR13/3. Sample locations are shown by either the actual sample pots in situ or by black circles or squares. Circles represent tube samples and squares block samples. Annotations show sedimentological Units and sedimentological properties below the unit scale. Unit properties are described in Table 1



Key for grain-size logs

Coarse sand Medium sand Fine sand Silt Clay Organic content
Carbonate content

Key for sediment logs

Moderately sorted sand Silt and sand with angular gravels and cobbles Gravel lense
Poorly sorted unconsolidated sand Poorly sorted consolidated sand Horizontal laminations
OSL and sedimentology sample location TL/GLSL sample from Thomas et al. 2002

Figure 5 Sediment and grain size logs for the Klipkraal Sands sampling profiles. Grain size logs are to the left of sediment logs and are at the same vertical scale. Grain size for KAR13/4 is from a single sample at 0.5 m. For details on the locations of profiles and their relationship to the feature as a whole see Figure 3 and Figure 4



Figure 6. Aerial view of the Klipkraal Sands. Dashed lines denote remains of 19th/20th century farming terraces. Sampling locations are marked by black circles. Image from Google Earth TM

4 DISCUSSION

The new data and analyses in this study allow us to both re-evaluate the mode and timing of Klipkraal sand ramp development, consider the feature in terms of the aeolian-hillslope model of ramp development (Rowell et al., 2018) and use the data to address emerging issues in sand ramp formation in general.

4.1 KLIPKRAAL SANDRAMP

4.1.1 Chronology

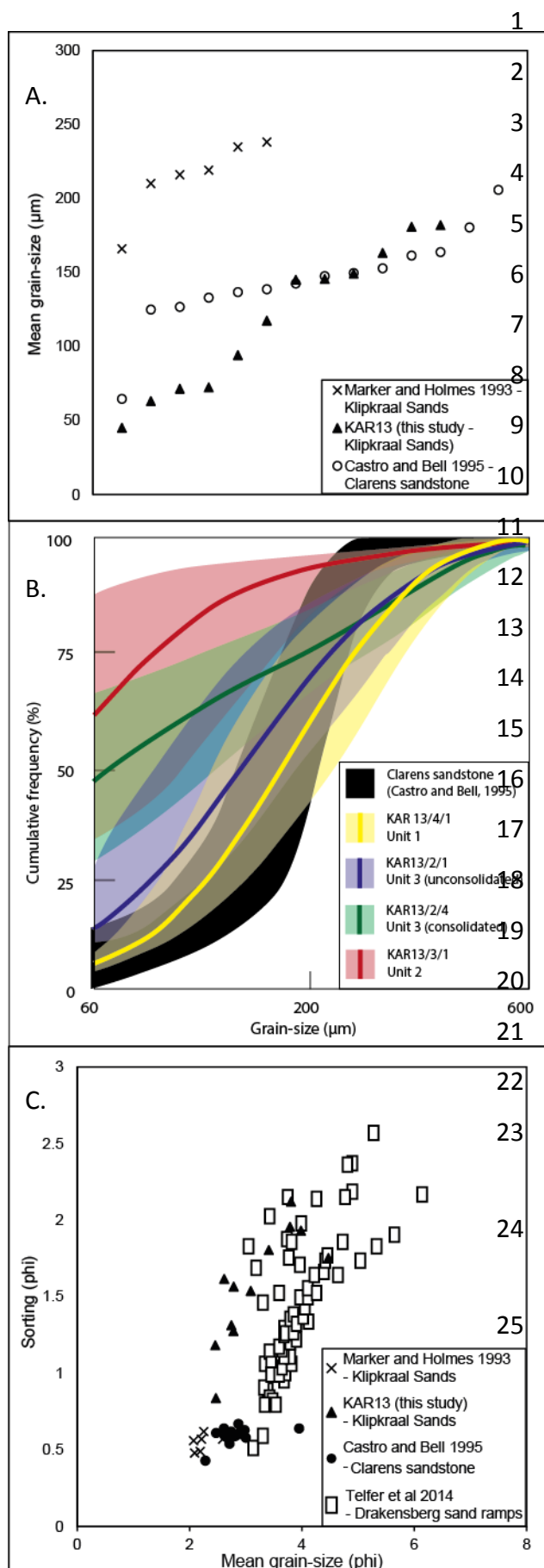
The assumed locational relationship between the samples from this study and luminescence samples reported by Thomas et al. (2002) is displayed in Fig. 3 and Fig. 5. Based on the site description, samples Shfd97039 and Shfd97040 are presumed to be taken from Unit 2 although no mention of a colluvial or palaeosol layer is made. Ages for these samples in Thomas et al. (2002) suggested accumulation of 2.4m of sediment between 9.6 ± 0.6 and 9.4 ± 0.6 ka (TL age) or 13.8 ± 0.7 and 13.3 ± 0.5 ka (GLSL age) depending on dating method. This is in approximate agreement with the ages obtained from this study (3.5 ± 0.3 ka, 6.0 ± 0.4 ka, 12.4 ± 1.0 ka) as both suggest some early Holocene accumulation (Fig. 5). However,

the chronology of Thomas et al. (2002) indicated rapid accumulation, akin to the mode of sand ramp accumulation identified in the Mohave Desert by Bateman et al. (2012), whilst more gradual accumulation through the Holocene is implied from data in this new study.

A significant difference in ages is observed between those derived from original samples taken from the toe of the sand ramp and published in 2002 and those from this study (section KAR13/2). Thomas et al. (2002) indicate rapid deposition centred on c.22 ka (Fig. 5). Sample Shfd97041 (TL age 23.9 ± 1.6) is in stratigraphic agreement with the ages obtained from this study (Fig. 5). However, basal sample W1487 (TL 20.5 ± 1.0 originally from Marker and Holmes, 1993) is significantly younger than the equivalent samples analysed in this study KAR13/2/3 and KAR13/2/4 (95.14 ± 5.26 ka and 86.82 ± 8.80 ka respectively). Different depositional histories are derived from the two chronologies: two phases of rapid accumulation between c.24-9 ka are suggested by Thomas et al. (2002) whilst this study indicates episodic accumulation over the past c.100 ka.

The precise sampling locations of Thomas et al. (2002) could not be re-established and thus differences between ages might reflect spatial variations in the deposition of the sand ramp. Sample W1487 is described as “basal” with no associated depth data so the precise relationship to samples KAR13/2/3 and KAR13/2/4 is unknown. Additionally, Shfd97041 and W1487 were collected during different field investigations and may originate from different sections, potentially explaining the apparent age reversal. Nonetheless, fieldwork in 2013 suggested that there is stratigraphic integrity in sediments exposed along the base of the ramp toe front, so we consider this explanation to be an unlikely cause of the age disparities between the old and 2013 samples.

An alternative, and more plausible, explanation for the differences in ages between studies relates to the luminescence dating itself. Luminescence techniques and protocols have advanced significantly since 2002 (Roberts et al., 2015) and ages in Thomas et al. (2002) may be associated with unaccounted measurement uncertainties. This interpretation is supported by the c.4 ka age difference exhibited by samples Shfd97039 and Shfd97040 when measured using TL and GLSL. Furthermore, the TL ages were derived from the use of



the multi-aliquot protocol, which is rarely employed today and which ‘merges’ data from multiple measurements that can average out and blur the records preserved within a sediment. That the original paper employed a further averaging of TL and IRSL data only adds to the uncertainty within the Thomas et al. (2002) chronology. If we restrict interpretation to the new ages presented in this study, derived using modern laboratory protocols from samples collected with greater stratigraphical information and context, then the Klipkraal ramp preserves a complex, multiphase record of accumulation within the last c100ka, and is not a feature that has developed simply through relatively rapid accumulation during the last ~20ka. An additional factor is that doses rates in this study (Table 2), calculated using modern approaches and DRAC (Durcan et al. 2015) are significantly lower than those used by Thomas et al. (2002).

Figure 7. Grain-size properties of the Klipkraal Sands. A). Mean grain-size measurements from this study compared to those in Marker and Holmes (1993) and samples of the Clarens Formation sandstone (Castro and Bell 1995) which forms the uppermost stratum in the local geology B). Grain-size distribution of representative samples from each of the Klipkraal Sands units compared to the Clarens Formation grain-size distribution from Castro and Bell (1995). C). Comparison of grain-size and sorting between the Klipkraal Sands study of Marker and Holmes, (1993) and this paper; the Clarens Formation sandstone (Castro and Bell, 1995; and Drakensberg sand ramps (Telfer et al., 2014).

4.1.2 Sediments

Marker and Holmes (1993) concluded that the Klipkraal Sands are far travelled aeolian sediments, presumed to originate from the Kalahari in the north during a period of aridity and strong aeolian activity (assumed to be the LGM based on TL dating of W1487 - 20.5 ± 1.0). Thomas et al (2002) suggested two periods of intense aeolian activity with reduced vegetation cover associated with strong anti-cyclonic conditions between 24-11 ka. The 'Kalahari origin' model was primarily based on comparison of particle size data with data from a thin section of Clarens Sandstone, which identified the Klipkraal Sands as slightly coarser than the Clarens sandstone, ruling the latter out as a sediment source for the material in the sand ramp (7a, 7c, Marker and Holmes, 1993).

The particle size data in this study, obtained by laser granulometry, indicate that the Klipkraal Sands are finer than previously suggested, with mean and median grain-sizes akin to the Clarens Formation sandstone (Castro and Bell, 1995) (7a, 7b). Particlesize distributions vary within the Klipkraal sand ramp, with a small proportion of grains larger than the Clarens Formation sandstone found in Units 1 & 3 (7b). Some of the differences in particle size distributions may be a result of different analytical methods with wet dispersion laser granulometry results not directly comparable to the dry sieving used by Castro and Bell (1995) (Konert and Vandenberghe, 1997). Additionally, the samples of Clarens Formation sandstone examined by Castro and Bell (1995) originate from Lesotho and regional properties of this lithology may vary.

Overall, the similarity in particle size properties of the Klipkraal Sands and the Clarens Formation sandstone means a local sediment source is highly likely. This hypothesis is enhanced by the granulometry data showing ramp sediments to be poorly sorted (Fig. 7c), which is at odds with the notion of long-distance aeolian transport (Nichols, 2009).

4.1.3. Accumulation history

There is some overlap in the OSL-Derived accumulation ages between the Klipkraal Sands and the sedimentologically and morphologically similar ramp features reported from the

Drakensberg foothills (Telfer et al., 2012) with both showing phases of accumulation within the Last Glacial cycle. At Noordbrabant West, c 450km to the northeast, deposition has been dated to between 45 ± 3 ka to 7.6 ± 0.6 ka with rapid deposition between c.18-15 ka (Telfer et al., 2012), which is in broad agreement with the ages obtained from the Klipkraal Sands. Noordbrabant West accumulation at 7.6 ± 0.6 ka is interpreted as colluvial, showing good agreement with the Unit 2 dates (3.5 ± 0.3 ka, 6.0 ± 0.4 ka, 12.4 ± 1.0 ka). Unlike the Klipkraal Sands, Noordbrabant West shows evidence for deposition around the LGM with dates of 26 ± 1.9 , 23 ± 1.5 and 17 ± 1.1 . Telfer et al. (2012; 2014) suggest periglacially weathered material transported by rivers provides the source of aeolian sediments with decreased vegetation cover and increased wind strength enabling transport. Periglacial weathering may play a direct role in colluvium accumulation in Unit 3 of the Klipkraal sand ramp and may also contribute to aeolian accumulation, although the poor sorting of the sediments and the absence of local river channels suggests the contribution is less significant than for the Drakensberg sand ramps.

4.2 THE AEOLIAN-HILLSLOPE SAND RAMP MODEL

Rowell et al. (2018, Fig. 1 this paper) have shown that sand ramps can be considered as part of a hillslope depositional continuum ranging from purely aeolian to purely gravity-controlled slope deposits. While first considered to be a climbing dune indicative of long distance aeolian transport (Marker and Holmes, 1993), the grain-size data in this study demonstrate that a local, colluvial sediment source cannot be discounted. This may be a more likely explanation for the formation of the main ramp body in the Karoo dryland environment where aeolian sediments and processes are neither prevalent today nor represented in other palaeoenvironmental studies. Interpreting process from the sediments alone is more challenging than previously suggested by Marker and Holmes (1993) and Thomas et al. (2002).

In a wider context, this challenge is exacerbated by the convergence of some attributes of aeolian and slope deposits. Aeolian deposition is not necessarily associated with well-sorted, cross-bedded sands (Bateman et al., 2007), and colluvium does not necessarily

1 contain large clasts or possess very poor sorting (Selby, 1993). In addition, the complexity of
2 sand ramps which, by definition, are a product of multiple processes adds further
3 uncertainty. In Rowell et al. (2018), OSL sensitivity data from Namibian sand ramps showed
4 that even in aeolian-dominated environments, both colluvial and aeolian sands can be
5 present within a single sample, indicating a complex interplay between all erosional and
6 depositional processes operating on sand ramps up to the sample scale.

7 At Klipkraal, Unit 1 is better sorted than the sediments of Unit 3 (Table 1, Fig.s 5, 7b) and has
8 an abrupt boundary with the former land surface of Unit 2. We interpret this unit as a
9 product of anthropogenic disturbance of the landscape in the last two centuries, formed
10 through aeolian reworking of sediments transported from the slope by water erosion to the
11 toe of the ramp and blown back up the slope. Therefore, OSL ages from Unit 1 represent a
12 period (c. 1863-1883) when human land use impacted erosion and geomorphic processes in
13 the region. Marker and Holmes (1993) indicate that the gullies post-date the cessation of
14 farming at Klipkraal suggesting this unit is most likely associated with erosion due to wheat
15 production.

16 Unit 2 is massive, with sandstone clast inclusions and a relatively high clay and organic
17 content (both c.2-3%). It is interpreted as a palaeosol formed in colluvium. Unit 3 contains
18 some structure with laminar bedding observed in several locations and occasional cross-
19 bedding described by Marker and Holmes (1993). Large clasts are absent from this unit but
20 small angular clasts <1cm in diameter are found sporadically and in some concentrated
21 lenses. These sediments are very similar to those described by Telfer et al., (2012, 2014) in
22 the Drakensberg foothills c 450 km to the northeast. These in turn show affinity to the
23 Quaternary Mastochini Formation colluvium (Botha, 1996; Clarke et al., 2003; Temme et al.,
24 2008). That is widespread in the steep terrain of this part of South Africa. Although Telfer et
25 al. (2012, 2014) propose that this unit can contain aeolian facies, based on the presence of
26 moderately sorted coarse silt/fine sand units with upslope cross-bedding and a near
27 absence of clasts, this highlights similarity between aeolian and colluvial deposits in this
28 region. Overall, our new results suggest that the Klipkraal Sands contain a significant
29 colluvial contribution placing them towards the hillslope end of the aeolian-hillslope

spectrum of sand ramp deposits. The sands of Unit 1 show that aeolian activity has occurred at Klipkraal, but only when conditions have been altered by human activity to enable a plentiful, mobile sediment supply.

The morphology of the Klipkraal ramp is similar to the “class 1” (small features, no gully dissecting the feature from the hillslope and no secondary dunes). sand ramp classification of Rowell et al. (2018) However, the extensive gullying present at the Klipkraal ramp has no equivalent in the Namibian sand ramps where the classification scheme was developed. The Klipkraal sand ramp sits low in the available accommodation space, with capacity for further accumulation upslope. It has no obvious potential modern aeolian sediment source suggesting it is starved of wind transported sediment. These factors combined with the greater precipitation and erodibility of the upslope bedrock (Watson et al., 1984; Selby, 1993) indicate that colluvium is an important source material for the formation of the feature and plays a more formative role than for the Namibian sand ramps. The sands of Unit 1 indicate that aeolian activity is an influential process at Klipkraal but only when environmental conditions have been locally modified by human activities (Fig. 6) that led to gullying and sediment becoming available for aeolian transport.

4.3 SANDRAMPS: VALUABLE PALAEOCLIMATE PROXIES OR ARCHIVES OF REGIONAL ENVIRONMENTAL DYNAMICS?

Since their first systematic analysis in the Mohave Desert (Lancaster and Tchakarian, 1996), sand ramps have been viewed as a valuable ‘geoproxy’ source of palaeoenvironmental and palaeoclimatic data in regions that may be limited in the range of available proxy data sources. As analyses have proceeded, the inherent complexity and diversity of sand ramps has emerged, such that they do not necessarily represent ‘amalgamated accumulations of aeolian, fluvial and talus deposits’ that are simple to interpret as a ‘record of the response of aeolian processes to climatic change’ (Lancaster and Tchakarian, 1996:151).

The systematic analysis of a series of sand ramps in Namibia (Rowell et al., 2017) showed how accommodation space and sediment supply, which can vary through time in response

to changes in climatic and other supply drivers, dominate as controls on the varying ramp morphologies that occur. As with the Mohave ramps of Lancaster and Tchakarian (1996), those investigated by Rowell et al. (2018) are primarily aeolian features with more limited contributions of sediment from slope-derived processes, a reflection of the desert affinities of the regions studied.

The Klipkraal Sands, and the Drakensberg features of Telfer et al. (2012), provide a somewhat different context for ramp investigations. Away from major desert areas, but within marginal dryland contexts, they have provided an opportunity to examine sand ramps that occur further towards the 'hillslope' end of the aeolian-hillslope continuum (Fig. 1). Occurring in areas where wind-driven sediment transport is not (under natural environmental conditions) a part of the geomorphic process regimes operating today, ascribing a significant part of their development to aeolian processes in the past has major implications for environmental and climatic inferences in the late Quaternary.

Ambiguity surrounding the origin of the Klipkraal Sands means that accumulation cannot be interpreted clearly as evidence of the occurrence of aeolian activity in this part of the Karoo region during the last glaciation, particularly in terms of long-distance transport (Marker and Holmes, 1993). Therefore previous interpretations of reduced vegetation cover and strong anticyclonic conditions (Thomas et al., 2002) cannot be confirmed from data derived from the sand ramp. Sedimentologically, there is a greater likelihood that the bulk of the ramp body has been derived as colluvium originating from the Clarens Formation sandstone. Additionally, the paucity, high spatial variability, and low resolution of other available Late Quaternary records from the region mean environmental processes cannot be inferred from environmental conditions determined from other proxy sources. 450 km to the northeast, Telfer et al. (2014) have argued that there is sedimentological evidence from the Masotcheni Formation colluvium for some aeolian input under LGM periglacial conditions. Current data from Klipkraal does not allow such an assertion to be made from this location.

Rowell et al. (2018) suggest that periods of regional sediment availability can be identified from the primarily aeolian Namibian sand ramp record, but *only if* environmental controls

are known and multiple sand ramps are analysed in unison. Therefore, further work is needed, both to constrain the environmental significance and expand the number of analysed features, before sand ramps can be reliably used as a palaeoenvironmental proxy in the semi-arid region of southern Africa.

The evidence for aeolian activity having formed the upper, historical, sediments at Klipkraal is much stronger. Documented and evidenced human agency rests behind the occurrence of late 19th century wind-blown sediment transport that formed Unit 1 in the sedimentary sequence at Klipkraal. In this respect, the feature meets the criteria for being regarded as a sand ramp, since the total sediment body includes hillslope and aeolian deposits but, without this agriculturally-derived intervention, we contest that this landform would more appropriately be regarded as a colluvial apron. The sand ramp at Klipkraal is therefore a further piece of evidence for the significant impact that the arrival of European farmers had on the landscape of the Karoo region (Boardman et al., 2003; Key-Bright and Boardman, 2006; Boardman 2014).

5 CONCLUSION

Re-analysis of the Klipkraal sand ramp feature with new chronometric and sedimentological data has necessitated a revision to the published palaeoenvironmental interpretation and accumulation history of the feature. Previous interpretations proposed a primarily aeolian accumulation history, between 22-11 ka (Marker and Holmes, 1993; Thomas et al., 2002). The improved chronology from this study indicates deposition occurred episodically within the c.100- 0.14 ka period. Additionally, particle size data from this study suggests the material is finer and more poorly sorted than originally suggested by Marker and Holmes (1993). This suggests a close affinity between the ramp sediments and the local Clarens Formation sandstone which crowns the escarpment against which the ramp has accumulated. Comparison with the sediments of the Mastocheni Formation colluvium (Botha, 1996; Dardis, 1990; Temme et al., 2008) and sand ramp sediments from the

Drakensberg (Telfer et al., 2012, 2014) are inconclusive. Site sedimentology suggests that deposition is due to both colluvial and aeolian processes. The latter is primarily responsible for formation of the surface unit which has a direct relationship to enhanced sediment supply as a result of human disturbance during the 19th and 20th centuries.

This analysis highlights the difficulties that can arise in interpreting sand ramp sediments, particularly in marginal environments such as the semi-arid Karoo region. While general principles of ramp development have been established (Rowell et al., 2018), it is necessary, for all sand ramps, to consider the local context and establish the local controlling factors of ramp features before they can be utilised effectively as palaeoenvironmental or palaeoclimatic archives.

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