Playas and Lunettes on the Southern High Plains: Morphometric and Spatial Relationships

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The Southern High Plains of northwestern Texas and eastern New Mexico usually is characterized as a featureless plateau, "the largest level plain of its kind in the United States" (NOAA 1982:3). The region is remarkably flat but not altogether devoid of relief. The most ubiquitous geomorphic features are the thousands of small (<5 km^2), circular, seasonally dry depressions, or playas, some of which are accompanied by a crescentic ridge, or lunette, on their eastern sides.

Although the origins of playas and lunettes have long been debated, previous studies of the features on the Southern High Plains were limited to small and sometimes geologically unrepresentative areas of the region. The results of these studies cannot be applied, therefore, to the entire region. Given the large numbers of playas and lunettes over such a large area and given their apparent genetic relationship, a systematic regional investigation of the distribution or morphometry of these landforms is crucial to understanding their origins.

This paper investigates the physical and spatial relationships of playas and lunettes on the Southern High Plains. The paper provides a statistical description of the playas and assesses the relationships, if any, between playa variables and the occurrence of lunettes. Toward this end, the analysis considers such physical variables of playas as orientation (aspect), area, depth, roundness, and substrate characteristics. The distributions of playas and lunettes also are compared with the particle-size characteristics of the substrate in which they occur.

Understanding playa and lunette development and distribution is important for several reasons. First, the Southern High Plains supports an agricultural economy based on cotton and feed grain production that is greatly enhanced by irrigation. Water to support this industry largely is mined from the Ogallala aquifer in the absence of dependable rainfall and permanent surface water. Playas significantly influence surface and groundwater hydrology by providing surface water drainage and major zones of recharge for the rapidly declining Ogallala aquifer (Nativ and Riggio 1990; Stone 1990; Scanlon et al. 1994). Second, an analysis of the distribution of playas and lunettes may shed light on their origins. Third, playas and lunettes also are significant components of the Southern High Plains landscape and thus they may contain clues to Quaternary paleo-environments. A better understanding of their genesis will advance our understanding of the geomorphic evolution of a substantial portion of interior North America.

Geomorphology of the Southern High Plains

Regional Setting

The Southern High Plains, also known as the Llano Estacado ("Stockaded Plains") (Bolton 1990:243), is a virtually featureless constructional surface occupying an area of approximately 130,000 km^2 in northwestern Texas and eastern New Mexico (Figure 1). Defined by 50- to 200-meter escarpments on the western, northern, and eastern sides, the plateau grades imperceptibly into the Edwards Plateau to the south. Elevations range from 750 m above sea level in the southeast to 1500 m above sea level in the northwest.

The climate of the region is warm, semiarid, and continental, hence its classification as BScDw: steppe with dry winters (Russell 1945). As is typical of semi-arid, continental regions,

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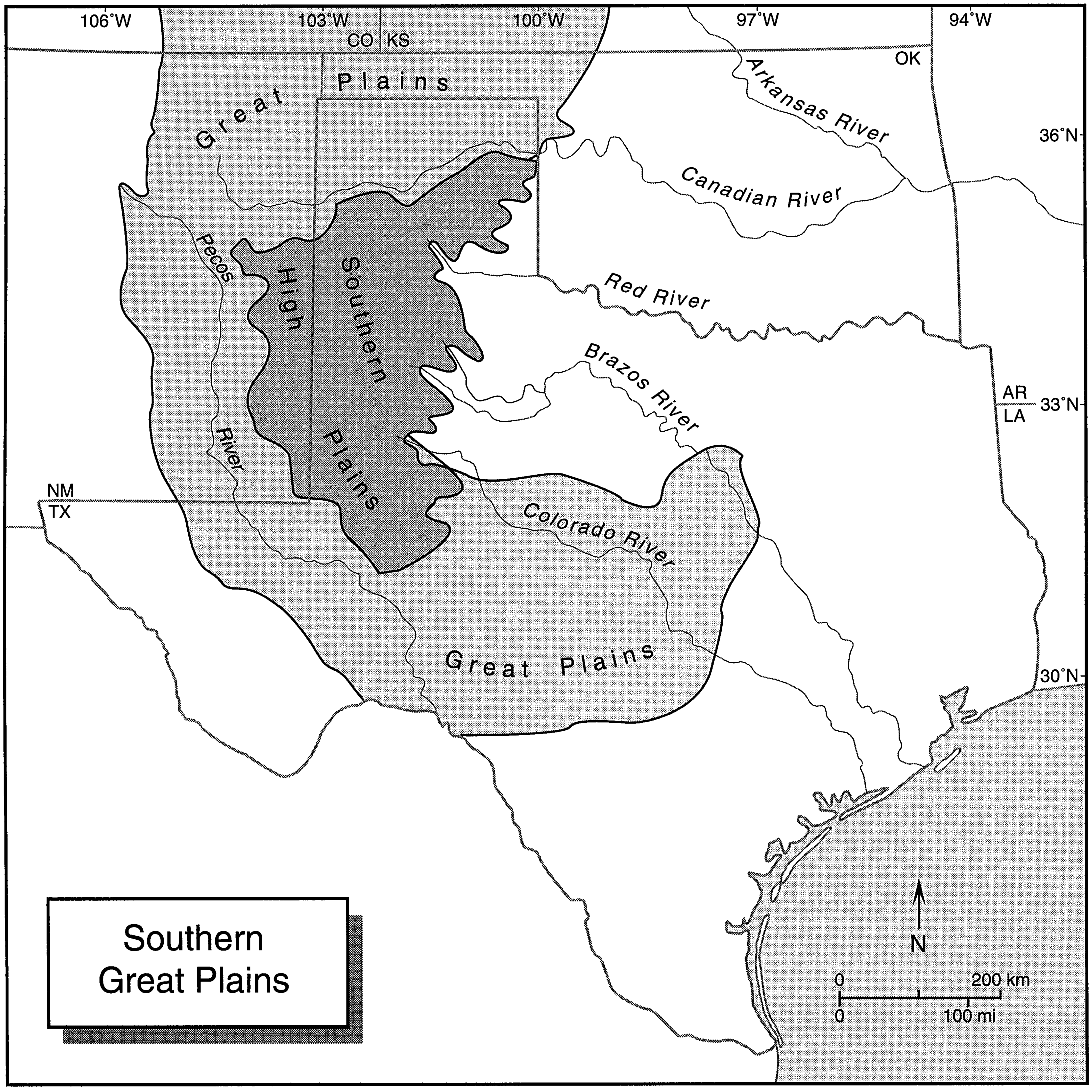

Figure 1. The southern Great Plains of the south-central United States with the location of the Southern High Plains.

annual precipitation varies considerably from year to year. Equally notable is the wind, which blows almost constantly across the open, flat landscape. Average wind speeds range from 16 to 24 kph and speeds more than 80 kph are common (Lotspeich and Everhart 1962; NOAA 1982).

The stratigraphy and geologic setting of the Southern High Plains is well-known (Reeves 1976; Gustavson and Finley 1985; Holliday 1985; 1989; 1995; and Gustavson et al. 1990; 1991). The Ogallala Formation constitutes the bedrock of the Southern High Plains. Consisting of both alluvial and eolian deposits resting unconformably on Permian, Triassic, Jurassic, and Cretaceous strata, the Ogallala is capped by a pedogenic calcrete that forms the "caprock" escarpment defining three sides of the Southern High Plains.

The modern surface of the Southern High

Plains is covered by the Blackwater Draw Formation, which is a widespread eolian deposit derived from the Pecos River Valley (Reeves 1976; Holliday 1989). This deposit varies in thickness and particle size from a thin veneer of sandy loam in the southwest to a thick deposit of clay loam in the northeast. Exposures of the Blackwater Draw Formation show as many as six buried soils, plus the surface soil, all of which indicate episodic deposition and soil formation due to climatic change (Holliday 1989; 1990; 1991). Lake sediments occur below, within, and inset against the Blackwater Draw Formation (Reeves 1976; Holliday 1995). Playas are set into the Blackwater Draw Formation and lunettes rest on top of the unit.

Playas and Lunettes

Playas are small (<5 km^2), shallow, internally drained, roughly circular to oval depressions with a small, flat central floor (Figures 2 and 3). The Southern High Plains also contains about 40 much larger (tens of square km) lake basins with water during all but the driest of times (Reeves 1966; 1990). These basins or "salinas" are not equivalent in either form or origin to the small playas and hence they are not considered in this study.

Estimates of the number of playas on the Southern High Plains vary from 17,000 (Grubb and Parks 1968; Lehman 1972) to 19,000 (Schwiesow 1965) in Texas alone and from 30,000 (Osterkamp and Wood 1987) to 37,000 (Redell 1965) in the entire region. But these

Figure 2. "Silver dollars": small playas of the Southern High Plains following heavy rains. Photo courtesy High Plains Underground Water Conservation District No. 1, Lubbock, Texas.

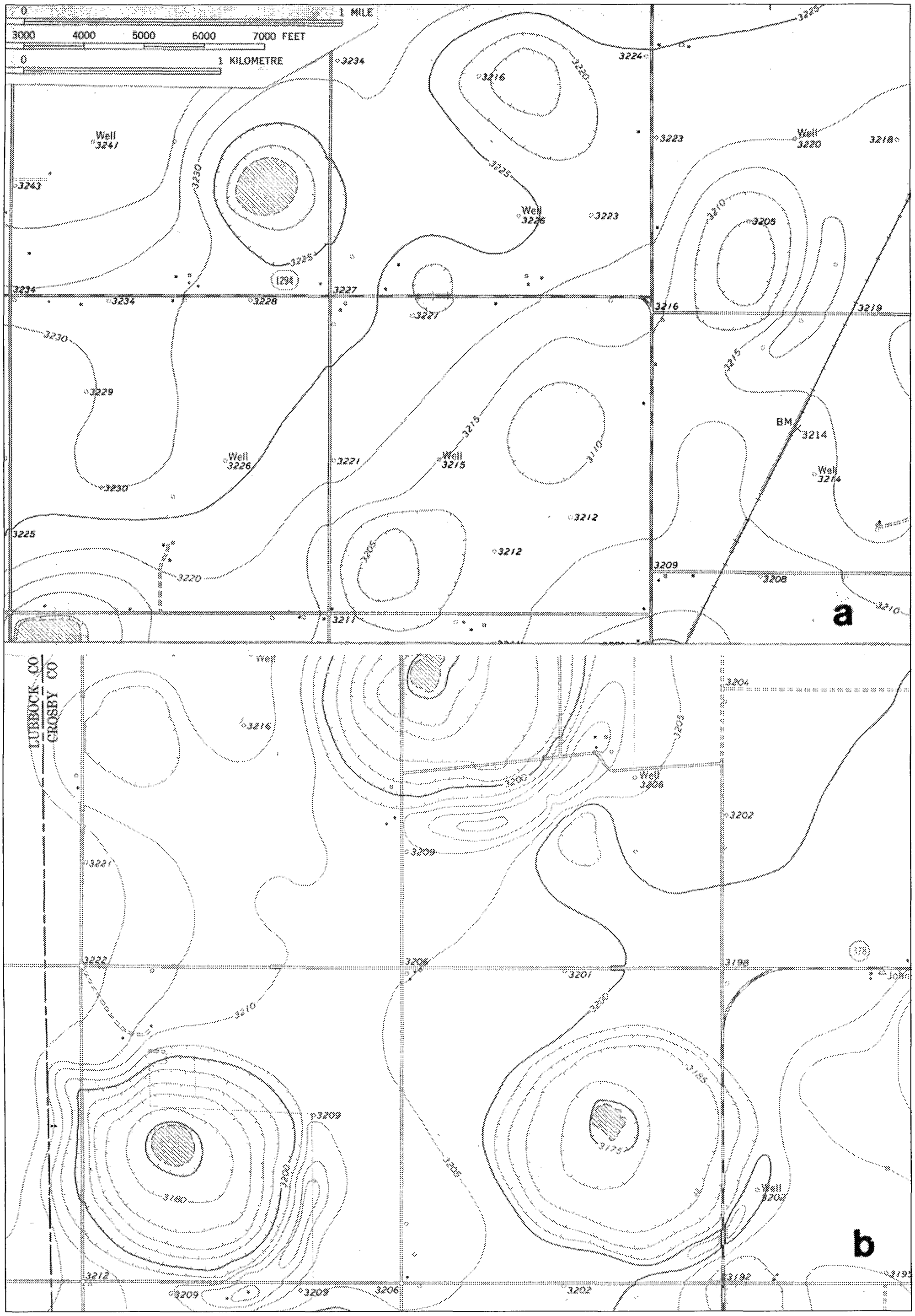

Figure 3. Topographic maps of: (a) typical small playas; note the small, low lunette adjacent to the easternmost playa (from the Idalou 7.5′ quadrangle); and (b) typical playas with large lunettes (from the Petersburg 7.5′ quadrangle). The contour interval is 5 feet.

numbers are confusing because fully 65 percent of the Southern High Plains is in Texas (Figure 1) and because Texas, by most estimates, accounts for the majority of the playas. It follows then that the total number of playas is closer to 20,000 than over 30,000. The problem with such counts resides in the source for these data. Not all playas appear on topographic maps and not all depressions are seasonally dry lake basins. Soil surveys are helpful because of the unique soils found in the playas (discussed below), but not all regions of the Southern High Plains have reasonably current published surveys. Aerial and satellite photography probably is the best source of data, but complete coverage of the region is expensive. Similarly, there are no data on the number of lunettes or the percentage of playas that contain lunettes.

While the small playas have been studied for decades (Baker 1915; Evans and Meade 1945; Judson 1950; Reeves 1966; 1971; 1990; Osterkamp and Wood 1987), their origins and evolution remain controversial and their stratigraphy poorly known. Processes proposed for the development of the basins (Reeves 1966) include wind deflation, subsidence, piping, meteorite impact, and animal activity. The most recent and comprehensive studies of small playa-basin development are those of Osterkamp and Wood (1987), supported by Reeves (1990), and Gustavson et al. (1994). The Osterkamp-Wood model, based largely on hydrologic data (Wood and Osterkamp 1987) and some field data, proposes playa-basin development by eluviation of fine-grained clastic and organic material and carbonate dissolution. The Gustavson model, based on stratigraphic and geomorphic relationships, proposes playa-basin development via fluvial processes that enlarged the basins by means of centripetal drainage, followed by eolian processes that removed the fluvially redeposited sediment and that deflated other basin fill along with some of the Blackwater Draw Formation.

Two distinct types of lake sediment fill the playas (Holliday 1985; 1995). The most common sediment is a clayey, dark grey, weakly calcareous deposit. The layer has no formal lithostratigraphic designation, but is known informally as the Randall clay based on county soil surveys (classified as a Pellustert). The Lipan clay (also a Pellustert) is a soil series locally common in playas with a sandier fill. The other type of sediment is a silty to loamy, light grey, highly calcareous deposit. This layer is known informally as the Arch Loam, again based on the associated soil series mapped on county soil surveys (classified as a Calciorthid). Locally, the Arch loam occurs as a bench around the edges of playas with the Randall clay in the center inset against the Arch.

The age of the playa basins can be inferred from a dozen or so sites. Based on radiocarbon ages or archaeological data or both from within the fill in the basins (Sellards 1938; Roberts 1942; Judson 1953; Holliday 1985; 1995; Johnson et al. 1987; Osterkamp 1990; Holliday et al. 1994), all sites in these investigations contain fills that are at least 10,000 years old with some as old as 35,000 years.

The lunettes of the Southern High Plains, meanwhile, are relatively low dune ridges, usually crescentic, on the eastern to southeastern sides of playas (Figure 3b). The larger lunettes are up to 10 m high and extend one-fourth to one-half the circumference of the associated playa (Figure 3b). Small lunettes cannot always be identified on topographic maps with a contour interval of five feet.

Lunettes, first named by Hills (1940), have been studied in Africa, Australia, and North America (Coffey 1909; Stephens and Crocker 1946; Huffman and Price 1949; Price 1963; Campbell 1968; Bowler 1973; Dare-Edwards 1982). Studies of lunettes on the Southern High Plains are less plentiful by comparison to investigations of the more ubiquitous playas. Noteworthy, however, is the research of Judson (1950), Reeves (1965), and Holliday (1985) who present stratigraphic and geochronologic data on lunettes and Judson (1950) and Holliday (1985) who propose genetic relationships between lunettes and playas.

Lunettes consist of materials derived from deflation of both the Blackwater Draw Formation and the lake sediments in the basins. Soils on the lunettes are mapped as the Drake clay loam (classified as an Ustorthent), derived largely from calcareous playa fill. The fact that the dunes are stratified and contain buried soils demonstrates that the sediment accumulated episodically in dune-building phases followed by long periods of stability (Judson 1950; Holliday 1985; n.d.). Radiocarbon ages show that some of the dunes accumulated for as much as 30,000+ years (Holliday 1985; n.d.).

Several studies on the Southern High Plains propose relationships between playa size and density and their distribution on the Southern High Plains and relationships between playa and lunette distributions. These are as follows:

(1) Playa frequency and substrate texture.
 (A) Playas are more numerous in fine-textured soils (Lotspeich and Coover 1962).
 (B) The frequency of large playas increases from south to north (Grubb and Parks 1968) and playas formed in loamy soils generally are smaller and shallower than those formed in clayey soils (Gustavson et al. 1994).
 (C) Playas increase in occurrence from the southwest to the northeast due to decreased permeability of fine-textured soils (Harris et al. 1972).
 (D) The highest density of playas is along the eastern edge and northeastern corner of the Southern High Plains due to increased precipitation in the east and a thickening and fining of soils to the northeast (Walker 1978).

(2) Playa size and substrate texture.
 (A) Playas formed in finer-textured soils generally are shallower than those formed in coarser-textured soils (Lotspeich et al. 1971).
 (B) Playas become deeper and wider from the southwest to the northeast as the Blackwater Draw Formation becomes thicker and finer-grained in the same direction (Reeves 1971).
 (C) Playas increase in size from the southwest to the northeast due to decreased permeability of fine-textured soils which increases runoff and standing water, resulting in increased area occupied by playas (Harris et al. 1972).
 (D) Playa growth is related to infiltration of water through the substrate (Osterkamp and Wood 1987); therefore, large playas should be more numerous in more permeable substrata than in finer substrata because increased permeability promotes rapid playa growth.
 (E) Playa growth is related to runoff and wind deflation (Gustavson et al. 1994); therefore, large playas should be more numerous in the more easily eroded substrata.

(3) Playa size and lunette formation.
 (A) Playa depth controls occurrence of lunettes; deep playas yield lunettes (Reeves and Parry 1969).
 (B) Most large playas ($\geq$0.6 km diameter or $\geq$ approx. 300,000 km^2) have lunettes (Reeves 1990).

(4) Lunette frequency and substrate texture.
 (A) Lunettes typically do not occur in fine-textured soils (Lotspeich and Coover 1962).

(5) Structural controls on playa distribution.
 (A) Investigations of linear alignments of playas and possible structural controls on their distribution showed either no alignments or no relationship between observed alignments and structural features (Reeves 1972; Woodruff et al. 1979; Collins 1990). Osterkamp and Wood (1987) suggest that playa distribution is largely controlled by linear structural features such as near-surface joints and fractures as well as basement structures. Their examples of linear playa development are limited to an area of southeastern New Mexico off of the Southern High Plains proper.

These studies present multiple hypotheses on playa-lunette relationships and their distribution across the Southern High Plains. Based as they are on general field observations or on analyses of small and possibly unrepresentative areas of the plains, their conclusions are often contradictory.

Research Objectives and Methods

The paper seeks to resolve some of the contradictions outlined above by examining a large data set of playa variables and providing a statistical description of playas and their relationships with lunette occurrence. This research tests all of the hypotheses of playa and lunette distribution noted above, except for those on playa alignments via structural controls. These were not pursued based on the mostly negative results and conclusions reached by previous investigators.

This study consists of an extensive and an intensive component. The extensive component involves a study of the total number of playas and lunettes and their distribution across the Southern High Plains. Countings of playas and lunettes on all 540 complete and partial 7.5′ topographic quadrangles covering the level High Plains surface permitted construction of frequency distributions and descriptive statistics of the number of playas per quadrangle, the number of lunettes per quadrangle, and the percentage of playas with a lunette per quadrangle.

The intensive component measures the physical attributes of playas on a sample of the topographic quadrangles. The impracticality of gathering morphometric data for all playas and lunettes led to the design of a systematic sampling strategy. In order to ensure equal representation of the entire area, the procedure for constructing the intensive sample was as follows. First, an outline of the Southern High Plains was superimposed on an index grid of 7.5′ topographic quadrangles. Only quadrangles with areas entirely on the plains were considered as eligible (N = 480). Second, sample quadrangles were selected at every third quadrangle in latitude and every fourth quadrangle in longitude. This strategy yielded a set of 40 out of a possible 480 quadrangles, covering about 4 percent of the region (Figure 4).

In both the extensive and intensive components, playas were identified by hachured contours and/or the intermittent standing water symbol on the quadrangles; lunettes were identified on topographic maps as crescentic ridges around the outside of some playas. Identification of these landforms was augmented by reference to county soil surveys. Playas too shallow to be indicated by the five-foot contour interval or by the intermittent standing water symbol were in some cases identifiable by the presence of the Randall or Lipan soil series. Lunettes too low in elevation to appear on topographic maps were identified by the Drake soil series. For the intensive component of the investigation, identifications of playas or lunettes based on topography were verified by examination of soil surveys. These identifications were not verified, however, for the extensive component of the study.

The number of playas determined from the unverified count of the 40 sample quadrangles is more than double that of the verified count (2844 unverified versus 1229 verified). The inflation of the unverified counts is probably erroneous because many of the topographic features counted as playas were not small lake basins. This dilemma is especially true in the sandier areas where it is almost impossible to differentiate deflation areas in dunes ("blowouts") from playas in the absence of verification from soil surveys. For example, the maximum number of playas per quadrangle in the verified intensive count is just 98 as compared to 434 in the unverified extensive count. Playa frequency distributions of the intensive and extensive components (Figure 5a) are strongly skewed and somewhat leptokurtic, indicating that the data are not distributed normally. The Kolmogorov-Smirnov Text comparing the two components (including differences in means and variances; Table 1) yielded a P value for playa distributions indicating a significant difference in the verified versus unverified counts. On this basis, the results of the verified playa count (the 40 quadrangles used in the intensive component) were used to correct the results of the extensive, unverified playa count. The verified counts in each substrate region (Figure 4) were compared with the unverified counts from the same quadrangles to determine the percentage overestimation of playa counts for that region. The resulting percentage was used to correct the total unverified count for each region resulting from the extensive component.

In the case of lunettes, the verified 40-quadrangle count is similar to the unverified 40-quadrangle count (68 verified lunettes versus 65 nonverified lunettes) (Figure 5b) and the P value indicates that the unverified lunette count is reliable (Table 1). These results are reasonable because lunettes are more easily identified than playas owing to the arcuate, concentric contour lines bordering playas. These are difficult to confuse with any other feature.

The quadrangles were prepared for digitizing into an Arc/Info geographic information system by converting the latitude and longitude measurements for each quadrangle into Universal Transverse Mercator (UTM) units which allowed measurements to be reported in meters. The outermost hachured contour was considered the playa perimeter. Each playa was assigned a unique number that included the quadrangle number (01–40) and the playa number for that quadrangle (01–98). The playas were then digitized and their areas calculated in square meters. In order to obtain a

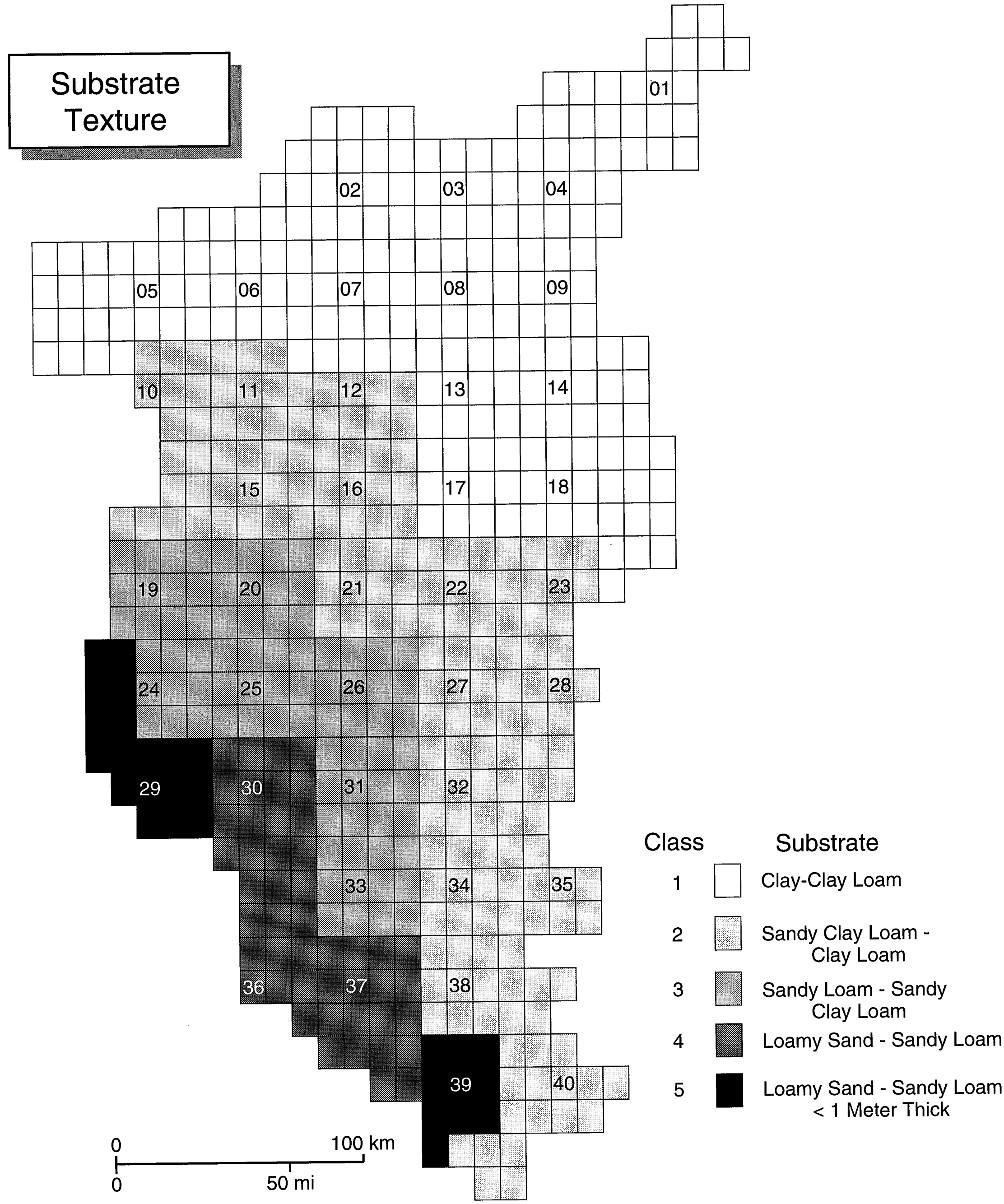

Figure 4. The distribution of substrate textural classes for 7.5′ quadrangles on the Southern High Plains. The numbered quadrangles constitute the sample for the intensive component of the analysis.

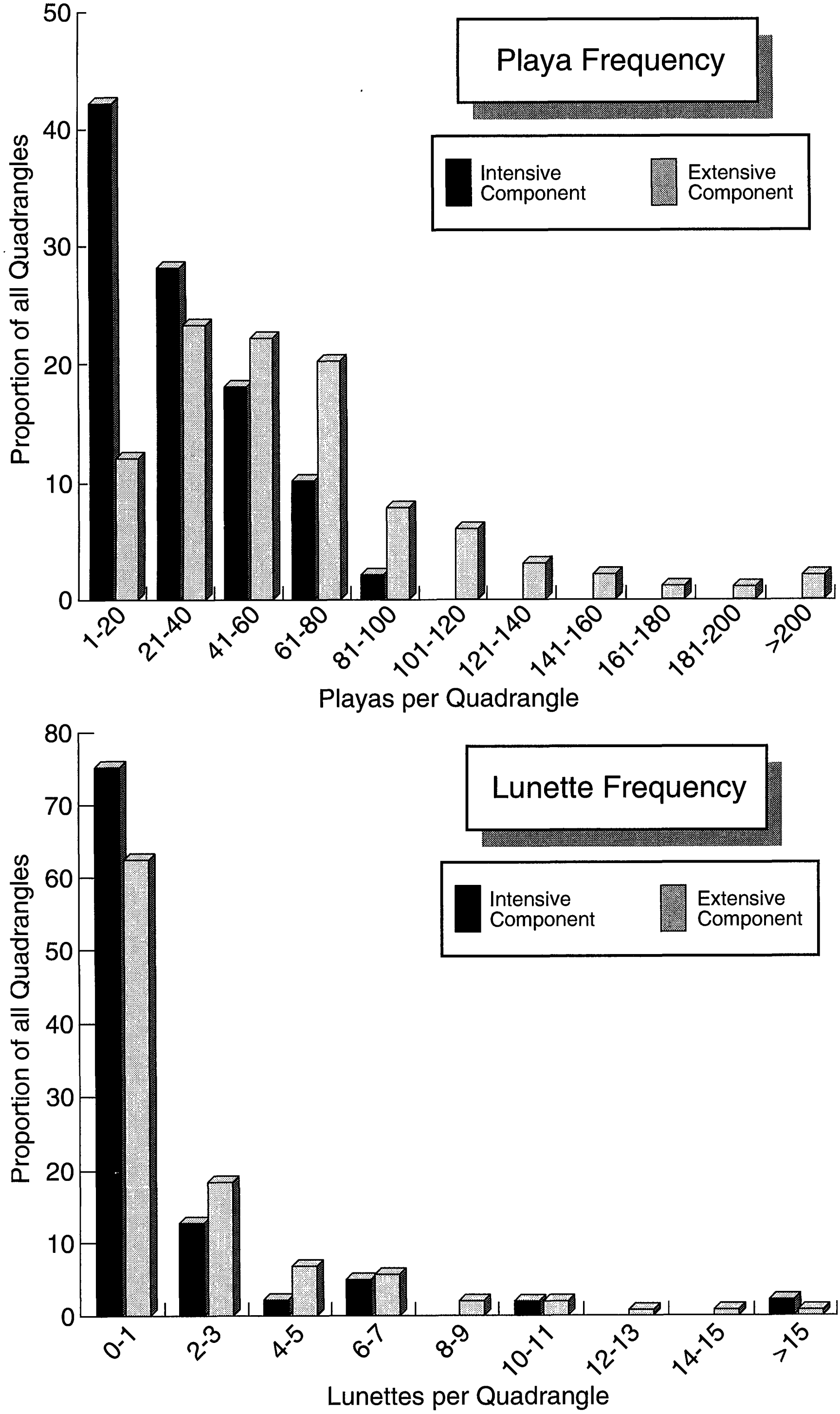

Figure 5. The frequency distribution of playas (a) and lunettes (b) based on counts of the intensive and extensive analyses.

Table 1. Results of Npar1way and Kolmogorov-Smirnov Analyses.

Analysis	Variables Tested	P value
Npar1way[a]	Area by substrate	0.0001
	Depth by substrate	0.0001
	Roundness by substrate	0.0001
	Roundness by depth	0.0340
Kolmogorov-Smirnov[b]	Intensive-extensive playa count comparison	0.0000
	Intensive-extensive lunette count comparison	0.5928

[a]Tests variable distribution across the classes of substrate and depth.
[b]Tests the relationship between the intensive and extensive populations.

maximum diameter, a Fortran program was written to compare x,y coordinate pairs making up each playa. The program also reported the aspect of the maximum diameter in degrees east of north (0–179).

The presence or absence of a lunette was noted for each playa by using a zero for lunette absence and a one for lunette presence. The depth of each playa was noted as the number of hachured contours within each playa (0–9). The lithology of the Blackwater Draw Formation substrate associated with each quadrangle (substrate class variable) was derived by comparing the location of sample quadrangles to a substrate particle-size map developed by Holliday (1989). The substrate particle classes are: 1) clay—clay loam; 2) sandy clay loam—clay loam; 3) sandy loam—sandy clay loam; 4) loamy sand—sandy loam; 5) loamy sand—sandy loam less than 1 meter thick (Figure 4). The roundness for each playa was calculated by an index in which roundness = 4(area)/pi (maximum diameter squared) (Ebdon 1977).

The resulting playa variables used in the study and their units of measurement are as follows:

(1) Area (in square meters).
(2) Maximum Diameter (in meters).
(3) Aspect (of maximum diameter in degrees from north, 0–179).
(4) Roundness Index (0–1, 1 = round).
(5) Substrate Particle Class (1–5, fine-coarse).
(6) Depth (in meters).

Presence or absence of a lunette also was noted. Playas and lunettes also were grouped into sixteen size classes based on area: increments of 0.1 km^2 up to 1.5 km^2 and one group greater than 1.5–4.8 km^2.

The playa variables include a mix of ratio, ordinal, and nominal data. Therefore, the requirements for parametric statistical analysis (normally distributed, continuous data) were not met and hence a nonparametric was called for, namely the Npar1way analysis procedure (Table 1). This procedure tests to see if the distribution of a variable has the same location parameter across different groups. The median scores and analysis-of-variance options were selected. A significance level of 0.05 was chosen; values less than 0.05 indicate rejection of the null hypothesis.

Playa descriptive statistics (Table 2) were performed based on the following null hypotheses generated from the various observations regarding playa and lunette relationships itemized above: There are no significant differences in playa area by a substrate class; in playa depth by substrate class; in playa roundness by substrate class; in playa area by playa depth; in playa area by playa aspect; in playa depth by playa aspect; in playa roundness by playa depth; in playa area by playa roundness; and in playa roundness by playa aspect.

Similarly, for analyzing the relationship between playa variables and the occurrence of lunettes there are no significant differences in area of playas with lunettes and playas without lunettes; in the depth of playas with lunettes and playas without lunettes; and in the substrate class of playas with lunettes and playas without lunettes.

Results and Discussion

As noted earlier, this study consists of two components: the intensive (with verified playa and lunette counts from the 40-quadrangle sample area) and the extensive (with nonverified playa and lunette counts from the 540 quadrangles encompassing the region). The intensive component is analyzed first because the substrate data helps to clarify the playa and

Table 2. Descriptive Statistics for Playas with and without Lunettes.

Variable	Lunette[a]	Minimum	Maximum	Mean	Median	S.D.
Area (in m^2)	0	2,599	4,080,000	197,900	81,060	338,000
	1	28,190	4,832,000	661,600	472,100	792,400
Depth (in m)	0	0.75	14.5	3.07	2.28	2.56
	1	0.75	14.5	17.75	6.10	3.29
Aspect (in degrees)	0	0.2	179.9	97.35	114.50	55.96
	1	4.9	177.9	83.02	59.47	55.05
Roundness index	0	.24	.93	.68	.70	.13
	1	.27	.90	.65	.65	.15
Substrate class	0	1	5	2.08	2	1.23
	1	1	3	2.00	2	.55

[a]Lunette 0 refers to playas without lunettes (N = 1161); Lunette 1 refers to playas with lunettes (N = 68).

lunette distributions in the extensive component of the study.

Intensive Component

The influence of substrate particle size on playa and lunette characteristics was analyzed by calculating frequencies per quadrangle within each substrate class and by testing null hypotheses concerning playa area, depth, roundness, and aspect (Table 1). Although this frequency distribution is discussed more fully in the following section, a preview of the results may be useful here. First, the numbers of playas are highest in the coarsest substrate (class 5) and then decrease from finest to coarsest in the remaining four classes (Figure 6). Second, playas with the greatest area occur in fine-grained substrate (class 1), followed by decreasing playa area as substrate coarsens (classes 2 through 4), albeit with a slight increase in the coarsest and thinnest class (Figure 7a). Third, the relationships of both playa area to substrate texture and playa depth to substrate texture are statistically significant (Table 1); the null hypotheses are rejected.

The trends in frequency and area generally confirm the observations of Lotspeich and Coover (1962), Grubb and Parks (1968), Reeves (1971), and Harris et al. (1972), although none of these investigators noted the higher frequencies of playas in the coarsest and thinnest substrate. The frequency trend roughly correlates to the wind erodibility of the regional soils: the coarsest (sandy) soils are the most erodible followed by the finest (clay and clay loam) soils (Lyles 1977; Breuninger et al. 1989). The latter are more easily eroded because the fines form sand-sized aggregates (Chepil and Woodruff 1963; Breuninger et al. 1989). The high numbers of playas in the most easily erodible substrate (classes 1 and 5) support arguments by Gustavson et al. (1994) that playa formation is related to wind deflation.

Variations in roundness with changes in texture (Figure 7c) generally support interpretations of the influence of texture on frequency. The playas in the most erodible substrate (classes 1, 2, and 5) have, for that reason, the widest range in roundness values. The relation-

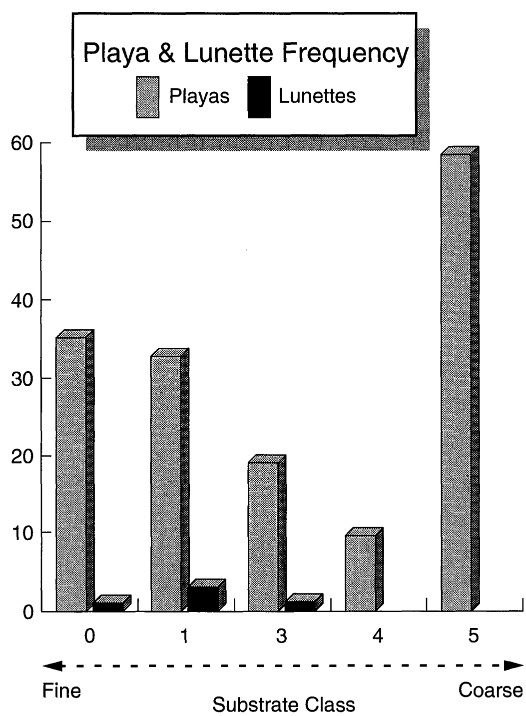

Figure 6. Proportion of playas and lunettes by substrate class.

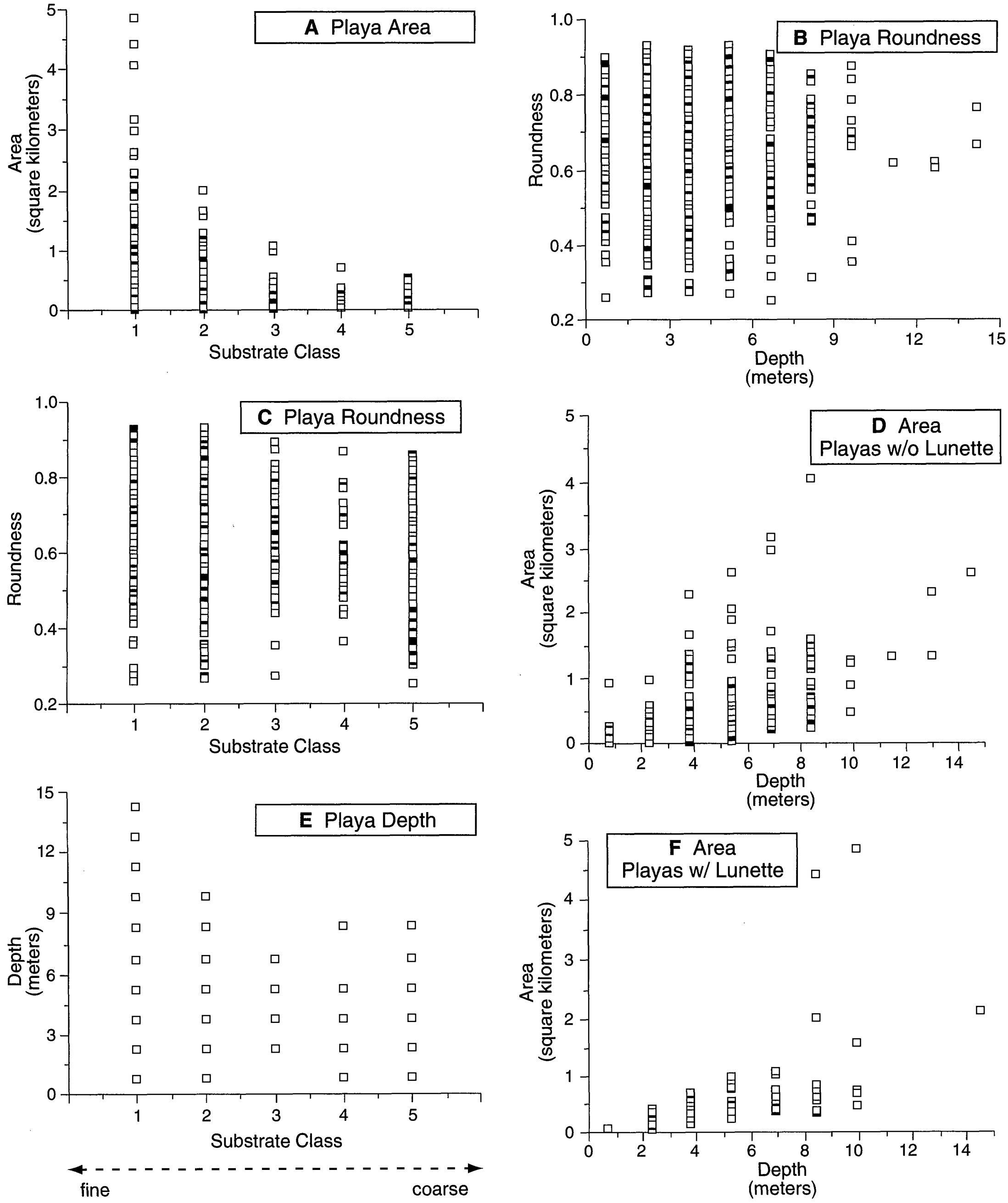

Figure 7. Plots of (a) playa area by substrate texture; (b) playa roundness by playa depth; (c) playa roundness by substrate texture; (d) playa area compared to playa depth for playas without lunettes; (e) playa depth by substrate texture; and (f) playa area compared to playa depth for playas with lunettes.

ship of roundness to substrate texture is statistically significant (Table 1), and, hence, the null hypothesis is rejected.

The increase in playa area as substrate texture fines substantiates the proposition by Harris et al. (1972) and Gustavson et al. (1994) that playas grow as runoff increases. As the Blackwater Draw Formation becomes finer, permeability decreases and runoff into the playa increases. Increased runoff, in turn, enlarges the area of the playa by centripetal erosion (Gustavson et al. 1994). The material eroded into the basin then is removed by deflation. Increased runoff also results in more water in those basins for longer periods of time, which is likely to increase organic matter production which aids in the formation of wind-erodible aggregates (Breuninger et al. 1989). The higher frequency and larger areas of playas in the finest, least permeable soils also indicates that infiltration and dissolution does not play a significant role in playa growth.

While all substrate classes have shallow playas, substrate class 1 demonstrates a full range of playa depths (1–14 m) (Figure 7e). Playa depth may be a function of playa age and the process or processes that promote playa growth, but other variables may be important as well. The depth to the Ogallala Caprock (i.e., thickness of the Blackwater Draw Formation) and depth to indurated sediments of the several lacustrine formations interbedded within the Blackwater Draw Formation may play an important role in controlling playa depth as well as playa area and frequency. These resistant deposits could inhibit the vertical (depth) expansion of playas as they increase their lateral expansion (area). Fracturing and dissolution of the Caprock also might contribute to the increased numbers of playas where the substrate is shallow over the Caprock. Data on the distribution, extent, and depth of the resistant lake deposits are not available, however, and data on depth to the Caprock are very limited.

Comparison of playa roundness to playa depth (Figure 7b) also suggests the importance of runoff in maintaining playa roundness. Playas less than 8 m deep have a wide range of roundness values, but deeper playas tend to have higher roundness values. The roundness of the latter probably is maintained by surface runoff which tends to be more intense and more erosive on the steeper playa margins. The relationship of roundness to depth is statistically significant (Table 1), and the null hypothesis is rejected.

The playas counted in the intensive component vary in size from 0.26 km^2 to 4.83 km^2 (Table 2), but virtually all of these (98.5 percent) are less than or equal to 1.5 km^2 and over half (647 out of 1229) are less than or equal to 0.1 km^2 (Figure 8). Smaller and more shallow playas are found in all textural classes (Figures 7a and 7e), but both the largest and the deepest playas are located in the finest substrate in the north-central region of the Southern High Plains. The largest playas are not the deepest, however (Figures 7d and 7f). The Blackwater Draw Formation is thickest in this area which allows playas to deepen without resistance unless they encounter resistant layers such as indurated lacustrine carbonates, at which point deepening ceases and widening increases.

Comparisons of playa area and aspect (Fig-

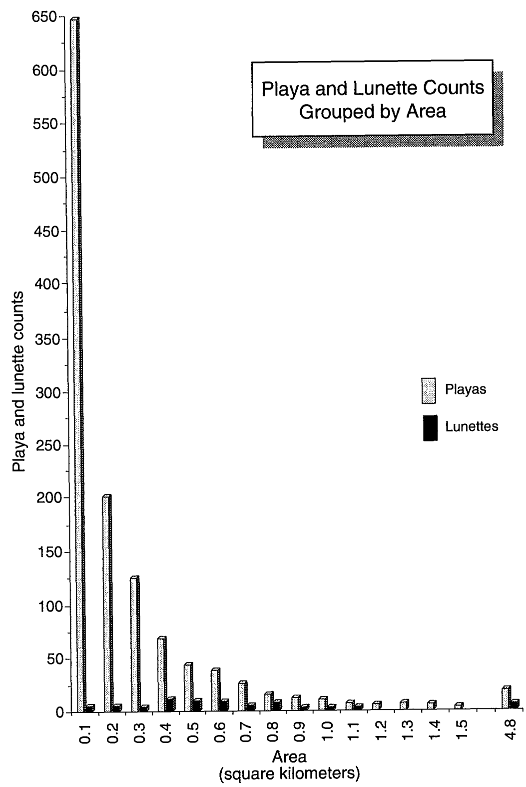

Figure 8. Frequency of playas and lunettes grouped by playa area.

ure 9) reveal no obvious trends, although most playas, independent of size, exhibit aspects of 0–45° and 105–180°. Assuming that the elongation of playa basins is a function of wind direction and, hence, of wave erosion (Reeves 1966; Price 1972; Kaczorowski 1977), then the two sets of playa aspects noted above correspond to winds bearing 270–315° and 195–270°, with the caveat that playas are susceptible to a wider range of winds. Note, however, that these two bearing ranges are similar to the bearings (185–215° and 270–330°) reconstructed by Reeves (1965) based on lunettes adjacent to saline playas. Reeves (1965) initially proposed age groupings for this set of bearings, and later added that playa size is a function of age (Reeves 1990). Having said that, however, playa area does not appear to be a function of aspect (Figure 9); moreover, limited dating of playa fills suggest that the size of playa basins is not directly related to their age (Gustavson et al. 1994; Holliday n.d.).

No significant relationship was observed for the following variables: playa area by playa aspect; playa depth by playa aspect; playa area by playa roundness; playa roundness by playa aspect; or playa aspect by substrate class. Small and large playas exhibit a full range of roundness index values and a full range of aspects. The data and the plots for these comparisons are presented elsewhere (Sabin 1992).

Several trends are apparent in comparisons of playas with lunettes and those without them. Lunettes are disproportionately associated with larger and deeper playas. The highest frequency of lunettes is associated with larger playas in the range of 0.3–0.8 km^2, but over half of the playas are less than or equal to 0.1 km^2, as noted above (Figure 8). Comparing playa area and depth for playas with and without lunettes reveals substantial differences (Table 2). Not all large or deep playas have lunettes, but few small playas do. The relationship between playa variables and lunette occurrence was further analyzed by testing the null hypothesis that no significant difference exists between playas with lunettes and those without them. In these analyses, playa area and playa depth are strong indicators of lunette presence with P values of 0.0001.

Reeves and Parry (1969) earlier observed an association between the occurrence of lunettes and deeper playas. They explained this association by noting that in shallow playas lacustrine fill is deflated and lost downwind because of its fine texture. The deeper playas, though losing their fine sediment downwind, accumulate the remaining coarse sediment along the playa rim, thus contributing to lunette development. Their hypothesis did not take into account, however, the potential for sand-size aggregation of fines or other lithological characteristics of the deflating sediment (e.g., carbonate content).

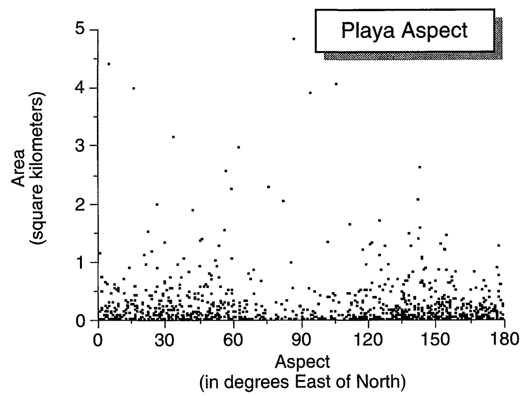

Figure 9. Plot of playa area and playa aspect.

Although lunette presence correlates with playa size, it is not correlated with substrate class; the null hypothesis is accepted. The frequency of lunettes per quadrangle within each substrate class further illustrates the distribution of lunettes relative to substrate class. The highest frequency of lunettes is found in class 2 (3.2/quad) with progressively lower frequencies in class 3 (1.4/quad) and class 1 (0.8/quad). No lunettes occur in substrate classes 4 and 5. Factors other than the texture of the Blackwater Draw Formation appear to control the occurrence of these dunes, and those factors are taken up in the following section.

Extensive Component and Frequency Distribution Comparison

The count of playas and lunettes from the extensive component yielded 33,367 playas and 1,085 lunettes. Application of the "correction factor" determined from comparison of the verified versus the unverified playa counts on the intensive 40-quadrangle study yielded a playa count of 19,630. This count does not include small, shallow playas or filled playas that do not appear on topographic maps or county soil surveys (for example, Sellards 1938; Johnson et al. 1987). A more realistic count of playas is, therefore, probably around 25,000.

The choropleth map of lunette density shows that dunes tend to be common throughout the northern two-thirds of the Llano Estacado and most numerous in the central section of the plains (Figure 10). The map directly contradicts Lotspeich and Coover's (1962) observation that lunettes typically do not occur in fine-textured soils. In fact, the map indicates that lunettes occur in areas dominated by medium- to fine-textured substrate. The coarse substrate that underlies the southwestern region of the Southern High Plains exhibits very few lunettes, but lunette occurrence is not directly related to substrate texture: lunettes are more commonly associated with the larger and deeper playas, and these are less frequent in the central Llano Estacado than in areas to the north.

In sum, other factors appear to control lunette occurrence. Clearly, lunettes are derived largely from calcareous lake sediments, but the origin and distribution of these marls is poorly understood. Formation of these carbonate deposits may be related to the proximity of older carbonate such as Pleistocene marls or the Caprock Calcrete or perhaps groundwater chemistry or both.

Summary

The most ubiquitous geomorphic features on the Southern High Plains are the small playas (<5 km diameter) that pock the surface. The region contains approximately 25,000 small playas, 1,100 of which have a lunette bordering their east-southeast rims. About half of the playas are less than or equal to 0.1 km^2 and 98.5 percent are less than or equal to 1.5 km^2. The playas are inset into the sheets of eolian sediment that blanket the region (the Blackwater Draw Formation) and the lunettes rest on top of these layers.

Statistical data indicate that variation in texture (particle size) of the Blackwater Draw Formation substrate exerts significant control on the occurrence and distribution of playas as well as on the playa variables of area, depth, roundness, and aspect. This substrate is finest (clay—clay loam textures) in the northern and northeastern Southern High Plains and coarsest (loamy sand—sandy loam) in the southwest. Playas are most numerous in the most easily erodible portions of the substrate: the highest counts occur in the sandy textures in the southwest, followed by the finest textures in the northeast. The finest sediment forms sand-size aggregates that are susceptible to wind erosion. Playa areas and the range in playa area are greatest in the finest textures. Mean playa area decreases as substrate texture coarsens. The largest range of playa depths and the deepest playas also occur in the finest substrate. The playas with the largest areas are not the deepest, however. As playas deepen by deflation, resistant layers probably produce lateral rather than vertical expansion. Playa depth and area are influenced, therefore, by local thicknesses of the Blackwater Draw Formation or by depth to more resistant layers interbedded in the Blackwater Draw Formation.

Playas in the finest substrate also have the highest roundness index with roundness decreasing with the coarsening of substrate particle size. Roundness decreases in coarse material which erodes more readily, and it increases in fine-textured substrate by increasing surface runoff which helps maintain playa roundness.

The relationship of substrate texture to playa distribution and related variables supports the erosion hypothesis of playa formation and development. Playas are deeper, larger, and rounder in the easily-eroded finest textures of the Blackwater Draw Formation. While the eluviation and dissolution hypothesis of Osterkamp and Wood (1987) suggests that playa area and depth should increase with increasing permeability, the reverse is actually the case. The finest textures are the least permeable of the Blackwater Draw Formation.

Playa variables strongly associated with presence of lunettes are area and depth. Playas with lunettes have a mean area and depth significantly greater than playas without lunettes, but not all large playas have lunettes. Playa aspect and roundness offer only weak indications of lunette occurrence, and substrate class seems to exert no role at all.

The relationship between playa depth and lunettes probably is a function of the occurrence of lake sediment that can produce lunettes via deflation. Deeper playas may be

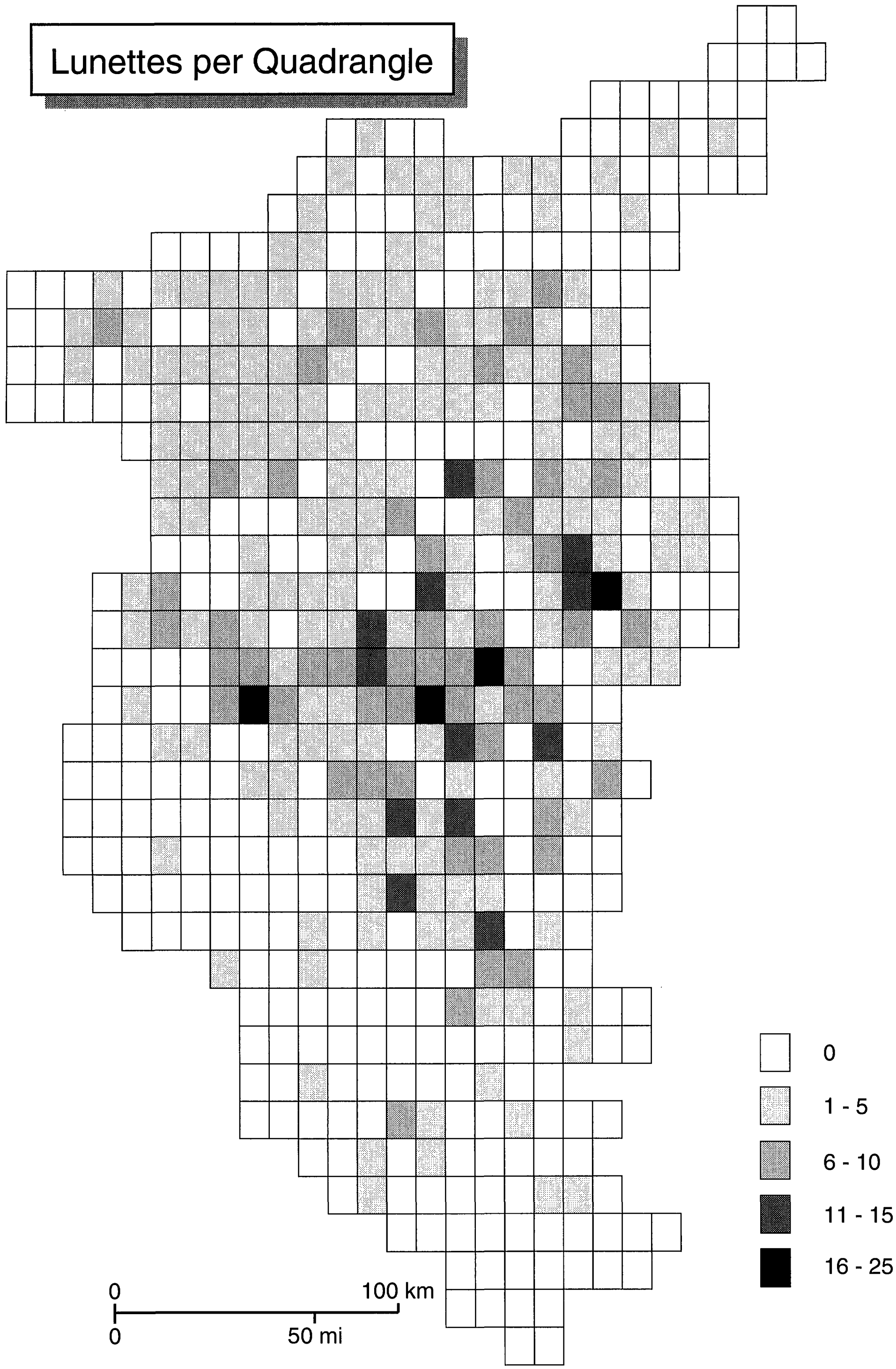

Figure 10. Lunette density on the Southern High Plains by 7.5′ quadrangle. These counts come from the extensive component of the analysis.

more likely to contain lake carbonates because they are closer to or intersect the water table. The highest frequency of lunettes, however, is in the intermediate textures of the Blackwater Draw Formation which have neither the largest nor the deepest playas. This distribution suggests that lunette distribution (and the distribution of lake carbonates within playas) is controlled by factors other than substrate texture. These factors may include: a locally shallow water table which could promote formation of calcareous lake sediments; proximity to one of the indurated marls interbedded in the Blackwater Draw Formation; or proximity to the Ogallala caprock. Definitive conclusions on the causes of lunette distribution will require more data on the thickness of the Blackwater Draw Formation and the distribution of resistant lacustrine carbonates.

The conclusions of this study raise a number of problems for future research. The ubiquity of playas on the High Plains landscape notwithstanding, their genesis and development remain enigmatic. Better understanding of these basins will require more information on the thickness and textural variation of the Blackwater Draw Formation and the regional distribution of erosion-resistant calcretes and lacustrine carbonates. Age relationships among lunettes and among playas of varying size and geographic distribution also may provide clues to their development. These data in tandem with the knowledge gained from this and previous studies will substantially increase our understanding of these features on a featureless plain, or more specifically, of the roles of wind deflation and subsidence on playa formation and regional landscape evolution, playa impacts on groundwater recharge, and on the paleoenvironmental significance of playa and lunette formation.

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Sabin, Ty J., and Holliday, Vance T. 1995. Playas and Lunettes on the Southern High Plains: Morphometric and Spatial Relationships. *Annals of the Association of American Geographers* 85(2):286–305. *Abstract.*

The surface of the Southern High Plains is dotted with thousands of small (<5 km^2), circular, seasonally dry depressions, or playas, some of which are accompanied by a crescentic dune ridge, or lunette. The playas are inset into the sheets of eolian sediment that blanket the region (Blackwater Draw Formation) and the lunettes rest on the eolian mantle. Approximately 25,000 small playas, 1,100 of which have a lunette, were counted from all 540 topographic quadrangles covering the region (verified using data from soil surveys). Statistical analyses of the physical and spatial relationships of playas and lunettes were undertaken to better understand the origins and development of playas, and their relationship to lunettes. Data were collected from a subset of 40 topographic maps, digitized on a GIS, and analyzed using a nonparametric statistical procedure. Variation in texture of the Blackwater Draw Formation exerts considerable control on the distribution and size of playas. Playas are most numerous in the coarsest (sandy), most easily deflated substrate, followed by the finest substrate which produce erodible, sand-size aggregates. The deepest playas and those with largest area also are in the finest, easily erodible substrate. These data support the hypothesis of playa development by erosion rather than by dissolution and subsidence. Lunettes most often are associated with deeper and wider playas. Presence or absence of lunettes probably is related to the nature of the playa fill and is not a function of substrate texture. Lunettes form from deflation of calcareous playa fill which is more common in larger playas. Otherwise, the controls on the distribution of this fill are unknown.
Key Words: lunette, playa, Southern High Plains.

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