GEOLOGY OF THE QUATERNARY DUNE SANDS IN EASTERN MAJOR AND SOUTHERN ALFALFA COUNTIES, OKLAHOMA

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INTRODUCTION

Purpose of Investigation

While it has long been recognized that extensive stabilized dune fields border most of the major streams in north central and western Oklahoma, these areas have received very little geologic investigation. This study was focused on one small area of dunes in order to describe their morphology, and to explain their origin and history. To accomplish these objectives, studies on dune morphology, sedimentology, soil development, and paleowinds were conducted.

Study Area

Location and Physiography

The area chosen for study is approximately the southern third of Alfalfa County and the eastern half of Major County in north central Oklahoma (Figure 1). This area was chosen after a regional survey revealed that the dune fields are readily apparent on topographic maps and had been mapped by the United States Soil Conservation Service. The soils mapping was important in that the dune soils were divided

Figure 1. Location of Study Area. (Base map modified from a version published by University of Oklahoma Press, 1980.)

into five different series, none of which contain any significant areas of non-aeolian soil. Thus, it was possible to identify dune fields solely from soil-survey maps. This was not the case in other counties, where soils that developed within dune fields commonly were also mapped on eroded or scarped alluvial terrace deposits.

As defined above, the study area contains 640 sq. mi., in approximately 450 of which dunes are present. By far, the most extensive development of dunes is along the Cimarron River, extending 5 to 17 mi. north from the modern course of the river, and for approximately 30 mi. along the river. The dunes extend along the river eastward and westward from the study area. Another much smaller area of dunes is in a roughly circular area between Deep Creek and the Cimarron River (Plate 1).

Accessibility

Access to the study area is provided by the state highway network. Highway 60 traverses the northern portion of the dune area and passes through the town of Fairview (Plate 1) where motel accommodations are available. Highway 51 is just to the south of the study area and passes through duned areas which are continuous with those studied. Highways 8 and 58 also pass through the study area, mainly in a north/south direction (Plate 1).

Off the hard surface highways, access generally is provided by graded section-line roads. In many areas, these roads are covered with deep, loose sand and are difficult to travel in standard passenger cars. Within sections, there are many oil-field lease roads that can be used with landowners' permission. In some of the most rugged dune terrain, these lease roads offer the only vehicular access, because section line roads have not been established.

Modern Climate

As reported in the Soil Surveys of Major and Alfalfa Counties, Oklahoma (Soil Conservation Service, 1968, 1975), the modern climate of the study area is characterized by variation that occurs gradually from season to season, but can also occur very rapidly within seasons. Basically, the area has a temperate, subhumid, continental climate that is interrupted by periods of storminess as warm, humid air masses from the Gulf of Mexico collide with cool, dry air masses from the north. At times air masses of Pacific origin also affect the area. In Spring and Fall, the weather is the most variable. Storm fronts sweep the area from the north or west bringing rains and gusty winds. Usually, the storm fronts are preceded by very strong southwesterly winds, commonly having gusts in excess of 40 mph.

Climatic records within the study area have been made at Fairview, the county seat of Major County (Plate 1). Records from 1932 to 1962 yield an average annual temperature of 61.6 deg. F. The coldest month is January, which has an average temperature of 38.2 deg. F. and the hottest month is July, when the average temperature is 83.5 deg. August has the highest average daily high temperature at 96.5 deg. January has the lowest average daily low temperature, 26.1 deg. In June and July average daily high temperatures are 92.4 and 96.2 deg. The hottest temperature recorded during the period of record is 113 deg. and the coldest is -7 deg.

Average annual precipitation is 27.99 in., two-thirds of which falls during the Spring and early Summer months. A lesser peak of precipitation occurs in the Fall. The driest year during the period of record was 1956 with 11.67 in. of precipitation. The wettest year was 1957, with precipitation totaling 49.22 in. May is the wettest month and January the driest.

The prevailing wind direction is southerly, ranging from southwesterly to southeasterly. During midwinter, north to northwesterly winds predominate. Annually, the average hourly wind speed is about 13 mph, but during March and April the average wind speed increases to about 15 mph (Soil Conservation Service, 1968).

Soils

Soil Classification. Soils in Oklahoma are currently classified using the United States Comprehensive Soil Classification System which has been operative in Oklahoma since 1965. The system defines soil classes based on observable or measurable physical properties, but does not include genesis. In the comprehensive system, soil classes are defined by diagnostic horizons. The presence or absence of specific horizons is used as a differentiating characteristic. Soil taxonomy precisely defines the diagnostic horizons of mineral and organic soils, as well as other layers or horizons and macrofeatures. Properties used for differentiation of soil classes include; depth, color, texture, structure, and other significant features of each horizon. Significant features may include; cation exchange capacity, extractable bases and hydrogen content, total phosphorus and carbonate, pH, percent organic matter, and particle size distributions. (Soil Conservation Service, 1968, 1975; Gray and Roozitalab, 1976).

The comprehensive system has six categories: order, suborder, great group, subgroup, family, and series. Ten orders are recognized: Entisols, Vertisols, Inceptisols, Aridisols, Mollisols, Alfisols, Ultisols, Spodosols, Oxisols, and Histosols. The first seven orders occur in Oklahoma, with Alfisols and Entisols found on dunes of the study area. Properties used to differentiate the soil orders are those that tend to give broad climatic groupings, except that Entisols and Histosols occur in many climates (Soil Conservation Service, 1968, 1975; Gray and Roozitalab, 1976).

Soil orders are each divided into suborders that are differentiated on the basis of the presence or absence of waterlogging or soil differences resulting from vegetation or climate.

Within suborders, great groups are defined by uniformity in the kinds and sequence of major horizons. Major horizons are those that have accumulated clay, iron, or humus, or that have a pan that interferes with root growth or water movement.

Subgroups consist of one central (typic) segment of a great group and intergrades. Intergrades are those soils that have properties of one great group and one or more properties of another great group.

Soil families are established within subgroups on the basis of engineering properties and properties that affect plant growth. These properties include; texture, mineralogy, temperature, reaction, permeability, horizon thickness, and consistence.

A soil series is a group of soils that have soil profiles almost alike. A soil profile is a sequence of natural layers (horizons) in a soil and extends from the ground surface to the underlying parent material. Except for the texture of the surface horizon, a soil series will have major horizons that are similar in thickness, arrangement, and other important characteristics. Each soil series is named for a town or other notable geographic feature which is located near the area where a series was first described and mapped. The classification of dune soil series in the study area is given in Table I.

As reported by Gray and Roozitalab (1976), Alfisols occur in climates having periods when evapotranspiration exceeds precipitation. Water movement through the soil has

TABLE I

CLASSIFICATION OF DUNED
SOIL SERIES

Series	Family	Subgroup	Order
Aline	sandy, mixed, thermic	Psammentic Paleustalf	Alfisol
Nobscot	loamy, mixed, thermic	Arenic Haplustalf	Alfisol
Pratt	sandy, mixed, thermic	Psammentic Haplustalf	Alfisol
Tivoli	mixed, thermic	Typic Ustipsamment	Entisol

been adequate to remove free carbonates from the upper horizons, but has not removed most of the exchangeable bases. Alfisols may have fragipans, natric and petrocalcic horizons, plinthite, or other diagnostic features.

One suborder, the Ustalfs, contains dune soils. The subgroup of Paleustalfs are thick soils formed on uplands. They may have a calcic horizon associated with the argillic horizon, but never have natric horizons or duripans within three feet of the surface. The subgroup of Haplustalfs are developed on recent erosional surfaces or on deposits that have a thin argillic horizon with a gradual boundary. They have no duripans or natric and petrocalcic horizons within five feet of the surface.

Entisols are usually found in floodplains or on dunes. They show little evidence of soil development. Their A horizons have only limited accumulation of organic material and are directly above the C horizon. Often, these are young soils which have not existed long enough for clay eluviation to have formed other horizons.

The youngest dune soils are in one suborder, the Psamments. The soil texture is uniformly sand or coarse loamy sand. Psamments occur under any vegetation and in any climate. In Oklahoma, Psamments have only one great group, the Ustipsamments.

Often soils of one series will differ in the texture of the surface layer, the amount of stoniness, possible use, or the steepness of slopes. When such differences exist the soil series may be divided into phases. Commonly, soil series found in duned areas are divided into phases based on steepness of slopes on which the soil evolved (Soil Conservation Service, 1968, 1975).

Soil Series. The duned areas of Major and Alfalfa Counties have been mapped by personnel of the Soil Conservation Service. Soils formed in the dunes are classified into five different series, based on each soil's degree of maturity and on mechanical analysis. The following discussion is paraphrased from work of the Soil Conservation Service (1968, 1975), and includes observations made during this study. Each dune soil series is described generally, starting with the least mature soil as judged by evaluation of a soil's horizon development, including organic content, clay enrichment or depletion, and depth of alteration. A detailed soil-profile description (Soil Conservation Service, 1968, 1975) of each dune-soil series is given in Appendix A.

Sand Dunes, Lincoln Material. Although not considered a soil series by the Soil Conservation Service (1968), this material is mapped using the symbol Ss (Plate 1) and will be referred to as a soil in this study. The soil borders the Cimarron River on the modern floodplain (Figures 2, 3, 4, 5). The surface layer consists of light-brown fine to medium grained sand about 4 in. thick. It is underlain by loose, reddish yellow, calcareous, fine to medium grained sand that extends to the bottom of the dune.

Tivoli. The Tivoli soil series is mapped using the symbol TrD (Plate 1). It is located in belts as wide as 1 mi. that parallel the river. Generally, the Tivoli is on higher parts of the floodplain away from the river, or on the lowest terrace of each reach of the river (Figures 2, 3, 4, 5, 6).

This weakly developed soil formed in lime-free, fine to medium grained sand. The surface layer, as thick as 12 in., is yellowish to dark grayish brown noncalcareous sand. Beneath this surface layer and to the bottom of the deposit, the sands are reddish to brownish yellow and generally noncalcareous.

Pratt. Pratt soils have a complex relationship to other dune soils. Three mapping units (phases) are used by the Soil Conservation Service (1968, 1975) depending on the

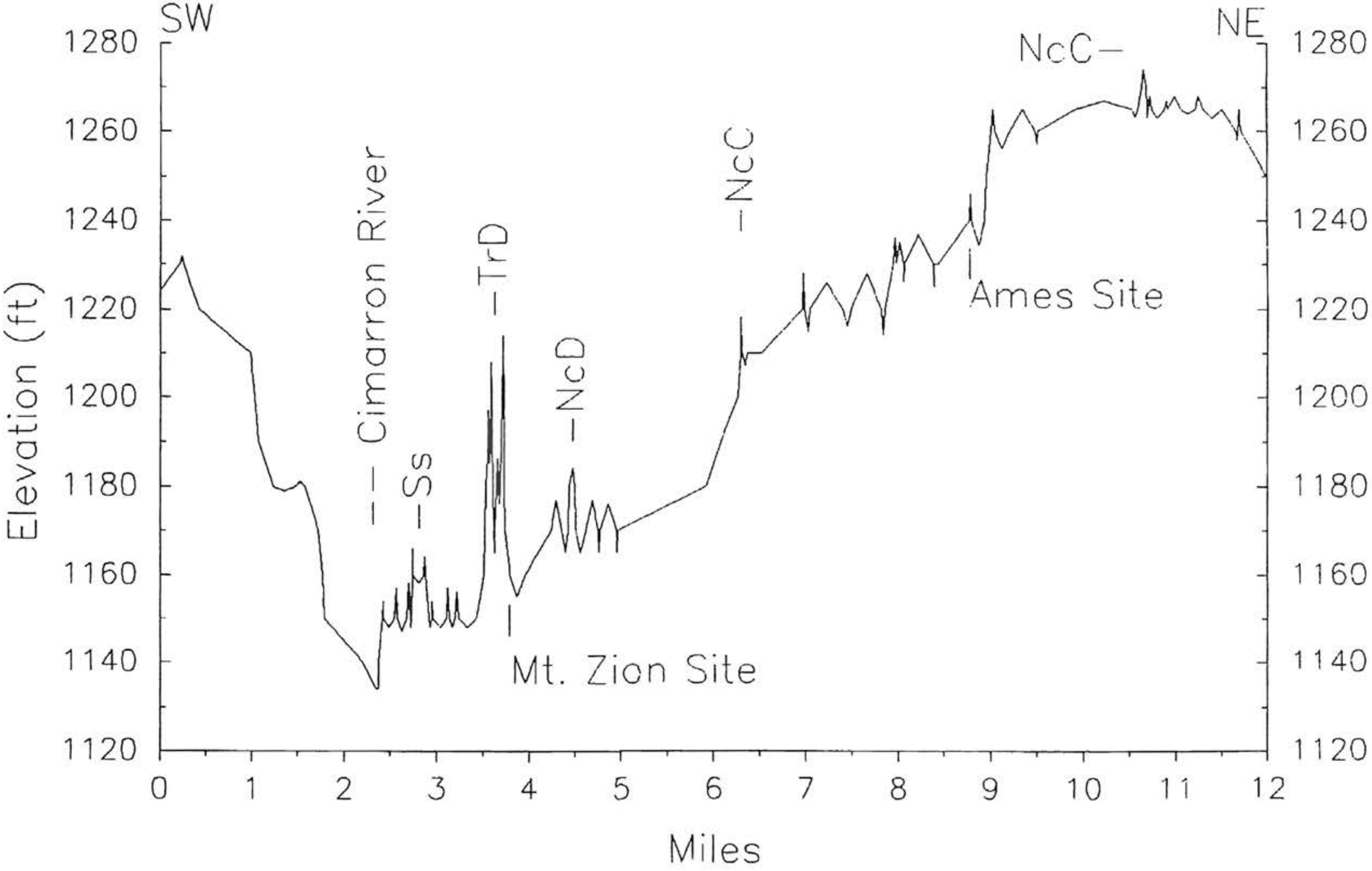

Figure 2. Mt. Zion Topographic Profile. Soils shown are Recent (Ss), Tivoli (TrD), and Nobscot (NcD, NcC). (Line of section on Plate 1)

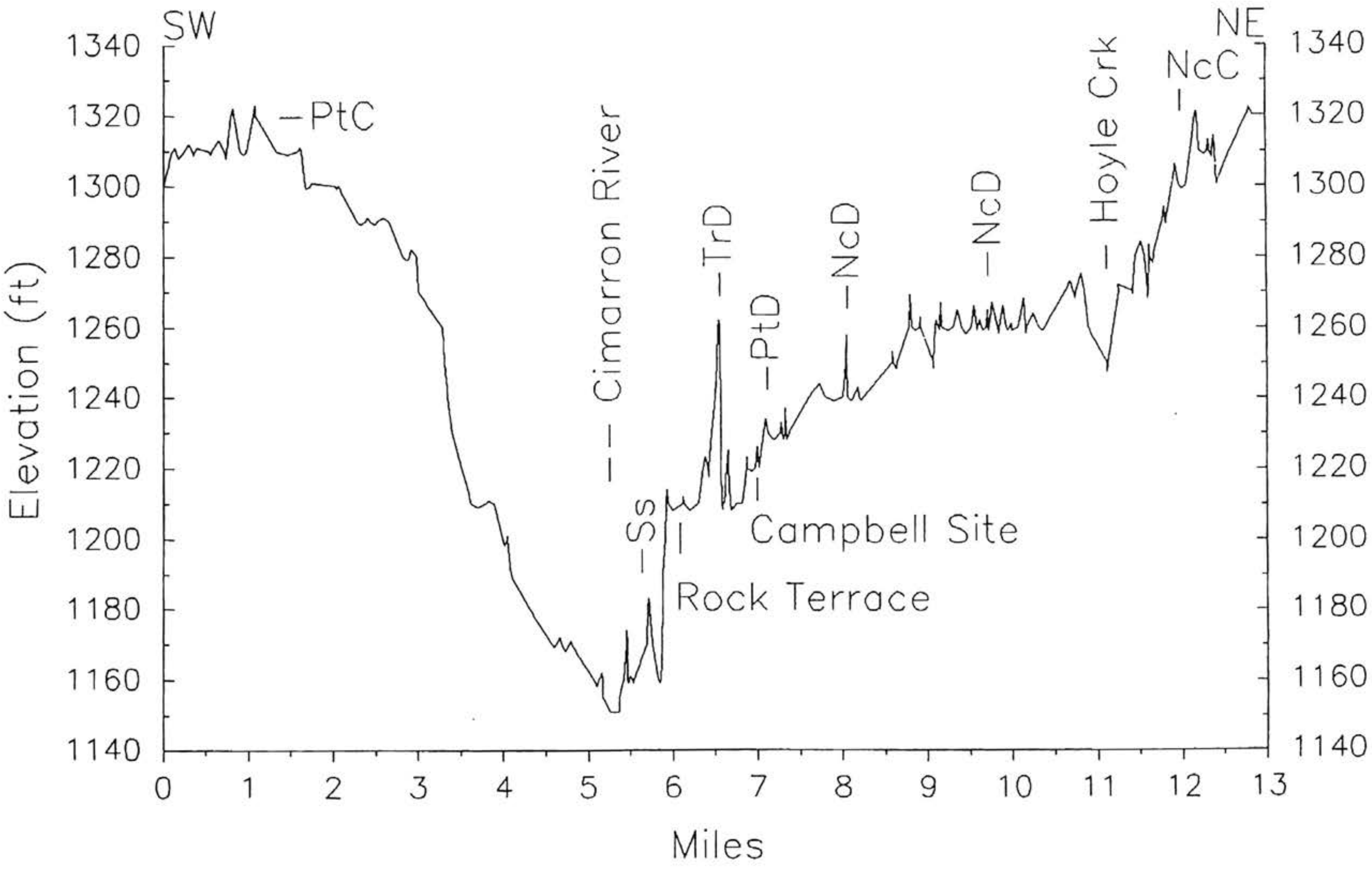

Figure 3. Campbell Topographic Profile. Soils shown are Recent (Ss), Tivoli (TrD), Pratt (PtD, PtC), and Nobscot (NcD, NcC). (Line of section on Plate 1)

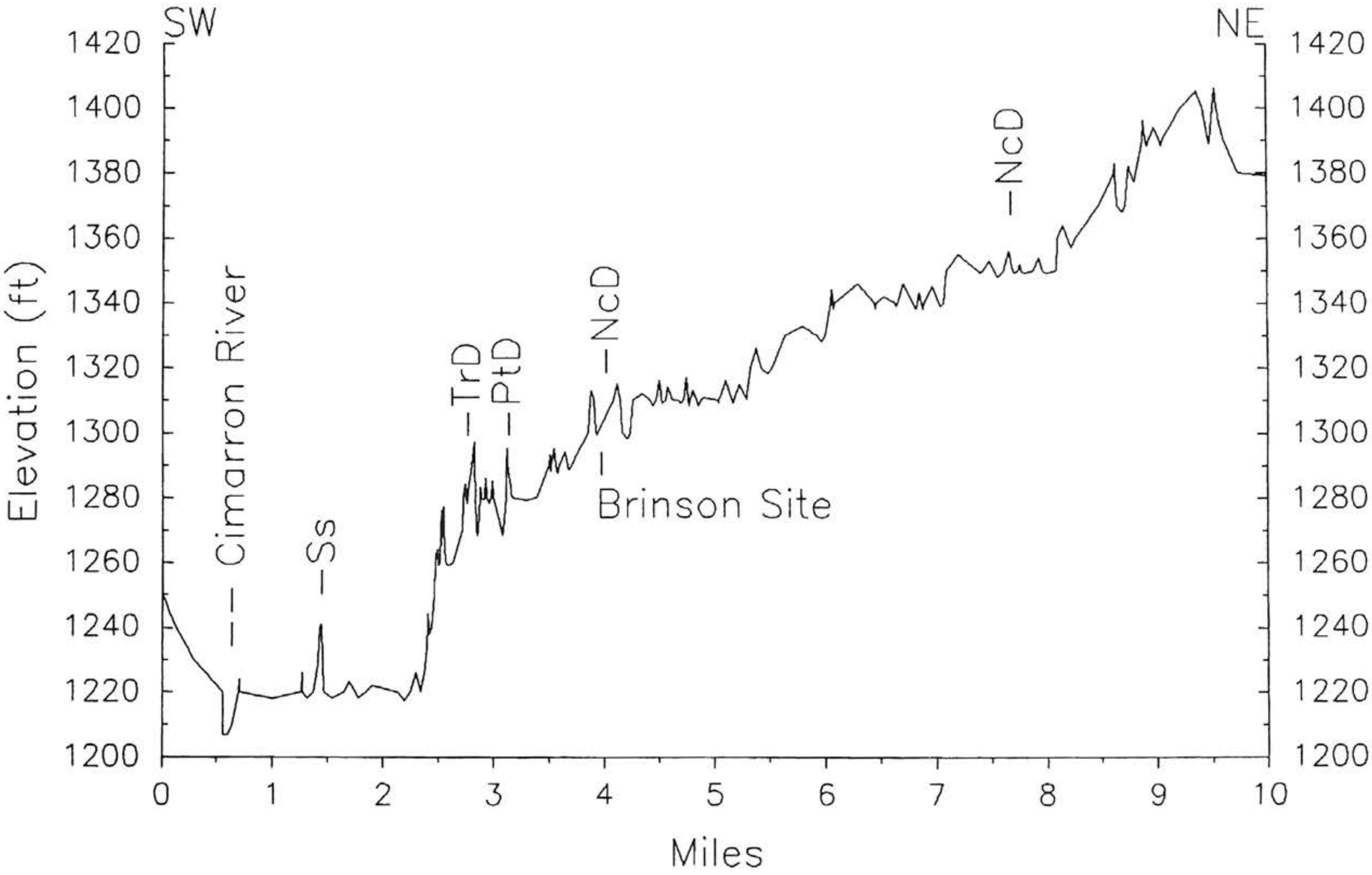

Figure 4. Brinson Topographic Profile. Soils shown are Recent (Ss), Tivoli (TrD), Pratt (PtD), and Nobscot (NcD). (Line of section on Plate 1)

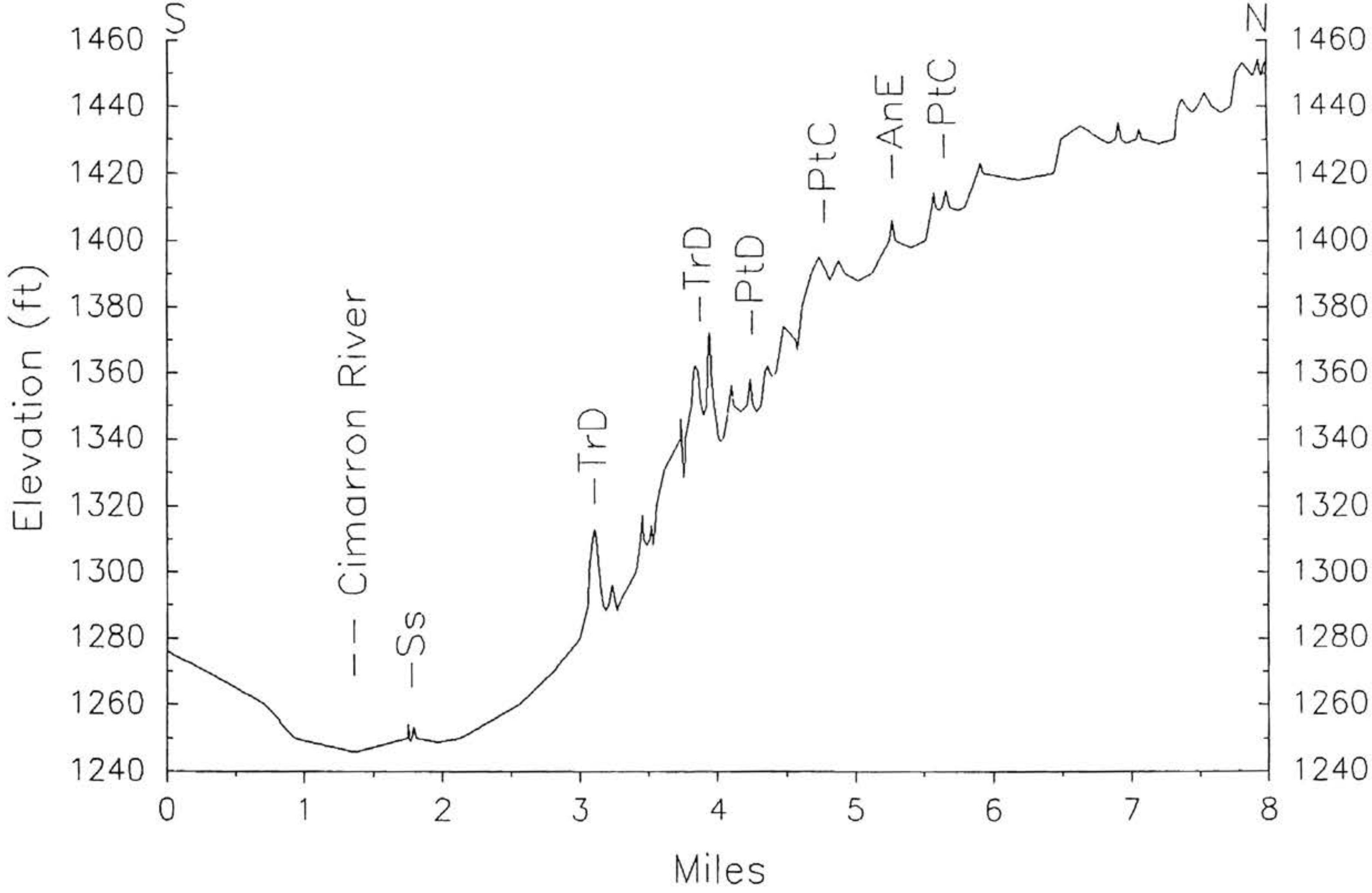

Figure 4. West County Line Topographic Profile. Soils shown are Recent (Ss), Tivoli (TrD), Pratt (PtD, PtC), and Aline (AnE). (Line of section on Plate 1.)

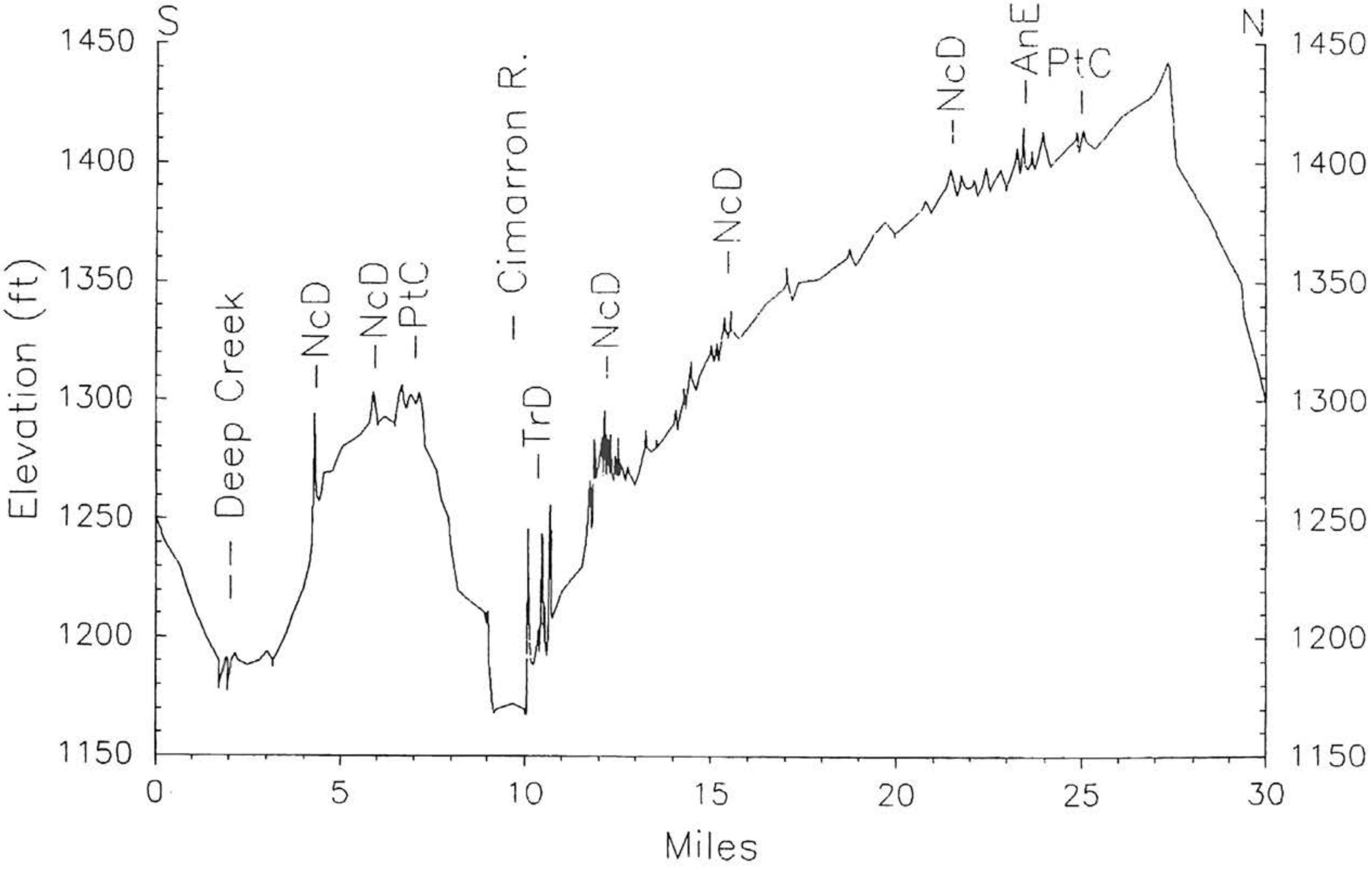

Figure 6. Master Topographic Profile. Soils shown are Tivoli (TrD), Nobscot (NcD), Pratt (PtC), and Aline (AnE). (Line of section on Plate 1)

amount of slope. PtB soils developed on slopes of less than 3 percent, PtC soils on slopes of 3 to 5 percent, and PtD soils developed on slopes greater than 5 percent. PtB soils were mapped with PtC in this study.

All Pratt soils were formed in loamy fine to medium grained sand. The surface horizon is 6 to 14 in. thick and is brown to dark brown. The B horizon, about 20 in. thick, ranges from light yellowish brown to dark brown. In some high terrace localities, a few thin, discontinuous clay- and iron-enriched bands (often referred to as lamellae) are present. The C horizon, which extend to the bottom of the deposit, is reddish yellow in color.

Pratt soils generally occupy low topographic positions relative to adjacent dune soils. Commonly, they are within and between areas of Tivoli and Nobscot soils, and are expressed as low undulating (PtB), hummocky (PtC), or low duned (PtD) relief. These areas of Pratt soils may be interpreted as having been developed in interdune areas between the higher Tivoli and Nobscot dunes. Some Pratt soils may have catena-relationships with other dune soils, implied by their positions on the lower slopes of the larger dunes. Another interpretation of the topographically high/low relationship could be that some Pratt soils represent a surface over which younger dunes migrated.

In contrast, some areas of Pratt soils are beyond the Nobscot soils on the highest terraces, where they extend to the drainage divide between the Cimarron and Salt Fork

Rivers (Plate 1; Figures 5, 6). These low-relief areas generally are composed of blowout and parabolic dunes. Similar small areas of Pratt soils are found between Deep Creek and the Cimarron River (Soil Conservation Service, 1968; Figure 6).

Commonly, areas of Pratt (PtD) soils are developed on dunes having somewhat sharper relief than dunes with Nobscot (NcD) soils, but less than dunes with Tivoli soils. These dunes generally occupy a position between Tivoli and Nobscot soils (Plate 1; Figures 3, 4).

Nobscot. Like the Pratt soils, phases of the Nobscot soils are mapped using symbols referenced to the degree of slope on which the soils are developed. NcC soils (Plate 1) are developed on hummocky terrain with 3 to 5 percent slopes. NcD soils (Plate 1) are found on rolling dunes having 5 to 8 percent slopes.

Several very small areas were mapped by the Soil Conservation Service (1968) as Nobscot-Pratt Complex using the map symbols NpC and NpD. The pattern of the Pratt and Nobscot soils was considered by the Soil Conservation Service as too complex to permit the mapping of them separately. In these areas, Nobscot soils are on the higher duned areas and Pratt soils are on the lower slopes and interdune areas. Owing to their small areal extent, the NpC and NpD map units were not judged as extensive enough to be important in the study area and were included as NcD on Plate 1. However, the NpC and NpD soil mapping units are much more extensive in western Major County (Soil Conservation Service, 1968).

The Nobscot surface layer ranges from 4 to 10 in. thick of dark grayish brown fine grained sand. A leached A2 (E) horizon 5 to 14 in. thick consists of very pale brown fine grained sand. The B horizon, about 40 in. thick, is yellowish red loamy fine grained sand with numerous thin (1/8 to 1/2 in.) lamellae spaced 1 to 8 in. apart. The C horizon consists of reddish yellow loamy fine to medium grained sand. A few lamellae may be in the upper part of the C horizon.

Nobscot soils are farther from the river than Tivoli soils. The NcD phase is found no lower than the second terrace above the river. Near the center of the study area, Nobscot soils blanket one or more higher terraces and grade into discontinuous dunes that cross successively higher terraces. In some places they extend to a drainage divide (Plate 1; Figures 2, 3, 4, 6). In the southeastern part of the study area, the NcD phase grades into the NcC which continues on scattered dunes upward to a divide (Plate 1; Figures 2, 3). Small areas of Nobscot soil are between Deep Creek and the Cimarron River (Plate 1; Figure 6).

Aline. Within the study area, Aline soils have been mapped by the Soil Conservation Service (1975) only in Alfalfa County. The map symbol used is AnE. Where this soil series overlaps the boundary between Major and Alfalfa Counties, the unit is mapped in Major county as Pratt (PtD) (Soil Conservation Service, 1968).

The surface layer of Aline soil consists of brown fine grained sand, as thick as 8 inches. An A21 subsurface layer is light brown fine grained sand about 26 in. thick. Beneath the A21 horizon, an A22 and B2t horizon is defined. The A22 is about 40 in. thick, consists of light brown fine grained sand, and contains lamellae that are the B2t horizon. The lamellae are 1/4 to 3 in. thick, and are 1/2 to 5 in. apart. Material in the lamellae is reddish yellow sandy clay loam to loamy fine sand with clay coatings and clay bridges. The C horizon was not described by the Soil Conservation Service (1975), and was not observed during this study.

Considering the extent of lamellae development and the topographic position (Figures 5, 6), within the study area Aline soil probably is stratigraphically equivalent to Nobscot (NcC) soil. Also, where similar lamellae were observed in Pratt (PtD) soil on the high terraces, it too may be equivalent to the Aline.

At some localities, dunes are in areas mapped as soils of the floodplain or alluvial terrace. These occurrences were considered to be of areal extent insufficient to warrant mapping (Soil Conservation Service, 1968, 1975).

Vegetation

Vegetation on the dunes is controlled by the soil development and the extent of grazing. Plants that become dominant under heavy grazing conditions may be considered to have been the colonizers (to some extent) during stabilization of active dunes. The following discussion is a compilation from the previously cited Soil Conservation Service publications, and the author's observations. Each dune-soil series is considered in order of maturity.

The most modern sand dunes, Ss (Plate 1), have only recently been stabilized. The principal grasses on these dunes are little bluestem, sand bluestem, sideoats gramma, sand paspalum, sand dropseed, sand bur, and blue gramma. The most common bushy plants are sand plum, sand sagebrush, and skunkbush. Yucca and prickly pear cactus are also common.

Tivoli soils are on dunes that are only slightly older. Where protected from overgrazing, this soil supports the following mixture of grasses: 30 percent little bluestem, 20 percent sand bluestem, 10 percent big sandreed and Illinois bundleflower, and 10 percent Texas bluegrass, with the remaining 30 percent being made up of big bluestem, sand dropseed, sand lovegrass, Scribner panicum, perennial lespedeza, and bigtop dalea. Sand paspalum, Texas bluegrass, Scribner panicum, bigtop dalea, and sand dropseed increase with heavy grazing. Severe overgrazing results in the establishment of annual brome, sand bur, showy partridgepea, nightshade, and wild buckwheat. Common brushy plants include sand sagebrush, locust, skunkbush, sumac, wild grape, and wild plum. Yucca and prickly pear are common. Many interdune depressions contain cottonwood, elm, and cedar trees. North- and northeast-facing slipfaces of older dunes within this soil series commonly are timbered with blackjack oak, elm, hackberry, cedar, and plum.

Pratt soils, with their thicker A and clay enriched B horizons, are more mature than Tivoli soils. Pratt soils support excellent stands of grasses comprised of 30 percent little bluestem, 20 percent sand bluestem, and 10 percent indiangrass. The remaining 40 percent is made up of approximately equal amounts of Texas bluegrass, big bluestem, switchgrass, sand lovegrass, tall dropseed, Illinois bundleflower, queensdelight, and bigtop dalea. Where overgrazed, Texas bluegrass, tall dropseed, bigtop dalea, and queensdelight increase along with sand plum, skunkbush, and locust. Eventually, climax grasses can be replaced by sand bur, sand dropseed, red lovegrass, deervetch, wild buckwheat, camphorweed, blue gramma, many weeds, locust, coralberry, sagebrush, wild plum, sumac, and skunkbush. Pratt soils also are capable of supporting trees such as blackjack oak, elm, hackberry, cottonwood, and cedar. The trees are most common on shaded slipfaces and in interdune depressions, and are not as numerous as on Nobscot soils.

Although Aline soils are similar and are probably the stratigraphic equivalent of Nobscot (NcC) soils, they support a mixture of vegetation types that is almost identical to that of the Pratt soils. Aline soils probably differ from Nobscot (NcC) soil in that Aline developed beneath a grassland cover rather than blackjack oak timber.

With their leached A2 (E) horizon and lamellae development, Nobscot soils are the most mature dune soils in the study area. They are well suited as rangeland, supporting abundant stands of grasses where the dominant native oaks are controlled. The prevalent grasses are sand bluestem and little bluestem with lesser amounts of sand lovegrass, switchgrass, and purpletop. However, much of the extent of the Nobscot soils is covered by blackjack oak, elm, plum, skunkbush, soapberry, hackberry, sumac, and other woody plants. Heavy grazing allows sand paspalum, sand dropseed, sagebrush, and blue gramma to increase rapidly and also tends to allow the oaks to spread into grasslands.

Interdune depressions generally have a better developed soil profile, with thicker and more organically rich A horizons and a greater clay content throughout the profile, than the surrounding dunes (Soil Conservation Service, 1968, 1975). Therefore, the depressions support a plant community that differs from the dunes. The depressions have a shallow water table and many contain shallow seasonal ponds. Some of these ponds become dry only during the driest of years. Plants that are commonly found in the interdune depressions or around the ponds are smartweed, wild millet, spikerush, sedges, burreed, tearthumb, aneilema, and cattails. Water-loving trees such as willow and cottonwood are common.

Wildlife

As reported by the Soil Conservation Service (1968, 1975), the distribution and population of wildlife in the dune area is dependant on the relative mix of vegetation types and the supply of water. Three major habitats exist:

interdune wetlands, grassed dunes with thickets, and timbered dunes with some thickets and grassland.

Interdune ponds and marshes are home to most of the fauna that normally live in such areas in north central Oklahoma. Examples include many species of puddle ducks, geese, herons, rails, redwing blackbirds, and shore birds. The migratory birds are especially abundant during Spring and Fall migrations. However, small breeding populations are resident year-round. Wetland mammals are mink, muskrat, raccoon, and occasionally beaver along the few through-flowing streams.

Openland wildlife is abundant in the grassy and thicketed dune areas. This habitat is the best in the state for quail and wild turkey (Soil Conservation Service, 1975). Other commonly found birds are mourning doves, meadowlarks, field sparrows, crows, scissortail flycatchers, hawks, and various songbirds. Mammals include cottontail rabbits, jackrabbits, deer, foxes, coyotes, bobcats, skunks, and armadillos.

The timbered areas also support a varied population of wildlife including birds such as thrushes, woodpeckers, crows, bluejays, robins, vireos, woodcock, and also quail and wild turkey. Examples of woodland mammals are deer, squirrels, bobcats, and opossums.

Drainage

The primary drainage for the study area is the Cimarron

River and its tributaries. The river crosses the area from northwest to southeast (Plate 1), flowing with a gradient of about 4.4 ft. per mi. from an elevation of 1245 ft. to 1112 ft. (Figure 7).

There are four major tributary streams. Deep Creek is located in the southern part of the study area and enters the river from the southwest (Plate 1). It is intrenched in a wide valley (Figure 6) that may have been a past meander loop of the Cimarron River (Soil Conservation Service, 1968). Upstream, one finds Hoyle Creek, Indian Creek, and Eagle Chief Creek. All join the Cimarron from the north (Plate 1). Of these, Eagle Chief Creek is the largest with its valley width, gradient (Figure 7), and terrace development suggesting that it may flow in a valley originally occupied by the Salt Fork River at a time when Salt Fork was a tributary to the Cimarron (Fay, 1965). Generally, there are no channeled drainage networks extending from Hoyle or Indian Creeks. Their flow appears to be supplied almost entirely by ground water, because no drainage networks have yet developed in the duned areas.

Geology

The study area is directly underlain by Permian red beds, consisting of interbedded shales and sandstones. The strata dip gently to the southwest with resistant beds forming small buttes and east-facing escarpments in the extreme west and southwest part of the study area.

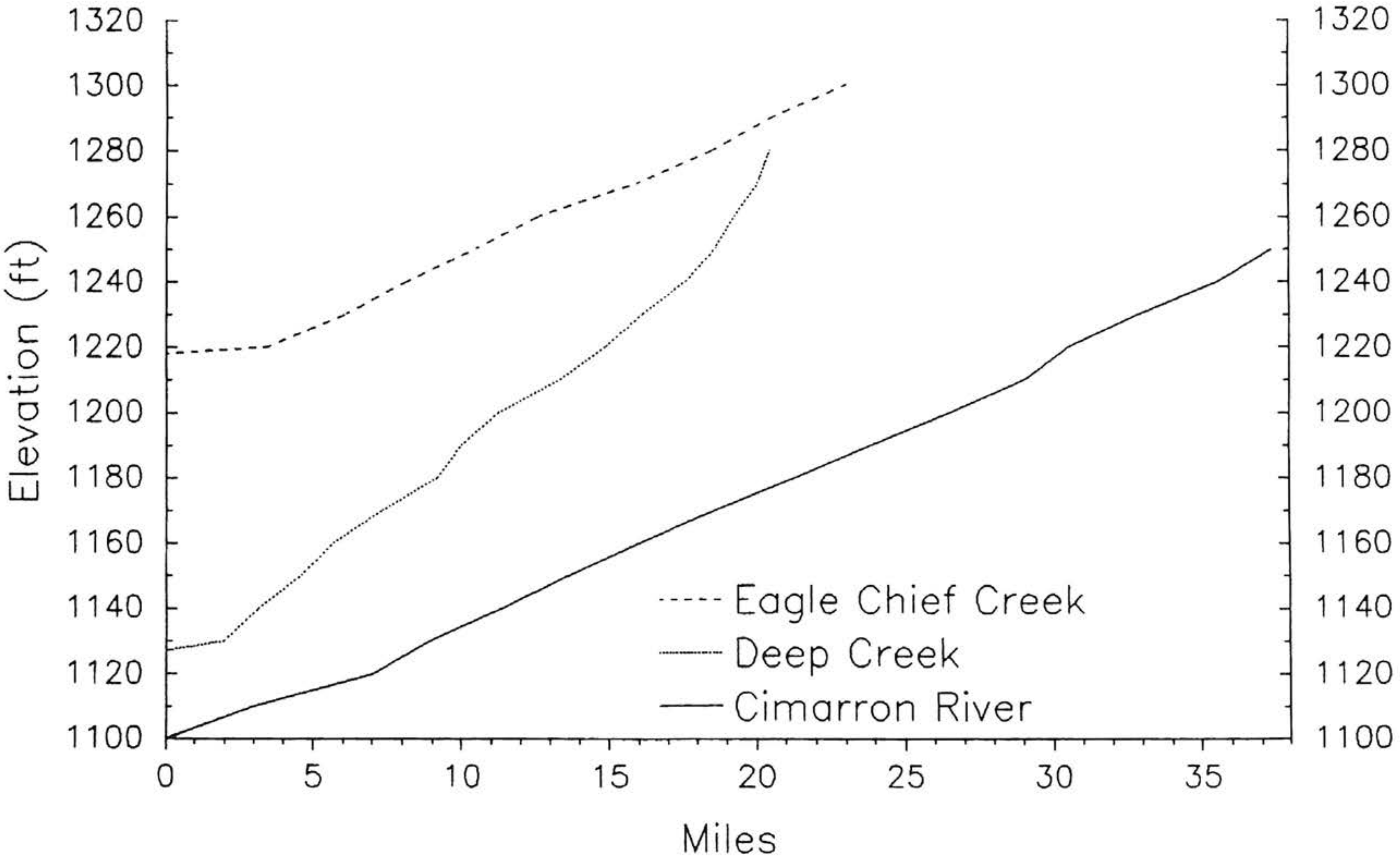

Figure 7. Gradients of Cimarron River, Deep Creek, and Eagle Chief Creek. (Cimarron River profile extends across entire study area; creek profiles begin at their mouths.)

Gypsum beds of the Blaine Formation cap the escarpments and buttes to the southwest. The Flowerpot Shale of the El Reno Group underlies the Blaine in the western and southwestern parts of the study area (Plate 1). The Cimarron River flows in a broad valley cut primarily in this formation. Underlying the Flowerpot Shale, the Cedar Hills Sandstone Member of the Hennessey Shale is locally exposed (Plate 1). The Cedar Hills consists of brownish red sandstone, and silty sandstone interbedded with silty shale and siltstone. It is approximately 130 ft. thick (Soil Conservation Service, 1968). In most of the study area, the Flowerpot and Cedar Hills are covered by soil, alluvium, or sand dunes. Generally, the rock units are exposed only on steep slopes or in severely eroded areas.

Quaternary geology of the area is recorded by floodplain and alluvial terrace deposits, sand dunes, and a small exposure of volcanic ash.

Floodplain deposits mainly are in a broad belt along the Cimarron River with lesser areas along the several major creeks. Noteworthy deposits are also found in the previously described valley drained by Deep Creek, and along Eagle Chief Creek.

Most of the alluvial terrace deposits are to the north of the Cimarron River, and are expressed as a series of "steps" in the topography (Figures 2, 3, 4, 5, 6). In one locality (SW corner, S21, T21N, R10W), a terrace (Rock Terrace site, Plate 1; Figures 3, 8) at about 50 ft. above

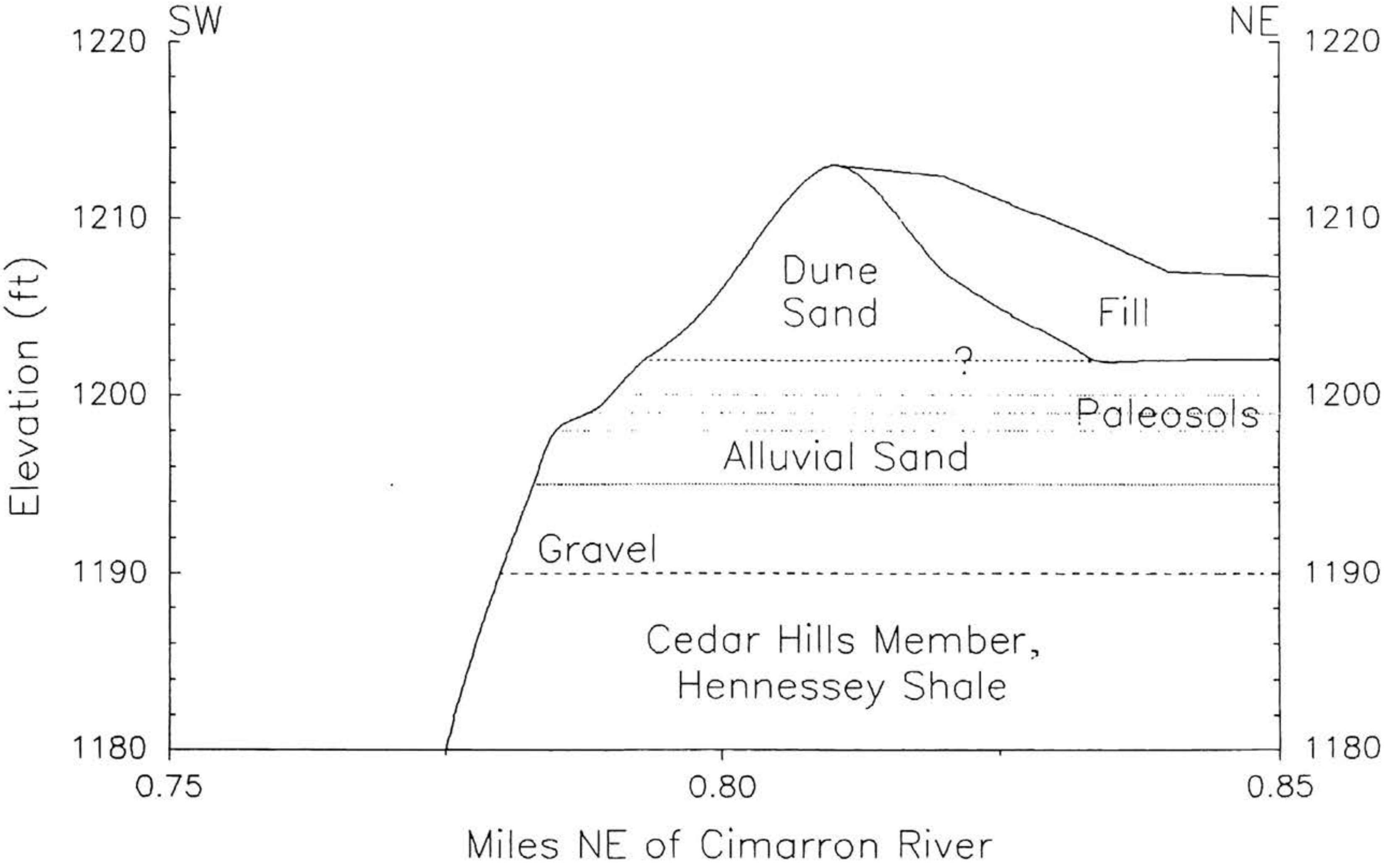

Figure 8. Rock Terrace Stratigraphic Profile. (Location on Plate 1)

the river is shown as a cut terrace in Cedar Hills sandstone and shale overlain by gravel, alluvial sand, and Tivoli dune sand. Within the alluvial terrace material, there are one conspicuously developed and two less well developed paleosols, as shown by the relative amount of organic darkening and thickness of each A horizon. A terrace sequence developed to the north of Deep Creek is similar to that north of the Cimarron River (Figure 6).

Dune sand is on the modern floodplain of the Cimarron River and is on all successively higher terrace levels. The sand thins and dune occurrence and height diminish with increasing distance from the river (Figures 2, 3, 4, 5, 6). In the Deep Creek and Eagle Chief Creek valleys, dune sand only overlies terrace deposits (Figure 6).

The volcanic ash deposit has been studied by Carter (1985) and Ward (1990). It is on an unmapped terrace remnant at an elevation of about 1200 ft. and is approximately 90 ft. above the Cimarron River. The location is just to the southwest of the mouth of Deep Creek (NW, SE, S28, T20N, R10W). The alluvial terrace deposit contains petrified wood and cobbles as large as 8 in. in diameter. Correlated as one of the Pearlette ash falls, the ash has been dated using fission-track methods to approximately 600,000 yrs. B.P. (Ward, 1990).

CHAPTER II

LITERATURE REVIEW

Many authors have contributed to a large body of work concerned with all topics related to sand dunes. Their work was of great help in the completion of this study. Many authors' contributions are noted in this chapter. Others, whose work may be of interest to the reader, but was of less importance to this thesis, have their works listed in the selected bibliography.

Local Investigations

The literature review has revealed no other work directly concerned with the dune fields of Major and Alfalfa Counties. However, several authors have documented the occurrence, form, or age of dunes in several nearby geographic areas.

Melton (1940) investigated the ages and paleowind directions of dunes developed on the High Plains of Texas, Oklahoma, Kansas, and New Mexico. His study included dunes developed in Woods County, Oklahoma which is adjacent on the west to Major county (Figure 1). Therefore, Melton's study included dunes that are partly continuous with those of Major and Alfalfa Counties.

Melton proposed a basic system of dune classification and documented several types of dunes on the High Plains. He specifically defined dunes like those along the Cimarron River in Major county as "source bordering lee dunes" (Melton, 1940, p. 122). Additionally, he described three sets of dunes, differing in morphology and paleowind directions, and estimated ages for each set. Melton's Series I dunes consist of active and anchored blowouts formed during the last 5,000 yrs. Wind directions are toward N. 10-70 deg. E., noting that in western Oklahoma some dunes indicate winds toward N. 10-40 deg W. Series II blowout and windrift dunes are 5,000 to 12,000 yrs. old and indicate paleowinds toward N. 40-70 deg. E. Series III blowout and windrift dunes are estimated to be more than 15,000 yrs. old and indicate uniform paleowinds toward S. 65-70 deg. E. Melton also discussed the possibility that even older dunes (Series IV) might be preserved in some areas.

Gould and Lonsdale (1926) included sand-dune areas in their work on the geology of Texas County, Oklahoma. They found stabilized dunes and some active dunes developed on the north side of the Cimarron River. The sand was reported to thin to the north, and was considered to all be of Quaternary age.

Smith (1938, 1940), Fent (1950), and Frye and Leonard (1952) described sand dunes in central and southwestern Kansas. These dunes mainly are south of the Cimarron and Arkansas Rivers. They were interpreted as three or four cycles of dunes. The cycles range from more modern distinct dunes to ancient subdued dunes with distinct soil profiles. Ages are estimated as being no earlier than late Wisconsinan to modern.

Regional Investigations

Nebraska

Smith (1965), Ahlbrandt and Fryberger (1980), and Ahlbrandt, Swinehart, and Maroney (1983) documented the structure and history of the Nebraska Sand Hills. Smith described three sequences of dunes: (a) transverse dunes that indicate north to northwesterly wind, and dated as early Wisconsinan, (b) longitudinal dunes that indicate westerly to northwesterly wind, and dated as late Wisconsinan, and (c) parabolic and barchan dunes that indicate north-northwesterly to northwesterly wind, and dated as post-Wisconsinan. Smith believed that most of the parabolic and barchan dunes formed during the arid Altithermal interval, approximately 8,500 to 4,000 yrs. B.P. (Antevs, 1955).

Ahlbrandt and Fryberger (1980), and Ahlbrandt and others, (1983) also described the structure of the Nebraska dunes, and found evidence of multiple episodes of dune-building. They differ from Smith on timing and morphology, documenting that longitudinal dunes described by Smith are transverse dunes, probably formed at the same time as the transverse dunes that Smith described.

Their interpretations call for four periods of dune activity. The first dates from the early Holocene and was followed by extensive but poorly documented activity occurring between 7,500 to 4,500 yrs. B.P., during the arid Altithermal. The best documented major arid interval is dated between 3,000 to 1,500 yrs. B.P. Arid intervals within the last few hundred years are also documented. Wind directions are indicated to have been northwesterly, except that the most modern dunes were constructed by southwesterly winds.

All three papers discuss soil structures that appear to be analogous to lamellae in some soils of the study area, and described in this paper. Ahlbrandt, and others (1983) interpreted these structures as having formed during the last 2,000 yrs.

Warren (1976) considered the morphology and sediments of the Nebraska dunes in relation to their wind regime. He concluded that northwesterly winds predominated, but that southwesterly winds were important during growth of very large dunes. Warren also noted that near-surface sand samples are enriched in silt and clay, and he describes and gives size analyses for subsoil lamellae.

Maroney and Swinehart (1978) documented the occurrence of mid-Holocene eolian activity in the Nebraska Sand Hills and the stabilization of the dunes by late Holocene. Several radiocarbon dates are given in support.

Three papers concerned with the Nebraska Sand Hills are contained in the United States Geological Survey Professional

Paper 1120. Two are important to this study. Ahlbrandt and Fryberger (1980), considered the history and structure of the dune field in detail. Main points are that the sand hills formed since late Wisconsinan, show evidence of multiple episodes of activity, indicate effective wind directions somewhat different from those of the present, and that the dunes contain lamellae. Bradbury (1980) used radiocarbon dates and pollen analysis to conclude that major Sand Hills dune deposition predates the Wisconsinan glacial maximum. He also stated that much of current Sand Hills topography may have formed during the Altithermal interval.

Madole (1981) studied the changes in soil development along a transect from the Nebraska dunes into Colorado. He found that soils are similar between these two regions, and that those soils also are similar to dune soils found along the Cimarron River in southwestern Kansas. He concluded that eolian activity has been almost simultaneous over large areas of the central Great Plains, during periods of prolonged regional drought.

From piston cores, Wright and others (1985) collected and dated pollen and organic samples from interdune lakes within the Sand Hills. Dates from basal sediments fall in the range of 9,000 to 12,000 years B.P., prairie vegetation is suggested by pollen analysis, and no sand was recovered from cores, suggesting that the dunes have not migrated or experienced major modification during the last 9,000 years.

Colorado and Wyoming

Ahlbrandt (1973) gave a complete description and history of the Killpecker dune field of southwestern Wyoming. He was particularly concerned with the source of the dune sand, sand textural parameters, and the geologic history. He used radiocarbon dates, archaeological evidence, and relative stratigraphy to conclude that the dunes formed in the last 20,000 yrs., were very active during glacial interstades, and were less active during stades.

Gaylord (1982) discussed the Ferris dune field of south-central Wyoming. He documented structure and morphology of the dunes, noting a preponderance of low-angle, planar cross stratification. He used radiocarbon dates and estimates of dune migration rates to interpret history of dune activity from the late Pleistocene through the Altithermal interval. Dunes have stabilized increasingly since the Altithermal.

Muhs (1985) sampled dune soils along a 325-km transect from Nebraska into Colorado. He found that similarity exists between surface dune soils along the transect, that in some areas paleosols developed on dune sand are buried by more recent dunes, and that most of the dunes are parabolic, indicating a paleowind blowing from north 30-40 deg. west. Muhs observed no subsoil lamellae or even any dune-crest soils that had developed a B horizon. He concluded that the dunes of Colorado are correlative with dunes in the Nebraska Sand Hills, that they probably were active from 3,000 to 1,500 yrs. B.P., and that older, possibly Altithermal dunes are buried beneath the younger dunes.

Southwestern States

Huffington and Albritton (1941) divided dunes to the northeast of the Pecos River, in southwestern Texas, into two formations. The Judkins dune sand is reddish brown, somewhat indurated, enriched in clay and silt, and roughly correlated to Melton's series III dunes. The Monahans sands are gray, unconsolidated, lacking in clay and silt, and are correlated to Melton's series I dunes. The younger dunes are much less subdued by erosion than the older dunes.

Hefley and Sidwell (1945) described the geology and ecology of fixed and active dunes in Bailey County, Texas. They noted modern dunes migrating to the east-southeast, and report at least two stages of dune formation. External morphology of dunes was described, along with some sedimentologic data.

Gile (1979) described three Holocene eolian geomorphic surfaces in Bailey County, Texas; he dated the surfaces according to degree of soil development. The oldest surface (Longview) is dated at 7,000 to 4,000 yrs. B.P. on the basis of pronounced lamellae and associated artifacts. Also raised was the possibility of even older soils, which could be defined by advanced clay enrichment between lamellae. The Muleshoe surface is dated at 4,000 to 100 yrs. B.P., based upon the lack or poor development of lamellae and a stratigraphic position above the Longview surface. The young

Fairview surface is considered to have formed after settlers began farming in the area. Gile included detailed soil profile descriptions (noting A2 (E) horizons under oak vegetation), and discussed a possible illuvial process of lamellae formation.

Holliday (1984) documents a probable two-event period of eolian activity in northwestern Texas and eastern New Mexico. He gives evidence of dune activity between 6,500 and 5,500 and between 5,000 and 4,500 yrs. B.P.

Much of the same area of southwest Texas was studied by Carlisle and Marrs (1982). They used remote-sensing techniques and LANDSAT imagery to map modern regional windflow characteristics, which were compared to observations of the land surface. They documented conflicting wind directions and the resulting dunes, which have complex morphology and show no evidence of migration.

Hack (1941) described in detail the stabilized and active dunes in a portion of Arizona. The account covers the morphology of the dunes, their geographic occurrence, age, and sedimentology. Of particular interest are multiple cycles of Holocene activity recorded, and the observation that dunes are now stabilized in areas where annual rainfall is 12 to 15 in., but dunes are still active in areas with less than 9 to 10 in. of annual precipitation.

Midwestern States

Two writings on sand dunes along the shores of Lake

Michigan are considered here, one by Bailey (1917) and the other by Cressey (1928). Bailey had a love for the dunes and wrote about them in a wonderful descriptive style; of note are a table of airborne travel distances for particles of various sizes, and a description of a blowout (Bailey, 1917, p. 46, 81). Cressey wrote a much more rigorous and detailed description of the dunes. He considered many aspects of the dunes including external morphology, sedimentology, internal stratification, sand source and transportation, and history.

Grigal, Severson, and Goltz (1976) reported on multiple cycles of dune activity in a large dune field in north-central Michigan. The dune form is primarily parabolic and indicates a northwesterly paleowind. Four buried soils are in eolian sand above a non eolian soil, in an area of stabilized dunes. Radiocarbon dates from two of the soils and pollen analysis indicate that the non eolian soil was buried about 8,000 years ago with the dunes remaining active until 3,000 to 4,000 years ago.

Coastal Dunes

William Cooper (1958, 1967) wrote two books on the coastal dunes of Oregon and Washington, and California. He gave a complete, detailed, and illustrated description and history of the dunes. Several episodes of eolian activity were documented, with intervening periods of soil development; these events took place within the last 18,000 years.

Inman, Ewing, and Corliss (1966) reported on an area of barchan dunes migrating across a tidal flat near Guerrero Negro, Baja California, Mexico. They observed dunes averaging 6 m. high being formed under wind velocities of no more than 12 m/s (27 mph). The dune sands were fine grained, well sorted, and had slightly positive skewness (Inman's). Internal ripple laminations were nearly horizontal and about 2 mm thick.

Morphologic and Sedimentologic Investigations

The literature concerned with morphology and sedimentology of dunes is very extensive. Therefore, this section will only consider several of the contributions most important to this study, with others simply listed for the interested reader. Several publications that report on the general nature of dunes or dune fields were helpful. These include works by Cornish (1897), Glennie (1970), Wilson (1973), Cooke and Warren (1973), and Fryberger and Ahlbrandt (1979).

External Morphology

Fryberger (1979) recognized that dune forms can be placed into five groups based on wind regime. Different wind regimes create dunes with differing forms and number of slipfaces. Figure 9 illustrates major dune forms and shows the dominant wind patterns.

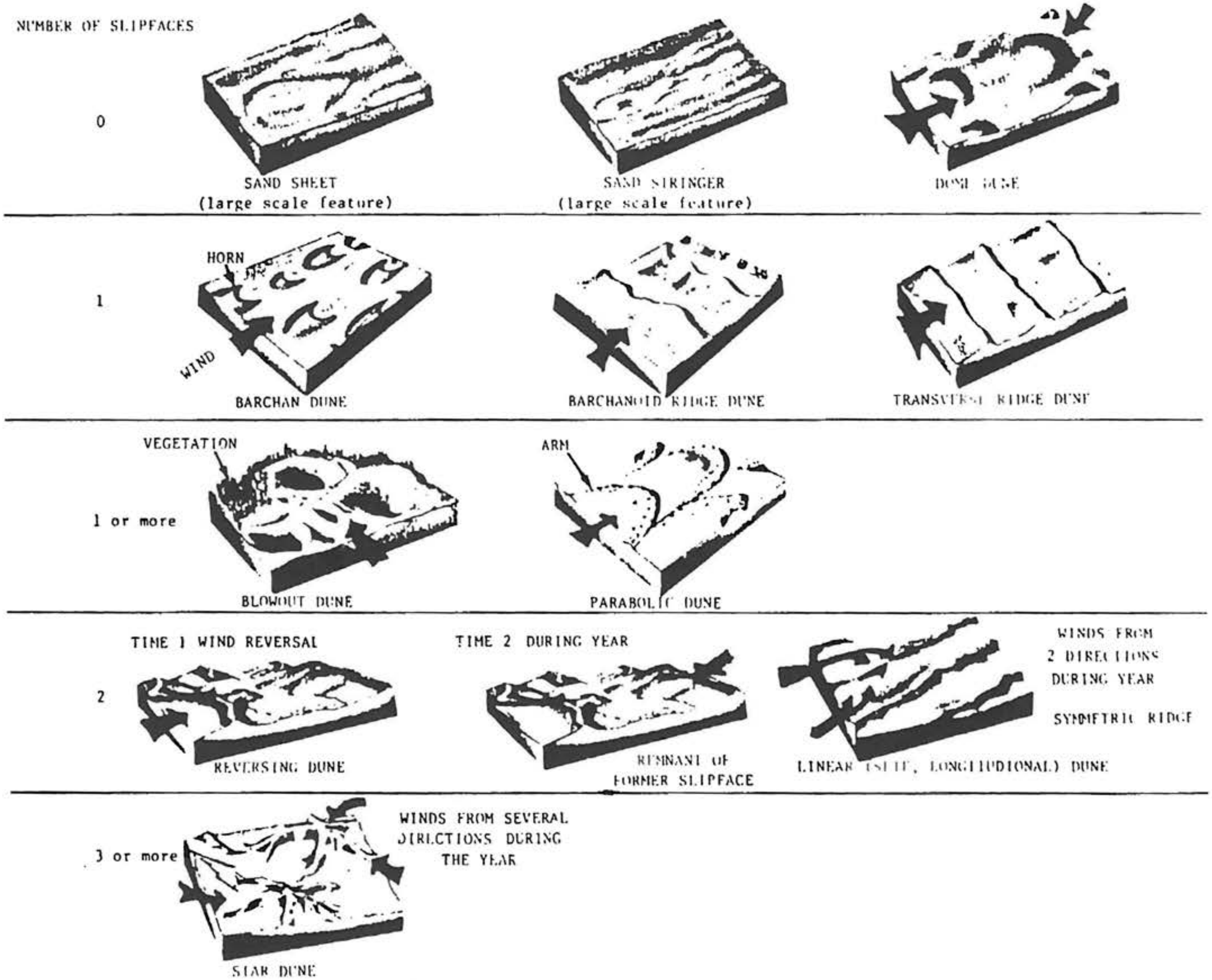

Figure 9. Basic Eolian Bedforms. (modified from Ahlbrandt and Fryberger, 1982)

As reported by Ahlbrandt and Fryberger (1982), sand sheets, sand stringers, and dome dunes do not develop slipfaces and are generally associated with unidirectional winds. Barchan, barchanoid ridge, transverse ridge, and parabolic dunes also form under unidirectional winds, but develop one slipface. Blowout and parabolic dunes sometimes develop more than one slipface, usually due to the influence of vegetation or varying winds. Two slipfaces develop on linear (seif, longitudinal) dunes and reversing dunes. Winds resulting in linear dunes commonly blow from different quadrants (Bagnold, 1941, Tsoar, 1983), with reversing dunes formed by winds that blow from nearly opposite directions. Star dunes form where winds commonly blow from at least three different directions (McKee, 1966, 1979; Fryberger, 1979).

McKee (1966) and Ahlbrandt (1974, 1975) document that unidirectional winds often produce a progression of dune forms. Progressing downwind each of these dune forms may grade into the next, dome to transverse to barchan to parabolic.

Smaller dunes of one type may be superimposed on larger dunes of the same type, resulting in the formation of compound dunes. If dunes of differing types are superimposed, the resulting form is known as a complex dune (McKee, 1979; Figure 10).

Other works mainly concerned with morphology of dunes are by Beadnell (1910), Finkel (1959), and Wilson (1972).

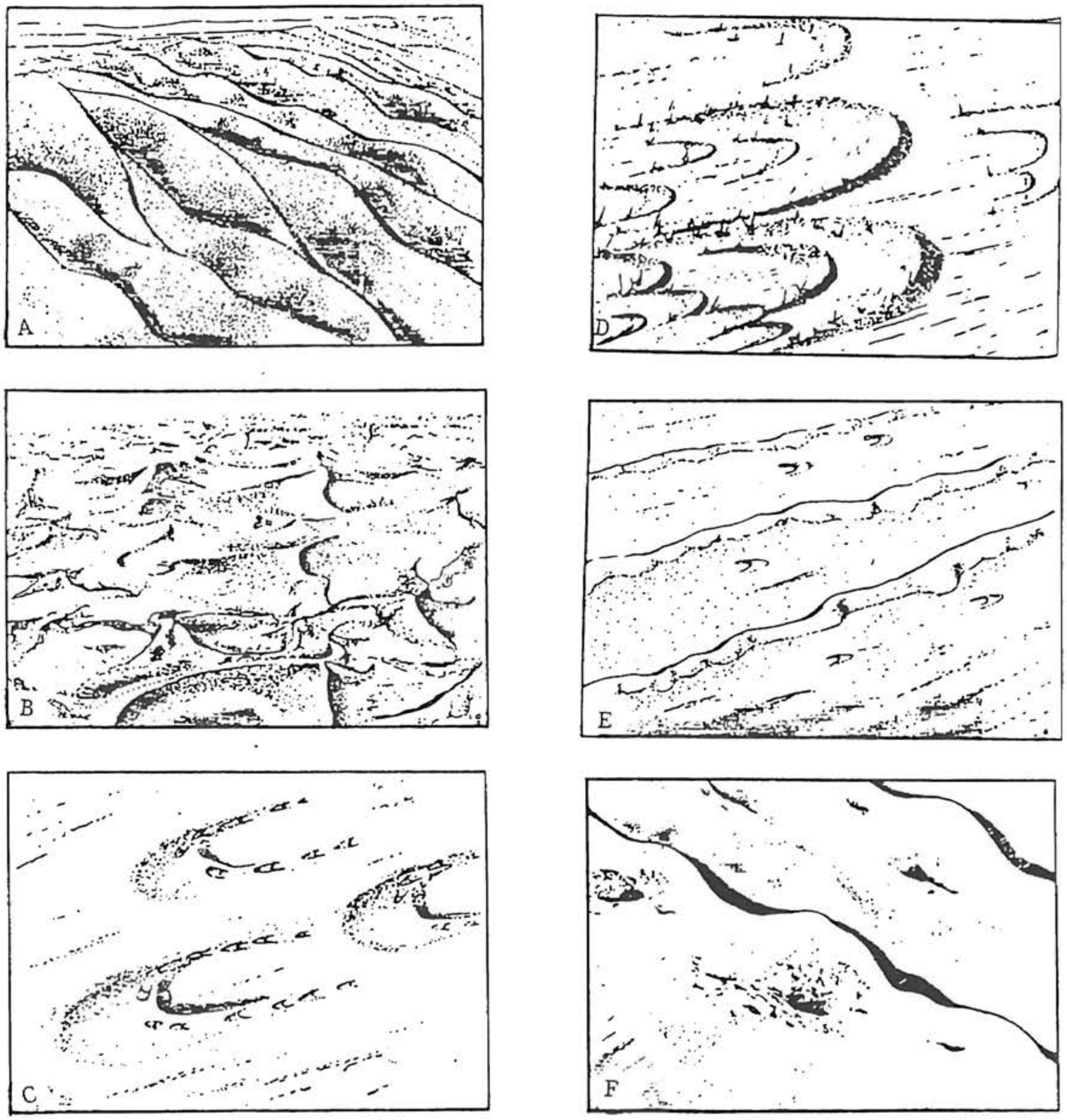

Figure 10. Compound Bedforms: (A) Barchanoid Ridge, (B) Star, (C) Barchan, (D) Parabolic. Complex Bedforms: (E) Linear and Barchan, (F) Barchanoid Ridge and Blowout. (modified from McKee, 1979)

Internal Structure

The sedimentary structure most often encountered in dunes is laminated cross-strata. These strata can include normal, inversely, and non graded beds, even and discontinuously laminated beds, ripples, and lag deposits along bounding (erosional) surfaces. Cross-strata can be classified according to genesis into slipface and topset deposits. Generally, slipface strata will be concave up, convex in parabolic dunes (Ahlbrandt, 1975), and have steep downwind dips in their upper portions which approach the angle of repose (34 deg.) for dry sand. Topset strata will dip upwind at substantially lower angles and are often convex up (Ahlbrandt and Fryberger, 1982; Figure 11).

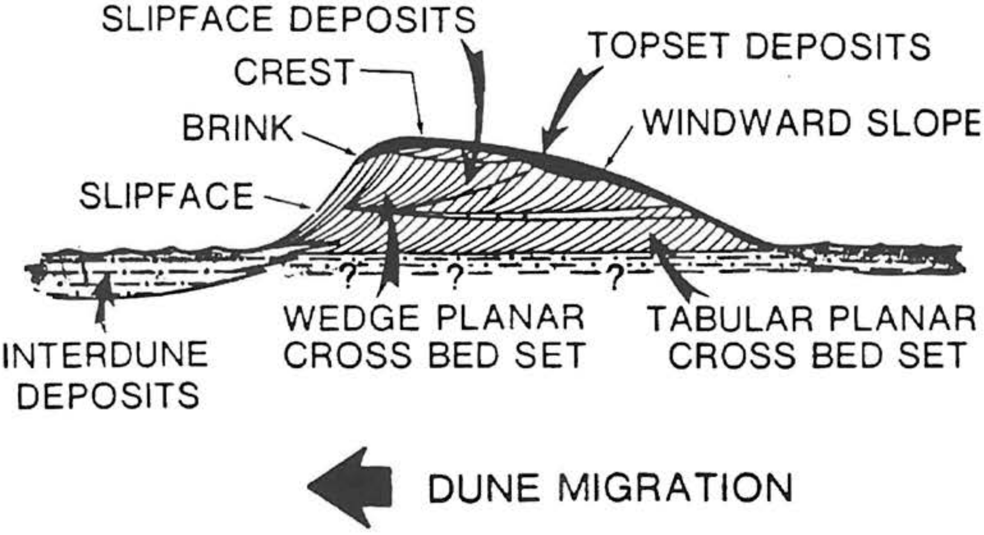

Figure 11. Cross-sectional View of a Barchanoid Ridge Dune. (from Ahlbrandt and Fryberger, 1982).

Ahlbrandt and Fryberger (1982) give the mean dip angle and mean angular deviation of dip direction for cross-strata within several types of modern dunes. Respectively, the mean dips and angular deviations are: transverse ridge dunes, 24 deg. and 32 deg.; barchan dunes, 22 deg. and 54 deg.; and blowout dunes, 16 deg. and 54 degrees. Parabolic dunes have a mean angular deviation of dip direction of 62 degrees.

Laminated strata are produced by three different processes; avalanche (sand flow), saltation, and grainfall. Avalanche processes take place on slipface slopes. Downslope, within a single bed, an avalanche can produce inversely graded, nongraded, and normally graded indistinct laminae.

The saltation process results in the formation of migrating ripples and deposits of distinct ripple laminae. Generally, topset strata are composed of ripple laminae. These may be inversely graded because coarser grains accumulate at ripple crests, or discontinuously and evenly laminated with alternating fine and coarser grained sand (Ahlbrandt and Fryberger, 1982). Hunter (1977) and Kocurek and Dott (1981) described in detail the genesis of low angle cross-stratification by wind-generated ripples.

Grainfall deposits are produced when sand-charged winds decelerate near obstacles and sand is removed from saltation or suspension. They are characterized by even, parallel, normal or inversely graded laminated strata, that quickly thin downslope. Grainfall deposits commonly accumulate until unstable slopes are produced, resulting in avalanches (Hunter, 1977, Ahlbrandt and Fryberger, 1982).

Goldsmith (1973) considered the effect of vegetation on the internal geometry of sand dunes from several coastal locations. One conclusion was that grasses can lead to low dips of dune laminae.

Two articles of note have as their major subject the effect and occurrence of plant- and animal-related structures in dune sands. Glennie and Evamy (1968) defined and described the traces and effects of plant roots in dune sand. Ahlbrandt and others (1978) documented the bioturbation of dune sand by various organisms.

Other authors reporting on sedimentary structures in dunes include: Bigarella, Becker, and Duarte (1969), McKee, Douglass, and Rittenhouse (1971), Fryberger, Ahlbrandt, and Andrews (1979), Hunter (1980), Ahlbrandt and Fryberger (1980), Kocurek (1981), and McKee (1982).

Texture

Ahlbrandt (1975) collected sand samples in a grid pattern from a dome, transverse, barchan, and parabolic dune. He found that mean grain size varied from 1.2 to 2.3 phi, that the sands are moderately to very well sorted, and that sorting improved downwind in the dune field and with sampling height in each dune. For sand samples from the dome dune, sorting coefficient values ranged from 0.70 to 0.93, skewness values ranged from -0.62 to 0.38, and kurtosis values ranged from 0.18 to 0.61. The transverse dune samples had sorting values ranging from 0.52 to 0.77, skewness values ranging from -0.40 to 0.55, and kurtosis values ranging from 0.25 to 0.65. Sorting values from the barchan dune samples ranged from 0.45 to 0.72, skewness values ranged from -0.58 to 0.26, and kurtosis values ranged from 0.18 to 0.82. The parabolic dune samples had sorting values ranging from 0.35 to 0.59, skewness values ranging from 0.01 to 0.32. and kurtosis values ranging from 0.34 to 0.76. Plots of skewness vs mean grain size led to the conclusion that skewness is dependant on grain size, because coarser samples had progressively higher skewness values and finer samples had progressively more negative values. Plots of kurtosis vs mean grain size were contradictory for different dune types, and it was concluded that kurtosis was not useful for distinguishing dune types.

In a survey of published information from five continents, Ahlbrandt (1979) reported that 466 dune sand samples show a mean grain size generally in the fine sand range (0.125 - 0.25 mm). Mean diameters ranged from -0.68 phi (1.6 mm) to 3.4 phi (0.1 mm). The dune sands also are mostly moderately well sorted (0.50 - 0.71; 1.4 - 2.0, Trask, 1932). It was noted that 175 inland dune sand samples had a much wider range of mean grain sizes (mostly 0.50 - 0.125 mm) and sorting values (mostly 0.30 - 1.0) than did sands from coastal dunes, and that skewness values showed wide negative to positive scatter (mostly -0.20 to 0.50). Kurtosis values tended to be mostly platykurtic (0.40 - 0.60). Forty interdune sand samples were mostly bimodal in the sand fraction and had higher silt and clay contents than sand samples from adjacent dunes. Warren (1972) reported similar results from bimodal interdune sands collected in the Tenere Desert, Niger.

Using the same 506 samples, Moiola and Spencer (1979) found that dune sands from different environments could be distinguished by discriminant analysis. Moderately to well sorted, fine- to medium-grained dune sand from inland areas was differentiated from well sorted fine grained coastal dune sand and from moderately to very poorly sorted interdune sand.

Marrs and Gaylord (1982) reported that most dune sands have mean diameters of .25 mm and bulk densities of 2.0 gm/cm^3. For sand of this size and density, they calculated that a wind (at 4 m height) of 6 m/s (13.4 mph) is necessary to initiate and sustain sand movement.

Sneh and Weissbrod (1983) compared the size-frequency distribution of rippled flank sands from longitudinal dunes to slipface sands from other dune types. They reported mean grain sizes ranging from 1.7 to 2.7 phi, recorded means and ranges of sorting characteristics for the sands, and concluded that rippled flank sands can be differentiated from slipface sands of other dune types on the basis of sorting changes along the slopes.

Quaternary Dating Investigations

In recent decades, the knowledge of Holocene geologic and climatic history has grown tremendously. For the plains, geologists and archaeologists are combining radiocarbon dates with artifacts, fossils, pollen analysis, and stratigraphy to develop an absolute chronology. Contributing authors include Antevs (1955), Deevey and Flint (1957), Weakly (1962), Reeves (1973), Benedict (1973, 1979), Wendland and Bryson (1974), Mahaney (1976), Brackenridge (1980), Hall (1982, 1988), and Hall and Lintz (1984).

CHAPTER III

METHODOLOGY

Estimation of Paleowind Directions

To estimate paleowind directions, slipface orientations on stabilized dunes were recorded from stereopairs of aerial photographs at the scale of 1:20,000. Clear acetate was attached to one photograph of each pair, and the stereopair was viewed with 4x magnification and no magnification. For reference, photograph number, section corners, and section numbers were placed on the acetate, in black. Dune crestlines were traced in blue. Assuming that paleowinds were normal to observed slipfaces, short lines normal to the slipfaces were drawn in red. Because most crestlines are somewhat sinuous, each change in crestline orientation was assumed to require the interpretation of a separate slipface.

By placing each acetate drawing over the corresponding soils map, orientations of inferred wind lines were measured relative to section line roads in degrees East of North. Each measurement was recorded, grouped according to the dune soil mapped at that location. Grouping by soils was done so that the hypothesis of shifting wind directions through time could be tested.

Estimation of Relative Ages of Dunes

While comparing the dune slipface orientations to the soils maps, in those places where the base of a slipface was also a dune soils boundary, a record was made of the upwind soil series and the downwind soil series. Because it often appeared that a younger dune had encroached on a stabilized dune, a compilation of this relationship was thought to be a possible indicator of relative age. Results are given in Table II.

TABLE II

NUMBER OF OBSERVATIONS OF UPWIND/DOWNWIND RELATIONSHIPS

		Upwind Soils						
		Ss	TrD	PtD	PtC	NcD	NcC	AnE
Downwind Soils	TrD							
	PtD		31					
	PtC		14	11		2		7
	NcD		1	8				
	NcC					2		

Field Techniques

Familiarity with the study area was gained by driving all section line roads and open oil-field lease roads within the area. During this preliminary survey, sites believed to be worthy of further investigation were noted on topographic maps and on soil-survey maps. Some sites had already been noted from the study of aerial photographs. These sites were visited where access was available.

Sand Sampling

Bulk samples of dune sand were collected at sites of opportunity where near vertical exposures were found, generally road cuts below crests of dunes. Several samples were obtained with a bucket auger or from cores taken to describe paleosol soil profiles. Hand trenching was done at road-cut sites to assure that samples were taken from sand that was in-place stratigraphically. Samples were collected from beneath the soil horizon in most instances. However, at a few sites, samples were taken in the B horizon, between lamellae. The soil series mapped at each site was recorded and the site location was marked on U.S.G.S. topographic maps and Soil Conservation Service soil-survey maps. When visible, the internal structure at each sampling site was measured and recorded, and some internal structures were photographed. Estimated depth of each sample below the ground surface was recorded to the nearest foot. Samples were analyzed for grain size, Munsell color, roundness, and visual estimation of mineral composition.

Bulk samples of alluvial material were obtained and documented in the same way as samples of dune sand. Three samples of terrace alluvium were obtained from the paleosol soil-profile description cores (Appendix B), and one was taken from the Rock Terrace road cut (Figure 8, Plate 1). Another sample was taken from a cutbank of the Cimarron River, from medium-scale crossbedded sand, and one sample was taken from a recent overbank deposit adjacent to the river.

Auger Cores

One objective of this study was to find in the dunes material in-place and suitable for radiocarbon dating. After none was found during the site-survey and sand-sampling phase of the investigation, a search for organic-rich paleosols was begun. Most of the dunes were believed to overlie terrace or floodplain alluvium; therefore, a program of coring with a bucket auger was begun at sites (Plate 1) judged likely to have floodplain or terrace deposits within 16 ft. of the surface.

Twenty-three exploratory auger cores were done, 20 of which bottomed in alluvium that had recognizable soil development at the surface. Where a paleosol was found that appeared to be sufficiently organic-rich for radiocarbon dating, other cores were done as offsets, to test the hypothesis of a spatial (terrace) surface. Total depth of each core was recorded, along with depths of paleosols encountered (Table III). Locations of cores were recorded on topographic maps and soil-survey maps.

TABLE III

SUMMARY OF AUGER-CORE RESULTS

Core Number	Surface Soil	Depth to Paleosol(s)	Paleosol Development#	Total Depth
1	NcD	14'	weak	16'
2	TrD	11'	very weak	16'
3	NcD	7'	very strong	12'
4	NcD	5'	very strong	8'
5	NcD	10'	strong*	12'
6	TrD	10'	weak	12'
7	NcD	9'	weak	16'
8	PtD	4'	weak	12'
		7'	very strong	
9	TrD	6'	weak	12'
		9'	very strong	
10	NcD	7'	strong	16'
11	NcD	7'	strong	12'
12	Ss	9'	weak	16'
		11'	strong	
13	TrD	8'	weak	16'
		11'	very strong	
14	PtC	4'	weak	16'
		8'	very strong	
15	TrD	5'	weak	12'
		9'	very strong	
16	TrD	5'	weak	12'
		10'	very strong	
17	TrD	none**		16'
18	NcC	6'	very strong	12'
19	NcC	5'	very strong	8'
20	PtC	13'	weak	16'
		15'	weak	
21	PtC	13'	weak	16'
22	PtD	6'	very weak	12'
23	TrD	none***		16'

\# Based on the relative degree of organic darkening in the A horizon.

* A horizon not discernible, B horizon prominent.

** Core bottomed, still in dune sand.

*** Core bottomed in alluvium below at least 8 ft. of dune sand, but no discernible boundary was present.

Probe Cores

Several paleosols suspected to be rich in organic material were sampled, and the samples were tested for organic carbon. Results are given in Table IV. Four of the most enriched paleosols were selected for further study. Their sites were cored using a truck-mounted hydraulic coring probe. This probe allowed collection of a continuous undisturbed core. Three cores were obtained, sampled for sieve analysis, and the profiles described by Dr. Brian Carter of the Agronomy Department, Oklahoma State University (Appendix B). One site was not cored fully because looseness of the dune sand prevented proper anchoring of the probe.

After inspection of the probe-core data, each site was sampled again with a bucket auger, to obtain organic samples for radiocarbon dating and additional sand samples for sieve analysis.

Laboratory Techniques

Sand samples were air-dried, mixed, and disaggregated before being split to approximately 50 gm. for sieve analysis. Standard A.S.T.M. testing sieves were used in quarter-phi increments, ranging from .25 to 4.25 phi, except that sieves for .5, 1.0, and 4.0 phi were unavailable. Each sample was shaken for 15 minutes on a Rho-Tap machine, and the sand retained on each sieve was weighed to the nearest thousandth gram on a Mettler PL200 electronic balance.

Most samples were inspected with a 10x hand lens during

TABLE IV

ORGANIC CARBON DETERMINATIONS

Core Number	Depth	% Organic Carbon	% Organic Matter
7	9'	0.31	0.53
		0.32	0.56
8	7'	0.34	0.58
		0.28	0.48
10	7'	0.47	0.81
		0.49	0.85
12	9'	0.28	0.48
		0.27	0.47
	11'	0.50	0.85
		0.53	0.91
13	8'	0.34	0.59
		0.37	0.63
	11'	0.75	1.29
		0.76	1.31
15	9'	0.61	1.05
		0.60	1.03
18	6'	0.31	0.53
		0.31	0.54
20	13'	0.12	0.21
		0.13	0.22
	15'	0.29	0.49
		0.24	0.42

the sieve analysis, to determine the degree of rounding and to estimate the percent quartz, feldspar, rock fragments, and aggregates. The sand was generally subrounded, and in all samples, more than 90 percent was quartz. Feldspar and rock fragments invariably were present in small, insignificant amounts. Several samples collected from blowouts or parabolic dunes contained sand-sized aggregates formed of clay-sized material. Inspection of sand in place at several of these sample sites revealed that the aggregates were present, loose in the sand. It was concluded that these aggregates were formed before deposition in the dune, and so they were included as sand-sized material during sieve analysis.

The dry color of each sample was determined by comparison to the standard Munsell color chart. Comparisons were made in sunlight. Results are listed in Appendix C.

Statistical Methods

Sieve Data Analysis

Analysis of the sieve data was done using previously published procedures. The data were converted to cumulative percent vs phi and plotted on probability paper. One hundred percent was assumed to be the total weight of retrieved sample after sieving, including the pan fraction (Folk and Ward, 1957). The average procedural loss was .448 percent, with the largest loss being 2.171 percent. Only two other samples had more than 1 percent loss.

Phi values at 5, 16, 25, 50, 75, 84, and 95 percent were picked from the probability curves. These values are listed in Appendix D. The values were used to compute mean grain size, sorting (standard deviation), skewness, and kurtosis using the formulas of Folk and Ward (1957). The sorting coefficient of Trask (1932) was also calculated for comparison. Ninety-five samples were evaluated; with the results also tabulated in Appendix D.

Cumulative-percent curves for each sample were produced, along with mean, maximum, and minimum curves for each soil series and alluvium (Appendix E). Mean curves for differing geomorphic areas were also drawn. Comparisons were made between curves so that relationships might be discerned. Curves and their textural parameters were also used to discriminate between dune sand and alluvium from the soil probe-cores.

Discriminant Analysis

After visually comparing the cumulative percent curves for various dune-sand samples and the average curves for each soil series, it was evident that some degree of difference was present. An attempt was made at defining each soil series by discriminant analysis (Moiola and Spencer, 1979), the first step of which is to determine that the samples do in fact differ.

To test the hypothesis that the samples differed significantly, a method given by Miller and Kahn (1962) was chosen. They describe an analysis-of-dispersion method which tests the hypothesis that the means of two groups differ significantly by using a simultaneous treatment of several variables. The test is appropriate, for it can discriminate between closely related groups, and is much more sensitive than testing individual pairs of variables. The four variables chosen to be tested simultaneously were mean, sorting, skewness, and kurtosis as previously computed. The final test statistic is distributed as Chi-squared.

Results are given in Table V. They indicate that computation of a discriminant function is not appropriate. However, as will be discussed in Chapter 4, the results do shed some light on the geologic history of the area.

TABLE V

VALUES OF CHI-SQUARED FOR THE TESTS OF DIFFERENCE BETWEEN DUNE SANDS

	TrD	PtD	NcD	PtC	NcC	AnE
Ss	2.77	3.81	13.43	21.11	8.12	13.01
TrD		3.47	16.04	21.85	7.03	14.08
PtD			2.29	4.42	5.08	8.58
NcD				2.81	7.96	11.62
PtC					4.00	9.75
NcC						4.48

Significance Levels: .01 - 13.28 d.f. = 4
.05 - 9.49

Paleowind Velocity Analysis

Completion of the grain-size analysis made possible the estimation of wind velocities present in the active dune fields. Computational procedures used were those developed by Bagnold (1941) and modified by Marrs and Gaylord (1982). Cumulative-percent values based on each samples' sand fraction were used to compute a modal phi value for each dune-sand sample. Each modal value was estimated by using the computer-aided curve-fitting procedure described in

Appendix F. The modal values were used in calculation of the threshold wind velocities at 4 meter height, which estimate the winds necessary to begin and sustain sand movement. Threshold velocities also estimate wind velocities that supply the most energy to dune fields (Marrs and Gaylord, 1982).

The phi value corresponding to the maximum 2 percent on each dune-sand cumulative-percent curve was used to estimate the maximum wind velocities in active dune fields. Maximum winds are defined as those that were not exceeded often enough to alter the grain size distribution of the sand (Marrs and Gaylord, 1982). Thus, as used here, "maximum winds" refers to sustained winds rather than to gusts. Recorded in Appendix G are computed threshold and maximum wind velocities, and their corresponding grain sizes.

Threshold and maximum wind velocities were grouped by soil series, and the average, maximum, and minimum values were noted. One threshold velocity value each from the TrD, PtD, PtC, and NcD soil phases was deleted from further analysis; these values were deemed to be much to low to be realistic. (Also, these velocity values were computed from modal values that were suspect, due to the poor fit of their source curves to the real data.)

To search for any significant differences between the mean threshold or mean maximum wind velocity values for each soil series, standard Student's-t and Analysis-of-Variance tests given by Devore and Peck (1986, p. 373, 566) were performed. Each mean threshold and mean maximum velocity value for each soil series was tested against all others; results are in Table VI. Analysis of Variance was done using a single-factor F test, which was appropriate for the unequal sample sizes. Results are in Table VII.

TABLE VI

CALCULATED VALUES OF STUDENT'S-t FOR TESTS OF PALEOWIND VELOCITIES

					Threshold Velocity Values		
	Ss	TrD	PtD	PtC	NcD	NcC	AnE
Ss		1.63	1.32	0.77	0.61	1.70	0.81
TrD	1.93		0.30	1.46	1.71	0.38	1.65
PtD	1.61	0.66		0.95	1.10	0.09	1.41
PtC	2.54*	0.21	0.72		0.16	0.87	1.25
NcD	2.05*	0.24	0.55	0.05		0.96	1.11
NcC	2.35*	0.36	1.10	0.71	0.61		1.83
AnE	1.32	0.65	0.15	0.77	0.58	1.10	
	Maximum Velocity Values						

* Significant at .05 d.f. = $N_1 + N_2 - 2$

Sample Size:
Ss - 8
TrD - 13
PtD - 8
PtC - 17
NcD - 24
NcC - 8
AnE - 8

Note: TrD, PtD, PtC, and NcD each had one sample omitted from the Threshold Velocity test.

TABLE VII

CALCULATED VALUES OF F FOR TESTS OF PALEOWIND VARIANCE

Wind Velocity	F calc	F tab .05
Threshold	1.349	2.238
Maximum	1.152	2.233

Threshold d.f. = 6,75 Maximum d.f. = 6,79

Paleowind Orientation Analysis

Data from measurement of the slipface/paleowind orientations were first displayed graphically, to gain some idea as to their distributions (Watson, 1966). These graphs are in Figures 12 through 18. The data appear to be fairly well grouped, although somewhat skewed and in two cases, Nobscot (NcD) and Tivoli, apparently bimodal. Since the orientation data for these two major soil series appear to be bimodal, skewness and kurtosis measures were not computed. Additionally, a Chi-squared test (Batschelet, 1981, p. 71) was selected to test the hypothesis that the orientations for each soil are random. Results are given in Table VIII.

Concluding that the slipface/paleowind orientations were non random, the mean orientations, **m**, the mean angular deviations, s, and the concentration parameters, r and k, (Batschelet, 1981, p. 7, 10, 34, 47; Mardia, 1972; Watson, 1966; Reyment, 1971; Till, 1974) were computed for each soil series. Note, that because circular distributions are

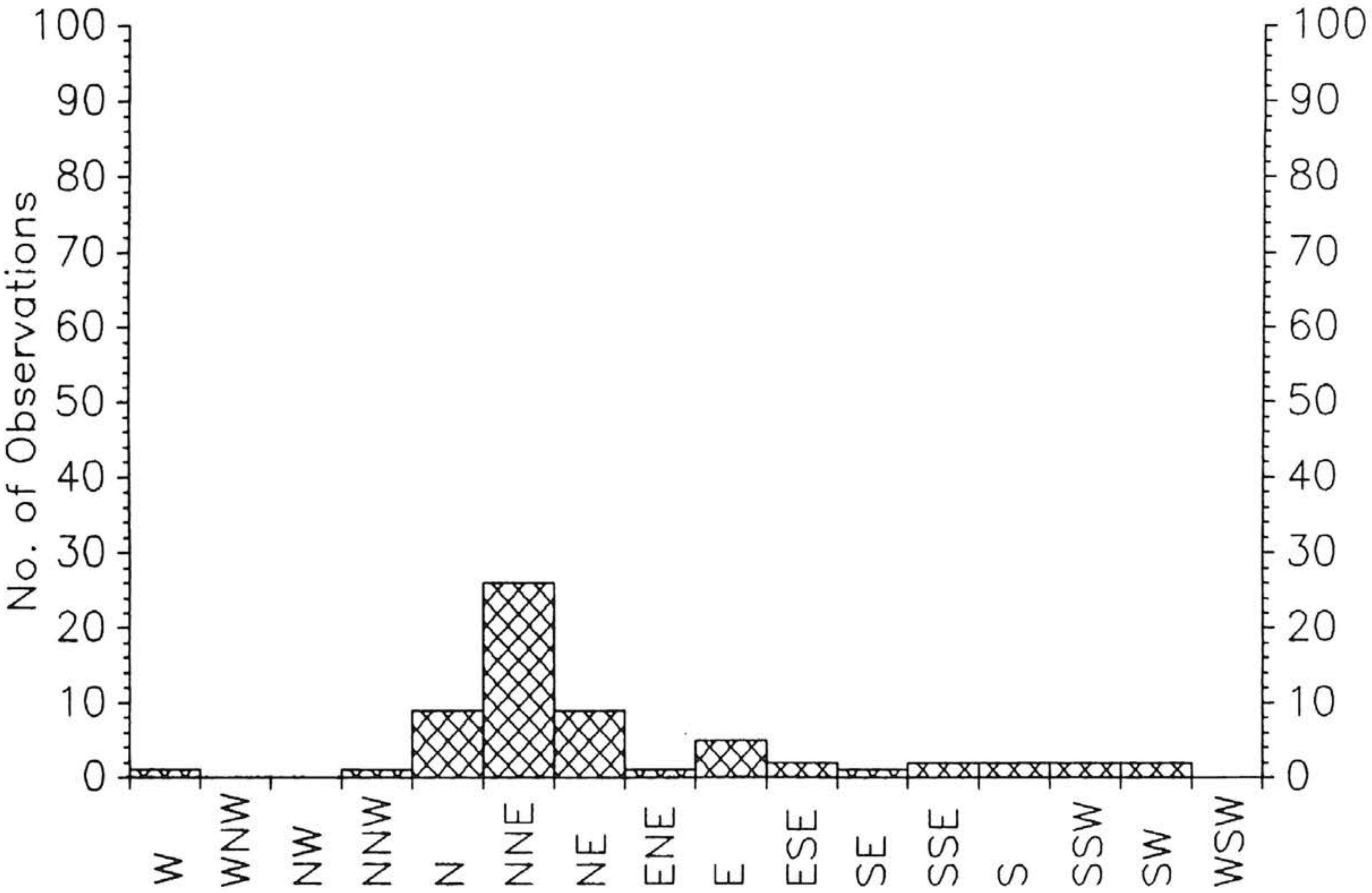

Figure 12. Slipface-paleowind Orientations, Recent (Ss) Dunes.

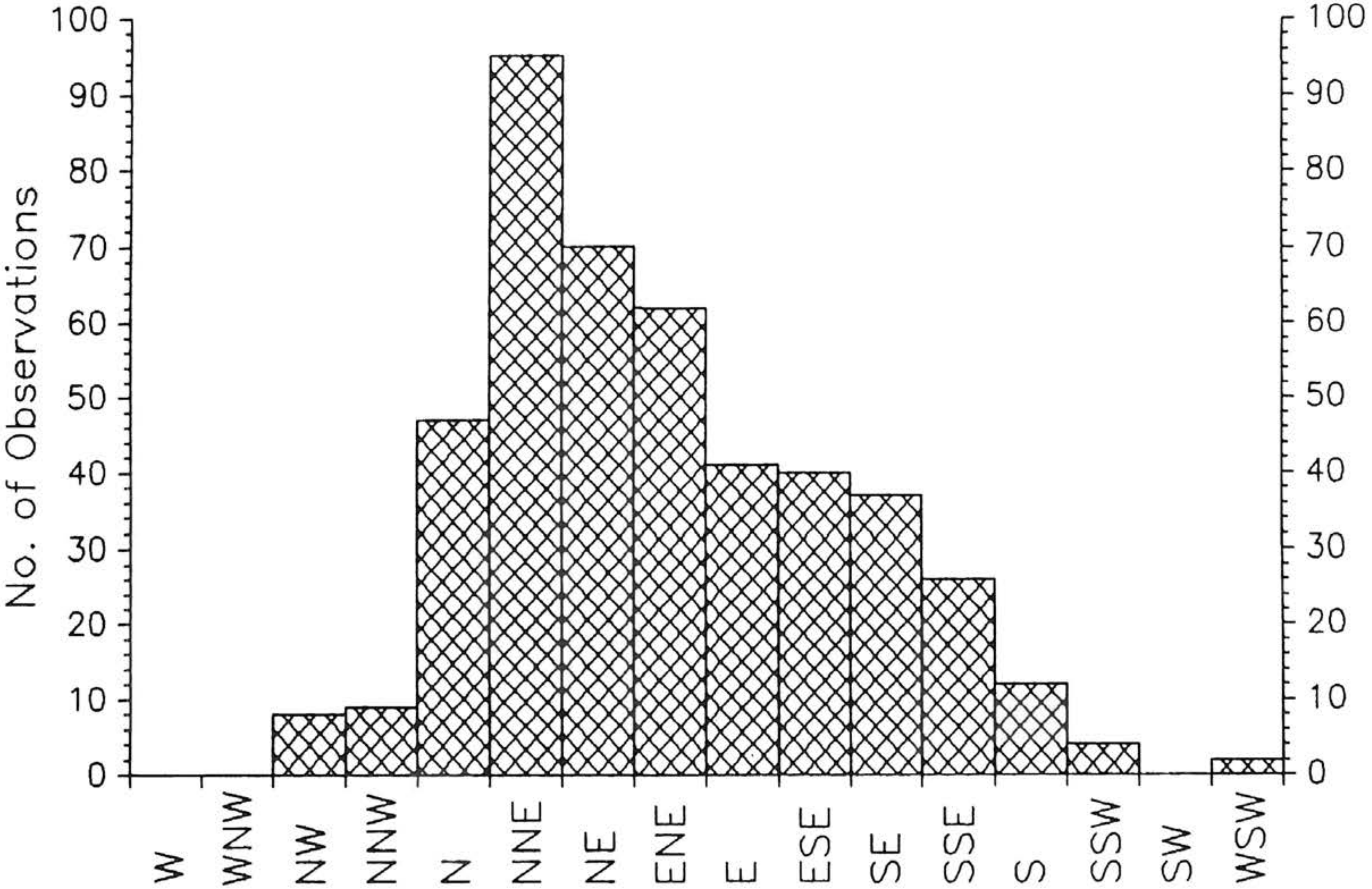

Figure 13. Slipface-paleowind Orientations, Dunes of Tivoli Series.

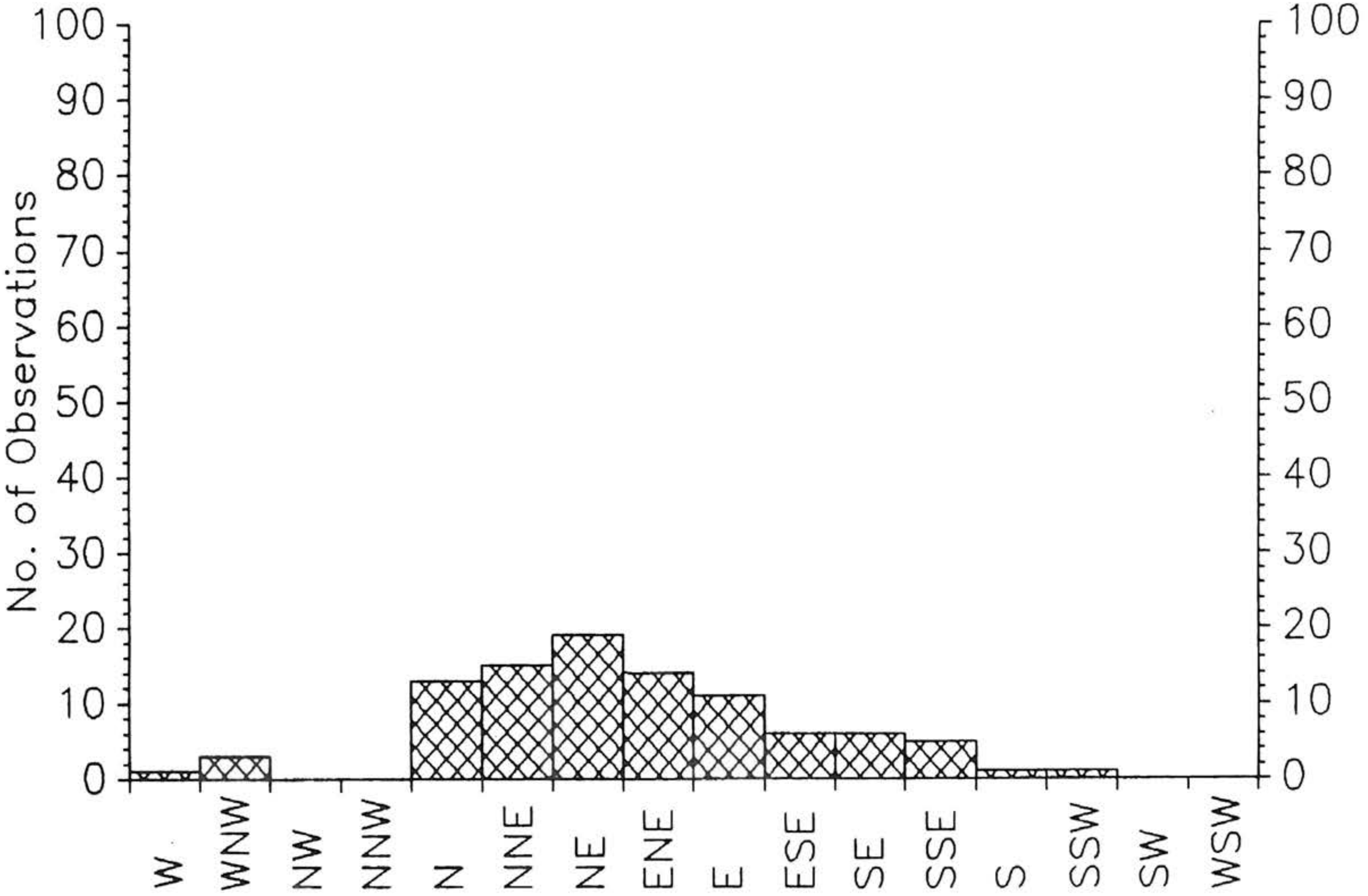

Figure 14. Slipface-paleowind Orientations, Dunes of Pratt (PtD) Series.

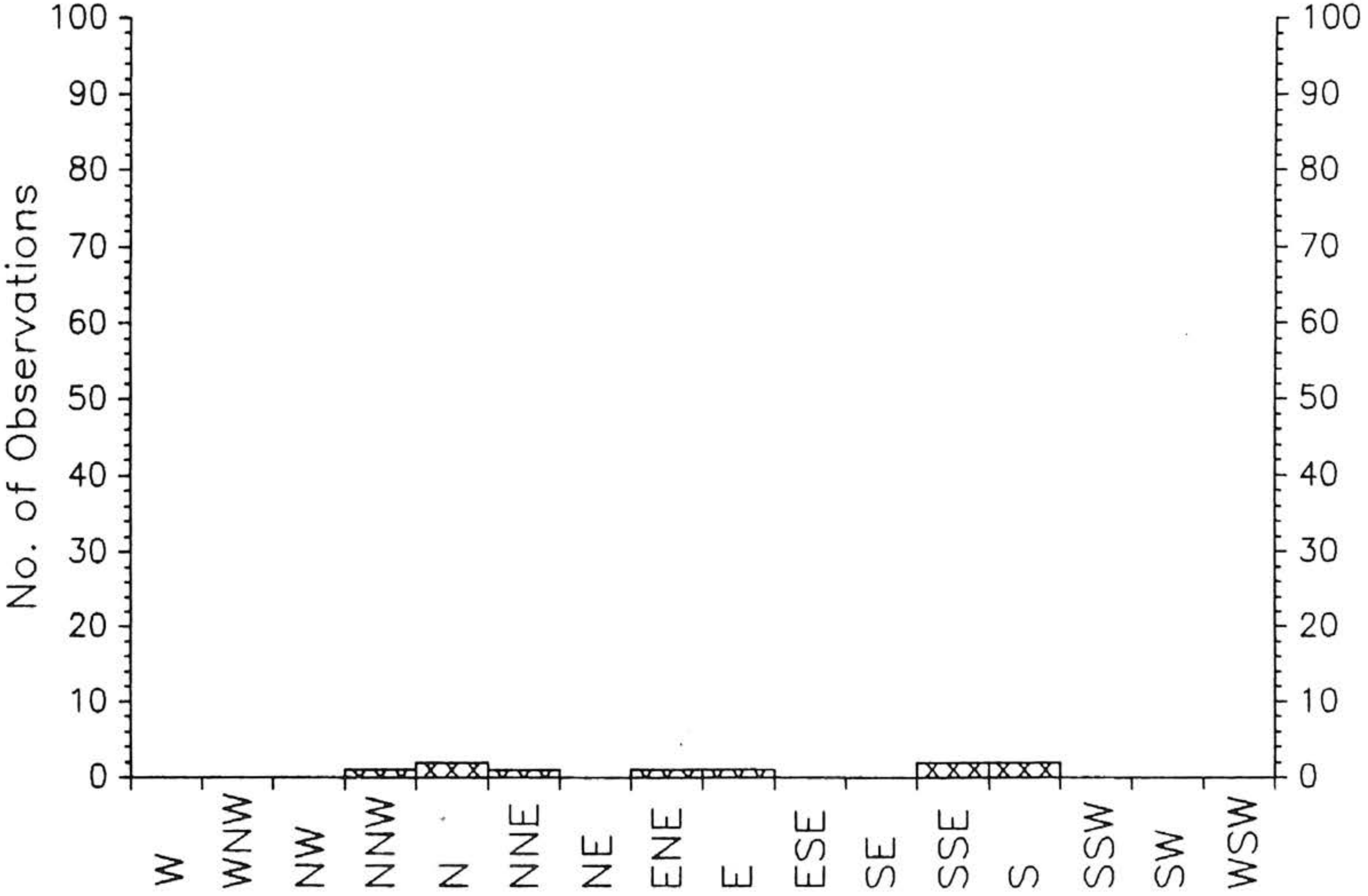

Figure 15. Slipface-paleowind Orientations, Dunes of Pratt (PtC) Series.

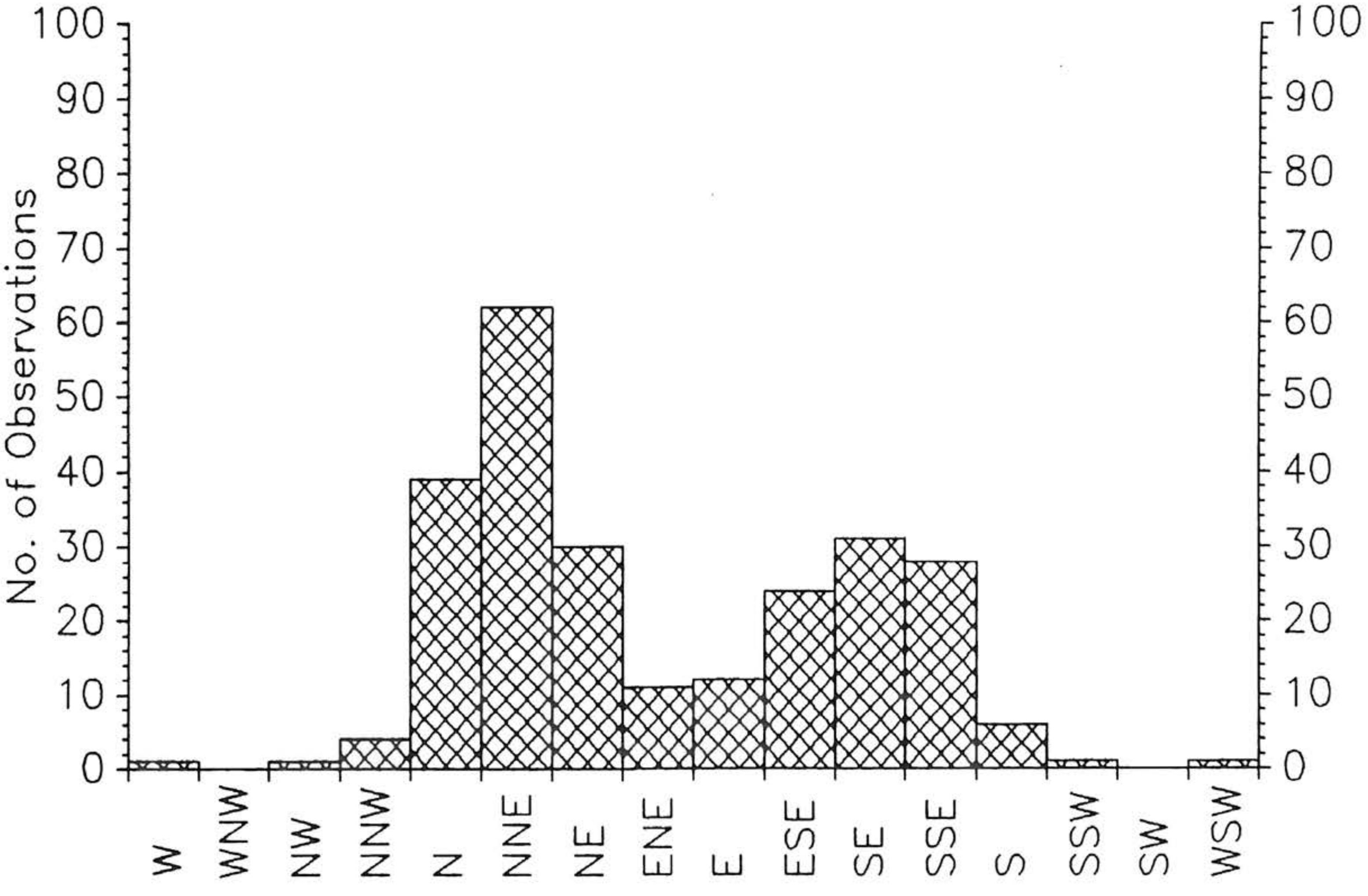

Figure 16. Slipface-paleowind Orientations, Dunes of Nobscot (NcD) Series.

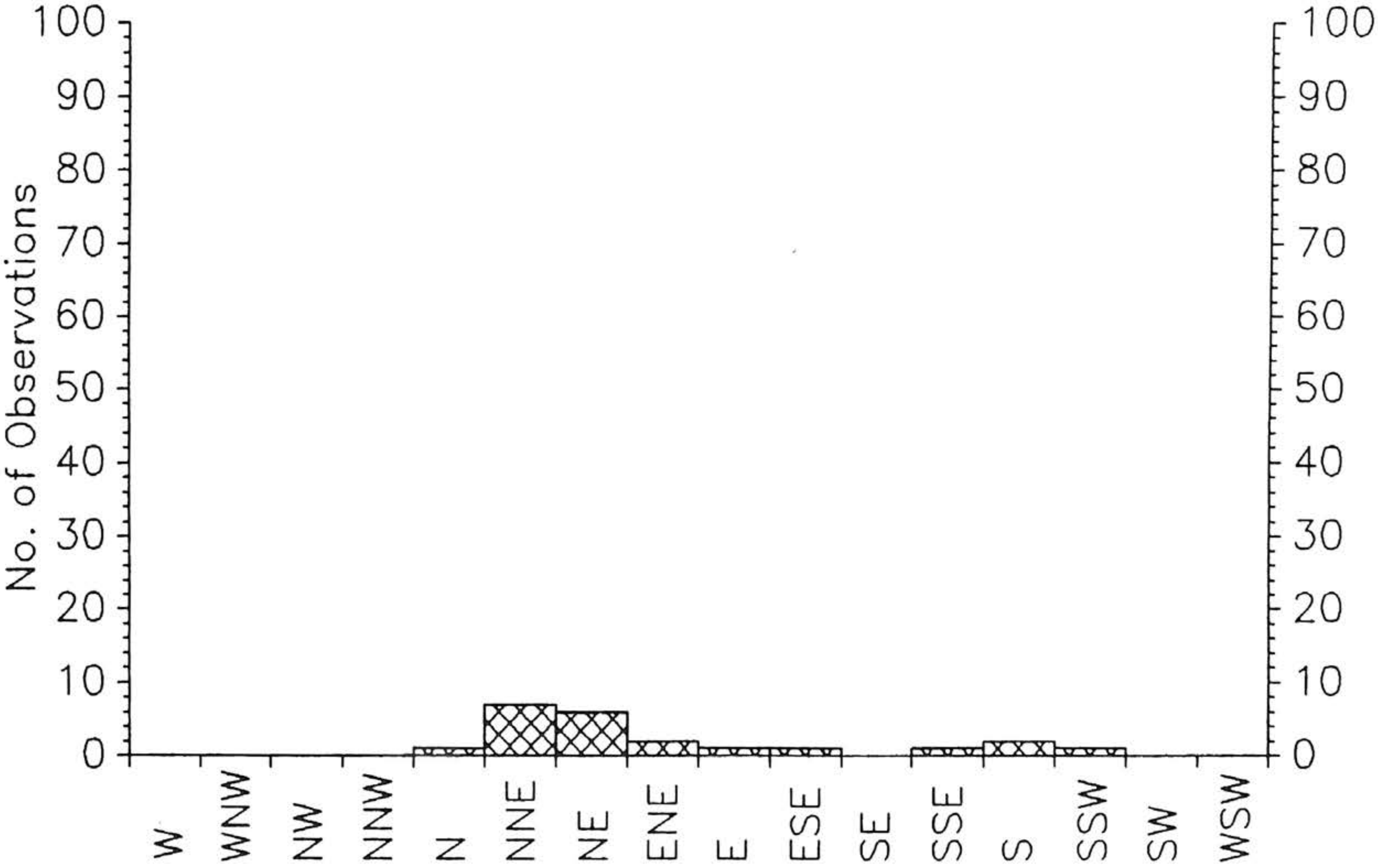

Figure 17. Slipface-paleowind Orientations, Dunes of Nobscot (NcC) Series.

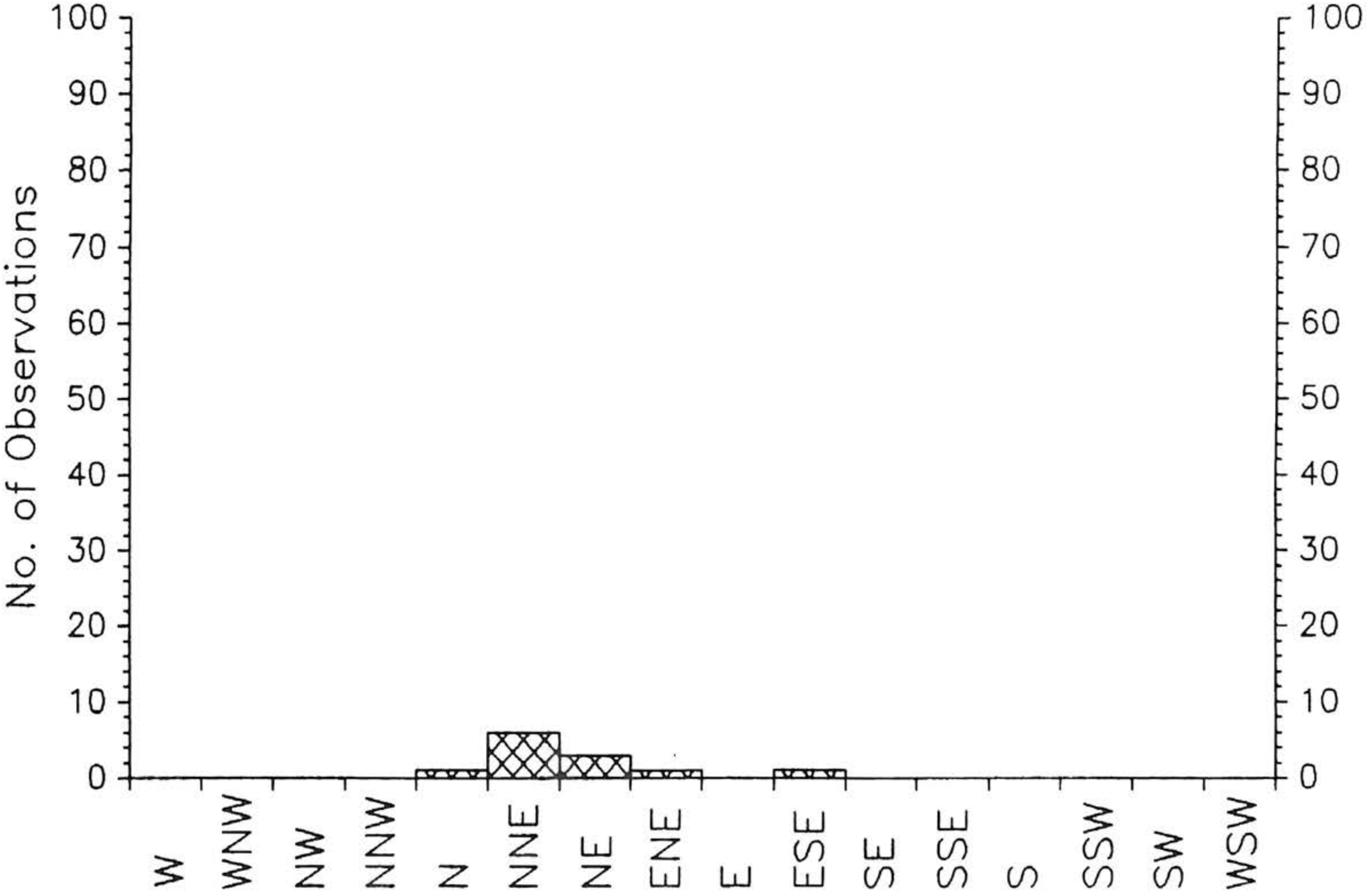

Figure 18. Slipface-paleowind Orientations, Dunes of Aline Series.

TABLE VIII

VALUES OF CHI-SQUARED FOR TESTS OF RANDOMNESS

Soil	Chi-squared calc	Chi-squared tab .05	d.f.
Ss	66.7	16.9	9
TrD	637.0	44.0	30
PtD	25.0	21.0	12
PtC	4.8	3.8	1
NcD	386.5	35.2	23
NcC	128.3	7.8	3
AnE	42.0	3.8	1

plotted on a unit circle, **r** denotes the length of the mean vector, and varies from 0.0 to 1.0. As **r** increases, the mean angular deviation decreases, reaching a value of 0.0 if **r** equals 1.0 (Batschelet, 1981, p. 34). Also, **k** is related to the density of a data distribution and is the circular analogue of the linear standard deviation (Reyment, 1971, p. 27). As **r** increases **k** increases. Tables are available for converting between **s**, **r**, and **k** (Batschelet, 1981).

For the bimodal distributions, these descriptors were computed for all data points and for the distributions around each mode. An ad hoc method, discussed by Batschelet (1981, p. 50), of separating data in bimodal distributions was used. The resulting distributions show a northeasterly directed paleowind, mode A, and a southeasterly directed paleowind, mode B. The descriptors are given in Table IX.

Given the apparent bimodal nature of some, and the possibly skewed nature of all the orientation data, a Chi-squared test given by Batschelet (1981, p. 109) was chosen to test whether the samples from each soil series differed significantly. This test does not specify the type of difference and requires a large sample size. Further testing or careful inspection of the samples is necessary to determine the nature of significance. Data from the PtC, NcC, and AnE soil phases were too few to include them in the tests. Results are given in Table X.

TABLE IX

ORIENTATION PARAMETERS

Soil	m*	s**	r	k
Ss	34.32	48.28	0.6450	1.716
TrD	60.05	49.17	0.6317	1.654
Mode A	42.00	40.11	0.7550	2.412
Mode B	119.81	38.96	0.7689	2.537
PtD	56.37	48.06	0.6483	1.732
PtC	83.38	68.47	0.2859	0.597
NcD	62.46	55.37	0.5331	1.267
Mode A	22.24	23.08	0.9189	6.464
Mode B	133.74	25.14	0.9037	5.507
NcC	53.86	49.53	0.6264	1.630
AnE	35.35	25.99	0.8972	5.171

* m is given in degrees east of north

** s is given in degrees

TABLE X

VALUES OF CHI-SQUARED FOR TESTS OF DIFFERENCE IN ORIENTATION DATA BETWEEN SOILS

	TrD	PtD	NcD
Ss	19.43	16.16	14.16
TrD		8.36*	38.14
PtD			28.87

* only value not significant at .05

d.f. = 1,5 for TrD/Ss, PtD/Ss, NcD/Ss, PtD/NcD.
d.f. = 1,11 for TrD/NcD, TrD/PtD.

After determining that differences probably exist, tests to determine whether the significant differences were between sample means or concentration parameters (specifically **k**), or both, were performed. Two Watson-Williams tests were selected; one to test the hypothesis that two mean angles differ significantly from each other, and the other to test whether the concentration parameters (**k** values) from two samples significantly differ (Mardia, 1972, p. 154, 161). Because both tests are parametric, assuming a von Mises distribution and, for the test of differences between means, average values of **r** greater than 0.75, their use must always be interpreted with care. The test statistic for both tests is approximately distributed as F, and if the assumptions are met, values of F calc greater than F tab are interpreted to mean that there is significant difference between the populations sampled. Less refined versions of both tests are also given by Batschelet (1981, p. 95, 122). Results are listed in Tables XI and XII.

TABLE XI

CALCULATED VALUES OF F FOR TESTS OF MEAN ORIENTATION

	TrDA	TrDB	PtD	PtC	NcDA	NcDB	NcC	AnE
Ss	1.4	121*	6.1*	2.8	4.5*	212*	2.0	.005
TrDA		272*	6.7*	3.2	29.9*	424*	1.3	.33
TrDB			89.1*	2.3	538*	8.8*	33.0*	46.4*
PtD				.93	43.1*	162*	.04	2.2
PtC					12.6*	7.1*	.78	2.1
NcDA						1163*	16.6*	3.3
NcDB							76.3*	127*
NcC								1.2

* Significant at .05 d.f. = 1, N - 2 and N = $n_1 + n_2$

Sample Size (n):
TrDA - 335
TrDB - 118
PtD - 95
PtC - 10
NcDA - 150
NcDB - 104
NcC - 22
AnE - 12

TABLE XII

CALCULATED VALUES OF F FOR TESTS OF k

	TrDA	TrDB	PtD	PtC	NcDA	NcDB	NcC	AnE
Ss	2.7*	2.7*	.2	23.9*	2.7*	2.7*	.9	5.9*
TrDA		1.1	1.4*	3.2*	3.0*	2.5*	.3	2.2
TrDB			1.5*	3.4*	2.9*	2.4*	1.7	2.1
PtD				24.5*	4.4*	3.7*	1.1	6.0*
PtC					9.7*	8.2*	21.1*	23.2*
NcDA						1.2	4.8*	1.4
NcDB							4.0*	1.2
NcC								3.5*

* Significant at .05 d.f. = $n_1 - 1, n_2 - 1$

Note: Sample sizes are listed in Table XI.

CHAPTER IV

OBSERVATIONS AND INTERPRETATIONS

External Dune Morphology

Dune Size, Slope, and Type

There are marked differences in dune size and type among the several soils formed within duned areas. Generally, three main groupings can be made, dunes of the modern floodplain, dunes of the low terraces, and dunes of the high terraces.

Floodplain Dunes. Recent dunes of the modern floodplain are all of the Ss (Sand Dunes) phase of the Lincoln Soil Series, except that a few Tivoli dunes are on higher portions of the floodplain. At numerous places dunes appear to have formed at locations of former channel banks or along accretion ridges on point bars. These dunes mostly form long transverse ridges with portions of the ridges showing definite barchanoid tendencies (Figure 9). Some ridges are more than a mile long, but most are measured in hundreds of yards.

In other areas, the dunes are more nearly parabolic, with the nose portions of some adjacent dunes appearing to coalesce and to form a continuous transverse ridge as described and pictured by Melton (1940, p. 123, 155). These ridges generally are very sinuous in map view, with the longitudinal sides of the parabolic form forming narrow ramps that join the ridge from the windward side. Isolated parabolic and barchanoid dune forms are not uncommon.

As represented on topographic maps and reported by the Soil Conservation Service (1968), these dunes are only rarely more than 25 ft. high. More generally, they are from 8 to 15 ft. high. The transverse ridges are highest. Slipface slopes approach the angle of repose for sand, with many as steep as 28-30 degrees.

Low Terrace Dunes. Tivoli dunes of the lowest terrace generally bury the terrace escarpment and extend away from the river beyond the scarp. The escarpment probably was the locus for initiation of dune-building. These dunes commonly have the same coalescent parabolic form described earlier, and many have a long transverse ridge above the terrace scarp. Most individual ridges are several hundred yards long, but some are much longer. Away from the scarp, dunes generally are sinuous, transverse and barchanoid ridges (Figures 9, 19) with some slipface slopes near 28 degrees. The ridges generally intersect, with the dune at the intersection appearing to have accreted in place, somewhat resembling a star dune. This topographic form seems to be that which Melton (1940, p. 131) referred to as "peak-and-fulje". In some areas, blowouts and parabolic forms are superimposed on transverse forms, and have created a dune

Figure 19. Aerial Photograph of Tivoli, Pratt, and Nobscot Dunes. (Scale: 1:20000; Location centered on S11, T21N, R11W)

morphology that is so complex as to defy effective description (Figure 19). Such areas seem to be like the ones that Smith (1940, p. 154) called "chaotic". A few isolated Tivoli dunes are a more pronounced barchanoid shape. Most of these are surrounded by nearly level terrace alluvium or small "rolling" areas of Pratt soils.

Tivoli dunes are as high as almost 70 ft., but more generally are between 15 and 40 ft. high. In many cases, the highest dunes appear to have accreted in place. The sides of such dunes appear to be oversteepened due to formation of blowouts with at least some of the excavated sand having been deposited on top of the dune. At one site (W/2, SW, SW, S13, T21N, R11W), this form of dune growth was observed taking place. From 1 to 3 ft. of fresh rippled sand was deposited along the brink of a stabilized, 60-ft., transverse Tivoli dune. Sample 204 was collected here and tested as a fine grained sand with the second-best sorting of any sample. The slipface side of this dune was covered by a dense growth of large trees with tops extending well above the dune brink, whereas the stoss side was much oversteepened (30-40 deg.) and vegetated with a few scattered clumps of grasses.

A Pratt phase (PtD), developed on slopes of more than 5 percent, is found on dunes of the low terraces, just to the northeast of the Tivoli dunes. At some places, these dunes apparently are overlapped by Tivoli dunes. They are similar to the Tivoli dunes, but generally are lower, more rounded, and have slipfaces with less remaining slope than Tivoli dunes. Considering the relative weathering differences, these Pratt dunes seem more closely related to Tivoli dunes than to Nobscot (NcD) dunes.

On the average, Nobscot (NcD) dunes of the second terrace are similar in height to Tivoli dunes. However, because of greater width, they appear to be more massive. Many are located above a terrace escarpment. Several large areas are covered completely by dunes with sinuous transverse and barchanoid ridges (Figures 9, 19). As on Tivoli dunes, many ridges intersect; and at intersections, the dunes seem to have accreted in place and somewhat resemble star dunes. Thus, morphology of these Nobscot dunes is similar to that of Tivoli dunes, except that the Nobscot dunes have the appearance of being more weathered. In fact, their slipface slopes are generally only 7 to 20 deg. It would appear that the Nobscot (NcD) and Tivoli dunes formed in much the same way, under very similar conditions. However, the Nobscot dune-forming climatic event was probably of greater duration, as made evident by the much greater areal extent of these dunes.

High Terrace Dunes. On dunes of the higher terraces soil series are variable. The dunes are mapped as Nobscot Series with slopes of 5 to 8 percent (NcD), Nobscot Series with slopes of 3 to 5 percent (NcC), Pratt Series with slopes of 3 to 5 percent (PtC), Pratt Series with slopes greater than 5 percent (PtD), and Aline Series (AnE). The major differences among the map-units seems to be in steepness of slope and the grain size of soil, except that not all PtC phase soils contain lamellae. Dunes between Deep Creek and the Cimarron River generally are high-terrace dunes, but are mapped only as Nobscot (NcD) and Pratt.

Erosion has reduced slipface slopes on Nobscot (NcD), Pratt (PtD), and Aline dunes to range from 7 to 20 deg. Heights are from 10 to 25 ft. The low-terrace Nobscot dunes grade into high-terrace Nobscot dunes. The Nobscot (NcC) and Pratt (PtC) dunes are from 5 to 20 ft. high, and the steepest slopes are less than 10 degrees.

Nearly all high-terrace dunes are blowout-and-parabolic types. A few small barchanoid transverse ridges and isolated barchan dunes also can be identified (Figure 9). The boundary between the high-terrace dunes and the low-terrace dunes is gradational, regardless of the soil series involved.

Paleowinds

Orientation of Paleowinds

Examination of Figures 12 through 18, which graphically represent the slipface/paleowind directions, show that the dunes of most soil series have their modal slipface orientation facing, and, by deduction, had effective sand-moving paleowinds blowing toward the NNE. The one exception is Pratt (PtD) dunes, which have a modal direction of NE. Also, Tivoli and Nobscot (NcD) dunes have a second modal orientation at ESE and SE. As indicated by Table VIII, the distributions appear to be strongly nonrandom. The conclusion is justified that the most common effective sand-moving paleowinds were south-southwesterly to southwesterly for all soil series, with the Tivoli and Nobscot (NcD) dunes also having a strong west-northwesterly to northwesterly wind component. The fact should be noted that dunes of all other soil series have some slipfaces that indicate northwesterly winds, raising the possibility that these distributions are also bimodal. Unfortunately, their low number of observations prevents a definitive judgement, except possibly for the Pratt (PtD) dunes.

Upon examination of the mean orientations listed in Table VIII, one sees that except for the northwesterly paleowind modes (TrDB and NcDB) of the Tivoli and Nobscot (NcD) dunes, all mean directions are within the northeast quadrant. Table X shows that in some cases the variation may be statistically significant.

As seen in Table XI, as expected, the northwesterly TrDB and NcDB mean paleowind orientations of the Tivoli and Nobscot (NcD) dunes are significantly different from the southwesterly paleowind orientations (except for TrDB vs PtC). The orientations of the TrDB and NcDB modes are also significantly different from each other. However, it must be noted that many data points in the TrDA, TrDB, NcDA, and NcDB distributions are hand picked. Therefore, any given observation could belong to the other modal distribution for that soil series. Thus the TrDB and NcDB distributions may not be statistically different.

The PtC, NcC, and AnE mean orientations appear to show no meaningful significance patterns other than stated above. Their low sample numbers and possible bimodal distributions would seem to account for the other tabulated significant differences. They do not test as significantly different from each other.

Among the remaining southwesterly mean paleowind orientations for the Ss, TrDA, PtD, and NcDA dunes, only the difference between the Ss and TrDA orientations is not significant. However, caution must be exercised in interpretation, because the test used is parametric, the TrDA and NcDA distributions have been manipulated, the Ss and PtD distributions may be bimodal, and some average **r** values are less than 0.75 (Batschelet, 1981, p. 97).

Table XII seems to hold very little geologically significant information. The significant differences between the **k** (angular deviation) values were quite predictable from the listed values of **r** and **k** in Table IX. The PtC values were significantly different from all other values, but significance is not deemed important because the Pratt (PtC) dunes yielded the fewest number of data points and the points were widely spread. It is noted that there is no significant difference in the **k** values between either the TrDA and TrDB or NcDA and NcDB distributions. This lack of difference may mean that these data distributions were suitably picked, which would give more confidence in their mean paleowind orientations. The interpretative cautions which apply to the test of differences in mean orientation, except for the constraints on the average value of **r**, also apply to this test of significant differences between **k** values.

It would seem then, that the predominant effective sand-moving paleowind orientation for dunes of all soil series was south-southwesterly. Also, during the two major dune-forming episodes, Tivoli and Nobscot (NcD), northwesterly winds were very important. Dunes of the other soil series have been discernibly affected by northwesterly winds, although possibly not as significantly as Tivoli and Nobscot (NcD) dunes. While it is probable that the difference in effective wind orientations was seasonal, it is also possible that winds from one quadrant formed dunes which were reworked by winds from the other quadrant. Other than the possibility that quite ancient dunes are present that were formed by predominant northwesterly winds (Melton, 1940), there seems to be insufficient reason to conclude that the effective sand-moving paleowind orientations have changed significantly through time or were different from those of today, except that seasonal effects may have been more pronounced.

Velocities of Paleowinds

The averages of the threshold paleowind velocities in miles per hour for the dune soils are Recent (Ss), 12.34; Tivoli, 11.52; Pratt (PtD), 11.79; Pratt (PtC), 12.27; Nobscot (NcD), 12.26; Nobscot (NcC), 12.19; and Aline, 12.83.

The average maximum paleowind velocities for the dune soils are Recent (Ss), 17.32; Tivoli, 16.16; Pratt (PtD), 16.61; Pratt (PtC), 16.38; Nobscot (NcD), 16.36; Nobscot (NcC), 16.10; and Aline, 16.77. The threshold velocities range from 9.55 mph to 13.83 mph with an overall average of 12.14 mph. The maximum velocities range from 13.28 mph to 19.21 mph with an overall average of 16.46 mph. These values are consistent with modern average wind velocities of about 13 mph in the study area (Soil Conservation Service, 1968, 1975), and are also consistent with computed velocities reported for sand of similar grain size (Evans, 1962; Marrs and Gaylord, 1982; Ahlbrandt, and others, 1983).

As suggested by the test values listed in Tables VI and VII, there was very little, if any, important differences among the paleowind velocities when dunes of the different soil series were active. Table VII shows that there was no significant difference between the variances of the winds for any of the dune soils. Table VI records only significant differences between the maximum velocity means of the Ss soil phase and the PtC, NcD, and NcC soil phases. The difference between the Ss phase velocities and the others can be attributed to the nearness of the Recent (Ss) dunes to their source area. The higher computed wind velocities for the Recent (Ss) dunes probably are a consequence of retention of larger sand grains. In other dunes with longer exposure to wind sorting, these grains were probably removed during migration or deeply buried during vertical accretion.

Alternatively, other sand source areas may not have contained the larger grains.

Certainly, as computed, paleowinds were strong enough to have carried the sand. Because they compare favorably with modern winds, it can be concluded that given a drier climate, the dune fields could be active.

Internal Structure

At all sites where the internal structure of dunes was evident, that structure was of laminae. At some sites and depths, laminae were disrupted or obscured by bioturbation, other deformation, erosion, and/or pedogenic processes.

Bedding Features

Generally, laminae are almost uniform, with thicknesses ranging from 1/8 to 1/2 in. (Figures 20, 21, and 22). The steepest dip is 26 degrees, but cross laminae this steep are not common. These steepest dips are usually in the smaller Recent (Ss) and Tivoli dunes. More commonly, dips are from near zero to only a few degrees. Low dips are the norm in the larger dunes of all soil series. Low dips may be attributed to any or all of the following causes: formation as climbing translatent (ripple) strata (Hunter, 1977; Kocurek and Dott, 1981), the presence of vegetation on the dunes (Goldsmith, 1973), or upward and/or upwind accretion (Melton, 1940; Smith, 1940).

One unusual observation in several of the larger dunes

Figure 20. Laminated Structure and Upward-darkening Units, Deep Cut Site.

Figure 21. Laminated Structure and Burrows, Deep Cut Site.

Figure 22. Laminated Structure, Burrows, and Horizontal Root Trace, Deep Cut Site.

was the occurrence of sets of relatively thick beds, each of which was very light-colored near the base, darkened upward, and contained several laminae (Figures 20, 23, and 24). These sets of beds are in series with the top of each unit marked by a very thin clay layer. The clay layers seem to be depositional and not related to lamellae. At the Deep Cut site (NE, SE, SE, S14, T20N, R11W; Plate 1) in a 60-ft., Nobscot dune (Figure 25), lamellae were developed at depths of 2 to 4 ft., whereas the units with clay layers occurred lower in the deposit, below the possible paleosol.

One explanation for the darkening-upward sequences of beds, is that each unit in the sequence represents one sand-

Figure 23. Upward-darkening Units, Deep Cut Site.

Figure 24. Upward-darkening Unit and the Wedging Effect of Multiple Bounding Surfaces, Deep Cut Site.

Figure 25. Wide View of the Deep Cut Site. A paleosol is just above the person's head.

storm episode. The clean sand at the base could record deposition during the height of the storm, and darkening could be from relative increase in clay deposition as the storm abated and wind velocities fell. The clay layer could have resulted from settling of dust from still air after the storm. A similar sequence of events happens on a lesser scale during most Springs, when gusty southwest winds precede thunderstorms; the storms are followed by west-to-northwesterly winds carrying dust. Although not likely, another explanation could be that the clay deposition was unrelated to sand deposition, but that once the clay was in place some was translocated by water down into the sand.

Bioturbation

Evidence of bioturbation by plants and animals was very commonly observed. Many filled burrows were seen at several sites, and nearly all dunes were penetrated by the roots of various plants. Burrows several inches long and up to 3 in. in diameter were very common (Figures 21, 22, 26, and 27). These burrows were always filled and were easily visible, because the fill sand was generally of a different, generally lighter, color than the burrowed sand. At the Rock Terrace site (Plate 1), several much larger, filled burrows were noted in the terrace alluvium (Figure 28).

Figure 26. Laminated Structure and Burrows, Deep Cut Site.

Figure 27. A Filled Burrow.

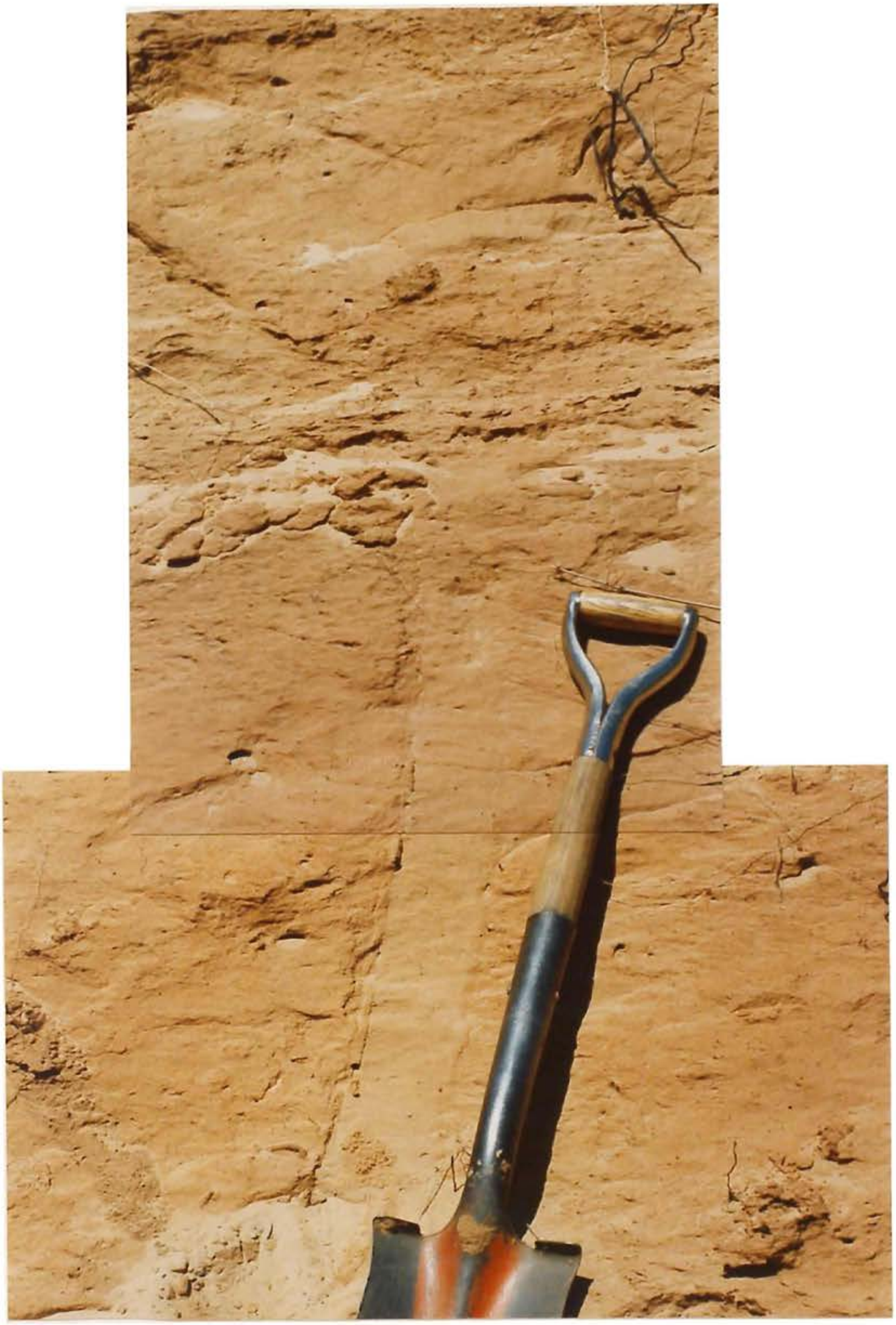

Figure 28. Filled Burrows, Rock Terrace Site.

But, owing to the indistinct boundary between the terrace alluvium and dune sand at this site, whether these burrows continued upward into the dune sand could not be confirmed.

Modern roots are very common in the dune sand, with some extending to depths of tens of feet. Traces of ancient roots are expressed as hematized cylinders and organically darkened cylinders. Figure 29 shows the bottom side of an undercut at the Deep Cut site (Plate 1). The reddish circles are sites of former root penetration, with some still having the root present. Several horizontal root traces are also evident. Figure 22 shows a nearly horizontal root trace that contains root fragments and is darkened. In one cutbank of a Recent (Ss) dune (NW, SE, SW, S9, T21N, R11W), root tubules that had been cemented (apparently with calcium carbonate) were observed being isolated by the wind's removal of surrounding sand.

Deformation

Evidence of deformed layers was observed at only two sites. The structure shown in Figure 30 was developed in a Pratt (PtC) dune, and that in Figure 31 at the Deep Cut site (Plate 1). The exact nature of either structure was not determined, but deformation could have been due to slumping or possibly to draping of laminae over rough surfaces.

Figure 29. Hematized Root Traces, Deep Cut Site.

Figure 30. Deformed Laminae in a Pratt (PtC) Dune.

Figure 31. Deformed Laminae in a Nobscot Dune, Deep Cut site.

Erosional Surfaces

Several apparent bounding (wind-scour) surfaces were observed. Taken at the Core 1 site (Plate 1), Figure 32 shows two-dimensional configuration of a buried bounding surface in a Nobscot (NcD) dune; the lower unit is cross laminated, but layering in the upper essentially is horizontal. The upper unit also contains sand-sized clay grains. Sand samples 40 and 41 were taken above and below the irregular contact. Figure 24 shows the wedging effect of several episodes of scour and fill activity. The photo was taken at the Deep Cut site (Plate 1).

Figure 32. Bounding Surface in a Nobscot Dune, Core 1 Site.

Pedogenic Structures

Soil Horizons. Figures 25 and 33 show a probable soil horizon developed and buried in the Nobscot dune at the Deep Cut site (Plate 1). The horizon is sub-parallel to the ground surface, bioturbated, and shows no internal laminated structure. Lamellae were only observed in this dune above the presumed buried soil. Figure 34 shows a buried solum in a dune mapped as Pratt (PtC) at the Core 20 site (Plate 1). The figure shows a buried A horizon and a B horizon that contains several lamellae. No lamellae were developed above the buried A horizon. At this site, the Pratt (PtC) soil apparently evolved in a mantle of dune sand deposited over a

Figure 33. Close-up of the Paleosol, Deep Cut Site.

Figure 34. Paleosol in a Dune of the Pratt (PtC) Series, Core 20 Site.

dune on which Nobscot or Aline soil was developed.

Lamellae. Lamellae are in several of the older dune soils. They are best developed in the Aline (Figure 35) and Nobscot (Figure 36) soils. Some Pratt soils that developed on the high terraces also contain lamellae. Lamellae were not observed in the more modern dune soils, Recent (Ss), Tivoli, and Pratt of the lower terraces.

Figure 35. Lamellae in a Dune of the Aline Series.

Figure 36. Soil Profile in a Dune of the Nobscot (NcD) Series.

Lamellae seem to have developed from several related, but not exclusive processes. In some locations, they are very thin (young?), and almost exactly follow the laminated structure of the dune. The laminae in which lamellae are present appear to have been enriched in rock fragments eroded from the shaly Permian redbeds. Thus, a geologic process (deposition of clay transported as rock fragments) seems to be influencing the pedogenic development. In a few isolated spots, lamellae of this type have small downward warps, possibly due to translocation caused by downward-moving water or to compaction. Robinson and Rich (1960) concluded that lamellae primarily resulted from wind or water deposition, but considered the unaltered lamellae sediment to have been finer than sand-sized rather than sand-sized rock fragments.

Most lamellae developed somewhat horizontally. They thicken and thin, branch, cross, and ordinarily have no apparent relationship to the internal stratification of the dune. Figure 35 shows a soil profile containing such lamellae along with a few indistinct lamellae that roughly follow cross lamination in the lower part of the figure. Lack of relationship to internal stratification is very apparent in Figure 37, which shows one lamella crossing a filled burrow. This type of lamella apparently has developed from processes not related to deposition of sand. It is explained best by theories that call for the deposition and translocation of clays (probably air-fall) by a moving water front within the soil profile (Folks and Riecken, 1956;

Wurman, Whiteside, and Mortland, 1959; Dijkerman, Cline, and Olsen, 1967; Gray, Meksopon, and Peschel, 1976).

Figure 37. Lamella Crossing a Filled Burrow in a Dune of the Nobscot Series.

When water is carrying clay through dune sand, it follows stratification within the dune to some extent (Ahlbrandt and Fryberger, 1982). This could explain why some lamellae are aligned roughly with cross laminations. An example of lamellae parallel to cross lamination is shown in Figure 38. Note that numerous lamellae cross from one lamina to another, possibly along ripple cross strata.

Figure 38. Lamellae Parallel to Cross-laminae.

The evidence suggests that the abundance and thickness of lamellae is an indicator of a soil's age. Although, it is not known exactly what other factors might influence lamellae development, it is probable that factors such as slope position, amount of interstitial clay, average grain size of the sand, sorting, and frequency of precipitation contribute to the speed of development. But, in general, the more advanced the development of lamellae, the greater the age of the soil and thus, the dune (Gile, 1979).

Sieve Analysis

Statistical Results

Means, Sorting, Skewness, and Kurtosis. Using phi values from probability plots, the formulas given by Folk and Ward (1957) were used to compute statistical moments for each sample. Computed on the total sample, the average textural parameters for the dune sand samples are mean, 2.316 phi; sorting, 0.693 phi; skewness, 0.1897; and kurtosis, 1.1247. When the parameters are calculated only on the sand fraction of each sample, the results become mean, 2.259 and sorting, 0.675. Skewness and kurtosis do not change.

The textural parameters were seen to vary considerably both overall and within each dune soil series. The ranges for all 80 dune samples is as follows: mean, 1.863 - 3.137 phi; sorting, 0.4462 - 1.1608 phi, skewness, -0.0451 to 0.4008; and kurtosis, 0.8801 - 1.6483. The means of five samples were in the medium grained sand range, whereas two sample means were in the very fine grained sand range. The remaining sample means were in the fine grained sand range. Considered in the conversational terms of Folk and Ward (1957), two samples each were well sorted (0.35 - 0.50) and poorly sorted (1.0 - 2.0), with the remainder being moderately sorted (0.50 - 1.0). Thirteen samples had nearly no skewness (-0.10 to 0.10), with only one being very slightly negative. The remainder were positively skewed, with eight samples being very positively skewed (0.30 - 1.0). Two samples were very leptokurtic (1.5 - 3.0), 32 were leptokurtic (1.11 - 1.5), and the remaining 46 were mesokurtic (0.9 - 1.11). As computed here, the kurtosis of normal curves is equal to 1.00.

Two samples of water-deposited sand were taken from the modern Cimarron River channel. Their average textural parameters are mean, 2.258 phi; sorting, 0.533 phi; skewness, 0.178; and kurtosis, 1.168. These values fall well within the ranges of values for the dune sand, which does not rule out the river channel as a source of the dune sand. Average values of the textural parameters for each dune soil series, including means from terrace alluvium samples, are given in Table XIII. The difference in mean grain size and mean sorting between the terrace alluvium and any of the dune sands is considerable. The dune soil series are listed in rough order of distance from the Cimarron River; therefore a tendency toward decrease mean grain size of sands with distance from the river is evident. Other notable trends are the moves toward poorer sorting and greater skewness with distance from the river.

TABLE XIII

AVERAGE TEXTURAL PARAMETERS

Soil	Mean	Sorting	Skewness	Kurtosis
Ss	2.157	0.662	0.114	1.082
TrD	2.332	0.616	0.112	1.049
PtD	2.337	0.689	0.157	1.100
NcD	2.281	0.687	0.219	1.163
PtC	2.344	0.719	0.225	1.183
NcC	2.545	0.766	0.207	1.016
AnE	2.344	0.814	0.284	1.156
Terrace Alluvium	3.264	1.444	0.263	1.110

Means and sorting given in phi units.

Generally, one would expect that sorting would become better with distance from the river, assuming that the river is the source of the sand. Since this is not true, a plausible explanation is called for. Table XIV may provide that explanation.

TABLE XIV

MEAN 95 PERCENT VALUES OF PHI

Ss	TrD	PtD	NcD	PtC	NcC	AnE
3.363	3.438	3.662	3.707	3.853	4.043	4.085

The values of phi increase (grain size decreases) to the right, which indicates an increasing amount of fine grained material in samples collected farther from the river. Silt and clay in dune sand leads to poorer sorting and higher skewness. The finer material could have been added to the dune sand as loess; or the primary source of sand in dunes on the higher terraces may not have been the river.

The probable primary source of sand for the high-terrace dunes is terrace alluvium, with some possible contribution from the river. This interpretation is supported by observations that most high terrace dunes are parabolic or blowout, and some contain sand-sized clay grains. Also, several of the cumulative-percent curves plotted from sand of the high terrace dunes, group closer to the terrace alluvium curves, than to the curves plotted from dune sand collected on the lower terraces (Appendix E).

Low-terrace Nobscot (NcD) dunes occupy an intermediate, transitional position between high terrace dunes and low terrace dunes of other soil series (Plate 1). Nobscot (NcD) dunes found farthest from the river primarily are discontinuous parabolic and blowout types. Those nearest the river form a nearly continuous band of mostly barchanoid ridge and transverse dunes. These dunes have less fine grained material than those farther from the river, and probably have a former, higher channel and floodplain of the river as their primary source area.

The Tivoli and Pratt dunes of the lowest terrace and high floodplain appear to have former channels and parts of the modern floodplain as their sand source. In the study area, the river has migrated southwestward. Clear evidence is given by the series of terraces formed northeast of the river (Fay, 1965), and by longtime residents of the region who report channel migration to the southwest of more than 1/2 mi. in this century. So, in most instances the sand source for these dunes would be the former channels and higher floodplain deposits to the northeast of the present channel.

The Recent (Ss) and a few of the lowest Tivoli dunes appear to have as their sand source the modern or very nearly modern river channel and floodplain.

Discriminant Analysis

Examination of Table V reveals a pattern of significance which appears to hold geologic importance. The table is arranged, left to right, according to distance from the Cimarron River to dunes of each soil series, which is also according to postulated relative age (Table II). At the .05 significance level, the PtD dune sand is not significantly different from any other. Note that it occupies a central position both geographically (Plate 1) and in time. With the exception of the AnE dune sand, there are no significant differences between any of the dune sands apparently older than PtD, or between the two dune sands apparently younger than PtD. However, both younger dune sands do significantly differ from those sands older than PtD, noting the exception of NcC dune sands. The AnE and NcC exceptions from the pattern may be reasonably explained by: (1) their smaller number of samples relative to the other dune soils, (2) their enrichment in silt and clay (Table XIV), and (3) for the case of NcD vs AnE, the fact that most Aline dunes are blowout and parabolic types developed mostly from terrace alluvium, while many of the Nobscot (NcD) dunes are transverse or barchanoid ridges apparently developed with a greater input of sand derived directly from the riverbed.

It can be concluded, that the distribution of significance values in Table V support the relative age relationship suggested by the upwind/downwind relationships (Table II). Therefore, dunes nearest the river generally are youngest, with the dunes becoming progressively older with increasing distance from the river, as is suggested by significant differences between the means of sand statistical measures if age differences become great enough. Support for the above conclusion also comes from the fact that soils formed on dunes at greater distances from the river have more mature soil profiles, as indicated by their thicker horizonation and greater abundance of lamellae (Soil Conservation Service, 1968, 1975).

Alternatively, another explanation for the distribution of significance values in Table V, could be progressive change in the sand source area through time. This interpretation would not change the relative age determination.

After completing the means-testing stage of the discriminate analysis, no attempt was made to compute a discriminate function. The fact that sands from adjacent dune soil series are not significantly different, would make such a function meaningless. For example, if a function was computed to separate Nobscot (NcD) from Tivoli dune sand, there would still be a possibility that an individual sand sample could be from a Pratt (PtD) soil.

Probe Cores

Mt. Zion Core

The Mt. Zion probe core was made just downwind of the slipface of a 60-ft. Tivoli dune (NE, SE, NE, S11, T20N, R10W; Plate 1), and reached a depth of 192 inches. The surface soil at the site was mapped as Pratt (PtC), which the field description (Appendix B) would seem to confirm. A stratigraphic profile is given in Figure 39.

Three paleosols were encountered. The first paleosol was at a depth of 32 in., the second at 80 in., and the third at 176 inches. The shallower paleosol was interpreted as having developed in dune sand, based upon results of sieve analysis (Appendix D, Sample 82). It was less well developed than the surface soil. The soil encountered at 80 in. had a well developed profile; it apparently evolved in floodplai or terrace alluvium (Appendix D, Sample 83; Appendix E). A sample of its sandy A horizon was obtained for radiocarbon

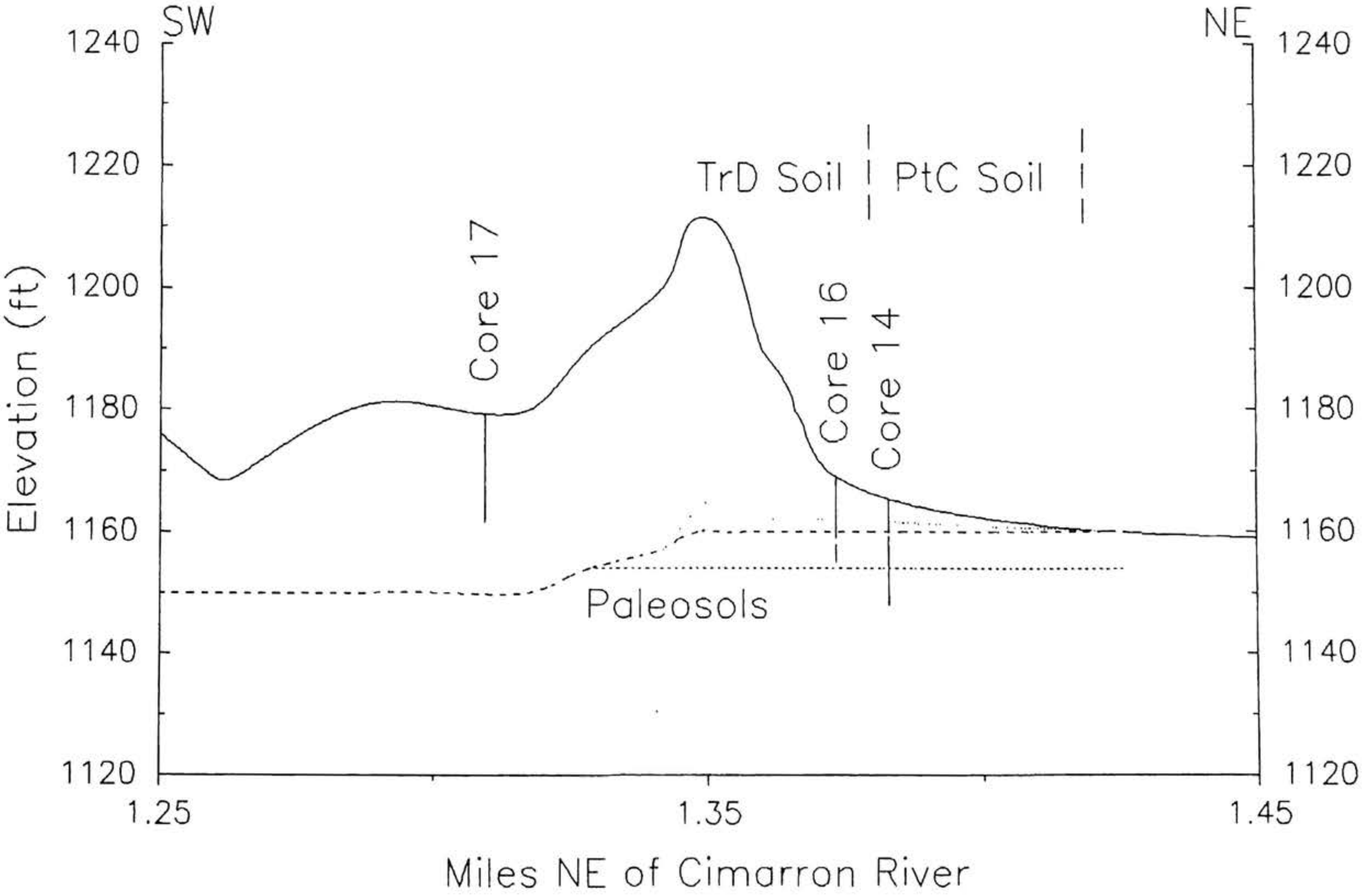

Figure 39. Stratigraphic Profile of the Mt. Zion Core Site. (Location on Plate 1)

dating. Results are in Table XV, p. 116. The deeper paleosol was not sampled.

Campbell Core

The Campbell probe core (SE, SE, SE, S21, T21N, R10W; Plate 1) was taken in an interdune depression very near a mapped boundary between Tivoli and Pratt (PtD) soils (Soil Conservation Service, 1968; Figure 40). It was just downwind from the slipface of a 30-ft. Tivoli dune. The surface soil was closer in development to the Pratt Series (Appendix B). One distinct paleosol was encountered at 108 inches. The slope of the cumulative-percent curve from a sample taken below the paleosol indicated that it was developed in terrace alluvium (Figure 41; Appendix D, Sample 78; Appendix E). The A horizon had a high clay content, and was sampled for dating (Table XV).

During the bucket-auger survey of the site, there was some indication (a darkened, finer grained layer) that another paleosol might be at a depth of about 70 inches. This possible soil was not seen in the probe core, and its presence or absence is not confirmed by the sieve analysis of several samples from the site (Appendix D, Samples 74, 75, 76, and 77; Figure 41).

Ames Core

The Ames probe core (NW, SW, NW, S3, T20N, R9W; Plate 1) was taken along a section line road which cut through the

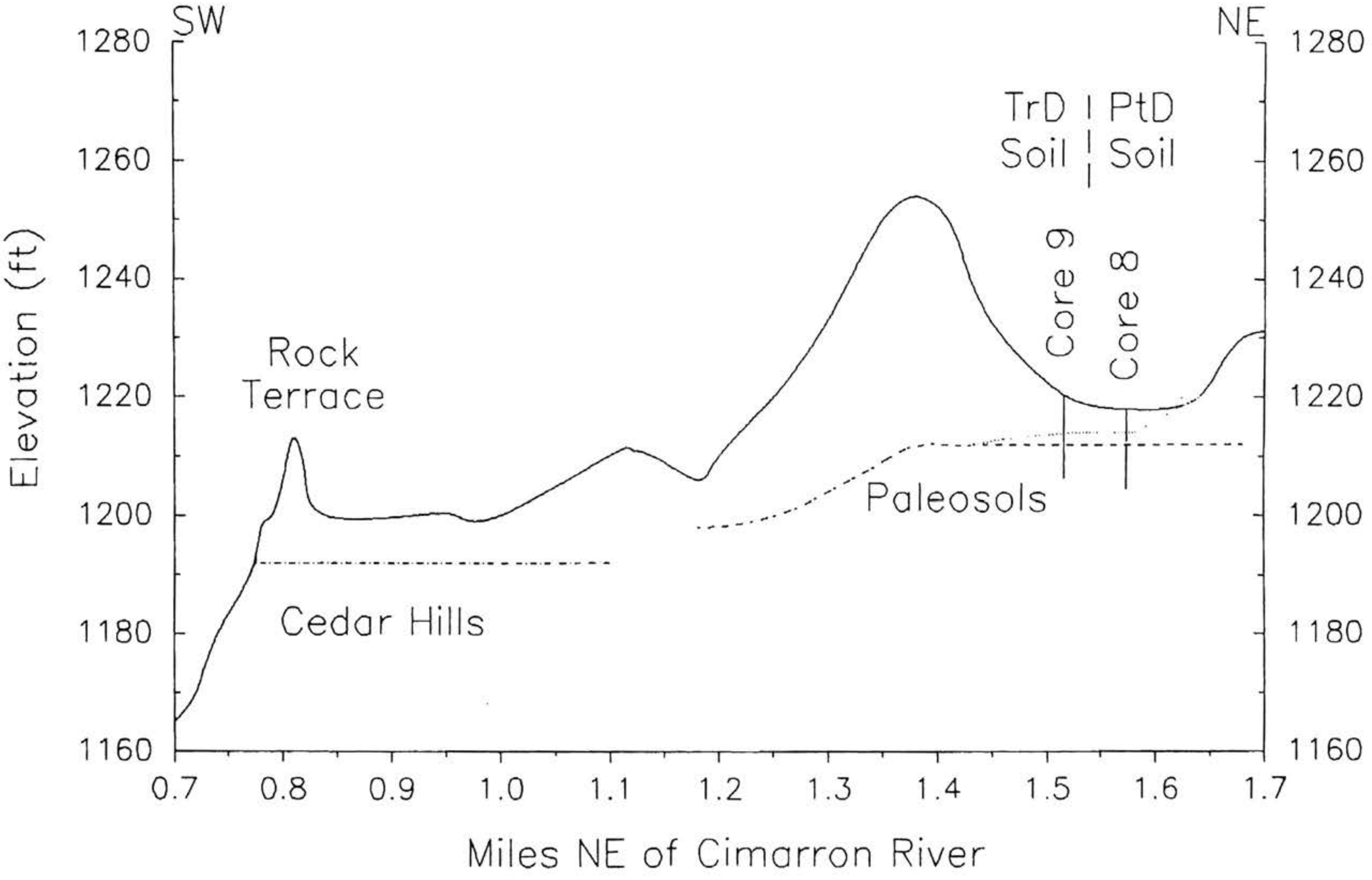

Figure 40. Stratigraphic Profile of the Campbell Core Site. (Location on Plate 1)

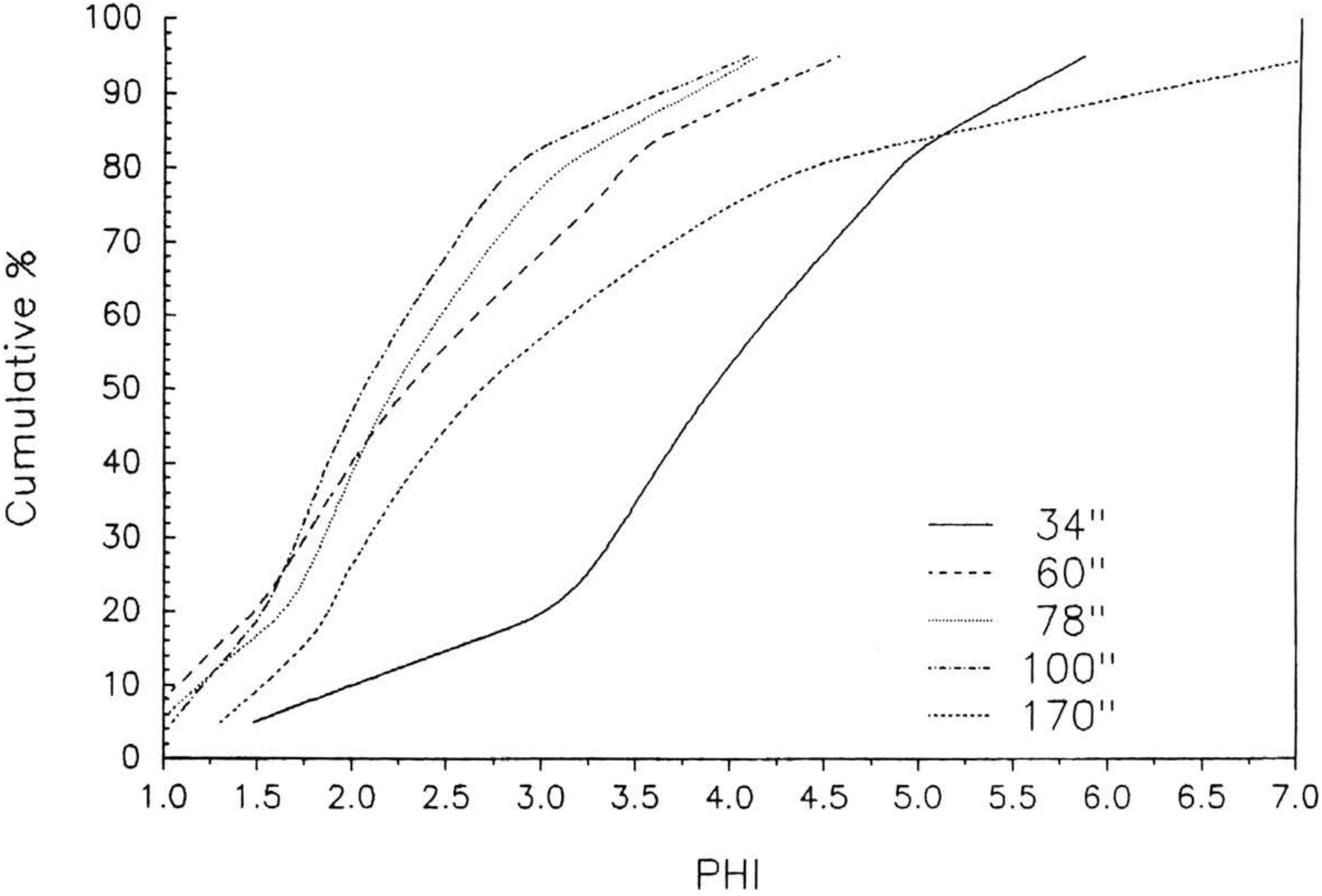

Figure 41. Cumulative-percent Curves for Sand Samples Collected from the Campbell Core. (Location on Plate 1)

edge of a Nobscot (NcC) dune. There would have been approximately 5 ft. of dune sand at the site had the roadcut not been present. The dune sand was sampled a few feet from the probe site at a depth of 2 ft. (Appendix D, Sample 62). The core encountered one paleosol at an estimated depth of 8 ft. below the original ground surface. The slope of the cumulative-percent curve plotted from a sample taken below the paleosol (Appendix D, Sample 63) indicates that the paleosol was developed in terrace alluvium. The A horizon had a high clay content, and was sampled for dating (Table XV). The B horizon was different from others seen in that it contained iron-and-manganese concretions. A stratigraphic profile is given in Figure 42.

Brinson Core

The Brinson site (SE, SE, SW, S17, T22N, R11W; Plate 1) was cored only to 3 ft. with the soil probe. Deeper coring with the probe was not possible, due to looseness of the dune sand. One lamella was seen near the base of the 3-ft. core. A stratigraphic profile is given in Figure 43.

Later, the probe site was cored with a bucket auger to obtain a sample for dating. The auger passed through 12 ft. of dune sand before encountering the clay loam of a buried soil. Unfortunately, there was no organically darkened A horizon at the site. Another hole was augered approximately 100 ft. away, in a small interdune depression. This hole encountered a paleosol at 7 ft., and here it is rich in

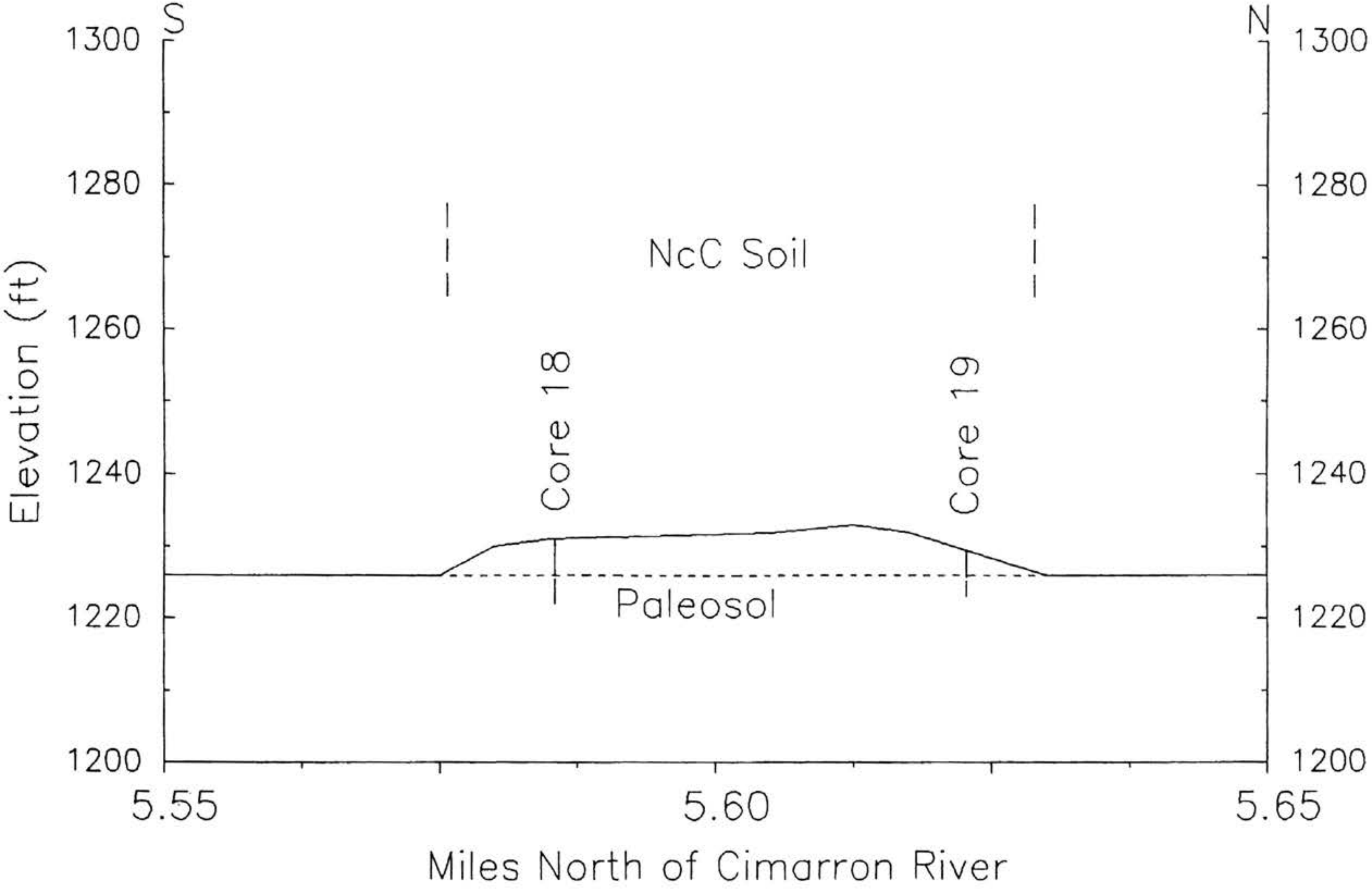

Figure 42. Stratigraphic Profile of the Ames Core Site. (Location on Plate 1)

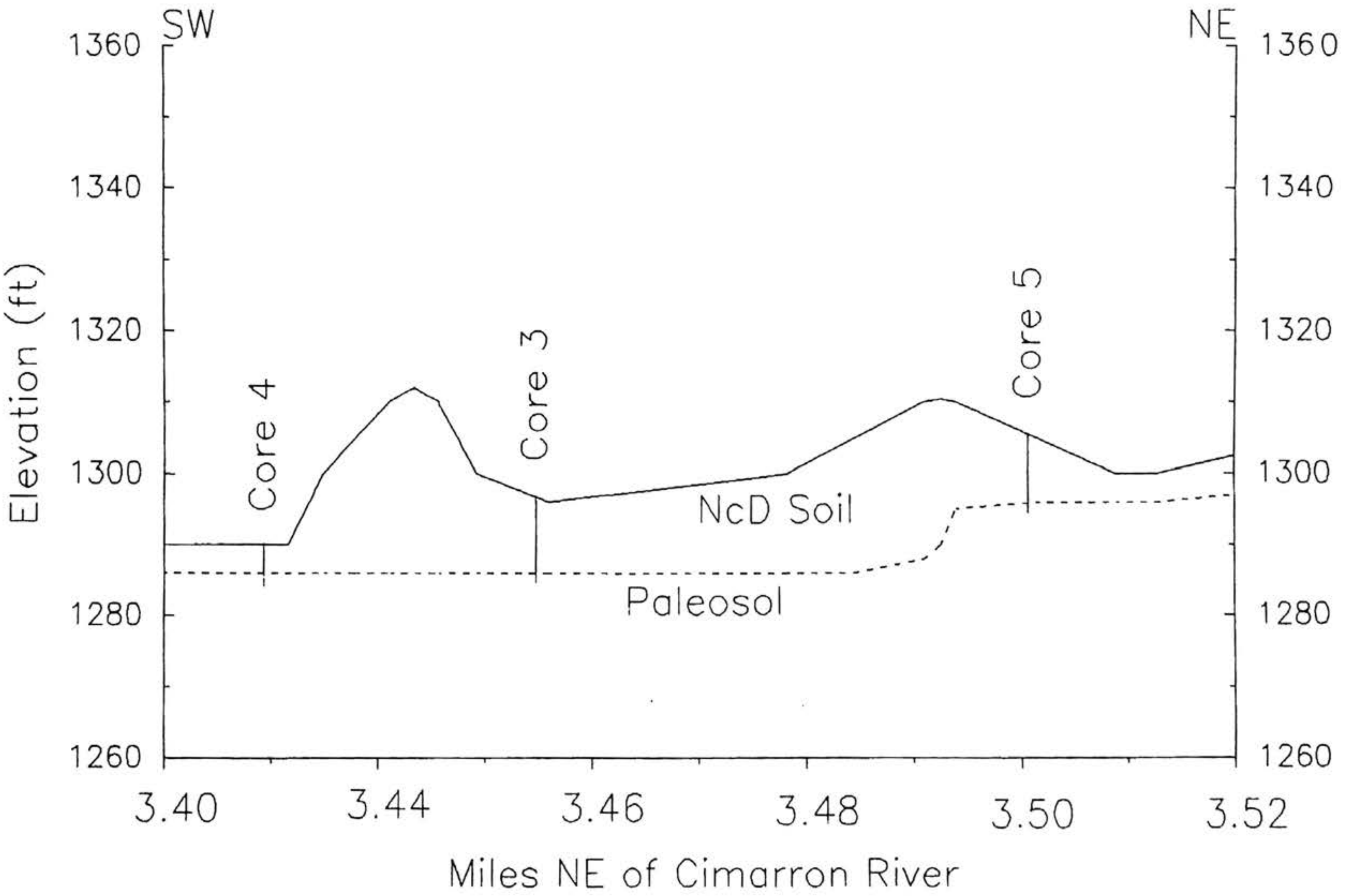

Figure 43. Stratigraphic Profile of the Brinson Core Site. (Location on Plate 1)

organic material. A sample was taken for radiocarbon dating (Table XV). One sieve sample (Appendix D, Sample 401) was taken from this hole at 4 ft. Its cumulative-percent curve has a shape that is similar to those of the other two interdune samples (Appendix D, Samples 74, 81).

Radiocarbon Dates

Procedure

Each paleosol sample was sealed in an air-tight, sterile plastic bag as soon as possible after recovery. These were shipped for processing to Krueger Enterprises, Inc., Cambridge, Massachusetts. There the entire sample was dispersed in a large volume of water and the clays and organic matter were eluted from any sand and silt by sedimentation and decantation. The clay/organic fraction was treated with hot dilute HCl to remove carbonates. The sample was passed through a 100-mesh sieve, washed, dried, and roasted in oxygen to recover carbon dioxide from the organic matter for analysis.

Results

All dates were C-13 corrected, and are based on the Libby half-life of 5570 years. Each date is referenced to A.D. 1950. Results and lab numbers are listed in Table XV.

The dates correlate well with previously published chronologies for dune-building climatic episodes throughout the Great Plains states. The two phased minor peak of dune

TABLE XV

RADIOCARBON AGES

Sample	Krueger #	Date (years B.P.)	Accuracy
Mt. Zion	GX-14706	1,200	+/- 70
Ames	GX-14709	6,385	+/- 285
Brinson	GX-14708	7,645	+/- 280
Campbell	GX-14707	11,345	+/- 425

activity, documented in the Rocky Mountain basins and approximately duplicated in the Nebraska Sand Hills, could correlate with the date from below the Tivoli dune at the Mt. Zion site (Ahlbrandt and others, 1983). Also, the stratigraphic position (Figure 39), soil development (Appendix B), and date of 1,200 yrs. B.P. suggest that this paleosol correlates with the Caddo and Copan paleosols (Hall, 1988). Both the Ames and Brinson dates from beneath Nobscot dunes fall within the well documented arid Altithermal interval (Ahlbrandt and others, 1983).

The age of the Campbell sample correlates to the most ancient published dates for the beginning of dune deposition in several dune fields of the Great Plains (Bradbury, 1980; Ahlbrandt and others, 1983, Wright and others, 1985). However, the surface soil at the site is mapped as Pratt (PtD) (Soil Conservation Service, 1968; Plate 1). It has only a small amount of clay in the B horizon, and contains no lamellae (Appendix B). Thus, the relative maturity of the soil would not seem to support such an ancient date. The seemingly anomalous date could have several possible explanations.

The previously described possible paleosol in the dune sand could account for the older date. However, even if present, the paleosol would not appear to be mature enough to account for the date. An unconformity could be present in the dune sand, but an unconformity without soil development would be almost impossible to detect with an auger sample or even in a 1-in. core. Notably, as shown in Figure 40, the cumulative-percent curve for the sample taken at 60 in. has a slightly different shape and distinctly less slope than the curves for the samples taken at 78 and 100 inches. This difference could be an indication of the presence of an unconformity, but is by no means definitive.

CHAPTER V

GEOLOGIC HISTORY

Prior to the beginning of dune sand deposition, the Cimarron River underwent a long period of cyclic entrenchment. The river migrated southwestward as it cut through soft Permian redbeds. Evidence of entrenchment and migration is left in the form of successively higher alluvial terraces extending away from the river to the northeast (Fay, 1965). The higher terraces apparently had more time to develop soil profiles before the initiation of eolian activity, because buried soils at these localities have much more clay than those of the lower terraces.

The Cimarron River seems to have flowed through the valley now occupied by the entrenched Deep Creek during one episode (Soil Conservation Service, 1968). The river left a broad floodplain and at least three terrace levels to the north (Figure 6). The switch to a position near the present river channel probably occurred before initiation of dune-building in the region, because all dunes in this area are located on the terraces and no evidence of dunes was found on the abandoned floodplain. The dunes on the terraces are mapped in either the Nobscot or Pratt soil series. The sand-source apparently was the abandoned floodplain and local terrace alluvium.

Eolian activity seems to have been initiated some time prior to 11,000 yrs. B.P., as indicated by the age of buried soil in the Campbell core. Assuming that Melton (1940) was somewhat correct in assigning an age greater than 15,000 years to windrift high-terrace dunes, there could have been earlier eolian activity in the area. The possibility is supported by at least one large Nobscot (NcC) dune (E/2, S22, T20N, R9W), which could correlate with the Series III dunes described by Melton (1940), and the paleosol developed on the rather large dune found buried below Nobscot lamellae at the Deep Cut site.

Some older dunes probably were reworked during the subsequent Altithermal episode or later eolian activity, which raises the possibility that the highest terraces may have dunes of several different ages. If true, this circumstance could explain the observation that some dunes have much more strongly developed B horizons and lamellae than others, but still others have no lamellae at all. Additional support for reworking is given by the paleosol beneath Pratt (PtC) soil (Figure 34). It is also possible that some differences in soil maturities could be caused by progressive stabilization rather than by reworking.

It can be stated with some confidence that eolian activity was extensive in the study area during the arid Altithermal interval, 8,500 to 4,000 yrs. B.P. Dates from the Ames and Brinson cores from beneath Nobscot dunes fall within that time period (Table XV), which would indicate that the majority of Nobscot dunes and others containing similarly developed lamellae date from the Altithermal (Gile, 1979). Compared to Recent (Ss), Tivoli, and other low-terrace dune soils, the relatively large areal extent of the Nobscot dune soils and other similar high-terrace soils suggests that eolian activity was more widespread and probably of longer duration.

During the Altithermal, the lowest terrace of the Cimarron River apparently was the floodplain. Present areas of complex transverse and barchanoid ridge Nobscot (NcD) dunes received abundant sand blown from this floodplain and from around the river channel. Hall (1988) has documented widespread stream entrenchment during this time. The river sand source decreased in importance to the northeast as the sand was trapped in the dune field. Concurrently, the more limited sand contribution of the alluvial terraces increased to the northeast. In response to change in the amount of sand supply, the morphology of the dunes gradually changes to the northeast across the dune field, from the higher, complex transverse and barchanoid ridge forms to lower, simpler parabolic and blowout forms.

Many dunes probably have migrated less than a few hundred yards, as indicated by the abundance of near horizontal internal structure. Such structure is consistent with that of parabolic and blowout dune types or vertical dune accretion due to conflicting winds; and can also be caused by the presence of vegetation and/or moisture during dune formation (Goldsmith, 1973; Gaylord, 1982). Therefore, dune morphology, internal structure, and strong evidence for conflicting paleowinds during Nobscot and Tivoli deposition would seem to support the apparent lack of significant migration. In some localities, it appears that the dunes may have actually accreted upward and upwind, as suggested by Smith (1940, p. 161) and Melton (1940, p. 128).

The exact manner in which the Pratt dunes fit into the eolian history of the region is difficult to ascertain. In many areas, PtC phase soils obviously occupy interdune depressions and lower slopes of both younger and older dunes (Soil Conservation Service, 1968, 1975). Hence, their relationship to the other soils is controlled by slope, rather than age. Evidence (Table II) is provided by the relatively large number of times PtC phase soils were observed at the toe of slipfaces on dunes of other soil series. Elsewhere, PtC phase soils are observed to overlie eolian paleosols that contain lamellae. Therefore, these PtC phase soils represent an eolian event that probably is younger than the Altithermal, but predates Tivoli deposition.

The Pratt (PtD) soils can be divided into those located between the Tivoli and Nobscot dunes, and those on high terraces above the Nobscot (NcD) dunes. On the basis of observations made in this study, high-terrace PtD phase soils contain lamellae and low-terrace PtD phase soils do not. Thus, it seems that the two areas of Pratt (PtD) soils are of different age. The high-terrace Pratt (PtD) dunes are mostly parabolic and blowout, and possibly formed during the latter part of the Altithermal because their lamellae are fewer and thinner than those in nearby Nobscot soils. As suggested by topographic position and relative soil maturity, low-terrace Pratt (PtD) dunes probably are older than Tivoli and younger than Nobscot dunes, and share their sand-source areas and morphology. The sharp appearance and soil maturity of low-terrace Pratt (PtD) dunes would seem to place them closer to Tivoli dunes in age.

The Tivoli dunes are the youngest of the more extensive dunes. Their age, as suggested by the Mt. Zion sample, places their activity during a known period of Rocky Mountain basin eolian activity from about 2,300 to 500 yrs. B.P. (Ahlbrandt and others, 1983). Possibly, the Tivoli dunes represent a late phase of this activity, whereas the adjacent Pratt (PtD) dunes are from an early phase of the same event. Additionally, the paleosol sequence beneath the Mt. Zion dune could mean that Tivoli eolian activity began as recently as the end of Caddo (Copan) soil development, 1,000 years ago, and continued through the dry climate peak from 600 to 400 years ago (Hall, 1988).

It would appear that climatic conditions during Tivoli deposition were much the same as during Nobscot deposition. However, the lesser areal extent of Tivoli dunes could argue that their arid climatic event was of shorter duration than that of Nobscot dunes. Also, compared to winds during

Nobscot (NcD) deposition (Figure 16), the less pronounced bimodality of Tivoli slipface/paleowind orientation data (Figure 13) suggests that winds were more variable in direction during Tivoli deposition, with the northwesterly wind component not as strongly developed.

Dunes of the Ss soil phase formed quite recently on the modern floodplain. Some of them are almost indistinguishable from Tivoli dunes, and probably are almost as old. Others are very near the modern river channel, barely are stabilized, and can be no more than a few tens of years old. This very recent dune activity correlates with eolian activity in the Rocky Mountain basins (Ahlbrandt and others, 1983). Certainly, some of the youngest dunes were active during the Dust-bowl years, and some are reported to have been active even before then by longtime residents of the area.

To summarize, all Nobscot (NcD) dunes, most of the high terrace Nobscot (NcC), Pratt (PtD), Aline, and some Pratt (PtC) dunes can be correlated to the widespread Altithermal climatic event. The numerous investigations discussed in Chapter II document similar Altithermal eolian activity in the Nebraska Sand Hills, the Killpecker and Ferris dune fields of Wyoming, the Wray, Greely, and Fort Morgan dune fields of Colorado, the Sand Hills of Bailey County, Texas and north-central Michigan, and even in the coastal dunes of California, Oregon, and Washington. There is some suggestion that a few dunes, most likely NcC phase and/or Aline soils, are from an even older climatic event. This is possible since separate studies (Melton, 1940; Gile, 1979; Bradbury, 1980; Gaylord, 1982; Ahlbrandt and others, 1983; Wright and others, 1985) document that eolian activity was widespread during the late Pleistocene and early Holocene in several of the dune fields listed above.

The absence of lamellae indicates that some high-terrace and all low-terrace Pratt (PtC) dunes are post-Altithermal in age; whereas low-terrace Pratt (PtD) and Tivoli dunes are from 500 to possibly 2,300 years old, based upon the Mt. Zion radiocarbon date, relative soil maturity, and regional correlation. Relative soil maturity indicates that Recent (Ss) dunes are a few hundred years old to modern.

It must be noted that in the study area, the relationships between dune soils, dune types, and dune ages is quite complex. Also, when dealing with multiple cycles of aridity, with the consequent reworking and differing ages of stability, there will necessarily be gradations among all of the variables which are studied. Thus, this history must be regarded as somewhat simplified.

CHAPTER VI

CONCLUSIONS

Owing to the complex nature of dune fields in Major and Alfalfa Counties and the extensive discussion with interpretations that has already been written, only several major observations will be made here.

1. There has been eolian activity along the Cimarron River during the known late Pleistocene and Holocene arid climatic events of the central Great Plains.
2. The Cimarron River and/or its alluvial terraces have been primary sources of dune sand.
3. Paleowinds were not significantly different from today's in velocity or direction, but may have had more pronounced seasonal differences.
4. When properly defined, soil mapping units provide information sufficient for distinction between Holocene dunes of differing ages.
5. Well developed lamellae in dune soils are indicators of stability since Altithermal time.
6. Textural parameters may be used to distinguish between dune soils of differing ages, if the age difference is great enough.

Recommendations

As is usually the case with a work of this nature, many more questions have been raised than have been answered. Many of them could lead to further study, some possibilities for further study are listed below.

1. Four radiocarbon dates are not nearly enough to fully characterize the periods of eolian activity along the Cimarron River. Since it has been established by this study that datable soil material is present below the duned areas, more dates should be obtained and correlated to dune soils.
2. Many terrace levels are northeast of the Cimarron River in this area. They should be mapped and dated. Included with the project should be the exact nature of the relationship between the Deep Creek Valley, the Eagle Chief Creek Valley, and the Cimarron River.
3. This study did not consider the groundwater hydrology of the duned area, which could be an extensive study.
4. The dune fields extend to the east and west of the study area, and dune fields are developed along other rivers in western Oklahoma. Similar studies should be done to confirm and augment the observations made in this study.

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APPENDIXES

APPENDIX A

TYPICAL SOIL PROFILES

Aline (SCS, 1975)

Profile of Aline fine sand, 0 to 3 percent slopes, 950 feet east and 300 feet south of the northwest corner of section 22, T. 27 N., R. 9 W., Indian Meridian.

A1 - 0 to 8 inches, brown (10YR 5/3) fine sand, dark brown (10YR 3/3) when moist; weak, fine granular structure; loose, very friable; slightly acid; gradual, wavy boundary.

A21 - 8 to 34 inches, light-brown (7.5YR 6/4) fine sand, brown (7.5YR 5/4) when moist; weak, very fine, granular structure; loose, very friable; slightly acid; clear, wavy boundary.

A22 & B2t - 34 to 72 inches, (A22 horizon) light brown (7.5YR 6/4) fine sand, brown (7.5YR 5/4) when moist; single grain; loose; contains bands (lamellae) one-fourth inch to 3 inches thick and one-half inch to 5 inches apart, of reddish-yellow (5YR 6/6) loamy fine sand, yellowish-red (5YR 5/6) when moist, that are the B2t horizon; material in the bands (lamellae) has weak, medium subangular blocky structure; slightly hard, friable; some coatings and clay bridges between the sand grains in the bands; slightly acid.

Reaction throughout the profile is medium acid to neutral. The A1 horizon is brown, pale brown, yellowish-brown, or grayish-brown. The A2 horizon is light brown, brownish-yellow, light yellowish-brown, yellow or reddish-yellow. The B2t horizon consists of bands (lamellae) that are one-fourth inch to 3 inches thick and are between alternating layers of material that make up the A2 horizon.

Nobscot (SCS, 1968)

Profile of Nobscot fine sand, rolling, 1,200 feet north and 100 feet east of the southwest corner of the northwest quarter of section 19, T. 20 N., R. 13 W., Indian Meridian, on east side of road in native vegetation.

A1 - 0 to 5 inches, dark grayish-brown (10YR 4/2) fine sand, very dark grayish-brown (10YR 3/2) when moist; weak, medium and coarse, granular structure; soft when dry, very friable when moist; pH 7.0; irregular, clear boundary.

A2 - 5 to 17 inches, very pale brown (10YR 7/4) fine sand, light yellowish brown (10YR 6/4) when moist; single grain (structureless); loose when dry or moist; pH 6.0; gradual boundary.

B2t - 17 to 46 inches, yellowish-red (5YR 5/6) loamy fine sand containing thin bands (lamellae) of light sandy clay loam or fine sandy loam from 1 to 4 inches apart; yellowish-red (5YR 4/6) when moist; weak, fine, granular structure; soft when dry, loose when moist; pH 6.0; diffused boundary.

C - 46 to 60+ inches, reddish-yellow (7.5YR 7/6) light loamy fine sand, reddish-yellow (7.5YR 6/6) when moist; massive; soft when dry, very friable to loose when moist; pH 6.0; a few bands like those in B2t horizon in the upper part.

The A1 horizon ranges from 4 to 10 inches in thickness. Thickness varies considerably within a few inches. The surface layer is mostly fine sand, but there are spots of loamy fine sand, generally on the lower slopes. Colors range from dark grayish brown to brown.

The B2t horizon ranges from heavy fine sand to loamy fine sand and contains thin bands (lamellae) of sandy clay loam and fine sandy loam. The thin bands are 1/4 to 1/2 inch thick and are 1 to 8 inches apart. When the B2t horizon is dry, it ranges from reddish-yellow to brown.

<u>Pratt</u> (SCS, 1968, 1975)

Profile of Pratt loamy fine sand, undulating, 225 feet east and 300 feet south of the northwest corner of the northwest quarter of section 22, T. 23 N., R. 12 W., Indian Meridian, on east side of road in cultivated field.

A1 - 0 to 6 inches, brown (10YR 5/3) loamy fine sand, dark brown (10YR 3/3) when moist; weak granular structure; loose when dry or moist; pH 6.7; clear boundary.

B2t - 6 to 25 inches, brown (7.5YR 5/4) coherent loamy fine sand, dark brown (7.5YR 4/4) when moist; weak, medium granular structure; loose when dry, loose to very friable when moist; pH 6.7; gradual boundary. (in Alfalfa County this horizon is recognized to have a few thin lamellae)

C1 - 25 to 43 inches, reddish-yellow (7.5 YR 6/6) loamy fine sand, strong brown (7.5YR 5/6) when moist; single grain; loose dry or moist; pH 6.7.

C2 - 43 to 54+ inches, reddish-yellow (7.5YR 6/6) light loamy fine sand, strong brown (7.5YR 5/6) when moist; single grain; loose when dry or moist; pH 6.5.

The A1 horizon ranges from 6 to 14 inches in thickness and when dry from brown to dark brown in color. When moist, this layer ranges from dark brown to dark grayish-brown. The A1 horizon is light brown in spots where the wind has blown away particles of organic matter. When dry, the B2t horizon ranges from light yellowish-brown to dark brown or brown. The profile ranges from slightly alkaline to slightly acid. A darker colored, buried soil occurs in places below a depth of 30 inches.

<u>Sand</u> <u>Dunes</u>, <u>Lincoln</u> <u>Material</u> (SCS, 1968)

Not profiled.

<u>Tivoli</u> (SCS, 1968)

Profile of Tivoli find sand, rolling, about 475 feet east and 50 feet south of the northeast corner of the northwest quarter of section 10, T. 20 N., R. 10 W., Indian Meridian.

A1 - 0 to 4 inches, yellowish-brown (10YR 5/4) fine sand, dark brown (10YR 4/3) when moist; structureless (single grain); loose when dry or moist; noncalcareous; pH 7.0; clear boundary.

C - 4 to 60+ inches, reddish-yellow (7.5YR 6/6) fine sand, strong brown (10YR 5/6) when moist; structureless (single grain); loose when dry or moist; noncalcareous; pH 7.2.

The A horizon ranges from dark grayish-brown to yellowish-brown. It is as much as 12 inches thick in some areas, but average thickness ranges from 4 to 12 inches. This layer ranges from fine sand on the steeper slopes to loamy fine sand on some of the low dunes. The C horizon ranges from reddish-yellow to brownish-yellow. This soil profile is generally free of lime throughout.

APPENDIX B

SOIL DESCRIPTIONS FROM PROBE CORES

Ames Core

Ap - 0 to 34 inches, strong brown (7.5YR 4/6) when moist, loamy fine sand/loamy sand; few, faint strong brown (7.5YR 5/8) mottle; medium structure; very friable; abrupt boundary.

A,b - 34 to 49 inches, medium brown (7.5YR 4/2) when moist, sandy clay; few, fine, soft, black (N 2/) Mn/Fe concretions; massive, medium subangular blocky structure; firm; gradual boundary.

Bg,b - 49 to 80 inches, pinkish gray (7.5YR 7/2) when moist, sandy clay loam; fine, distinct, strong brown (7.5YR 5/8) mottle; few, soft, fine to medium, black (N 2/) Mn/Fe concretions; weak, medium subangular blocky; firm; clear boundary.

Bc1,b - 80 to 108 inches, medium brown (7.5YR 4/6) when moist, loamy sand; clear, distinct, pinkish gray (7.5YR 7/2) mottle; medium structure; very friable; gradual boundary.

Bc2,b - 108 to 122 inches, strong brown (7.5YR 5/6) when moist, sandy loam; few, distinct, pinkish gray (7.5YR 7/2) mottle; medium structure; friable.

The Ap horizon appeared to be water wash sand in the roadside ditch with an indeterminate thickness of dune sand at its base. Before the road construction there would have been approximately 5 feet of NcC dune sand above the cored interval. Sieve sample #62 was collected at a depth of two feet in the nearby dune sand, and sample #63 was taken from the core at a depth of 9 feet (50" in the core) below the original ground surface.

Campbell Core

A - 0 to 22 inches, dark brown (7/5YR 3/3) when moist, loamy sand; one medium, subangular blocky structure; friable; gradual boundary.

Bw - 22 to 50 inches, medium brown (7.5YR 4/4) when moist, loamy fine sand; one medium, subangular blocky structure; very friable; gradual boundary.

C - 50 to 108 inches, strong brown (7.5YR 4/6) when moist, loamy sand; massive structure; very friable; abrupt boundary.

A,b - 108 to 124 inches, dark brown (10YR 3/3) when moist, clay loam; two medium subangular blocky structure; firm; clear boundary.

Bw1,b - 124 to 150 inches, medium brown (10YR 4/3) when moist, sandy loam/loam; few, faint pale brown (10YR 6/3) mottle; two medium subangular blocky structure; friable; gradual boundary.

Bw2,b - 150 to 174 inches, light yellowish brown (10YR 5/4) when moist, sandy loam; few, faint dark yellowish brown (10YR 4/6) mottle; one medium subangular blocky structure; friable; clear boundary.

BC,b - 174 to 186 inches, pale brown (10YR 6/3) when moist, loamy sand; few, faint dark yellowish brown (10YR 4/6) mottle; one medium subangular blocky structure; friable.

The surface soil was mapped by the SCS as PtD. As noted during the bucket auger survey, a paleosol may have been present in the C horizon near a depth of 70". The following sieve analysis samples were collected: #74 at 34", #75 at 60", #76 at 78", #77 at 100", and #78 at 170".

Mt. Zion Core

A - 0 to 9 inches, medium-dark brown (10YR 4-3/3) when moist, fine sandy loam; weak, medium subangular blocky structure; very friable; gradual boundary.

AB - 9 to 14 inches, dark yellowish brown (10YR 4/4) when moist, fine sandy loam; weak, medium subangular blocky structure; very friable; gradual boundary.

Bw - 14 to 24 inches, strong brown (7.5YR 4/6) when moist, loamy fine sand; weak, medium subangular blocky structure; very friable; gradual boundary.

Bw/A - 24 to 32 inches, dark yellowish brown (7.5-10YR 4/6) when moist, fine sandy loam; weak, medium subangular blocky structure; very friable; abrupt boundary.

A,b - 32 to 51 inches, medium brown (10YR 4/3) when moist, fine sandy loam; weak, medium subangular blocky structure; very friable; gradual boundary.

C - 51 to 80 inches, brown (7.5YR 5/4) when moist, loamy fine sand; massive structure; very friable; abrupt boundary.

A,2b - 80 to 102 inches, dark grayish brown (10YR 4/2) when moist, loamy fine sand; weak, medium subangular blocky structure; very friable; gradual boundary.

A2,2b - 102 to 124 inches, dark yellowish brown (10YR 4/3-4) when moist, fine sandy loam; weak, medium subangular blocky structure; very friable; gradual boundary.

Bw,2b - 124 to 166 inches, medium yellowish brown (10YR 4/4-5/6) when moist, loamy sand; few, faint yellowish brown (10YR 5/6) mottle; massive structure; very friable; gradual boundary.

C,2b - 166 to 176 inches, brownish yellow (10YR 6/6) when moist, loamy sand; massive structure; very friable; abrupt boundary.

A,3b - 176 to 184 inches, medium brown (10YR 4/3) when moist, loamy sand; weak, medium subangular blocky structure; very friable; gradual boundary.

C,3b - 184 to 192 inches, reddish yellow (7.5YR 6/6) when moist, loamy sand; few, faint light brown (7.5YR 6/4) mottles; massive structure; very friable.

The surface soil was mapped by the SCS as PtC. Sieve analysis samples were collected from the core as follows: #81 at 18", #82 at 60", #83 at 138". The water table was encountered at a depth of 108".

APPENDIX C

MUNSELL SAMPLE COLOR

Sample	Soil	Depth ft	Color	Sample	Soil	Depth ft	Color	Sample	Soil	Depth ft	Color
27	AnE	3.0	7.5 YR 4/4	8	PtC	4.0	5 YR 4/6	10	TrD	2.0	7.5 YR 5/6
44	AnE	5.0	7.5 YR 5/6	26	PtC	1.2	10 YR 6/6	11	TrD	8.0	7.5 YR 6/6
117	AnE	4.0	7.5 YR 4/6	32	PtC	7.0	7.5 YR 5/6	17	TrD	8.0	7.5 YR 6/6
118	AnE	4.0	7.5 YR 5/4	45	PtC	12.0	7.5 YR 5/4	19	TrD	6.0	7.5 YR 7/6
119	AnE	6.0	7.5 YR 5/4	46	PtC	4.0	7.5 YR 4/6	20	TrD	6.0	7.5 YR 5/6
				58	PtC	6.0	7.5 YR 4/6	21	TrD	3.0	7.5 YR 5/6
60	NcC	5.0	5 YR 4/4	103	PtC	3.0	5 YR 4/6	22	TrD	2.0	7.5 YR 6/6
61	NcC	5.0	5 YR 4/6	104	PtC	7.0	7.5 YR 5/6	23	TrD	3.0	7.5 YR 6/6
62	NcC	2.0	7.5 YR 5/6	108	PtC	6.0	7.5 YR 5/4	30	TrD	4.0	7.5 YR 6/6
122	NcC	4.0	10 YR 6/4	109	PtC	8.0	7.5 YR 4/6	36	TrD	8.0	5 YR 6/6
123	NcC	4.0	10 YR 7/4	110	PtC	4.0	5 YR 4/4	51	TrD	5.0	7.5 YR 7/4
				112	PtC	4.0	5 YR 5/6	53	TrD	6.0	7.5 YR 5/6
7	NcD	6.0	7.5 YR 6/4	113	PtC	5.0	7.5 YR 5/8	56	TrD	5.0	5 YR 6/6
33	NcD	5.0	7.5 YR 6/6	114	PtC	4.0	10 YR 6/4				
38	NcD	3.0	7.5 YR 5/8	115	PtC	3.0	7.5 YR 5/4	101	XLs	0.2	10 YR 7/3
39	NcD	4.0	7.5 YR 7/4	116	PtC	3.0	5 YR 4/6	205	XLS	2.0	10 YR 8/3
40	NcD	6.0	7.5 YR 5/6	202	PtC	5.0	7.5 YR 6/6				
41	NcD	8.0	7.5 YR 4/6					37	XNpD	5.0	7.5 YR 7/6
42	NcD	7.0	7.5 YR 5/6	12	PtD	4.0	7.5 YR 6/4	52	Xxal	12.0	5 YR 5/6
43	NcD	5.0	7.5 YR 5/6	13	PtD	4.0	7.5 YR 8/4	204	XSs	1.0	7.5 YR 7/4
47	NcD	15.0	7.5 YR 6/6	16	PtD	7.0	7.5 YR 7/4				
49	NcD	5.0	5 YR 5/8	24	PtD	4.0	10 YR 6/6	62	Ames	2.0	7.5 YR 5/6
55	NcD	3.0	5 YR 4/6	31	PtD	8.0	7.5 YR 5/4	63	Ames	9.0	10 YR 6/4
59	NcD	7.0	7.5 YR 6/6	48	PtD	6.0	7.5 YR 5/6				
102	NcD	4.0	7.5 YR 5/6	54	PtD	4.0	5 YR 5/8	71	Brin	4.0	7.5 YR 6/6
105	NcD	3.0	7.5 YR 5/6	100	PtD	4.0	5 YR 4/6				
106	NcD	4.0	7.5 YR 4/6					74	Camp	3.0	5 YR 4/6
107	NcD	3.0	5 YR 4/6	14	Ss	2.0	10 YR 7/4	75	Camp	5.0	7.5 YR 5/4
111	NcD	4.0	7.5 YR 6/6	15	Ss	3.0	7.5 YR 8/4	76	Camp	6.5	5 YR 5/8
120	NcD	8.0	7.5 YR 4/6	28	Ss	4.0	7.5 YR 7/4	77	Camp	8.3	7.5 YR 5/6
121	NcD	4.0	7.5 YR 5/6	29	Ss	4.0	7.5 YR 7/6	78	Camp	14.2	10 YR 7/3
201	NcD	7.0	7.5 YR 6/6	34	Ss	3.0	10 YR 8/4				
				35	Ss	4.0	7.5 YR 7/4	81	Zion	1.5	5 YR 5/4
3	NcD	9.0	7.5 YR 6/4	57	Ss	4.0	7.5 YR 7/4	82	Zion	5.0	7.5 YR 5/4
4	NcD	13.0	7.5 YR 6/6	203	Ss	3.0	7.5 YR 7/4	83	Zion	11.5	10 YR 6/3
5	NcD	18.0	5 YR 5/8								
6	NcD	34.0	5 YR 5/6								

Notes: XLs samples are modern river-wash sand.
XNpD sample was of suspect origin and was not included in any statistics.
Xxal sample is terrace alluvium from the Rock Terrace site.
XSs sample is from an active sand accumulation on the ridge crest of a Tivoli dune, and was not included in any statistics.

APPENDIX D

PHI VALUES AND STATISTICAL MEASURES

Sample	Soil	Depth ft	5% phi	16% phi	25% phi	50% phi	75% phi	84% phi	95% phi	Mean phi	Sort	Sort Trask	Skew	Kurt
27	AnE	3.0	1.14	1.52	1.77	2.17	2.85	3.35	4.97	2.35	1.038	1.27	0.376	1.452
44	AnE	5.0	1.40	1.77	1.90	2.28	2.88	3.22	3.85	2.42	0.734	1.23	0.289	1.028
117	AnE	4.0	1.06	1.41	1.62	2.02	2.64	3.07	4.05	2.17	0.868	1.28	0.310	1.199
118	AnE	4.0	1.22	1.52	1.73	2.07	2.58	2.92	3.56	2.17	0.705	1.22	0.244	1.122
119	AnE	6.0	1.58	1.94	2.10	2.53	3.11	3.38	4.00	2.62	0.726	1.22	0.203	0.979
60	McC	5.0	1.28	1.74	1.93	2.54	3.58	4.08	5.08	2.79	1.161	1.36	0.327	0.944
61	McC	5.0	1.15	1.62	1.83	2.24	2.78	3.06	3.64	2.31	0.738	1.23	0.131	1.074
62	McC	2.0	1.60	1.88	2.00	2.37	2.87	3.13	3.69	2.46	0.629	1.20	0.239	0.984
122	McC	4.0	1.56	1.93	2.10	2.53	3.05	3.31	4.13	2.59	0.733	1.21	0.191	1.106
123	McC	4.0	1.81	2.03	2.17	2.55	2.96	3.17	3.68	2.58	0.570	1.17	0.146	0.970
7	McD	6.0	0.10	1.31	1.42	1.88	2.82	2.56	3.47	1.92	0.824	1.41	0.015	0.989
33	McD	5.0	1.32	1.62	1.79	2.11	2.53	2.79	3.35	2.17	0.600	1.19	0.192	1.124
38	McD	3.0	1.28	1.60	1.78	2.09	2.49	2.76	3.32	2.15	0.599	1.18	0.178	1.178
39	McD	4.0	1.29	1.63	1.80	2.17	2.65	2.92	3.57	2.24	0.669	1.21	0.193	1.105
40	McD	6.0	1.19	1.50	1.69	2.02	2.51	2.90	3.66	2.14	0.724	1.22	0.290	1.238
41	McD	8.0	2.13	2.54	2.75	3.13	3.50	3.67	4.29	3.11	0.610	1.13	0.015	1.180
42	McD	7.0	1.34	1.67	1.82	2.10	2.50	2.84	3.62	2.20	0.637	1.17	0.303	1.368
43	McD	5.0	1.82	2.11	2.28	2.70	3.18	3.42	3.93	2.74	0.647	1.18	0.133	0.961
47	McD	15.0	1.09	1.38	1.52	1.98	2.53	2.88	3.58	2.08	0.752	1.29	0.243	1.015
49	McD	5.0	1.27	1.54	1.72	2.04	2.52	2.83	3.38	2.14	0.642	1.21	0.247	1.074
55	McD	3.0	1.21	1.52	1.70	2.00	2.42	2.72	3.46	2.08	0.641	1.19	0.251	1.272
59	McD	7.0	1.01	1.28	1.43	1.86	2.40	2.81	3.72	1.98	0.793	1.29	0.307	1.147
102	McD	4.0	1.23	1.57	1.77	2.10	2.56	2.84	3.58	2.17	0.674	1.20	0.212	1.219
105	McD	3.0	1.72	1.93	2.04	2.34	2.73	2.96	3.56	2.41	0.536	1.16	0.265	1.093
106	McD	4.0	1.49	1.84	1.97	2.30	2.73	2.98	3.60	2.37	0.605	1.18	0.213	1.138
107	McD	3.0	1.20	1.58	1.79	2.14	2.63	2.92	3.89	2.21	0.743	1.21	0.233	1.320
111	McD	4.0	1.40	1.76	1.88	2.21	2.61	2.94	4.34	2.30	0.740	1.18	0.344	1.648
120	McD	8.0	1.78	2.02	2.17	2.56	3.01	3.22	3.71	2.60	0.592	1.18	0.147	0.943
121	McD	4.0	1.78	2.00	2.13	2.48	2.95	3.23	3.87	2.57	0.624	1.18	0.271	1.046
201	McD	7.0	0.76	1.20	1.44	2.00	2.74	3.07	3.70	2.09	0.913	1.38	0.153	0.927
3	McD	9.0	1.38	1.74	1.88	2.26	2.82	3.18	3.91	2.39	0.744	1.22	0.290	1.105
4	McD	13.0	1.32	1.66	1.88	2.17	2.62	2.91	3.66	2.25	0.668	1.18	0.227	1.296
5	McD	18.0	1.13	1.42	1.59	1.95	2.41	2.71	3.68	2.03	0.710	1.23	0.266	1.283
6	McD	34.0	1.29	1.69	1.88	2.28	2.81	3.22	4.12	2.40	0.811	1.22	0.271	1.239

8	PtC	4.0	1.29	1.65	1.82	2.15	2.57	2.92	3.77	2.24	0.693	1.19	0.264	1.357
26	PtC	1.2	1.32	1.65	1.82	2.13	2.58	2.88	3.52	2.22	0.642	1.19	0.239	1.183
32	PtC	7.0	1.47	1.87	2.03	2.48	3.02	3.27	3.73	2.54	0.692	1.22	0.117	0.936
45	PtC	12.0	1.87	2.16	2.32	2.69	3.12	3.34	3.72	2.73	0.575	1.16	0.108	0.948
46	PtC	4.0	1.48	1.82	1.95	2.33	2.83	3.11	3.63	2.42	0.649	1.21	0.208	1.002
58	PtC	6.0	1.90	2.33	2.57	3.12	3.63	3.96	4.77	3.14	0.842	1.19	0.090	1.110
103	PtC	3.0	1.18	1.50	1.71	2.06	2.53	2.86	3.94	2.14	0.758	1.22	0.272	1.379
104	PtC	7.0	1.03	1.32	1.48	1.88	2.26	2.58	3.68	1.93	0.715	1.24	0.235	1.384
108	PtC	6.0	1.44	1.85	2.00	2.39	2.88	3.18	3.89	2.47	0.704	1.20	0.206	1.138
109	PtC	8.0	1.30	1.60	1.78	2.08	2.56	2.88	3.68	2.19	0.681	1.20	0.297	1.244
110	PtC	4.0	1.38	1.71	1.86	2.16	2.60	2.89	3.91	2.25	0.678	1.18	0.310	1.401
112	PtC	4.0	1.23	1.56	1.78	2.13	2.61	2.91	4.38	2.20	0.815	1.21	0.292	1.546
113	PtC	5.0	1.23	1.66	1.86	2.31	2.93	3.24	4.03	2.40	0.819	1.26	0.202	1.071
114	PtC	4.0	1.33	1.65	1.81	2.06	2.46	2.76	3.41	2.16	0.594	1.17	0.278	1.311
115	PtC	3.0	1.18	1.56	1.80	2.22	2.88	3.25	4.08	2.34	0.862	1.26	0.245	1.103
116	PtC	3.0	1.02	1.31	1.47	1.93	2.53	2.98	3.78	2.07	0.835	1.31	0.298	1.072
202	PtC	5.0	1.42	1.79	1.93	2.34	2.88	3.13	3.58	2.42	0.664	1.22	0.168	0.932
12	PtD	4.0	1.30	1.76	1.91	2.27	2.66	2.87	3.32	2.30	0.583	1.18	0.060	1.101
13	PtD	4.0	1.81	2.22	2.45	2.96	3.43	3.60	4.07	2.93	0.687	1.18	-0.045	0.953
16	PtD	7.0	1.23	1.61	1.81	2.18	2.73	3.02	3.53	2.27	0.700	1.23	0.182	1.024
24	PtD	4.0	1.28	1.69	1.87	2.23	2.76	2.99	3.48	2.30	0.658	1.21	0.149	1.017
31	PtD	8.0	0.90	1.22	1.42	1.89	2.39	2.71	3.45	1.94	0.759	1.30	0.162	1.072
48	PtD	6.0	1.23	1.51	1.70	2.02	2.49	2.82	3.43	2.12	0.660	1.21	0.251	1.142
54	PtD	4.0	1.37	1.83	2.00	2.41	2.90	3.16	3.62	2.47	0.673	1.21	0.102	1.020
100	PtD	4.0	1.42	1.77	1.90	2.22	2.73	3.13	4.40	2.37	0.792	1.20	0.401	1.474
14	Ss	2.0	0.85	1.17	1.35	1.84	2.33	2.58	3.23	1.86	0.714	1.31	0.108	1.002
15	Ss	3.0	1.13	1.52	1.78	2.22	2.76	3.02	3.47	2.25	0.730	1.24	0.066	0.983
28	Ss	4.0	1.23	1.61	1.79	2.08	2.46	2.67	3.11	2.12	0.551	1.17	0.106	1.150
29	Ss	4.0	1.48	1.85	1.98	2.32	2.79	3.07	3.68	2.41	0.639	1.19	0.231	1.109
34	Ss	3.0	1.17	1.68	1.88	2.32	2.83	3.08	3.53	2.36	0.708	1.23	0.056	1.018
35	Ss	4.0	1.27	1.63	1.82	2.14	2.55	2.81	3.31	2.19	0.603	1.18	0.142	1.145
57	Ss	4.0	0.93	1.34	1.58	2.00	2.43	2.66	3.17	2.00	0.669	1.24	0.026	1.083
203	Ss	3.0	1.06	1.43	1.63	1.99	2.45	2.74	3.40	2.05	0.682	1.23	0.175	1.170
10	TrD	2.0	0.96	1.31	1.50	1.98	2.46	2.76	3.34	2.02	0.723	1.28	0.109	1.017
11	TrD	8.0	1.54	1.91	2.06	2.42	2.83	3.04	3.40	2.46	0.564	1.17	0.076	0.990
17	TrD	8.0	1.79	2.07	2.22	2.54	2.95	3.13	3.46	2.58	0.518	1.15	0.108	0.943
19	TrD	6.0	1.94	2.16	2.28	2.54	2.89	3.06	3.40	2.59	0.446	1.13	0.167	0.981
20	TrD	6.0	1.28	1.62	1.81	2.14	2.56	2.77	3.27	2.18	0.589	1.19	0.123	1.089
21	TrD	3.0	1.41	1.82	1.97	2.38	2.98	3.34	3.97	2.51	0.768	1.23	0.253	1.039
22	TrD	2.0	1.23	1.54	1.74	2.04	2.43	2.67	3.21	2.08	0.584	1.18	0.146	1.176
23	TrD	3.0	1.13	1.47	1.69	2.06	2.54	2.83	3.38	2.12	0.681	1.23	0.153	1.080
30	TrD	4.0	1.18	1.59	1.82	2.21	2.68	2.92	3.47	2.24	0.679	1.21	0.084	1.096
36	TrD	8.0	1.18	1.57	1.76	2.07	2.38	2.57	3.04	2.07	0.533	1.16	0.027	1.231
51	TrD	5.0	1.93	2.22	2.37	2.72	3.08	3.26	3.60	2.73	0.514	1.14	0.045	0.968
53	TrD	6.0	1.05	1.46	1.71	2.12	2.64	2.98	3.58	2.19	0.763	1.24	0.143	1.113
56	TrD	5.0	1.48	1.90	2.08	2.53	3.02	3.23	3.57	2.55	0.649	1.21	0.024	0.908

101	XLs	0.2	1.28	1.67	1.83	2.14	2.54	2.76	3.27	2.19	0.574	1.18	0.137	1.149
205	XLs	2.0	1.59	1.90	2.00	2.26	2.60	2.82	3.32	2.33	0.493	1.14	0.220	1.188
37	XNpD	5.0	1.65	1.96	2.12	2.50	2.95	3.21	3.84	2.56	0.645	1.18	0.184	1.083
52	Xxal	12.0	1.44	2.16	2.62	3.94	5.06	5.60	6.68	3.90	1.655	1.39	0.005	0.880
204	XSs	1.0	2.03	2.23	2.35	2.66	2.98	3.15	3.48	2.68	0.451	1.13	0.095	0.946

Probe Core Samples:

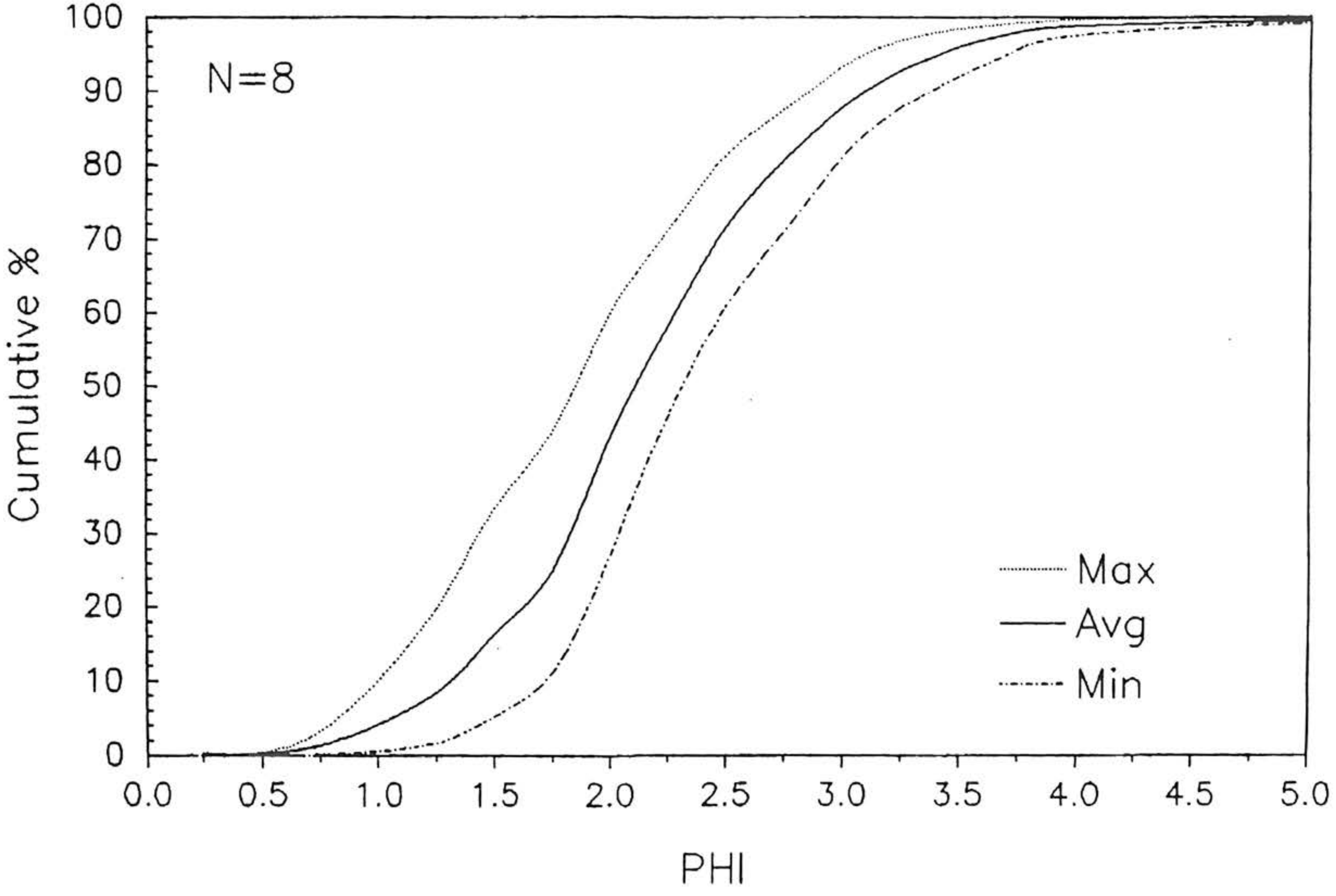
62	Ames	2.0	1.60	1.88	2.00	2.37	2.87	3.13	3.69	2.46	0.629	1.20	0.239	0.984
63	Ames	9.0	1.77	2.11	2.37	3.07	3.85	4.69	6.42	3.29	1.349	1.27	0.350	1.288
71	Brin	4.0	1.18	1.72	1.92	2.53	3.15	3.45	4.31	2.57	0.907	1.28	0.105	1.041
74	Camp	3.0	1.48	2.64	3.24	3.90	4.71	5.08	5.86	3.87	1.274	1.21	-0.070	1.225
75	Camp	5.0	0.89	1.32	1.63	2.29	3.26	3.62	4.56	2.41	1.131	1.41	0.196	0.924
76	Camp	6.5	0.98	1.46	1.76	2.22	2.91	3.36	4.13	2.35	0.953	1.29	0.206	1.123
77	Camp	8.3	1.05	1.41	1.63	2.06	2.68	3.10	4.08	2.19	0.881	1.28	0.280	1.180
78	Camp	14.2	1.31	1.77	1.97	2.69	3.99	5.01	7.08	3.16	1.684	1.42	0.476	1.171
81	Zion	1.5	2.34	3.01	3.30	3.76	4.58	4.85	5.71	3.87	0.971	1.18	0.171	1.077
82	Zion	5.0	1.45	2.03	2.26	2.81	3.40	3.64	4.45	2.83	0.858	1.23	0.063	1.076
83	Zion	11.5	1.20	1.76	1.97	2.60	3.40	3.78	5.04	2.71	1.269	1.31	0.069	1.447

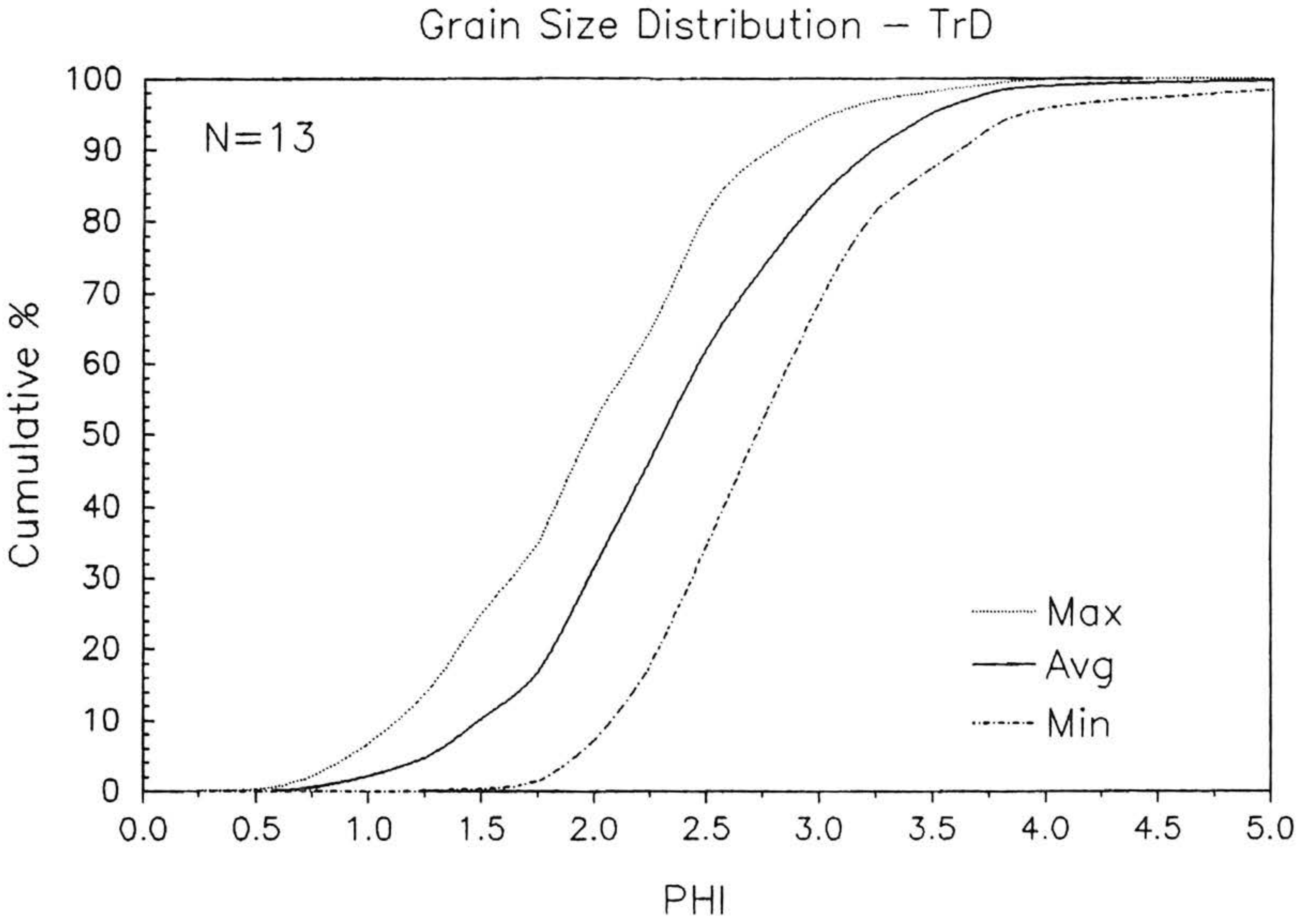
Notes: XLs samples are modern river wash sand.
XNpD sample was of suspect origin and was not included in any statistics.
Xxal sample is terrace alluvium from the Rock Terrace site.
XSs sample is from an active accumulation on the ridge crest of a Tivoli dune, and was not included in any statistics.

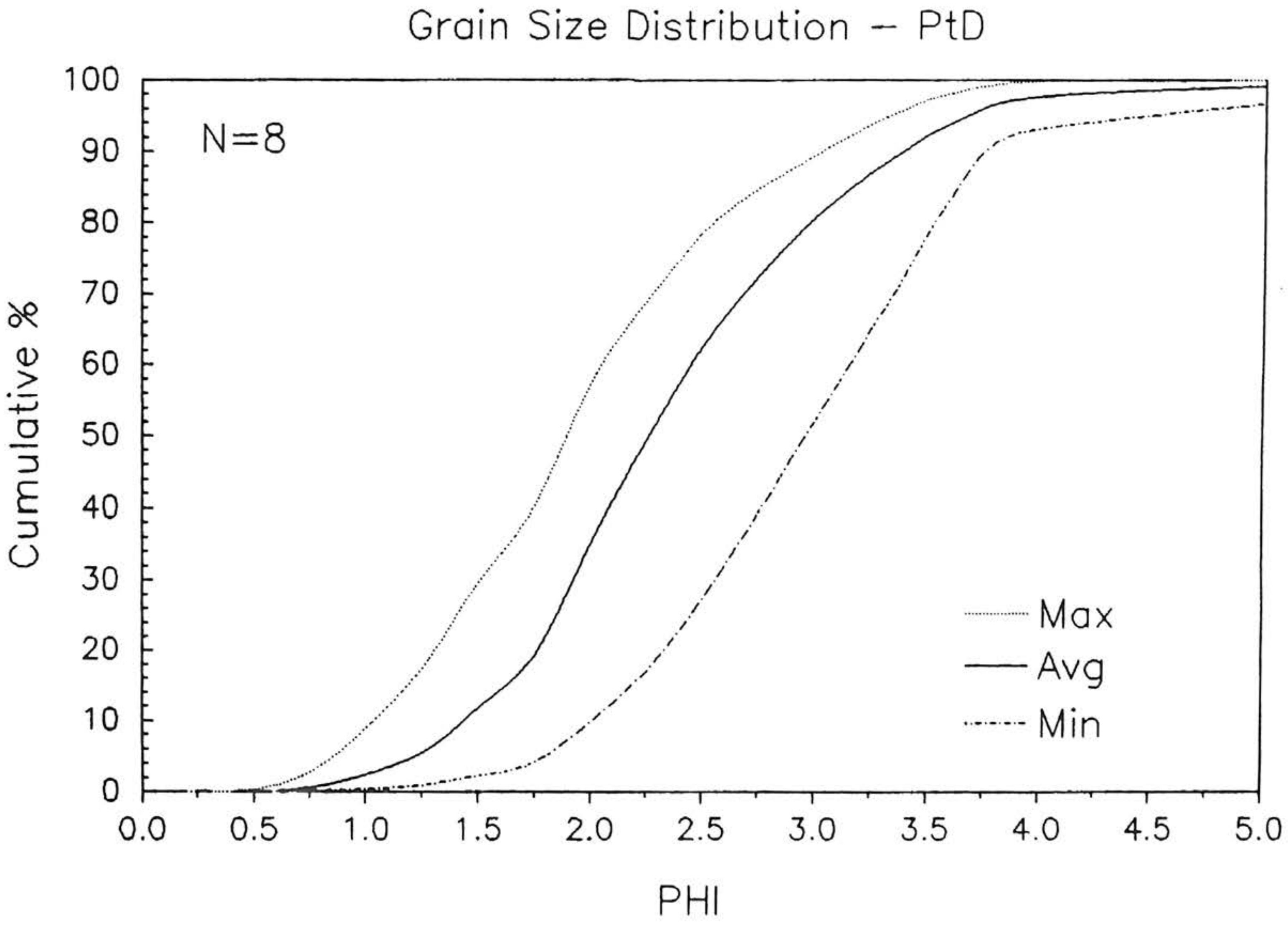
APPENDIX E

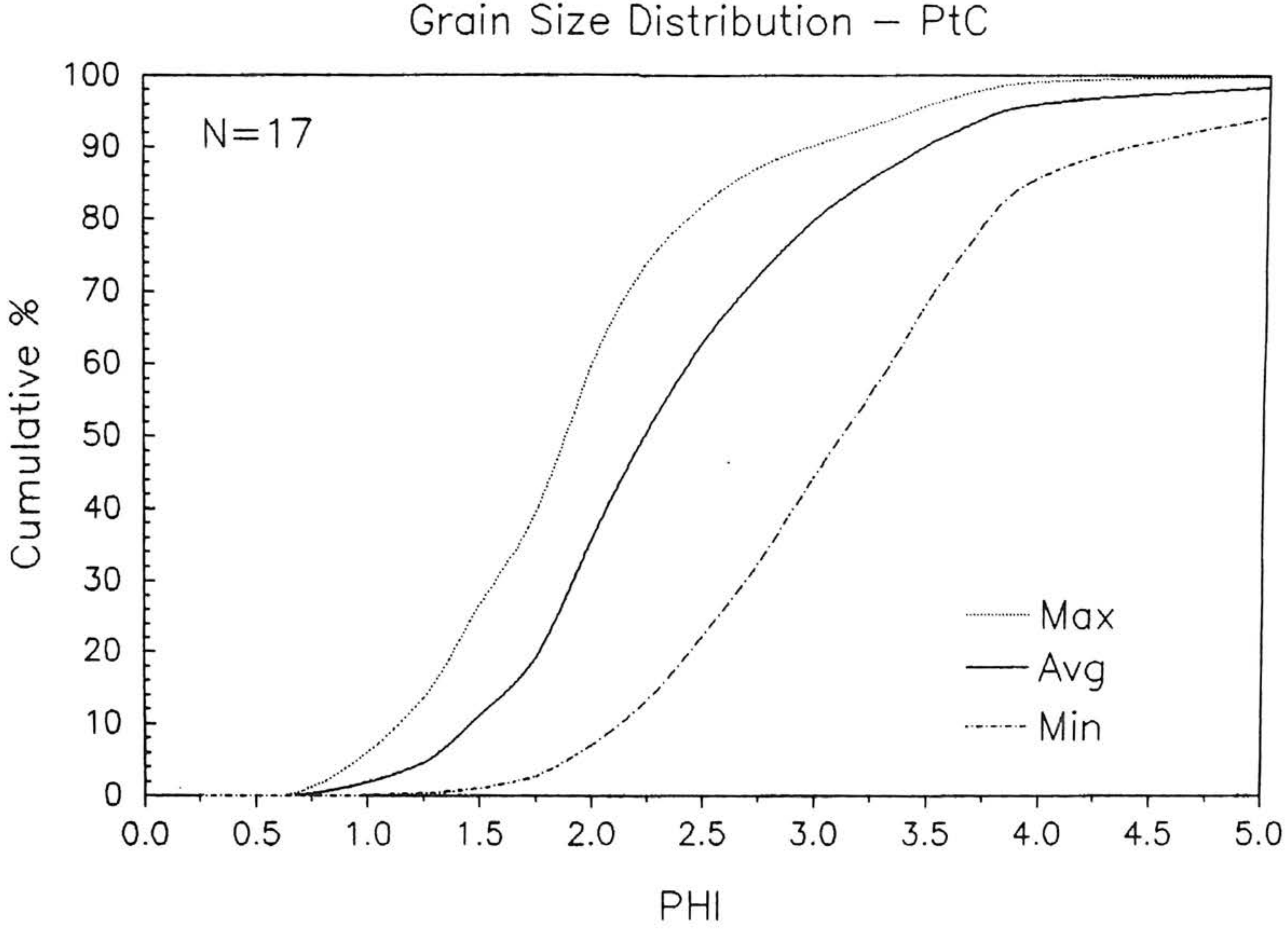
SELECTED CUMULATIVE-PERCENT CURVES

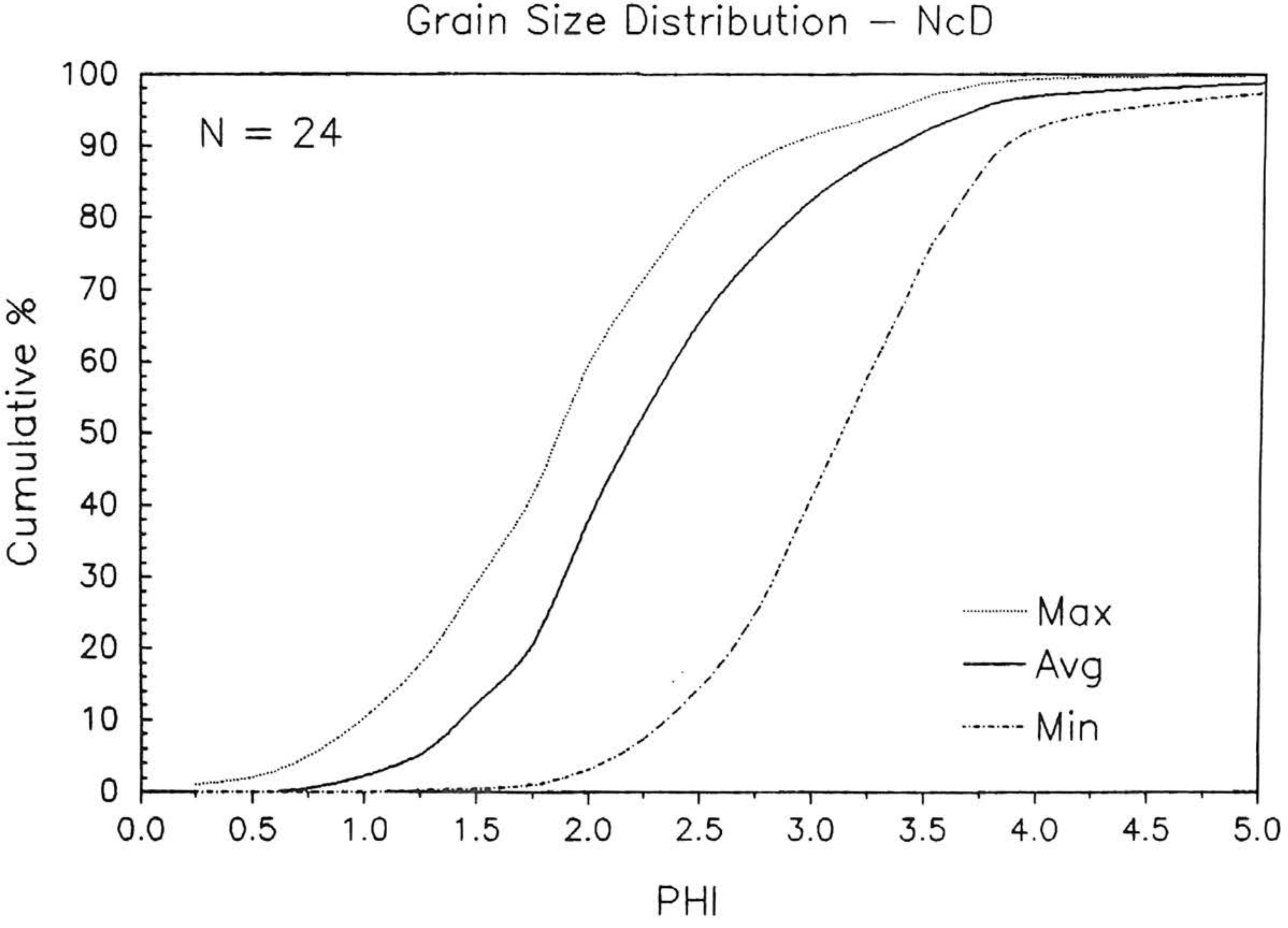
Grain Size Distribution – Ss

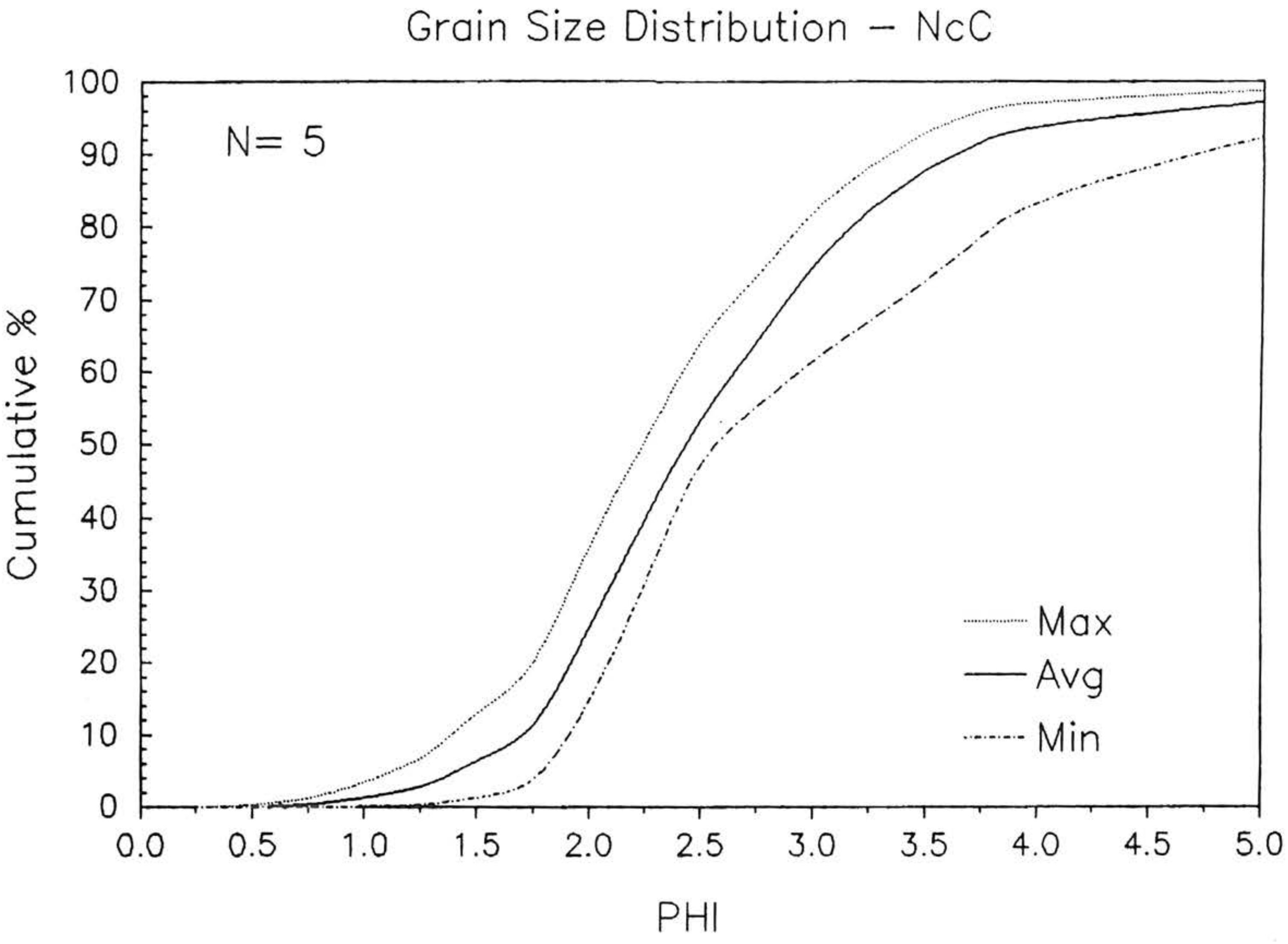


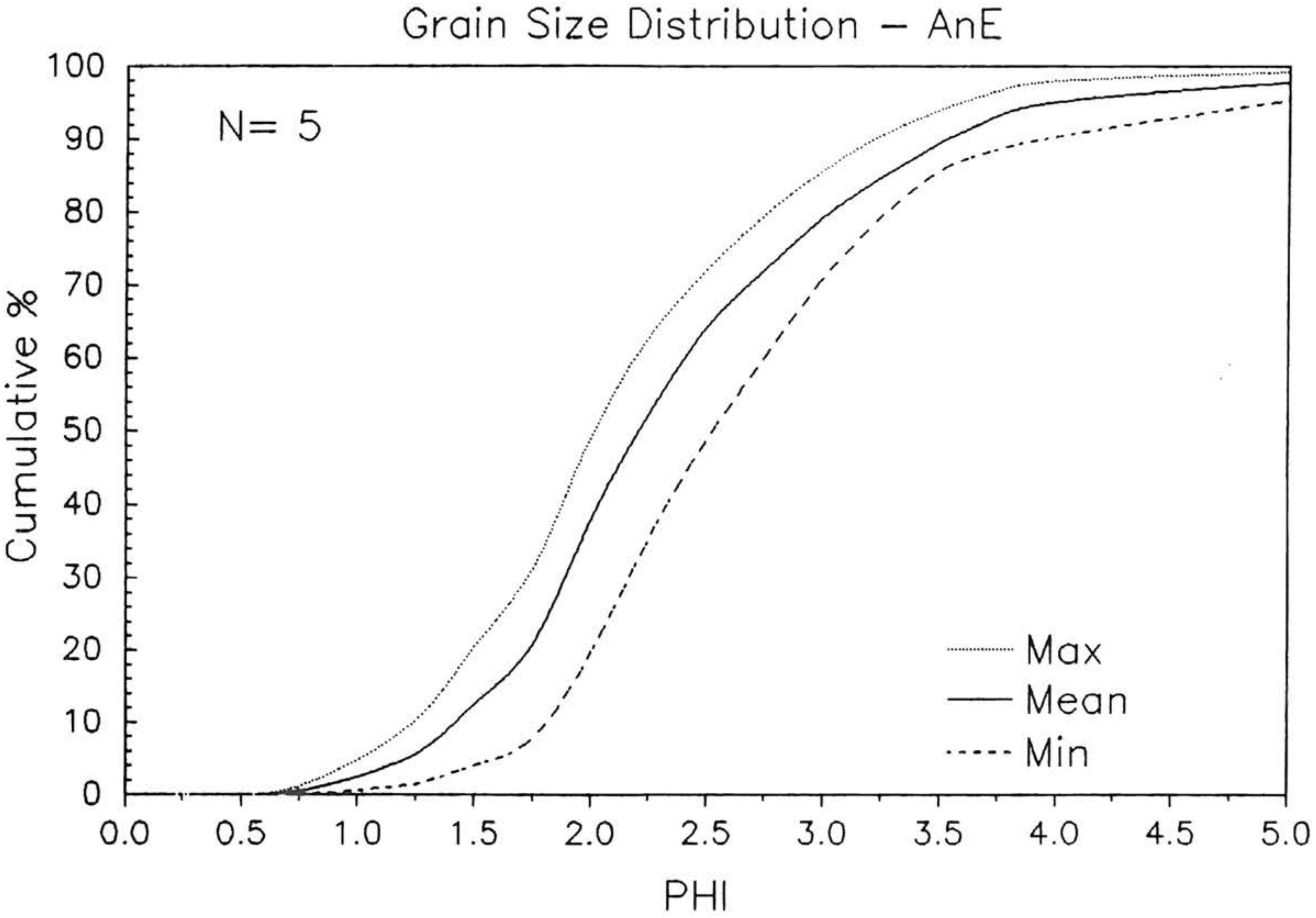

Grain Size Distribution – TrD
N=13
Cumulative %
0
10
20
30
40
50
60
70
80
90
100
PHI
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Max
Avg
Min


Grain Size Distribution - PtD
N=8
Cumulative %
0
10
20
30
40
50
60
70
80
90
100
PHI
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Max
Avg
Min

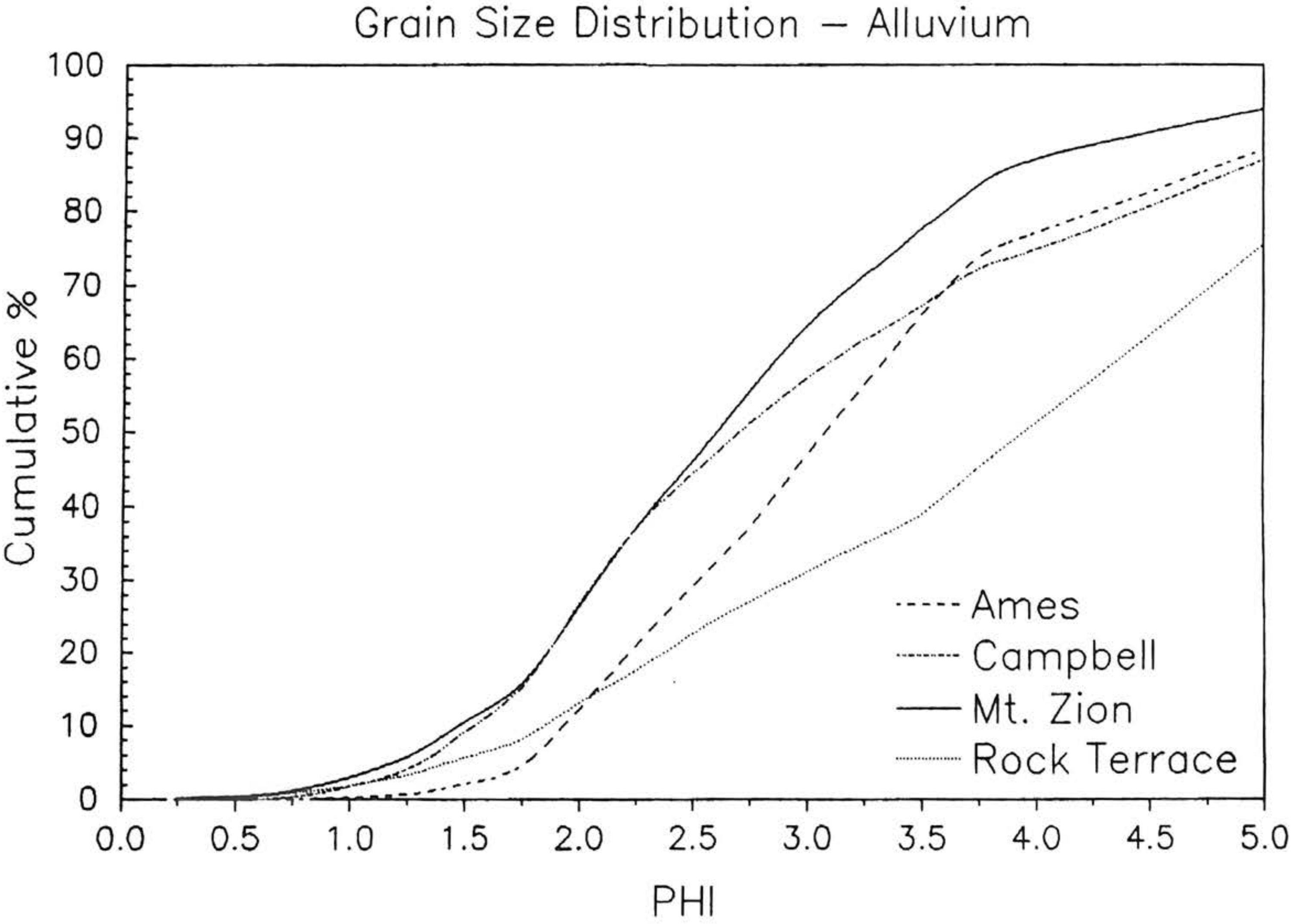

Grain Size Distribution – PtC
N=17
Cumulative %
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
PHI
Max
Avg
Min


Grain Size Distribution — NcD
N = 24
Cumulative %
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
PHI
Max
Avg
Min


Grain Size Distribution – NcC
N= 5
Cumulative %
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
PHI
Max
Avg
Min



Grain Size Distribution – AnE


Grain Size Distribution – Alluvium
Cumulative %
100
90
80
70
60
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
PHI
Ames
Campbell
Mt. Zion
Rock Terrace

APPENDIX F

METHODOLOGY OF MODE CALCULATION

Modal values for the dune sand cumulative per cent curves were calculated using a basic language computer program which found the formula for the curve, and then searched systematically for the mode. Operation of the program proceeded as follows. Six data points were selected from the lower portion of each cumulative per cent curve such that the mode was judged to fall within that portion of the curve. The data were then entered into the program as X and Y coordinates. The program then calculated a fifth degree polynomial giving the formula for the curve. Once the formula was found, Y was calculated for each X within the data range using increments of .01 phi. Next, the calculated Y values within the data range were searched for the largest increment of change between successive Y values. The corresponding X value was thus the modal value for the curve, and was printed both in phi units and in millimeters.

To check on the accuracy of the curve fitting process, the entire range of computed X and Y values was also printed so that the calculated values could be compared to the experimental values. A second, and sometimes a third, set of six points obtained by moving up the curve in quarter phi increments were also run in the program. This allowed each calculated curve to be compared to the experimental data so that the modal value from the best fit curve could be chosen for the calculation of wind velocities. In almost all cases, any discrepancy between the calculated curve and the experimental curve was less than .001 per cent, which yielded an accuracy for the phi modal values of at least .01.

Special thanks goes to James Blackburn of the mathematics faculty of Tulsa Junior College for the writing and instruction in the use of this computer program.

APPENDIX G

COMPUTED PALEOWIND VELOCITIES

		Grain Size		Threshold Velocity		Maximum Velocity	
Sample	Soil	Mode	Max 2%				
		mm	mm	m/s	mph	m/s	mph
27	ANE	0.320	0.560	6.00	13.43	7.88	17.62
44	ANE	0.294	0.443	5.83	13.05	7.22	16.15
117	ANE	0.305	0.560	5.84	13.06	7.88	17.62
118	ANE	0.295	0.485	5.79	12.95	7.48	16.74
119	ANE	0.244	0.412	5.21	11.65	7.02	15.71
60	NCC	0.335	0.531	6.18	13.83	7.73	17.30
61	NCC	0.282	0.554	5.59	12.50	7.85	17.57
62	NCC	0.248	0.392	5.30	11.86	6.87	15.37
122	NCC	0.240	0.425	5.15	11.52	7.11	15.91
123	NCC	0.225	0.335	5.03	11.25	6.41	14.34
7	NCD	0.297	0.578	5.74	12.85	7.97	17.82
33	NCD	0.267	0.452	5.48	12.26	7.28	16.29
38	NCD	0.285	0.465	5.70	12.76	7.37	16.48
39	NCD	0.285	0.467	5.70	12.75	7.37	16.49
40	NCD	0.301	0.513	5.85	13.08	7.64	17.09
41	NCD	0.119	0.288	2.83	6.33	5.95	13.30
42	NCD	0.288	0.455	5.74	12.83	7.30	16.33
43	NCD	0.197	0.358	4.54	10.16	6.62	14.81
47	NCD	0.273	0.531	5.50	12.31	7.73	17.30
49	NCD	0.292	0.463	5.78	12.92	7.35	16.44
55	NCD	0.289	0.491	5.73	12.81	7.51	16.81
59	NCD	0.300	0.561	5.78	12.93	7.88	17.64
102	NCD	0.267	0.489	5.44	12.18	7.51	16.79
105	NCD	0.229	0.353	5.07	11.34	6.57	14.69
106	NCD	0.240	0.419	5.15	11.53	7.06	15.80
107	NCD	0.261	0.521	5.35	11.96	7.68	17.18
111	NCD	0.271	0.447	5.53	12.37	7.25	16.22
120	NCD	0.223	0.352	4.96	11.10	6.56	14.67
121	NCD	0.232	0.351	5.11	11.42	6.55	14.64
201	NCD	0.279	0.732	5.42	12.11	8.59	19.21
3	NCD	0.268	0.448	5.51	12.32	7.26	16.24
4	NCD	0.288	0.455	5.74	12.83	7.30	16.33
5	NCD	0.296	0.527	5.76	12.89	7.71	17.24
6	NCD	0.272	0.485	5.52	12.35	7.48	16.74

8	PTC	0.285	0.484	5.68	12.72	7.48	16.72
26	PTC	0.288	0.460	5.73	12.82	7.33	16.40
32	PTC	0.242	0.434	5.18	11.58	7.17	16.05
45	PTC	0.192	0.319	4.49	10.04	6.27	14.02
46	PTC	0.282	0.420	5.71	12.78	7.07	15.82
58	PTC	0.123	0.367	2.90	6.48	6.68	14.94
103	PTC	0.282	0.506	5.63	12.59	7.61	17.01
104	PTC	0.298	0.563	5.77	12.90	7.89	17.65
108	PTC	0.239	0.436	5.11	11.44	7.18	16.07
109	PTC	0.294	0.462	5.81	13.00	7.35	16.44
110	PTC	0.267	0.449	5.48	12.26	7.27	16.26
112	PTC	0.276	0.497	5.56	12.43	7.55	16.90
113	PTC	0.272	0.499	5.51	12.32	7.56	16.91
114	PTC	0.273	0.461	5.57	12.45	7.34	16.42
115	PTC	0.271	0.522	5.46	12.22	7.69	17.20
116	PTC	0.291	0.565	5.67	12.69	7.90	17.68
202	PTC	0.258	0.431	5.41	12.09	7.14	15.98
12	PTD	0.199	0.476	4.47	9.99	7.43	16.61
13	PTD	0.130	0.376	3.11	6.95	6.75	15.10
16	PTD	0.286	0.499	5.68	12.71	7.56	16.91
24	PTD	0.252	0.480	5.26	11.78	7.46	16.68
31	PTD	0.293	0.627	5.66	12.66	8.18	18.30
48	PTD	0.292	0.477	5.76	12.89	7.44	16.64
54	PTD	0.200	0.458	4.50	10.07	7.33	16.39
100	PTD	0.272	0.448	5.55	12.42	7.26	16.24
14	SS	0.297	0.636	5.70	12.75	8.22	18.38
15	SS	0.285	0.539	5.64	12.61	7.77	17.38
28	SS	0.286	0.505	5.68	12.70	7.60	17.00
29	SS	0.243	0.406	5.20	11.64	6.98	15.62
34	SS	0.257	0.548	5.28	11.81	7.82	17.50
35	SS	0.280	0.476	5.62	12.58	7.43	16.61
57	SS	0.277	0.628	5.47	12.24	8.18	18.31
203	SS	0.278	0.569	5.53	12.37	7.92	17.72
10	TRD	0.290	0.604	5.64	12.62	8.08	18.08
11	TRD	0.200	0.416	4.54	10.15	7.04	15.75
17	TRD	0.181	0.342	4.27	9.55	6.47	14.48
19	TRD	0.182	0.286	4.35	9.74	5.94	13.28
20	TRD	0.257	0.463	5.35	11.97	7.35	16.44
21	TRD	0.287	0.460	5.72	12.80	7.33	16.40
22	TRD	0.284	0.485	5.66	12.66	7.48	16.74
23	TRD	0.283	0.529	5.61	12.55	7.73	17.28
30	TRD	0.248	0.512	5.19	11.61	7.63	17.07
36	TRD	0.279	0.522	5.57	12.46	7.69	17.20
51	TRD	0.154	0.302	3.75	8.38	6.11	13.66
53	TRD	0.283	0.574	5.57	12.46	7.95	17.78
56	TRD	0.189	0.423	4.34	9.71	7.09	15.87

VITA

Raymond G. Brady

Candidate for the Degree of

Doctor of Education

Thesis: GEOLOGY OF THE QUATERNARY DUNE SANDS IN EASTERN MAJOR AND SOUTHERN ALFALFA COUNTIES, OKLAHOMA

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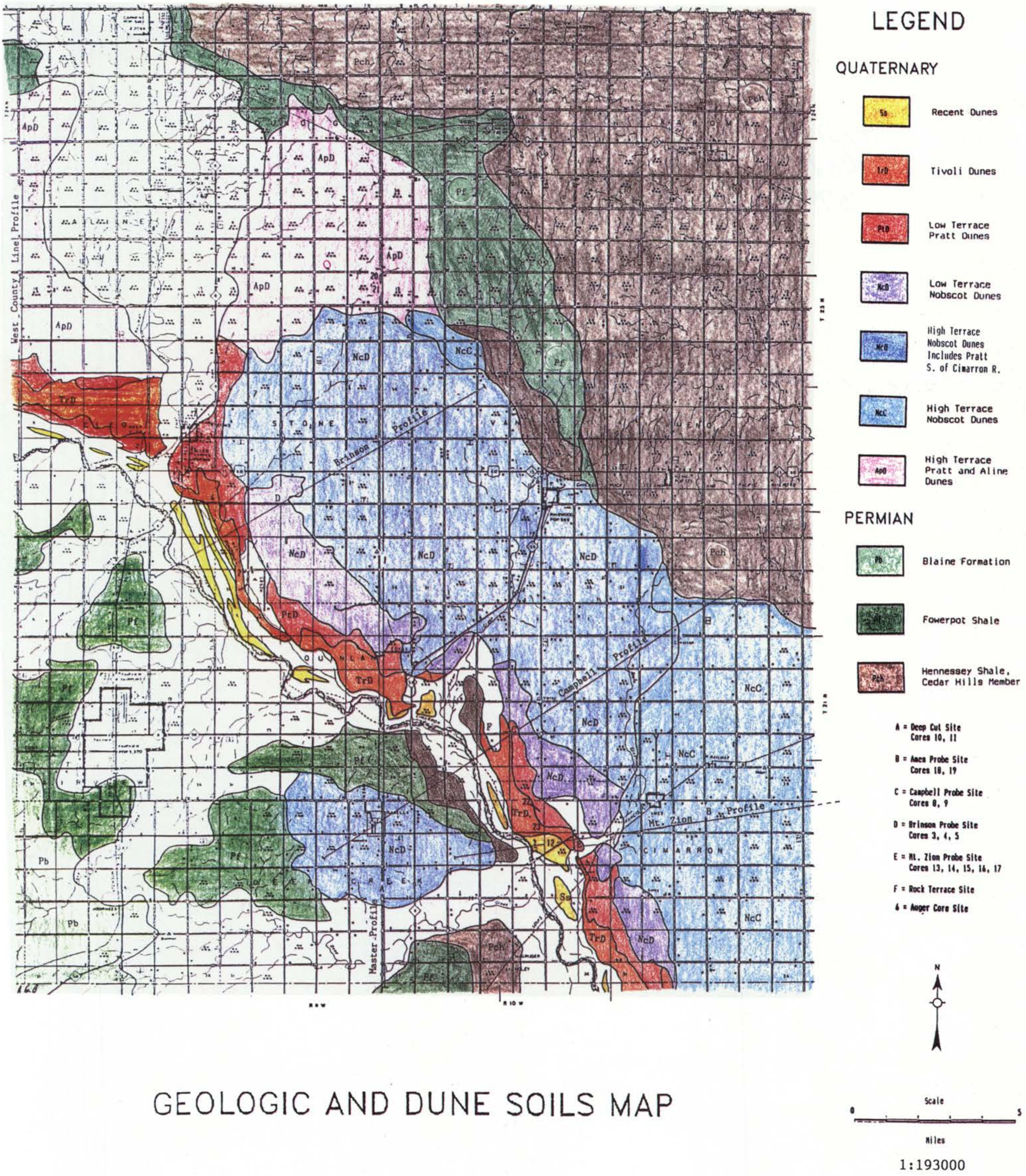
PLATE 1



GEOLOGIC AND DUNE SOILS MAP

EASTERN MAJOR AND SOUTHERN ALFALFA COUNTIES OKLAHOMA

By Raymond G. Brady

Geologic and Soils Boundaries Adapted
from Soil Survey Maps of Major and Alfalfa Count

Published by the
UNITED STATES DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
1969, 1975

Base Map Prepared by the
OKLAHOMA DEPARTMENT OF TRANSPORTATION
PLANNING DIVISION

in cooperation with the
U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY DEPARTMENT
1979