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Feature Article

THINKING LIKE A DUNE FIELD: GEOLOGIC HISTORY IN THE NEBRASKA SAND HILLS

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Abstract

The Nebraska Sand Hills region is a giant dune field that is presently stabilized by prairie vegetation. During numerous severe droughts within the last 15,000 years, the dunes have lost their plant cover and have migrated freely. Wetlands between dunes are extensive in the central Sand Hills and are connected to the Ogallala aquifer. Lakes and wetlands formed when dunes blocked and deranged stream systems. Evaporation of water from wetlands may benefit adjacent dune vegetation during extended droughts by locally increasing humidity and rainfall. Buried bison tracks are abundant within the dunes, suggesting that grass and water remained available in some interdunes, even during episodes of dune migration. Study of the geologic processes operating within this dune field enhances not only our ability to read the paleoclimatic history of the Great Plains, but also our understanding of features found within analogous deposits from the rock record.

Introduction

In *Sand County Almanac*, Aldo Leopold, one of America's foremost ecologists and conservationists, wrote lyrically of the interplay between Earth and life. In the chapter entitled "Thinking Like a Mountain", we learn that Escudilla Mountain has reason to worry: Due to the extirpation of New Mexico's native wolf population, deer are ravaging the vegetation on Escudilla's slopes, speeding erosion and the mountain's ultimate demise. If the sand dunes in Nebraska are also thinking, their issue is probably with grass. To form and remain active, a dune field needs wind and sand that is accessible to that wind. These dunes are presently fettered, their migration halted by a thin veneer of prairie grasses. Even as the winds shriek over the landscape, the short thicket of stems renders the underlying sand immobile.

The Nebraska Sand Hills (Fig. 1), then, are a sobering example of climate change. Giant dunes, in form resembling those found in the hyperarid parts of southern California and the Middle East, are now covered with vegetation that, in some years is reminiscent of Ireland. Extensive wetlands and numerous lakes lie in the corridors between the dunes. Aptly dubbed a "Desert in Disguise" (Sletto, 1997), the Sand Hills have lost their grass cover and become fully active several times within the last 15,000 years.

Situated, like the Sand Hills, at high latitude in the core of a large continent, the Gobi of central Asia has remained arid for millions of years because mountains prevent entry of moist air masses from the Indian and Pacific Oceans. Under the present climatic and tectonic regime, the Sand Hills region is bathed by moist air masses that arrive each summer, moving unimpeded all the way from the Gulf of Mexico.

The Great Plains today is one of the major crop-producing areas of the world. Much of the agricultural production west of the 97th meridian is dependent on irrigation from the High Plains (Ogallala) aquifer. The Sand Hills are a major recharge area for the sands and gravels that comprise the aquifer, and about 65% of the total water in storage is in Nebraska (Weeks and Gutentag, 1988). The geologic histories of the Sand Hills dunes and of the aquifer are intertwined: both have responded dramatically to drought episodes. Blockage of streams by dunes has caused the level of the aquifer to rise 25 m in at least one part of the dune field, and water vapor evaporated from interdune wetlands may help to keep the dunes grass-covered and stabile.

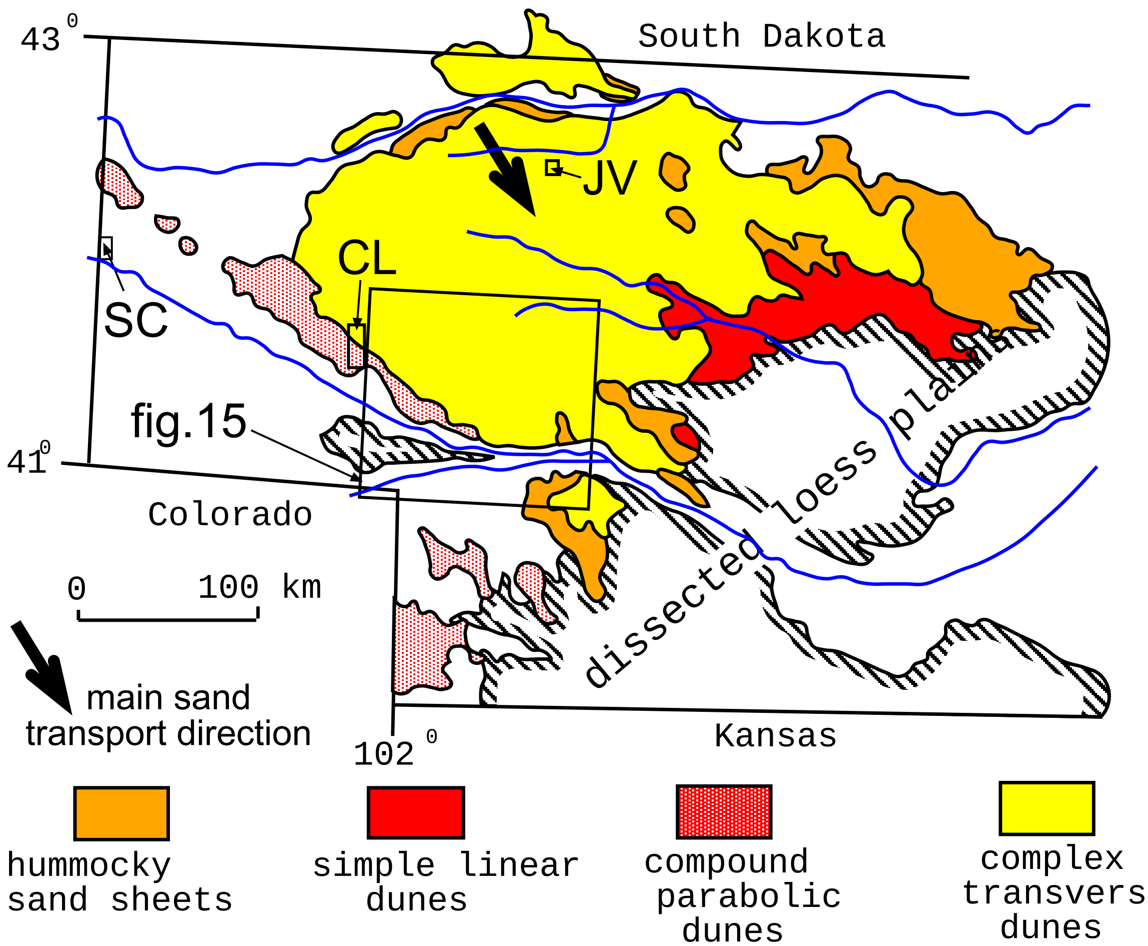

Figure 1. Map showing the distribution of wind-blown sand, generalized dune types, and thick (Peoria) loess deposits in Nebraska. Locations described in text: SC, Sheep Creek dune dam (Fig. 4); CL, Crescent Lake and Blue Creek area (Fig. 2); JV, Jumbo Valley (Fig. 5). Map modified from Stokes and Swinehart (1997).

One motivation for geologic research in the Sand Hills region is simply to document the range of climatic fluctuations recorded in the sediments. This record, mainly preserved in buried soils exposed in blowouts and in peat and lake sediments accumulating between the dunes, provides clear evidence of numerous severe droughts that lasted at least several decades and, unlike the Dust Bowl drought, led to full mobilization of the sand sea. The last such "mega-drought" ended about 1000 years ago. It seems clear that future droughts of similar magnitude would have a devastating effect on non-irrigated agriculture and would seriously deplete the aquifer.

The Atlas of the Sand Hills (Bleed and Flowerday, 1990) provides excellent summaries of many aspects of the Sand Hills region. The purpose of this paper is to review some of the recent research carried out in the Sand Hills, and to show how such studies can aid geologic interpretation of ancient strata.

Dating the Dunes and the Dune Field

The Sand Hills were long viewed as a Pleistocene (Ice Age) feature (Smith, 1965). A paper by Ahbrandt et al. (1983) presenting abundant evidence of Holocene (within the last 10,000 years) dune migration stirred much interest within the geosciences community: If the dunes were active recently, the implication is that they could well become active in the near future (Muhs and Holliday, 1995). The early evidence was based on radiocarbon dates on organic-rich soils and peat deposits that underlie dune sand. The dated material was produced during wet periods, and the dune sand was clearly younger, but how much younger? Now there are considerably more radiocarbon dates to support the idea of widespread dune mobility in the Holocene, and an exciting new technique called optically stimulated luminescence (OSL) now allows the timing of sand deposition to be directly dated. OSL dates from outcrops reported by Stokes and Swinehart (1997) indicate widespread middle- and late-Holocene activity.

Demonstration that much of the material in the dunes is Holocene is not necessarily an indication that the dune field formed that recently. A sand dune moves like a tank tread; as it migrates downwind, older material exposed on the upwind side is eroded, moved forward, and "recycled" onto the leading edge. Many earlier workers assumed the dunes of the Sand Hills were the same age as the late Pleistocene "Peoria" loess (dust deposit) that lies south and east of the dunes. They reasoned that finer grained material moved by the wind in suspension would leave behind the coarser material that was driven by saltation. Ahlbrandt et al. (1983) showed that the present generation of dunes overlies the loess, and is thus younger, but it does seem likely that a dune field (or fields) was present while the older (Pleistocene) loess was being deposited. Stokes et al. (1999) recently published a series of OSL dates from core hole samples taken through the back side of two large dunes in the northern Sand Hills. Their dates suggest that although there is a remnant of 10-15,000 year-old dune sand, as much as 3/4 of the material in the dunes was deposited during the Holocene. Smaller dunes are likely to have been completely reworked during the last 10,000 years.

Dunes that Block Streams and Make Wetlands

Because the Great Plains occupy the core of the North American continent, rainfall is sparse and highly variable. Air masses moving north from the Gulf of Mexico are today's main source of moisture; most rainfall events take place from May through July, and are triggered by eastward moving storms. Forman et al. (1995) note that long-term droughts on the Plains could result from the weakening or eastward migration of the Bermuda High—the large-scale gyre that currently brings the moist air northward from the Gulf.

Satellite views of Earth show that the surfaces of the continents are dominated by the action of streams. The area occupied by the dunes, wetlands and lakes of the Sand Hills region is an exception to this generalization, and, before the dune field organized into its present form, was probably occupied by integrated fluvial drainages. Our work in the western Sand Hills, concentrated at the southern edge of the dune field near the head of Blue Creek in Garden County (Loope et al., 1995; Mason et al., 1997), has revealed some of the details of how dunes and streams interact during severe droughts. Dunes blocked a large stream system (the present Snake Creek and Blue Creek drainages) that flowed southeastward from the vicinity of Wyoming-Nebraska border to join the North Platte near present-day Llewellyn, Nebraska. Blue Creek now flows in a valley cut into

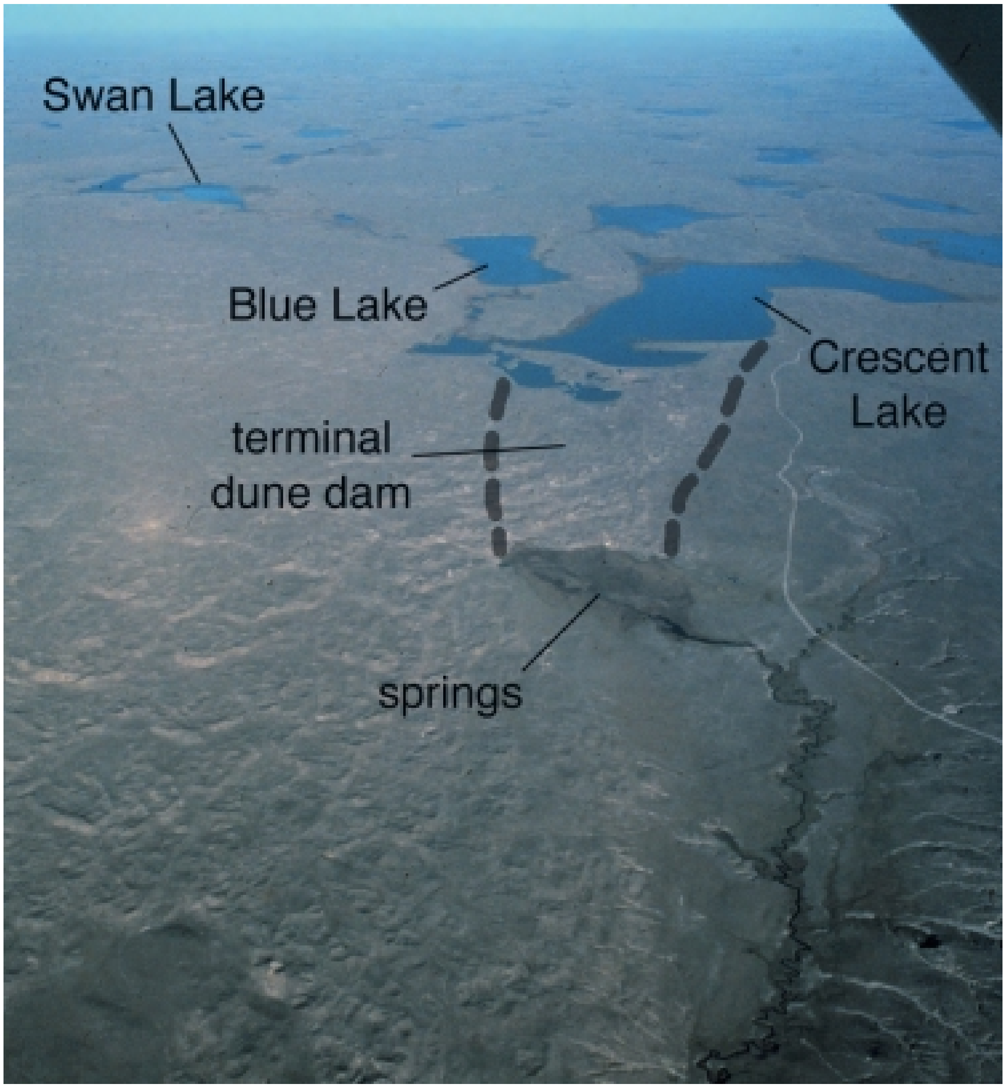

Figure 2. An aerial view looking northward of the springs flowing from the terminal dune dam at the head of Blue Creek, and Crescent, Blue and Swan Lakes. Photo by Jon Mason

Ogallala Group bedrock and, at its head, emerges at the base of a sand dune that fills that valley (Fig. 2). One thousand lakes lie to the north; Crescent Lake (the one nearest the head of Blue Creek) is only 2.5 km away from the springs at the head of Blue Creek but is 25 m higher in elevation. Our drilling, coring, and sampling activity has been especially concentrated near the springs at the head of Blue Creek and in the area just east of Alliance, where Snake Creek disappears at the western edge of the Sand Hills. Our evidence indicates there were two episodes of stream blockage by dunes, one just prior to 12,000 years, and another just prior to 6,000 years ago.

We started our work near the head of Blue Creek because the idea that Sand Hills dunes had been actively migrating within the last 10,000 years (Ahbrandt et al., 1983) had been challenged by Herb Wright of University of Minnesota. Based on their analysis of a 14 meter-long sediment core that they retrieved from the center of Swan Lake (just northwest of Crescent Lake (Fig.2) Wright et al., (1985) argued that the dunes surrounding the lake had been immobile for the last 10,000 years. Their core contained only peat and lake mud; it was devoid of sand. They interpreted the sediments as a record of a steadily rising regional water table—an indication that the climate had become increasingly wet since 10,000 years ago. They reasoned that if the dunes surrounding the lake had been mobile, sand would have been abundant in the core. Our work supports their view that the water table at Swan Lake has risen more than 14 meters, but we interpret this rise as the result of local, not regional, changes. Blockage by dunes of the through-flowing ancestor of Blue Creek caused the water table to rise and peat to start accumulating. Our cores show that some of the dunes that surround Swan Lake overlie peat and that these dunes were actively migrating during much of the last 10,000 years. The wind carries sand by the process of saltation— the grains seldom reach heights more than a meter above the land surface. Sand isn't present in the center of the lake basin because vegetation at the lake margin trapped the saltating grains. In the Crescent Lake area it is clear that the area occupied by wetlands has been steadily increasing for the last 12,000 years, and therefore that the elevation of the upper surface of the High Plains aquifer has risen by 25 meters in the same amount of time. We interpret this rise as the result of the drastic changes brought to this watershed by dune blockage. As long as streams were through-flowing, the water table remained low and few lakes or wetlands existed. The dunes that blocked the streams greatly retarded the movement of water toward the Platte River. As the water table rose and wetlands expanded, and as the water table gradient increased within the terminal dune dam, the flow of the springs at the head of Blue Creek was augmented. The elevation of the wetlands behind the dune dam (and, therefore, their area) cannot increase further because spillover to Blue Creek now takes place at the eastern margin of Crescent Lake (Fig. 2).

One of the most obvious examples of wind-blown sand interfering with a stream outside the main Sand Hills is found 5 km north of Henry, adjacent to the Nebraska / Wyoming state line (Figs. 3 and 4). A large compound parabolic dune has migrated across and completely filled a 2.5 km-long stretch of the 1.5 km wide and 20 m deep Sheep Creek Valley. The 1896 Patrick topographic map shows Sheep Creek north of the blockage as an ephemeral stream disappearing into the dune sand, while south of the dune dam, only a dry valley is shown. The Interstate Canal, built in 1911, crosses Sheep Creek about 10 km to the north and local residents say that a major canal break in the 1930's diverted a significant amount of water into Sheep Creek for a few weeks. This flow cut a narrow, 7-meter-deep, channel through the dune dam and greatly reduced the area of wetlands, both upstream and downstream from the dam. We have no dates on the emplacement of this dam but hypothesize it occurred within the last few thousand years.

Peat Accumulation and Wetland-Atmosphere Feedbacks

Wetlands are also widespread in the northern Sand Hills, especially in Cherry County. The interdune valleys yield abundant hay that ranchers use to feed their cattle over the winter months. As every rancher knows, many portions of these interdune areas

Figure 3. Coring the sediment record at Swan Lake (Garden County, NE); 16.5 m of peat and lake mud have accumulated since about 10,700 years ago. Photo by Don Rosenberry, U.S. Geological Survey.

are accumulating peat so rapidly that the surface will not support the weight of a tractor. At Jumbo Valley, in south-central Cherry County (Fig. 5), peat has reached a thickness of about 7 meters (Fig. 6). The oldest peat we have sampled yields radiocarbon dates of about 12,500 years and contains abundant spruce pollen and spruce needles (Barbara

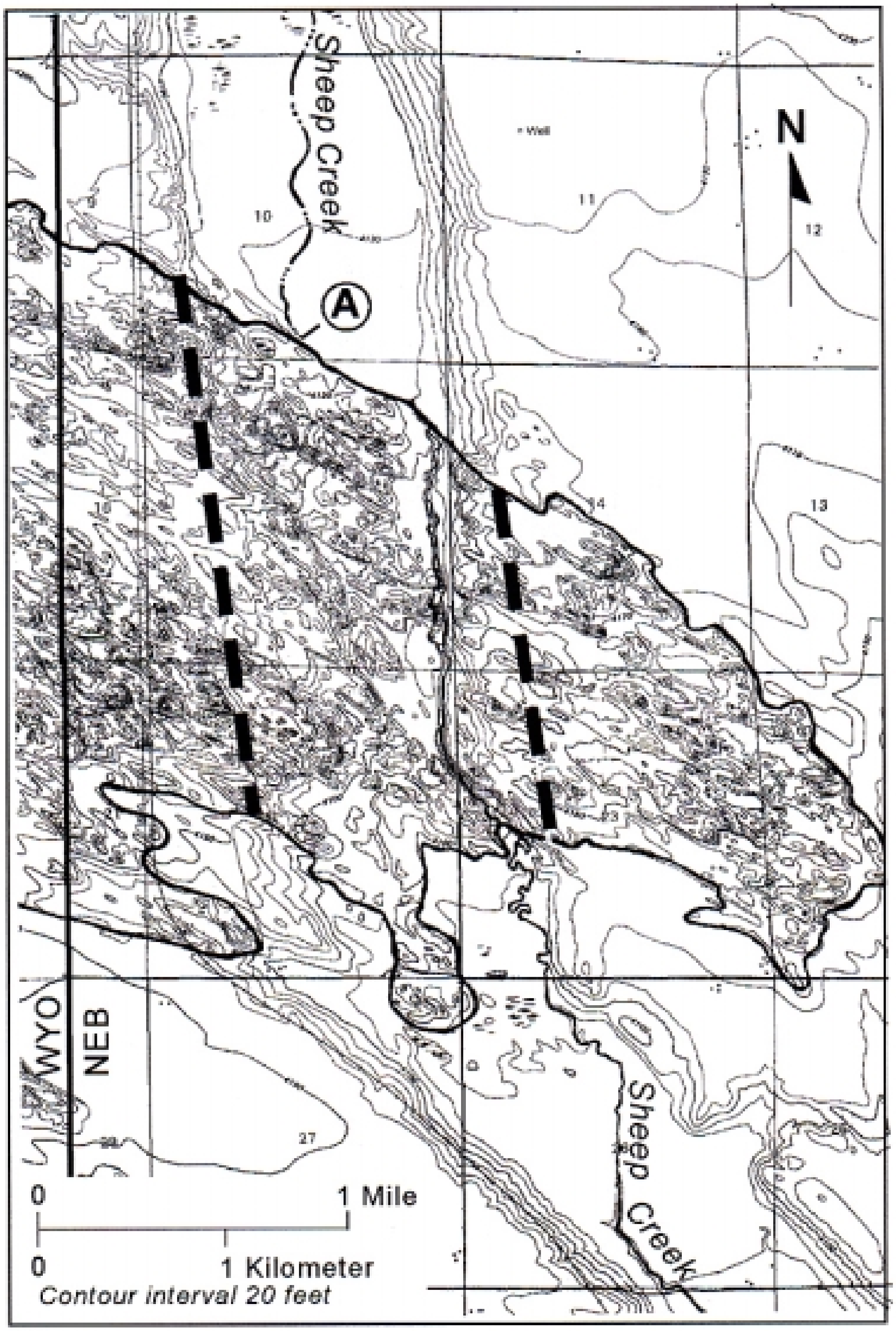

Figure 4. Sheep Creek dune dam in the southwestern corner of Sioux County. The heavy dashed lines indicate the approximate boundaries of the buried valley. The circled A points to where Sheep Creek is shown disappearing into dune sand on the 1896 Patrick topographic map. Base map modified from the Torrington SE, WYO-NEBR 1:24,000 scale USGS topographic map.

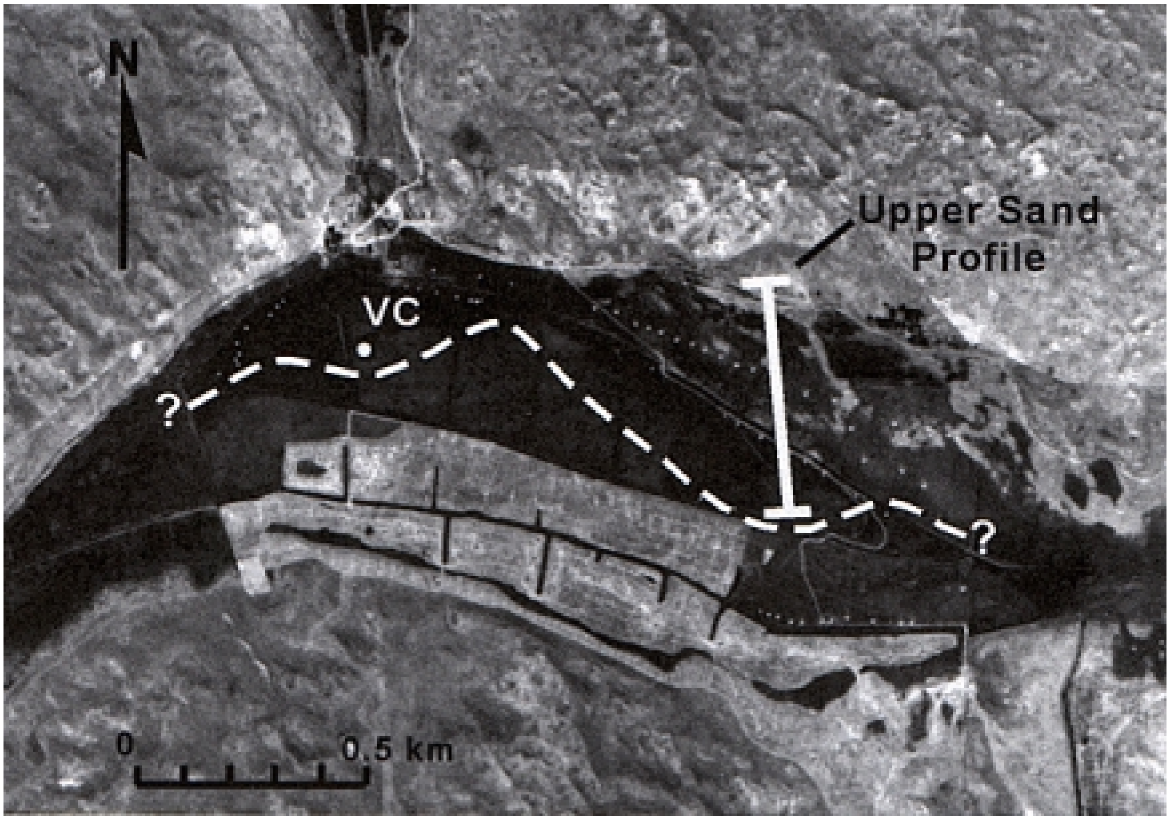

Figure 5. Aerial photo of Jumbo Valley, Cherry County, taken in August, 1984. The valley is situated between 50 m high sand dunes and has been partially hayed (the light-toned rectangular area on the south side). Haystacks show as light dots. A series of drainage ditches has been cut into the peatland to facilitate drainage for cutting hay. The area noth of the white dashed line is the approximate distribution of the uppermost wind-blown sand sheet. The location of vibracore VC 93-16 is at the dot labeled VC.

Nicholson, *personal communication*). We assume that the water table rise that allowed the preservation of peat was triggered by dune migration, but we do not yet know whether the spruce trees were restricted to the interdune valleys or if they grew on the dunes as well. Because of the early experimental work of Charles Bessey that led to the planting and growth of pine forests on dunes near Halsey and southwest of Valentine, we know that the dunes can support trees (Miller, 1990). Fire appears to be the environmental factor that currently maintains grassland vegetation. Spruce pollen disappears from the peat at about 10,500 years ago, and the wetlands flora has been dominated by sedges (*Carex*) since that time (Peggy Bolick, *personal communication*; Fig. 6). A number of glacial relict species are, however, still found in the wetlands, including cotton grass and marsh marigold (Steinhauer et al., 1996), and fish like the northern redbelly dace (Hrabik, 1990)

Although the ultimate source of most of the water that falls as rain on the Great Plains is the Gulf of Mexico, there is a strong likelihood that much of the water that

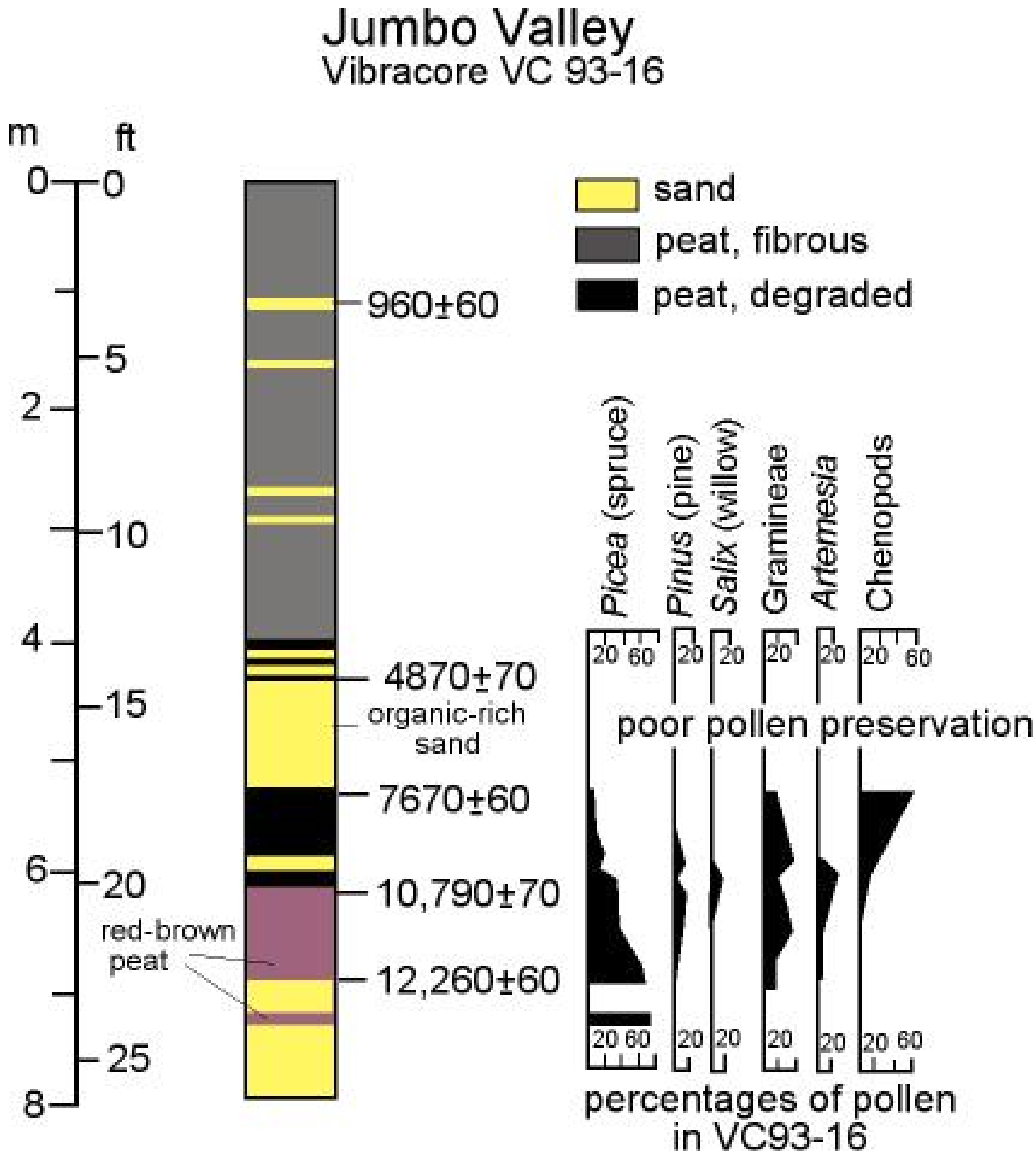

Figure 6. Stratigraphy, radiocarbon ages and preliminary pollen data from VC93-16. Refer to Fig. 5 for location in Jumbo Valley. Note that between 6.7 and 5.2 m there is a change from a spruce/grass dominated pollen profile to a grass/pigweed profile. The pollen record was analysed by M. Bolick of the University of Nebraska State Museum. Figure modified from Ponte (1995).

comes to the Great Plains from the sea will fall from clouds more than once before it finally returns there. The total volume of water returned annually by rivers to the sea (35,000 km^3) is only about 30% of the annual precipitation on the continents; the remainder is evaporated directly or is transpired by plants. The Great Plains and the Sahel region on the southern edge of the Sahara are subject to especially long-term droughts. There is evidence that evaporation from the land surface is an important source of atmospheric moisture in these regions; if the sources of surface moisture can be depleted, the droughts may be self-reinforcing (Nicholson, 1988). In the last 50 years, there has been a tremendous increase in irrigation in the parts of the Great Plains that have access to the High Plains (Ogallala) aquifer. Coinciding with this boom in irrigation is a trend of increasing precipitation in the same areas. A recent study by Moore and Rojstaczer (1999) indicates this is a cause-and-effect relationship—the increases in precipitation are concentrated in the summer months and are irrigation induced. Apparently, much of the irrigation water that directly evaporates or is transpired from the corn fields condenses and falls nearby.

We aren't advocating a "Rain Follows the Center Pivot" campaign, but are intrigued with the possibility that an understanding of how irrigation augments regional rainfall could be of use for deciphering the paleoclimatic record of the Sand Hills. River systems efficiently channel water that has fallen onto the continents back to the sea. In arid regions, wetlands are widespread only in areas where glaciers or dunes have modified river systems. Wetlands are widespread in western and central Sand Hills. We speculate that evaporation from the wetlands between the Sand Hills dunes "recycles" water stored in the High Plains aquifer in basically the same way that irrigation does. Thus, as long as there are interdune wetlands supplying abundant water vapor to the atmosphere during the critical summer growth season, the grasses on the adjacent dunes will benefit in two ways: 1) they will not need to transpire as much water; and 2) they will receive more rainfall. Compared to other kinds of soils, the weakly developed soils on the dunes, have very low water-storage capacity; the dune grasses would thus seem to be quite vulnerable to drought. Were droughts like those experienced in the Dust Bowl years of the 1930's more severe in Oklahoma and Kansas because, unlike the central and northern plains, that region lacks extensive wetlands to provide a "drought cushion"? Because the wetlands and lakes of the Sand Hills are hydrologically connected to a vast aquifer, drawdown during a long-term drought would take place much more slowly than in the northern plains where most surface water is underlain by materials with low permeability.

From the sediment record, we know that the Sand Hills have undergone many episodes of active migration in the last 15,000 years, but how much of a drought is needed to cause the dunes to lose their grass cover and become active? Are all parts of the dune field equally susceptible to activation? From the above discussion of the potential effect of local sources of atmospheric moisture, it seems reasonable to hypothesize that the dunes in the central Sand Hills lost their grass cover only after a substantial portion of the interdune wetlands were desiccated. In this particular part of the Sand Hills, we believe this happened most recently about 1,000 years ago. In 1992, Chuck Markley of UNL's Conservation and Survey Division alerted us to the presence of sand layers beneath the surface of Sand Hills peatlands. Evidence in our cores (Figs.7 and 8) suggests that during prolonged droughts, the water table in interdune peatlands fell and sheets of eolian sand were driven from the dunes far into the interdunes (Ponte,1995). If lush wetland vegetation had been present, the sand could not have saltated across these surfaces. In this case, it appears that the grasses lost their grip on the sand, and the wetlands dried up at the same time. This makes sense in terms of the above suggestion that droughts are self-reinforcing and that evapotranspiration from wetlands helps to maintain grass on the dunes. One way to test this idea would be to compare the recent geologic record of eolian activity and drought at two types of dune sites within the Sand Hills: those adjacent to interdune wetlands and those distant from wetlands. In figure 9, our data from the dune field as a whole show several radiocarbon and OSL dates from buried soils and dune sands that are considerably younger than 1,000 years.

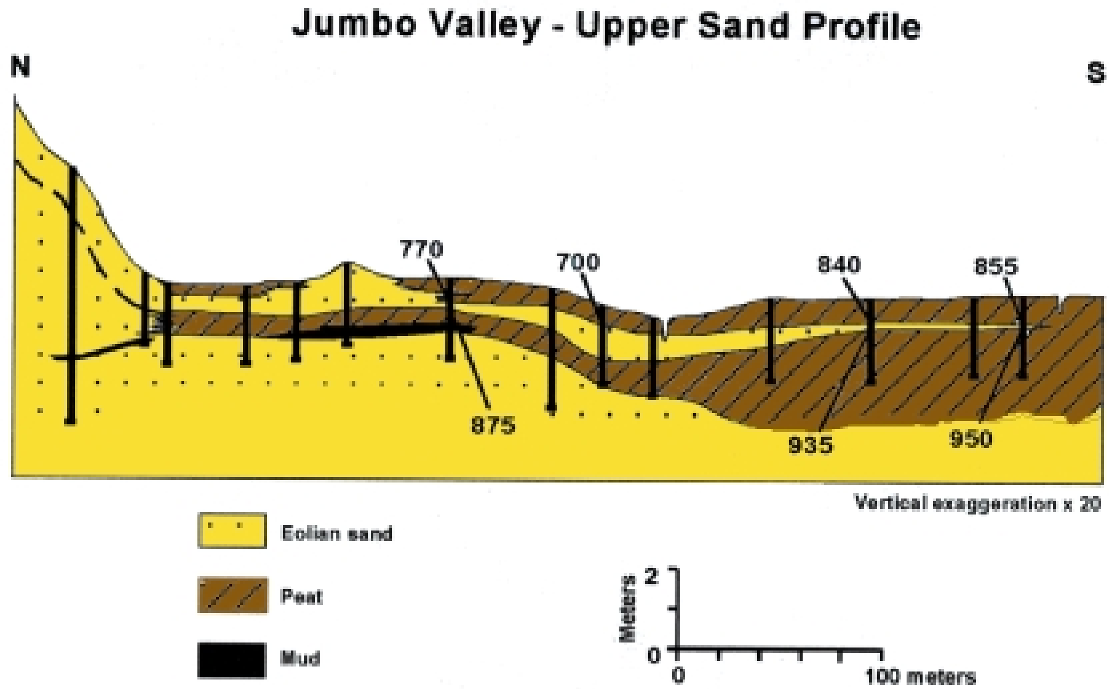

Figure 7. North to South vibracore transect in the Jumbo Valley peatland (refer to Fig. 5 for location) showing the distribution of the upper sand sheet. The radiocarbon ages shown are average ages of two to four samples of sedge seeds recovered from 1 to 2 cm below or above the sand sheet. Each age has an error (one standard deviation) of about +50 years.

Dune and Interdune Paleoecology

Two lines of evidence suggest that not all interdune wetlands were lost during drought episodes. The survival of relict plants like cotton grass suggest that suitable wetland habitat has been available within the dune field for at least 12,000 years.

Another clue that some wetlands were maintained comes from disturbed layers of sand within the dunes (Fig. 10). When we first saw these features, we thought they might be produced by snow that, having become interbedded with sand during winter storms, later melted. During some winters in the Killpecker Dunefield north of Rock Springs, Wyoming, considerable thicknesses of snow accumulate on the lee faces of sand dunes (Steidtmann, 1973). If the snow is then buried by sand, the snow can persist for months or years. When the snow eventually melts, the overlying layers of sand will be distorted. Earthquake shocks are another possibility: they can liquefy dune sand, allowing layers to be folded and broken. But the sand must be water saturated for this mechanism to work, and nearly all of the deformed layers we have observed are high within dunes and have

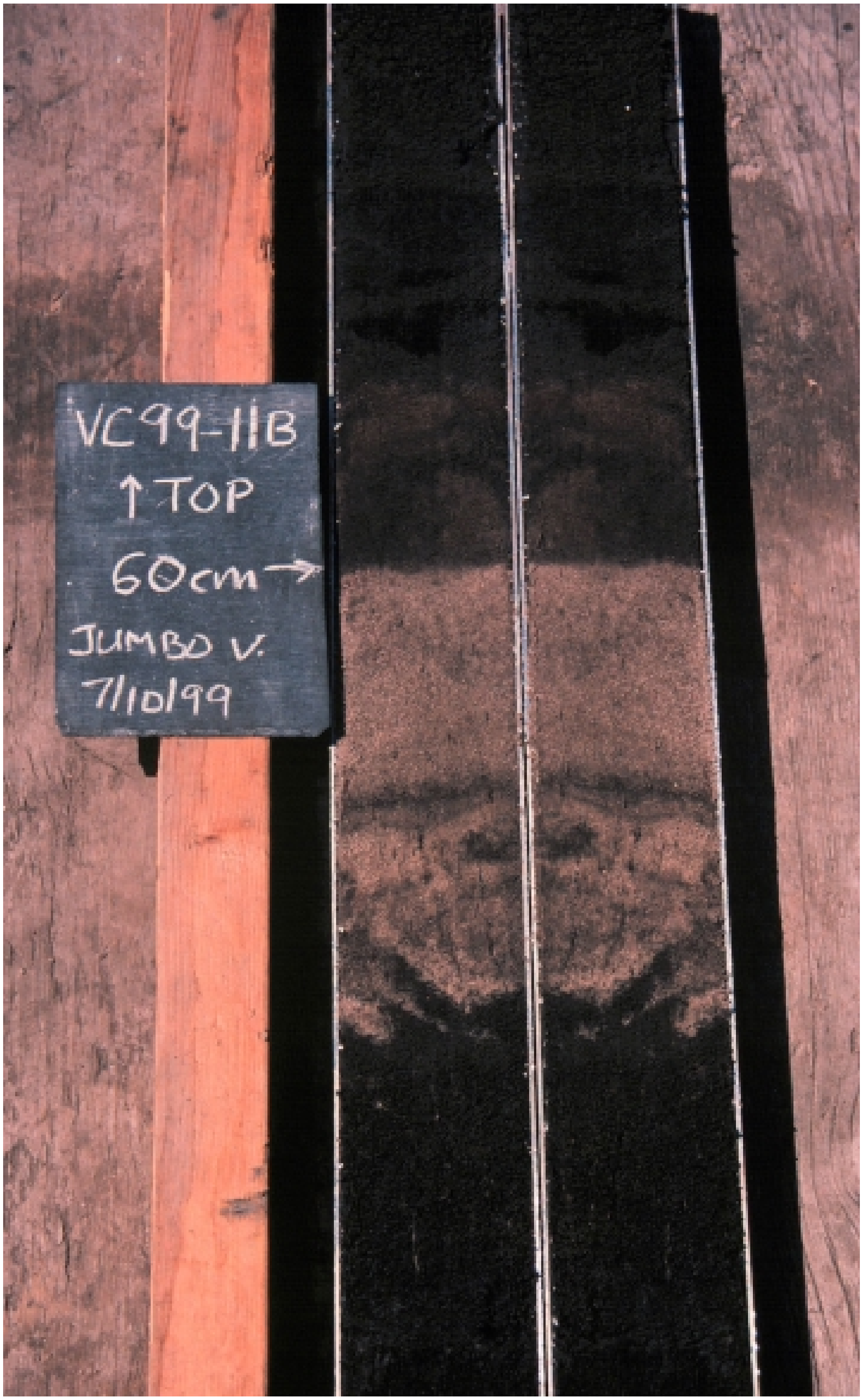

Figure 8. Thin sand under- and overlain by peat in a vibracore from Jumbo Valley (see Fig. 7 for age and distribution). Sand was driven into the valley during a drought interval when the wetland was desiccated. Photo by Jim Swinehart.

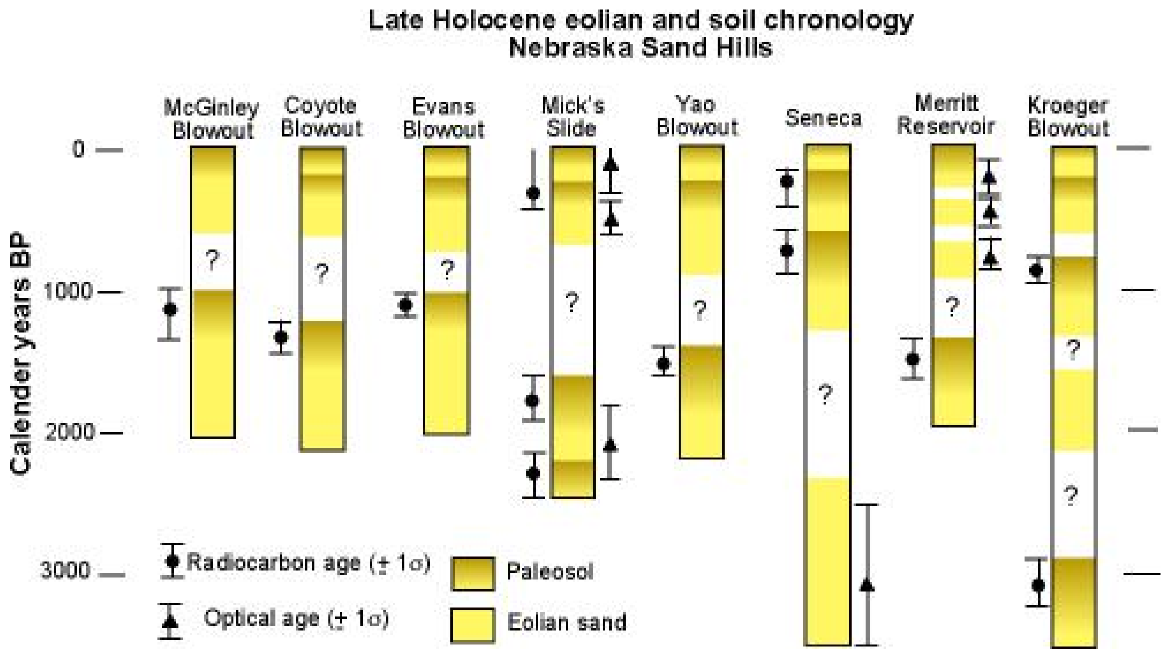

Figure 9. Eolian and paleosol stratigraphy versus time for eight locations scattered across the Sand Hills. The thickness of any given section ranges from 3 to 20 m. Blank spaces are estimated intervals of missing sediment either due to erosion or nondeposition. Radiocarbon ages from the Seneca locality are from Muhs et al (1997) and the optical (OSL) ages are from Stokes and Swinehart (1997).

Figure 10. Dune sand exposed at excavation site for Calamus Dam near Burwell, NE. Sloping layers of sand indicate dune advanced from left to right. Arrows mark zones of disturbed layering interpreted as bison tracks. Frozen paleontologist (Bob Hunt, UNSM for scale). Photo by David Loope.

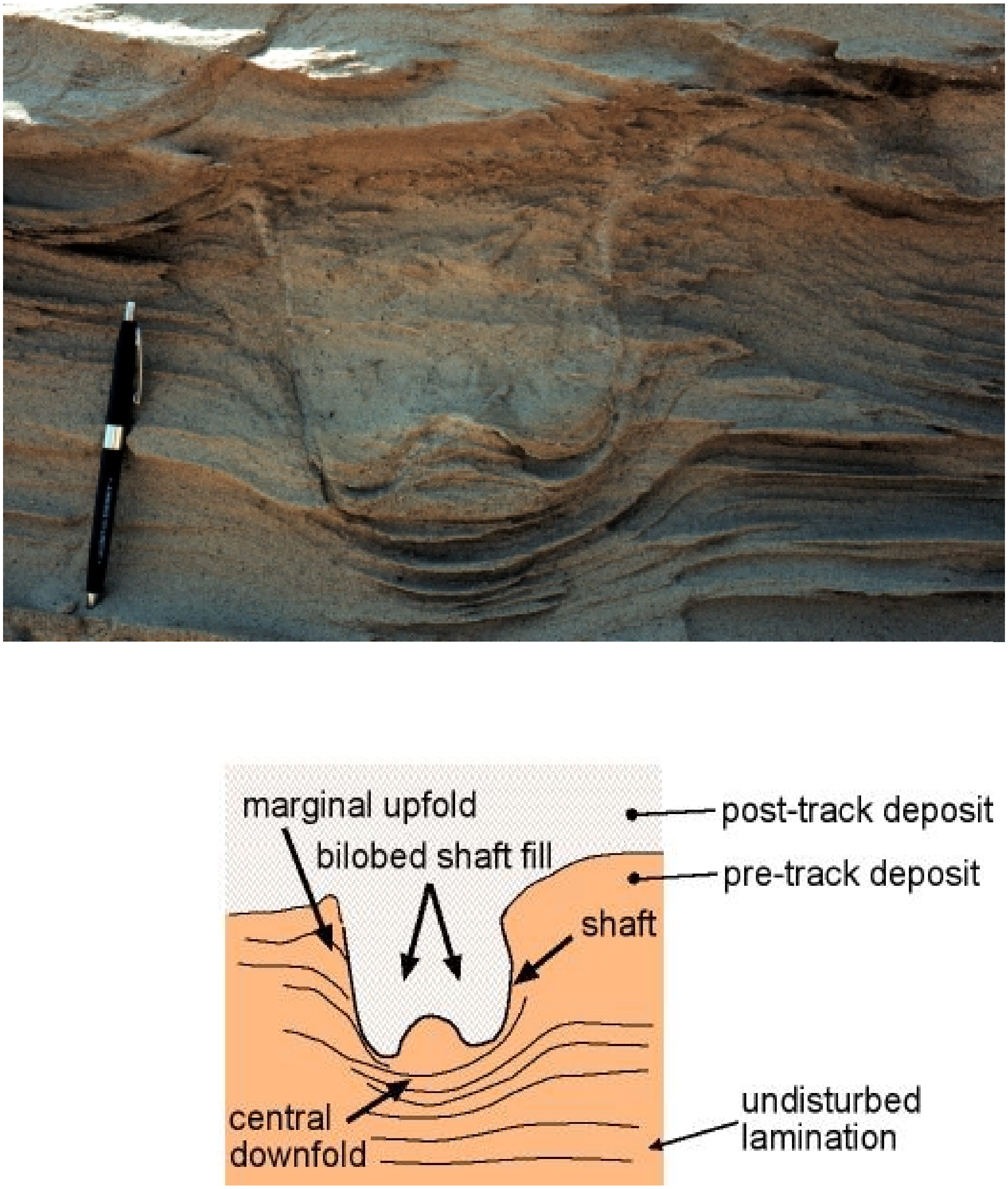

Figure 11. Detail of buried bison track exposed in dune deposits near Burwell, NE (Loope, 1986) and interpretive diagram based on Allen (1989).

never been below the water table. Upon closer observation, the contorted sand layers in the Nebraska Sand Hills turn out to be of a quite different origin—when the details of their morphology are clearly seen (Fig. 11), they can be recognized as bison tracks in vertical cross-section. The bison walked on the dunes when their lee slopes were covered with wind ripples—a clear indication that the slopes were nearly bare of vegetation. The tracks are sufficiently common throughout the dune field to indicate that the animals must have had local supplies of food and water, and interdune wetlands seem to be the most likely sources (Loope, 1986).

Rain- and Dustfall on the Dunes

Seeking shelter from winter winds and exposure to the winter sun, ranchers in the northern and central Sand Hills have commonly chosen to place their homes at the bases of steep, south-facing slopes . These slopes are steep and long because they represent the lee (downwind) side of giant dunes that, when mobile, migrate southward primarily under the influence of northerly and northwesterly winds. Summer cloudbursts in the Sand Hills can deliver several inches of rain in less than an hour. On the basis of common sense or simple laboratory studies, it would seem that dune sand could soak up all rainwater that falls on it. The lee slopes of many of the largest dunes in the Sand Hills, however, are deeply gullied and alluvial fans have been built at the break in slope (Sweeney,1999; Fig. 12). Sand entrained by the runoff can rapidly bury fences or other property (Fig. 13).

Figure 12. Gullies cut during summer thunderstorms into the leeward (downwind, south-facing) slope of a 60 meter-high dune east of Hyannis, NE. Each gully feeds an alluvial fan. Railroad and power lines in foreground. Photo by David Loope

Recognizing the possibility that sand can be rapidly deposited at the toe of a sand dune allowed us to reinterpret some famous dinosaur fossils in Mongolia (see below). Perhaps more importantly, the plants that grow on the Sand Hills (and keep these stabilized dunes from starting to migrate again) are sustained by summer rainfall. Any water that runs off the dunes (rather than infiltrating the sand) is unavailable for plant growth. Studies carried out along the coast of Holland have shown that runoff from certain parts of dunes after rain events is caused by water repellency of the sand. Organic coatings on the grains appear to give the Dutch dunes their tendency to repel water, and may likewise be responsible for the runoff from the Sand Hills (Joe Mason, *personal communication*).

Using the scanning electron microscope, thin coatings of clay can be observed on sand grains from Sand Hills dunes (Fig. 14). Although this finer material makes up only about 2% of a typical sand sample, its presence greatly enhances the water-holding capacity of the soil, making life on the dunes significantly easier for plants. The ancient

Figure 13. Truck buried by sand washed from steep lee face of dune during thunderstorm in July of 1991. Dumbbell Ranch, north of Hyannis, NE. Photo by Linda Brown.

Figure 14. Clays that coat and bridge the surfaces of four sand grains (from Ehrman, 1987). Field of view is 300 microns. Clay is deposited by infiltrating rain water and may have been delivered as dust fall or may have been inherited from the river deposits that supplied the sand to the dune field.

bison tracks (Fig. 11) are, like their modern counterparts made by Sand Hills cattle, steep sided. Such tracks are produced in slightly cohesive sand that allows the shaft of the track to stay open rather than slumping inward. The morphology of the ancient tracks indicates that the modern dune sand is not anomalous--the clay-coated grains have been around for thousands of years. The bridges connecting the coatings of adjacent sand grains show that the clay is emplaced by infiltrating water carrying fine particles downward through the pore spaces of sand that lies above the water table. Two different explanations have been proposed to account for the source of the clay: according to the "top-down" hypothesis, the fine material originated as atmospheric dust and is washed directly into the dunes by rainwater (Winspear and Pye, 1995). Another possibility (the "inheritance" hypothesis) is that the fine particles were carried in suspension by a stream that lost its water (and fine sediment load) to the thirsty sands of its dry channel. Later, wind carried away the already coated sand grains to form dunes (Wilson, 1992; Loope and Dingus, 1999). According to this hypothesis, the bridges connecting the clay coats of adjacent sand grains within the dune are produced when infiltrating rainwater redistributes fine material that was already present. Dust has certainly fallen onto the surface of the Sand Hills, and we know that the source of the sand for the dunes was dryland streams, but, so far, it has proven difficult to say which process has been more important for the Sand Hills dunes.

Evidence of Former Dune Dams

There are only a few ways to form lakes on the unglaciated portion of the Great Plains, and our experience with the dune dams in the western Sand Hills (see above) has led us to interpret several other ancient lake deposits in western Nebraska as products of the same processes. When sand dams are still in place (as in Garden County), it is, of course, much easier to make the case for dune blockage. In 1995, Bruce Bailey of the University of Nebraska State Museum alerted us to the presence of a thick body of lake sediments that contain abundant fish and amphibian fossils and lie within the canyon of the Niobrara River west of Valentine. Detailed investigation of the site indicates that two large lakes-- the eastern one possibly 20 km long and the western one at least 4 km long-- occupied the floor of the canyon about 40,000 years ago (Swinehart et al., 1996). The great thickness of the lake deposits (as much as 55 m) and their presence near the rim of the canyon seem to preclude stream blockage by landslides from the canyon walls. Large dunes are present on the tableland both north and south of the modern canyon and at least 30 m of dune sand is present immediately down gradient from the thickest portion of the western lake fill.

While mapping the geology of the North Platte River valley in 1977, Bob Diffendal of UNL's Conservation and Survey Division encountered lake deposits lying 70 meters above river level and below a 10,500 year-old soil. Flushed with confidence from our discovery of the "living dune dam" in Garden County, we summoned our courage, and proposed that dunes at the southern margin of the Sand Hills had blocked both the North and South Platte, forming lakes far up the North Platte valley (Swinehart and Loope, 1992). We argued that the large, triangular patch of dunes in Lincoln County (south of the rivers; Figs. 1 and 15) was an additional result of the blockage. Unlike Blue Creek and the Niobrara River, the Platte, of course carries snow melt from the continental divide. Blocking such a river with dunes would seem to require a huge climate change.

But to provide some perspective, in the middle 19th century (before dams had been built in its upper watershed), the South Platte was typically dry during July, August, and September from Fort Morgan, Colorado to its junction with the North Platte (NRC, 1992:140).

Dan Muhs and his U.S. Geological Survey colleagues, originally dune-dam skeptics, recently analyzed the mineralogy and elemental chemistry of the sand from dunes south of the Platte to see if any of it came from the Sand Hills. The results indicate

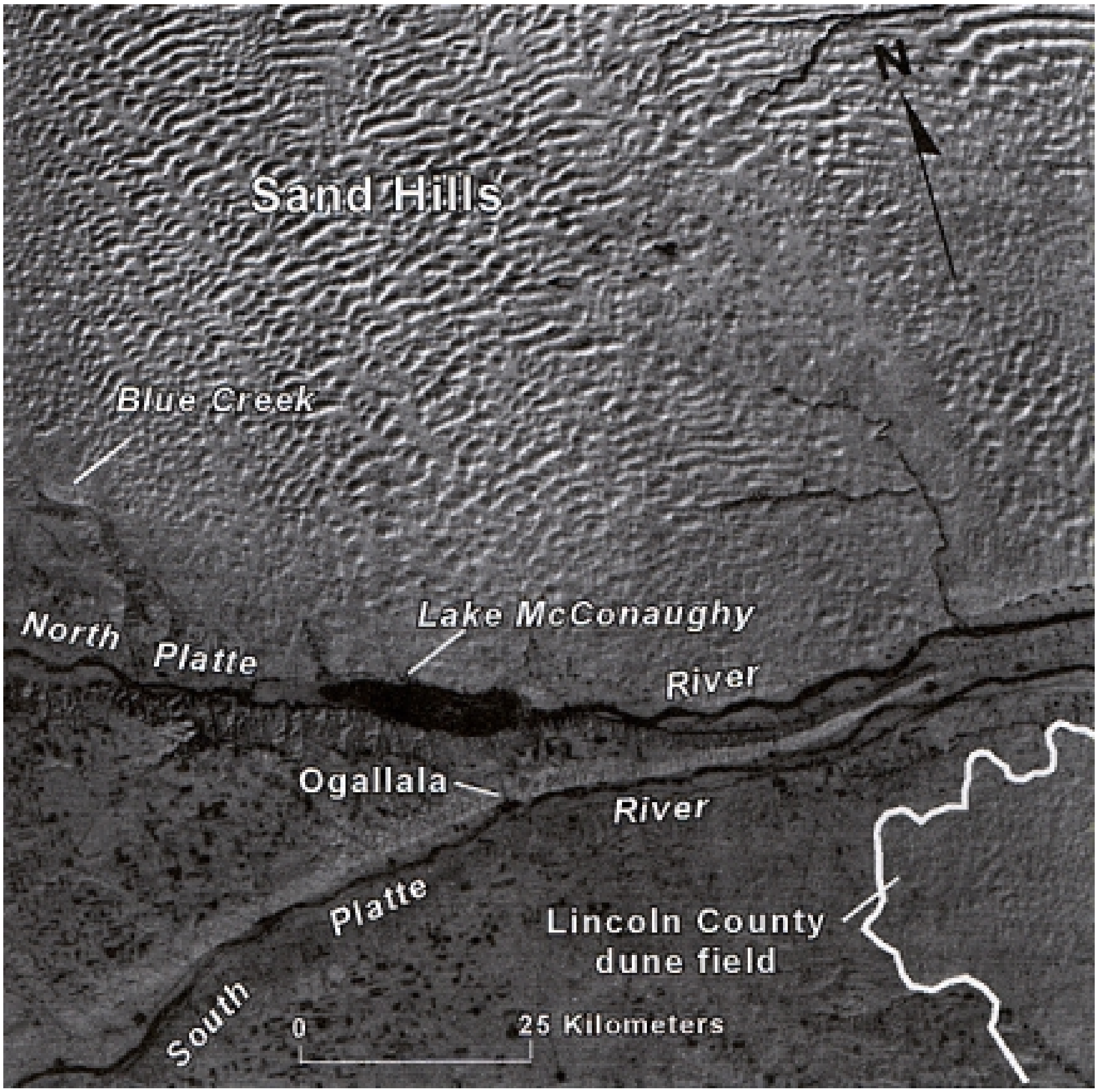

Figure 15. Landsat image (MSS band 7) of the south-central Nebraska Sand Hills, North and South Platte rivers and the western half of the Lincoln County dune field. The landscape is accentuated by snow cover and a low sun angle.

that the Sand Hills were, along with the South Platte River, a major source of that sand (Muhs et al., 2000), and thus are consistent with the dune-dam hypothesis. Additional work is needed to further test this hypothesis.

The Sand Hills as a Modern Analog for Study of Ancient Eolian Sandstones

Eolian (wind-blown) sandstones are well-represented in the stratigraphic record. On the Colorado Plateau of western United States, they comprise a 3500 m-thick Late Paleozoic through middle Mesozoic (about 300 to 150 million-year-old) sequence (Kocurek, 1988). On the Great Plains, the 25-30 million-year-old (Miocene) Arikaree Formation contains dune deposits that can be seen along the summit-to-museum trail at Scotts Bluff National Monument and in Bear Creek and Lone Tree canyons in Goshen County, Wyoming (Bart, 1977).

Tracks— The tracks we've found in the Sand Hills are no larger than those made by modern bison. But, in eolian strata exposed near the southern margin of the dunes and within the Pliocene Broadwater Formation, we have found tracks that are considerably larger (Myers, 1993; Fig. 16). These 2-3 million-year-old strata contain skeletons of probiscideans (elephants and their relatives), and we surmise that these animals made the big tracks. These older wind-blown sands are uncemented and are interbedded with river-deposited sands. These deposits may have been an important and immediate source of sand for the present-day Sand Hills, especially if after their deposition, downcutting by streams could have lowered the water table, leaving these deposits high, dry, and available to the wind.

Dune deposits are also widespread in the Late Cretaceous (75 million-year-old) Djadokhta Formation of the Gobi Desert in east-central Asia. These sandstones were made famous in the1920's by field parties from the American Museum of Natural History led by Roy Chapman Andrews. At Flaming Cliffs in southern Mongolia, they found abundant skeletons and egg-filled nests of a diverse group of dinosaurs and mammals. Most dinosaur tracks are discovered when sedimentary rocks split along bedding planes, revealing a plan view of the features. The soft sandstones of the Djadokhta rarely split this way, however, and, despite the abundance of their bones, the tracks of dinosaurs were unknown from the Djadokhta Formation until they were observed in vertical cross-section in cliff exposures of the dune deposits (Loope et al., 1998). Preserved exactly like the bison tracks within the Sand Hills (with steep sides and individual toeprints), these tracks prove once again that, like everyone else, scientists see what they are prepared to see.

Dinosaur Fossils Preserved Adjacent to Dune Deposits--The fabulous fossils of the Gobi are preserved as unscavenged skeletons, suggesting that they were rapidly buried and perhaps buried alive. Because they are found in a formation with abundant dune deposits, the animals have long been thought to have been overwhelmed and buried by dune sand during violent desert wind storms. A recent study, however, points out that none of the skeletons at Ukhaa Tolgod (an especially fossiliferous site west of Flaming Cliffs) lie within well-bedded dune sand (as would be expected if the animals had been quickly buried in a wind storm). Instead, they lie within structureless (unbedded) sandstone laterally adjacent to the slopes of the ancient dunes.

Figure 16. Wind-blown sheet sands of Pliocene age (about 2 million years old) containing the footprint of an elephant-like mammal, probably *Stegomastodon sp.* The locality is near the head of Whitetail Creek, about 20 km north of Ogallala. Photo by Jim Swinehart

The thick wind-blown formations of western United States contain neither abundant fossils nor structureless sandstones, but would be expected to contain plenty of evidence of desert wind storms. Observations of saltating sand on modern dunes indicate that the material accumulates in distinctly layered deposits. Being buried alive by blowing sand means you are unable to outrun a migrating dune.

Sandslides, triggered by heavy rainfall events, appear to be a more likely burial agent for the Gobi dinosaurs (Loope et al., 1999). In general, a dune field isn't a dangerous place to be in a rainstorm—water infiltrates the permeable sand and, weeks later, may eventually reach the groundwater table. The devastating mudslides and debris flows that have claimed many human lives recently in Central and South America were triggered by elevated pore water pressure that develops when the downward infiltration of water through slope material is stopped by underlying bedrock. The Mongolian dunes developed calcite-cemented soil layers about a meter below their steep leeward slopes. These layers impeded the downward infiltration of rainwater and, when the sand above the soil layer became saturated during heavy rainstorms, elevated pore-water pressure caused the meter-thick deposit of sand to move rapidly downslope, burying anything in its path. Luckily for the ranchers living at the bases of Sand Hills dunes, the Nebraska slopes are not underlain by impermeable soil layers and apparently cannot generate lethal sandslides.

Carbon-rich Interdune deposits—Some of the geologists who have studied the Sand Hills are very interested in the origin (and location) of oil and gas in ancient sedimentary rocks. A large volume of petroleum is trapped within the Late Paleozoic Tensleep Sandstone and the Jurassic Nugget Sandstone —dune sands deposited in what is now western and central Wyoming about 300 and about 175 million years ago. Ahlbrandt and Fryberger (1981) pointed out that the hydrocarbons now trapped in the dune sandstones may have had their source as organic-rich interdune deposits similar to those now accumulating in the peat-accumulating valleys of the Nebraska Sand Hills.

Not all geologists are convinced that organic-rich interdune deposits are likely to act as source rocks for hydrocarbon reservoirs, but it does seem likely that interdune wetlands like those of the Sand Hills have been extensive in the geologic past. What would these deposits look like if turned to rock and exposed in a cliff face? Typically, sediments rich in organic matter (like coal and shale) retain their dark color even after generating hydrocarbons, but typical interdune deposits in the rock record are light-colored or red, suggesting desert-like conditions during deposition. Also possible, however, is that the organic matter generated in environments like those in the Sand Hills wetlands was decomposed before it was buried by advancing dunes. Along with the organic matter, the peat that accumulates in Sand Hills interdunes contains abundant silt that was transported to the site as dust. What would happen to the interdune deposits if the water table dropped and didn't come back up for hundreds of years? It would either catch fire and burn (like the peat lands in southeast Asia during the El Nino of 1998) or would be broken down by the combined action of aerobic microbes and burrowing invertebrates. The silt, however, would remain, as would evidence of the burrows produced during the "feeding frenzy". Flat-lying, red siltstones are common within sandstone formations mainly composed of dune deposits. Abundant burrows typically extend downward from the siltstones, suggesting that the long-term fate of the Sand Hills peat, rather than to produce oil and gas, is to become worm food.

Evidence of Vegetation on Ancient Dunes--Dunes are today generally restricted to deserts and beaches--areas where loose sand is not held in place by vascular plants. Plants are especially effective because they increase the surface roughness, greatly reducing the wind's velocity at the land surface. Because grasses didn't evolve until about 20 million years ago, and land plants in general have only been on the scene since about 400 million years ago, some geologists have speculated that dunes were more widespread earlier in Earth's history. Although sandstones representing ancient dunes have been recognized in strata as old as 2.1 billion years, they do not represent an especially large part of early sedimentary record. Before land plants stabilized river banks, streams would have been much more laterally mobile, allowing them to rework deposits of wind-blown sand before they had accumulated into large dunes (Eriksson and Simpson, 1998).

Although we know a great deal about the plants that grew in ancient swamps, plants do not fossilize well in most upland plant habitats. The oldest clear evidence of vegetation that grew on uncemented sand dunes comes from southern Mongolia, where rhizoliths (calcified plant roots) are found in great abundance within 75-million year-old dune deposits (Loope and Dingus, 1999). The fossilized roots of the dune-dwelling plants lie parallel to the steeply sloping sand layers that accumulated on lee slopes—a growth pattern that efficiently exploits the soil water that is held longer in the finer grained sands than in ancient coarser layers.

Conclusions

If, like Aldo Leopold's New Mexican mountain, our dune field has a long memory, what stories could it tell? Although we know that there have been many episodes of dune activity in the Sand Hills during the Holocene, we do not yet have an accurate chronology of these events, nor do we know if different parts of the dune field have been more active than others. Our best estimate of the most significant periods of dune activity is given in Figure 17. OSL dating, which frees researchers from dependence upon carbon-rich deposits for samples, should be very useful. Although geologists typically study young, uncemented sediments to help them to understand older strata, the reverse process can also be lucrative. We have never had the chance to see a deep cross-section through a Sand Hills dune, but observations of cliff faces in Utah and Wyoming can give us some clues. Future work will take advantage of both perspectives.

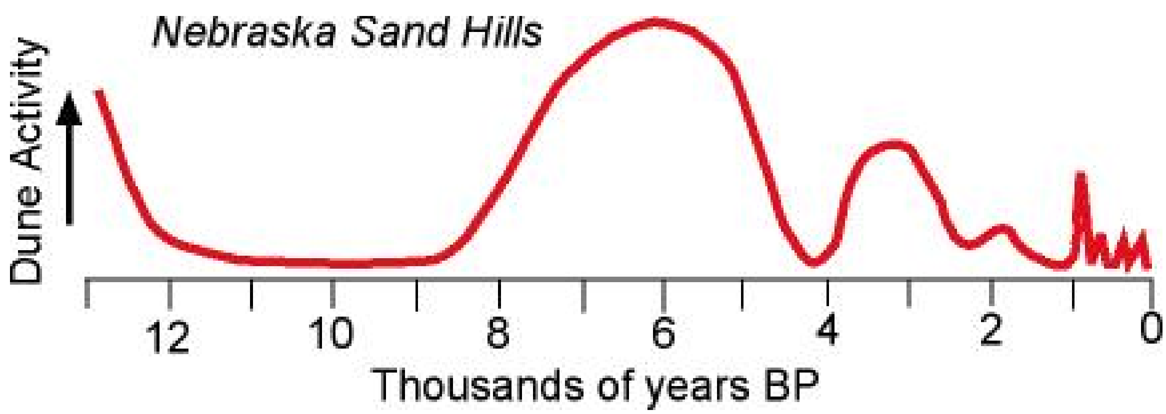

Figure 17. Estimates of intervals and relative intensities of sand dune activity in the Sand Hills during the last 13,000 years.

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