Dune-dammed paleovalleys of the Nebraska Sand Hills: Intrinsic versus climatic controls on the accumulation of lake and marsh sediments

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ABSTRACT

Although running water is the dominant geomorphic agent on Earth, eolian processes can gain ascendancy in regions where the climate is arid, vegetation is sparse, and abundant sand is available for transport. With climate change, the boundaries between fluvial-dominated and eolian-dominated areas may shift. Although there have been few reports in the North American literature of river systems blocked by dune sand, our work in the Nebraska Sand Hills provides evidence of multiple episodes of such blockage events. During prolonged arid intervals in latest Pleistocene and middle Holocene time, eolian dune sand blocked two large valley systems in western Nebraska. These blockages raised the water table of the High Plains aquifer as much as 25 m over an area of 7000 km^2 and created over one thousand lakes. Wetlands far removed from the discharge points of the buried paleovalley system are strongly alkaline (exceeding 250 000 mg/L total dissolved solids [TDS]). Relatively fresh (280 mg/L TDS), flow-through lakes are present at the distal end of the system where the gradient of the water table is steep and the cross section of the buried valley is large. Anomalously thick marsh and lake sediments accumulated in deep paleovalleys upstream of dune dams near the southern margin of the Sand Hills. Our cores and radiocarbon dates from Blue and Crescent Lakes reveal their histories to be quite distinct from adjacent Swan Lake; these differences are best explained by multiple blockage events. Our work explains why lakes are most abundant in the driest part of the Sand Hills. It also provides another line of evidence for major dune activity in the Sand Hills region during Holocene time and shows that factors other than regional climate, specifically location, height, and hydraulic conductivity of dune dams, can control the rise and fall of the ground-water table and the chemistry of lakes.

INTRODUCTION

The Nebraska Sand Hills provide dramatic evidence of recent climate change near the center of the North American continent. The Sand Hills cover 50 000 km^2 of the central Great Plains (Fig. 1) and constitute the largest sand sea in the western hemisphere (Smith, 1965; Ahlbrandt and Fryberger, 1980). The grass-stabilized eolian bedforms are up to 130 m high and have been modified only slightly by pedogenic and fluvial processes. Precipitation ranges from an annual average of 580 mm on the east margin of the dune field to 430 mm on the western margin. Nearly 75% of the present-day precipitation takes place from April to September; 50% falls in May, June, and July when warm, moist air from the Gulf of Mexico is drawn northward and low-pressure disturbances are frequent (Wilhite and Hubbard, 1990).

Large, active dunes are today limited to areas where annual rainfall is <250 mm (Goudie, 1983). In Africa, evidence of blockage and diversion of stream courses by dune sand is widespread (Grove and Warren, 1968; Grove, 1985). Major drainage systems that lie below Quaternary dunes and sand sheets of the eastern Sahara testify to dramatic climate change (McCauley et al., 1982). The distribution of lacustrine calcareous mudstone within the Namib Sand Sea shows that the terminus of the Tsondab River, presently blocked by 100-m-high linear dunes, has retreated 38 km since about 35 000 yr ago (Teller and Lancaster, 1986). In North America, Moses Lake in the drainage of Crab Creek, Washington (Hutchinson, 1957), a series of Holocene lakes in Lake Canyon, Utah (Graf, 1989), and a now-vanished upper Quaternary lake in central Alaska (Lea et al., 1992) appear to be the only sizable, previously described lakes dammed by dunes. Although the possibility of a genetic link between the blockage of drainages and the origin of lakes in the Nebraska Sand Hills was first mentioned 90 yr ago (Barbour, 1903), specific lakes and blockages have been discussed only very recently (Loope and Swinehart, 1992; Keen, 1992).

Our work on the late Quaternary record of the Sand Hills indicates that dune sand blocked surface drainages during episodes of prolonged drought and thereafter controlled a water-table rise of as much as 25 m. The distribution and age of sediments in Sand Hills lakes demonstrate that a detailed climate signal cannot be deciphered from interdune deposits without full knowledge of the location and history of dune dams. In the western Sand Hills, paleovalley networks partly filled with eolian sand control the distribution of about 1000 interdune lakes spread over 7000 km^2.

REGIONAL SETTING AND PREVIOUS WORK

The dunes of the Sand Hills overlie between 150 and 300 m of coarse late Cenozoic clastic deposits—the thickest part of the High Plains aquifer, a hydrogeologic unit that stretches from Texas to South Dakota (Weeks and Gutentag, 1988). The aquifer is the principal source of water in one of the

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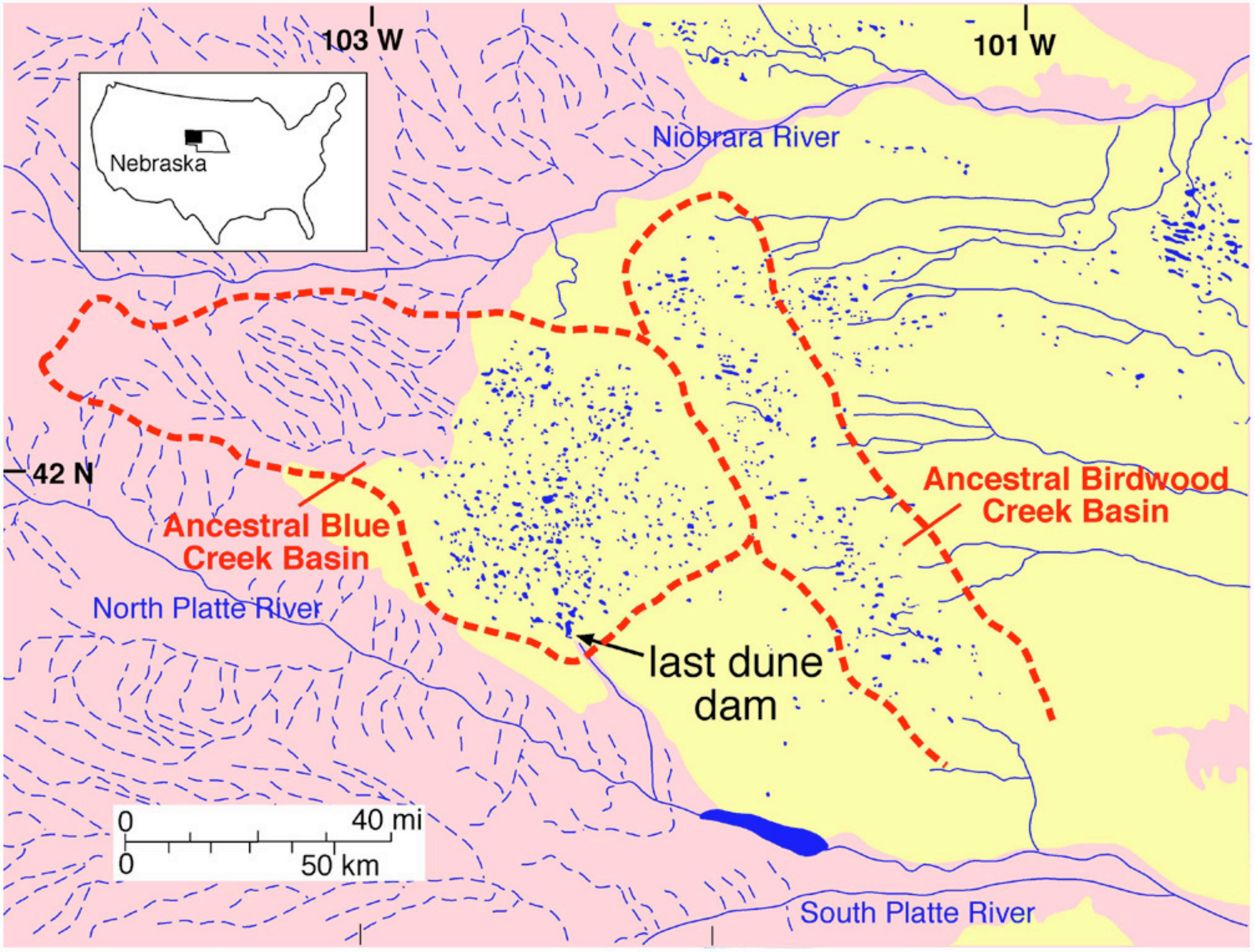

Figure 1. In the western Sand Hills, two large, partly deranged Pleistocene drainage systems contain over 1000 lakes. Ancestral Blue Creek drained 5800 km^2, with its headwaters west of the western margin of the Sand Hills, and its mouth south of the southern margin of the dune field. To the east, a cluster of lakes occupying 3100 km^2 of the Sand Hills region may occupy the pre-dune headwaters of Birdwood Creek. Note difference in drainage density between Sand Hills (shaded) and surrounding parts of the Great Plains.

major agricultural areas of the United States. Owing to the high recharge rates of dune sand and the thickness of sand and gravel beneath the Sand Hills, 65% of the water stored in the aquifer is in Nebraska (Weeks and Gutentag, 1988). Unconsolidated Quaternary fluvial sands, eolian sand sheets (Myers et al., 1992), and fluvial sand and gravel of the Pliocene Broadwater Formation (Swinehart et al., 1985) separate the Quaternary dune sand from underlying strata of the Miocene Ogallala Group in many places.

The local source of sand for the Sand Hills is Miocene through Pleistocene strata deposited by streams flowing eastward from the western plains and Rocky Mountains. The eolian bedforms compose about 80% of the total sediment volume in the sand sea. Although the thickness of Quaternary eolian sand below interdune surfaces of most of the region rarely exceeds 10 m, in the south-central and west-central areas, up to 20 m of sandy sediment is present (Swinehart, 1990).

The dune field has long been thought to have formed during Pleistocene time (Smith, 1965; Wells, 1983). Some recent workers (Ahlbrandt et al., 1983; Swinehart, 1990), however, have argued that much of the sand, including that within some of the largest bedforms, was reworked during early to late Holocene time. Holocene eolian activity has been well documented in adjacent parts of the Great Plains: Colorado (Forman et al., 1992; Muhs, 1985), Wyoming (Gaylord, 1990), Kansas (Johnson and Sophocleous, 1991), and Texas (Holliday, 1989).

In contrast to the studies emphasizing Holocene dune mobility, a study by Wright et al. (1985) concluded that the dunes near Swan Lake in the southwestern Sand Hills have been stabilized by grass for the last 9000 yr. This paper focuses on the geologic setting and history of Swan Lake and other lakes nearby and attempts to reconcile major episodes of Holocene eolian activity with the evidence for a long-term, nearly continuous rise of the water table described by Wright et al. (1985).

BURIED PALEOVALLEYS AND DUNE-DAMMED LAKES IN THE WESTERN SAND HILLS

Surface Observations

Across broad areas of the Sand Hills, interdune surfaces intersect the ground-water table, forming extensive wetlands. Paradoxically, the part of the sand sea with the least precipitation—the western Sand Hills—contains the greatest number of lakes. Estimates of the total number of interdune lakes in the region vary from 1500 to 2500; lakes range from highly alkaline and saline (pH as high as 10.8, and exceeding 250 000 mg/L TDS) to nearly neutral and relatively fresh (280 mg/L TDS)(Bleed and Ginsburg, 1990; Gosselin et al., 1994). In most geologic settings, topographically lower lakes are more saline than those at higher elevations; T. C. Winter pointed out that lakes become increasingly fresh with decreasing altitude in the western Sand Hills (Swinehart et al., 1988).

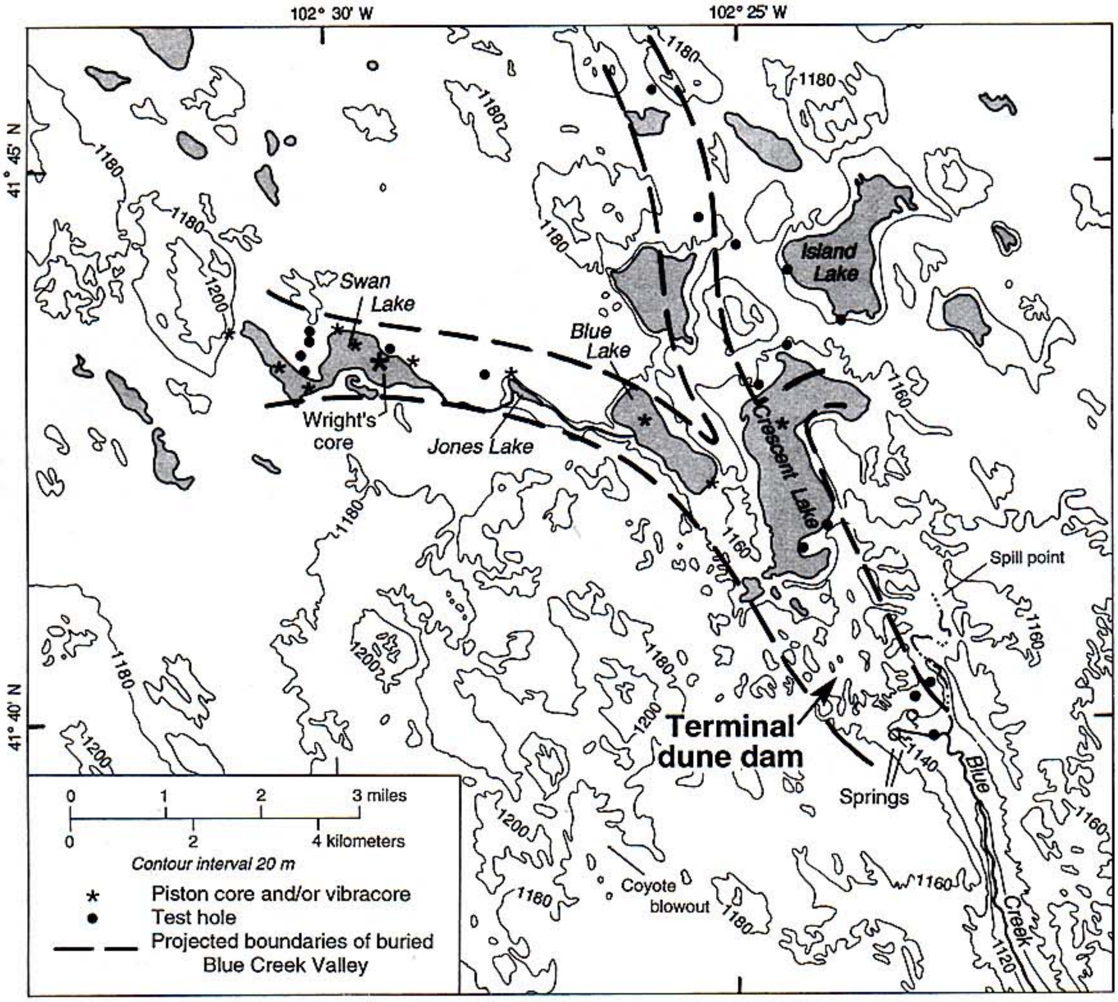

Figure 2. At the southern margin of the Sand Hills (see Fig. 1), springs at the head of Blue Creek (lower right) emerge from a sand dam, the southernmost of numerous sand bodies that block this major paleovalley (see Figs. 3 and 4). Configuration of the buried valley system is based on vibracores, rotary-drilled test holes, outcrops, long axes of lakes, and the dimensions of Blue Creek valley. The high water table behind the terminal dune dam creates lakes in interdune positions. None of the lakes presently has natural surface water inlets or outlets. Note position of intermittent stream course just east of the terminal dune dam that acted as a spillway when the level of Crescent Lake was 2 m higher.

Eastward-flowing water courses on the dune- and lake-free tableland west of the Sand Hills disappear when they reach the western margin of the sand sea (Fig. 1). At the southern edge of the Sand Hills, Blue Creek, a perennial, spring-fed stream that occupies a valley cut into Miocene bedrock, emerges from dune sand (Figs. 2, 3, and 4). Spring water discharging at the rate of 0.5 m^3/sec at the head of Blue Creek has a conductivity of 330 μS/cm (Katz, 1987), whereas springs downstream are much less conductive. At the mouth of Blue Creek, 62 km from its head, conductivity is down to 120 μS/cm (Katz, 1987). The conductivity of the southernmost lakes in the Sand Hills (about 300 to 600 μS/cm [McCarraher, 1977]) is similar to that of springs at the head of Blue Creek and indicates that water from these lakes feeds the springs. The steep (1:80) ground-water gradient between the lake and springs contrasts with the 1:450 gradient of Blue Creek and the 1:1100 slope of the ground water table north of the lake.

Subsurface Data

Most Sand Hills lakes are shallow and are typically underlain by thin (<2 m) beds of organic-rich, lacustrine mud (gyttja). At 5.5 m, Blue Lake is the deepest lake in the region and lies adjacent to 1.4-m-deep Swan Lake. Swan Lake is bounded on the west by a 60-m-high compound parabolic dune and nearly bisected by several smaller dunes (Fig. 2). At Swan Lake, H. E. Wright cored an anomalously thick, sand-free sequence consisting of 7 m of gyttja directly overlying 7 m of peat and peaty gyttja (Wright et al., 1985; Fig. 5).

New subsurface data from 18 rotary test holes, seven vibracores, and four piston cores near the southern margin of the Sand Hills (Figs. 2, 6, and 7) provide the basis for a reinterpretation of the Holocene history of the area. Rotary drilling revealed that, within the relatively small study area, there is >30 m of relief on the upper surface of the Ogallala Group (Fig. 6A). The magnitude of this relief appears to diminish northward (Figs. 6A, 6B, 6C). Our 14 radiocarbon

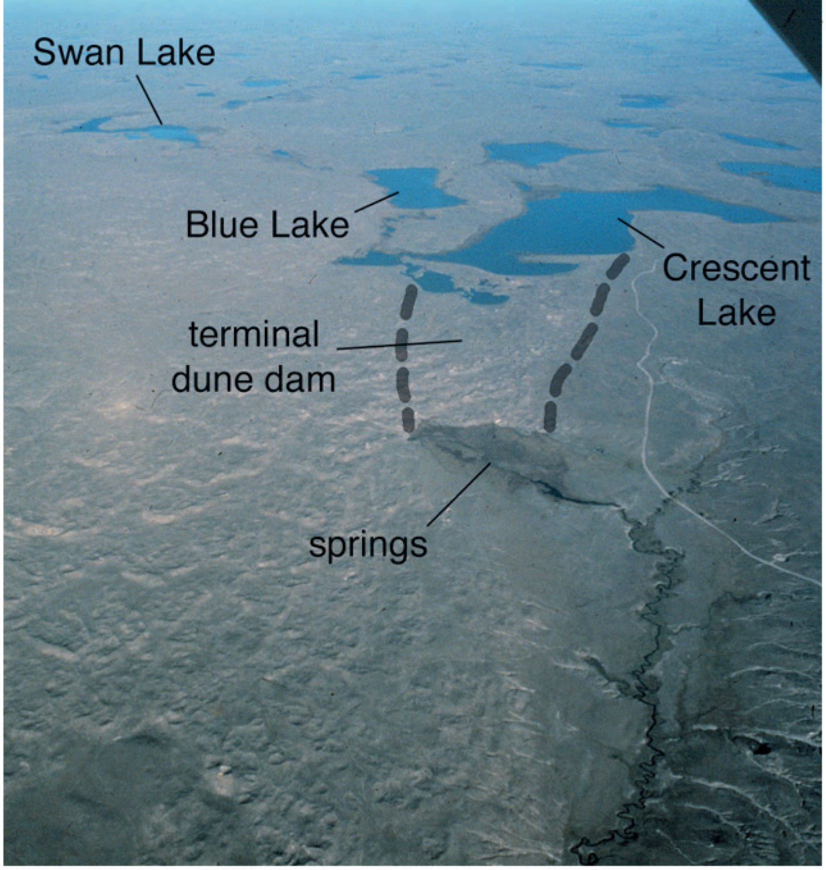

Figure 3. Oblique, northward view of the springs at the head of Blue Creek, the terminal dune dam, and Crescent, Blue, and Swan Lakes (see Fig. 2).

dates from three different lakes (Table 1) establish a chronologic framework for correlation and interpretation. Wright et al. (1985) dated the base of the Swan Lake peat at 8950 yr B.P. and the base of the gyttja at 3680 yr B.P. Our dates from above and below the gyttja-peat contact indicate that these deposits are conformable (Table 1, PC92-2; Fig. 5). From two of our cores just north of Swan Lake, peat beds just above the Ogallala Group are dated at 9880 and 10 670 yr B.P. Because the dated material lies below 28 m of dune sand, these cores demonstrate Holocene movement of the compound parabolic dunes that nearly bisect Swan Lake (Fig. 6B; Table 1, TH2-B-93).

Although early Holocene material is widespread in the subsurface below Swan Lake (Figs. 5 and 6B), early Holocene material was not encountered in the subsurface in the vicinity of Blue or Crescent Lake (Figs. 6A and 6C). At a drill site on the shore of Crescent Lake (Fig. 6A), at a depth of 25.9–27.4 m below the surface, and about 4 m above the top of the Ogallala, we recovered carbonized plant fragments that have been AMS (accelerator mass spectrometry) dated at 3220 yr B.P. (Table 1, TH21-B-92). Plant fragments at the base of 10 m of lacustrine mud in Crescent Lake were AMS dated at 3050 yr B.P. (Table 1, C-93-21). We have an AMS age of 4330 yr B.P. from plant fragments beneath 11.6 m of gyttja in Blue Lake (Table 1, B-93-18).

Our additional piston cores and dates from Swan Lake indicate that the single 14 m core described by Wright et al. (1985) is representative of the entire eastern part of the lake basin. In the western basin, however, sand beds that we could not penetrate with our piston corer lie beneath only 1.5 m of gyttja. Vibracores along the north shores of Swan and Jones Lakes revealed thick wedges of structureless sand that are interbedded with peat and gyttja (Fig. 7). The peat and gyttja in these vibracores are late Holocene in age (Table 1, VC92-4, VC92-12) and are thus correlative with the sand-free gyttja reported from the eastern basin of the lake by Wright et al. (1985; Fig. 5).

Interpretation: Geomorphic Elements

We interpret the large, ovoid cluster of lakes in the western Sand Hills (Fig. 1) as the product of the blockage of ancestral Blue Creek by dunes. An elongated cluster of lakes farther east and oriented north-northwest–south-southeast may occupy the former headwaters of Birdwood Creek (Fig. 1). Although Blue Creek occupies a valley cut into sandstone of the Miocene Ogallala Group, the springs at its head emerge from a mass of dune sand (Figs. 2, 3, and 4). On the basis of rotary drilling, outcrops, the orientation of the long axes of lakes, and the dimensions of Blue Creek's valley, we project a 1200- to 2200-m-wide, 30-m-deep buried fluvial paleovalley between Swan Lake and the head of Blue Creek, 8 km southeastward (Fig. 2). The southernmost lake in the western Sand Hills (Crescent Lake) lies 2 km north and 25 m above the point where springs emerge from the dune sand. The mass of eolian sand that fills the paleovalley just north of the Blue Creek springs acts as a dam (Loope and Swinehart, 1992; Keen, 1992). This "terminal dune dam" is the southernmost of scores of valley-blocking sand bodies; modern lakes and Holocene lacustrine and wetland sediments occupy the parts of the paleovalleys not filled by dune sand.

Lake level behind a dam is determined by the balance between input (ground water and surface water inflow plus precipitation) and output (evaporation and seepage through the dam). The hydraulic conductivity of the fine to medium sand at this site ranges from 20 to 40 m/day and that of the underlying Ogallala bedrock is about 5 to 30 m/day. Any organic or fine clastic material overlying or infiltrating the sand decreases the hydraulic conductivity (Graf, 1989). Because the mud that accumulates on lake bottoms prevents outflow, movement of water from lakes to aquifers takes place through coarse sediment of the littoral zone (Winter, 1976). Crescent Lake, the largest lake in the Sand Hills region, has sufficient fetch to produce a wide littoral zone. The high flow rate of water through the coarse littoral sediments has slowed the rate of lake-level rise. Swan Lake has a smaller fetch and narrower littoral zone, and the early- to mid-Holocene marsh sediment at the base of the Swan Lake cores is extremely impermeable. Continued deposition of such material should lead to the steady rise of the water level behind the dune dam, and, potentially, to spillover and destruction of the dam.

Although dune sand is presently mounded across the position of the paleovalley, an abandoned spill point for the system lies on Ogallala bedrock about 1 km east of the sand-filled paleovalley, at an elevation 2 m higher than the adjacent lake surface

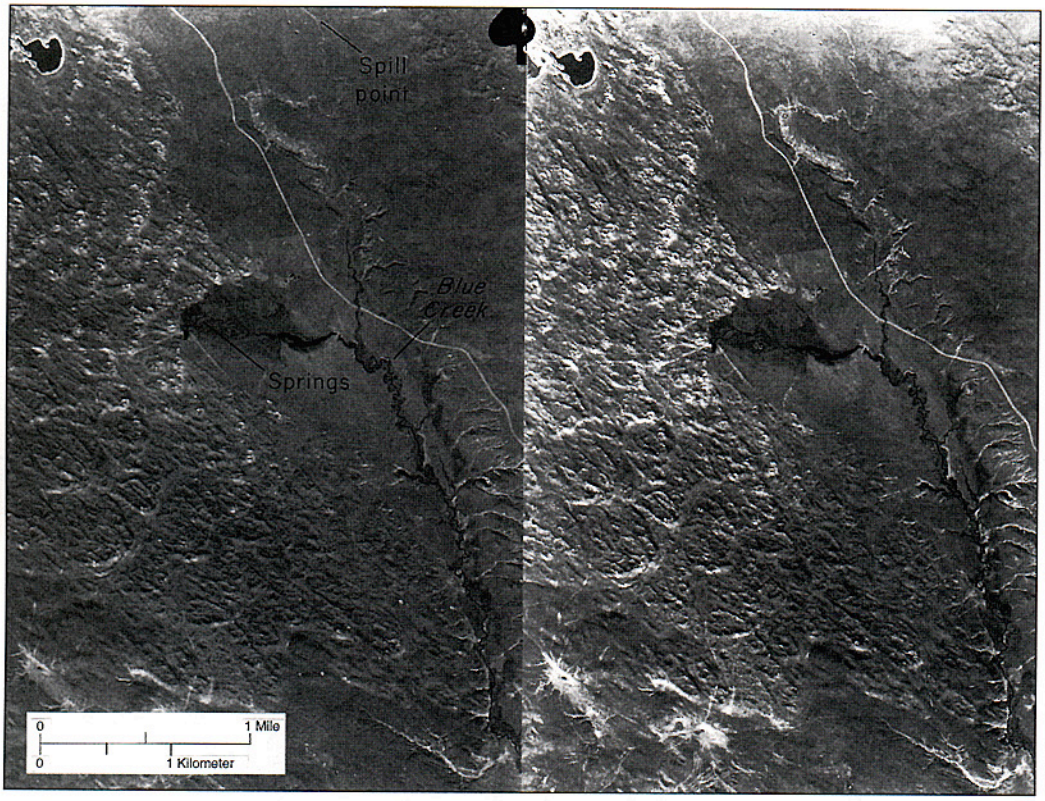

Figure 4. Stereo pair of vertical aerial photographs showing springs at the head of Blue Creek emerging from dune sand. Note position of abandoned spill point. Width and depth of the bedrock valley in the lower right are similar to those of the paleovalley beneath and north of the dune dam. The compound parabolic dune lying south of the springs and crowding the west edge of Blue Creek valley may have been part of the original terminal dune dam. If so, the springs could have migrated as much as 3.5 km headward since blockage.

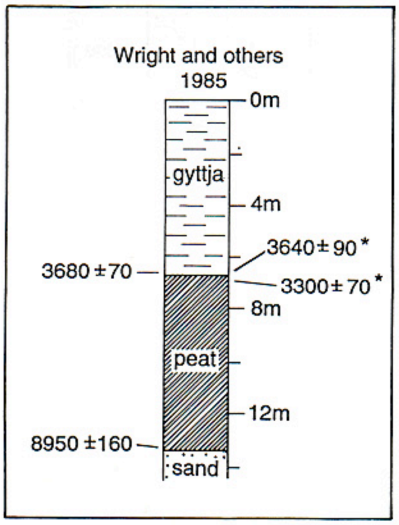

Figure 5. Generalized stratigraphic column and radiocarbon dates at Swan Lake. Dates by Wright et al. (1985) are to the left of the column; new dates (Table 1, PC92-2) are marked by asterisks.

(Figs. 2 and 4). A sinuous channel below this spill point that is cut into Ogallala rocks testifies to overflow during a former lake highstand. Catastrophic drainage of the lake immediately behind the dam did not take place because the spillover is floored by partially lithified material, not dune sand. Seepage through the dune dam must have taken place at a sufficient rate to prevent massive overflow and deep entrenchment. We have not found lacustrine sediments south of the present southern boundary of the lake basin. If any upstream migration of the Blue Creek springs has taken place since blockage, it is limited to a maximum of 3.5 km (Fig. 4).

Reestablishment of Blue Creek as a throughgoing stream would require that many dune dams be removed. If the southernmost dune dam were overtopped, then the southernmost lake or cluster of lakes would drain, and the head of Blue Creek would migrate upstream several kilometers to the base of the next dam. A counterintuitive conclusion of our work is that a positive change in the water budget could cause a drastic drop in the water table throughout the catchment area due to overtopping and removal of the dune dams.

Interpretation: Timing of Blockage

At least two distinct episodes of blockage are required to explain the history of sedimentation in Swan, Blue, and Crescent Lakes. We postulate that the blockage at Swan Lake formed prior to 10 600 yr B.P. (Fig. 6B; Table 1, TH2-B-93) and that the dune dams that formed Blue and Crescent Lakes were emplaced during remobilization of this part of the dune field during the mid-Holocene (prior to 4300 yr B.P.; Fig. 6C and Table 1). We think that the earlier blockage at Swan Lake must have occurred after 12 000 yr B.P. because the western United States was relatively moist prior to that time (Thompson et al., 1993). Haynes (1991) presented evidence for a drought on the Great Plains from 11 300 to 10 900 yr B.P. The

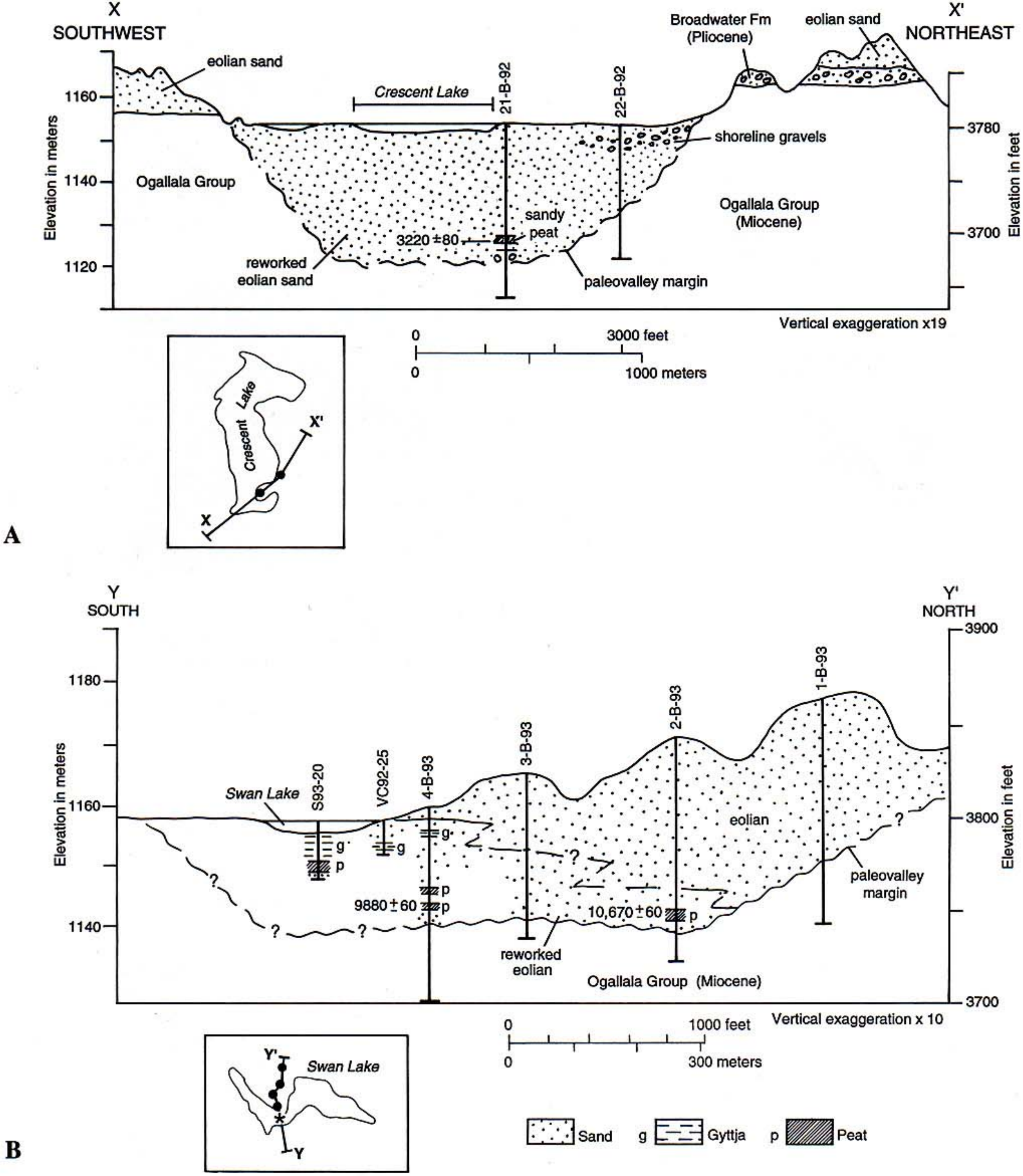

Figure 6. Cross sections showing stratigraphic relationships and radiocarbon dates (see Table 1). On location maps, piston cores and vibracores are represented by asterisks, test holes by black dots. (A) Transverse cross section (X–X′) of interpreted paleovalley immediately north of terminal dune dam (see Fig. 2). The AMS radiocarbon date of 3220 yr B.P. (Table 1) establishes a middle Holocene age for the southernmost dune dam on Blue Creek. (B) Transverse cross section (Y–Y′) of interpreted paleovalley from Swan Lake northward across the compound parabolic dunes.

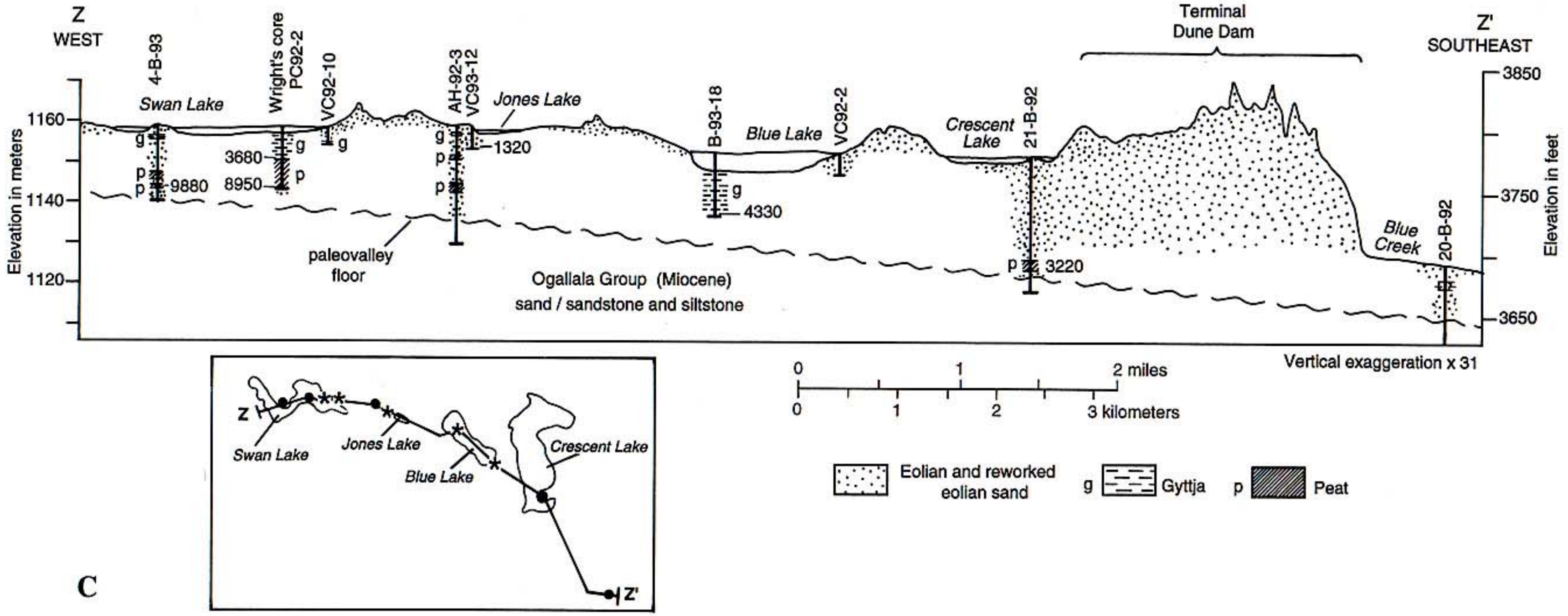

Figure 6. (*Continued*). (C) Longitudinal cross section (Z–Z′) along west axis of buried paleovalley. Early Holocene sediments are present beneath Swan Lake but are absent from Blue and Crescent Lakes.

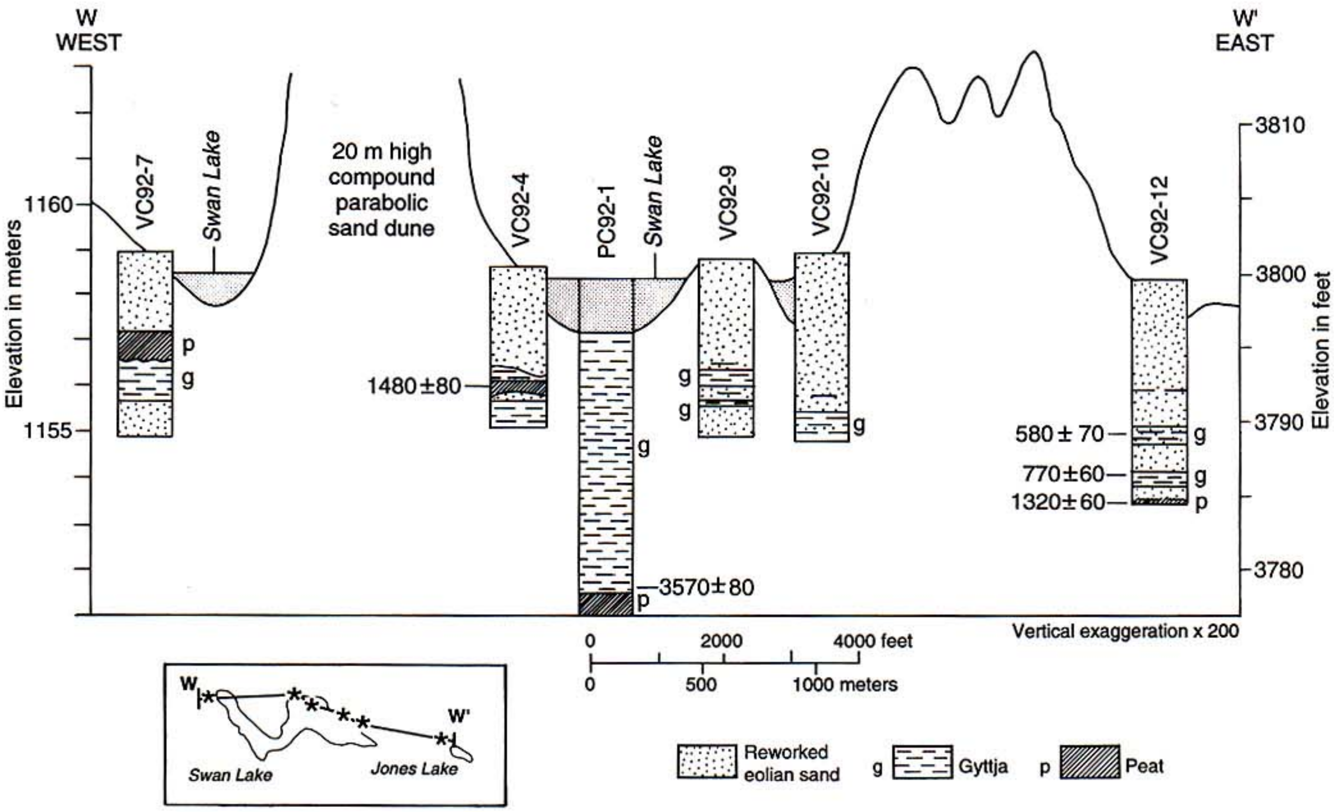

Figure 7. Section (W–W′) of interbedded sand and paludal sediments of late Holocene age in vibracores from vicinity of Swan Lake to Jones Lake. Sand intervals are interpreted as evidence for shoreline regressions resulting from eolian sand mobility.

TABLE 1. RADIOCARBON DATES FROM SWAN AND CRESCENT LAKE AREA

Drill hole, core, or outcrop	Legal location	Depth* (m)	Uncalibrated radiocarbon date† (yr B.P.)	Material	Lab number
VC 92-12	SE SW NE SE sec. 17, T. 20 N., R. 45 W.	3.49–3.57	580 ± 80	Gyttja	Beta-55038
		4.44–4.51	770 ± 60	Gyttja	Beta-55039
		5.05–5.11	1320 ± 70	Peaty muck	Beta-55040
McGinley blowout	SW NE NE SW sec. 26, T. 19 N., R. 46 W.	3.1–3.15	1260 ± 130	Soil humate	Beta 50436
Coyote blowout	center SW SW sec. 6, T. 19 N., R. 44 W.	2.6–2.65	1425 ± 55§	Soil humate	Beta 50439/ETH
VC 92-4	NW SW NW NW sec. 10, T. 20 N., R. 45 W.	2.78–2.82	1480 ± 80	Gyttja	Beta-54124
C-93-21 (Crescent Lake)	NE NW SW NE sec. 17, T. 20 N., R. 44 W.	9.85–10.0	3050 ± 60§	Plant fragments	Beta 66050/CAMS-9019
TH 21-B-92	NW NE NE SE sec. 20, T. 20 N., R. 44 W.	25.9–27.4	3220 ± 80§	Plant fragments	Beta 54387/CAMS-3225
PC92-2 (Swan Lake)	SW NE NW SE sec. 10, T. 20 N., R. 45 W.	6.49–6.5	3640 ± 90	Gyttja	Beta 55043
		6.5–6.51	3300 ± 70	Peat	Beta 55042
PC92-1 (Swan Lake)	SE SE NW NW sec. 10, T. 20 N., R. 45 W.	5.95–6.0	3570 ± 80	Gyttja	Beta 55041
B-93-18 (Blue Lake)	NE NE NW NW sec. 18, T. 20 N., R. 44 W.	11.4–11.6	4330 ± 60§	Plant fragments	Beta 65049/CAMS-9018
TH 4-B-93	NE NW NE SE sec. 9, T. 20 N., R. 45 W.	15.2–16.1	9880 ± 60§	Plant fragments	Beta 65046/CAMS-8323
TH 2-B-93	NW SE SE NE sec. 9, T. 20 N., R. 45 W.	28.3–29.0	10 670 ± 60§	Plant fragments	Beta 65225/CAMS-8341

*Depth in lakes are below top of sediment.
†All ages adjusted for ^{13}C.
§AMS date.

absence of peat deposits dating between 12 000 and 14 000 yr B.P. suggests that blockage took place well after the last glacial maximum.

The second arid episode (ca. 4300 yr B.P.) most likely reflects the middle Holocene period of minimum effective moisture in the Great Basin and Colorado Plateau recently summarized by Thompson et al. (1993, fig. 18.14). Lake and pollen data from the north-central United States also support a middle Holocene period of minimum effec-

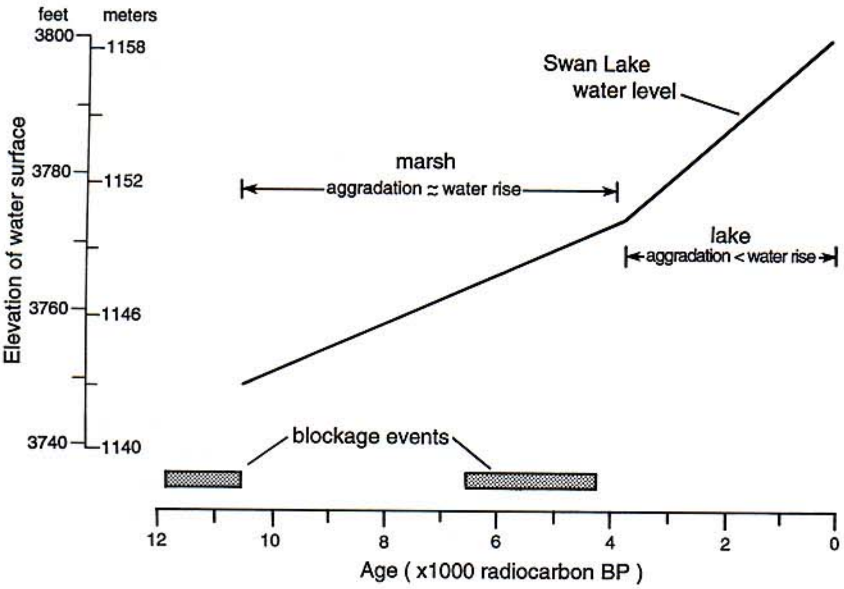

Figure 8. Interpretation of the history of water-level change at Swan Lake, based on distribution and age of sedimentary facies (Table 1, Figs. 5 and 6B). Marsh sediments steadily accumulated from about 10 600 to 3700 yr B.P. as a result of emplacement and sealing of a dune dam just east of Swan Lake. Emplacement of younger dams south of Blue and Crescent Lakes lowered the gradient of the water table through the Swan Lake dam and led to the formation of an open-water lake.

tive moisture (Webb et al., 1993). Holliday (1989) demonstrated evidence for a prolonged drought and widespread eolian activity on the southern High Plains between 6500 and 4500 yr B.P.

The littoral sand wedges that were observed to be interbedded with gyttja in vibracores along the north shores of Swan and Jones Lakes resulted from shoreline progradation. Because the region has no streams, eolian activity is the likely process for sand delivery to lake shorelines. The wedges therefore suggest several episodes of late Holocene (post–1500 yr B.P.) eolian activity. This is corroborated by observations of numerous Holocene paleosols buried by thick eolian sand deposits in the Sand Hills region (Swinehart et al., 1992), including the immediate vicinity of Swan Lake (Coyote and McGinley blowouts, Table 1).

Discussion

Because sand was absent from their single core from the center of Swan Lake, Wright et al. (1985) argued that the dunes that surround the lake have been grass-covered and immobile since marsh sediments started to accumulate in an interdune swale about 9000 yr ago. They interpreted the peat-to-gyttja transition as the record of a regional climatic shift toward wetter conditions at about 3700 yr ago that changed the marsh into a lake. Their interpretation is at odds with the conclusions of Ahlbrandt et al. (1983) and Swinehart (1990) that called for greater aridity and major dune activity during at least two intervals in the Holocene (7500–5000 and 3500–1500 yr B.P.). The interpretation of regional paleoclimate of Wright et al. (1985) fails to explain the lack of early Holocene peat in Blue and Crescent Lakes. The absence of such sediment cannot be explained by the effects of topography—the bases of the late Holocene deposits in these lakes lie at lower elevations than the base of the early Holocene fill at Swan Lake (Fig. 6C).

Why is sand absent from the eastern basin of Swan Lake if the adjacent dunes were active during the Holocene? In contrast to the interpretation by Wright et al. (1985) that the lack of sand in their core means that the dunes were not active in the Holocene, we suggest that riparian vegetation supported by the high water table in the dune-blocked paleovalley prevented the spread of sand into the center of the marsh. Sand reaching the lake during late Holocene time would have been deposited in the littoral zone, not the center of the lake.

Blockage of the large Nebraska paleodrainages required several important preconditions. Because the sediment-carrying capacity of free-flowing water greatly exceeds that of the wind, surface discharge must have ceased for an extended time period, perhaps several hundred years. Lake Canyon, Utah, contains a sediment record of Holocene lakes that formed behind dune barriers that were emplaced during three distinct arid episodes (Graf, 1989). Because the bedrock catchment area for the Utah lakes was small (16.6 km^2), flash floods sufficient to destroy dams were uncommon, and each lake persisted for >400 yr.

We postulate that as the Sand Hills area became increasingly arid and vegetation became sparse, dune sand would have covered a larger and larger proportion of the interfluves. Infiltration of precipitation into the permeable dune sand would have reduced the magnitude of runoff events, and as rainfall diminished further, surface flow would have ceased when subsurface flow through the unconsolidated, highly permeable alluvium on the floor of the channel (derived in large part from the Broadwater Formation) and the underlying poorly consolidated sediments of the High Plains aquifer could accommodate all the water input to the drainage basin. Given the high hydraulic conductivity of the materials that underlie the Sand Hills, it seems likely that prolonged drought would have eventually eliminated surface flow in many reaches of the streams of the region. The sand-carrying capacity of the wind is reduced in the lee of obstacles to air flow such as cliffs and stream banks (Greeley and Iversen, 1985, p. 197). This tendency probably led to preferential deposition of eolian sand in valleys. Large masses of dune sand then moved into blocking positions on the dry floors of streams that lacked the potential to generate flash floods.

DEPOSITIONAL CONTROLS AT SWAN LAKE: CLIMATIC OR INTRINSIC?

Thick peat deposits beneath the floor of Swan Lake (Fig. 5) indicate that a slow, steady rise of the water level in the basin began in early Holocene time and continued for over 6000 yr. Gyttja above the peat indicates that this slow rise was followed by a more rapid rise that, at about 3700 yr ago, created the open-water conditions present today (Fig. 8). Rather than interpreting the 17 m rise of the wetland surface during Holocene time as a result of a long-term trend toward a wetter regional climate (Wright et al., 1985), our working hypothesis for the history of the Swan Lake basin calls upon locally controlled changes in the rate of ground-water flow and requires two arid episodes during which dunes blocked dry stream courses.

Marshes initially formed in a dune-blocked, minor (western) arm of the paleovalley system (Fig. 2) about 10 600 yr ago and thereafter steadily aggraded for >6000 yr (Figs. 5 and 8). Ingram (1982) showed that, in areas of much higher precipitation, peat accumulation impedes the drainage of rain water, resulting in the growth of ground-water mounds and domed mires. We suggest that in the Sand Hills, peat accumulation did not passively keep pace with the rise of the water table, but rather that the deposition of this impermeable material actively contributed to the rise of the water table by progressively impeding the down-gradient movement of water through the valley-blocking dune sand. We link the rapid rise of water level starting at 3700 yr B.P. (Fig. 8) to a second blockage event that took place down flow from Swan Lake (emplacement of the dune dams southeast of Blue and Crescent Lakes). The second blockage flattened the water-table gradient through the Swan Lake dam, further slowing ground-water flow and drowning the marsh. Gyttja was then deposited conformably upon the peat.

During arid intervals, blocked paleovalleys would have continued to receive ground water discharged from surrounding dunes, and any drop in the elevation of lakes and marshes would have acted to reduce hydraulic head and down-gradient seepage from the wetlands. Because most ground-water seepage from lakes takes place through littoral sediments (Winter, 1976), the impermeable sublittoral sediment that accumulated during wet intervals would have acted as an effective seal if lake level dropped by 1 or 2 m during drought episodes. We have found neither desiccation cracks nor bison-trampled zones in gyttja deposits, suggesting to us that the long-term rise of the water table/wetlands surface noted by Wright et al. (1985) was not punctuated by large-scale (>5 m) falls of water levels. Our interpretation that the water table along blocked paleovalleys remained relatively high during arid intervals is consistent with paleoecological evidence (Loope, 1986). Contorted laminations are very common within the cross-strata and interdune deposits of the Sand Hills and are the result of trampling by bison. The abundance of tracks within sets of cross-strata composed of wind-ripple laminae indicates that the animals were present in the region while the dunes were vegetation free and migrating (Loope, 1986). We postulate that wetland environments within blocked paleovalleys persisted during episodes of dune mobility and were the primary sources of vegetation and surface water for these animals.

After 10 000 yr of sedimentation and water-table rise, Swan Lake is now nearly full of impermeable sediment. The difference in elevation between its surface and the water table beneath the dunes to the north and south (transverse to the paleovalley) is very small. This situation, combined with the low elevation of the now-abandoned spill point on the east side of Crescent Lake, indicates that the water-table rise cannot be sustained very far into the future. The present extent of wetlands in the study area is therefore near both the maximum for Holocene time and the maximum possible.

Although it receives higher rainfall, the central Sand Hills area has relatively few lakes compared to our study area (Fig. 1). There, the Dismal, Middle Loup, and North Loup Rivers occupy deeply incised valleys and the ground-water table lies far below the floors of many adjacent interdunes. Two factors may be responsible for the better integration of drainage in the central Sand Hills: (1) destruction of dune dams was hastened by higher rainfall and greater ground-water discharge (Bentall, 1990), and (2) the very elongate interdunes of this area lie parallel to the slope of the Great Plains surface, thereby decreasing the effectiveness of the dunes as dams.

We postulate that the paleovalleys control the wide variation of lake water chemistry in the western Sand Hills: the fresh-water lakes at the southern margin of the sand sea, where the gradient of the ground-water table is steep (Winter, 1986), are flow-through lakes that lose salts to the springs at the head of Blue Creek. Only short segments of thick, sand-filled paleovalleys lie between these lakes and the discharge point. We interpret the alkaline, saline lakes to the north, however, as discharge points for closed, local ground-water flow systems (Toth, 1962; Gosselin et al., 1994): these lakes cannot lose salts to the regional aquifer because they occupy an area with a low hydraulic gradient and because ground-water flow through the thinner valley fills in the north is impeded by the thick, impermeable mud deposited in lakes to the south.

The capillary fringe in sand is thin, and sedimentary structures show that upland vegetation was very sparse when dunes were active; the diminished stream flow that allowed blockage therefore cannot be explained by an increase in evapotranspiration. The blockages of valleys by dune sand—like the giant bedforms themselves—testify to long periods during which precipitation was much less than at present.

It is likely that Sand Hills lake and marsh sediments preserve a detailed record of Holocene climate change on the Great Plains, but this record is strongly overprinted by complex local histories involving the emplacement and progressive sealing of at least two generations of dune dams. The importance of these local events is best demonstrated by the sharply contrasting stratigraphic records of adjacent lakes (Fig. 6C).

Several climate models predict increasing aridity on the Great Plains with the onset of greenhouse-induced warming (Manabe and Wetherald, 1986; Hansen et al., 1988; Rosenweig and Millel, 1993). If the regional climatic signal can be extracted from the widespread, locally thick lacustrine sediments of the Sand Hills, then a better understanding of the factors that led to prolonged Holocene arid episodes could emerge, thereby improving our ability to predict the direction and severity of future climate change for the interior of North America. The climate signal, however, will not emerge until we have a thorough knowledge of the geometry, sedimentology, hydrogeology, and geologic history of the dune-dammed wetlands and buried paleovalleys.

CONCLUSIONS

1. Lakes and marshes of the western Nebraska Sand Hills are products of the blockage of throughgoing drainages by dunes.
2. Thick sediment accumulations are to be expected in the axes of blocked valleys directly up flow from dune dams.
3. The distinctly different histories of adjacent lakes can be explained by multiple episodes of dune blockage.
4. Peat and lake mud sealed the dune dams and lead to steady sediment aggradation and maintenance of a high water table behind dams during long droughts. A *positive* change in the water budget could cause breaching of dune dams and thereby *lower* the water table over a broad area.
5. Although changes in the regional climate and water budget are likely to leave a record in the sediments of dune-dammed

wetlands, this record is strongly overprinted by intrinsic, local controls that include the position, height, and hydraulic conductivity of dune dams.

6. Dunes were active and precipitation was greatly reduced on the central Great Plains just prior to 10 000 and again prior to 4300 yr B.P.; shorter periods of dune activity are also recorded in the late Holocene (post–1500 yr B.P.).

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