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Aeolian cliff-top deposits and buried soils in the White River Badlands, South Dakota, USA

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Abstract: Aeolian deposits in the North American Great Plains are important sources of Holocene palaeoenvironmental records. Although there are extensive studies on loess and dune records in the region, little is known about records in aeolian cliff-top deposits. These are common on table (mesa) edges in the White River Badlands. These sediments typically have loam and sandy-loam textures with dominantly very fine sand, 0.5–1% organic carbon and 0.5–5% $CaCO_3$. Some of these aeolian deposits are atypically coarse and contain granules and fine pebbles. Buried soils within these deposits are weakly developed with A-C and A-AC-C profiles. Beneath these are buried soils with varying degrees of pedogenic development formed in fluvial, aeolian or colluvial deposits. Thickness and number of buried soils vary. However, late-Holocene soils from several localities have ages of approximately 1300, 2500 and 3700 ^{14}C yrs BP. The 1300 ^{14}C yr BP soil is cumulic, with a thicker and lighter A horizon. Soils beneath the cliff-top deposits are early-Holocene (typically 7900 but as old as 10000 ^{14}C yrs BP) at higher elevation (~950 m) tables, and late-Holocene (2900 ^{14}C yrs BP) at lower (~830 m) tables. These age estimates are based on total organic matter ^{14}C ages from the top 5 cm of buried soils, and agreement is good between an infrared stimulated luminescence age and bracketing ^{14}C ages. Our studies show that cliff-top aeolian deposits have a history similar to that of other aeolian deposits on the Great Plains, and they are another source of palaeoenvironmental data.

Key words: Aeolian, buried soil, cliff-top deposits, South Dakota, badlands, mesa, Great Plains, Holocene.

Introduction

Late-Quaternary aeolian deposits cover much of the semi-arid North American Great Plains (Thorp and Smith, 1952; Forman *et al.*, 2001; Muhs and Zárate, 2001). The processes responsible for these terrestrial sediments are very sensitive to climate and consequently provide information on Holocene and Pleistocene palaeoenvironments (e.g., Ahlbrandt *et al.*, 1983; Gaylord, 1990; Muhs and Maat, 1993; Madole, 1994; 1995; Holliday, 1995; 1997; 2001; Loope *et al.*, 1995; Muhs and Holliday, 1995; 2001; Muhs *et al.*, 1996; 1997a; 1997b; 1999a; 1999b; Mason *et al.*, 1997; Stokes and Swinehart, 1997; Wolfe, 1997; Swinehart, 1998; Arbogast and Johnson, 1998; Woodhouse and Overpeck, 1998; Wolfe and Lemming, 1999; Loope and Swinehart, 2000; Wolfe *et al.*, 2000; Forman *et al.*, 2001; Muhs and Zárate, 2001). Based on these studies, it is now believed that Holocene droughts were frequent on the Great Plains and the magnitude of these prehistoric droughts may have exceeded those historically documented for the region. However, correlating periods of inferred aridity between subregions (i.e., between individual dunefields) remains problematic (Muhs and Wolfe, 1999; Forman *et al.*, 2001). The apparent lack of regional synchrony has three potential explanations that are not mutually exclusive: (1) real subregional variability in climate; (2) non-climatic events reflected in the aeolian geomorphic record; or (3) poor resolution in numerical chronology. This last explanation is due largely to a reliance on soil organic matter derived radiocarbon ages with poor resolution and large uncertainties.

We studied soil stratigraphy and developed a chronology from seven sections in aeolian cliff-top (ACT) deposits in South Dakota. These results are part of a larger project that includes study of a variety of Quaternary aeolian deposits in the White River Badlands. ACT deposits are narrow mantles of sediment that thin rapidly away from escarpment crests (Sharp, 1949; Wilson, 1989;

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Pye and Tsoar, 1990; Hetu, 1992; Begin *et al.*, 1995; David, 1995). Unvegetated escarpment faces typically serve as a local sediment source for ACT deposits (Wilson, 1989; Hetu, 1992; Begin *et al.*, 1995; David, 1995), and processes contributing to the formation of ACT deposits are well documented. According to wind-tunnel investigations by Bowen and Lindsey (1977), as air passes over an escarpment its velocity increases and may be almost twice the original velocity at the crest. Flow separation takes place immediately beyond the crest and any sediments entrained during the acceleration are deposited. Based on research in southwestern Saskatchewan, David (1995) suggested that ACT sediment is derived from colluvium that forms on the slopes during dry periods. Soils form in the ACT deposits during moister periods when spring rains wash the source sediment completely downslope. Hetu (1992) further suggested that these processes are a significant component of bluff erosion, that infrequent high-magnitude storms may entrain 165 g material, and that the poor sorting typical of ACT deposits results from variable wind-gust speeds and the deposition of sediments on snow (nivation).

Previous studies have noted the presence of ACT deposits in the White River Badlands of South Dakota (White, 1960; Harksen, 1967; 1968; Harksen and Macdonald, 1969). Harksen (1967) was among the first to conduct detailed studies of aeolian deposits on upland surfaces in the badlands. Although his interest was drawn primarily to older aeolian deposits, which he formally named the Red Dog Loess (Harksen, 1968), he did document the presence of younger aeolian deposits, including ACT deposits. Harksen (1968) and Briggs (1974) suggested the soil at the base of these deposits correlated with the Sangamon Geosol that is widely preserved in the North American midcontinent.

In an earlier paper, White (1960) argued that the ACT deposits and multiple buried soils observed in upland situations in the badlands were Holocene, based on the presence of archaeological evidence within the buried soils of the ACT deposits. White (1960) also recognized the potential palaeoenvironmental significance of the ACT record and hypothesized that periods of buried soil formation represented relatively mesic climatic conditions. In contrast, he thought that periods of more active aeolian accumulation correlated with relatively xeric conditions. White (1960) further suggested that a regional correlation of these postglacial aeolian deposits might be possible. In this paper, we test the hypotheses of previous workers who have studied ACT deposits in the White River Badlands. Detailed stratigraphic, pedologic and geochronologic investigations allow us to infer the timing of aeolian activity in this area and compare the chronology to others in the Great Plains.

Study area

The study area is located in the White River Badlands of South Dakota, USA, and includes Badlands National Park and Buffalo Gap National Grassland (Figure 1). The White River Badlands area is well known for Tertiary mammalian fauna and has been investigated by geologists since the mid-nineteenth century (see Macdonald, 1951, for a review of that literature). However, with the exception of some modern erosion-rate studies (Schumm, 1956; Hadley and Schumm, 1961), little work exists on the Holocene stratigraphy or geomorphology of the area. ACT deposits occur at approximately two elevations: a parabolic dune-covered surface at 830 m elevation, which is the interfluve between tributaries of the White River, and a surface at 950 m elevation covered by fluvial deposits, parabolic dunes and loess. This latter surface is the interfluve between the White and Cheyenne Rivers (Figure 1).

The study area lies within the heart of the semi-arid mixed-grass ecosystem of the Great Plains. Average annual precipitation is approximately 400 mm, over half of which falls during the spring and early summer. Annual average temperature for the area is 10.3°C, with an average growing-season temperature around 20°C (Owenby and Ezell, 1992). Climate, constrained by local edaphic conditions, results in the mixed-grassland cover dominated by western wheatgrass (*Agropyron smithii*), needle grasses (*Stipa* spp.), grama grasses (*Bouteloua* spp.) and buffalo grass (*Buchloë dactyloides*) (Küchler, 1964).

Methods

ACT deposits were studied at seven natural exposures along table edges at Norbeck Pass (~850 m), Bouquet Table (~830 m), Cuny Table (~950 m) and Sheep Mountain Table (~950 m). Soils and sediments were described and sampled for characterization following methods outlined in Catt (1990) and Birkeland (1999). Laboratory characterizations include determination of particle-size distribution by the hydrometer method and sieving of the sand fraction (Gee and Bauder, 1986), organic carbon content by the dichromate method (Allison, 1965; Janitsky, 1986), and total carbonate content with a Chittick apparatus (Machette, 1986).

This study relies on total soil organic carbon ages because macrofossils are rarely preserved in Great Plains aeolian sediments. Organic carbon is commonly dated from buried soils in Great Plains aeolian deposits and typically yields results that are stratigraphically consistent and in good agreement with ages from other material (e.g. charcoal ^{14}C ages or luminescence ages) (Haas *et al.*, 1986; Martin and Johnson, 1995; Holliday, 2001). These soils tend to be slightly carcareous and are not as problematic as ages from soils where podzolization is a dominant pedogenic process (Matthews, 1980; Geyh and Roeschmann, 1983). However, different organic fractions from the same soil may yield ages that vary by as much as 1000 years (Martin and Johnson, 1995) and have a natural age/depth gradient as much as 700 years per cm (Matthews, 1981). As Catt (1990) notes, soil ^{14}C ages indicate apparent mean residence times of the organic matter contained within them, and, assuming no contamination, provide a maximum age for overlying deposits and a minimum age for underlying deposits.

The upper 5 cm of buried A-horizons were collected for radiocarbon dating from natural exposures that were cleaned at least 0.5 m into the exposed face, and were then pretreated following Johnson and Valastro (1994) to minimize contamination. Pretreatment included removal of any modern rootlets with a 53 μm sieve, removal of the sand fraction to concentrate organic matter and removal of $CaCO_3$ with 2 N HCl. Radiocarbon ages were determined at the Illinois State Geological Survey (ISGS) by the liquid scintillation counting method, the INSTAAR AMS Radiocarbon Preparation and Research Laboratory (NSRL) and the NSF Arizona AMS Laboratory (AA). Radiocarbon ages are corrected for δ^{13}C fractionation and are reported in ^{14}C yr BP. Calibrated ages are presented in Table 1 and, because soils form over a period of time and do not yield a discrete age but rather an integration of all the organic matter that has accumulated and been mixed by various pedoturbations, calendar age ranges are reported at two standard deviations. Calibrated ages were determined using the CALIB 4.3 program (Stuiver and Reimer, 1993).

Luminescence analysis was performed at the US Geological Survey Luminescence Laboratory in Denver, Colorado, with Daybreak Thermoluminescence (TL) systems using Schott BG-39 and Kopp 7–59 as well as a Pyrex window for filters under the photomultiplier tube for infrared stimulated (IRSL) analysis. IRSL and TL techniques were applied to the same aliquots. IRSL is measured on multiple aliquots using natural sunlight in Denver Colorado as a bleach.

The dose delivered to the samples comes from ^{40}K, mainly

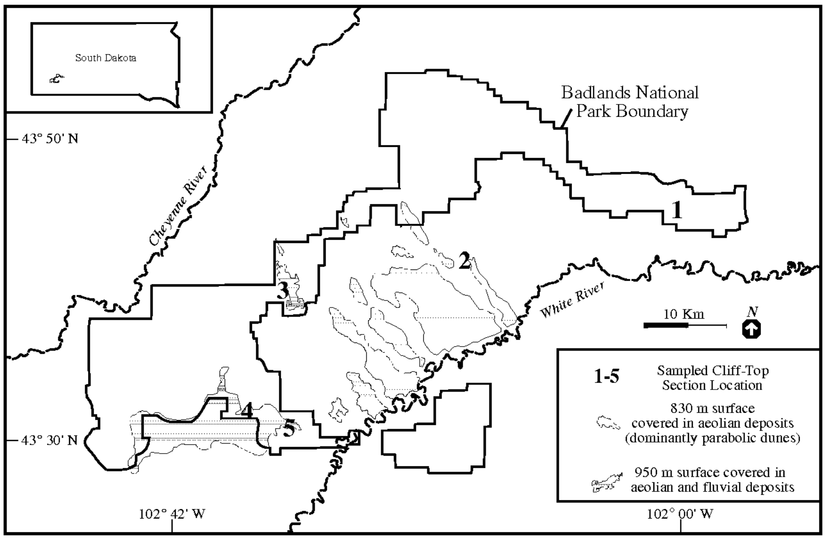

Figure 1 Locations of the study area within South Dakota (inset) and the sampled ACT deposit sections: (1) Norbeck Pass; (2) Bouquet Table; (3) Sheep Mountain Table; (4) Cuny Table Nellie sections; (5) Cuny Table Frieda section.

from alpha, beta and gamma radiation emitted by ^{238}U/^{234}U and ^{232}Th and their daughter products in the sediment matrix. Cosmic-ray contributions accounted for 2.5–3.25% of the dose for the sample. These contributions were obtained via calculation of present depth, elevation and latitude of the sample using tables from Prescott and Stephan (1982). Concentrations of K, U and Th were determined by instrumental neutron activation analyses (INAA). Gamma-ray spectrometry also allows the calculation of U and Th concentrations by measurement of activities of late daughters in the chain. Gamma-ray spectrometry is then used to obtain limits or measures of the possible extent of any radioactive disequilibrium in the U and Th decay chains when compared against the INAA analyses, and to allow for heterogeneity in the sediment matrix. These analyses are used for quality control only, and the dose rate was calculated from the INAA values. The water contents used for the dose-rate calculations were the field values, with an uncertainty that should encompass the extremes at $\pm 2\sigma$.

Stratigraphy

All sections examined contain buried soils formed in fluvial, aeolian or colluvial sediments that are overlain by ACT deposits. These lowest-buried soils are typically ~7900 ^{14}C yrs BP at higher-elevation tables, and ~2900 ^{14}C yrs BP at lower tables (Figure 2). ACT sediments typically have loam and sandy-loam textures with dominantly very fine sand, 0.5–1% organic carbon and 0.5–5% CaCO$_3$. Sand ranges from 32 to 85%, and occasional (<1%) pebbles occur where coarse grains are located downslope and are hence available for transport by wind gusts. However, some ACT deposits on Cuny Table contain over 50% pebbles above the shallowest, probably late-Holocene, buried soil. Hetu (1992) also documents ACT deposits that are coarser than typical aeolian deposits. The ACT deposits are thought to be aeolian because they are located at cliff edges at the highest point in the landscape, are restricted to within 10–15 m of cliff edges, and only contain pebble-size grains where they are exposed lower in the cliff face (Figure 3). Thickness of the ACT deposits and number of buried A-C and A-AC-C soils within them vary, although late-Holocene soils from several localities have average ages of ~1300, ~2500 and ~3700 ^{14}C yrs BP (Figure 2). The 1300 ^{14}C yr BP soil is cumulic, with a thicker and lighter A horizon. Above the uppermost-buried soils are about 1 m of crudely laminated ACT deposits. The modern surface is vegetated but there is no A horizon developed in it.

Sheep Mountain Table (~950 m elevation)

The lowest stratigraphic unit at Sheep Mountain Table (Figure 1) is 3–4 m of interbedded very fine sand/coarse silt and silty gravel. This is overlain by 22 cm of well-sorted fine loamy sand, then 18 cm of gravelly sandy loam, and then a buried soil with an ABb4-BCb4 profile. The ABb4 horizon has the colour of an A horizon, but also has a strong subangular blocky structure more typical of a B horizon, and is developed in clay loam. Several splits of a sample from this horizon were radiocarbon dated at different laboratories (Table 1) and range in age from 5850 to 6910 ^{14}C yr BP. The bottom of the ABb4 has an age of 7790 ± 170 ^{14}C yr BP (NSRL-10914). Above this soil is 215 cm of ACT deposits that have loam textures, 0.4 to 0.8% organic carbon, 0.9 to 5.4% CaCO$_3$, and contain three buried soils with A-C profiles (Figure 4; and Table 2). The lowest soil in the ACT deposits has an age of 3800 ± 70 ^{14}C yr BP (ISGS-4200), the middle soil has an age of 2390 ± 70 ^{14}C yr BP (ISGS-4197), and the uppermost soil has an age 1310 ± 70 ^{14}C yr BP (ISGS-4195) from the top 5 cm and 2070 ± 70 ^{14}C yr BP (ISGS-4196) from the bottom 5 cm. In addition to the soil ages, charcoal was collected at 90 cm below the surface and has an age of 405 ± 150 ^{14}C yr BP (NSRL-10632). Luminescence ages (Table 3) agree well with the soil radiocarbon ages and are 2680 ± 150 (IRSL), 3380 ± 210 (TL total bleach method), and 3130 ± 1190 years ago (TL partial bleach method). These are splits from a sample collected between the Ab2 (2390 ^{14}C yr BP) and Ab3 (3800 ^{14}C yr BP) soils.

Cuny Table (~950 m elevation)

Four sections were studied on Cuny Table, here informally referred to as the Nellie, Nellie West, Nellie East and Frieda sections. These sections are located on the northeast side of Cuny Table along its north-facing bluff (Figure 1). The three Nellie sections are all within 500 m of each other. The lowest-buried soil at the Nellie section has an Ab4-A/Cb4-Cb4 profile, is developed in aeolian sand and yielded an age of 7910 ± 160 ^{14}C yr BP (NSRL-10917). Above this soil is 220 cm of ACT deposits with sandy loam to clay loam textures, 0.4 to 0.8% organic carbon, 0.9 to 5.4% CaCO$_3$ and three buried soils with Ab-Cb profiles. The middle of these has an Ab2-A/Cb2 profile and an age of 2540 ± 39 ^{14}C yr BP (AA-39204). The uppermost-buried soil has a cumulic A horizon 42 cm thick that is darkest between 20 and 28 cm (10 YR 3/1 versus 10 YR 3/2). The top of cumulic Ab1 has an age of 1287 ± 41 ^{14}C yr BP (AA-39205) and the middle darker zone has an age of 1418 ± 38 ^{14}C yr BP (AA-39203).

At the Nellie West section the lowest-buried soil is formed in

Table 1 Calibrated radiocarbon ages

Section	Horizon sampled	Collection depth (cm from surface)	Lab. number	Material dated	Corrected age (^{14}C yr BP)	Calibrated age* (calendar yr BP)	Range (2 sigma)**	δ^{13}C ‰
Bouquet Table	Ab2 top	56–61	NSRL-11259	Total OM***	1280 ± 30	1186, 1201, 1235, 1251, 1257	(1154–1286)	–18.4
	Ab4 top	100–105	NSRL-11260	Total OM	2950 ± 45	3079, 3091, 3105, 3128, 3138, 3152, 3156	(2953–3317)	–16.4
Norbeck Pass	Ab1 top	75–80	AA-39199	Total OM	1333 ± 38	1278	(1176–1306)	–20.2
	Ab2 top	135–140	AA-39200	Total OM	3654 ± 42	3932, 3939, 3977	(3839–4090)	–17.4
Sheep Mountain Table	Charcoal	90	NSRL-10632	Charcoal	405 ± 140	496	(303–543)	–19.4
	Ab1 top	100–105	ISGS-4195	Total OM	1310 ± 70	1263	(1062–1334)	–19.3
	Ab1 bot	147–152	ISGS-4196	Total OM	2070 ± 70	2003, 2030, 2036	(1874–2302)	–19.1
	Ab2 top	162–167	ISGS-4197	Total OM	2390 ± 70	2355	(2211–2725)	–19.6
	Ab3 top	190–195	ISGS-4200	Total OM	3800 ± 70	4152, 4174, 4207, 4219	(3934–4415)	–19.4
	ABb4 top	220–225	NSRL-10629	Total OM	5850 ± 195	6665, 6712, 6714	(6283–7207)	–17.8
	ABb4 top	220–225	ISGS-4201	Total OM	6340 ± 70	7265	(7031–7424)	–19.7
	ABb4 top	220–225	NSRL-10631	Base Soluble OM	6870 ± 155	7679	(7432–7973)	–19.3
	ABb4 top	220–225	NSRL-10630	Base Soluble OM	6910 ± 185	7968, 7709, 7719	(7430–8146)	–19.7
	ABb4 bot	260–265	NSRL-10914	Base Soluble OM	7790 ± 170	8560, 8567, 8588	(8205–9029)	–18.8
Cuny Table – Nellie	Ab1 top	100–105	AA-39205	Total OM	1287 ± 41	1190, 1198, 1240, 1248, 1258	(1094–1291)	–20.9
	Ab1 mid	120–125	AA-39203	Total OM	1418 ± 38	1307	(1279–1388)	–21.3
	Ab3 top	151–156	AA-39204	Total OM	2540 ± 39	2728	(2471–2750)	–20.4
	Ab4 top	220–225	NSRL-10917	TotalOM	7910 ± 60	8651, 8670, 8697	(8545–9003)	–20.2
Cuny Table – Nellie West	Ab2 top	177–182	NSRL-11255	Total OM	1390 ± 70	1294	(1175–1411)	–18.9
	ABb3 top	210–215	AA-39201	Total OM	2547 ± 40	2734	(2473–2751)	–20.9
	Ab4 top	265–270	AA-39202	Total OM	7859 ± 52	8605, 8621, 8627	(8483–8979)	–19.3
Cuny Table – Nellie East	Lowest Ab top	280–285	NSRL-10918	Total OM	10400 ± 70	12337	(11784–12837)	–21.3
Cuny Table Frieda	Ab1 top	180–185	NSRL-11256	Total OM	2790 ± 65	2870, 2913, 2915	(2760–3136)	–18.1
	Ab2 top	210–215	NSRL-11257	Total OM	3640 ± 55	3929, 3945, 3967	(3780–4144)	–18.4
	Ab3 top	290–295	NSRL-11258	Total OM	7990 ± 55	8812, 8826, 8871, 8876, 8903, 8907, 8983	(8614–9025)	–18.9

*Radiocarbon ages were calibrated using the CALIB 4.3 program (Stuiver and Reimer, 1993).
**Age range for charocal sample is one sigma.
***Organic matter.

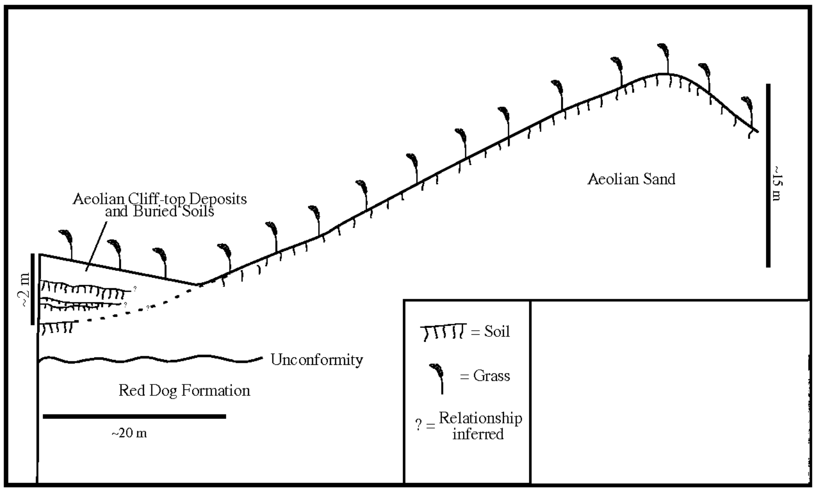

Figure 2 Schematic of aeolian cliff-top deposits, buried soils and other Quaternary deposits. Question marks and dashed lines represent inferred relationships. The relationships shown here are based on auger samples at the Nellie section at Cuny Table. Scales are approximate and vary. The arrow in the inset photograph points to the lowest buried soil at Sheep Mountain Table, above which there are 2 m of ACT deposits.

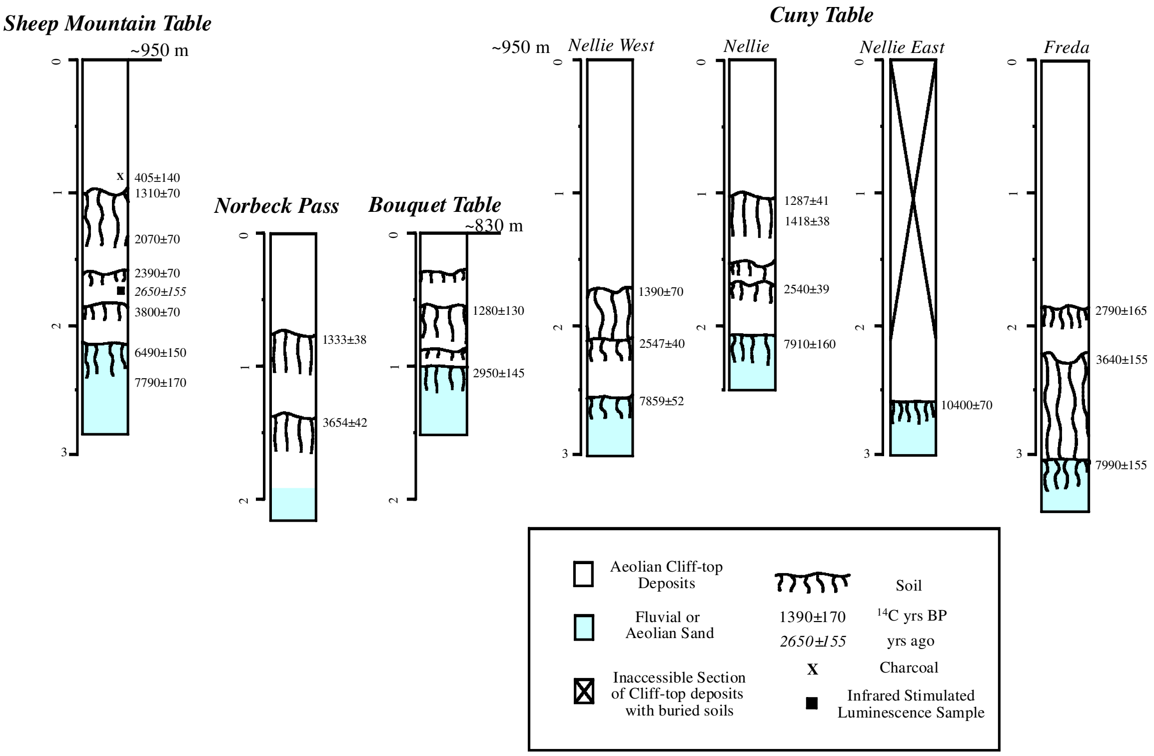

Figure 3 Studied stratigraphic sections naturally exposed in the White River Badlands. Elevations are approximate; depths are in metres from the surface.

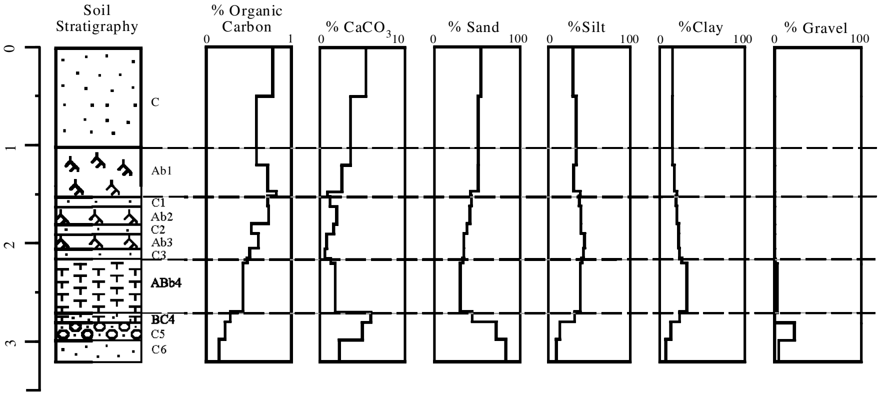

Figure 4 Soil stratigraphy, percent organic carbon, percent calcium carbonate and particle-size distribution at the Sheep Mountain Table section. These data are typical of the cliff-top deposits, although the underlying sediments vary (see text).

Table 2 Luminescence ages of splits from a sample collected at Sheep Mountain Table. The Ab2 (162–167cm) soil above this sample has an age of 2390 ± 70 ^{14}C yrs BP (ISGS 4197) and the Ab3 (190–195cm) soil below has an age of 3800 ± 70 ^{14}C yrs BP (ISGS –4200)

Ages	K (%)	U (ppm)	Th (ppm)	Elevation (m)	Depth (cm)	H_2O (%)	Dose rate
2680 ± 150 (IRSL)	2.05	3.04	11.20	945	180	18	4.74
3380 ± 210 (TL Total Bleach)	2.05	3.04	11.20	945	180	18	4.74
3130 ± 1190 (TL Partial Bleach)	2.05	3.04	11.20	945	180	18	4.74

Table 3 Sediment characteristics of the Sheep Mountain Table section

Sample ID	% Organic C	% CaCO3	% Clay	% Silt	% Sand	% VC	% C	% M	% F	% VF	% >2 mm	USDA texture class
0–50 cm C1	0.8	5.4	15	31	54	1	4	14	44	37	0	Sandy loam
50–100 C2	0.6	3.6	15	33	51	0	4	14	49	32	0	Loam
100–147 Cumulic Ab1 that includes 147–152	0.7	2.6	17	31	51	0	2	10	42	45	0	Loam
147–152 Ab1 (darker)	0.8	0.9	19	39	42	0	2	7	42	49	0	Loam
152–162 Cb1	0.7	1.3	19	37	43	0	1	6	33	49	0	Loam
162–180 Ab2	0.7	1.9	20	40	41	0	1	5	41	53	0	Loam
180–190 Cb2	0.5	1.6	21	40	38	0	1	6	36	57	0	Loam
190–205 Ab3	0.6	0.8	22	44	34	0	2	6	37	55	0	Loam
205–215 Cb3	0.5	0.6	23	43	34	1	6	12	34	47	1	Loam
215–220 ABb4 (darker)	0.5	1.3	26	41	33	1	8	14	39	38	1	Loam
215–270 ABb4	0.4	1.8	32	39	30	1	7	17	37	36	3	Clay loam
270–280 BCb4	0.3	6.0	23	32	44	3	12	19	39	27	0	Loam
280–298 Gravel	0.2	5.0	13	15	72	5	14	25	38	19	23	Gravelly sandy loam
298–320 Sand	0.1	2.3	7	10	83	2	12	21	46	19	5	Loamy sand
320+ Laminated silt/VF Sand (Red Dog Loess?)	0.1	4.7	11	72	16	0	1	2	10	87	0	Silt loam

VC = 2–1 mm; C = 1–0.5 mm; M = 0.5–0.25 mm; F = 0.25–0.125 mm; VF = 0.125–0.053 mm.

aeolian sand and dates to 7859 ± 52 ^{14}C yr BP (AA-39202). Above this are 265 cm of ACT deposits that have sandy loam to clay loam textures, 0.3 to 0.9% organic carbon and no $CaCO_3$. There are three buried soils in the ACT deposits. The lowest has an ABb3 profile similar to the ABb4 horizon at Sheep Mountain Table, and an age of 2547 ± 40 ^{14}C yr BP (AA-39201). The middle has a cumulic Ab2 profile 33 cm thick, and an age of 1390 ± 170 ^{14}C yr BP (NSRL-11255). The uppermost-buried soil has a 50 cm thick cumulic Ab1 profile that is weaker and lighter (i.e., Ab4 and Ab3 = 2.5 YR 3/1, Ab2 = 2.5 YR 2/1 and Ab1 = 2.5.YR 3/2) than the underlying soils. This section differs from the Nellie section in that the zone above the uppermost-buried soil is thicker and more clearly bedded.

At the Nellie East section there is a channel-shaped discontinuity at least 100 m wide and 20 m thick that is filled with interbedded sand and gravel. Above this is aeolian sand with a buried soil that has an Ab-Bwb-Cb profile, and an age of 10400 ± 70 ^{14}C yr BP (NSRL-10918). This provides a maximum age for the 340 cm of overlying ACT deposits, which contain at least five buried soils that were not analysed because they could not be safely sampled.

The Frieda section is located on the eastern end of Cuny Table (Figure 1). Here the lowest-buried soil has an Ab3-Cb3 profile and is formed in well-sorted, aeolian, sand, and has an age of 7990 ± 155 ^{14}C yr BP (NSRL-11258). Above this there are 320 cm of ACT deposits that are set against a vegetated dune form. ACT deposits have loamy sand to loam textures, 0.2 to 0.5% organic carbon, and 0.0–1.7% $CaCO_3$. There are two buried soils in the ACT deposits. The lowest is an 80 cm thick cumulic Ab2 horizon with an age of 3640 ± 155 ^{14}C yr BP (NSRL-11257), and the uppermost has an Ab1-Cb1 soil that has an age of 2790 ± 165 ^{14}C yr BP (NSRL-11256).

Bouquet Table (~825 m elevation)

The section described and sampled on Bouquet Table is located in Buffalo Gap National Grassland (Figure 1). The lowest-buried soil here has an Ab-2A/Bb-2BCb-2Cb profile and is developed in both ACT deposits and colluvium derived from Tertiary calcareous sediments. Above this is 100 cm of ACT deposits that contain three buried soils with A-C profiles, the middle of which (Ab2) has a cumulic A horizon. ACT deposit have sandy loam textures, 0.3 to 0.6% organic carbon and 0.4 to 0.9% $CaCO_3$. Total organic matter from the top of the cumulic Ab2 has an age of 1280 ± 130 ^{14}C yr BP (NSRL-11259) and the lowest Ab4 has an age of 2950 ± 145 ^{14}C yr BP (NSRL-11260).

Norbeck Pass (~850 m elevation)

The section described at Norbeck Pass is the northernmost sampled section (Figure 1). The site is different in that it is located on a ~100 m wide ridge, rather than a several kilometre wide table, and there is no soil developed in the sediments underlying the ACT deposits. The stratigraphy includes an approximately 20 cm thick pebbly clay loam with 0.3% organic carbon and 8.4% $CaCO_3$. Overlying this is 190 cm of ACT deposits with loam and clay loam textures, 0.5 to 1.6% organic carbon and no $CaCO_3$. There are two buried soils with A-C profiles in the ACT deposits. The lowest has an age of 3654 ± 42 ^{14}C yr BP (AA-39200) and the uppermost has an age of 1333 ± 38 ^{14}C yr BP (AA-39199).

Discussion

Although both the thickness of the ACT deposits and the number of soils buried in them vary among sections, a clear chronological pattern of landscape stability is apparent between soil development and contrasting aeolian accumulation. On the bases of the ~10000 ^{14}C yr BP age at the Nellie East section, ACT sediments probably accumulated throughout the Holocene and during the late Pleistocene. However, these early Holocene ACT sediments and buried soils are preserved only on the higher (950 m) tables (Figure 3). At the sections studied at this elevation, the oldest soils are developed in deposits other than ACT sediments. On Cuny Table, ACT deposits overlie well-sorted dune sands above fluvial gravels, but on Sheep Mountain Table ACT deposits are above interbedded gravel and very fine sand/coarse silt. On Cuny Table, the lowest-buried soil has an age of ~7900 ^{14}C yrs BP at three sections, which is close in age to the cold event between 7650 and 7200 ^{14}C yrs BP (the so-called '8200 yr event') recorded in Greenland ice cores (Alley *et al.*, 1997). This is also a time when closed-basin lakes to the east switch from fresh to saline (Fritz *et al.*, 2000). It is tempting to correlate these events, but the lowest-buried soil at Sheep Mountain Table has an age somewhere between 5800 and 6900 ^{14}C yrs BP, which is much later then the aforementioned events. Probably, the early-Holocene ACT record is incomplete because of high badland erosion rates (Hadley and Schumm, 1961), and requires more work before such correlations can be tested.

The late-Holocene record, however, is more complete, probably because there has been less time to erode it. In the late Holocene, ACT sedimentation occurred in periods after ~3700, ~2500 and ~1300 ^{14}C yr BP (Figure 5). Based on ages from the bottom of the 1300 ^{14}C yr BP soil at Sheep Mountain and Cuny Table, the latest aeolian episode occurred after several centuries of cumulic soil formation. The luminescence ages agree well with the radiocarbon chronology at Sheep Mountain Table (Figure 3; Table 2) and could be used to resolve the chronology of aeolian sedimentation further. However, it is likely that these deposits accumulate continuously, albeit slowly, because there are no soil horizons developed in these sediments at the modern surface and there is typically a metre of aeolian sediment burying the uppermost-buried soil. The late-Holocene record presented here compares well with those mentioned in the introduction in that there is evidence for episodic Holocene aeolian activity. The periods of soil formation seem to correlate quite well with nearby localities that have well-constrained age control, especially Wolfe *et al.* (2000) and Goble *et al.* (2001). These periods are also similar to millennial-scale climate cycles in the North Atlantic (Bond *et al.*, 1997; 2001).

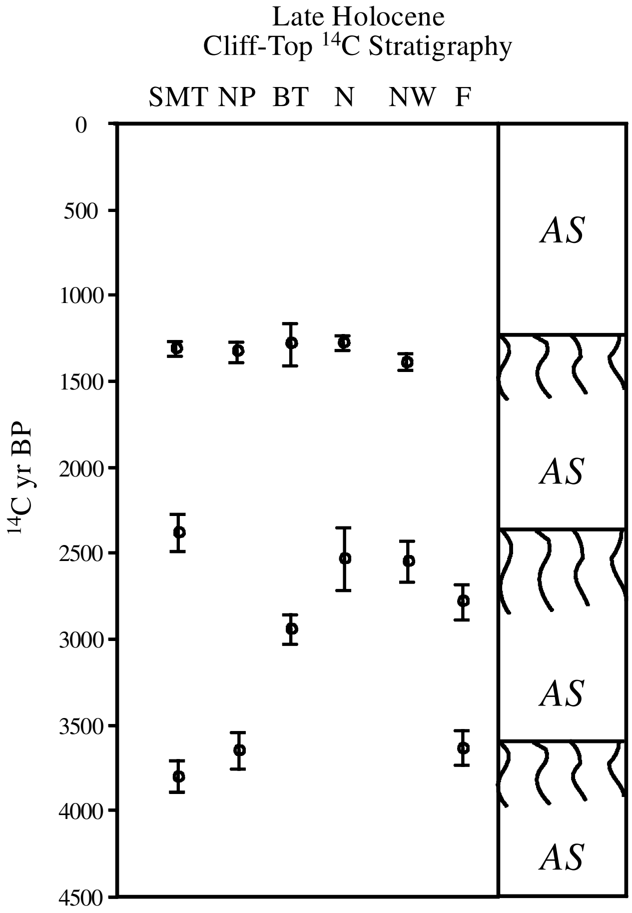

Figure 5 Late-Holocene periods of aeolian sedimentation (AS) and pedogenesis. Only age estimates from the top 5 cm of buried soils are included here because they represent a maximum age of burial by aeolian sedimentation. Radiocarbon ages are plotted against section location; SMT = Sheep Mountain Table; NP = Norbeck Pass; BT = Bouquet Table; F = Frieda; N = Nellie; NW = Nellie West.

Conclusion

Just as with other studies of Holocene aeolian deposits from the Great Plains, the White River Badlands ACT deposits provide evidence of episodic aeolian sedimentation. It appears that these deposits formed over most of the Holocene, including the lowest soil previously thought to correlate to the Sangamon Geosol (Harksen, 1968; Briggs, 1974). Our data support White's (1960) hypothesis that the age of the buried soils in the ACT deposits are consistent throughout this subregion of the North American Great Plains, probably as a result of climatic influence. These ACT deposits are a valuable source of palaeoenvironmental proxy, as others most likely are in similar settings.

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