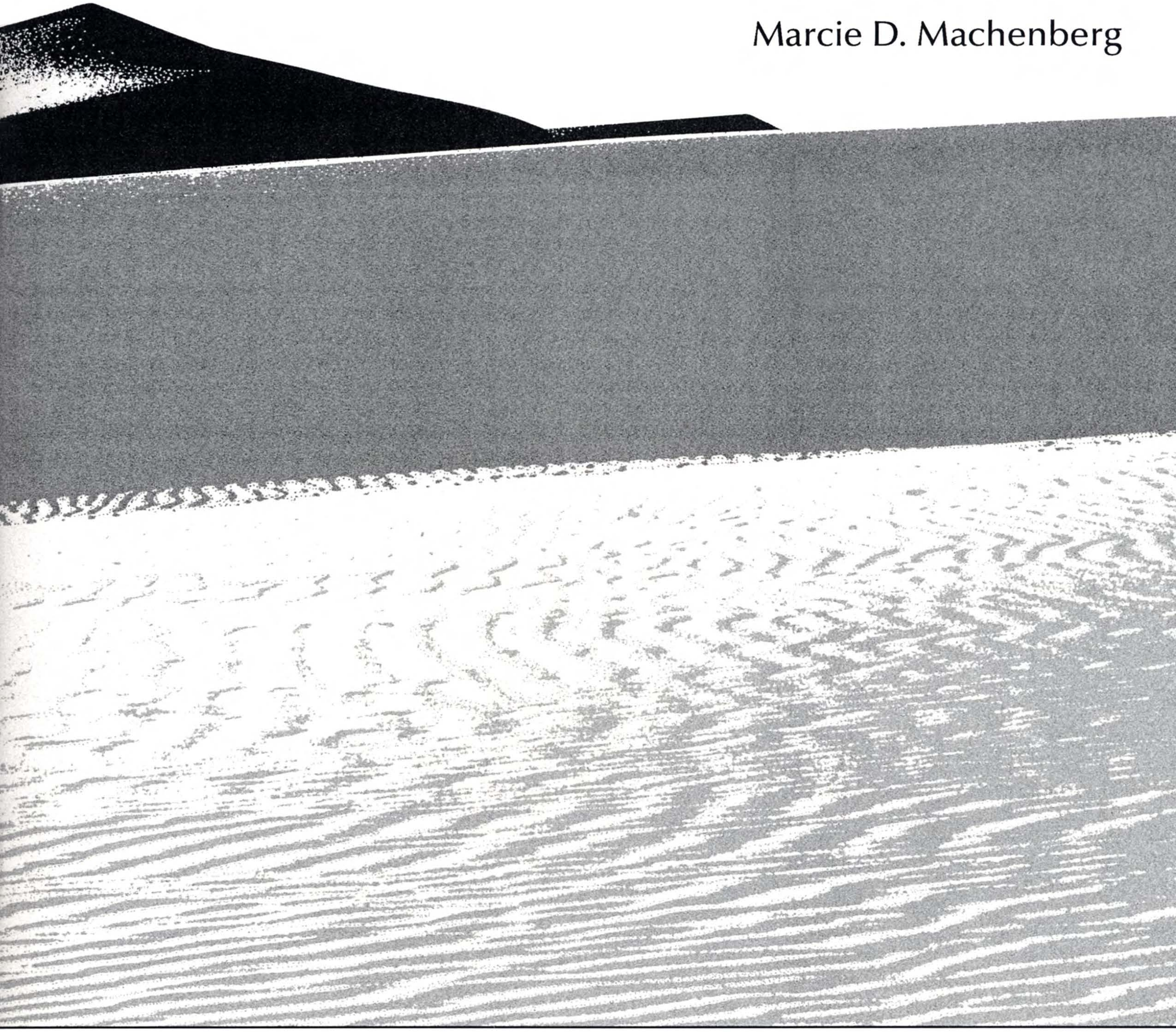
Guidebook 21

Geology of Monahans Sandhills State Park, Texas

Marcie D. Machenberg



Bureau of Economic Geology • W. L. Fisher, Director
The University of Texas at Austin • Austin, Texas 78713

1984

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ABSTRACT

Sand dunes at Monahans Sandhills State Park display a variety of dune forms that develop under a unique trimodal wind regime. Large expanses of unvegetated sand form aklé dunes having reversing slip faces. Smaller dune forms in the park include wind-shadow, coppice, transverse, barchan, and parabolic dunes. Blowout dunes also occur in the heavily vegetated cover sands of the Pecos Plain surface. Seasonal wind regimes can be divided into three groups: summer, winter, and spring winds. Persistent summer winds from the south-southeast build long transverse dunes. These are modified by erratic gusty winds in the spring (transitional), and winter winds from the north and west during the passage of storm fronts. Dunes shift position as much as 65 ft (20 m) under the influence of strong transitional winds but migrate slowly back to their approximate original location so that net migration over the course of a year is negligible. The Monahans Sandhills have been occupied by people for more than 10,000 yr, as evidenced by several archeological discoveries. Native plants and animals have developed special adaptations in order to survive on the limited resources of this sandy, everchanging environment.

KEYWORDS: Dunes, eolian features, eolian sedimentation, wind erosion, deserts, archaeology, Monahans, Pecos Plain, Texas, state parks

INTRODUCTION

Along the western margin of the Southern High Plains lies a belt of active and vegetated sand dunes created by windblown sands that began accumulating several thousand years ago. The dunes create a dynamic landscape that shifts in response to constantly changing winds. Ivory-colored sand creates a variety of dune forms, including long, sharp-crested ridges up to 85 ft (25 m) high and sandy hills anchored by a dense cover of native shin oak trees. The sandhills, with their specially adapted plants and animals, represent a unique environment.

Human fascination with the Monahans Sandhills began more than 10,000 yr ago. The dunes have meant many things to the peoples inhabiting this region. The sandhills sheltered abundant game hunted by nomadic Paleo-Indians, supplied water to modern Indians, and hindered westbound settlers in covered wagons. Today the sandhills offer a variety of opportunities for recreation and nature study to the many visitors of Monahans Sandhills State Park.

This guidebook provides the reader or park visitor with a better understanding of the origin of the sandhills, their geological characteristics, and the interactions between the physical and biological processes characteristic of the sandhills. It explains that the dynamic nature of the dunefield is a function of variables such as sand supply, precipitation, vegetation, complex local winds, and human occupation. A map of dune environments (in pocket) shows the distribution of process-related dune forms within the park.

The Park

Interest in preserving part of the sandhills was generated by University of Texas professor Roy Bedichek with his book *Adventures with a Texas Naturalist* (1947). Dr. Bedichek's vivid description of the unique assemblage of plants and animals found in the region prompted local residents to form an association intent on establishing a State park in the area. Under the guidance of J. Conrad Dunagan, a Monahans businessman, the association convinced the State of Texas of the ecologic and historic significance of the sandhills, and in 1957, a small section of the sandhills east of Monahans was leased by the State for public recreational use. Monahans Sandhills State Park now encompasses approximately 3,840 acres (1,554 hectares) of active and stabilized dunes 5 mi (8 km) east of Monahans, Texas (fig. 1). The park straddles the Ward-Winkler county line and is easily reached by Interstate Highway 20, less than an hour's drive

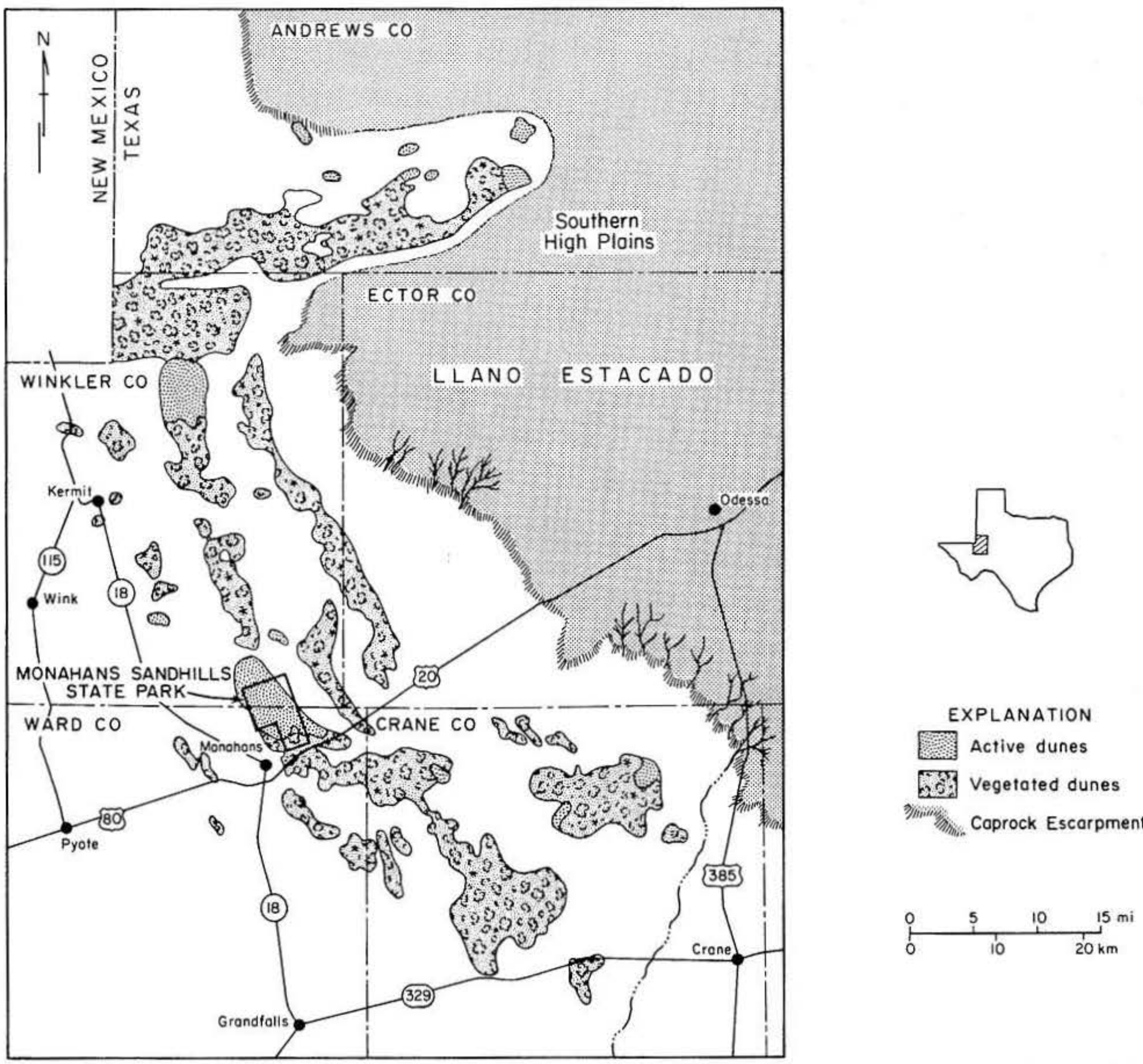


Figure 1. Location map of Monahans Sandhills in West Texas (modified from Waitt, 1969).

west from the Midland-Odessa area. The Park Headquarters and Museum, located at the entrance to the park, houses several displays on the area's history, native animals and plants, and the Indian artifacts that are representative of materials uncovered occasionally by the shifting sands. Just outside the building, an archeological site, consisting of the excavated skeleton of a young Indian, has been preserved. Park Road 41 provides access into the dunefield, where small sand mounds gradually give way to giant undulating dunes. There are several picnic areas and full camping facilities. A concession stand occupies the relocated section house that was used by the Texas and Pacific Railroad during the late 19th century. Visitors may also see a pumping oil well, evidence of the rich petroleum resources underground; Monahans Sandhills is the only State park in Texas in which an operating pumpjack may be viewed by visitors.

Regional Setting

The Pecos Plain forms the broad surface across which the dunes have spread. This flat to rolling terrain separates the low Sacramento Mountains of New Mexico from the Southern High Plains of Texas (fig. 2). The Monahans Sandhills consist of a linear belt of sandy deposits approximately 70 mi (110 km) long and 20 mi (32 km) wide that extends from southern Crane County northward into Andrews County and the southeastern corner of New Mexico. Fifteen miles (24 km) to the east, the Caprock Escarpment, which marks the southwestern edge of the Southern High Plains (or Llano Estacado), rises 300 ft (90 m) above the sand-covered plain. This topographic escarpment was present when dune building occurred and was an effective barrier to windblown sediment transport along its entire length.

The climate of the Pecos Plain is semiarid. Rainfall averages approximately 12 inches (30 cm) per year. Most precipitation falls in the spring and early summer during localized thunderstorms. As in any semiarid area, rainfall is highly variable from year to year. The region is subject to severe droughts; in West Texas droughts occurred in 1880, 1891, 1934, and 1957 (Pigott, 1977). Although droughts cause the margins of the dunefield to encroach over the vegetated plain, dunefield expansion during droughts is counterbalanced by vigorous vegetation growth during wet years. Winter months are dry and snowfall is infrequent. Extremes in temperature are characteristic of this environment. At Monahans, the coldest recorded temperature was -8°F (-22°C) and the record high was 110°F (43°C). Mean monthly temperatures range from 43°F (6°C) in January to 82°F (28°C) in August. Relative humidity is generally low year-round.

Dust storms are common from late winter through early spring. Visibility is often reduced to near zero when loose, surficial sediment is carried in large clouds. Sustained winds of up to 36 mph (58 km/h) often blow across the dunefield. Major frontal systems moving in from the north, known in Texas as "blue northers," are accompanied by strong winds, which can cause extensive flattening of dune crests; however, the effects of such storms are short-lived.

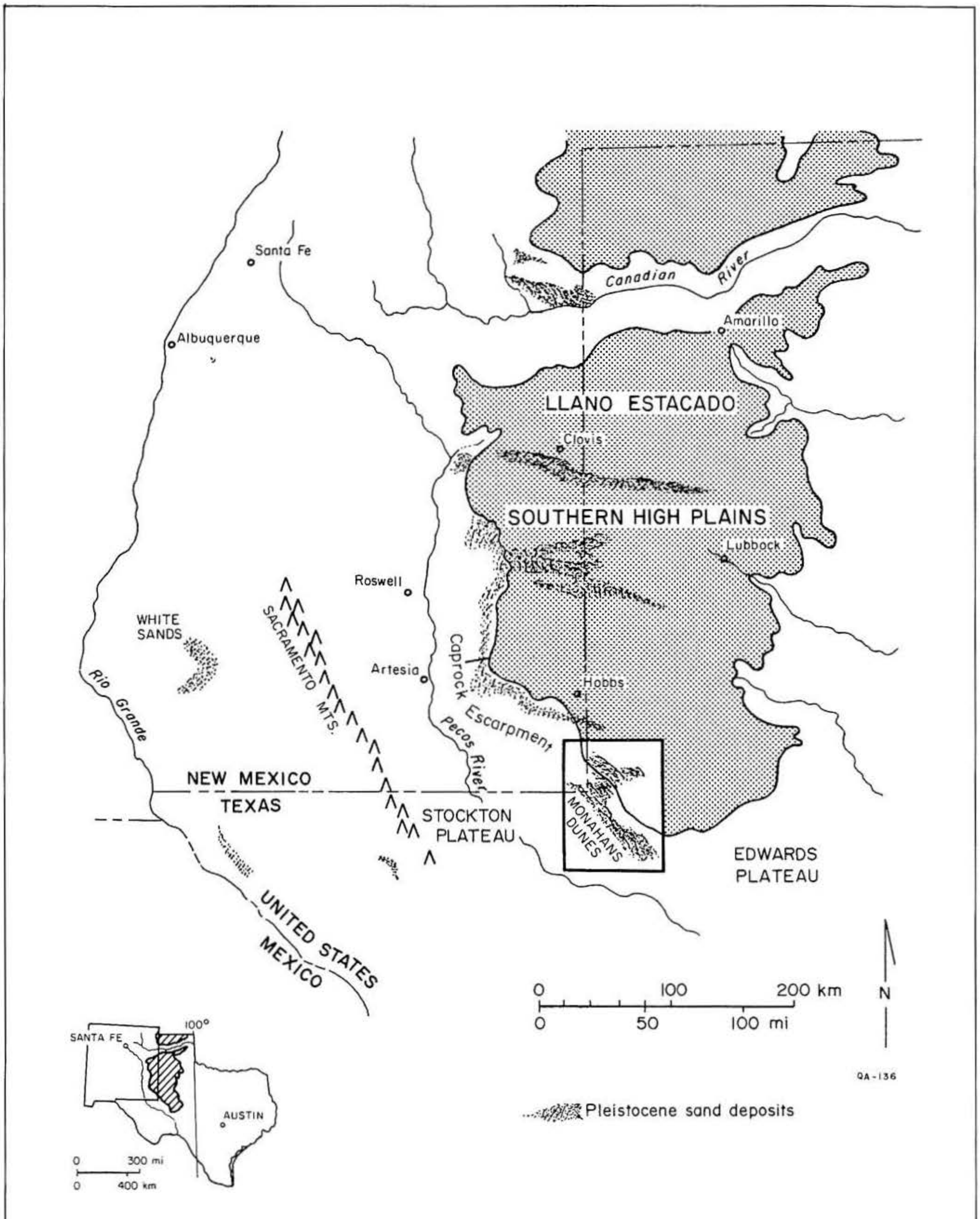


Figure 2. Physiographic features of West Texas and eastern New Mexico (modified from McCauley and others, 1981). The boxed area is shown enlarged in figure 1.

Origin of the Sandhills

Within the geologic time scale (fig. 3), the Monahans dunefield is a young feature, originating during the last several thousand years. Before sand covered its surface, the soil of the Pecos Plain supported prairie grasses growing under relatively humid conditions. Rainfall was significantly greater than at present, and permanent streams flowed across the plains. These streams transported sediment eastward from eroding mountains in what is now New Mexico.

Throughout the late Pleistocene Epoch (fig. 3), in the late stages of the last ice age, the climate of the Southern High Plains alternated between more arid stages and wetter, **pluvial,**[1] periods (fig. 4). These cycles corresponded to stages of glacial advance and retreat in other parts of North America. As the most recent ice age came to a close, the climate gradually became drier and warmer and the streams became ephemeral. The sand and silt once carried by

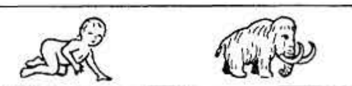
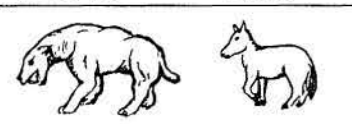
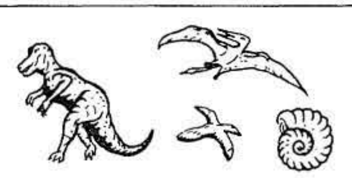
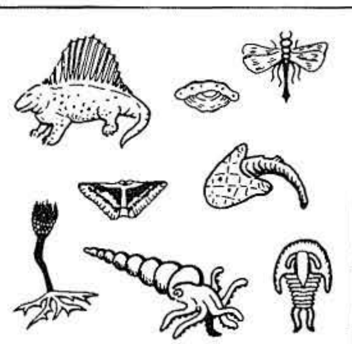
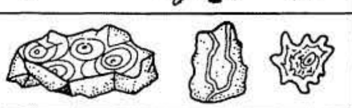
ERA	PERIOD	EPOCH	AGE (Millions of years ago)	SUCCESSION OF LIFE	TYPICAL LIFE FORMS	MAJOR GEOLOGIC EVENTS	MONAHANS AREA HISTORY
CENOZOIC Age of Mammals	QUATERNARY	Holocene Pleistocene	1.5		Homo sapiens Woolly mammoth	Worldwide glaciation	Sand dune accumulation, climatic shifts
	TERTIARY	Pliocene Miocene Oligocene Eocene Paleocene	12 25 36 60 63		Saber-tooth cat Horses Primitive mammals	Alps, Himalayas, Cascade ranges formed	Ogallala Formation deposited, erosion
MESOZOIC Age of Reptiles	CRETACEOUS		135		Dinosaurs First flowering plants	Rocky Mts. formed	Marine sandstones, carbonates, and shales deposited
	JURASSIC		181		First birds	Sierra Nevada Mts. formed	
	TRIASSIC		230		Ammonoids		Lacustrine and fluvial deposits
PALEOZOIC Age of Invertebrates	PERMIAN		280		Reptiles	Appalachian Mts. formed	Accumulation of evaporites, carbonates
	PENNSYLVANIAN MISSISSIPPIAN		310 345		Insects Coal forests Amphibians		Tectonic activity forms basins and arches
	DEVONIAN		405		Brachiopods Fish		
	SILURIAN		425		Crinoids		Uplift and erosion
	ORDOVICIAN		500		Nautiloids		
	CAMBRIAN		600		Trilobites		Marine transgression
PRECAMBRIAN ERAS PROTEROZOIC ARCHEOZOIC			4000+		Algae Worm tubes Indirect evidence of life		Formation of Texas craton
Approximate age of the earth more than 4 billion years							

Figure 3. Geologic time scale (modified from Matthews, 1963) and major geologic events affecting the Monahans area.

[1]Words printed in boldface are defined in the glossary, p. 33.

streams lay unconsolidated and exposed along the floodplains, ready to be carried by the wind. Investigations of the most ancient deposits of dune sands suggest that winds of several thousand years ago, **paleowinds**, blew from the northwest, concentrating sand in a linear belt along the southwest margin of the Southern High Plains. About 16,000 yr B.P. (before the present), a period of exceptional aridity affected the Monahans area (Wendorf, 1961). It was probably at this time that the areal extent of active dunes reached a maximum.

Fossil pollen found in sediments in the region is useful in reconstructing the prehistoric environment. Pollen from moist-climate plant species is preserved between thick sequences of eolian sand, indicating that an earlier episode of dune building was well underway approximately 25,000 yr B.P. Fossilized bones of extinct species of camel, mammoth, and giant bison are found in the sands, providing further evidence of dune age.

Today, most of the sand-belt dunes are stabilized by heavy vegetation. Large areas of active dunes have remained unstable because of the influence of local topography, water-table fluctuations, and former land use practices, such as grazing, which prevented the establishment of stabilizing plant growth.

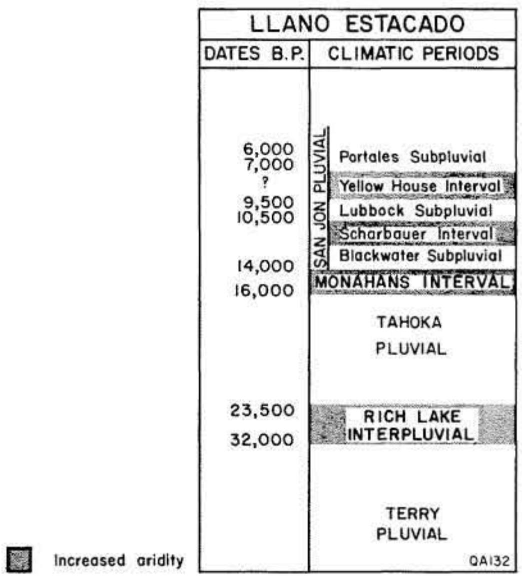


Figure 4. Late Pleistocene climatic chronology of the Llano Estacado (after Wendorf, 1961).

Early Inhabitants

The Monahans region is rich in remnants of Paleo-Indian cultures. The arid climate and depositional setting have enhanced preservation and recovery of buried artifacts and fossils. A skeleton, thought to be that of one of the earliest human inhabitants of North America, was excavated only 50 mi (80 km) east of Monahans. This early inhabitant may have lived approximately 10,000 yr B.P., during the Early Man or Paleo-Indian period. These peoples were nomadic hunters and gatherers; their distinctive flint projectile points have been found among bones of mammoth, giant bison, and other now-extinct animals. Paleo-Indian cultures gradually gave way to those of modern American Indians, such as the Comanche tribes. Habitation of the sandhills was fairly continuous throughout this transition, as evidenced by the evolution of projectile point styles and other artifacts discovered within the dunefield.

Indians utilized all aspects of the sandhills. They relied on the rolling topography to conceal themselves from enemies. They depended on the hidden interdunal ponds as a source of water, and they hunted the abundant wildlife there. Flour made from the large acorns of the indigenous shin oak was a dietary staple for the Indians. Today, all that remains of this native culture is flint chips, broken animal bones, and charred hearth stones; these artifacts are occasionally unearthed by wind erosion and are most commonly found in deep blowouts (fig. 5). *Park visitors should be aware that State regulations prohibit personal collecting.*

Settlers making their way westward tended to avoid Monahans dunes because of the threat of sudden Indian attack and because their heavily laden covered wagons could not easily traverse the dunefield; progress was sometimes limited to as little as 5 mi (8 km) per day. The first written description of the dunes dates back to 1848 when Captain R. M. Marcy of the United States Army travelled through Texas and New Mexico during a mapping expedition (Eifler, 1970). Development started in earnest in 1880, when ground water was discovered beneath the dunes and the Texas and Pacific Railroad selected Monahans as a watering stop between the Pecos River and Big Spring, Texas. The railroad provided the necessary transportation link between this largely unexplored territory and centers of commerce, and homesteaders soon moved in. Ranching was the main form of livelihood until 1928, when oil was discovered in Ward County. The economy quickly came to center on the petroleum industry, much as it does today.

Figure 5. Chips of flint, bone, and darkened hearth stones mark the site of an ancient Indian campsite. The large stone in the foreground is approximately 6 inches (15 cm) in diameter.

SAND GRAINS - BUILDING BLOCKS OF DUNES

The most striking feature of sand from Monahans is its apparent homogeneity, or uniformity, from grain to grain. The fine, well-sorted grains have an average diameter of less than 0.009 inch (0.22 mm). **Eolian** (wind-driven) processes transport the grains selectively so that coarser and heavier grains are concentrated farther north in the dune belt, while more easily transported, dust-sized particles have been **winnowed** (selectively transported) away.

Sand color is a function of mineral content. The Monahans Sandhills are composed primarily of clear quartz (98 percent), which appears light tan because of minor amounts of iron-rich clays. The brightly colored grains that compose the remaining 2 percent are pieces of chert (red), tourmaline (black), feldspar (pink), magnetite (black), and rock fragments (brown).

A close-up view of a single quartz grain, enlarged 240 times (fig. 6), reveals the well-rounded shape that is characteristic of dune sand. Repeated impact against other quartz grains has abraded corners from the originally angular fragments. Tiny scratches give the grains a greasy luster. Percussion scars, or crescent-shaped gouges, indicate that these grains have been extensively reworked (eroded and redeposited) by eolian processes.

The sand was originally derived from the erosion of igneous and sedimentary rocks in the southern Rocky Mountains (Waitt, 1969). This material was transported to eastern New Mexico and West Texas by fluvial processes and deposited on the floodplain of the ancestral Pecos River. Sediment is also derived from the Ogallala Formation, a weakly cemented sandstone exposed along the Caprock Escarpment east of Monahans.

Figure 6. Scanning electron micrograph of a well-rounded quartz grain enlarged 240 times from Monahans, Texas. The surface of the grain is covered with minute percussion scars caused by grain-to-grain impacts.

Sand Movement

Dunes are dynamic landforms that shift continually in response to winds of changing velocity and direction. Wind speed must exceed the **threshold velocity** of 14 mph (23 km/h) for sand grains to be set in motion. Air currents lift and carry sand grains a short distance downwind before dropping them back to the ground. The impact of landing causes other grains to bounce forward (fig. 7). Sand transport by this process of short skips is called **saltation.** Larger sand grains, bombarded by saltating grains, are pushed along the ground rather than moved through the air. This type of movement, called tractional motion, or **surface creep,** accounts for approximately one-fourth of all sand movement in deserts. Patient observers will discover that ripple forms migrate downwind by the combined processes of saltation and surface creep.

Grains move along a sandy surface until they encounter an obstacle such as a rock or clump of vegetation--anything that increases the roughness of the ground surface. This causes a localized reduction in wind velocity, and the sand drops out of suspension. A pile of sand quickly grows because the mound itself reduces the carrying capacity of the wind.

As more sand is deposited, the pile develops a classic dune profile, characterized by a gentle **windward slope** and a steep **lee slope** or **slip face** (fig. 8). Saltating grains move up the windward slope of the dune until they are carried over the **crest** (fig. 9). The sand blankets the slip face surface after falling through a pocket of relatively quiet air, called the **leeward zone of separation.** Deposition continues near the summit of the dune, and eventually the lee slope becomes oversteepened. Fine-grained, dry sand can develop slopes of up to 34° before becoming unstable. When this **angle of repose** is exceeded, a slip face forms when sand flows noncohesively in lobate (lobe-shaped) masses (fig. 10) until slope stability is reestablished. However, when moist sand slopes become unstable, sand slumps down the slip face as a cohesive sheet, wrinkling upon impact at the toe of the dune (fig. 11).

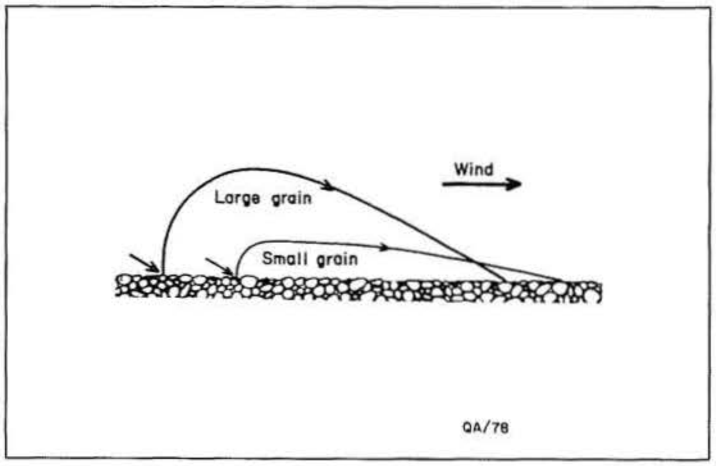


Figure 7. Movement of sand grains by saltation (from Allen, 1970).

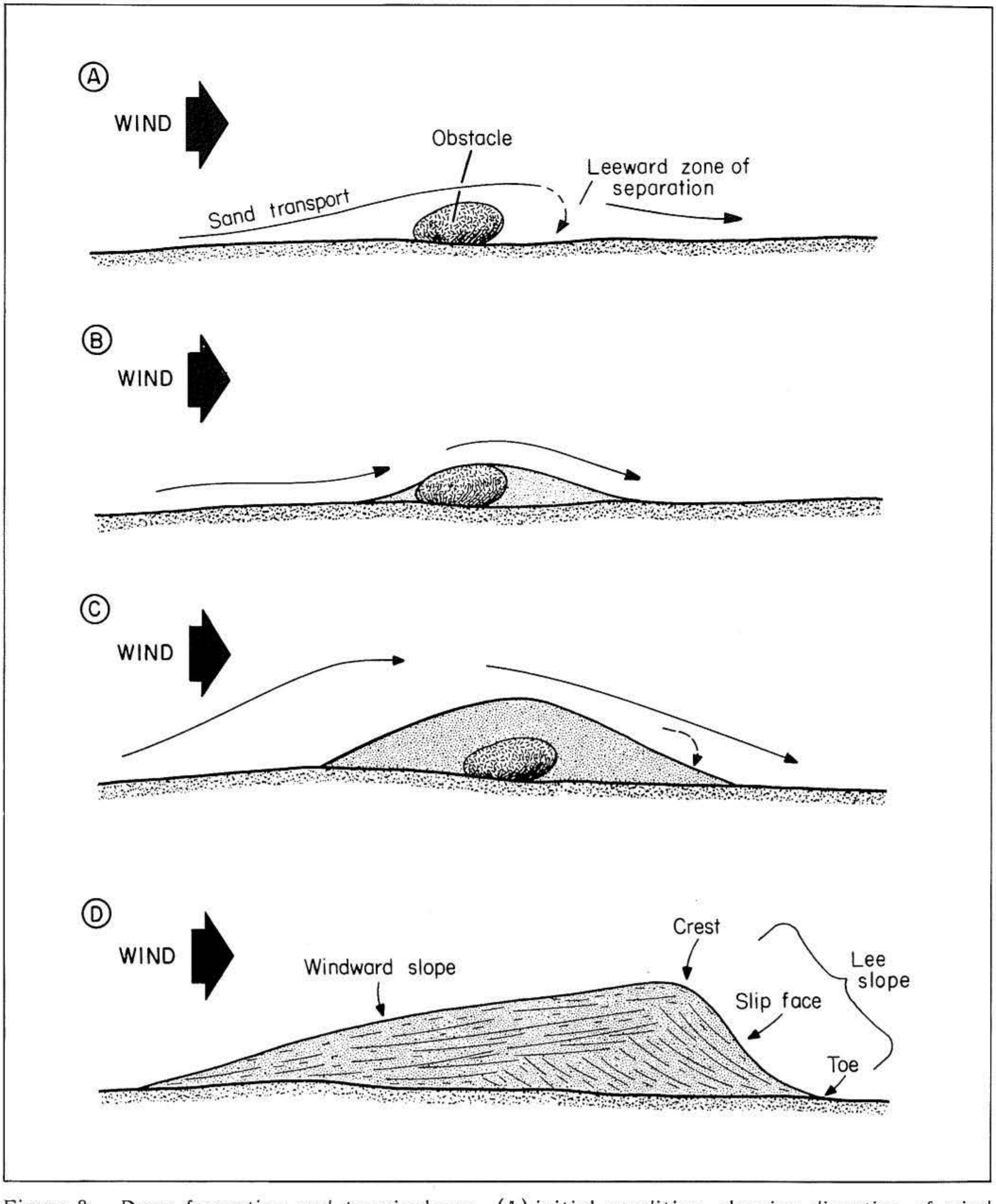


Figure 8. Dune formation and terminology: (A) initial condition, showing direction of wind and sand transport paths, (B) deposition downwind of an obstacle, creating a tapered wind-shadow dune form, (C) sand accumulating on both the upwind and downwind sides of the obstacle, creating an embryonic transverse dune, (D) cross-sectional view of a well-developed dune, showing internal sedimentary structures.

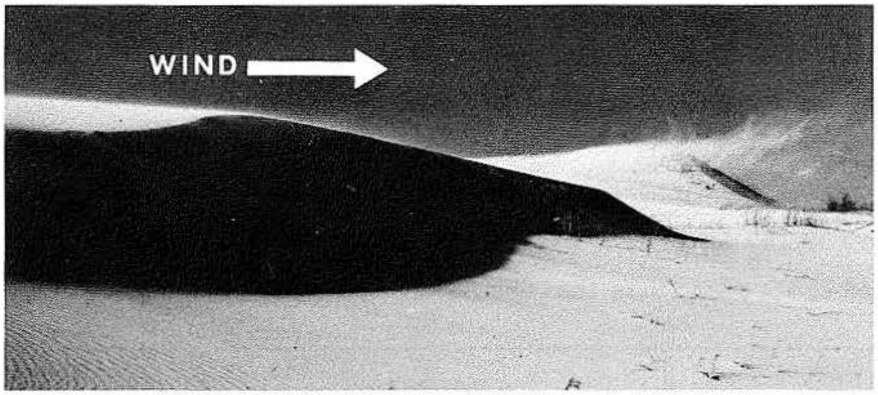


Figure 9. Saltating sand grains blanketing the slip face after falling through the leeward zone of separation. Winds of up to 35 mph (56 km/h) were blowing from the west (left to right) when this picture was taken in March 1981. Dune height is approximately 9 ft (2.7 m).

Figure 10. Lobate sandflow on the dune's slip face. Avalanching occurred in response to unstable slope conditions. Note the overhanging lip of sand at the crest, where previously the wet sand was able to support itself at a steeper angle than the normal 34° angle of repose.

Figure 11. Slump deposits forming on a wet slip face. Sand sheets move downslope along a well-defined plane, producing wrinkled deposits at the toe of the dune.

Dune Form

Several types of dunes occur in the park (fig. 12). Probably the single most important control on dune development in a given setting is the **wind regime,** or strength and directional variability of local winds. The complex relationship between other factors such as precipitation, vegetation, and available sand supply also has a strong influence on dune forms. The most mobile dune forms will be described first, then those that are partly or totally anchored.

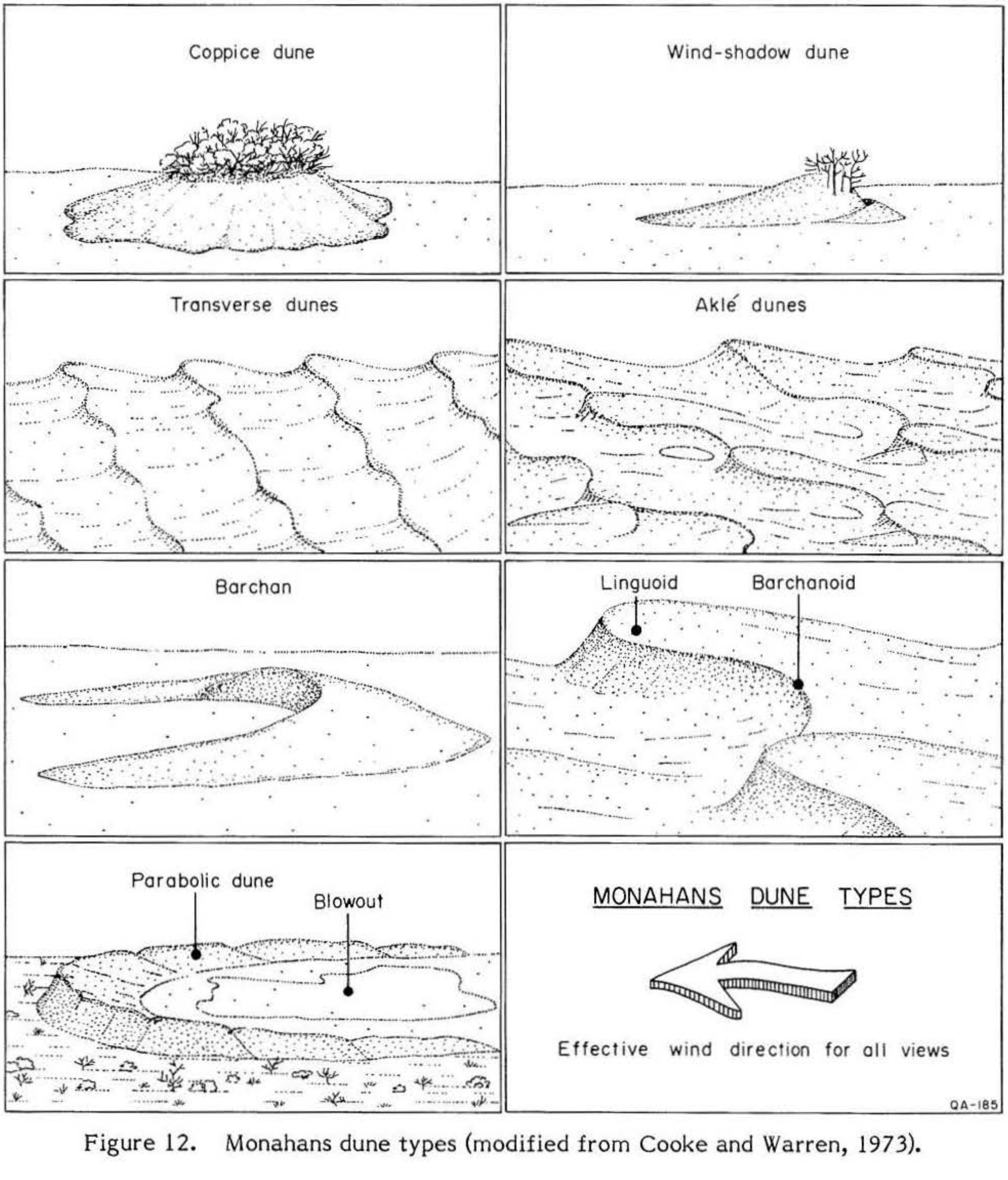
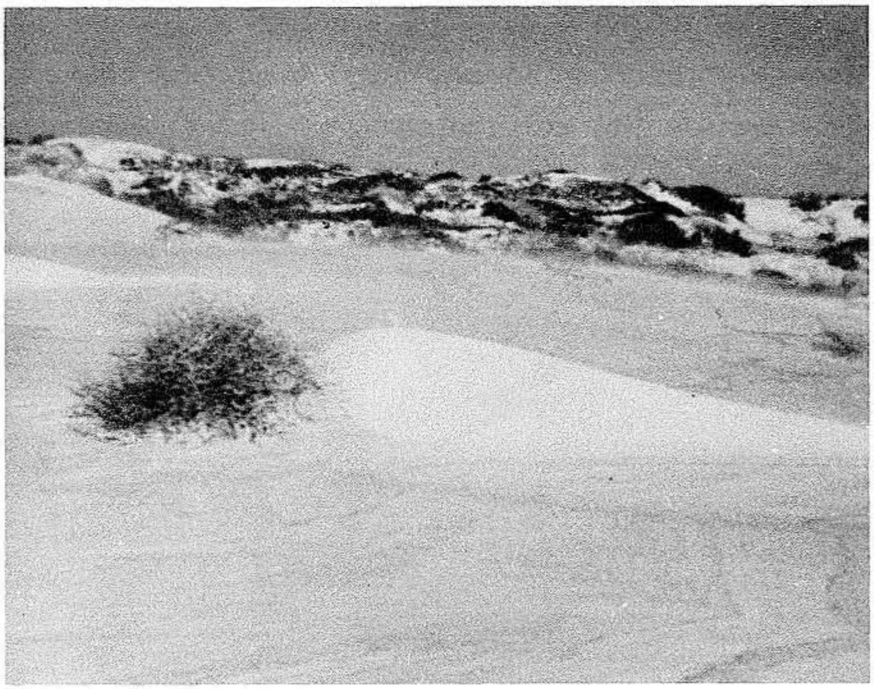


Figure 12. Monahans dune types (modified from Cooke and Warren, 1973).

Wind-shadow dunes (fig. 13) are long, tapered dunes parallel to the direction of effective winds. They form in the small zone of quiet air immediately downwind of an obstacle such as a clump of vegetation. Relatively small volumes of sand are incorporated in these dune forms; consequently, they form very quickly, especially under the influence of high-velocity storm winds.



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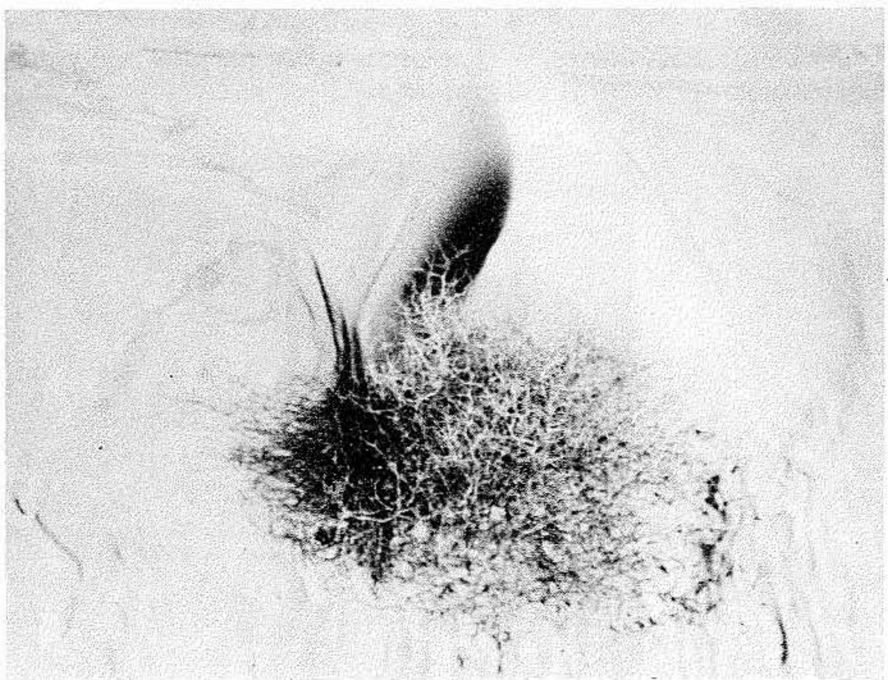

B

Figure 13. Wind-shadow dune forming in the lee of a small shrub. (A) Transverse view. Effective winds are blowing left to right. (B) Looking downwind. (Photographs by G. DePaul.) Dune is approximately 5 ft (1.5 m) long.

Vast areas of active sand develop larger dune forms. To an observer on the ground, the giant dunes so popular with park visitors appear to sprawl haphazardly in every direction. However, when the dunes are viewed from the air, a regular pattern of crests emerges. Long, straight-crested, or **transverse dunes,** oriented perpendicular to the dominant southeasterly wind direction, occur in parts of the park during the summer months. Frequently, two dune trends intersect to form a reticular, gridlike network. The resulting dune form is characteristic of **aklé dunes,** a complex dune pattern of parallel wavy crests (fig. 14). Aklé dunes are composed of smaller **barchanoid** (crescent-shaped) and **linguoid** (tongue-like) dune elements (fig. 15).

Figure 14. Aklé dunes, a type of complex parallel wavy dune. The unbroken dune crest (right) is approximately 330 ft (100 m) long.

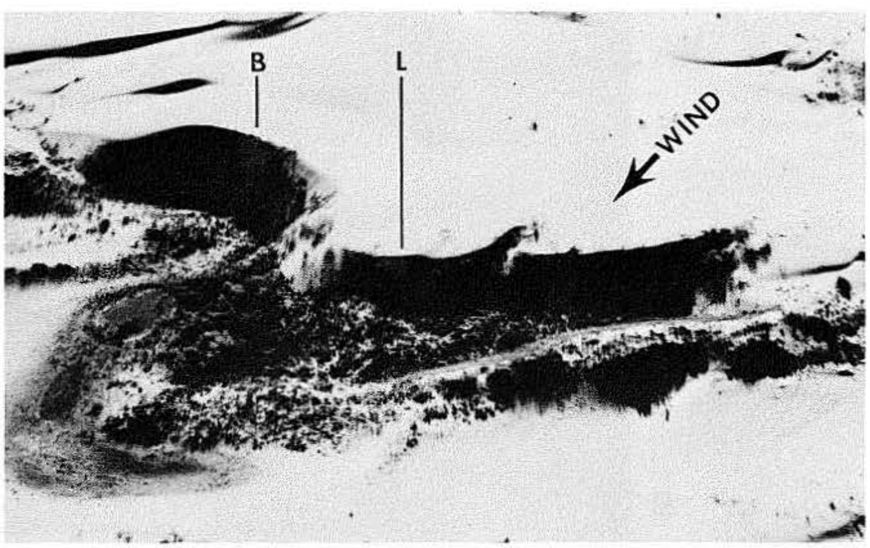

Figure 15. Oblique aerial photograph of barchanoid (B) and linguoid (L) dune forms. Slip face height is approximately 5 ft (1.5 m). The U-shaped ridge marks the former position of the dune crest. View is toward the north. The direction of the most recent sand-moving wind is shown by the arrow.

Aklé dunes result from the interaction of two or more seasonal wind regimes. In the Monahans area, winds from three different directions influence dune form, and these can be separated into seasonal groups: (1) summer, (2) fall and winter, and (3) spring, or transitional, winds (fig. 16).

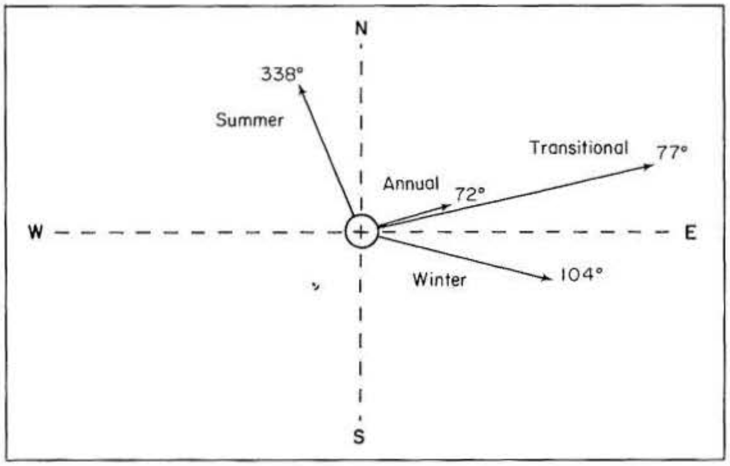

Figure 16. Seasonal sand drift potential at Monahans, Texas. The length of the arrows is proportional to the potential amount of sand movement, and direction is designated in degrees from the azimuth (north).

Gentle but persistent winds blow from the southeast during the summer (May-August). These winds build long, tall dunes oriented northeast-southwest. Sand is pushed to the northwest by the winds, so the dunes have steep slip faces that slope northwest. Summer dune forms are substantially modified by winter storm winds from the northwest during September through February, and by transitional spring winds in March and April. Both of these wind regimes produce gusty, high-velocity winds that lack the directional steadiness of summer winds. Sand moves to the southeast in the winter, and northeastward under the influence of transitional spring winds. This creates a set of smaller lee projections, oriented downwind of and at about a 30° angle to the main dune trend. When summer returns, prevailing southeasterlies rework the dunes and the newly created forms are nearly obliterated (fig. 17).

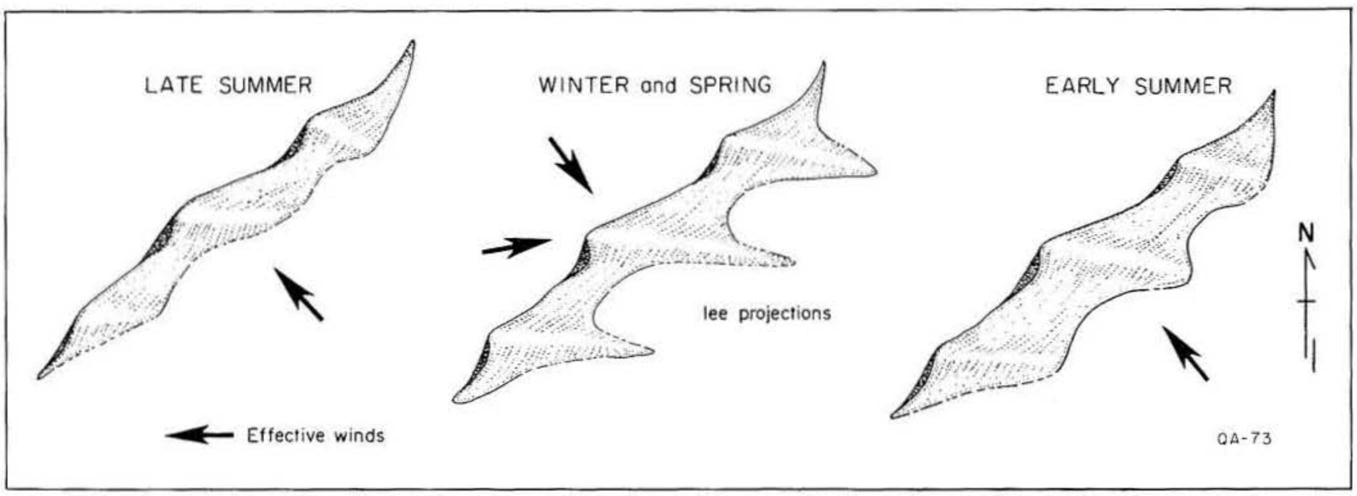

Figure 17. Seasonal changes in dune form, showing the development and ultimate erosion of lee projections.

Blowouts are erosional dunes that occur where stabilizing plant growth is locally disrupted. Fires, overgrazing, and trampling by livestock often lead to blowout development. Blowouts form as sand is scoured from the disrupted area; their depth depends on the local water table, below which the sands are more consolidated and erosion-resistant.

Blowouts may develop into U-shaped, or **parabolic**, dunes, under the influence of a constant, unidirectional wind regime. The rounded end always points downwind. Sand scoured from the base of the originally bowl-shaped depression is redeposited along the margins and leading edge of the dune. The trailing ends become stabilized by vegetation, whereas the central portion continues to move downwind. The orientation of parabolic dunes, conspicuous from an aerial perspective, indicates that winds at the time the dunes formed were from the west-northwest. This change in wind direction suggests that these dunes developed under climatic conditions different from those of today; in other words, these blowouts are relict features of a previous climatic regime.

Coppice dunes are dome-shaped dunes that are anchored by vegetation. In the park, the miniature shin oak tree (*Quercus havardii*) influences coppice dune formation. When the shin oak spreads into areas of loose sand, the aboveground part of the plant traps windblown sand, while its extensive root system holds subsurface sand in place. The upward growth of the tree continues during sand deposition. Coppice dunes also increase in relative height by the process of losing sand from around their root-anchored bases. These two mechanisms produce coppice domes that are more than 20 ft (6 m) high.

Dune Migration

The complex trimodal wind regime of the area causes marked seasonal variations in dune position and form but prevents net dune migration in any one direction. Progressive changes in dune form for a year-long period are shown in figure 18. The slip face reverses its orientation while the dune crest shifts laterally; the greatest change occurs during the spring windstorms. However, by the end of the year, the dune is in approximately the same position and form as when the year began.

As active as the dunes are seasonally, long-term rates of dune migration are negligible. Positions of dune crests and dunefield margins, traced on a series of aerial photographs in the 25-yr period between 1954 and 1979, showed that the margins of the dunefield fluctuated, but no net migration of dunes was evident (Machenberg, 1982). The Monahans Sandhills have apparently attained a state of dynamic equilibrium under present conditions, adjusting to changes in local winds, precipitation, and vegetation.

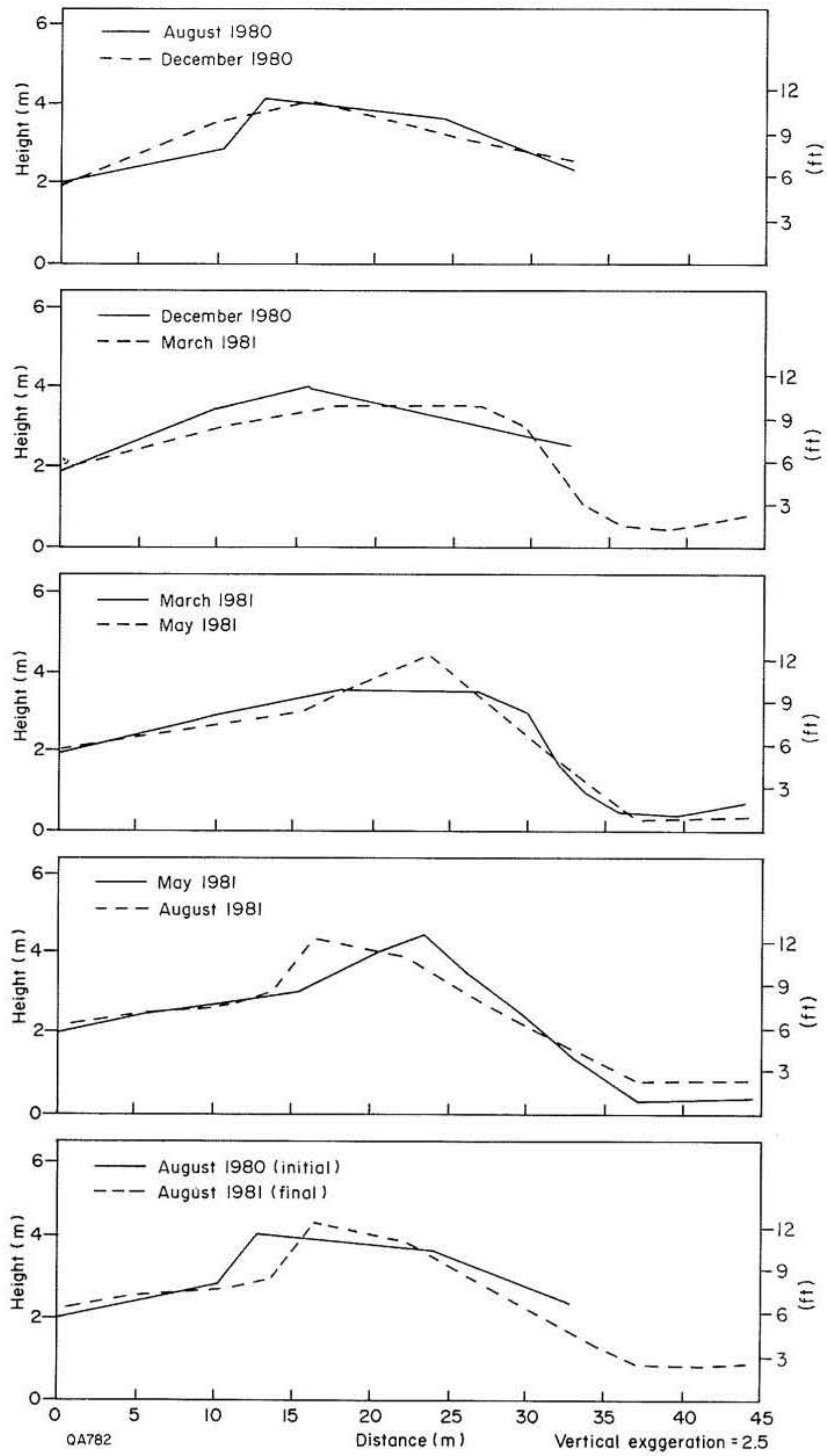

Figure 18. Changes in dune profile, August 1980-August 1981 (from Machenberg, 1982).

Depositional History

Geologists can reconstruct dune environments by interpreting the sedimentary structures preserved in the dunes. Steeply dipping deposits produced by grain saltation may alternate with sandflow lobes, creating the distinct pattern of bedding (sediment layers) that characterizes a relict slip face (fig. 19). Migrating ripples are preserved on windward slopes as wavy laminations or as thin depositional layers. Ponds that formed between the dunes after heavy rains are preserved as horizontal beds of organic-rich material that may contain snail shells.

If a slice were cut through the dunes, a cross section such as the one shown in figure 20 might be revealed. This composite diagram was constructed from exposures throughout the dunefield and provides a record of deposition spanning approximately 40,000 yr.

The thick sequence of sand deposits rests on a much older **caliche** (lime-rich) deposit. A brownish-red, **argillaceous** (clay-rich) sand body, the Judkins Formation, was deposited directly on the caliche layer. An **unconformity**, or surface of erosion, separates these two units, which differ significantly in age. The Judkins Formation, tentatively dated as 25,000 yr old (Huffington and Albritton, 1941), represents the first major period of dune building to affect the area and includes minor amounts of interdune pond sediments. Overlying the Judkins is a thin, light-gray **calcareous** sand thought to indicate a pluvial, or wetter, climatic period of dune stability because of its distinctive **lithology**, preserved pollen, and abundant fossil remains. Two more dune-building periods followed, and in both, light-gray quartz sand was deposited. Another phase of dune stability resulted in the formation of a **paleosol** preserved as a layer of

Figure 19. Internal sedimentary structures characteristic of a previous slip face depositional environment. Dark sandflow deposits dip at a 34° angle. These are separated by lighter sandfall sediments that have fallen over the dune's crest after saltating up the windward slope. Contorted beds associated with slumping of wet sand are visible in the lower left of the photo. Pencil in lower left is 6 inches (15 cm) long.

brown silty sand containing plant debris. Remnants of a set of red sand dunes lie unconformably above the paleosol. Topping the section is the loose, tan quartz sand of the Monahans Formation, which makes up the active dunes seen today.

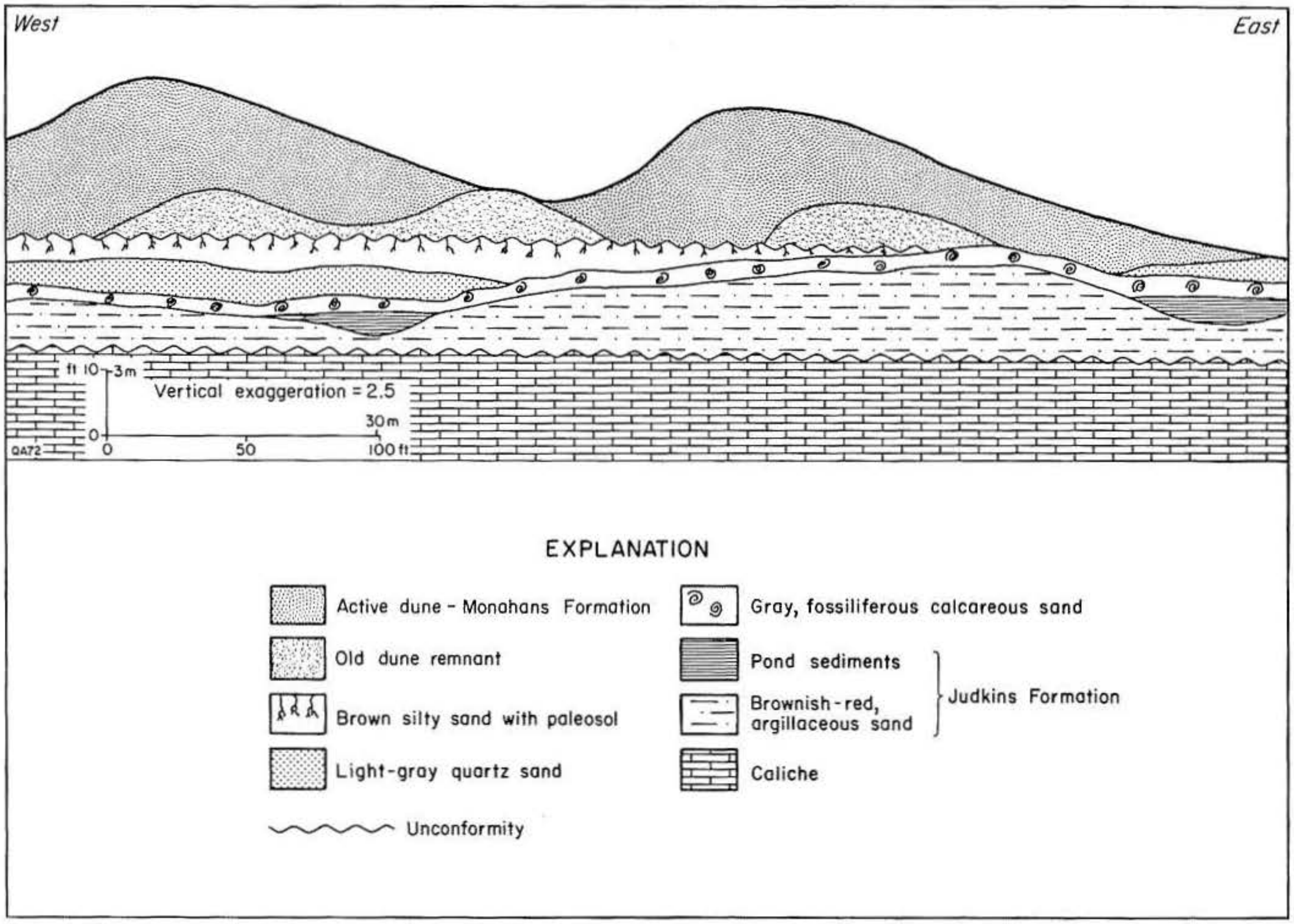

Figure 20. Generalized cross section of deposits found within the Monahans dune area (modified from Green, 1961). Only a few of these deposits would be exposed at any single locality.

Hidden Water

Although this seemingly barren, dune-covered landscape appears completely dry, the surficial sand actually acts as a natural underground reservoir. Spaces between loosely packed spherical sand grains give unconsolidated eolian deposits porosities between 30 and 45 percent (Freeze and Cherry, 1979). Infiltrating rainwater is effectively stored within these pore spaces. Below the top few inches of dry sand, intergranular water is tightly held in place by capillary forces. Water is an important stabilizing agent for maintaining dune form; not only does it give the sand cohesiveness but it also provides the necessary moisture for growth of stabilizing vegetation. In years of drought, the subsurface reservoir is depleted, vegetation dies off, and sand is released, thereby increasing the supply of dune sand.

The sandhills support a variety of plants including trees, grasses, succulents, and wildflowers. The dominant plant is the shin oak (*Quercus havardii*), a small tree indigenous to this region. Shin oaks, which rarely grow taller than 3 ft (1 m), produce a profusion of large acorns. In the more heavily vegetated areas of the park, the shin oak forms a dense miniature forest. The tree's extensive root system effectively anchors sand deposits (fig. 21); shin oak roots longer than 70 ft (20 m) have been found in the park. Honey mesquite (*Prosopis glandulosa*) grows in thickets bordering the active dune areas, and desert willow (*Chilopsis linearis*) thrives in the moist interdunal depressions. Both of these plants spread rapidly, colonizing large areas of the dunefield after periods of increased rainfall.

Grasses, important in dune stabilization, include the "climax" species: plains lovegrass (*Eragrostis intermedia*), sand bluestem (*Andropogon hallii*), sandreed (*Calamovilfa gigantea*), and panic grass (*Panicum havardii*). Yucca and cactus also colonize the dunes. Abundant wildflowers dot the landscape with color, especially after spring and summer rains.

Most plants growing in the Monahans Sandhills are adapted to the semiarid climate and are drought-resistant. However, a succession of dry years can severely reduce the density of vegetative cover. Even **phreatophytes**, plants whose roots reach the water table, are susceptible to prolonged droughts. In the sandhills, most of the trees and shrubs are phreatophytes. **Mesophytes** (plants that require a moderate supply of moisture), such as the numerous grasses, and **xerophytes** (plants capable of growing under conditions of limited water

Figure 21. Dome-shaped coppice dune stabilized by the miniature shin oak *(Quercus havardii)*. Note the extensive root system. The south side of this dune, exposed to prevailing winds much of the year, is undergoing erosion. View is toward the north.

availability), like cacti, invade those areas previously occupied by woody plants, taking advantage of the reduced competition for water and nutrients.

Vegetation is essential to dune stability. A smooth, vegetation-free surface maximizes efficient sand transport because it cannot effectively reduce wind velocity. Furthermore, in the absence of buried root networks, even older, stabilized dunes are likely to erode. Vegetated dunes that border blowouts commonly exhibit active erosion on south-facing sides because summer winds cause greater environmental stress on vegetation. Plants on northerly slopes lie within a sheltered microenvironment and experience more new growth because they are protected from sandblasting, dehydration, and solar flux.

EOLIAN ENVIRONMENTS OF MONAHANS SANDHILLS STATE PARK

Although park visitors are most familiar with the inviting expanses of active dune sand, several other types of environments occur in the park, each displaying a unique combination of physical and biological characteristics. Distribution of the various environments is shown on the accompanying map (in pocket). The map shows the wide range of environments that can be encountered within the park's boundaries. Map units are defined on the basis of landforms and processes that are active today or were active in the past. A description of each map unit follows.

Active Dunes

The active dunes in the park are totally or predominantly unvegetated (fig. 22) and shift in response to seasonal winds. Most active dunes are aklé dunes, the complex, parallel, wavy dune form described earlier. Smaller patches of active sand do not display the reticular, or netlike, pattern characteristic of aklé dunes but consist of smaller barchanoid and linguoid dune forms (fig. 15). Other, mostly small, areas contain straight-crested transverse dunes oriented perpendicular to the prevailing southeast (summer) wind direction (fig. 12).

Approximately 45 percent of the park (1,750 acres or 708 hectares) consists of active dunes. These dunes range in height from a few meters to more than 85 ft (25 m). Most of the year, linear dune crests extend unbroken for as much as 950 ft (280 m). The largest dunes are located in the less accessible northwest end of the park. Southeasterly winds, blowing across a broad expanse of unvegetated sand, reach maximum strength because they are not diminished by friction associated with the vegetation that surrounds the dunefield. Sand supply is greatest here because grains are concentrated in the middle of the dunefield by the variable seasonal winds.

Active dunes are the principal habitat of several species of insects and other arthropods. Beetles dig complex burrows (fig. 23) into the rippled sand, seeking shelter from the weather as well as from predators. Scorpions (fig. 24) can occasionally be found in this environment, but their protective coloration hides them well.

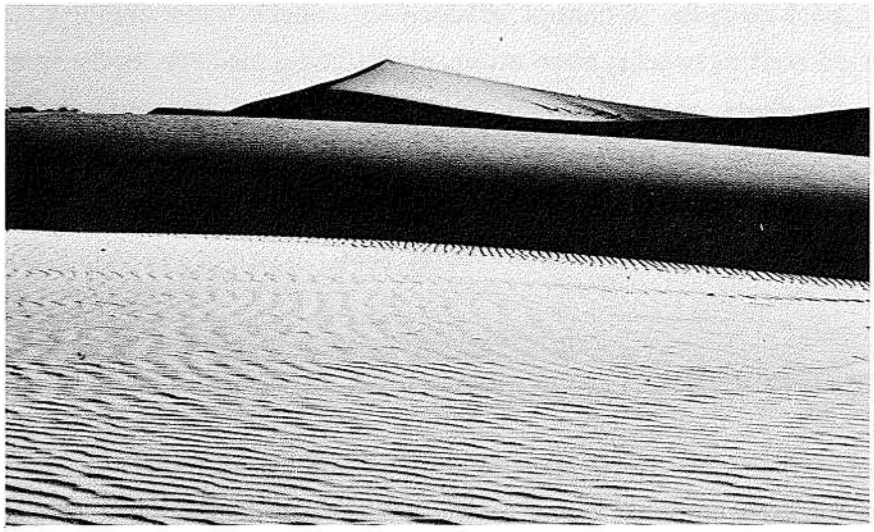

Figure 22. Active, vegetation-free dunes. View is looking north. Rear dune is approximately 80 ft (24 m) high.

Figure 23. Structure formed by a burrowing beetle. Approximate width of sand pile is 2.5 inches (6 cm).

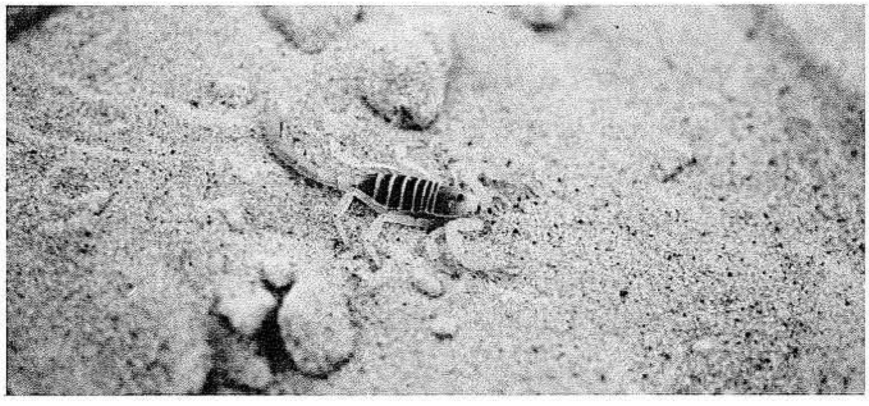

Figure 24. Scorpions are occasionally seen in the active dune areas. Total length of the scorpion is approximately 3.2 inches (8 cm).

Coppice Dunes

Dome-shaped coppice dunes produce a hilly, or hummocky, topography. Coppice dunes are distributed along the edges of active dunes, occasionally occurring as isolated patches within an expanse of unvegetated sand. Coppice dune areas are rarely totally vegetated, consisting instead of a mixture of exposed sandy depressions and vegetation-covered hills. With its dense shin oak cover, the coppice dune setting provides a protective habitat for several species of rodents, birds, reptiles, and amphibians. Relict sedimentary structures can occasionally be observed in the steep sides of the coppice dunes. During windstorms, dry, loose sand is deposited in the lee of coppice dunes in the form of long, pointed, wind-shadow dunes.

Stabilized Blowout Dunes

On the vegetation-covered sandy plains surrounding active dune areas, clusters of blowout dunes frequently occur in sharply defined elliptical patches (fig. 25). Sand is spread downwind from the point where vegetation was originally disrupted. Most of the blowout depressions in the region have been somewhat stabilized by vegetation and probably represent eolian activity during the previous arid climatic phase, approximately 14,000 yr B.P. Vegetation that stabilizes blowouts consists of mesquite, yucca, shin oak, grasses, and wildflowers. Plant diversity is

Figure 25. Oblique aerial view of active (A) and vegetated (V) blowouts on the mesquite-covered sandy plain. View is eastward along Interstate Highway 20. (Photograph courtesy of the Texas Department of Highways and Public Transportation.)

generally greater here than in any other environment in the park; consequently, these areas support a greater variety of animal species. Small mammals such as packrats, spotted ground squirrels, and kangaroo rats live here.

Included among the areas mapped as stabilized blowout dunes are several active blowouts. Blowout dunes are good indicators of a stressed environment, and new blowouts are forming today outside the park boundaries. Blowout development is related to land use changes that affect the ability of vegetation to stabilize the dunes. An example is the recent construction of oil field access roads through the vegetated dunes that flank the west margin of the park. Blowouts have developed in several areas, reactivating movement of loose sand and making it difficult to keep thoroughfares sand-free. Other changes in land use that could influence blowout development include overgrazing and increased ground-water withdrawal.

Interdune Flats

Within the fields of active sand dunes, smooth, elongate areas occupy some of the topographically lower interdunal depressions. **Deflation** has exposed a more resistant horizon at **base level.** Lag deposits of coarse sand and chert granules mantle some of these hard surfaces. The coarse grains are the winnowed residue left by winds that were capable of transporting only the finer particles.

Some interdune flats are floored by **caliche,** or hardpan, a white, lime-enriched soil. Caliche horizons range in thickness from 6 to 20 inches (15 to 50 cm) (fig. 26). At the base of other depressions are exposures of horizontally bedded, reddish sands (fig. 27). These are older eolian sediments that have been weakly cemented by halite and gypsum precipitated from hard ground water. The red sand color is produced by oxidation of constituent mineral grains that contain iron, such as magnetite, and by silt and clay particles that have infiltrated pore spaces between sand grains. Interdune flats rarely contain standing water because the resistant layers flooring interdune flats usually lie above the local water table. The densely packed or cemented sediments, however, retain more moisture than do the surrounding mobile sands. During droughts, interdune flats may be coated with a white efflorescence of **evaporite** minerals deposited by the slow evaporation of mineral-rich pore waters.

Interdune flats frequently yield evidence of Indian occupation. Chips of flint, bone fragments, and stone implements are concentrated with the lag deposits after the finer sand grains enclosing the artifacts have been winnowed away. These items are thereby effectively dropped from their original position within dune sediments onto the underlying hard surface.

Interdune flats typically lack vegetation, but some animals take advantage of the firm substrate in this otherwise "soft" environment. Burrows will not collapse and thus the amount of material that must be moved is less than that required for burrows in loose sand. Ants tunnel passageways through the red sediments, and burrowing owls nest within caliche horizons. Coyotes also use caliche exposures to keep their toenails from growing uncomfortably long.

Figure 26. Thin layer of caliche (C) exposed in an interdune flat. Vegetation in foreground is 18 inches (45 cm) high.

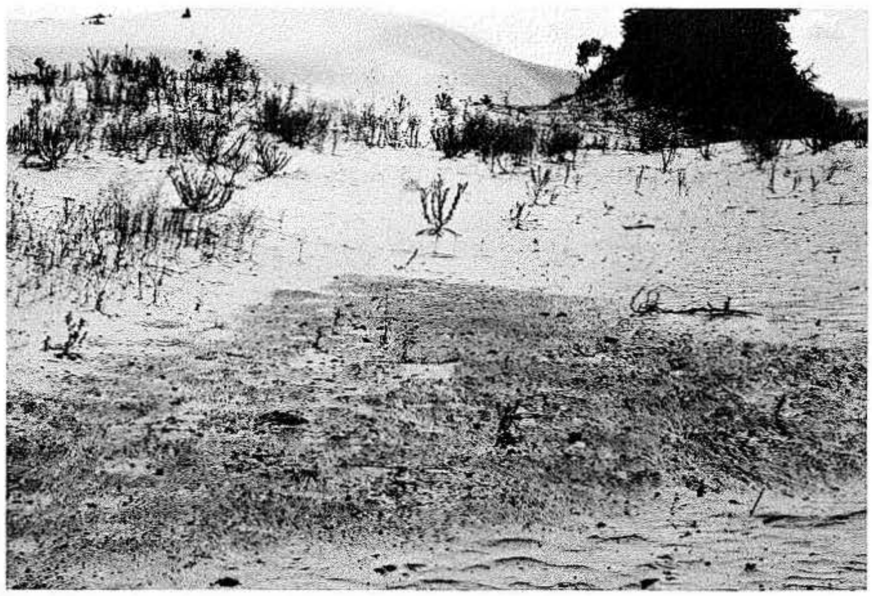

Figure 27. Interdune flat floored with older, reddish eolian sands. Note the coppice dune, approximately 10 ft (3 m) high, in the background.

Ephemeral and Permanent Fresh-Water Ponds

After heavy rains, numerous shallow ponds form in the interdune depressions (fig. 28). However, most of these ponds are temporary, disappearing completely within a few months. When the water has either evaporated or infiltrated, dry basin floors appear brownish red because of accumulated organic matter and muddy sediment, or they may be coated with a residue of evaporite minerals. A few permanent pools exist within the boundaries of the park (fig. 29). Impermeable caliche layers below such ponds prevent water from rapidly percolating into deeper deposits. This configuration, in which ground water collects at a higher level than in surrounding areas, is called a **perched water table.** Ponds form wherever the topographic surface is below the top of the water table.

As dunes migrate, the positions of interdunal ponds change as well. Active dunes commonly migrate into the ponds, creating a unique assemblage of sedimentary features. Avalanching deposits spread horizontally underwater, and a layer of heavy mineral grains marks the maximum extent of each flow. These discontinuous deposits are separated by structureless accumulations of saltating sand that settle out through the water column. When the ponds evaporate, polygonal **desiccation cracks** develop because sediment volume decreases as the deposits dry. The open cracks extend only a few centimeters into the sediment and are soon filled by fine-grained windblown sand (fig. 30). This cycle is repeated during each successive episode of ponding. Where preserved, these sedimentary features identify sites of older ponds within surrounding eolian deposits.

Permanent and ephemeral ponds create a favorable habitat for plants and wildlife. Plants that require substantial amounts of moisture, such as sandreed, bulrush, and willow, thrive near the ponds. The water supports a great variety of aquatic and amphibious animals such as frogs,

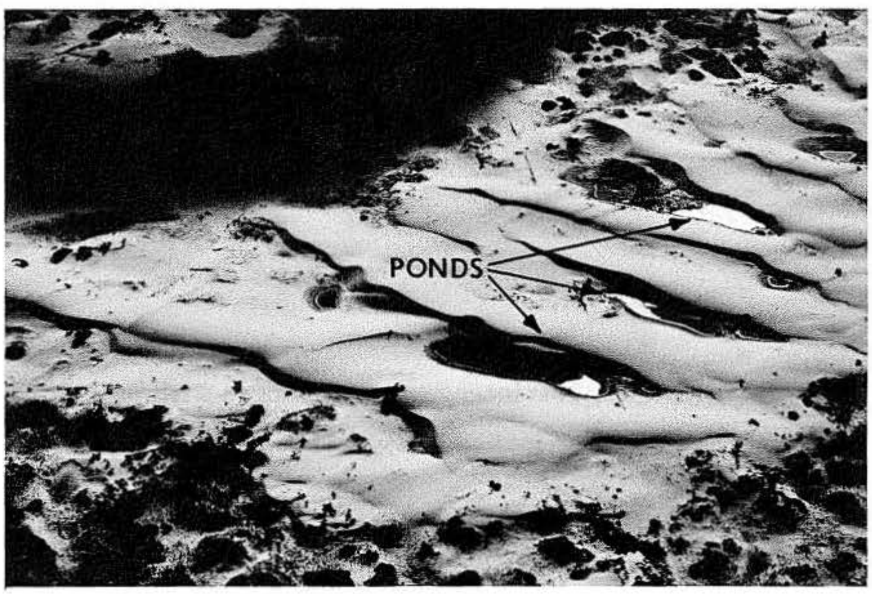

Figure 28. Oblique aerial photograph of the dunefield, showing the extent of interdune ponding after an exceptionally wet summer (July 1981). Dune crest in foreground is approximately 650 ft (200 m) long. View is toward the northeast.

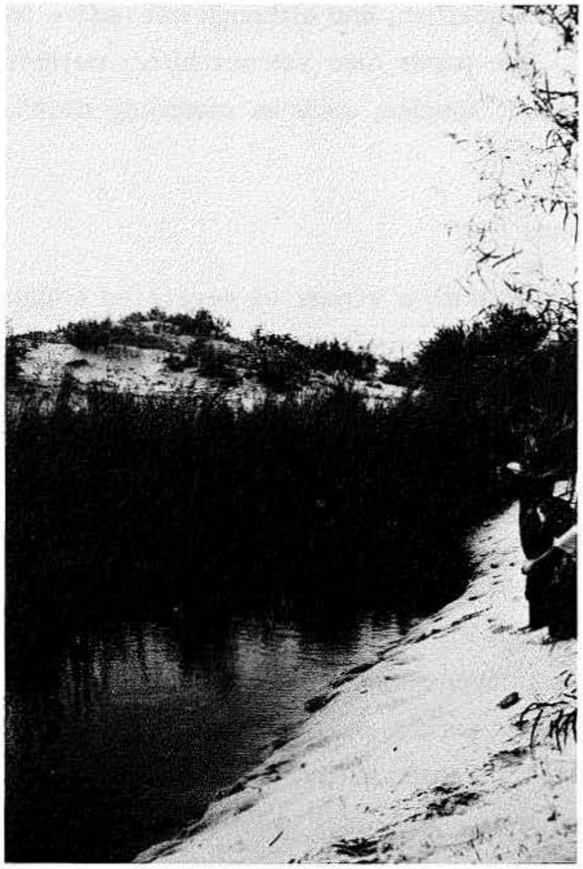

Figure 29. Permanent pond located in the park's northwest corner. Water depth rarely exceeds 3 ft (0.9 m). A small population of goldfish continues to thrive in this pond after several years.

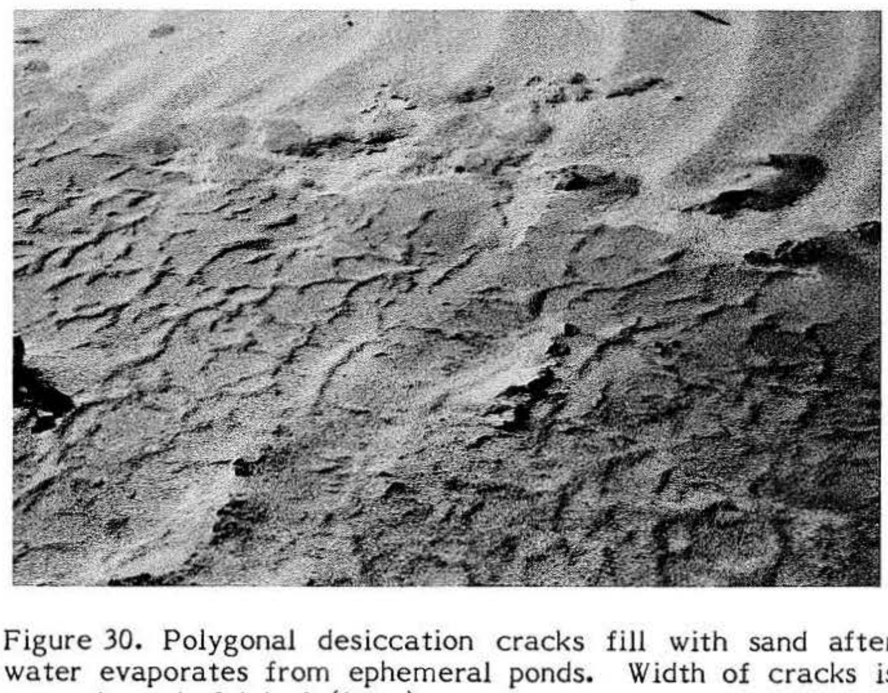

Figure 30. Polygonal desiccation cracks fill with sand after water evaporates from ephemeral ponds. Width of cracks is approximately 0.4 inch (1 cm).

toads, water striders, and beetles. One pond even contains goldfish, and although not native to this area, they have thrived here for several years. The ponds also attract birds; patient birdwatchers are likely to spot many migrant and resident species, such as mourning doves, quail, and sandhill cranes (appendix B).

Vegetated Cover Sands

Much of the flat surface of the Pecos Plain is covered with a veneer of vegetated eolian sand generally less than 3 ft (1 m) thick. This deposit, the cover sands, is much older than the active dunes, possibly deposited as early as 1.4 m.y. B.P. (Beard and others, 1982). Cover sands are stabilized by vegetation and are generally no longer influenced by eolian processes. Locally, however, blowouts interrupt the vegetative cover and reactivate sand movement. Topography of the vegetated cover sands is flat to rolling, consisting of low, closely spaced, shrub-covered coppice dunes that have been subdued by **mass wasting** (gravity-induced erosion). Through time, vegetation colonized and effectively stabilized the originally bare sand.

Grazing is the dominant land use of the vegetated cover sands in and around the park. Although densely vegetated, the cover sands support mostly shrubs and woody plant species of little nutritional value to grazing animals such as cattle. Consequently, many acres of this habitat type are needed to feed each animal. One rancher who leases grazing rights to the property surrounding the park reported in 1980 that each year approximately 75 head of cattle are rounded up from a 50-section parcel of land (one section equals 640 acres, or 1 mi^2). This level of usage allows one animal slightly more than 425 acres (170 hectares). Increasing the herd size here would most likely result in overgrazing, a problem that apparently does not now exist.

Man-Modified Land

Within the park, several areas have been modified to accommodate recreational and educational uses. These areas, here termed "man-modified land," include roads, parking lots, residences, maintenance facilities, picnic areas, campgrounds, the interpretive center, a concession stand, and an operating pumpjack. The two camping areas are situated in long interdune depressions. Picnic areas are located in the vegetated, hummocky areas of the park, providing a sense of seclusion and proximity to nature. The park facilities were designed to provide necessary amenities and access to the most popular attractions while minimally disturbing the environment.

The oil well is in the picnic area west of the campground and is operated by the holders of the Sealy Smith lease. Numerous oil and gas fields surrounding the park attest to the economic resources underground.

CONCLUSIONS

Each of the varied types of environments within the Monahans dunefield--active dunes, coppice dunes, stabilized blowout dunes, interdune flats, fresh-water ponds, and vegetated cover sands--displays unique botanical, biological, and physical characteristics. Eolian environments are dynamic; the complex trimodal wind regime and fluctuations in available moisture change the extent of the eolian environment all the time.

Wind, sand supply, precipitation, vegetation growth, human intervention, and other factors combine in a system that maintains a delicate balance within the dunefield. This system ultimately derives its power from the sun; solar energy drives the atmospheric parameters, which in turn affect the physical environment (fig. 31). Within the confines of the park, this system has apparently attained a state of **dynamic equilibrium.** The use of the term "dynamic" to describe conditions implies that change is a normal and expected aspect of dunefield stability. Dunefield size is not constant, but varies when examined within the context of a historic timescale (less than 100 yr). Drought may cause active dunes to migrate out onto the vegetated cover sands, but plant cover colonizes these sandy deposits when the rains return. It is only when long-term climatic fluctuations or man-induced stresses progressively affect the system that equilibrium is disrupted (fig. 32).

The unique sand-filled environment of Monahans Sandhills State Park has been preserved for all to enjoy. Park visitors are greeted by new vistas created by the constantly shifting dunes. A sense of timelessness exists here. The wind erases footprints in the sand daily, leaving behind no evidence of the day's activities; wind-rippled slopes are all that remain. It is this aspect of ceaseless change as well as the assemblage of plant and animal life that make Monahans a special place to be explored by those who seek a dramatic expression of nature.

ACKNOWLEDGMENTS

The author extends sincere thanks to Edith Grissom and other staff members of Monahans Sandhills State Park, who were most helpful in providing access to historical information concerning the park's development. David Riskind, of the Texas Parks and Wildlife Department, kindly assisted with the identification of plant species. Thanks are also due T. C. Gustavson, L. F. Brown, Jr., R. W. Baumgardner, Jr., R. J. Finley, S. C. Caran, and T. Hentz for critically reviewing the manuscript. Their suggestions greatly improved the clarity of the material.

Word processing was by Dorothy C. Johnson under the supervision of Lucille C. Harrell. Editing was by Amanda R. Masterson. Text illustration preparation was by James A. Morgan. The plate was drafted by Jeff Horowitz and text drafting was by Margaret R. Day, Margaret L. Evans, Jamie McClelland, and Richard M. Platt, under the supervision of Dan F. Scranton and Richard L. Dillon. Publication design was by Margaret L. Evans.

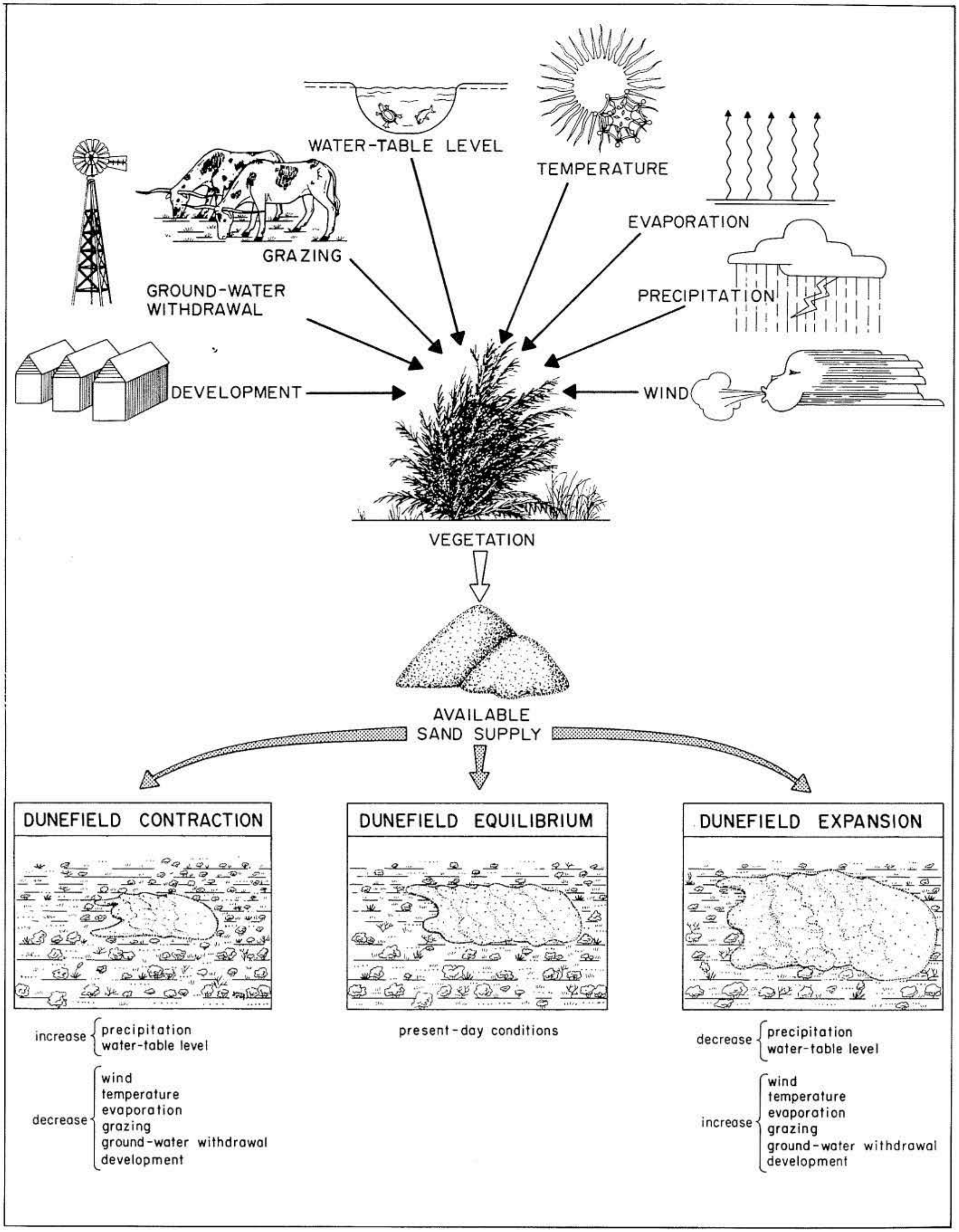

Figure 31. Model of dunefield equilibrium.

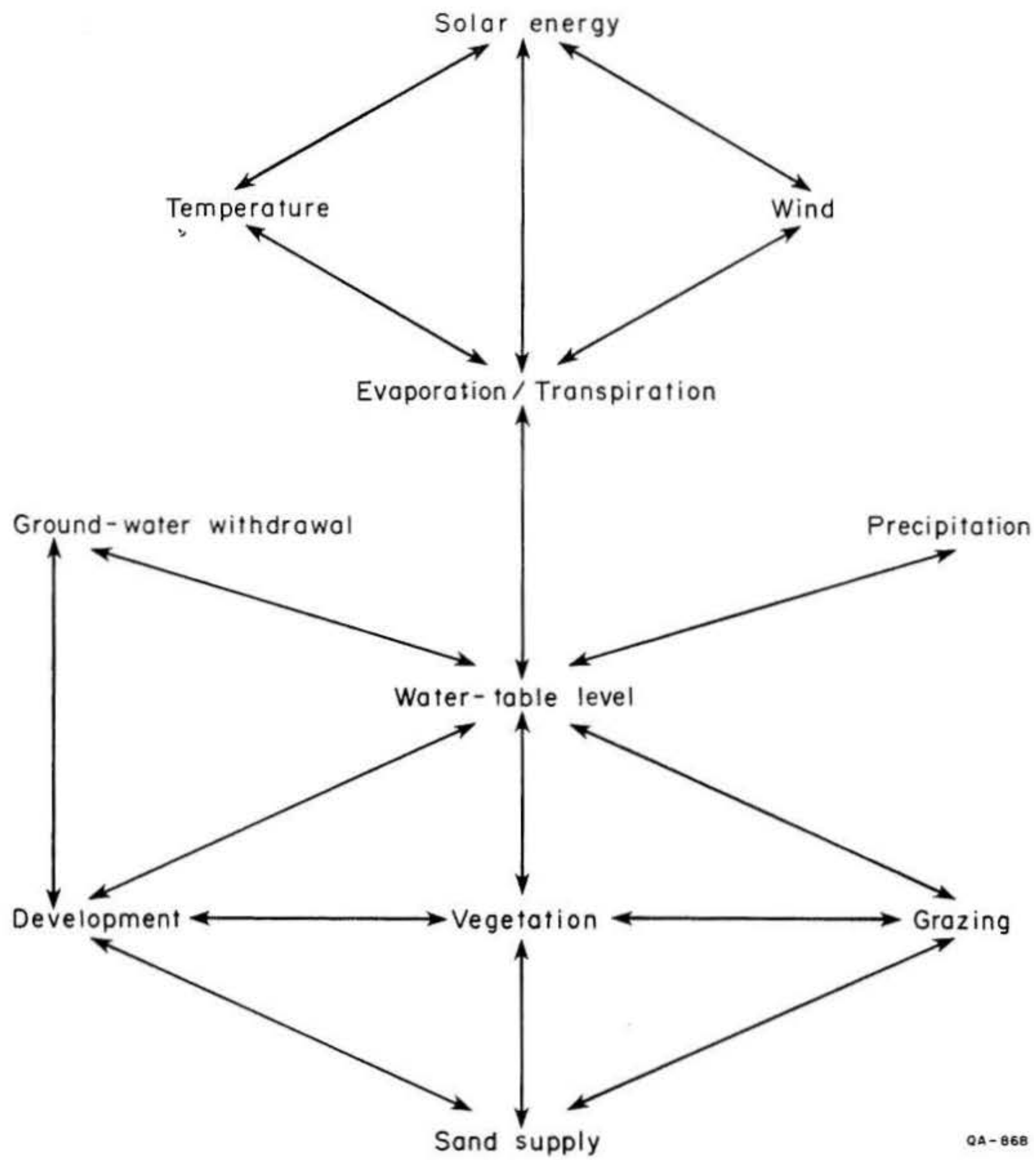

Figure 32. Dunefield equilibrium as a function of changing natural and man-induced parameters.

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GLOSSARY

Aklé dunes--A gridlike pattern resulting from the intersection of two linear dune trends; a type of complex, parallel, wavy dune form.

Angle of repose--The maximum stable slope attainable by unconsolidated material. For loose sand, the angle of repose is approximately 34°.

Argillaceous--A term describing sediments containing appreciable amounts of clay.

Barchanoid--A dune form characterized by its crescent-like shape, in which the horns point downwind.

Base level--A horizon below which erosion cannot occur due to high water content or resistant **lithology.**

Blowout--A trough-shaped hollow formed by wind erosion on a preexisting dune or other sand deposit.

Calcareous--Containing calcium carbonate.

Caliche--A relatively hard deposit, near the surface or exposed by erosion, cemented by carbonates precipitated from solute-rich waters.

Coppice dune--A mound of sand built around and held in place by vegetation. In the Monahans area, the shin oak influences coppice dune formation.

Crest--The highest point of a dune, separating the **windward slope** from the **lee slope.**

Deflation--The scouring or removal of sediment by wind erosion.

Desiccation crack--Polygonal crack formed by shrinkage of clay in the course of evaporative drying.

Dynamic equilibrium--A concept applied to a system in which physical parameters vary about a mean equilibrium condition.

Eolian--Applied to deposits arranged by the wind; wind-driven.

Evaporite--A mineral deposited by the extensive or total evaporation of solute-rich waters (examples--halite and gypsum).

Lee slope--The steep slope of a dune facing the direction of prevailing winds; see **slip face.**

Leeward zone of separation--A small pocket of quiet air that exists immediately downwind of a dune's crest.

Linguoid--A dune form characterized by its tongue-like shape, with the rounded end pointing downwind.

Lithology--The sediment composition of a geologic deposit.

Mass wasting--The slow downslope movement of sediment induced by gravity.

Mesophytes--Plants requiring a moderate supply of water.

Paleosol--A buried soil profile.

Paleowind--The wind regime of a previous climatic period.

Parabolic dune--A U-shaped dune form with the rounded end pointing downwind.

Perched water table--The water table of a saturated zone separated from an unsaturated zone by an impermeable horizon.

Phreatophytes--Plants whose roots extend down to the water table.

Pluvial--Relating to former periods of abundant rainfall or increased moisture.

Saltation--The process by which sand grains are moved downwind by a series of short jumps or skips, after being struck by landing grains.

Slip face--Portion of the **lee slope** that is maintained at the **angle of repose** by the processes of sand flow and slumping.

Surface creep--The downwind movement of particles along the ground surface.

Threshold velocity--The minimum speed at which wind will begin moving particles of sand. For the fine-grained quartz sand of Monahans, the threshold velocity is approximately 14 mph (23 km/h).

Transverse dune--An asymmetrical ridge of sand oriented perpendicular to the prevailing wind direction.

Unconformity--A surface of erosion.

Wind regime--The directional variability and velocity distribution of winds at a particular locality.

Wind-shadow dune--A long, tapered dune form, elongated parallel to the prevailing winds, which develops in the lee of an obstacle, such as a clump of vegetation.

Windward slope--A dune's gentle slope, which faces away from the direction of prevailing winds.

Winnow--To separate fine particles from coarser ones by the action of the wind.

Xerophytes--Plants that grow in or on extremely dry soils.

APPENDIX A: Nearby Points of Interest

The Odessa Meteor Crater, located 23 mi (37 km) east of Monahans and 6 mi (10 km) south of Odessa, is a circular depression with a raised rim, attributed to the impact of at least two meteorites. Several small pieces of iron-nickel meteorite have been recovered from the area. A short marked trail circles the crater.

In nearby Midland, the Permian Basin Petroleum Museum has numerous displays depicting the development of the petroleum industry in this oil-rich region. Historical aspects of early life on the Southern High Plains are also featured.

Another geologic feature is the Wink Sink, located between Wink and Kermit just south of State Highway 115. Eighteen miles (29 km) north of Monahans, this large sinkhole suddenly formed in June 1980 (Baumgardner and others, 1982). Collapse of sediments into the hole is attributed to the dissolution of bedded salt deposits 1,500 ft (450 m) underground. Although located on private land, the Wink Sink is visible from the main highway. No visitor facilities are available.

Guadalupe Mountains National Park is 125 mi (200 km) west of Monahans. It is famous for its limestone cliffs, such as El Capitan, which consist of ancient reef structures. This same rock formation continues into New Mexico and houses the underground passages of Carlsbad Caverns National Park, a 2½-hr drive from Monahans.

Another area of active dunes is the gypsum dunes of White Sands National Monument, located approximately 225 mi (360 km) to the west, near Alamogordo, New Mexico. The world's largest gypsum dunefield, it covers an area of more than 300 mi^2 (775 km^2). The sparkling white sand contrasts sharply with Monahans' light-tan quartz sand.

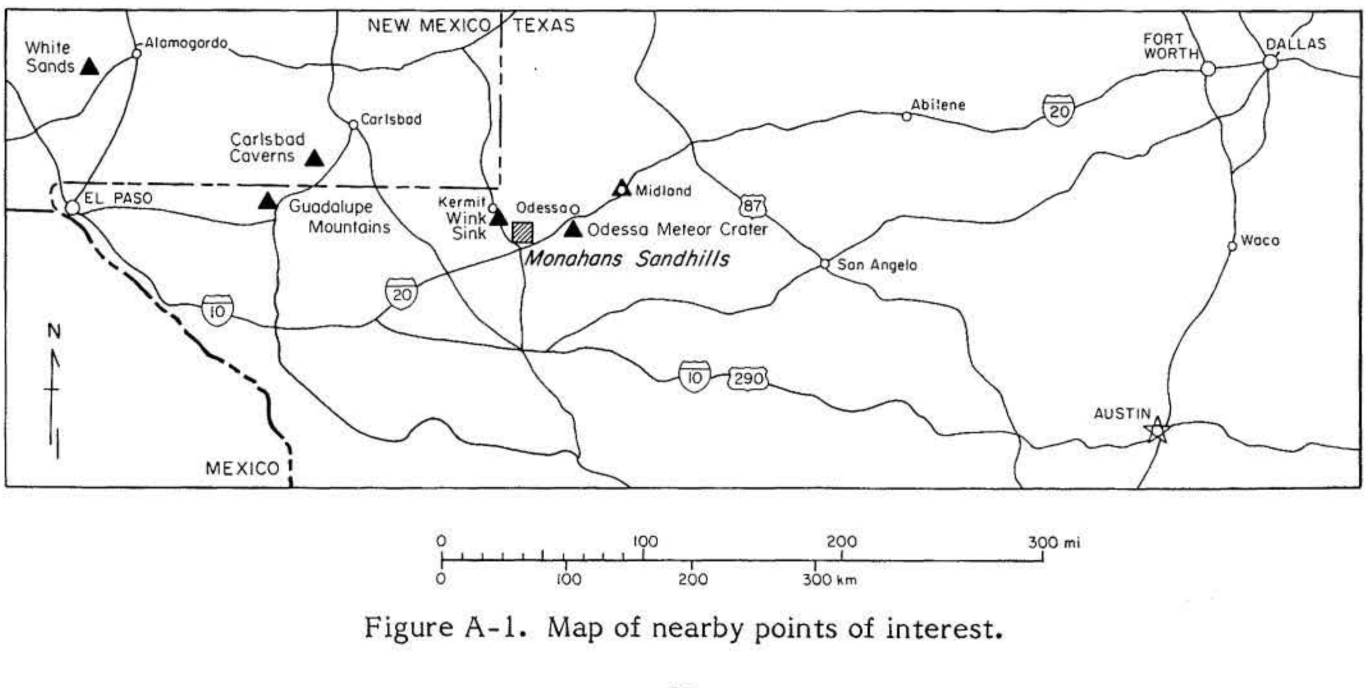

Figure A-1. Map of nearby points of interest.

APPENDIX B: Birds identified at Monahans Sandhills State Park

The bird species that have been spotted in the park and their relative abundance throughout the year are presented in the following list (Williams, 1981).

LEGEND

Sp	-	March-May	A	-	Abundant
S	-	June-August	C	-	Common
F	-	September-November	F	-	Fairly common
W	-	December-February	U	-	Uncommon
			R	-	Rare

	Sp	S	F	W
Turkey Vulture	U	U	U	
Sharp-shinned Hawk				U
Red-tailed Hawk				F
Swainson's Hawk	U	U	U	
Ferruginous Hawk				F
Harris' Hawk	C	C	C	C
Marsh Hawk	U		U	F
Prairie Falcon				U
American Kestrel	A		A	A
Scaled Quail	A	A	A	A
Sandhill Crane				U
Killdeer	C	C	C	C
Mourning Dove	A	A	A	A
Yellow-billed Cuckoo		U		
Roadrunner	F	F	F	F
Great Horned Owl	F	F	F	F
Burrowing Owl	F	F	F	F
Poor-will	A	A	U	
Common Nighthawk	C	C	C	
Black-chinned Hummingbird	F	F	F	
Common Flicker			F	F
Ladder-backed Woodpecker	F	F	F	F

	Sp	S	F	W
Western Kingbird	C	C		
Cassin's Kingbird	U		U	
Scissor-tailed Flycatcher	C	C	C	
Ash-throated Flycatcher	F	F		
Eastern Phoebe			R	
Say's Phoebe			A	A
Horned Lark				U
Barn Swallow	U		U	
Cliff Swallow	U		U	
White-necked Raven	F	F	F	U
Verdin	U	U	U	U
House Wren	U		U	
Bewick's Wren	U		U	U
Cactus Wren	A	A	A	A
Mockingbird	A	A	A	A
Brown Thrasher	U		U	
Crissal Thrasher				R
Sage Thrasher				U
Hermit Thrush	U		U	
Mountain Bluebird				U
Ruby-crowned Kinglet	F		F	U

	Sp	S	F	W
Water Pipit			U	U
Loggerhead Shrike	A	C	A	A
Solitary Vireo	U		U	
Orange-crowned Warbler	U		U	
Yellow Warbler	F		F	
Yellow-rumped Warbler	F		F	U
MacGillivray's Warbler	U		U	
Wilson's Warbler	F		F	
House Sparrow	A	A	A	A
Western Meadowlark	F	F	F	A
Yellow-headed Blackbird	F	F		
Red-winged Blackbird	C	C	C	C
Scott's Oriole			R	
Northern Oriole	C	C	U	
Brewer's Blackbird	U		A	A
Great-tailed Grackle	U	U	U	
Brown-headed Cowbird	C	C	C	C
Western Tanager	U		U	
Pyrrhuloxia	A	A	A	A
Black-headed Grosbeak	U		U	
Blue Grosbeak	A	A	U	
Painted Bunting	U		U	
House Finch	A	A	A	A
Pine Siskin	U		U	U
American Goldfinch			U	F
Lesser Goldfinch	C	C	A	C
Green-tailed Towhee	U		U	
Rufous-sided Towhee	U		U	U
Lark Bunting	C		C	C
Vesper Sparrow	F		F	F
Black-throated Sparrow	C	C	C	C
Dark-eyed Junco	U		U	U
Gray-headed Junco				R
Chipping Sparrow	C		C	C
Clay-colored Sparrow	F		F	
Field Sparrow	U		U	U
White-crowned Sparrow	C		C	C
Lincoln's Sparrow	U		U	
Song Sparrow	U		U	

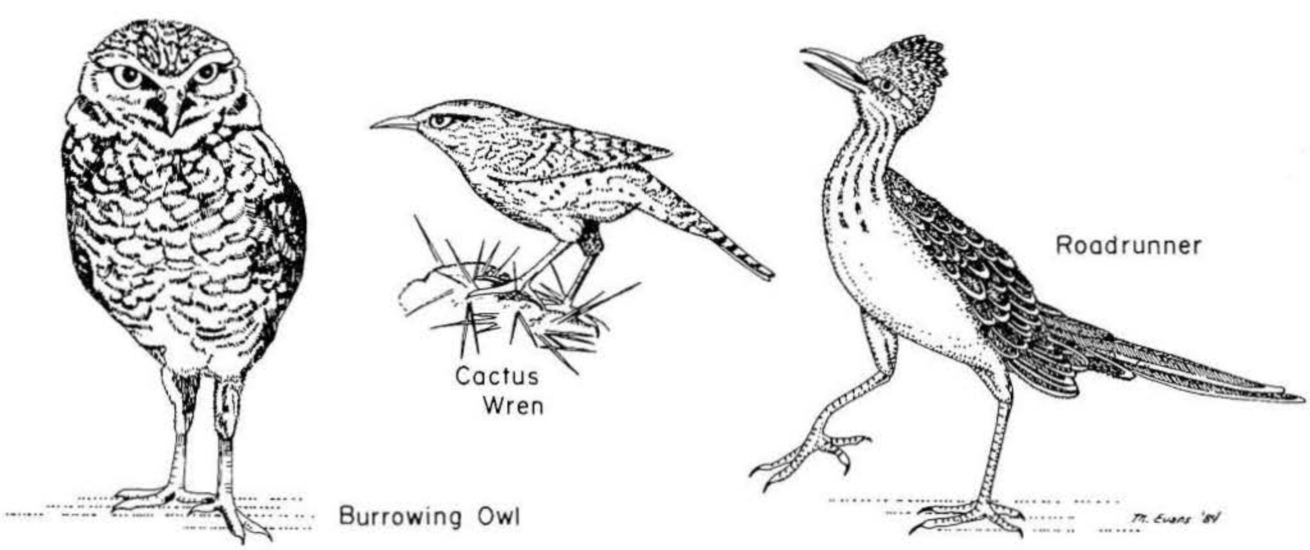

Figure B-1. Some resident bird species seen at Monahans Sandhills.

APPENDIX C: Suggestions for Further Reading

In addition to the publications cited in the references, the following books and articles are useful for more detailed information on sand dunes, plant life, and the early history of the area.

<u>Sand Dunes</u>

Atkinson, R., 1981, White Sands: wind, sand and time: Globe, Arizona, Southwest Parks and Monuments Association, Popular Series No. 21, 44 p.

An easy-to-understand account of the gypsum dunes of White Sands National Monument near Alamogordo, New Mexico. This brochure traces the geologic history of the monument, its plant and animal life, and its early human inhabitants.

Bagnold, R. A., 1941, The physics of blown sand and desert dunes: London, Methuen, 265 p.

A highly technical text that deals with the most basic principles of sand transport and dune formation. Still considered a scientific classic.

Melton, F. A., 1940, A tentative classification of sand dunes; its application to dune history in the Southern High Plains: Journal of Geology, v. 48, no. 2, p. 113-174.

This article describes the conditions of sand supply and vegetation necessary to produce various dune types. Melton cites the Monahans Sandhills for several examples of dunes.

McKee, E. D., and Douglass, J. R., 1971, Growth and movement of dunes at White Sands National Monument, New Mexico: U.S. Geological Survey Professional Paper 750-D, p. D108-D114.

McKee, E. D., and Moiola, R. J., 1975, Geometry and growth of the White Sands dunefield, New Mexico: U.S. Geological Survey Journal of Research, v. 3, no. 1, p. 59-66.

These two papers emphasize the relationship between preserved sedimentary structures within the gypsum dunes and their migration through time.

<u>Plant Life</u>

Carrell, C. L., 1971, A vegetative analysis of the Monahans Sandhills State Park, Texas: Alpine, Texas, Sul Ross State University, Master's thesis, 68 p.

The plant species in the park are identified and classified in this thesis.

Warnock, B. H., 1974, Wildflowers of the Guadalupe Mountains and sand dune country: Alpine, Texas, Sul Ross State University, 155 p.

A useful field guide to the numerous flowering plants that grow in the sandhills. Excellent color photographs are included for easy plant identification.

Early History

Monahan's Well: Monahans Chamber of Commerce, published semi-annually, 8 p.

This local historical newsletter recounts several tales of early Monahans settlers.

Texas Permian Historical Society, 1978, Water, oil, sand, and sky: a history of Ward County, Texas: Monahans Junior Chamber of Commerce, 483 p.

A detailed compilation of all aspects of Ward County's development, from before its official founding to the late 1970's.

Wedel, W. R., 1961, Prehistoric man on the Great Plains: Norman, Oklahoma, University of Oklahoma Press, 355 p.

Wedel's book is a readable account of early Indian lifestyles as inferred from artifacts and archeological sites.