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Holocene dune-sourced alluvial fans in the Nebraska Sand Hills

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Abstract

The large, stabilized dunes of the Nebraska Sand Hills are in a phase of degradation. The deposition of small-scale alluvial fans composed of well-sorted, fine- to medium-grained sand occurs when sand is transported via gullies on the lee side of large barchanoid-ridge dunes during infrequent, intense summer rain storms (>5 cm/h). The hydraulic conductivity of the dune sand itself is too high to allow Hortonian overland flow, but organically bound mats and crusts on the surface of the dunes help to impede infiltration. Secondary eolian bed forms at the crests of the dunes focus shallow groundwater and overland flow that erodes gullies. Internally, alluvial fans are dominated by laminated sands interpreted as sheetflood deposits. Depositional couplets of structureless (bottom) and laminated (top) sands may form from a combination of hyperconcentrated flow and sheetflood. Thickness of deposits varies with storm intensity and sediment supply in the gullies. The alluvial fans are Holocene in age, and gully initiation may have begun at the onset of a wetter climate when vegetation was less dense than at present. Water-laid sandstones associated with large-scale eolian cross-strata have been recognized in Precambrian, Devonian, and Cretaceous sequences. The alluvial fans from the Sand Hills may provide a new modern analogue for interpreting these ancient sandstones. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Dunes; Alluvial fans; Sheetflood; Climate; Nebraska

1. Introduction

1.1. Background and purpose

The formation of dune-derived alluvial fans is limited to stabilized dune fields that receive infrequent, intense rainfall. Degradation of the stabilized dunes of the Nebraska Sand Hills occurs following intense summer rainstorms when gullying of the dune lee faces results in the transport of sand to the bases of the dunes as small-scale alluvial fans (Fig. 1A,B). This is a unique setting for alluvial fan development, distinct from tectonically and climatically controlled alluvial fans bordering bedrock highlands. The Sand Hills fans are sourced from large dunes rather than mountains, are composed of a uniform grain size, and form in an area of relative tectonic stability.

Dune-sourced alluvial fans in Niger, similar to those in the Nebraska Sand Hills, were first studied

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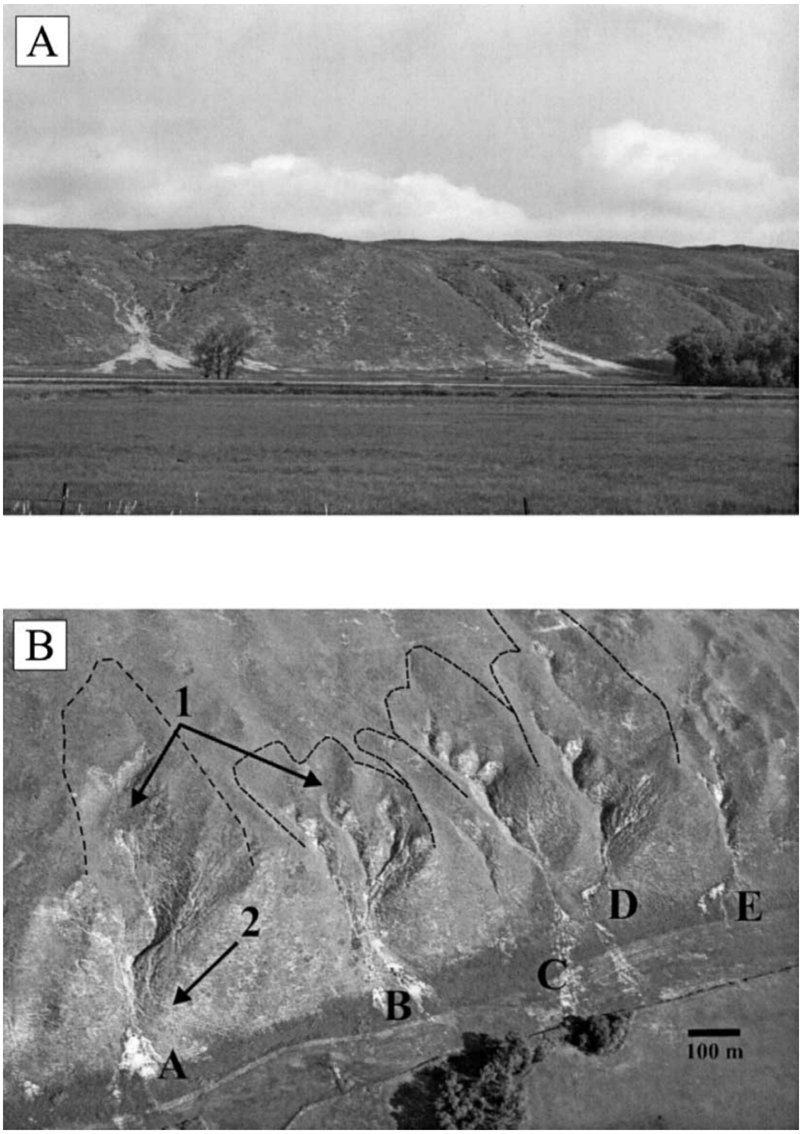


Fig. 1. (A) Sandy alluvial fans at the Monahan Ranch locality. Gullies incised the lee face of this 55-m high barchanoid-ridge dune. (B) Aerial photo, Monahan Ranch, 1998. Lee face of dune forms boundary between flat interdune in lower right and stoss slope in upper left of photo. Gullies of this dune were last active in May 1998. Each gully head terminates at the crest of a dune in a bowl (1) interpreted to be formed by secondary eolian bed forms. These bowls act as water-focusing mechanisms. Cattle pathways (2) are secondary features of gully erosion that may lead to the widening of the gully over time, but are not directly related to gully formation. Dashed lines indicate approximate drainage area that feeds the alluvial fans. The fans are labeled A through E. Note that D and E avulsed and flow parallel to the dune lee face.

by Talbot and Williams (1978, 1979). The dunes in Niger are at the southern semi-arid edge of the Sahara and are stabilized by grasses. Talbot and Williams described planar- and cross-stratification caused by sheetflooding and fluvial action. The Nebraska deposits lack the variety of structures found within the Niger fans. Other areas of modern dune degradation include the partially vegetated parabolic coastal dunes in Holland (Jungerius and van der Meulen, 1988), coastal dunes overlying granite bedrock in Brazil (Bigarella, 1975), and forested coastal dunes in Australia (Bridge and Ross, 1983). Sand Hills alluvial fans share only some characteristics of these modern dune-sourced alluvial fans. Smith (1965), Ahlbrandt and Fryberger (1980), and Swinehart (1990) first recognized gullies and alluvial fans in the Nebraska Sand Hills as degradational features, but no study was made of them.

The purpose of this study is to characterize the alluvial fans of the Sand Hills, to provide a complete description of the deposits and source area, and to interpret the history and processes of their deposition. We will show that local hydrology, climate, soils, dune morphology, and range management control the erosion of the dunes, and these factors will be discussed to develop a model for stabilized dune erosion.

The interpretation of dune-derived alluvial fans in Late Cretaceous rocks of Mongolia led Loope et al. (1998) to identify the Nebraska Sand Hills as a possible modern analogue. Water-laid strata have also been observed to intercalate with large-scale dune foresets in the Precambrian Makabeng Formation in South Africa (Simpson et al., 1999) and the Devonian New Mountain Sandstone of Antarctica (Wizevich, 1997). Our work suggests that this modern/ancient analogy is valid, and that ancient climatic conditions can be inferred for these regions.

1.2. Alluvial fan environment

Alluvial fans are conical deposits of sediment that form at the base of upland topography after sediment transported by an upland channel becomes unconfined as it enters a broad plain (Bull, 1977). Sedimentation is often sporadic and is a function of sediment supply, occurrence of infrequent storms, and tectonic activity. Deposition starts at the apex and ends at the toe. When alluvial fans become entrenched, the node of deposition occurs at the intersection point where the fan is no longer incised (Blair and McPherson, 1994). The radial profile is generally concave-up, due to sediments fining distally and the cross-fan profile is convex. Debris flows, sheetfloods, and fluvial processes are responsible for constructing alluvial fans. Size of the alluvial fans depends largely on the size of the drainage basin, and the extent of fans varies from tens of meters to kilometers (Blair and McPherson, 1994).

Sheetfloods are a major component of some alluvial fans (Bull, 1977; Hogg, 1982; Blair and McPherson, 1994). Classic work done by McGee (1897), Davis (1938), and Rahn (1967) defines sheetfloods as unconfined sheets of shallow water formed during severe rainfall. Sheetflooding is a fluid gravity process with sediment concentrations generally less than 20% (Blair and McPherson, 1994). Turbulent flow allows for sediment sorting. Sheetflooding is typical on alluvial fans or pediments following high intensity storms. Hogg (1982) defines several requirements for sheetflooding including high intensity rain, lack of vegetation, low permeability of the ground, and unconfined flow. Sheetfloods commonly originate on slopes greater than 20% and spread out onto slopes $< 10\%$ (Hogg, 1982).

Stream flow, which is confined to channels, results in deposits that consist of bed forms such as ripples and dunes associated with fluvial deposition when the alluvial fan surface becomes incised (Blair and McPherson, 1994).

Sediment gravity flows, including debris flows, are also a major contributor to the aggradation of alluvial fans (Blair and McPherson, 1994). Sediment gravity flows originate when poorly sorted rock and soil debris become mobilized because of the rapid introduction of moisture on hillslopes and channels or as failures on steep slopes (Johnson, 1970; Costa, 1984; Varnes, 1979). Debris flows tend to have high sediment concentrations (70–90% by weight), with sediments supported by cohesion, buoyancy, and dispersive stress. Flow is laminar resulting in the deposition of poorly sorted, unstructured material (Costa, 1988). Debris flows deposit lobes of sediment and levees that can spread over the whole alluvial fan surface (Johnson, 1970).

Other deposits associated with alluvial fans include hyperconcentrated flows, which are non-Newtonian, with sediment concentrations between 40% and 70% by weight. A mix of turbulent and laminar flow produces weak horizontal stratification and poor sorting (Smith, 1986). Deposits may also be lobate with lateral levees (Costa, 1988). Debris flows can grade into hyperconcentrated flows with an increase of water (Pierson and Scott, 1985). Hyperconcentrated flows are not classified as sediment gravity flows (Beverage and Culbertson, 1964).

2. Study area: geologic, climatic, and geographic setting

The Nebraska Sand Hills of the Great Plains physiographic province is the largest sand sea in the western hemisphere, covering approximately 50,000 km^2 (Smith, 1965). The dune field, stabilized by prairie grasses, occupies an area in north central Nebraska primarily between the Niobrara and Platte Rivers. Slipface orientations of the larger barchan and barchanoid-ridge dunes and cross-bed measurements by Ahlbrandt and Fryberger (1980) suggest that dominant wind directions during periods of eolian activity were from the north and northwest.

Smith (1965) conducted the first detailed study of the Sand Hills and interpreted three main periods of dune formation, each followed by climate change to moister conditions and dune stabilization. Smith (1965) believed that the dunes were built by strong periglacial winds during the early Wisconsin glacial period. Ahlbrandt et al. (1983) argued that the dunes had been active several times in the Holocene. According to Swinehart (1990), Loope et al. (1995), Mason et al. (1997), Stokes and Swinehart (1997), and Loope and Swinehart (2000), more recent age dates indicate that large dunes were active during the Altithermal/Hypsithermal warm period from 8000 to 5000 years B.P. Stokes and Swinehart (1997) and Muhs et al. (1997) documented late Holocene eolian activity.

The dune sand is derived from underlying and surrounding Tertiary sedimentary rocks, and Pliocene or more recent unconsolidated eolian and fluvial deposits sourced in the Rocky Mountains (Smith, 1965; Muhs et al., 1997). The sands are fine- to medium-grained, moderately well-sorted, and composed of quartz (50–75%), K-feldspar (9–25%), plagioclase (5–24%), minor amounts of chert and rock fragments, and clay (trace–4%) (Ahlbrandt and Fryberger, 1980). Clay (smectite, mixed-layer illite–smectite (I/S), and kaolinite) occurs as clay skins on sand grains (Winspear and Pye, 1995).

Swinehart (1990) provides a detailed outline of dune forms and distribution in the Sand Hills (Fig. 2). The sand sea includes sandsheets of low to moderate relief, parabolic, linear, dome (modified crescentic), barchan, and barchanoid-ridge dunes. Barchan-type dunes occupy the largest portion of the Sand Hills. Of these, barchans cover about 1/5 of the dune field and average 41 m high; and barchanoid-ridge dunes comprise about 1/4 of the sand sea, average 3–8 km long, and can be as high as 150 m from the crest to the interdune floor. On the basis of their size, these are considered draas by Wilson's (1972) classification scheme of eolian bed forms but are referred to here as dunes (Swinehart, 1990). The large barchanoid-ridge dunes that occupy the central Sand Hills are the focus of this study due to high concentration of gullies and alluvial fans. Gullies and fans of similar scale have not been observed in other parts of the dune field.

The climate of the Sand Hills region is semi-arid to sub-humid, influenced by its position relative to the Gulf of Mexico and the rain shadow of the Rocky Mountains, with annual rainfall averages increasing from 406 mm in the west to 610 mm in the east (Ahlbrandt and Fryberger, 1980). About 75% of the average annual precipitation falls between April and September, with 50% concentrated in May, June,

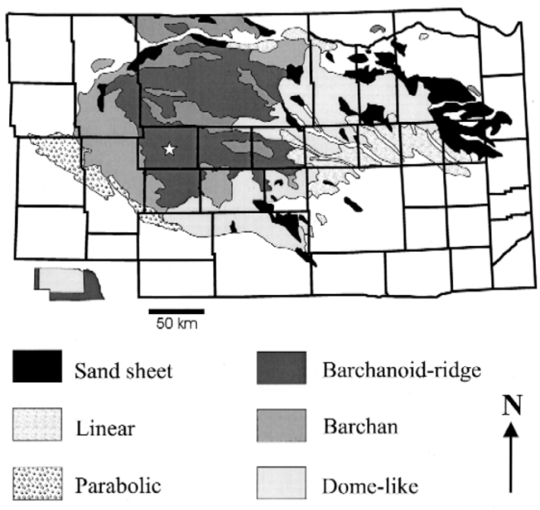


Fig. 2. Dune distribution map of the Nebraska Sand Hills (after Swinehart, 1990). The star symbol shows the location of Grant County.

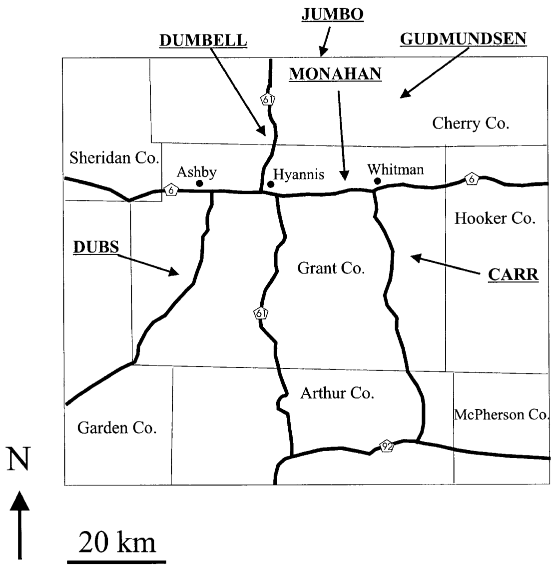


Fig. 3. Locations of chosen alluvial fan sites including Carr Ranch, Dubs Ranch, Dumbbell Ranch, Gudmundsen Sandhills Laboratory, Jumbo Valley, and Monahan (Circle Dot Ranch).

and July. Moisture is drawn from the Gulf of Mexico by southeasterly winds during frequent cyclonic storms (Wilhite and Hubbard, 1990). The most intense precipitation occurs in late spring and summer from convective storms that affect local areas (Lawson et al., 1977).

Deposition of fresh sediment on the alluvial fans takes place in response to infrequent and intense rainfall associated with summer convective storms. These events are called "washouts" by local ranchers, who have witnessed flows following rains with intensities of at least 5 cm/h. The average annual maximum 1-h rainfall for the Sand Hills region is approximately 2.5 cm, and the 100-year maximum 1-h rainfall is about 8 cm (Lawson et al., 1977). Ranchers report that "washouts" are infrequent occurrences. Frequency of activity, as recalled by ranchers at any one location, is either never, infrequent, or in some cases, approximately 10 years apart (Dubs locality mid-1970s and mid-1980s; Dumbbell locality July 1991 and June 1999). Since the heavy convective storms of the summer occur only locally, a specific dune receives a severe drenching very infrequently. An exception to this is the Carr Ranch locality, which received severe rains 2 years in a row that resulted in sand flows (May 1998, June 1999).

The Sand Hills are sparsely populated, so our attempt to record historic sand flow events was not very successful. Local newspapers in Grant County reported a washout in July of 1957 from a 17-cm rainfall that included antecedent moisture 2 days prior. Storms in 1991, 1993, 1998, and 1999 all produced alluvial fan activity at different locations.

Vegetation covers nearly 100% of the dune surface and is dominated by a variety of prairie grasses that include sand and little bluestem (*Andropogon hallii, A. scoparius*) and switchgrass (*Panicum virgatum*). Also found on the dune are sporadic occurrences of prickly-pear cactus (*Opuntia* spp.) and,

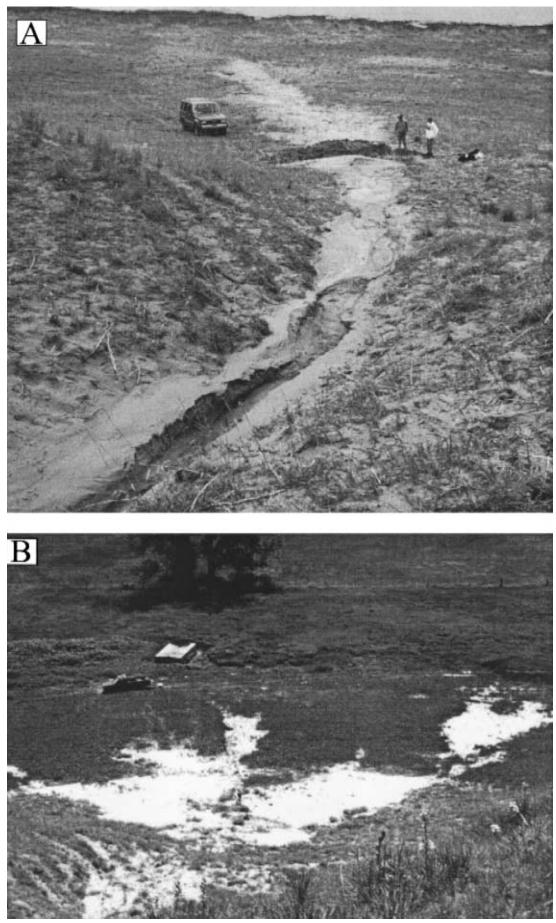


Fig. 4. (A) Finger or lobe deposition at the Dumbbell ranch. (B) Sheet deposition on Monahan Fan A. Sand stringers extend from the main area of deposition.

more commonly, small soapweed (*Yucca glauca*). Interdunes have a greater density and variety of vegetation, and some of these extend onto the alluvial fans. Common annuals include *Helianthis annuus* (common sunflower), *Argemone polyanthemos* (prickly poppy), *Salsola iberica* (russian thistle, or tumbleweed), sandbur (*Cenchrus* spp.), and prairie grasses. Common perennials include *Tradescantia bracteata* (spider wort), *Ipomoea leptophylla* (morning glory), and *Asclepias speciosa* (showy milkweed) (Kaul, 1990). Soil development on the dunes and alluvial fans is weak, characterized by Entisols with A/C or A/AC/C profiles.

3. Methodology

Gullies and alluvial fans tend to form on the large barchanoid-ridge dunes, many of which are present in Grant County (Fig. 3). Localities for the study were chosen based on degree of alluvial fan development, recent age of gully and fan activity, and accessibility. Localities included Monahan, Dubs, Dumbbell, Carr, Jumbo, and Gudmundsen ranches (Fig. 3).

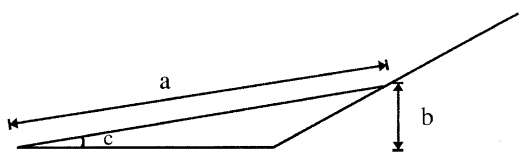
Field work included survey of fan surfaces and gullies with an electronic total station to determine slopes and geometries, trenching with shovels and a Bobcat with a backhoe attachment, collection of sediment samples, and the use of a constant head permeameter that measures saturated hydraulic conductivity.

Grab samples of laminated and structureless sands from recent alluvial fans were taken to determine any differences in grain size from one type of deposit to another. The samples were dried, split, and analyzed using a Coulter LS100Q laser diffractometer. Scanning electron microscopy of individual sand grains was performed to identify clay skins.

Table 1
Alluvial fan and gully characteristics

Location	Gully slope	Type	Fan slope	Apex-toe	Fan height	Recent thickness	Morphology	Deposits
Dubs	23.5°	bifurcating	7.1°	83.9 m	10.4 m	>0.5 m	sheet	laminated structureless
Gudmundsen	26.9°	single	7.8°	19.9 m	2.7 m	0.25 m	sheet	structureless
Dumbell	a	single	7.1°	52.8 m	6.5 m	0.32 m	lobe	structureless
Jumbo	5.1°	bifurcating	4.75°[b]	28.5 m[b]	a	a	sheet	laminated bioturbated
Carr	9.0°	single	a	171.3 m	a	1.10 m	sheet	laminated
Monahan A	16.9°	bifurcating	10.3°	63.0 m	11.3 m	0.26 m	sheet	laminated structureless
Monahan B	a	bifurcating	11.9°	86.4 m	17.8 m	0.25 m	lobe/sheet	laminated structureless
Monahan C	a	single	8.7°	155.8 m	23.5 m	0.27 m	lobe	laminated structureless
Monahan D	a	single	8.0°	120.5 m	16.7 m	0.46 m	lobe/incision	laminated structureless
Monahan E	a	single	9.45°	103.2 m	16.9 m	0.36 m	lobe	structureless

a= No Data
b=The Jumbo Valley alluvial fan is altered by cattle/4wd pathways that decrease the slope of the fan. Deposits extend into a densely vegetated marsh. Apex to toe measurements are taken up to the marsh. In the diagram, length a = the distance from the apex to the toe, b = fan height, and c = the fan slope.



4. Results

4.1. Alluvial fan and valley morphology

The Sand Hills alluvial fans are small-scale, a result of the small area that the gullies drain. Drainage areas within the ridge and swale topography at the tops of dunes range from approximately 900 m^2 to more than 24,300 m^2 (Fig. 1B). Fresh deposits occur as lobes (one or more) superimposed on a larger fan surface (Fig. 4A) or as sheets that cover most or all of the fan surface (Fig. 4B). The average slope of the alluvial fans is 8.8° (Table 1) with little variation due to the small and homogenous grain size. Some fans have a lower slope due to cattle paths or four-wheel drive roads that have altered the surface. The average

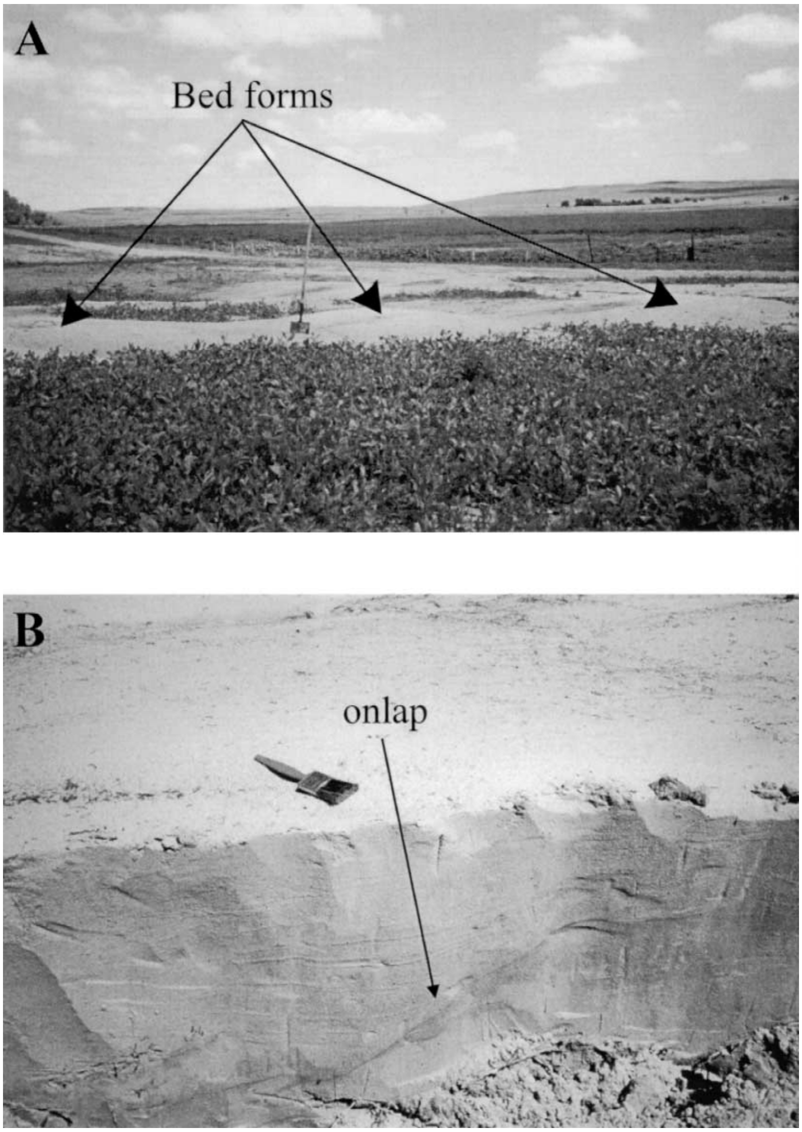


Fig. 5. (A) Low relief longitudinal bed forms deposited at the Carr Ranch in 1999. They occur as singular forms or a train of three to four bed forms. Flow is from left to right. (B) Cross-section of bed form composed of plane-bed laminations. The bed form appears to have been eroded and onlapped by a new bed form during the same storm event. Flow is from left to right.

extent from the apex to the toe is approximately 100 m (Table 1). Fans terminate in grassy interdune areas or heavily vegetated marshes.

Areas of deposition on the fan surface can change over time. This is especially noticeable with lobe deposition. For example, fans D and E at the Monahan locality (Fig. 1B) are built up high enough that recent deposits were diverted to the lower-lying west side of the fan, resulting in lobes that flowed parallel to the dune lee face. This is a common feature in most alluvial fan settings (Blair and McPherson, 1994). In some cases, narrow, thin sand stringers extend from the main fan >50 m into the interdune until they reach more dense vegetation. Gullies that are closely spaced often create coalescing alluvial fans in the interdune. Table 1 presents fan characteristics for 10 localities.

None of the alluvial fans observed are deeply incised. Where incision occurs, it is very shallow (<0.3 m). Trenches dug normal to flow at Monahan and Carr ranches show trough-like structures. In cross-section, these deposits are parallel laminated. The trough features represent channels cut and filled during the same storm event.

Deposition on the alluvial fans at the Carr Ranch in 1999 resulted in the formation of low-relief, longitudinal bed forms (Fig. 5A). Some fans had one bed form, whereas others had a train of three to four. From a distance, they give the fan surface a gently undulating appearance (amplitude 0.25 m, wavelength 3–4 m). Dips of the lee and stoss side of the bed form are similar, but the lee side is eroded to form a shallow chute. These bed forms are entirely laminated. In one case, one bed form was apparently built on top of another (both formed from the same storm event), causing erosion on the stoss side and onlap of sand onto the older bed form (Fig. 5B).

4.2. Feeder channel morphology

The heads of the feeder channels, or gullies, that feed Sand Hills alluvial fans initiate just below the dune crest and may later extend farther headward. Mature gully heads terminate at flat areas in the bottom of bowl-shaped topography at the crest of dunes (Fig. 1B), and young gully heads appear as a scar just below the inflection point of the dune. On top of dunes, unbreached bowls were found behind the young gully scars.

The feeder channel that leads to the fan is single or bifurcates into two or more straight or slightly sinuous channels upslope (Fig. 1B). Gully gradients range anywhere from 5° to 27° depending on the amount of incision into the dune (Table 1). Degree of incision gives a clue to the age of the gully; the more deeply incised it is (and the lower its inclination), the older it is. Older gullies are wide and have steep walls and broad bottoms, whereas younger gullies are very narrow. Dry grain flows from the walls fill the gully over time, resulting in less steep walls. The gully floors can be covered in wind ripples. Cattle commonly follow the edges of gullies producing fractures parallel to the gully that later cause slumping, adding another mechanism for gully filling (Fig. 6). We observed that most gullies have gradients between 15° and 24°, with several flatter intervals separated by terraces where waterfalls as high as 2 m form during heavy rains.

Using aerial photography, an attempt was made to measure rates of headward erosion of the gullies at the Monahan and Carr localities. Between 1942 and

Fig. 6. Slumping of gully walls, Carr Ranch. Slumps are a major supply of sediment to gullies. Cattle often follow the edge of gullies, resulting in fracturing and slumping.

1998, no new gullies were generated, and the existing gullies showed little to no extension headward into the dunes over this time period. Comparisons of a 1942 aerial photograph of a shallow gully at the Monahan Ranch locality and observations made in this study in 1998 show that the gully has not further incised the dune.

4.3. Hydrology

The dunes of the Sand Hills are composed of very permeable, homogenous sand up to 150 m above the watertable, so overland flow may seem unlikely to occur in this environment. However, running water must be a factor in gully erosion and deposition of

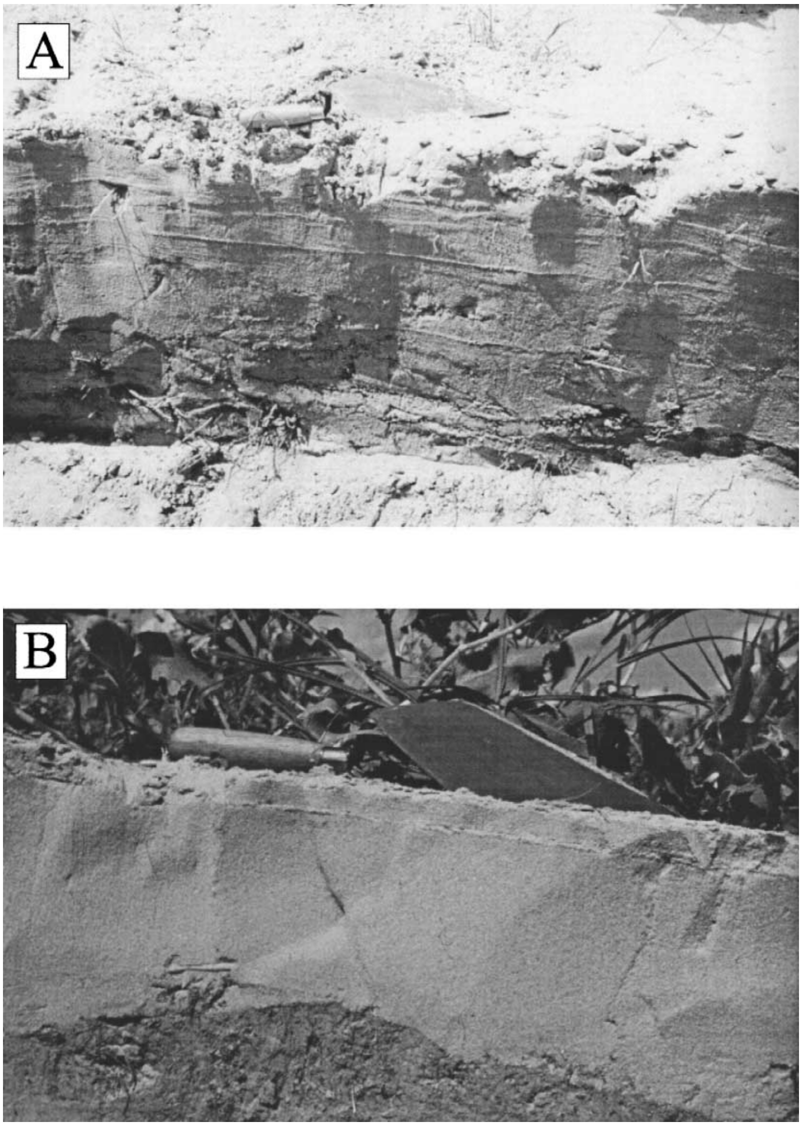


Fig. 7. (A) Laminated sands of an alluvial fan, Carr Ranch. Laminated sands are herein interpreted as upper plane-bed laminae deposited during sheetflood, a result of unconfined flow. Also note the broken crust at the surface of the deposit that may significantly lower the permeability of the sand during storm events. (B) Structureless sands of Monahan Ranch interpreted as hyperconcentrated flow. An increase in storm intensity may result in the transition to sheetflood, which is entirely turbulent, and the formation of depositional couplets.

sandy fan deposits, even though it was not observed on the dunes themselves during this study. Flowing water was witnessed during a heavy storm of July 1991 at the Dumbbell Ranch locality at the base of a dune (Linda Brown, personal communication, 1998). Observations of "plowed" grasses, "stepped" profiles created by waterfalls in the gullies, and primary sedimentary structures in alluvial fan trenches confirm that running water occurs in this environment during heavy rains.

We used a compact constant head permeameter, or Amoozemeter, to test the infiltration rates of the dune sand. The Amoozemeter allows measurement of the saturated hydraulic conductivity of the vadose zone in situ (Amoozegar, 1992). Experiments at 20-cm depth on the dune showed an average hydraulic conductivity of 6.7×10^{-5} m/s, which requires an equivalent rainfall of 24 cm/h to reach the infiltration capacity of the sand (Sweeney, 1999). Rainfall intensities this great have not been measured in the Sand Hills. Alluvial fan measurements gave slightly higher readings (9.4×10^{-5} m/s), possibly due to the recent age of the deposits and less time for settling or compaction. Both measurements closely resemble those for clean dune sand of 1.0×10^{-4} m/s (Bridge and Ross, 1983).

4.4. Description of alluvial fan stratigraphy

Several trenches were dug on the alluvial fans both parallel and perpendicular to flow to reveal recent and older deposits. Nearly all fresh sand is planar laminated, with a few examples of structureless sand.

Fresh deposits typically overlie an organic-rich horizon interpreted to represent the former vegetated alluvial fan surface. The contacts are sharp and irregular. Deposits contain abundant modern roots and burrows. Modern deposits are dominated by planar laminated sands (Fig. 7A). At two localities studied (Monahan, Dubs), structureless sands (below) and laminated (above) appear as depositional couplets (Fig. 7B). A trench at Monahan A revealed three possible depositional couplets (Fig. 8). Two deposits (Dumbbell, Monahan D) appear dominantly structureless and have a lobate geometry in cross-section with the thickest part of the unit towards the center, thinning on both sides.

Trenches as deep as 1.7 m reveal mostly structureless sand with intermittent poorly preserved laminations, some of which are traceable from trench to trench at the Monahan locality. Silt–clay lamellae were observed at a depth of 0.8–1.0 m; these fea-

Fig. 8. Three episodes of alluvial fan activity, Monahan Fan A. The most recent deposit (unit 1) of May 1998 is underlain by organic-rich horizon. Unit 2 is approximately the same thickness as unit 1. It is underlain by another organic-rich horizon that contains burrows or load structures. Unit 3 begins at the top of the second soil horizon.

tures are a result of illuviation of clay and silt from the surface (Winspear and Pye, 1995). Burrowing is common in the older deposits, often cross-cutting laminated sand. Bioturbators include plant roots, pocket gophers, snakes, ants, and cicadas. Although older, organic-rich layers are preserved in the lower fan, they are not preserved from the mid-fan to the apex.

Structureless deposits contain incorporated plant material consisting of root fragments up to 4 cm long. This sand is also slightly darker in color (2.5Y 7/3, air dry) than the laminated sands (2.5Y 6/3, air dry). Grain-size analysis consistently shows that the structureless sands contain 0.1–0.5% higher amounts of total clay than the associated laminated deposits (Sweeney, 1999). For a sand source that contains 1.5–3.0% clay, generally in the form of clay rims on sand grains, the small change is significant. A *t*-test performed on the grain-size data shows that the two types of deposits are significantly different at $p < 0.10$ based on the clay-size fraction (< 4 μm) (Sweeney, 1999).

5. Discussion

5.1. Relations between climate change, hillslope processes, and feeder channel responses

A source of water is necessary to allow the mobilization and transport of sand from the gullies to the alluvial fan surface. Where gullies head in the “bowl-shaped” topography on the stoss side near the crest of dunes, the grass in these topographic lows between secondary eolian bed forms tends to be denser and greener, indicating that more moisture reaches this area. These “bowls” act as focusing mechanisms for shallow groundwater and overland flow (Fig. 1B). Anisotropy of eolian cross-strata may allow lateral flow downslope along bedding of the superimposed eolian bed forms, aiding depression-focused shallow groundwater flow (McCord and Stephens, 1987). The spacing of superimposed linear eolian bed forms (trailing arms of parabolic dunes) also act as focusing mechanisms and control the fairly equal spacing of gullies and fans.

Gullies may initially form by seepage. Where unbreached bowls exist, ponding may occur for a short time during heavy rainfall events. The water infiltrates into the dune and exits high on the lee face, causing seepage-face erosion (Parker and Higgins, 1990). As seeping continues over a period of time, headward erosion of the gully eventually breaches the enclosed bowl.

Types of overland flow occur under different circumstances, as illustrated by Selby (1993). Hortonian overland flow occurs when precipitation rates exceed the infiltration capacity. Saturated excess flow occurs when water cannot infiltrate because the ground is already saturated. Subsurface storm flow occurs as flow through macropores of soil matrix as a result of a less permeable layer below and can emerge as overland flow.

The Amoozemeter data suggest that Hortonian overland flow cannot occur on the dunes because the infiltration capacity of the sand (at 20-cm depth) is greater than any recorded rainfall event, so something else must be impeding downward infiltration of water during heavy rain storms.

Jungerius and Ten Harkel (1994) found that the erosion of Dutch coastal dunes was not only a function of heavy rainfall. Some of the most intense storms resulted in no erosion, but if the surface is allowed to dry and a surface crust forms, erosion is initiated with the next large storm.

Two types of surficial crusts were observed on the Sand Hills dunes. Organically bound mats observed on the dunes around grasses act as water repellant features (Talbot and Williams, 1978; Thompson, 1983; Dekker and Jungerius, 1990; Selby, 1993). Repellancy may also be caused by the presence of humic acids and decomposing plant material (Dekker and Jungerius, 1990). Crusts that form on more sandy areas of the dune are a result of raindrop impacts. Impacts by large raindrops (3–5 mm) associated with high intensity rainstorms may compact the surface and create a crust, and additional sealing of the surface results from dispersal of finer grained sediment moving into soil pores (Morin et al., 1981; Hoogemoed and Stroosnijder, 1984; Romkens et al., 1990; Selby, 1993). These types of crusts (along with the focusing mechanisms of secondary eolian bed forms) allow for erosive overland flow to occur on a dune, resulting in the formation of gullies and fans.

Observations from aerial photographs support the hypothesis that gully formation and major incision is rare today and may have been more widespread at a time in the past when the dunes were less vegetated and infrequent storms caused erosion. Jungerius and Dekker (1990) attribute gully and rill erosion of dunes in the Netherlands to water repellant slopes steeper than 15° with sparse vegetation. Poor range management and influence of cattle in historic times resulted in the creation and/or growth of active blowouts in the Sand Hills (Smith, 1965). McIntosh (1996) reported that during the extreme drought of the mid-1890s (and possibly during the mid-1930s Dust Bowl), interdune lakes dried up and blowing sand was common. These conditions may have been conducive to gully formation. Erosion today is primarily related to the slumping of gully walls (Fig. 6), which widens the gullies.

5.2. Interpretation late Holocene stratigraphy

Laminated sands are identified as sheetflood deposits because they cover broad portions of the fan surface with uniform thickness. The laminations in sheetflood deposits are interpreted as upper-plane bed laminae deposited in shallow water (< 10 cm) with high velocities associated with intense storms.

Structureless sands are interpreted as hyperconcentrated flow deposits. The turbulent and laminar nature of hyperconcentrated flow results in poor sorting, which explains the structureless nature of the deposits as well as the higher clay content and incorporated plant material that is not observed in laminated deposits. In contrast, plant material floats at the top of the turbulent sheetflood and is deposited distally. The observed darker color of the structureless sands is a result of oxidized clay coats on the sand grains. The turbulent action of the sheetflooding washes some of the clay away, resulting in the lighter-colored sand. However, scanning electron microscopy of the sand grains reveals that sheetflooding does not remove all of the clay coatings (Sweeney, 1999). The short transport distance may allow only loose clay to be removed during sheetflood events.

The well-sorted nature of the deposits makes interpretation difficult. Sandy flows in the Dutch coastal dunes were described as "mudflow-like" (Jungerius and Ten Harkel, 1994) but they lack a significant fine-grained fraction. Debris flows can occur in sand-dominated material, as seen in nature (Johnson, 1970, p. 438) and modeled in the laboratory (Rodine and Johnson, 1976; Johnson and Martosudarmo, 1997). Sediment gravity flows may also be a source of structureless sand for the Sand Hills deposits from mass failures in the gullies at the onset of storms (Sweeney and Loope, 1999), but levee deposits are lacking and eyewitness reports by ranchers suggest the flows are water dominated.

Fresh deposits containing structureless and laminated couplets have been observed soon after deposition, leading to the conclusion that the structureless units are indeed depositional and not a result of bioturbation. This is also apparent because structureless units underlie laminated ones. These different types of deposits are related to the same storm event. Deposition of a structureless-laminated couplet might be explained by the onset of a hyperconcentrated flow as most of the sediment is flushed from the gully at the beginning of the storm, and as the storm intensity increases, turbulent sheetflood takes over. At Monahan Fan B, laminated deposits are absent from the upper fan surface but appear about mid-fan and extend distally. Flow may not have been entirely unconfined until mid-fan, although evidence for channelization in the upper fan was not observed.

The longitudinal bed forms found on alluvial fans at the Carr Ranch are similar to channel bars common in ephemeral and braided streams (Picard and High, 1973). Channel bars will form horizontal discontinuous stratification in shallow water with high current velocities. However, modified low-angle avalanche strata found in channel bars are absent. We interpret that the bed forms do not form simultaneously, but one at a time. Where three or four bed forms are found in a row, the first one may form, followed by erosion of a chute on the lee side, and then the formation of the next bed form and so on. It is possible that these bed forms from an unconfined setting may be related to the deposition from a hyperconcentrated flow.

The dune-sourced alluvial fans in Niger (Talbot and Williams, 1978, 1979) contain a wider variety of sedimentary structures than the Sand Hills fans. Structures such as trough cross-strata and ripples in the Niger deposits are the result of channelized flow on the fans. Niger fans are incised deeper than any fan observed in the Sand Hills. Channelized flow, or stream flow, allows sufficient water depths for subaqueous dune formation.

5.3. Dune erosion

Necessary factors for dune erosion, as observed in the Sand Hills, include the following: (i) infrequent, intense rainstorms; (ii) large dunes with steep lee faces; (iii) soil crust development; (iv) focusing topography; and (v) sparse vegetation. These same factors (except focusing topography) are also associated with dune-derived alluvial fans in the Sahel of Niger (Talbot and Williams, 1978, 1979). The Niger fans are dominantly in a phase of incision rather than aggradation. This is attributed to drier conditions, decreased sediment supply, and seasonal variations in vegetation cover (Talbot and Williams, 1979). Once a fan aggrades to a certain point, incision may occur leading to deposition at a lower elevation. This is currently rare in the Sand Hills but is common in the Sahel. Incision observed in the Sand Hills may be due to "streamlets" that form as the water source for sheetflooding diminishes (McGee, 1897). A change to wetter conditions should result in the spread of vegetation and the "healing" of the gullies and fans. Both active and healed gullies are found in the Sand Hills and are likely a function of disturbance, or lack thereof, by cattle.

Age constraint is poor for the deposits of the alluvial fans. Most of the deposits are historic in age; however, the onset of gully erosion and fan formation is not known. The lack of organic materials at depth in alluvial fan sequences precludes radiocarbon dating, but in the future, optically stimulated luminescence dating may prove useful for determining the age of these deposits. Dune degradation may have occurred within each period of dune stability in the past. Recognition of older fans may not be easy in cores or deeper trenches due to the effects of bioturbation. It is also possible that with the remobilization of the dunes, some alluvial fan sediments were eroded. We can conclude that the current succession of alluvial fans began to form sometime after the dunes last became stabilized. Dune activity has been more local and not widespread since about 0.8 ka (Muhs et al., 1997). Alluvial fan formation of the same scale as the Sand Hills in association with active dunes has not been observed. Anecdotal evidence from ranchers indicates that flooding on the fan surface may occur approximately once every 10 years. Since thickness of deposits varies greatly, a rate of deposition is difficult to determine using a thickness and recurrence interval. Most of the recent deposits that occurred in May 1998 were about 30 cm thick (Fig. 7B), but 1.1 m of sand was deposited on a fan at Carr Ranch at the same time. Thickness of any deposit is a function of the sediment supply and/or intensity of the storm (Fig. 9).

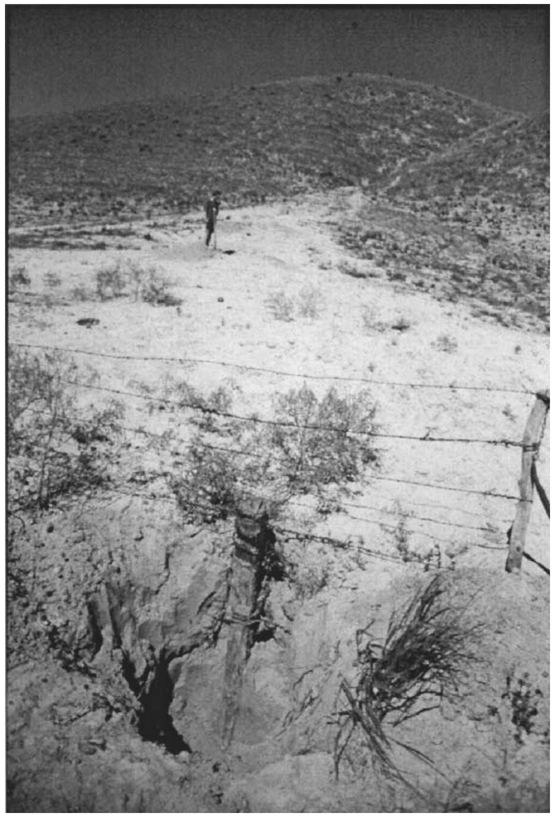


Fig. 9. Partial burial of fence post, Dubs Ranch. A storm in the 1970s resulted in the deposition of about 1.3 m of sand. This illustrates the variation in the thickness of deposits, which are a factor of sediment supply and storm intensity.

5.4. Ancient analogues

The Sand Hills may represent a modern analogue for older rocks that contain the same type of sedimentary structures and stratigraphic associations. If the Sand Hills were to be preserved in the rock

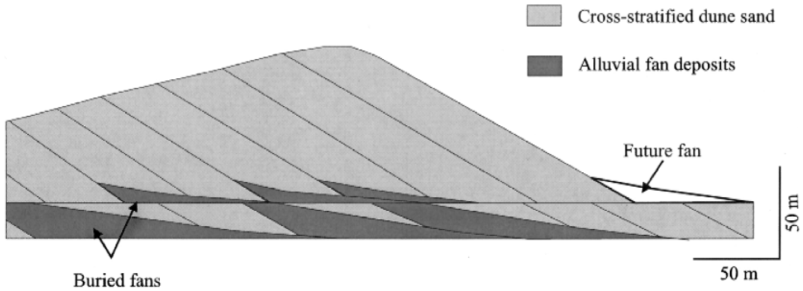


Fig. 10. Sketch of potential alluvial fan preservation, Nebraska Sand Hills. Similar associations exist for eolian cross-stratified sandstone and interpreted alluvial fan deposits in the Late Cretaceous of Mongolia (after Loope et al., 1999).

record, associations that might be found would include wedge-shaped structureless and laminated sands intercalated with eolian cross-strata (Fig. 10). Loope et al. (1998) described interbedded eolian and fan deposits from the Upper Cretaceous rocks of Mongolia. The fan deposits lacked stratification and contained relatively abundant articulated vertebrate skeletons. Loope et al. (1999) interpreted the fan deposits as landslides that changed to sediment gravity flows from dune slopes. The flows were triggered by intense rains that saturated the dune sand underlain by an impermeable caliche layer, resulting in the sliding of the dune sand. Because the Sand Hills dunes lack slope-parallel impermeable zones, translational slides like those interpreted from the Mongolian strata do not take place. The Devonian New Mountain Sandstone of Antarctica (Wizevich, 1997) contains structureless and laminated sandstones that are interpreted as sediment gravity flows derived from dunes during periods of high rainfall. The Precambrian Makabeng Formation of South Africa (Simpson et al., 1999) contains structureless fan-shaped sands associated with eolian cross-strata. These three ancient examples are all interpreted to be sandy alluvial fans composed of similar grain size with flows (sediment gravity flows for the Devonian and Cretaceous, and a turbulent, water-saturated flow for the Precambrian) triggered by intense rainfall. Each example lacks evidence of stabilizing vegetation, but since no modern unvegetated dunes that erode to form similar types of deposits have been observed, it seems likely that the ancient dunes were stabilized in some sense. It is also unknown if the ancient dunes had any type of sedimentary crusts or focusing secondary eolian topography near the dune crest.

6. Conclusions

Small-scale alluvial fans composed of homogeneous sand form in the Nebraska Sand Hills as a result of infrequent and intense summer convective storms that produce large amounts of rain in a short time period (at least 5 cm/h). Overland flow is necessary to erode gullies into the large, grass-stabilized barchanoid-ridge and barchan dunes and occurs when surface crusts form and impede infiltration. Overland flow on the dune is focused by secondary eolian topography near the crest of the dunes.

A model for dune erosion in the Sand Hills includes the following events: (i) During intense rainfall events in the past (> 100 years) when vegetation was less abundant on the dunes, depression-focused overland and shallow groundwater flow (aided by surface crusts) resulted in seepage-face erosion high on the dune lee face, starting alluvial fan deposition at the base of the dune. (ii) Headward sapping resulted in the breach of enclosed depressions, and overland flow acted as an erosive agent carving gullies into the dune. (iii) As vegetation in the area increased, gullies and fans healed; or if slumping and grain flow remained active in the gullies, new deposits accumulated on the fan during intense storms.

Alluvial fan deposits consist of two lithofacies dominated by planar laminated sands interpreted to be deposited by sheetflood processes, when unconfined flow emplaced a uniformly thick, laminated sand body over the fan surface. Less commonly, structureless sands interpreted as hyperconcentrated flood flows that have incorporated organic material and higher clay content were emplaced. The structureless and laminated sands form depositional couplets; structureless sands are deposited first by hyperconcentrated flood flow and as storm intensity increases, are covered by laminated sheetflood deposits. Longitudinal bed forms similar to channel bars consisting of plane-bed laminations found on these sandy alluvial fans may be related to hyperconcentrated flows during flooding of the fan surface.

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References

Ahlbrandt, T.S., Fryberger, S.G., 1980. Eolian deposits in the Nebraska Sand Hills. U. S. Geol. Surv. Prof. Pap. 1120A, 1–24.

Ahlbrandt, T.S., Swinehart, J.B., Maroney, D.G., 1983. The dynamic Holocene dune fields of the Great Plains and Rocky Mountain basins, USA. In: Brookfield, M.E., Ahlbrandt, T.S. (Eds.), Eolian Sediments and Processes. Elsevier, NY, pp. 379–406.

Amoozegar, A., 1992. Compact constant head permeameter: a convenient device for measuring hydraulic conductivity. In: Topp, G.C., Reynolds, W.D., Green, R.E. (Eds.), Advances in Measurement of Soil Physical Properties: Bringing Theory to Practice. SSSA Spec. Publ., vol. 30, pp. 31–42.

Beverage, J.P., Culbertson, J.K., 1964. Hyperconcentrations of suspended sediment. ASCE Proc. Hydraul. Div. J. 90, 117–128.

Bigarella, J.J., 1975. Structures developed by dissipation of dune and beach ridge deposits. Catena 2, 107–152.

Blair, T.C., McPherson, J.G., 1994. Alluvial processes and forms. In: Abrahams, A.D., Parsons, A.J. (Eds.), Geomorphology of Desert Environments. Chapman & Hall, NY, pp. 354–402.

Bridge, B.J., Ross, P.J., 1983. Water erosion in vegetated sand dunes at Cooloola, south-east Queensland. Ann. Geomorphol. 45, 227–244.

Bull, W.B., 1977. The alluvial fan environment. Prog. Phys. Geogr. 1, 222–270.

Costa, J.E., 1984. Physical geomorphology of debris flows. In: Costa, J.E., Fleisher, P.J. (Eds.), Developments and Applications of Geomorphology. Singer-Verlag, NY, pp. 268–317.

Costa, J.E., 1988. Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows. In: Baker, V.R., Kochel, R.C., Patton, P.C. (Eds.), Flood Geomorphology. Wiley, NY, pp. 113–122.

Davis, W.M., 1938. Sheetfloods and streamfloods. Geol. Soc. Am. Bull. 49, 1337–1416.

Dekker, L.W., Jungerius, P.D., 1990. Water repellancy in the dunes with special reference to the Netherlands. In: Bakker, W.M., Jungerius, P.D., Klijn, J.A. (Eds.), Dunes of the European Coast. Catena Suppl., vol. 18, pp. 173–183.

Hogg, S.E., 1982. Sheetfloods, sheetwash, sheet flow, or… Earth Sci. Rev. 18, 59–76.

Hoogemoed, W.B., Stroosnijder, L., 1984. Crust formation on sandy soils in the Sahel: I. Rainfall and infiltration. Soil Tillage Res. 4, 5–23.

Johnson, A.M., 1970. Physical Processes in Geology. Freeman, Cooper and Co., San Francisco, 557 pp.

Johnson, A.M., Martosudarmo, S.Y., 1997. Discrimination between inertial and macro-viscous flows of fine-grained debris with a rolling-sleeve viscometer. In: Chen, C. (Ed.), Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment. Proc. Am. Soc. Civ. Eng., vol. 1, pp. 229–238.

Jungerius, P.D., Dekker, L.W., 1990. Water erosion in the dunes. In: Bakker, W.M., Jungerius, P.D., Klijn, J.A. (Eds.), Dunes of the European Coast. Catena Suppl., vol. 18, pp. 185–193.

Jungerius, P.D., Ten Harkel, M.J., 1994. The effect of rainfall intensity on surface runoff and sediment yield in the gray dunes along the Dutch coast under conditions of limited rainfall acceptance. Catena 23, 269–279.

Jungerius, P.D., van der Meulen, F., 1988. Erosion processes in a dune landscape along the Dutch coast. Catena 15, 217–228.

Kaul, R., 1990. Plants. In: Bleed, A., Flowerday, C. (Eds.), An Atlas of the Sand Hills. Nebraska Conservation and Survey Division, Resource Atlas 5a, pp. 127–142.

Lawson, M.P., Dewey, K.F., Neild, R.E., 1977. Climatic Atlas of Nebraska. Univ. of Nebraska Press, Lincoln, p. 46.

Loope, D.B., Swinehart, J.B., 2000. Thinking like a dune field: geologic history in the Nebraska Sand Hills. Great Plains Res. 10, 5–35.

Loope, D.B., Swinehart, J.B., Mason, J.P., 1995. Dune-dammed paleovalleys of the Nebraska Sand Hills: intrinsic versus cli-

matic controls on the accumulation of lake and marsh sediments. Geol. Soc. Am. Bull. 107, 396–406.
Loope, D.B., Dingus, L., Swisher, C.C., Minjin, C., 1998. Life and death in a Late Cretaceous dune field, Nemegt Basin, Mongolia. Geology 26, 27–30.
Loope, D.B., Mason, J.A., Dingus, L., 1999. Lethal sandslides from eolian dunes. J. Geol. 107, 707–713.
Mason, J.P., Swinehart, J.B., Loope, D.B., 1997. Holocene history of lacustrine and marsh sediments in a dune-blocked drainage, southwestern Nebraska Sand Hills, USA. J. Paleolimnol. 17, 67–83.
McCord, J.T., Stephens, D.B., 1987. Effect of groundwater recharge on configuration of the water table beneath sand dunes and on seepage lakes in the Sandhills of Nebraska, USA, comment. J. Hydrol. 95, 365–367.
McGee, W.J., 1897. Sheetflood erosion. Geol. Soc. Am. Bull. 8, 87–112.
McIntosh, C.B., 1996. The Nebraska Sand Hills: The Human Landscape. Univ. of Nebraska Press, Lincoln, 266 pp.
Morin, J., Benyamini, Y., Michaeli, A., 1981. The effect of raindrop impact on the dynamics of soil surface crusting and water movement in the profile. J. Hydrol. 52, 321–335.
Muhs, D.R., Stafford Jr., T.W., Swinehart, J.B., Cowher, S.D., Mahan, S.A., Bush, C.A., Madole, R.F., Maat, P.B., 1997. Late Holocene eolian activity in the mineralogically mature Nebraska Sand Hills. Quat. Res. 48, 162–176.
Parker, G.G., Higgins, C.G., 1990. Piping and pseudokarst in drylands. In: Higgins, C.G., Coates, D.R. (Eds.), Groundwater Geomorphology; The Role of Subsurface Water in Earth-Surface Processes and Landforms. Geol. Soc. Am. Spec. Pap., vol. 252, pp. 77–110.
Picard, M.D., High, L.R., 1973. Sedimentary structures of ephemeral streams. Developments in Sedimentology vol. 17. Elsevier, NY, 223 pp.
Pierson, T.C., Scott, K.M., 1985. Downstream dilution of a lahar: transition from debris flow to hyperconcentrated streamflow. Water Resour. Res. 21, 1511–1524.
Rahn, P.H., 1967. Sheetfloods, streamfloods, and the formation of pediments. Ann. Assoc. Am. Geogr. 57, 593–604.
Rodine, J.D., Johnson, A.M., 1976. The ability of debris, heavily freighted with coarse clastic materials, to flow on gentle slopes. Sedimentology 23, 213–234.
Romkens, M.J.M., Prasad, S.N., Whisler, F.D., 1990. Surface sealing and infiltration. In: Anderson, M.G., Burt, T.P. (Eds.), Process Studies in Hillslope Hydrology. Wiley, NY, pp. 127–172.
Selby, M.J., 1993. Hillslope Materials and Processes. 2nd edn. Oxford Univ. Press, Oxford, 451 pp.
Simpson, E.L., Eriksson, K.A., Eriksson, P.G., Brumby, A., 1999. Genesis of massive sandstones interbedded with eolianites: the 1.8 Ga Makabeng Formation, South Africa. AAPG Abstr. 8, 130.
Smith, H.T.U., 1965. Dune morphology and chronology in central and western Nebraska. J. Geol. 73, 557–578.
Smith, G.A., 1986. Coarse-grained nonmarine volcaniclastic sediment: terminology and depositional process. Geol. Soc. Am. Bull. 97, 1–10.
Stokes, S., Swinehart, J.B., 1997. Middle- and late-Holocene dune reactivation in the Nebraska Sand Hills, USA. Holocene 7, 263–272.
Sweeney, M.R., 1999. Dune-sourced alluvial fans of the Nebraska Sand Hills. MS Thesis, Univ. of Nebraska, Lincoln, 75 pp.
Sweeney, M.R., Loope, D.B., 1999. Structureless and laminated sands of dune-sourced alluvial fans in the Nebraska Sand Hills. Am. Assoc. Petrol. Geol. Prog. 8, 136.
Swinehart, J.B., 1990. Wind-blown deposits. In: Bleed, A., Flowerday, C. (Eds.), An Atlas of the Sand Hills. Nebraska Conservation and Survey Division, Resource Atlas 5a, pp. 43–56.
Talbot, M.R., Williams, M.A.J., 1978. Erosion of fixed dunes in the Sahel, central Niger. Earth Surf. Processes 3, 107–113.
Talbot, M.R., Williams, M.A.J., 1979. Cyclic alluvial fan sedimentation on the flanks of fixed dunes, Janjari, central Niger. Catena 6, 43–62.
Thompson, C.H., 1983. Development and weathering of large parabolic dune systems along the subtropical coast of eastern Australia. Ann. Geomorphol. 45, 205–225.
Varnes, D.J., 1979. Slope movement types and processes. In: Schuster and, R.L., Krizek, R.J. (Eds.), Landslides: Analysis and Control. Natl. Acad. Sci. Spec. Rep., vol. 176. Washington DC, pp. 11–33.
Wilhite, D.A., Hubbard, K.G., 1990. Climate. In: Bleed, A., Flowerday, C. (Eds.), An Atlas of the Sand Hills. Nebraska Conservation and Survey Division, Resource Atlas 5a, pp. 17–28.
Wilson, I.G., 1972. Aeolian bedforms: their development and origins. Sedimentology 19, 173–210.
Winspear, N.R., Pye, K., 1995. The origin and significance of boxwork clay coatings on dune sand grains from the Nebraska Sand Hills, USA. Sediment. Geol. 94, 245–254.
Wizevich, M.C., 1997. Fluvial–eolian deposits in the Devonian New Mountain Sandstone, Table Mountain, Southern Victoria Land, Antarctica: sedimentary architecture, genesis, and stratigraphic evolution. In: Ricci, C.A. (Ed.), The Antarctic Region: Geological Evolution and Process. Terra Antarctica Publication, Siena, pp. 933–944.