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An optical luminescence chronology for late Pleistocene aeolian activity in the Colombian and Venezuelan Llanos

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ABSTRACT

The lowland savannas (Llanos) of Colombia and Venezuela are covered by extensive aeolian landforms for which little chronological information exists. We present the first optically stimulated luminescence (OSL) age constraints for dunes in the Llanos Orientales of lowland Colombia and new ages for dunes in the Venezuelan Llanos. The sampled dunes are fully vegetated and show evidence of post-depositional erosion. Ages range from 4.5 ± 0.4 to 66 ± 4 ka, with the majority dating to 27–10 ka (Marine Isotope Stage 2). Some dunes accumulated quickly during the last glacial maximum, although most were active 16–10 ka. Accretion largely ceased after 10 ka. All dunes are elongated downwind from rivers, parallel with dry season winds, and are interpreted as source-bordering features. As they are presently isolated from fluvial sediments by gallery forest it is proposed that activity was associated with a more prolonged dry season, which restricted gallery forest, leading to greater sediment availability on river shorelines. Such variability in dry season duration was potentially mediated by the mean latitude of the ITCZ. The cessation of most dune accretion after ca. 10 ka suggests reduced seasonality and a more northerly ITCZ position, consistent with evidence from the Cariaco Basin.

Introduction

Quaternary environmental changes in the Neotropics are of interest as the roles of both orbital forcing and abrupt North Atlantic-forced events can be identified in palaeoenvironmental records (e.g. Mosblech et al., 2012). In northern South America the Cariaco Basin record provides evidence for abrupt drying during the Younger Dryas (Hughen et al., 1996), distinct hydrological change across the Holocene (Haug et al., 2001) and the impact of Heinrich events (González et al., 2008). It has been proposed that the inter-tropical convergence zone (ITCZ) played a key role in driving past temporal/spatial variations in surface hydrological balance (Martin et al., 1997; Wang et al., 2004; Arbuszewski et al., 2013). In northern South America several high-altitude records from the Andean Cordillera have provided important insights into regional long-term palaeoenvironmental change (e.g. Groot et al., 2011), but our knowledge of environmental changes on the extensive lowland savannas (the Llanos) that occupy great swathes of the continent to the east (Figure 1) remains very limited. Several pollen records from the Colombian savannas (Llanos Orientales) are indicative of Holocene environmental change (Berrío et al., 2012), but these are relatively short, have limited age control and in some instances contain age inversions (Berrío et al., 2002). Notwithstanding, the extent of late Pleistocene "aridity" in these tropical lowlands is of great interest (Behling and Hooghiemstra, 1999; van der Hammen and Hooghiemstra, 2000), and might be variously linked to patterns seen in the Cariaco Basin records to the north and/or questions concerning wider shifts in aridity in the Amazon Basin to the south (Colinvaux et al., 2000).

The lowland Llanos savannas of Colombia and Venezuela stretch from the Andean foothills of Colombia to the Guyana Shield in the east (Figure 1). A remarkable feature of the landscape, readily apparent from satellite imagery, is the extensive coverage of aeolian landforms (Tricart, 1974; Roa Morales, 1979; Khobzi, 1981; Clapperton, 1993; Iriondo, 1999; Schargel, 2007; Figs. 1A & S1). These linear and elongated parabolic dunes are frequently (though not always) vegetated and there has long been speculation concerning their antiquity and palaeoenvironmental significance (Goosen, 1971; Tricart, 1974; Sarnthein, 1978; Colinvaux et al., 2000; van der Hammen and Hooghiemstra, 2000).

Although these dunes were assumed to be late Pleistocene landscape features (Goosen, 1971; Clapperton, 1993) limited chronological data renders their palaeoclimatic significance unclear (Tripaldi and Zárate, 2015). With the development of optically stimulated luminescence dating techniques, which provide an estimate of the time elapsed since sediments were last transported (i.e. exposed to light), stabilised and buried or presently inactive aeolian landforms can be used as archives of environmental change and long-term landscape evolution

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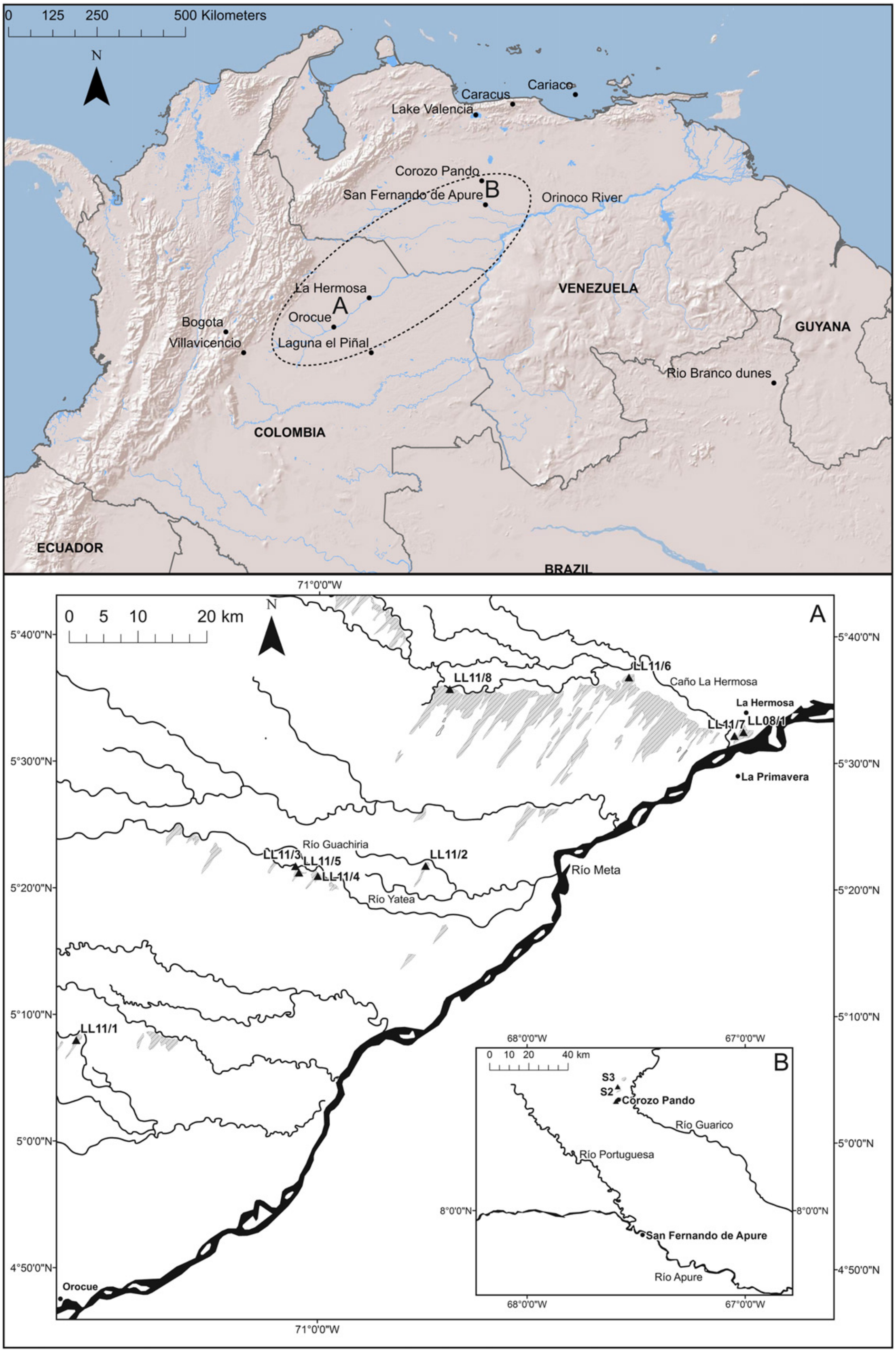

Fig. 1. – Regional map and topography of the study region (upper), showing the locations of major settlements and the Llanos savannas region (circled), as well as the Cariaco Basin and the dune systems in Guyana described by Teeuw and Rhodes (2004). Inset A: Dune distribution, sampling locations and major settlements within the Colombian study area. Inset B: sampling locations and major settlements within the Venezuelan study area. The sample site for the active dune crest S1A1 (Río Verde) is 90 km south of San Fernando de Apure.

(e.g. Telfer and Hesse, 2013). It has been demonstrated that extensive chronostratigraphic records from continental dune systems such as the Kalahari in southern Africa can provide insights into palaeoenvironmental change and aeolian landform response to climatic perturbation (e.g. Thomas and Burrough, in press). The dune systems of the Llanos Savannas in Colombia and Venezuela are particularly extensive (Tricart, 1974; Roa Morales, 1979; Khobzi, 1981), but far less studied. Presently the only published chronological data for these dunes (all from the Venezuelan Llanos) comprise two thermoluminescence (TL) ages (11.6 ± 1.6 ka & 36 ± 5 ka; Vaz and Miragaya, 1989), eight OSL ages (González et al., 2013) and two radiocarbon ages from buried soils (Roa Morales, 1979; 11,100 ± 450 ^{14}C yr BP and 12,300 ± 500 ^{14}C yr BP). The ages span the late Pleistocene and the Holocene, but their limited number and a lack of contextual information makes it difficult to interpret them (Tripaldi and Zárate, 2015). Here we provide OSL age constraints for a suite of stabilised aeolian landforms in the Colombian Llanos Orientales, at the western-most (and most humid) limits of the Llanos (Marchant et al., 2006), and for vegetated dunes at the northern margins the Venezuelan Llanos dune systems. In the Colombian Llanos Orientales these ages represent the first suite of optically stimulated luminescence age constraints for aeolian activity. We use these data to consider the antiquity of aeolian activity in this region and to evaluate dune formation within the context of late Pleistocene climatic and ecological change in northern South America. Rainfall amount and seasonality in this region are strongly controlled by the seasonal migration of the ITCZ, the positioning of which changed during the late Pleistocene and Holocene (Haug et al, 2001; Arbuszewski et al., 2013). Given the consistent alignment of the Llanos dunes parallel to the NE trade winds (Tricart, 1974; Figs. 1A and S1) we hypothesize that a change in the duration of the wet season, controlled by the ITCZ, was a key control on palaeo-dune activity. Given the limited description of the dune systems in Colombia (cf. Venezuela; Roa Morales, 1979) we also present initial data pertaining to dune sedimentology and geochemistry, in the context of dune sediment provenance, fluvial sediment supplies and evidence for *in-situ* chemical weathering.

Study area

The Llanos lowlands extend over 1.2 million km^2 from the Colombian Cordillera in the west to the Guyana Shield in Venezuela in the east (Fig. 1). The landscape is remarkably flat and typically lies 100–200 m above sea level. It is characterised by many meandering river systems, ultimately draining to the Orinoco River (via the Meta River) from the Colombian eastern Cordillera and from the Apure River in Venezuela (Fig. 1B). The modern vegetation comprises a mosaic of savanna grasslands, seasonally flooded grasslands, riverine gallery forests and *Mauritia* palm swamps (Blydenstein, 1967; Aymard and González, 2007; Berrío et al., 2012; Rangel and Minorta, 2014). Geologically, the Llanos lie within the foreland basin of the wider Orinoco Basin (Johnsson et al., 1988, 1991). The western parts are currently subsiding and contain sequences of coarse-grained clastic infill from the Andes, the deposition of which accelerated after major uplift of the Eastern Cordillera during the middle Miocene (Johnsson et al., 1988; Cooper et al., 1995). Following uplift, alluvial fans formed in the piedmont zone near the Eastern Cordillera and subsidence in the Casanare Province (Colombia), bounded by the Río Meta to the east, provided accommodation space for continued Pleistocene alluvial sedimentation, forming a merged and extensive "Alluvial Overflow Plain" (Goosen, 1971). Presently, there is repeated storage and fluvial reworking of sediments on the alluvial plain including, it seems, temporary storage as aeolian deposits (Johnsson et al., 1988).

Total rainfall across the Llanos ranges from 1000 to 2800 mm a^{-1}, increasing from 1200–1600 mm a^{-1} in the Venezuelan Llanos (Roa Morales, 1979) to 1800–2000 mm a^{-1} in the Colombian Llanos Orientales. Rainfall seasonality is extremely high and accordingly the Río Meta discharge is much reduced during the dry season (~400 m^3 s^{-1}) compared to the wet season (~8600 m^3 s^{-1}; Goosen, 1971). Similarly, the Orinoco River discharge downstream of the Llanos in Venezuela (Fig. 1) increases from 6000 m^3 s^{-1} in March to 60,000 m^3 s^{-1} in August (Nordin and Perez-Hernández, 1989). Seasonality is, however, spatially variable and the duration of the dry season shortens from five months (December–May) at the Colombian–Venezuelan border to two months near to Villavicencio in the southwest Llanos (Vélez et al., 2005). Wind speeds are highest during the dry season (Roa Morales, 1979; Nordin and Pérez-Hernández, 1989). In Venezuela, average wind speeds peak in February–April at 4.0–4.3 m s^{-1} (maximum speeds 16–19 m s^{-1}) and are dominantly from the ENE (Nordin and Pérez-Hernández, 1989).

Nine stabilised dunes were sampled in the western Llanos Orientales, Casanare Province, Colombia, along with two sites at northern margins of the Venezuelan Llanos dune systems in Guárico State, north of San Fernando de Apure (Fig. 1A and B). Sampling was guided by initial observations of satellite imagery, but was somewhat constrained in the field by safety concerns, which prevented sampling near to the Venezuelan/Colombia border, and by site accessibility (particularly the need for suitable river crossings). The contrasting drainage properties of the dune sands and the seasonally-flooded inter-dune areas (known locally as "*esteros*"; Fig. 2A) exert a strong influence on the vegetation cover, with the dunes typically covered with *Andropogon* sp. and *Aristida* sp. grasses (Berrío et al., 2002). The dunes are readily identifiable in remote sensing imagery (Figs. 3 and S1). The Orinoco dune systems in Venezuela, particularly in the "low Llanos" (Roa Morales, 1979) south of the Río Apure, are extensive and form parabolic, coalesced parabolic and linear (remnant elongated parabolic dune trailing arms) dunes (Roa Morales, 1979). Here, active dune crests can also be observed, possibly reflecting recent disturbance. The sample sites in the Venezuelan Llanos, north of the Río Apure, correspond to the "high Llanos" region and here the dunes, which are covered by oligotrophic savanna and dry deciduous and evergreen forest vegetation, are subtler, vegetated features that are seemingly more degraded and fragmentary than those of the low Llanos (Roa Morales, 1979).

Methods and materials

Field sites

The Llanos Orientales sample sites span ~120 km across Casanare Province from the western-most site (Finca Diamante, LL11/1, Fig. 1A) 38 km north of Orocue, to Finca La Hermosa (LL11/7, close to the River Meta and the town of La Hermosa). In the Llanos Orientales the dunes range from isolated low relief features with linear (elongate) morphologies, which are typical of the western parts of the study area, to much more extensive, laterally coalesced dune systems (Figs. 1A and 3) close to the Meta River in the northeast. The sampled dunes rise from ~2–3 m to as much as 20 m above the surrounding plains and in all cases were fully vegetated (Fig. 2). All of the dunes can be traced in an upwind direction to one of the NW–SE draining river channels that cross the study region, although the dunes and channels are today separated by extensive gallery forest vegetation (Figs. 1A, 3 and S1). In Venezuela, two vegetated dunes (Hato la Fe [S2] and Masaguaral [S3]) were sampled close to the town of Corozo Pando. Stabilised aeolian landforms in this region were previously described by Roa Morales (1979), who also reported the aforementioned radiocarbon ages from soils underlying the dunes. 160 km to the south, south of the Río Apure (Fig. 1A) vegetation cover on the dunes can be much sparser and active dune crests were observed. Here, an additional sample (1.2 m depth) from the active crest of one such dune (S1A1) was taken to provide a demonstration of OSL signal re-setting (Table S2).

For OSL dating, all of the dunes were sampled at their crest line and proximal to adjacent/upwind river channels. The samples were initially obtained via excavated pits. The Finca El Clavo site was studied in most detail and here three aligned dunes (Fig. 3C), sourced from the same

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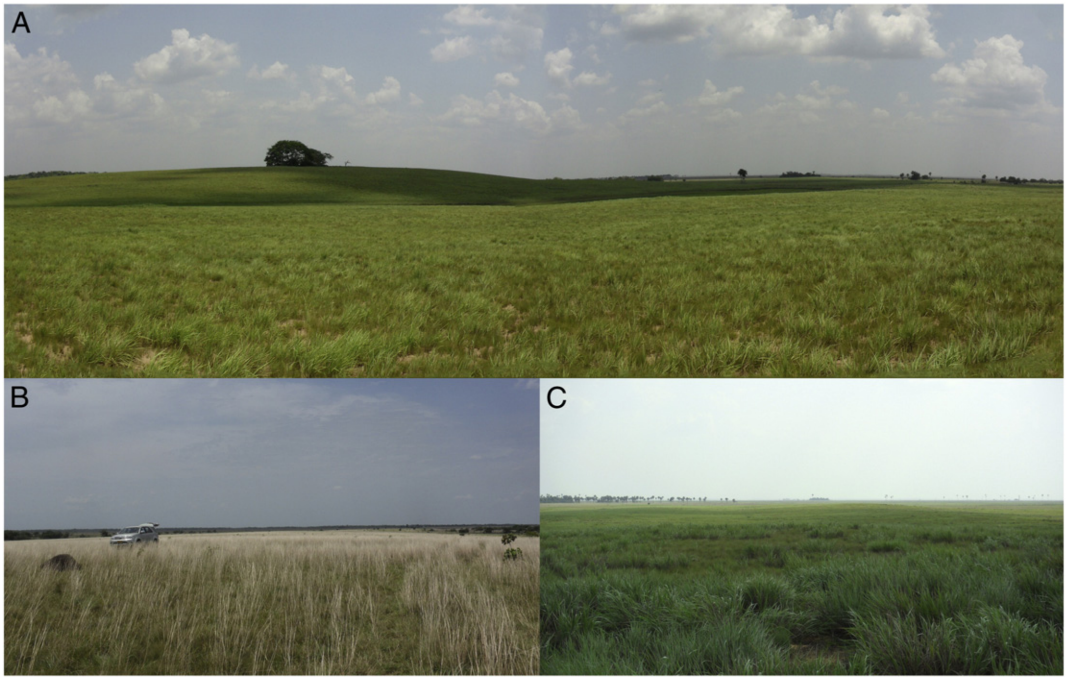

Fig. 2. Images of field sites A: Panoramic view looking obliquely downwind at site LL11/4 (Finca El Clavo), B: view downwind along the crest of LL11/1 (Finca Diamante), and C: view downwind along the crest of LL11/5 (Finca El Clavo).

channel (Río Yatea), were sampled. Later it was possible to revisit two dunes (LL11/4 and LL11/5) from Finca El Clavo to re-sample using a Dormer sand drill system, which permitted sampling to depths of 6 m. The augered samples are listed as LL12/1 and LL12/2 and were sampled within 20 m of the pits dug for LL11/4 and LL11/5 (respectively) (Table 1). Given the close association of the dunes with river channels,

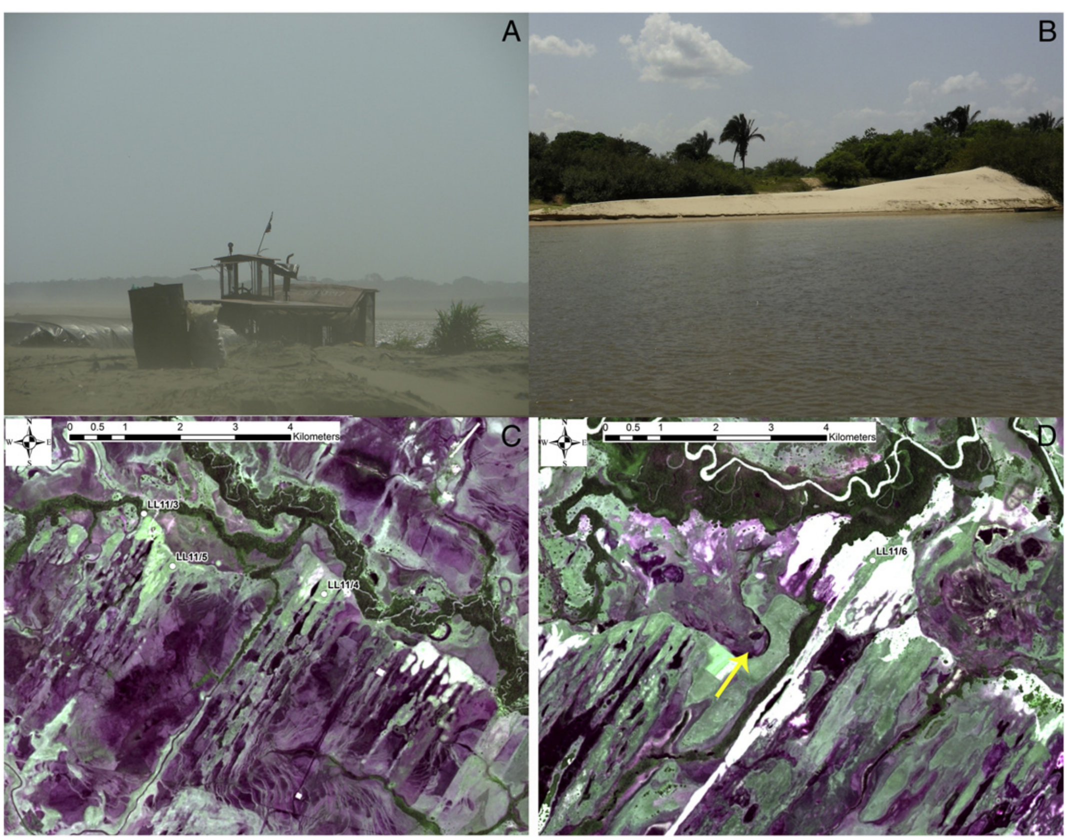

Fig. 3. A: Dust entrainment and sand movement on the shoreline of the Río Meta, April 2011. B: Sand bars exposed in the Caño la Hermosa close to site LL11/6. The adjacent *Mauritia* gallery forest can be seen in the background. C: Pan-sharpened Landsat 8 image of the Finca El Clavo sites (dunes LL11/3, LL11/4 and LL11/5 appear light green, *esteros* and surrounding alluvial plain purple and gallery forest around the Río Yatea appears dark green). D: Pan-sharpened Landsat 8 image of the Finca Palestina dune site (LL11/6). Note the eroded dune to the west of centre (yellow arrow). The river to the north of the image is the Caño la Hermosa.

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additional sediment samples were obtained from the sandy shorelines and bars of several rivers adjacent to the dunes to facilitate comparisons of sediment texture and geochemistry. The Río Yatea lies upwind of the dune sites at Finca El Clavo and the Caño la Hermosa lies upwind of the Finca Palestina (LL11/6) and Finca la Hermosa (LL11/7) dune sites (Fig. 1A; Table S4).

Laboratory methods

Particle size distributions (0.01–3000 μm) for dune and river sands were obtained using a Horiba LA950 laser particle size analyser following treatment with calgon dispersant. Metal oxide concentrations, used to calculate the chemical index of alteration (CIA; Nesbitt and Young, 1982), were determined via XRF (PANalytical Axios Advanced XRF spectrometer) at the University of Leicester with additional trace element concentration data determined via Inductively-Coupled Plasma-Mass Spectrometry (ICP-MS) at Royal Holloway, University of London.

Optically stimulated luminescence dating

Coarse-grained (180–212 μm) quartz extracts were prepared following standard methods and all OSL measurements were made on Risø DA20 TL/OSL readers. Stimulation (60 s at 125°C) was provided by blue LEDS (wavelength 470 nm) and OSL signals, derived from the first 0.5 s of stimulation (with a background signal obtained from the last 6 s), were detected with an EMI 9235QA photomultiplier tube via 7 mm of Hoya U-340 optical filter. All equivalent doses (D_e) were determined using the SAR protocol (Murray and Wintle, 2000, 2003) using small (2 mm) aliquots comprising approximately 150 individual grains. Aliquots showing poor OSL characteristics (recycling ratios outside 10% of unity, recuperation >5% of the natural OSL signal or evidence of feldspar contamination (Duller, 2003)) were rejected from the analysis. At least 16 aliquots passing these rejection criteria were used to determine the sample equivalent dose. Aliquot equivalent dose (D_e) estimates (Table 1) were derived using the Analyst software and the D_e uncertainties incorporate counting statistics, curve fitting uncertainties (Duller, 2007), a systematic instrument error (1.5%) and beta source calibration uncertainty (3%, Armitage and Bailey, 2005).

Dose rate determination

Environmental dose rates (Tables 1 and S1) were determined at Royal Holloway using ICP-MS for U and Th and ICP-OES or (if required) XRF at Leicester for K concentrations. These were converted to annual dose rates using standard conversion factors (Adamiec and Aitken, 1998) and adjusted for grain size (Mejdahl, 1979), HF etching (Bell, 1979) and water content (Aitken, 1985). Cosmic dose rate was calculated following Prescott and Hutton (1994). The assessment of the sample water content, which attenuates the radiation dose received by the quartz grains, represents an important source of uncertainty. The highly seasonal climate, coupled with the relatively surficial samples and field sampling at the end of the dry season, means that the measured water contents are potentially un-representative of the average burial water content. The applied 8 ± 5% water content with a large (absolute) uncertainty is considered capable of accounting for much of this variability, but it represents a constraint on the precision and accuracy of the reported ages. This is mitigated by the

Table 1
Optically stimulated luminescence dating results and summary data for the scatter in equivalent dose distributions. Further details of the dose rate determinations are provided in table S3. D_e distribution skewness was determined following Bailey and Arnold (2006), while CAM D_e and overdispersion were calculated following Galbraith et al. (1999). The age for LL12/2/6 using a water content of 8 ± 5% is 16.3 ± 1.1 ka. The dose rate and age for a 25 ± 5% water content are 1.61 ± 0.09 Gy ka^{-1} and 19.1 ± 1.3 ka.

	Site	Method	Depth (m)	N	CAM D_e (Gy)	OD (%)	Skew	Total dose rate (Gy ka^{-1})	CAM age (ka)
LL11/1/2	Finca Diamante	Pit	0.5	25	4.0 ± 0.3	25.9	0.73 ± 0.49	0.76 ± 0.04	5.3 ± 0.4
LL11/1/1		Pit	0.8	41	10.3 ± 0.4	16.1	0.85 ± 0.38	0.64 ± 0.03	16.2 ± 1.0
LL11/2/1	Finca el Danubia	Pit	0.65	31	3.3 ± 0.2	27.8	0.37 ± 0.43	0.65 ± 0.03	5.1 ± 0.4
LL11/2/2		Pit	1.0	20	6.9 ± 0.3	16.3	0.49 ± 0.55	0.65 ± 0.03	10.4 ± 0.7
LL11/2/3		Pit	1.65	30	10.4 ± 0.5	17.1	0.06 ± 0.45	0.70 ± 0.03	14.8 ± 1.0
LL11/3/1	Finca El Clavo (1)	Pit	0.6	32	2.8 ± 0.2	31.6	1.34 ± 0.43	0.61 ± 0.03	4.5 ± 0.4
LL11/3/2		Pit	1.2	33	3.7 ± 0.3	38.1	0.87 ± 0.43	0.58 ± 0.02	6.3 ± 0.5
LL11/4/1	Finca El Clavo (2)	Pit	1.0	24	7.8 ± 0.5	23.8	1.71 ± 0.5	0.60 ± 0.03	13.0 ± 1.0
LL11/4/2		Pit	1.8	32	10.0 ± 0.4	8.6	0.52 ± 0.43	0.65 ± 0.03	15.5 ± 0.9
LL12/1/1	Finca El Clavo (2)	Auger	1	32	8.3 ± 0.4	20.7	0.16 ± 0.45	0.51 ± 0.02	16.2 ± 1.0
LL12/1/2		Auger	2	18	9.4 ± 0.4	13.3	0.34 ± 0.58	0.46 ± 0.02	20.6 ± 1.3
LL12/1/3		Auger	3	18	9.0 ± 0.6	24.6	0.2 ± 0.52	0.49 ± 0.02	18.3 ± 1.5
LL12/1/4		Auger	4	29	10.0 ± 0.4	12.3	0.19 ± 0.45	0.43 ± 0.02	23.4 ± 1.4
LL12/1/5		Auger	5	18	14.3 ± 0.8	17.3	0.08 ± 0.58	0.66 ± 0.03	21.6 ± 1.6
LL12/1/6		Auger	6	30	19.5 ± 0.9	16.3	0.92 ± 0.45	0.75 ± 0.04	25.9 ± 1.7
LL11/5/1	Finca el Clavo (3)	Pit	1	21	8.3 ± 0.5	20.2	0.12 ± 0.53	0.66 ± 0.03	12.6 ± 0.9
LL11/5/2			2	41	10.1 ± 0.4	17.2	1.48 ± 0.77	0.46 ± 0.02	21.8 ± 1.2
LL12/2/2	Finca el Clavo (3)	Auger	2	19	10.4 ± 0.5	15.4	1.45 ± 0.53	0.61 ± 0.03	16.9 ± 1.1
LL12/2/3		Auger	3	26	11.2 ± 0.5	13.4	−0.09 ± 0.48	0.56 ± 0.03	20.0 ± 1.2
LL12/2/4		Auger	4	23	12.8 ± 0.6	16.3	0.41 ± 0.51	0.65 ± 0.03	19.8 ± 1.3
LL12/2/5		Auger	5	23	9.7 ± 0.6	23.1	0.1 ± 0.53	0.51 ± 0.02	19.0 ± 1.4
LL12/2/6		Auger	6	16	30.7 ± 1.2	7.0	−0.27 ± 0.61	1.46 ± 0.08#	21.1 ± 1.4
LL11/6/1	Finca Palestina	Pit	0.65	18	8.0 ± 0.6	25.2	0.69 ± 0.58	0.76 ± 0.03	10.5 ± 0.9
LL11/6/2		Pit	1.2	39	21.6 ± 1.1	19.1	0.23 ± 0.39	0.92 ± 0.04	23.6 ± 1.6
LL11/6/3		Pit	1.75	27	24.3 ± 1.0	10.7	−0.25 ± 0.47	0.75 ± 0.03	32.6 ± 1.9
LL11/7/1	Finca La Hermosa	Pit	0.75	43	10.6 ± 0.4	11.3	0.17 ± 0.37	0.82 ± 0.04	12.9 ± 0.7
LL11/8/1	Cuervas wells Gaitan	Cut	0.5	25	3.9 ± 0.3	28.6	1.61 ± 0.48	0.70 ± 0.03	5.6 ± 0.5
LL11/8/2		Cut	1.3	42	7.0 ± 0.3	17.2	0.22 ± 0.37	0.70 ± 0.03	10.0 ± 0.6
LL08/1/1	La Hermosa	Pit	1.0	25	30.7 ± 1.3	13.1	0.04 ± 0.49	0.64 ± 0.03	48.2 ± 2.8
LL08/1/2		Pit	2.0	33	35.0 ± 1.8	14.8	0.29 ± 0.43	0.53 ± 0.02	65.6 ± 4.2
S2 B1	Hato la Fe	Pit	1.0	20	5.2 ± 0.2	9.7	−0.03 ± 0.55	0.49 ± 0.02	10.6 ± 0.6
S2 A1		Pit	2.0	32	7.0 ± 0.3	11.4	0.81 ± 0.43	0.45 ± 0.02	15.6 ± 0.8
S3 B1	Masaguaral	Pit	1.0	22	5.2 ± 0.2	8.4	−0.12 ± 0.52	0.54 ± 0.02	9.7 ± 0.5
S3 A1		Pit	2.0	34	5.1 ± 0.2	11.5	0.11 ± 0.42	0.33 ± 0.01#	15.5 ± 0.8

#Ages for these samples are based on an estimated saturated water content of 37 ± 5% (see text).

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relatively high cosmic dose contribution to many samples, which comprises up to 42% of the total dose rate (average 26% Table S1) in some samples. A reduction of water content by 5% (in absolute terms) typically corresponds to a ~4% reduction in the resulting age. In the case of one sample (S3A1, Masaguaral), which lay close to the (dry season) water table, a saturated water content (37 ± 5%, Duller, 1996) was applied for the calculation of the annual dose rate.

Results

Dune morphology and sedimentology

The dunes in the Llanos Orientales are less extensive than those in the Venezuelan Llanos, particularly at the more humid western margins of the Colombian study area near to Orocue where they form isolated linear ridges (Fig. 1A). In the north of the Colombian sampling area the dunes are more extensive, particularly along the southwest margins of the Caño La Hermosa where we observe laterally (along the river channel) coalesced dunes that also display significant downwind (northeast-to-southwest) elongation. Digitisation of the dune features using satellite imagery demonstrates that the extent of down-wind elongation from the rivers, even for the more isolated dunes, can also be substantial (Fig. 1A, and S1). The southwestern-most site (LL11/1 — Finca El Diamante) extends up to 3.5 km from an upwind river channel. The largest sampled dune, site LL11/6 (Finca Palestina), forms part of a much wider system that can be traced downwind for ~10 km to the SW, and laterally along the west bank of the Caño La Hermosa upstream from its confluence with the Meta River for ~20 km (Fig. S1). In contrast to dunes in the "Lower" Llanos in Apure State (Venezuela) the sampled dunes in both Colombia and Venezuela (Fig. 1A and B) tend to form single downwind-extended (SW) ridges and they lack distinct parabolic nose/trailing arm features. However, dune long axis orientation in Colombia is very consistent, averaging 215 ± 3° for the sampled dunes. In several instances the dunes have clearly been eroded by more recent fluvial activity (Finca El Diamante (LL11/1) and Finca Palestina (LL11/6); Fig. 3D).

Throughout the study area the dune sands are strong brown (7YR 5/6) to yellowish brown (10YR 5/4) in colour, which contrasts with pale brown (10YR 6/3), greyish brown (2.5YR 5/2) and grey sands (10YR 5/1) found in the adjacent river channels. In section, the dune sands are relatively homogenous and present little evidence of sedimentary structure (Fig. S2). However, some features of relevance were apparent. At several sites (e.g. LL11/1, LL11/4, Masaguaral (S3) in Venezuela), plinthite nodules (e.g. Eze et al., 2014) have formed within 1 m of the surface, with strong red/grey mottling developed at Masaguaral. Additionally the upper 2 m LL11/4 at Finca El Clavo is characterised by coalescing and downwards-thickening clay lamellae. These are associated with enhanced clay and silt contents (>2 and >10% respectively) compared to (<1% clay and <5% silt) the sand body (e.g. Rawling, 2000).

The dunes are composed of sand-sized sediment (>75% sand, median grain size 1.0–2.6 ϕ), but with a significant tail of fines (up to 27% <63 μm or 4 ϕ), leading very negatively skewed particle size distributions (−0.4 to −0.5; Table S2; Fig. 4A). In several instances the proportion of fines increases down section from depths of around 0.7–1.0 m, reaching up to 27% < 63 μm at some sites. Texturally the dune sands are very similar at most sites (Fig. 4B) and they are finer-grained, more poorly sorted and more negatively skewed than the river sands. Exceptions to this are the three sites from Finca el Clavo, in particular LL11/3, which display textures more akin to the river sediments than the majority of dune sands; they are coarser grained, less skewed and better sorted than the other dune sites (Fig. 4). Observation of the dune sands using scanning electron microscopy (SEM) reveals the presence of fine-grained coatings on individual sand grains (Fig. 5A) as well as fine-grained aggregate particles (Fig. 5C). At LL11/4 (Finca El Clavo) many of the sand-sized grains are somewhat angular (Fig. 5B), but at other sites such as LL11/6 (Finca Palestina) the grains are more rounded (Fig. 5D). Energy dispersive X-ray analyses (EDXA) from the SEM observations demonstrate the presence of concentrations of iron on the surface of the sand grains and that the fine coatings on the grains are enriched in Al and Fe (Fig. S3).

The XRF and ICP-MS data demonstrate that the bulk dune sand composition is >97% silica (Table S3), indicative of a high mineralogical maturity (Muhs, 2004). The dune sands are depleted relative to Upper Continental Crust (UCC) composition (Taylor and McLennan, 1985) in several relatively mobile major and trace elements (Fig. 6). The concentrations of CaO, K_2O and Rb are particularly low, while the concentrations of Zr and Hf, which are associated with chemically-resistant minerals such as zircon, are moderately enhanced in some instances (Fig. 6B). The chemical index of alteration (Nesbitt and Young, 1982) for two of the dune samples exceeds 91 (Table S3). This compares to values of 70–79 for Orinoco River sands (calculated from the data presented by Johnsson et al., 1991; Table S3), which themselves are also considered mineralogically mature (98% SiO_2).

Optically stimulated luminescence dating

Sample OSL properties

Thirty-four OSL ages were obtained from 11 stabilised dunes (30 from Colombia and four from Venezuela). The intrinsic luminescence sensitivity of the quartz grains is variable, both within a single

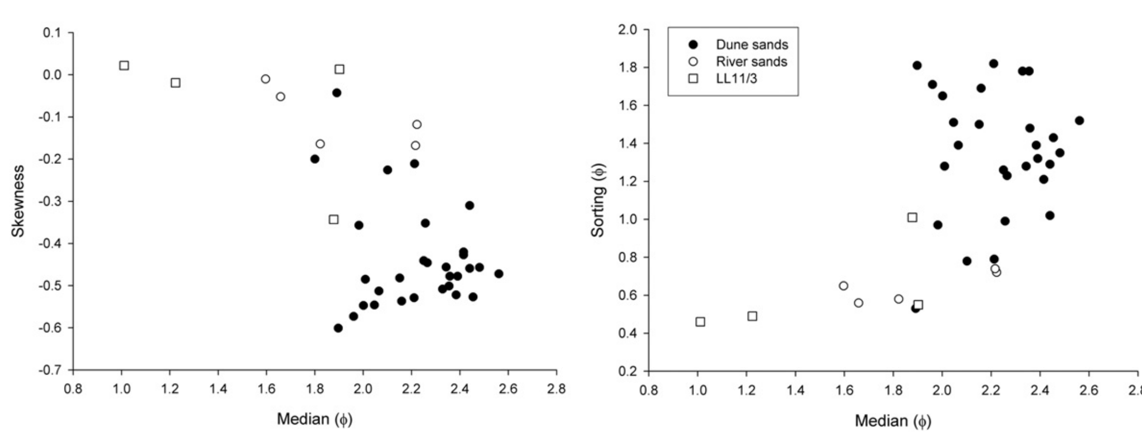

Fig. 4. Particle size distributions for river and dune sands compared. Site LL11/3 is marked as open squares to illustrate the textural contrast with the other dune sites.

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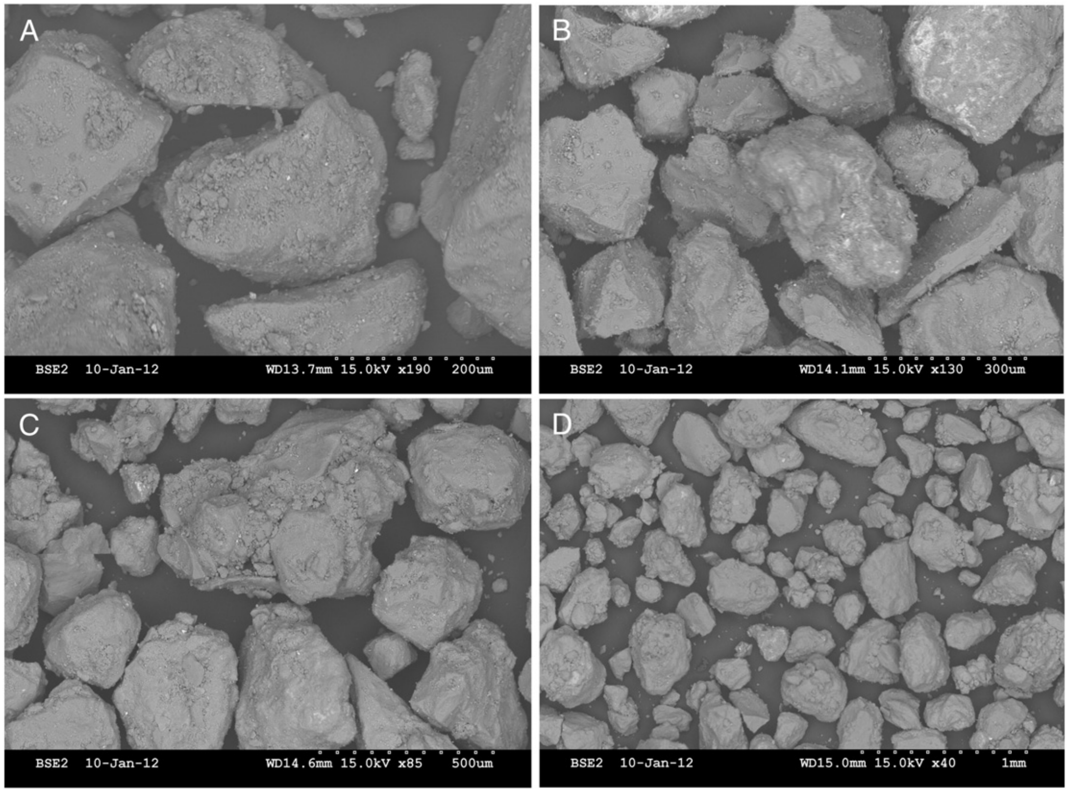

Fig. 5. SEM images of the dune sands A = LL11/1, B = LL11/4, and C = LL11/6 D = LL11/6. Note the presence of clay coatings (A), clay aggregates (C) and the angularity of several grains at site LL11/4 (B).

sample (Fig. 7C and D) and across the different sites. The latter is evidenced in the variable precision of individual aliquot equivalent dose estimates across some of the sites (Fig. 8). Although the present dataset is relatively small, it was also noticeable that the Venezuelan samples were more sensitive than the Colombian samples (measured OSL yields per unit dose per unit mass for Venezuela are on average three times those in Colombia). The sensitivity of the Colombian samples was also quite variable, however, with more than one order of magnitude variation in OSL sensitivity between some sites. This may reflect different sediment sources or differing degrees of grain sensitization through repeated burial and transport (Pietsch et al., 2008). Nonetheless, dose recovery experiments (Roberts et al., 1999; Wallinga et al., 2000) suggest that the SAR protocol is suitable for the samples in both Colombia and Venezuela (Fig. 7 and Fig. S4).

All equivalent dose (D_e) distributions show some overdispersion (OD, the relative spread of equivalent doses measured from individual aliquots after measurement uncertainties are excluded, Galbraith et al., 1999). Seven of the 34 equivalent dose distributions also exhibit significantly positively skewed D_e distributions (Fig. 8 and Table 1). OD values for the natural equivalent dose distributions range from 7% to 38% (Table 1). In contrast, OD values from dose recovery experiments on selected samples from the study (Fig. S4) range from 0.4 to 6.0%, demonstrating that the majority of the inter-aliquot scatter is generated in the depositional environment rather than by the measurement protocol. It has been shown that even undisturbed, well-bleached, multi-grain aliquots of quartz may produce D_e distributions that are overdispersed by between 9 and 19% (Jacobs et al., 2003). Larger inter-aliquot scatter for small aliquot datasets has been reported in other aeolian settings (e.g. Lomax et al., 2007). For comparable equivalent doses to this study Stone and Thomas (2008) and Telfer (2011) reported OD values of 10–61% and 14–20% (respectively) using 400 grain/3 mm aliquots of Kalahari sands. Using 2 mm aliquots Roskin et al. (2011) observed OD values between 3 and 100% for Negev Desert dunes. As observed here, they noted that high OD was mostly associated with surficial samples and, as here, the majority of samples produced OD values less than 25%. The OD observed in our dataset is therefore consistent with values reported for similar sedimentary settings and measurement conditions.

In terms of the specific sources of this overdispersion, inadequate bleaching prior to deposition is not generally considered to be a major source of the overdispersion in aeolian landforms. Considered further in the context of this study, we note that the potential source sediments (i.e. the river sands) do not exhibit fine grain coatings observed on the dune sands (i.e. the coatings are likely to be post-depositional features). Lomax et al. (2007) have also demonstrated that complete (albeit slower) bleaching of quartz still occurs in grains that have such coatings. In conjunction with the near-modern D_e obtained for the active dune at Río Verde (S1A1; Tables 1 and S2) we infer that inadequate bleaching is unlikely to be a significant source of our inter-aliquot scatter. The most scattered distributions are seen for the samples from LL11/1 (Finca Diamante) and particularly LL11/3 (Finca El Clavo site 1), but it is also noteworthy that at most sites OD is greatest in samples from the upper meter of the dune sediments. Post-depositional disturbance via bioturbation is therefore a plausible source of scatter. In many instances the D_e distributions are also broad rather than strongly skewed (Fig. 8; Table 1), which might be expected if grains are being moved both up (and possibly exhumed) and down profile. Beta dose rate heterogeneity, however, is also an additional potential contributor to inter-aliquot scatter in this context (e.g. Mayya et al., 2006). Consequently, all ages reported here were derived using the central age model (Galbraith et al., 1999), where the equivalent dose uncertainty takes into account the OD. With one exception (sample LL12/2/6 — but see below), this approach yields ages that are in stratigraphic order (cf. heavily bioturbated sites; Bateman et al., 2007; Bateman et al., 2008), thereby providing circumstantial support for the use of the central age model (CAM) equivalent dose estimate.

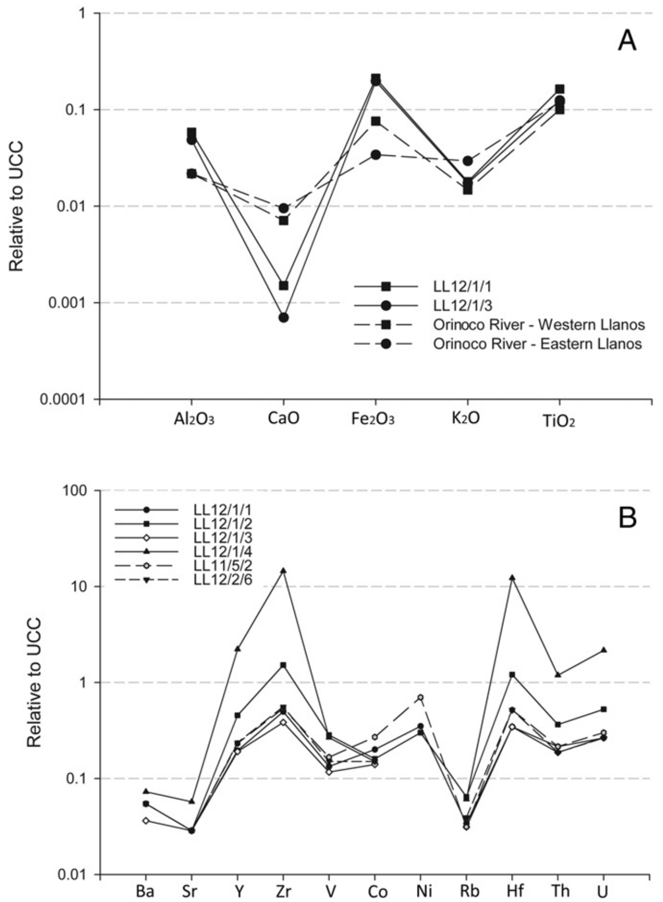

Fig. 6. – Metal oxide (A) and individual element concentrations (B) plotted relative to upper continental crust (UCC) concentrations (Taylor and McLennan, 1985) from selected dune sands in the Colombian Llanos.
The Orinoco River data were taken from Johnsson et al. (1991).

OSL ages

The OSL ages range from 4.5 ± 0.4 ka (LL11/3/1) to 66 ± 4 ka (LL08/1/2). (Table 1, Fig. 9). They indicate that the majority of sampled dunes predate the Holocene and that most were deposited during late Marine Isotope Stage (MIS) 2. The data also suggest that there may be substantially older dune sediments preserved at some locations (e.g. site LL08). The youngest site LL11/3 produced two mid Holocene ages, but also displayed the most overdispersed D_e distributions (Fig. 8). In the case of LL11/3/2, a distinct low dose cluster of aliquots may reflect exhumation and the presence of zero dose grains (Fig. 8). Ages from this site should thus be interpreted cautiously, pending further investigation. Otherwise, the only potential age inversion identified in the dataset is associated with the basal sample at site LL12/2/6 (Finca el Clavo). This sample has one of the least dispersed equivalent dose distributions (Fig. 8) and also one of the highest measured dose rates (Table 1). It is possible that the estimate of sample water content (near the base of the dune and closer to the seasonally flooded lowland areas) is not appropriate. Saturated sands, presumably indicating intersection with the water table, were directly observed at the base of S3 A1 (Masaguaral) in Venezuela. Age determinations for LL12/2/6 using an estimate of the saturated water content bring the age of LL12/2/6 in line with that of the overlying sample (LL12/2/5, 19.0 ± 1.4 ka) (Table 1). This is the case regardless of whether the estimated saturated water content is relatively high (37%; Duller, 1996 (21.1 ± 1.4 ka)) or low (25%; Bailey et al., 2001 (19.1 ± 1.3 ka)).

The challenges of identifying environmentally-meaningful "clusters" of dune activity from incompletely sampled dune systems are well-established (Stone and Thomas, 2008), but in the absence of significant prior information on the antiquity of these dune systems, several features of the available OSL chronology are noteworthy (Fig. 9). Holocene dune activity is clearly much more restricted than during the Pleistocene. However, where Holocene dune activity can be identified (see caveat above concerning LL11/3) it is confined to a relatively narrow time range (5.4 ± 0.7 ka, n = 5). Despite a sampling strategy biased towards near-surface (i.e. younger) samples, very few samples are younger than 10 ka, with the majority of ages relating to MIS2. During MIS2 a number of ages are consistent with deposition during the Last Glacial Maximum (21 ± 2 ka; Clark and Mix, 2002). The two 6 m sequences of dune sediment obtained from the cored dunes at Finca El Clavo (LL12/1 and LL12/2) are clearly clustered around this period. Finally, some significantly older dune activity occurred in the Llanos Orientales with ages from MIS3 (48.2 ± 2.8 ka) and the MIS4 (65.6 ± 4.2 ka) obtained from site LL08/1.

The two cored dunes at Finca El Clavo (LL12/1 and LL12/2) produce highly comparable ages and in both cases the sequences imply rapid accumulation (~1 m per thousand years) around the LGM, followed by slower depositional rates from 18 ka and then apparent stabilisation at ~12.5–13.5 ka. The ages from the upper 2 m of sediment at these sites, when considered in comparison to the lower 4 m, suggest a need for some caution when interpreting the age distributions at other sites where only relatively shallow (upper 2 m) samples were obtained, although in contrast, the extensive dune at Finca Palestina (LL11/6) produced an age of 33 ± 2 ka within 2 m of the surface, implying a much slower net rate of deposition on what is a much larger and (downwind) extended dune feature (Fig. 1A, Fig. S1). The full thickness of sand at this locale remains to be determined, but is potentially substantial. The same region, around the town of La Hermosa and close to the confluence of the Caño la Hermosa with the Río Meta, also illustrates a juxtaposition of dunes with very different ages (Fig. S5). The Finca la Hermosa (LL11/7/1) dune produced a near-surface OSL age of 12.9 ± 0.7 ka, while the dune 1.5 km to the east (LL08/1) is clearly of much greater antiquity (48.2 ± 2.8 ka and 65.6 ± 4.2 ka). The latter may represent the eroded remnants of an older dune as the course of the Caño La Hermosa appears to have changed substantially; the confluence with the Río Meta seemingly at one time further to the north of this site (Fig. S5). The sites from Masaguaral and Hato la Fe in Venezuela produce very comparable ages to one another, and fall with the late glacial age range of those from the Colombian Llanos, 350 km to the SW. As in Colombia, limited Holocene dune accumulation is implied and the older ages from both sites (15.5 ± 0.8 [S3A1] and 15.6 ± 0.8 ka [S2A1]) are broadly consistent with the radiocarbon ages (two sigma calibrated ranges of 11,600–13,770 cal yr BP and 13,210–15,910 cal yr BP), derived from material below dune sands (Roa Morales, 1979).

Discussion

Dune composition

The quartz-rich composition of the sediments, the fine grained tail within the particle size distributions, the presence of fine-grained coatings on the sand grains and clay/silt aggregates, as well as the high values for the CIA all contrast with the adjacent river sands and suggest significant *in-situ* chemical weathering of the dunes (e.g. Pye, 1981; Botha and Porat, 2007). Although the river sands (a possible approximation of the original composition of the dune sediments) themselves are mineralogically mature (Johnsson et al., 1991), significant post-depositional alternation has occurred within the dunes and rubification, presumably associated with formation of iron oxides (Fig. S1), is apparent (Pye, 1981). Plinthite formation, which was observed at several sites (Fig. S2), is a characteristic feature of weathering in tropical soils and its formation is typically associated with periodic oxidising/reducing conditions (Malagón and Ochoa, 1999). Here this is most likely associated with strong seasonal fluctuations in water

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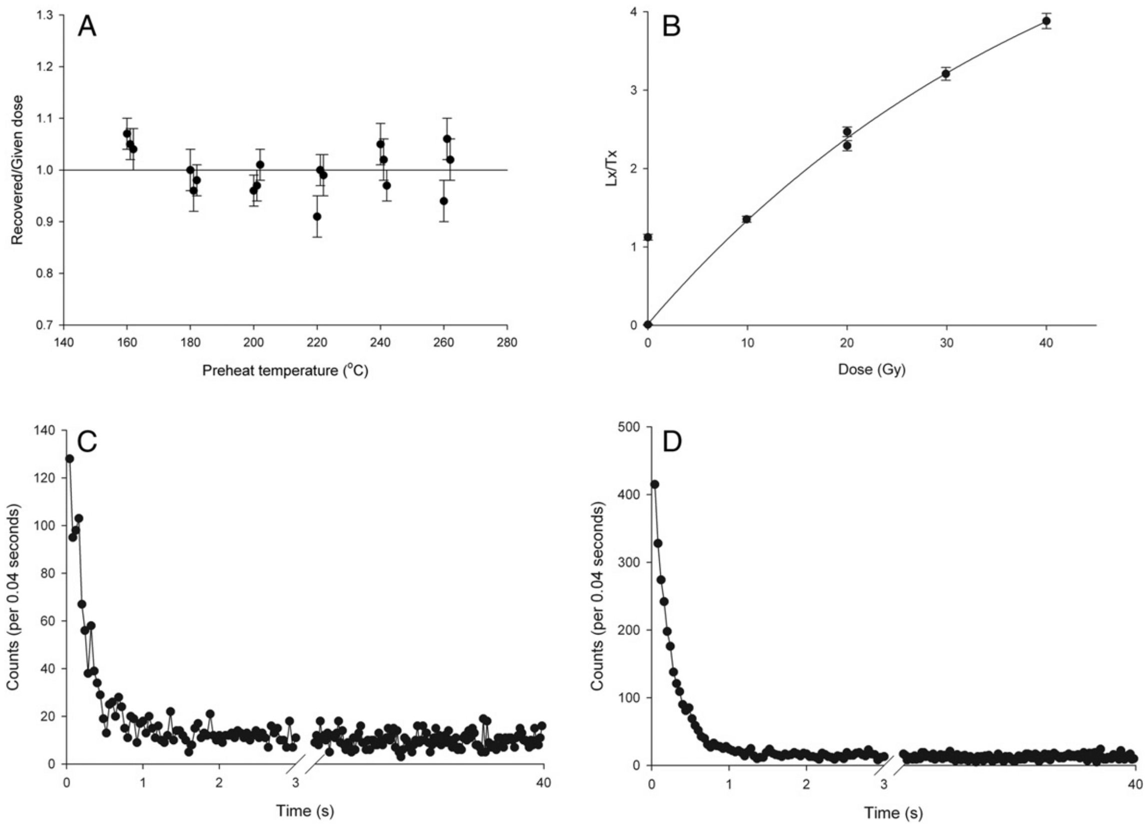

Fig. 7. Selected OSL data A: Results of a dose recovery preheat experiment for LL12/1/1 (Finca Diamante). The administered dose was 7.4 Gy. The measured mean for all aliquots (7.4 Gy) is plotted as a horizontal line B: Growth curve for a typical aliquot of LL11/6/1 (Finca Palestina). The natural sensitivity-corrected OSL signal is plotted on the Y axis. C and D: OSL shine down curves for aliquots prepared from LL11/4/2 (Finca El Clavo) illustrating the contrasting response of the brightest and dimmest aliquots to a 7.5 Gy test dose.

content (Sarmiento et al., 2004). The presence of fine-grained coatings and fine-grained aggregates, along with clay lamellae structures (likely formed via eluviation), which elsewhere have been demonstrated to become progressively better developed in older dune sediments (Holliday and Rawling, 2006), further suggest that the dunes have not been mobilised for some time. Overall, many of the features observed in the Llanos dunes are comparable to published descriptions of dune sand weathering and dune form degradation in tropical environments (e.g. Goudie et al., 1993).

OSL chronology for the Llanos dune systems

These data represent the first numerical age constraints for the Colombian Llanos Orientales dunes and serve to confirm their suspected late Pleistocene age (Fig. 9). Commonalities with the new age estimates from the Venezuelan Llanos are also observed, notably in the occurrence of late glacial dune accumulation. The available data imply that dune activity occurred throughout MIS2, and in at least one location (Finca El Clavo), this activity was focused around the LGM. A key observation is the limited occurrence of Holocene dune activity, which is confined to a single phase at 4.5–6.3 ka. This contrasts with tropical dunes described on the Branco River plains in Guyana to the east (Teeuw and Rhodes, 2004), which apparently accumulated throughout the Holocene, but it is consistent with the evidence for significant *in-situ* chemical weathering of the Llanos dune sands and the presence of pre-Holocene dunes elsewhere in tropical South America (Carneiro-Filho et al., 2002). The data also demonstrate variability in the dune history preserved at some sites, with evidence for both rapid, localized accumulation (e.g. Finca El Clavo), as well as more prolonged dune accumulation throughout MIS2 and MIS3 (e.g. Finca Palestina [LL11/6] and La Hermosa [LL08/1]). The ages from Colombia show similarities with those from Hato la Fe and Masaguaral in the Venezuelan Llanos, but more recent activity has also occurred in the Venezuelan Llanos. As well as our own observations of active dune crests in the "lower Llanos" south of the Río Apure recently-reported OSL ages for dunes near to the Río Portuguesa and further south near to the Río Capanaparo (González et al., 2013) range from 560 $\pm$ 50 years to 14,700 $\pm$ 1800 years. Although the relative uncertainties for these ages are large (the reasons for this and the method(s) of equivalent dose determination are not reported), they do show some similarities with our data in that we see late glacial and mid Holocene ages, and an absence of early Holocene ages. González et al. (2013) differ from the present study in the observation of relatively recent activity, which may reflect the less humid climate in the Venezuela Llanos, rendering the dunes more susceptible to remobilisation under current conditions. These younger ages are all confined to sites south of the Río Apure. The sites reported by González further north, near to the Río Portuguesa, are comparable to our study, spanning the mid-Holocene (4.5–6.5 ka) and the latest Pleistocene (10.5 ka). While the ages presented here are consistent with existing chronological data from the region, it appears that a longer (e.g. the ages from LL08/1 and the thickness of un-sampled dune sands at LL11/6), and probably more complex, aeolian sedimentation record exists in the Llanos than was previously supposed (cf. Roa Morales, 1979; Vaz and Miragaya, 1989; Colinvaux et al., 2000).

Controls on dune formation

Dune formation is controlled largely by variability in wind regime, sediment supply, and vegetation extent (driven in large part by moisture availability). The dunes are elongated to the southwest, parallel with the winter trade wind direction. It is readily apparent that the sampled dunes have all formed in close association with rivers draining to the southeast across the Llanos. The association with upwind rivers

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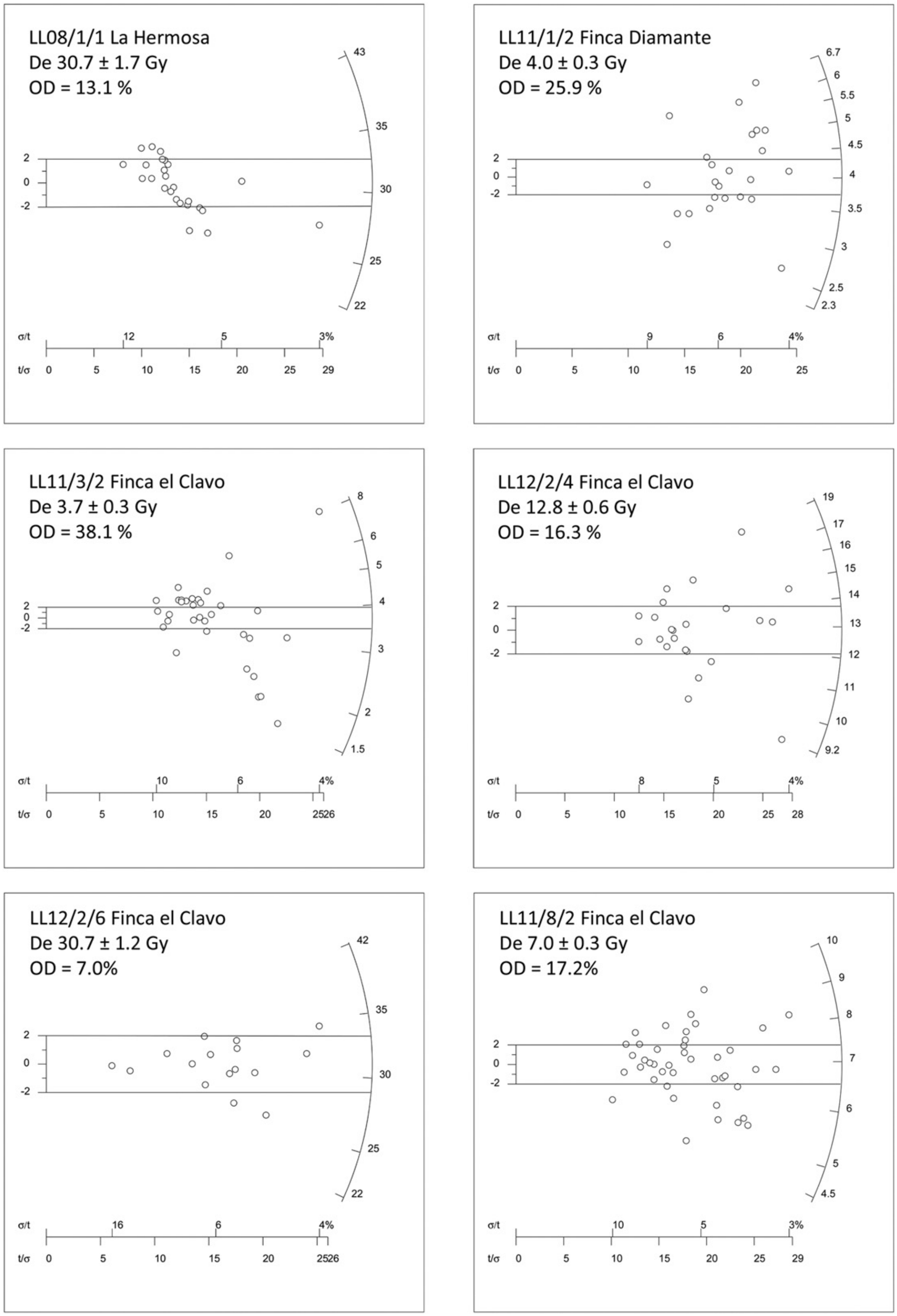

Fig. 8. Exemplar radial plots of equivalent doses for a range of samples across the study region. The bar is centred at the CAM equivalent dose, and all points that lie within the bar are consistent (at 2 standard errors) with this dose. Plotted using the Radial Plotter software. Vermeesch (2009).

implies that sediment supply is important in controlling phases of dune activity. This, in conjunction with the parabolic morphologies of the Llanos dunes (particularly in Venezuelan Llanos) leads us to interpret them as source-bordering features (Goosen, 1971; Roa Morales, 1979; Muhs and Holliday, 1995). Several other tropical South American (palaeo) dune systems show strong fluvial–aeolian coupling (De Oliveiria et al., 1999; Latrubesse et al., 2012; May, 2014; Tripaldi and Zárate, 2015), and active source-bordering systems are reported in the Bolivian Chaco (May, 2014). The formation of such systems need not be driven solely by changes in overall aridity. In Australia, relict source

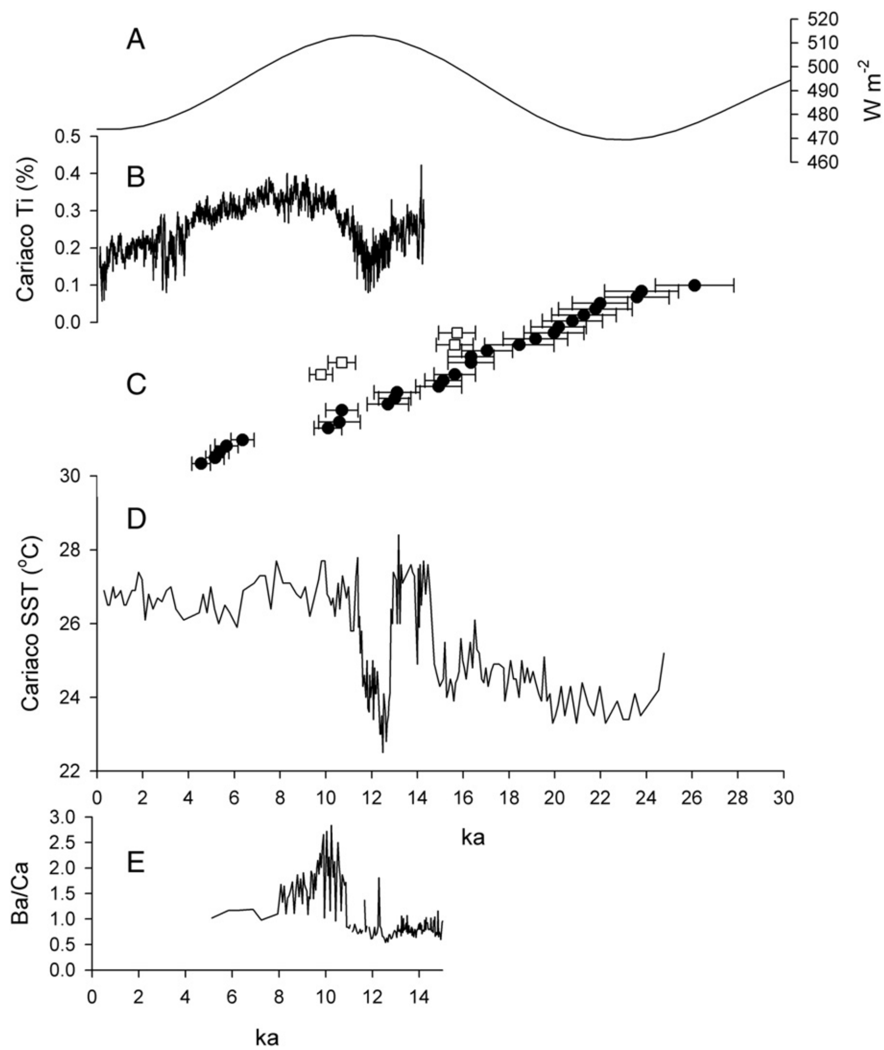

Fig. 9. OSL age distribution (C) from the Colombian Llanos (filled circles) and the four new ages from the Venezuelan Llanos (open squares). The ages are ranked and plotted on an arbitrary Y axis scale. They are plotted in relation to several datasets pertinent to consideration of the regional palaeoclimatic framework. A) June insolation at 0° latitude (Berger and Loutre, 1991), B) the Cariaco Ti (%) record for the Holocene, which has been interpreted as indicative of terrestrial runoff to the Cariaco Basin (Haug et al., 2001), C) Cariaco Basin sea surface temperature based on surface foraminifera Mg/Ca ratios, which has been linked to ITCZ migration (Lea et al., 2003), and D) foraminiferal Ba/Ca ratios from the Orinoco River mouth region, indicating an increased contribution of Andean/Llanos derived water to the Orinoco system 10.8–8 ka (Hoffman et al., 2014).

bordering dune systems dating to the late Pleistocene (Nanson et al., 1995; Page et al., 2001; Maroulis et al., 2007; Cohen et al., 2010) have been inferred to form under more seasonal climates, where the supply of sandy bed-load delivered to channels during the wet season is available for deflation from channels and bars during the subsequent dry season (Cohen et al., 2010).

Today, river discharge in the Llanos is highly seasonal, with extensive sand bars and sandy beaches forming during the January–March dry season (Fig. 3b). In the Orinoco River to the east of our study area, Nordin and Pérez-Hernández (1989) described the dry season exposure of up to 30–40% of the river bed and the rapid entrainment of sand to form dunes both within the channel and on the adjacent flood plain. In the Colombian Llanos Orientales, which is more humid than the sites described by Nordin and Pérez-Hernández (1989), the dunes are presently isolated from riverine sediment sources by dense stands of gallery forest (Berrío et al., 2000; Figs. 2, 3 and S1), which persist throughout the dry season. The extent of gallery forest in the Llanos is controlled by moisture availability and dry season severity (Behling and Hooghiemstra, 2000; Berrío et al, 2000, 2002; Wille et al., 2003), and gallery forest extent in some locations broadly maps to the zone of wet season inundation (Blydenstein, 1967). The extent of gallery forest seemingly fluctuated significantly during the late Pleistocene. Palynological data from Laguna el Piñal, to the south of our study area (Fig. 1), suggest reduced gallery forest abundance and drier conditions between 22,400–21,900 cal yr BP (UtC-5481; 18,290 ± 90 ^{14}C yr BP) and 12,790–12,620 cal yr BP (UtC-5834; 10,790 ± 60 ^{14}C yr BP) (Behling and Hooghiemstra, 1999). This trend is mirrored in Lake Valencia (Venezuela), which only became permanently inundated from c. 11,700–12,100 cal BP (Curtis et al., 1999). During MIS2 we propose that enhanced rainfall seasonality due to an extended dry season restricted gallery forest vegetation, which in combination with a more seasonal river flow regime (which would have maintained sediment supplies), increased potential for deflation of sands stored within channels, banks and bars, as well as the potential for erosion and exposure of pre-existing sediments due to periodic channel migration/flow (Khobzi, 1981). The net result would be the dry season formation of source-bordering dunes. The upper-most ages at several dune sites, the overall distribution of ages and available palynological data all suggest that this situation almost entirely ceased after 10 ka in the Llanos Orientales, and subsequently Holocene dune activity was rare. In some locations, river channels have clearly eroded the dunes (Figs. 3 and S4). The increasing importance of gallery forest and *Morichales* pollen types in palaeoecological records spanning the last 4000 years (Berrío et al., 2002, 2012) is consistent with a lack of late Holocene dune activity.

The largely Pleistocene age of the Llanos Orientales dune systems is apparent, as is marked inter-site variability in deposition rates (cf. Teeuw and Rhodes, 2004). Khobzi (1981) anticipated that dune formation in the Llanos would have required more arid conditions. Later van der Hammen and Hooghiemstra (2000) proposed that MIS2 rainfall in the Llanos would have needed to be reduced to as little as 50–60% of present values to generate "semi-desert conditions" (p. 731). The observation that the sampled dunes are likely to be source-bordering features moderates this statement, in that river flow would still be required to supply sediment. This was also recognised by Goosens (1971). However, in the Llanos Orientales a model of source-bordering dune accumulation implies a need for increased dry season length during both the LGM and much (some?) of the last glacial–interglacial transition, sufficient to restrict gallery forest extent. An obvious mechanism to increase seasonality is through the changing position of the ITCZ, particularly via a more southerly position during the boreal winter (e.g. Wang et al., 2004, 2006). Regional climate models have also simulated a much shorter LGM wet season and reduced annual rainfall in the northern tropics (Cook and Vizy, 2006). In the context of dune formation, the role of wind speed and sediment transport capacity should also be considered. Today trade wind speeds over northern South America are enhanced when North Atlantic SSTs are cooler (Black et al., 1999) and modelling evidence also suggests enhanced trade wind strength over northern South America during periods of North Atlantic cooling, both for LGM boundary conditions and for simulated abrupt North Atlantic freshwater forcing events (Broccoli et al., 2006). Although trade wind speeds on land are more complex to reconstruct, together these observations are consistent with evidence for MIS2 dune formation in the Llanos, whereby greater climatic seasonality and potentially enhanced surface wind speeds combined to promote widespread source-bordering dune formation.

The OSL age cluster centred at 10.3 ka (Fig. 9) represents the last evidence for significant dune mobilisation and this coincides with the onset of wetter early–mid Holocene conditions during 10.5–5.4 ka (Haug et al., 2001), as well as a shift in foraminiferal Ba/Ca ratios at the Orinoco River mouth (Hoffman et al., 2014) (Fig. 9). The latter was interpreted as a distinct pulse of north Andean-derived water entering the Orinoco system due to enhanced insolation-driven rainfall 10.8–8.0 ka (Hoffman et al., 2014). The gap in the OSL age distribution during the early Holocene is coincident with enhanced humidity inferred from the Cariaco Basin record (Haug et al., 2001) and the subsequent cluster of ages centred on 5.3 ± 0.7 ka coincides with an overall trend towards reduced terrestrial run-off. However, in spite of the subsequent continuation of this long-term aridity trend (Haug et al., 2001), including marked climatic variability 3.8–2.8 ka, the dunes that were sampled in the Colombian Llanos have seemingly remained stable since the mid Holocene. In contrast to the Cariaco record, local palaeoecological records are not suggestive of marked drying in the Colombian Llanos during the late Holocene and if anything suggest an increased abundance of gallery forest and palm swamp vegetation (Berrío et al., 2002, 2012), which would have limited sediment availability from the local river systems. Conversely, the dunes of the Venezuelan Llanos, south of the Río Apure, which today is a drier environment than our sites in Colombia, do show evidence of remobilisation in the late Holocene (González et al., 2013).

Finally, it is worth noting that this model of dune formation, in which sediment availability driven by seasonal river flow leads to aeolian transport and (geologically) instantaneous deposition within source-bordering dunes, has implications for the nature of preserved aeolian sedimentation record. In contrast to palaeo-linear dune systems, such as those in the Kalahari Desert, the continual availability of fresh sediment means that OSL age distributions from dunes may not be strongly skewed by reworking and biased towards to the last period of activity/the start of inactivity (e.g. Telfer and Hesse, 2013). There is no expectation that intense activity will lead to large-scale remobilisation of existing dune sediments, meaning there is potential for the preservation of long records of dune accumulation in this environment. Although fluvial reworking is apparent, the La Hermosa site (LL08/1) hints at this potential.

Conclusions

The Llanos savannas of Colombia and Venezuela are associated with an extensive coverage of aeolian landforms, which in the Colombian Llanos Orientales and Venezuelan Llanos sites investigated here, comprise well-vegetated and partially degraded source-bordering dunes. This work presents the first numerical age constraints for these landforms in Colombia and demonstrates that they are largely relict features that formed during the late Pleistocene. The majority of ages fall within MIS2, and although some near-surface samples suggest potential for mid Holocene activity or reworking, the majority of dune accumulation in this area ceased around 10 ka. These source-bordering dunes are presently isolated from fluvial sediment supplies by gallery forest systems. Enhanced late Pleistocene climatic seasonality is invoked to account for dune formation during MIS2. This would have restricted gallery forest extent and maintained a fluvial sediment supply for aeolian entrainment. A plausible mechanism for an increase in dry season duration is more southerly position of the ITCZ system, which is consistent with regional palaeoclimatic scenarios and can also account for the apparent absence of early Holocene dune formation. However, given the extent of the Llanos dunes, this model warrants further investigation in the context of a temporally and spatially expanded palaeodune activity dataset. The presently available data suggest both local-scale variation in dune accumulation records and that much older aeolian sediments may be preserved in some localities.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.yqres.2015.12.009.

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