SPATIAL DISTRIBUTION AND GEOMORPHIC EVOLUTION OF PLAYA-LUNETTE SYSTEMS ON THE CENTRAL HIGH PLAINS OF KANSAS

BY

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ABSTRACT

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Geographically and hydrologically isolated, ephemeral playa wetlands are ubiquitous features of the High Plains. Lunettes are dune-like features that form downwind of some larger playas. Although playas are important landscape elements, few systematic inventories have been conducted, and little is known about their evolutionary history. A comprehensive Geographic Information Systems database was created for Kansas utilizing several geospatial data sources, including aerial imagery, digital raster graphics, and SSURGO soils data. In addition, stratigraphic data collected from two representative playa-lunette systems (PLSs) were used to reconstruct paleoenvironment and geomorphic processes occurring within these systems throughout their formation and evolution.

Mapping results indicate there are more than 22,000 playas in Kansas, ranging in size from 0.03 ha to 188 ha, with a mean area of 1.65 ha. More than 80% of all playas are smaller than 2 ha and only about 400 are larger than 10 ha. Results indicate that previous High Plains playa inventories failed to identify most playas smaller than 2 ha because data sources were not of sufficient resolution. Additionally, playa identification criteria have not been consistent for all inventories, making it difficult to compare results and establish trends for various playa attributes across the entire High Plains.

Stratigraphic investigations of the two PLSs indicate they are composed of sediment spanning more than 40 kyrs, which began accumulating during at least Marine Isotope Stage (MIS) 3. Climate during MIS 3 was similar to modern: warm temperatures, low effective moisture, and playa floors exposed long enough to allow pedogenesis. During MIS 2, climate was relatively cool with higher effective moisture, and playas were inundated for longer periods. During the Pleistocene-Holocene transition, climate warmed, yet moisture availability remained relatively high. Several distinct shifts in $\delta^{13}C$ identify rapid climate changes associated with the Bølling-Allerød/Younger Dryas climate sequence. Warming continued into the Holocene, though moisture availability was highly variable; Holocene soils are common. Thus, PLSs represents a continuum of the uplands High Plains loess sequence, though deposits are altered by playa hydrology. Geomorphic processes alternated between fluvial- and eolian-driven as climate changed, and detailed records of environmental change throughout their evolution are preserved.

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CHAPTER 1. INTRODUCTION

Wetland ecosystems are some of the most threatened in the world. More than half the wetlands in the United States have been drained, filled, or otherwise altered, thereby endangering a diverse array of flora and fauna that depend on wetlands for survival (Fretwell et al., 1996). The State of Kansas is no exception: more than half of all known wetlands have been lost by conversion to agriculture and desiccation due to lack of available surface and ground water (Kansas Water Office, 2009).

Playa wetlands (or “playas”) are small, internally-drained basins with nearly level bottoms. They represent the most significant wetland resource for much of the High Plains, including Kansas (Fig. 1). Playas are located at the lowest elevations in closed watersheds, and hydrologic inputs are primarily from direct precipitation and runoff (Haukos and Smith, 1994; Tiner, 2003). Hydroperiods are quite variable among playas, seasonally, and annually, with several wet-dry cycles and prolonged dry periods common each year (Haukos and Smith, 1994). Playas have no natural outflows, so all stored water is lost through either evapotranspiration or infiltration into the playa floor (Rosen, 1994). Playas are typically associated with specific soil series that are characterized as hydric soils (i.e., soils wet long enough to produce anaerobic conditions) (Smith, 2003; Schaetzl and Anderson, 2005). Playa soils are very clayey (> 50%) (Allen et al., 1972), and soil series associated with Kansas playas, such as Randall, Lofton, Ness, Pleasant, and Feterita, are primarily composed of smectite clays (Soil Survey Staff et al., 2009). As a result, playa floors exhibit deep cracks during dry periods that allow rapid infiltration during initial wetting, but clays swell after prolonged wetting and playa floors become nearly impermeable (Scanlon and Goldsmith, 1997).

Playas are ubiquitous features on the High Plains (Sabin and Holliday, 1995; Quillin et al., 2005; Bowen et al., 2010). Many large playas have associated lunettes – isolated, eolian dune features that form downwind of the playa (Holliday, 1997). These associations are referred to hereafter as playa-lunette systems (PLSs). Playa-lunette systems are not unique to the High Plains; they have been identified in semi-arid to arid regions around the world, and they are particularly abundant in North and South America, Africa, Asia, and Australia (Goudie and Wells, 1995; Nanson et al., 1998; Harper and Gilkes, 2004; Rodriquez-Rodriquez, 2007).

Large PLSs, such as the two sites included in this study, commonly consist of seven zones: playa floor, annulus, bench, inflow channel, delta, lunette, and interplaya (Fig. 2). The playa floor is the zone intermittently inundated with water, which is underlain by hydric soils and supports aquatic vegetation (Allen et al., 1972; Smith, 2003). The annular region, or annulus, is the gently sloping zone between the playa floor and rim of the depression (Gurdak and Roe, 2009). Between the rim of the depression and interplaya, or lunette, if present, is a nearly-level bench. Where present, the lunette consists of sediment eroded from the playa floor and is composed of sandy silt deposits containing intercalated clay-rich soils. Expansive, flat, and typically loess-mantled uplands between adjacent playas and/or lunettes are referred to as the interplaya. Each of the study PLSs had a single inflow channel and associated delta.

Although PLSs are vital features of the High Plains, an accurate inventory does not exist for the State of Kansas. Additionally, despite appreciable research on the subject, the timing and processes of PLS formation and development remain unclear. These systems are particularly useful for paleoenvironmental reconstructions because they are influenced by fluvial, lacustrine, and eolian processes, with the dominant geomorphic process at a given time being dependent upon prevailing environmental conditions (Holliday et al., 1995; Holliday, 2004). Due to their small size and ephemeral nature of playas, PLSs are highly sensitive to climate fluctuations. Consequently, PLSs represent a unique, high-resolution (i.e., decadal to sub-millennial scale) terrestrial archive of paleoenvironmental information for the High Plains.

The goals of this project were to: 1) generate a comprehensive and detailed inventory of playas distributed throughout western Kansas; 2) reconstruct the paleoenvironment throughout PLS evolution; and 3) identify the primary processes and mechanisms of PLS formation and development. As a result, this dissertation consists of two primary components: 1) a GIS-based inventory of all playas in western Kansas; and 2) stratigraphic investigations of two PLSs on the High Plains of Kansas. A manuscript describing the GIS-based inventory is currently published as:

Bowen, Mark W., Johnson, William C., Egbert, Stephen L., and Klopfenstein, Scott T., 2010, A GIS-based approach to identify and map playa wetlands on the High Plains, Kansas, USA: *Wetlands*, v. 30, no. 4.

Stratigraphic data and paleoenvironmental reconstructions for the two PLSs are currently published as:

Bowen, Mark W. and Johnson, William C., 2011, Late Quaternary environmental reconstructions of playa-lunette system evolution on the Central High Plains of Kansas, United States, Geological Society of America Bulletin (Accepted).

A detailed description of new techniques used to develop a comprehensive playa GIS-database for western Kansas is provided in Chapter 3. Utilizing several geospatial data sources, including high-resolution aerial imagery, digital raster graphics, and SSURGO soils data, 22,045 playas were identified – more than doubling previous estimates. New radiocarbon, optically stimulated luminescence (OSL), isotope, magnetic, and sedimentological data are presented for two PLSs on the High Plains of Kansas in Chapters 5 and 6. Stratigraphic records for the two PLSs span more than 40 kyr and preserve evidence of regional and hemispheric-scale climate events. These data provide new information on the geographic distribution of playas and geomorphic processes involved in the formation and maintenance of PLSs. Understanding PLS distribution and geomorphic processes is essential because these systems provide a host of important functions, such as groundwater recharge, surface water storage, wetland habitat, nutrient cycling, particulate retention, and preservation of archaeological material (Haukos and Smith, 1994; Luo et al., 1999; Smith, 2003; Campbell et al., 2007; Gurdak and Roe, 2009).

CHAPTER 2. REGIONAL SETTING

Climate

Climate on the High Plains of western Kansas is semi-arid in the west and dry subhumid to the east (Veregin, 2005). Lane County, Kansas, has an average annual precipitation rate of 47.7 cm, ranging from a minimum of 0.76 cm in January to a maximum of 7.5 cm in June, with the bulk of precipitation falling during the growing season (Flora, 1948). Lane County also receives 53.3 cm of snowfall per year on average. Scott City, centrally located on the High Plains in neighboring Scott County, Kansas, has an average temperature range of -9 °C to 34 °C, receiving on average 50.8 cm of rain and 66 cm of snow per year since 1948 (High Plains Regional Climate Center, 2009).

Evaporation rates collected approximately 80 km to the southwest in Garden City, Kansas, the nearest evaporation weather station, ranged from a mean of 16.4 cm to 29.7 cm between April and July (Flora, 1948). These data indicate that during the growing season evaporation greatly exceeds precipitation. Winds on the High Plains of western Kansas blow from the northeast during the winter months at approximately 19.3 km/hour. The remainder of the year the winds are predominantly from the south and southeast at a slightly higher velocity. However, stratigraphic data throughout High Plains indicate that during much of the Quaternary winds were predominantly from the northwest (Muhs and Bettis, 2003).

Groundwater

The High Plains Aquifer, the most important water resource in western Kansas, is the predominant source of irrigation waters in western Kansas (U.S. Geological Survey, 2006). The aquifer underlies approximately 86,765 km^2 in 46 counties in western Kansas; it is also found in seven other states on the Great Plains. Originally referred to as the Ogallala Aquifer due to the importance of the Ogallala Formation in storing groundwater, it was renamed to the High Plains Aquifer because other contributing geologic units. The High Plains Aquifer is underlain by the Dakota and Permian Aquifers but is hydraulically isolated in north and central portions of Kansas by low permeability shales and chalks (Macfarlane et al., 2000).

The Ogallala or High Plains Aquifer has been in steady decline, particularly since the 1950s when pumping groundwater for irrigation began in earnest. McGuire (2006) analyzed groundwater levels from wells throughout the entire High Plains Aquifer region from about 1950, before substantial groundwater pumping began, to 2005. Over 3,600 wells were monitored from predevelopment to 2005, with 511 wells located throughout western Kansas. Based on area-weighted average water-level changes, the entire High Plains Aquifer has declined by ~4 m. The greatest decline was recorded in Texas at 11 m, while Kansas ranked second with a decline of 6 m. Of the 312 km^3, or 9 percent, of groundwater storage lost in the High Plains Aquifer since predevelopment, over 23 percent, or 73 km^3, of this storage was lost in Kansas.

Regional Stratigraphy and Environmental Interpretations

Sand and gravel eroded from the ancestral Rockies and deposited in western Kansas during the late Miocene to early Pliocene comprises the Ogallala Formation (Ludvigson et al., 2009), which forms the basal bedrock unit of PLSs. A thick, carbonate-rich zone forms the “caprock” of the Ogallala Formation, and this caprock, referred to hereafter as Ogallala calcrete, formed by pedogenic processes that terminated near the Pliocene-Pleistocene transition (Swineford et al., 1958; Gustavson and Holliday, 1999). Although calcrete beds are found throughout the Ogallala Formation (Diffendal, 1982), only the uppermost calcrete bed was encountered during coring. Four loess units commonly overlie Ogallala calcrete, including the Loveland, Gilman Canyon, Peoria, and Bignell units (Frye and Leonard, 1951; Muhs et al., 1999; Mason et al., 2008) (Fig. 3). Buried soils occur throughout the loess sequence, with the most prominent buried soils developed at the top of the individual units. The Sangamon Soil formed in the surface of Loveland Loess, the Gilman Canyon pedocomplex formed within Gilman Canyon loess, and the Brady Soil developed within the upper Peoria Loess. Several buried soils are common in Bignell Loess (Mason et al., 2003; Feggestad et al., 2004; Miao et al., 2007a).

On the Central High Plains, the Sangamon Soil is widespread, with development occurring throughout all of Marine Isotope Stage (MIS) 5 and most of MIS 4 (Forman et al., 1992; Maat and Johnson, 1996; Forman and Pierson, 2002; Mason et al., 2007). Previous research on the Great Plains indicates that during Sangamon Soil formation regional climate was warm and dry (Feng et al., 1994) or warm and humid (Muhs and Bettis, 2003; Karlstrom et al., 2008). In the Lower Mississippi River valley, the soil formed under a warm to hot climate with seasonal or longer periods of drought (Markewich, 2008).

Gilman Canyon loess deposition occurred slowly throughout MIS 3, and the unit, referred to as the Gilman Canyon Formation (GCF), is characterized by pedogenic alteration throughout (Johnson et al., 2007; Mason et al., 2007; Wang et al., 2009). Johnson et al. (2007) identified three distinct loess units and three soils within the upper two loess units at the type locality in southwestern Nebraska, with ages for the soil zone ranging from 38,370 cal yr B.P. to 25,580 cal yr B.P. Climate reconstructions for Southwestern Nebraska, based on $\delta^{13}C$ data, indicate that mean July temperatures were ~2 °C warmer than modern during pedogenesis within the lower GCF, but were ~5 °C cooler in the upper part of the formation (Johnson et al., 2007).

Peoria Loess overlies the GCF and is the thickest and most widely distributed loess unit on the Central Great Plains (Muhs et al., 1999). Loess deposition occurred predominantly during MIS 2, ~25–12 ka, and accumulated more rapidly than underlying loess units (Martin, 1993; Feng et al., 1994; Maat and Johnson, 1996). The climate was colder and/or drier than today (Muhs et al., 1999; Mason et al., 2007). Mason et al. (2007) asserts there is little evidence of pedogenic alteration below the surface soil within the loess unit, although Ruhe et al. (1971) identified several “dark bands” in Peoria Loess of western Iowa that they interpreted as a series of incipient paleosols. Banding and laminations within Peoria Loess, although rare, have also been identified in Nebraska (Thorp et al., 1951), Iowa (Daniels et al., 1960; Ruhe et al., 1971), and Illinois (Wang et al., 2000; 2003). Researchers suggested the bands represent periods of decreased loess deposition and incipient paleosol formation. In the Mississippi River near East St. Louis, Illinois, as many as 41 alternating A/C horizons have been observed in ~15 m thick Peoria Loess deposits (Wang et al., 2000; 2003). The 41 laminations were grouped into six paleosol complexes, which correspond to comparatively warmer and wetter climate periods between 24 ka and 11 ka.

The Brady Soil, developed within the upper Peoria Loess, began forming as early as ~15 ka (Mason et al., 2008), with pedogenesis being extinguished by deposition of Bignell Loess starting ~10–9 ka (Muhs et al., 1999; Johnson and Willey, 2000; Mason and Kuzila, 2000; Mason et al., 2003; Mason et al., 2008). The Pleistocene-Holocene (P-H) transition was a period of considerable climatic variability worldwide (Hughen et al., 1996; Alley, 2000; Koutavas et al., 2002), across North America (Yu and Wright, 2001; Yu, 2003; Grimm et al., 2006; Yu, 2007; Kennett et al., 2008), and on the Great Plains (Johnson and Willey, 2000; Bement et al., 2007; Mandel, 2008; Mason et al., 2008). Mason et al. (2008) suggested that during Brady Soil formation climate was characterized by increased effective moisture, which stabilized the landscape. Johnson and Willey (2000) examined climate gradients during the P-H transition along two transects extending west to east across Kansas and north to south through Nebraska and Kansas using stable carbon isotopes and magnetic susceptibility. They reported that C_3-dominated plant communities were replaced by C_4 grasses in western Kansas and correlate to an increase in July mean daily temperature of 8–10 °C from the Pleistocene to the Holocene. Data indicate that loess deposition ceased and pedogenesis was intense across the region during the P-H transition.

Deposition of Bignell Loess, the uppermost unit of the Great Plains loess sequence, began at the onset of the Holocene ~11–9 ka and continued episodically throughout the Holocene. Climate of this period was characterized by generally higher temperatures than present with persistent, recurring droughts common (Mason and Kuzila, 2000; Faulkner, 2002; Mason et al., 2003; Feggestad et al., 2004; Miao et al., 2007a). Thickness of the loess unit ranges from undetectable accumulations to ~6 m; greatest thicknesses are often observed downwind of dune fields, suggesting this unit was primarily derived from dune-field reactivation in Nebraska and eastern Colorado (Mason et al., 2003; Miao et al., 2007a; Miao et al., 2007b). Buried soils commonly occur within Bignell Loess, particularly within the upper portion of the unit, and range in age from ~10 ka to 1.6 ka (Mason and Kuzila, 2000; Mason et al., 2003; Miao et al., 2007b; Mason et al., 2008). Four buried soils dominated by C_4 vegetation were identified in Bignell Loess in southwest Nebraska, while intercalated loess deposits had a higher proportion of

C_3 vegetation (Feggestad et al., 2004). In extreme northwest Kansas, magnetic susceptibility data indicate four or five incipient buried soils occur throughout Bignell Loess (Johnson and Willey, 2000).

Ehmke Playa-Lunette System

Ehmke PLS is located in the western portion of Lane County, Kansas, an area with the highest density of playas in Kansas (Fig. 4). Ehmke playa has a surface area of 51 ha, an average depth of 0.75 m, an approximate storage volume of 390,000 m^3, and receives runoff from a drainage area of ~14 km^2. The lunette measures ~1 km in length, with a crest 11.5 m higher than the playa floor and ~6 m higher than the surrounding interplaya. An unpaved section-line road originally crossed the eastern flank of the lunette, and agricultural terraces constructed on the western flank and northern (windward) and southern (leeward) slopes of the lunette disturbed near-surface stratigraphy. The road was closed in the 1980s when an archaeological site (14LA311) was discovered on the lunette, at which time the entire lunette was seeded to Conservation Reserve Program grasses. Ehmke playa has remained uncropped and untilled throughout its history. It also represents a “typical” larger playa, with the long axis oriented southwest–northeast and a lunette to the southeast.

Ehmke PLS is a registered archaeological site (14LA311) and was studied by researchers from the Kansas State Historical Society (Witty, 1989). Researchers identified fossilized bone fragments from bison and horse and mammoth teeth fragments. Diagnostic artifacts, primarily projectile points, found within the lunette were identified to represent at least seven different cultural periods (Clovis, Hell Gap, Logan Creek, Table Rock, Woodland, Middle Ceramic, Late Ceramic); however, all artifacts were found out of context. Researchers noted that projectile points from all periods were made from Niobrara jasper, which is common in the region. This suggests there was a significant local population, not just isolated bands of migrating hunters. Additional evidence suggests that animals killed at the playa were butchered on site, indicating the site was not only used for hunting, but also camping.

A detailed land-cover map was generated for Kansas between 1995 and 2000 utilizing multitemporal Landsat Thematic Mapper imagery as part of the Kansas GAP analysis project (Egbert et al., 2001). Ehmke playa and associated lunette were mapped as Conservation Reserve Program grasses, dominated by the species *Andropogon garardii, Schizachyrium scoparium, Sorghastrum nutans,* and *Panicum virgatum*. The area immediately surrounding the playa was mapped as western wheatgrass prairie, while the surrounding uplands were mapped as cultivated land. Kindscher et al. (1996) conducted vegetation surveys within Ehmke playa, referred to as Meadowlark playa in their report. Vegetation was dominated by Buffalo grass (*Buchloe dactyloides*), little barley (*Echinochloa crusgalli*), wedgeleaf fog-fruit (*Lippia cuneifolia*), and spikerush (*Eleocharis macrostachya*).

Soils from the Natural Resource Conservation Service SSURGO database indicate that distinct soils occur within Ehmke playa, lunette, and interplayas. Soils within the playa were mapped as Ness clay, a soil found predominantly within upland depressions such as playas. Lunette soils have developed Ulysses silt loams and Ulysses-Colby silt loams, consisting of well-drained upland soils formed in deep loess. Interplayas are dominated by Harney silt loam, a well-drained soil series also formed in deep loess.

Bush Playa-Lunette System

Bush PLS, also within Lane County, Kansas, and 16 km southeast of Ehmke PLS (Fig. 4), was selected for many of the same reasons as Ehmke PLS. It is a grassland playa that has been untilled and uncropped throughout its history. Benchmark vegetation surveys were also conducted by Kindscher et al. (1996) at this site. This playa also represents a "typical" larger playa with the same orientation and lunette location as Ehmke PLS. Bush playa is somewhat smaller than Ehmke playa, with a surface area of 20 ha, average depth of 0.93 m, storage volume of 186,000 m^3, and drainage area of ~4.7 km^2. The lunette is ~0.7 km long and the crest is 7.5 m higher than the playa floor and 3–4 m higher than the surrounding interplaya.

Land cover in Bush playa, determined from the Kansas GAP analysis project, consists of short-grass prairie within the playa, while immediate surroundings were composed of western wheatgrass prairie. Vegetation surveys conducted by Kindscher et al. (1996), referred to as Chorus Frog playa in the report, indicate spikerushes (*Eleocharis macrostachya* and *E. acicularis*) were the dominant plant species within the playa. Interplayas were dominated by cultivated lands. Soils within Bush PLS, determined from SSURGO soils data, are similar to those found in Ehmke PLS, with Ness clay in the playa, Ulysses silt loam on the lunette, and Harney silt loam on interplayas.

CHAPTER 3. IDENTIFYING AND MAPPING PLAYA WETLANDS ON THE CENTRAL HIGH PLAINS OF KANSAS

The U.S. Fish and Wildlife Service began inventorying all wetlands, including playas, in the United States in 1979 using aerial photography for the National Wetlands Inventory (NWI) (Wilen and Bates, 1995). This inventory continues to be the only accurate and comprehensive inventory of wetlands for western Kansas. Only a small portion of the NWI for Kansas was available electronically during the mapping phase of this project, and playas were not specifically identified in the database. Thus, the NWI has little utility for playa studies within Kansas.

The goal of this mapping project was to generate a comprehensive and detailed inventory of playas distributed throughout western Kansas. Objectives were to: 1) develop and compare three distinct geospatial playa databases – two based on traditional data sources (i.e., soil survey data and topographic maps) (Guthery et al., 1981; Guthery and Bryant, 1982; Sabin and Holliday, 1995; Fish et al., 2000), and one combining traditional data sources with new high-resolution aerial imagery; 2) compare results from this project to playa mapping projects conducted for other regions of the High Plains; and 3) determine the most appropriate procedure to identify and map playas. To accomplish this, computer-based methods were developed that could easily be modified and expanded to include other regions and additional wetland types. To ensure the inventory remains robust and up-to-date, a digital playa inventory was developed as a GIS database that can be modified, expanded, and updated as new data become available.

Mapping Domain

Playas were identified and mapped for a 46 county region that covered 10,392,000 ha in western Kansas, referred to as the mapping domain (Fig. 5). The mapping domain was defined as extending from the northern border with Nebraska to the southern border with Oklahoma, from the western border with Colorado to approximately the center of Kansas along the eastern edge of counties extending from Smith County in the north to Barber County in the south (Fig. 5). Included were portions of the High Plains, Arkansas River Lowlands, Red Hills, and Dissected High Plains or Plains Border physiographic provinces (Fenneman, 1931; Schoewe, 1949).

Kansas Playa Inventory and GIS Database Development

Three individual playa databases were created in a GIS environment using the Natural Resource Conservation Service's Soil Survey Geographic (SSURGO) Database, digital raster graphics (DRGs), and high-resolution National Agriculture Imagery Program (NAIP) aerial imagery. Aerial imagery acquired as part of the NAIP was available state-wide in Kansas for the years 2003, 2004, 2005, and 2006. A range of playa hydrologic and vegetation conditions were depicted on the four years of imagery, aiding in playa identification. NAIP imagery for the 46-county study area was available as color orthoimagery with 2-m resolution for 2003–2005 and 1-m resolution for 2006.

A previously developed playa database based on a filtered SSURGO dataset that only included diagnostic playa soils (i.e., Randall, Lofton, Ness, Pleasant, and Feterita soil series) was used to construct the SSURGO playa database (Johnson and Campbell, 2004). The SSURGO playa database only includes 40 of the 46 counties in the mapping domain. Smith, Osborne, Russell, Stafford, Pratt, and Barber counties, all in the extreme eastern portion of the mapping domain, were excluded.

All upland closed depressions and hydrologically isolated water bodies mapped on DRGs were digitized on-screen ("heads-up") to create the DRG playa database for the entire 46 county mapping domain. If a closed depression consisted of more than one closed contour, only the innermost contour line was digitized. If a water body was enclosed within a closed contour, only the water body was mapped.

The NAIP playa database was developed by visually scanning four sequential years of NAIP imagery in 2.6 km^2 (1 mi^2) intervals to identify geographically and hydrologically isolated upland depressions and water bodies, which were digitized on-screen for all 46 counties. Water, a distinct natural vegetation pattern, or substantial decrease in vegetation density in cultivated fields must have been visible on at least one year of NAIP imagery or distinct soil boundaries must have been visible on at least two images.

Criteria used to identify playas included: 1) appropriate geomorphic position (i.e., located on broad, nearly-level uplands); 2) disconnection from stream networks (i.e., hydrologically isolated); 3) lowest elevation within a closed basin and completely surrounded by upland at the local scale (i.e., geographically isolated (Tiner, 2003)); 4) no mapped or visually identifiable source of outflow; and 5) circular to semi-circular form.

To ensure only geographically and hydrologically isolated features were mapped, a 15-m buffer was applied to the National Hydrography Dataset, and all overlapping playas were removed from the DRG and NAIP databases; similar procedures were conducted for the SSURGO database (Johnson and Campbell, 2004). A digital database of soils with sandy parent material derived from SSURGO data was used to remove all playas mapped in regions of expansive sandy soils. However, not all playas included in the DRG and NAIP databases were associated with clay-rich or hydric soils.

If a playa crossed county boundaries it was included in the county that contained the majority of the playa. If a playa was bisected by a road, the entire playa was digitized as a single playa. Since playas are typically round to elongate (Sabin and Holliday, 1995), particular emphasis was placed on identifying features with a similar morphology, although playas were not included or excluded based solely on this criterion. Finally, a minimum mapping unit of 0.03 ha (300 m^2) was established to include even very small playas; data resolution constraints prevented identification of smaller features. Individual GIS polygons were created for each playa, and surface area was calculated in GIS for each polygon in all three playa databases. Each entry in the databases includes geographic location, county of occurrence, surface area, perimeter, and absence/presence on the three data sources.

The NAIP database was intended to be inclusive, so when uncertainties in identification were encountered, the potential playa was digitized, included in the database, and noted for detailed review. All playas designated for review were subjected to detailed visual inspections to eliminate all non-playa features. This GIS-based verification was intended to be the most stringent to account for the difficulties in field-based verifications. Individual inspections included thorough examination of all four years of NAIP imagery, examination of color infrared NAIP imagery available for 2006, and 2008 NAIP imagery where available. DRGs, SSURGO soils data, the National Hydrography Dataset, and digital surficial geology data (Kansas Geological Survey, 1991) were also examined during individual inspections. Features inappropriately identified initially, such as large cattle ponds, erosion control ponds, and pits, were removed. Playas so heavily modified that the boundary of the playa floor could no longer clearly be identified, typically due to alteration for agriculture, were not included in the database.

After detailed visual inspection of the NAIP database was completed, low-altitude and ground-based verification was employed. Verification involved simply noting absence/presence by identification of a distinct soil or vegetation boundary or standing water visible on the ground; playa boundaries were not verified due to logistical constraints.

Ground-based verification consisted of driving along randomly selected roads through portions of 13 counties distributed throughout the mapping domain, and noting absence/presence of mapped playas. Because the database was rigorously inspected during GIS-based verification, potential playas were only removed from the database if it was certain that the mapped feature was not a playa. Approximately 500 playas were examined during ground-based verification and fewer than 10 were determined to be non-playa features during ground verification. Several other playas were visited but access and sight limitations because of conversion to agriculture prevented verification.

A light aircraft was employed for low-altitude verification following a prolonged wet period, with a flight path through 13 counties near the central and southern portions of the mapping domain. Several potential playa locations were pre-loaded into a GPS, and site-specific maps were produced. During the flight, GPS locations for approximately 100 larger playas (i.e., > 2 ha) and maps that included these playas and several other smaller playas surrounding each larger playa were compared to playas visible from the aircraft. Although only a limited number of larger playas were specifically examined, all playas identified in GIS, including all surrounding smaller playas, were visible on the ground. It is believed that not all playas visible on the ground were included in the database: lack of precise geographic location for these features during the flight prevented verification of omission.

Although less than 1% of playas originally included in the database were determined to be non-playa features, the true error rate of the NAIP database is unknown. Stringent criteria to exclude potential playas were lacking, so all observed natural, upland playa-like features remained in the database though some of these features may not function as playas. Additionally, playas may exist on the ground that were not included in the NAIP database.

Spatial Distribution of Playas in Kansas

There were 9,904 playas included in the SSURGO database, 10,390 in the DRG database, and 22,045 in the NAIP database. Of these, 4,076 playas were included in both the DRG and SSURGO databases, 5,826 in both the SSURGO and NAIP databases, and 6,501 in both the DRG and NAIP databases, indicating that most of the playas identified were unique to the data source used. The NAIP database represented an increase of 11,655 to 12,141 playas compared to DRG and SSURGO databases.

Although the NAIP database included more than twice as many playas as the DRG database, the size (i.e., surface area) range of playas represented by the two databases was roughly equivalent (Table 1). Playa size distribution for the SSURGO database differed considerably from the other two databases, particularly for playas with surface areas less than 2 ha. More than 30% of playas included in the NAIP and DRG databases were smaller than 0.4 ha, compared with only 0.1% of playas in the SSURGO database. Additionally, 82% of playas in the NAIP database had a surface area less than 2 ha, while the DRG database was comprised of 74%; only 43% of playas in the SSURGO database were smaller than 2 ha. For larger playas, size distribution among the three databases was similar; only 2 to 6% of playas included in the three databases were greater than 10 ha. The three databases only differed by 1% for playas less than 20 ha, and 99.9% of all playas were smaller than 100 ha, regardless of database.

Detailed spatial distribution data are provided only for the NAIP database because it was the most comprehensive and most rigorously verified. The majority of playas were grouped into three distinct high-density clusters that were separated by areas of low playa density along the Smoky Hill River to the north and the Arkansas River to the south, which flow from west to east (Fig. 5 and Table 2). The northern cluster was encompassed by Cheyenne, Sherman, and Thomas counties, with a small portion extending into northwestern Rawlins County. Playa density for these three counties ranged from 0.5 to 0.73 playas/km^2. This cluster contained more than 25% of all Kansas playas. Overall, the greatest density of playas was within the west-central portion of the mapping domain, particularly within Scott and Lane counties, with playa densities of 1.14 and 0.98 playas/km^2, respectively. These two counties ranked first and second in playa density and first and third in number of playas. Playas within Wichita, Greeley, and portions of Finney and Gray counties north of the Arkansas River also formed this west-central high-density cluster, with densities ranging from 0.44 to 0.66 playas/km^2. Nearly 40% of all Kansas playas were contained within these six counties. To the south, Haskell, Meade and Seward counties contained approximately 15% of all Kansas playas, and playa density ranged from 0.28 to 0.67 playas/km^2. More than 80% of all playas were located within these top 13 counties from the three clusters, which comprised less than 30% of the mapping domain.

Playa density decreased rapidly towards the eastern half of the mapping domain (Fig. 5). All counties in the easternmost tier of counties, extending from Smith to Barber counties, had 10 playas or fewer, excluding Barton County which had 40 mapped playas (Table 2). All counties had playa densities less than 0.01 playas/km^2. All counties in the column of counties immediately to the west, extending from Phillips to Comanche counties, had 100 playas or fewer, excluding Pawnee County which had 123. Pawnee County, with 0.06 playas/km^2, was the only county in the eastern tier to have a density greater than 0.05 playas/km^2. Within three of these counties (Barber, Comanche, and Stafford), no playas were identified.

This distribution, with rapid transition in playa density from west to east and along river valleys, was not surprising. Playas, as defined for this research, are predominantly upland features of the High Plains (Smith, 2003); density decreased rapidly towards river valleys and as physiographic province transitioned from High Plains in the west to Plains Border region to the east and Red Hills to the southeast.

Total playa land area by county ranged from at or near 0 ha in 4 of the 46 counties examined to 3,252 ha in Finney County (Fig. 5 and Table 2). No other county had greater than 3,000 ha composed of playas, and only six other counties (Meade, Scott, Lane, Thomas, Sherman, and Gray) had greater than 2,000 ha composed of playas. Fifteen counties, primarily located in the eastern half of the mapping domain, had less than 100 ha of total land area occupied by playas. Playas comprised at least 1% of total land area for only 5 counties and less than or equal to 0.1% for 23 counties.

Utility and Limitations of Data Sources

The SSURGO database is based on county-level soil surveys. Quality of soil surveys is quite variable for each county, and resolution is a major limitation of the database. SSURGO data for Kansas were based on 1:24,000 scale paper maps, with minimum mapping units approximately 2 to 4 ha. Thus, diagnostic playa soil units that occupy less than 2 ha are typically not included in the SSURGO database. During development of the NAIP database several errors were identified in the SSURGO database; not only were thousands of small playas omitted, but several large non-playa soil units were included. Contour intervals for DRGs are primarily 3 m and occasionally 1.5 m. Only the largest playa basins are deeper than 3 m, so the majority of playas are not mapped. Also, not all hydric soils, upland depressions, and water bodies are associated with playas.

This research highlights the potential limitations and problems associated with two widely-utilized data sources for playa identification and mapping. NAIP aerial imagery was incorporated to account for limitations associated with SSURGO data and DRGs. Imagery resolution is 1 m to 2 m, sufficient to identify even very small playas. Imagery is typically collected during the height of the growing season when precipitation and irrigation are at a maximum and water ponded in playas due to increased runoff aids in playa identification. Accordingly, based on field reconnaissance, a combination of data sources, particularly high-resolution aerial imagery with topographic and soils data, minimizes data limitations and provides the best estimate of playa distribution on the Kansas High Plains.

Playa Inventories on the Southern Great Plains

Until recently, most of the work identifying and mapping playas was focused on the Southern Great Plains, particularly within Texas (Guthery et al., 1981; Guthery and Bryant, 1982; Sabin and Holliday, 1995; Fish et al., 2000; Smith, 2003). One of the first systematic playa inventories on the Southern Great Plains was conducted by Guthery and Bryant (Guthery et al., 1981; Guthery and Bryant, 1982). They examined soil surveys for 52 counties in five states including southeast Colorado, southwest Kansas, eastern New Mexico, the panhandle of Oklahoma, and west Texas. They defined a playa to be an area composed of clay-rich, hydric soils (i.e., Randall, Ness, Lofton, and Stegall series soils) or mapped as an intermittent or permanent water body with playa-like features. Researchers identified 25,390 playas in the five-state study area with a mean size of 6.8 ha: 21% of all playas were less than 2 ha, about 50% were less than 4 ha, and only 4.4% were larger than 20 ha (Tables 1 and 3).

Sabin and Holliday (1995) inventoried playas on the Southern High Plains using 7.5’ U.S. Geological Survey (USGS) topographic maps and county soil surveys. Their project included an extensive component, in which all closed contours and intermittent water bodies were mapped on 540 topographic maps, and an intensive component that included verifying a sample of mapped playas by examining county soil surveys. They identified 33,367 playas from the extensive component, but, when applying a “correction factor” from the intensive component, playa number dropped to 19,630. However, the researchers stated that small, shallow playas and playas completely filled with sediment were not included in the intensive component, and asserted that a more accurate estimate was approximately 25,000. Playa surface area ranged from 0.26 ha to 483.2 ha; only about half of all playas were smaller than 10 ha, and 98.5% were smaller than 150 ha (Tables 1 and 3). Mean playa area for playas with and without lunettes, isolated dunes formed on the leeward side of some playas (Holliday, 1997), was 19.8 ha and 66.2 ha, respectively.

Fish et al. (2000) also utilized 7.5’ USGS topographic maps and county soil surveys to inventory all playas on the Texas High Plains and portions of the Texas Rolling Plains to create a digital playa database. Researchers defined a playa as a topographic depression with a diagnostic playa soil series, typically Randall clay, forming the floor. They identified 20,577 playas within a 65 county study area, ranging in area from 0.12 ha to 341.30 ha (Tables 1 and 3). Mean playa area was 7.58 ha; 78% of all playas were 10 ha or smaller, with approximately 6% smaller than 1 ha, and only 1.6% larger than 40 ha.

Based on these three playa inventories, all of which utilized similar data sources, an estimate of the number of playas on the Southern Great Plains is probably between 20,000 and 25,000. Total numbers of playas identified in the three studies are similar to Kansas, though study areas were larger (Tables 1 and 3). Mean playa area for the three methods ranged from approximately 6 to 20 ha, which is much larger than Kansas playas. All researchers noted that county soil surveys and 7.5' USGS topographic maps do not provide sufficient resolution to identify small and shallow playas. If high-resolution data, such as NAIP imagery, were utilized to inventory playas on the Southern Great Plains, playa numbers would likely be much greater than the 20,000 to 25,000 currently estimated, and mean playa area would likely be much smaller.

Playa Inventories in Colorado and Nebraska

The Rocky Mountain Bird Observatory recently conducted inventories of playas in Colorado and Nebraska using a variety of techniques as part of much larger playa assessment studies (Cariveau et al., 2007; Cariveau and Pavlacky, 2008). In Colorado, playas were identified as any feature that visibly contained water on at least one of several years of Landsat satellite imagery, was mapped as a lake, pond, or playa on the National Hydrography Dataset, or was mapped as a diagnostic playa soil in SSURGO; NAIP imagery was used to verify potential playas (Cariveau and Pavlacky, 2008). Roadside playa surveys were also conducted to identify additional playas and field-verify the presence of a sample of playas identified from the three digital data sources. Researchers identified 8,347 playas throughout 27 counties in eastern Colorado covering 11,340,000 ha (Tables 1 and 3). Mean playa size was 2.7 ha, and more than half of all playas were smaller than 2 ha. Playa density and abundance models developed by the researchers indicate that 18,178 ± 2,036 playas is a more accurate estimate, with approximately 7,000 playas smaller than 0.4 ha.

Researchers at the Rocky Mountain Bird Observatory also inventoried playas in 12 counties in southwest Nebraska (Cariveau et al., 2007). Playas were identified from a variety of data sources, including the NWI, SSURGO, Landsat satellite imagery, and NAIP imagery, though playa identification criteria were not explicitly stated. There were 15,389 playas identified comprising 8,834 ha, with a mean size of 0.57 ha (Table 3). More than half of all playas were smaller than 2 ha, and no playa exceeded 100 ha (Table 1). Field verification indicated that only 56 to 67% of the playas identified were present on the landscape. In addition, during field verification, numerous playas were present on the landscape that were not included in the database. Thus, large uncertainties exist regarding the number, distribution, and size of playas. Playa distribution and areal extent data for Colorado, and to a lesser extent Nebraska, are similar to Kansas (Tables 1 and 3). Large uncertainties in the Nebraska dataset prevent in-depth comparisons, but data indicate that playas in Colorado, Kansas, and Nebraska are much smaller than those mapped on the Southern Great Plains. Variations in estimates for the Southern Great Plains compared to Colorado, Kansas, and Nebraska are likely in part due to variations in climate and soils. However, most of the variation is probably related to differences in playa identification criteria and the utilization of higher resolution data sources to identify small playas in Colorado, Kansas, and Nebraska. These results demonstrate the need to inventory the entire High Plains using consistent identification criteria that incorporate high-resolution data sources to identify the entire size range of playas found throughout the High Plains.

Improving High Plains Playa Inventories

At least seven systematic playa inventories have been conducted for the High Plains, including all or portions of the Southern Great Plains (Guthery et al., 1981; Guthery and Bryant, 1982; Sabin and Holliday, 1995; Fish et al., 2000), eastern Colorado (Cariveau and Pavlacky, 2008), southwestern Nebraska (Cariveau et al., 2007), and Kansas (this study and Johnson and Campbell 2004). Although all inventories on the Southern Great Plains relied on topographic maps and soil surveys to identify playas, playa identification criteria differed slightly. Playa inventories for Colorado and Nebraska differed from previous inventories not only in data source, but also in playa identification criteria. Playa inventories conducted for this research incorporated traditional data sources, such as topographic and soils data, to aid in visual identification of playas on NAIP imagery, but also used slightly different playa identification criteria. Therefore, many of the discrepancies in playa inventories, particularly size distribution (Table 1), are likely the result of inconsistent playa identification criteria among the various researchers.

Although only a limited number of playas contained in the NAIP database have been field verified (i.e., < 1000), initial analysis of the database indicates that less than half the playas in Kansas were inventoried using traditional data sources such as topographic and soils data (Table 1). An improved playa inventory conducted for the entire High Plains would likely reveal that thousands more playas exist on the landscape than have yet been identified and mapped. While most of the additional playas identified in this study were smaller than 2 ha, total playa surface area increased by more than 20%. Thus, playas may be even more important elements of the High Plains than previously estimated due to the array of ecological functions provided by playas (Bolen et al., 1989; Haukos and Smith, 1994; Smith, 2003).

CHAPTER 4. STRATIGRAPHIC INVESTIGATION AND ENVIRONMENTAL RECONSTRUCTION METHODS

Sample Collection and Stratigraphy

Stratigraphy for each of the two PLSs was examined by collecting a series of cores along transects (Fig. 4). Cores were collected in clear plastic liners using a Giddings hydraulic coring machine in continuous 120-cm segments with a 5-cm diameter. Soil recovery from cores was near 100% with little compaction, so stratigraphy was well-preserved. At Ehmke PLS, five cores were also collected to bedrock refusal along a transect extending from the leeward base of the lunette to the northern interplaya using a CME hollow-stem auger drill rig (Figs. 2B and 4). Profiles and all core locations for each PLS were land-surveyed (Fig. 6).

Cores were described using standard methods of the U.S. Department of Agriculture National Soil Survey Center (Schoeneberger et al., 2002). Descriptions included soil horizon, Munsell color, texture, structure, redoximorphic features, carbonate occurrence, root and root trace size and density, and burrow traces or other evidence of bioturbation. Cores were divided into discreet 2–10 cm samples based on core stratigraphy; stratigraphic units with complex stratigraphy were sampled at the finer sampling resolution (i.e., 2 cm). Samples were analyzed for particle-size distribution (PSD), magnetic susceptibility (χ), and stable carbon isotopes ($\delta^{13}C$). To provide chronology, samples were also collected from buried soils for Accelerator Mass Spectrometry (AMS) radiocarbon analysis and from sedimentary units for Optically Stimulated Luminescence (OSL) dating.

Particle-size Distribution

Particle-size distribution (PSD) of samples was measured using a Malvern Mastersizer 2000 laser diffraction particle-size analyzer, with results expressed as proportion of the total sample comprising 89 size classes logarithmically spaced between 0.01 µm and 2000 µm. Samples were sonicated in deionized water for three minutes prior to analysis, no other pretreatments were conducted. Based on a series of experiments conducted on 40 soil samples collected from western Kansas, and experiments on 58 samples from Nebraska (Mason et al., 2007), particle size distributions after only a 3 minute sonication pretreatment were similar to samples subjected to 10% HCl, 30% H_2O_2, and sodium hexametaphosphate pretreatments prior to sonication.

Because laser diffraction techniques typically underestimate clay-sized fractions and overestimate silt-sized fractions of soil samples (Beuselinck et al., 1998; Buurman et al., 2001; Eshel et al., 2004), results were regressed against ASTM standard hydrometer analysis results (Fig. 7). A total of 30 samples collected from various horizons and zones throughout both PLSs were compared. When the clay fraction is adjusted to include all proportions less than 8 µm, R^2 increases from 0.76 to 0.87 ($p < 0.01$) for the clay fraction and from 0.33 to 0.70 ($p < 0.01$) for the silt fraction. Several variables were explored to identify changes in stratigraphic units (i.e., modal and median diameter, percent sand, silt, and clay, and multiple particle size ratios), and it was determined that the ratio of coarse silt (30 – 63 µm) to adjusted clay (< 8 µm) (hereafter referred to simply as clay or clay-sized) was most useful to due to distinct differences in clay and silt contents among units.

Stable Carbon Isotopes

Stable carbon isotope data ($\delta^{13}C$) recovered from bulk soil organic matter were used to estimate the proportion of total soil organic carbon (SOC) contributed by C_3 and C_4 plant biomass. Carbon, which has two naturally occurring stable isotopes, ^{12}C and ^{13}C, can reveal long-term changes in climate and vegetation patterns due to variations in discrimination against $^{13}CO_2$ by plant communities during photosynthesis (Smith and Epstein, 1971; O'Leary, 1988). This fractionation of stable carbon isotopes is preserved unaltered within the soil record as far back as the Miocene (Boutton, 1996; Cerling, 1999).

Ecosystems dominated by C_3 vegetation (cool-season grasses, trees, and shrubs) have $\delta^{13}C$ values ranging from about -35‰ to -20‰ and average -27‰, while C_4 vegetation (warm-season grasses) ranges from about -17‰ to -9‰ and average -13‰ (Smith and Epstein, 1971; Nordt et al., 1994). Several factors (e.g., atmospheric CO_2 concentration, temperature, amount and distribution of precipitation, soil characteristics, and disturbance history) influence plant community composition (Owensby et al., 1993; Polley et al., 1993; Boutton et al., 1994; Cole and Monger, 1994). The distribution of C_4 vegetation is primarily correlated to growing season temperature, with increased C_4 abundance as growing season temperature increases (Ehleringer et al., 1997). C_4 plant abundance also increases as precipitation decreases (Ehleringer et al., 1997; Clark et al., 2002). Landscape disturbance and variability in sediment accumulation rate, however, may result in expansion of C_3 plant communities (Feggestad et al., 2004).

As such, isotope data collected from lunettes and benches provide information about regional paleoclimate and episodes of landscape disturbance, though benches may also be influenced to some extent by playa hydrology. Within playas, C_3 plant species dominate when the floors become flooded, whereas upland C_4 plant species expand onto the playa floors as they dry out

(Haukos and Smith, 1997; Smith, 2003). Accordingly, Holliday et al. (2008) proposed that $\delta^{13}C$ data from playas indicate the frequency and duration of standing water in the basin.

Soil samples were initially treated with 1N HCl overnight (~16 hours) and then analyzed using a ThermoFinnigan MAT 253 Stable Isotope Ratio Mass Spectrometer, which also reports total organic carbon (TOC) within each sample. To estimate the proportion of soil organic carbon contributed by C_3 and C_4 plant biomass, a simple mixing model was used with the formula (Ludlow et al., 1976):

$$\%C_4 \text{ biomass} = ((\delta^{13}C_{SOC} - \delta^{13}C_{C3}) / (\delta^{13}C_{C4} - \delta^{13}C_{C3})) \times 100 \quad (1)$$

where $\delta^{13}C_{SOC}$ is the resultant $\delta^{13}C$ value of SOC, $\delta^{13}C_{C3}$ the mean value for C_3 plants (-27‰), and $\delta^{13}C_{C4}$ the mean value for C_4 plants (-13‰). To determine paleotemperature, an empirical equation was used to reconstruct mean July temperature with the following formula (Nordt et al., 2007):

$$T(°C) = 0.685(\delta^{13}C_{SOC}) + 34.9 \quad \text{(Eq. 2)}$$

Deviations in paleotemperature were based on comparisons to mean July temperature at Scott City, determined to be 25.6 °C from 1895 to 2009 (High Plains Regional Climate Center, 2009).

Magnetic Susceptibility

Samples for magnetic analysis were collected in clear, plastic 8-cm^3 cubes by insertion into cores at 2.5 cm to 10 cm intervals. Samples were dried at 60 ^oC for 48 hours to 72 hours prior to analysis. Magnetic susceptibility (χ) was measured using a Bartington meter and dual-frequency sensor. Low- (0.47 kHz) and high- (4.7 kHz) frequency measurements were collected with the Bartington system and normalized for mass, and results are reported in $10^{-8}m^3/kg$ (SI units).

On the central Great Plains, the magnetic signal is relatively small and consistent (Johnson and Willey, 2000), and enhancement is typically related to degree of pedogenesis (Evans and Heller, 2003). Local factors such as temperature, hydrology, and variations in sediment source, however, also influence magnetic enhancement. For example, cycling between saturated, anaerobic conditions and aerated, aerobic conditions eliminates much of the magnetic signal in soils.

Enhanced χ values are directly related to greater effective precipitation and associated with pedogenesis (Maher and Thompson, 1995; Geiss and Zanner, 2007), so data from lunettes and benches were used to infer relative changes in effective precipitation. Because χ is depleted during saturated conditions and repeated wet-dry cycles, playa χ data were used to infer relative changes in flood frequency and duration. Magnetic enhancement or depletion is based on comparison to underlying sediment or equivalent stratigraphic units in other cores.

Chronology

Sixteen samples collected from buried soils within both PLSs for radiocarbon analysis were submitted to the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) (Table 4). Pretreatment included drying at 60 ^{o}C, grinding, and removing rootlets; carbonates were removed by the radiocarbon laboratory. Four AMS radiocarbon ages (NOSAMS) are also available from previous investigations at Ehmke PLS. All ages are reported in calendar years (Table 4), using the Fairbanks calibration program (Fairbanks et al., 2005; Chiu et al., 2007).

Five samples collected from Peoria Loess at the crest of Ehmke lunette (ELC, Fig. 4) were dated using optically stimulated luminescence (OSL) techniques at the University of Nebraska Luminescence Geochronology Laboratory (Table 5). A single core was collected in a black core liner to avoid light contamination. The core was subdivided into ~15 cm segments in the laboratory, sealed, and stored in light-tight containers. Samples for OSL analysis were pretreated using standard methods (e.g. Hanson et al., 2009), and optical ages were determined using the single aliquot regenerative-dose (SAR) procedure (Murray and Wintle, 2000).

CHAPTER 5. PLAYA-LUNETTE SYSTEM STRATIGRAPHY

Ogallala calcrete forms the bedrock below PLS fill at both sites, though not all cores extend to calcrete. Sand content is greatest immediately overlying Ogallala calcrete, with deposits ranging from sandy clay to nearly all sand. Sand is orange to yellow, predominantly in the very fine to medium fraction, and was likely derived from the sand-rich Ogallala Formation.

The upland loess sequence is well-represented within Ehmke and Bush PLSs. Gilman Canyon Formation, Peoria Loess, Brady Soil, Bignell Loess, and Holocene-aged soils were commonly identified, while a potential Sangamon Soil was also identified within lunettes and interplayas. Detectable Loveland Loess, however, is not present within any PLS zone.

Sangamon Soil

A buried soil, likely the Sangamon Soil, which has developed into Ogallala calcrete, was identified at the base of lunettes and interplayas at both PLSs (Fig. 6). The soil is ~1 m thick in interplayas, while within Ehmke lunette the soil is 0.9–3.8 m thick. Within the lunette, the soil is thickest on the eastern lunette flank (Fig. 8). The soil at Bush lunette was only identified in cores BLN2, BLS1, BLS2, and BLW, and thickness ranges from 1.0 to 1.6 m (Fig. 9). Greater thickness on lunettes compared to interplayas suggests that playa floors were a significant sediment source to lunettes. Evidence of the Sangamon Soil is not preserved in either playa, possibly due to fluvial and eolian erosion and deflation of the unit.

The Sangamon Soil exhibits multiple cycles of pedogenesis and is characterized by 2–3 distinct B horizons with blocky structure and many iron-stained root traces. Soil texture is primarily silty clay loam, though sand lenses occur near the base. Soil color is predominantly dark yellowish brown (10YR 4/4) to yellowish brown (10YR 5/4). Magnetic susceptibility values are typically greater than those of the overlying GCF (Figs. 8–10). At Ehmke lunette, this unit is more than 2 m below buried soils that returned ages of ~38–40 ka.

It is possible that the Sangamon Soil identified in these PLSs may actually be the lowermost unit of the GCF pedocomplex. Where the GCF has developed on slopes, such as those of lunettes, horizons may be separated by a meter or more (Johnson et al., 2007). It is unlikely that the entire unit is part of the GCF, however, given the distinct differences in PSD and χ between the two units.

Research on the Southern High Plains indicates that playas were present on the landscape prior to deposition of the Blackwater Draw Formation (Holliday et al., 1996; Hovorka, 1997), which began more than 1.4 myr ago (Holliday, 1989). Radiocarbon data indicate that most playas present on the surface today formed between ~10 ka and 20 ka, though some playas have existed on the surface for more than 30 kyr (Holliday, 1997; Holliday et al., 2008). Playa-like basins greater than 30 kyr old have also been identified in Nebraska (Kuzila, 1994; Kuzila and Lewis, 1994). Fossil vertebrate records from southwest Kansas suggests that upland wetlands and ponds have been an integral part of the landscape since at least the late Pliocene (Emslie, 2007), so it is likely that PLSs existed in the region during and much earlier than the Last Interglacial.

Gilman Canyon Formation

The GCF pedocomplex on interplayas ranges from ~1.5–2 m thick at Ehmke PLS and is ~3 m thick at Bush PLS. The pedocomplex consists of two 25–50 cm thick B horizons separated by

20 cm of sediment in Ehmke interplaya. In Bush interplaya, two 20-30 cm thick B horizons overlie an approximately 1 m thick soil with A-B-A-B horizonation. Texture is principally silty clay loam, though sand and clay content are lower and silt content greater compared to the underlying Sangamon Soil (Figs. 8–10). Color is dark yellowish brown (10YR 3/4) throughout, and root traces and carbonate nodules are common. Magnetic susceptibility values are enhanced within soils, particularly in Bush interplaya (Figs. 8–10).

At Ehmke lunette, the GCF pedocomplex is 2.5–5.3 m thick with the greatest accumulation on the windward slope. Texture is similar to interplayas, but thin sand lenses are common throughout. The unit consists of multiple buried soils and sequences of 2-10 cm thick yellowish brown (10YR 5/4)/dark brown (10YR 3/3) and coarse/fine laminations. Two radiocarbon samples from the eastern lunette flank (ELE2) returned ages of 38,400 ± 260 cal yr B.P. at 4.2 m and 40,250 ± 290 cal yr B.P. at 6.2 m (Table 1), and two others from the leeward base of Ehmke lunette (ELS) dated to 40,060 ± 320 cal yr B.P. at 6.7 m and 42,050 ± 270 cal yr B.P. at 7.8 m.

Thickness of the GCF ranges from 0.8 m to 3.5 m in Bush lunette. The windward slope and western flank of the lunette consist of ~1–3 m of laminations similar to Ehmke lunette. The crest, eastern flank, and leeward slope consist of a 0.5–1.5 m thick, dark brown (10YR 3/3) cumulic soil with A-B-B horizonation and silty clay loam texture. From the crest of Bush lunette (BLC), the GCF dates to 31,880 ± 260 cal yr B.P. at 8.7 m and 40,160 ± 300 cal yr B.P. at 9.5 m (Table 4), 0.5 m above the contact with Ogallala calcrete. On the windward lunette slope (BLN2), the GCF returned ages of 32,730 ± 270 cal yr B.P. at 6.7 m and 34,820 ± 220 cal yr B.P. at 7.6 m, and 29,420 ± 220 cal yr B.P. at 6.2 m from the leeward base of the lunette (BLS2). Magnetic susceptibility is variable through the GCF, though it is enhanced within buried soils and decreases near the top of the unit (Fig. 9).

At Ehmke PLS, the GCF is similar throughout the playa, southern annulus, southern bench, and delta (Figs. 11 and 12); it was not identified within the eastern annulus, northern bench, core EBS2 from the southern bench, or inflow channel. The 1.7–2 m thick GCF is gleyed, consisting of light olive brown (2.5Y 5/3) silty clay with low χ values. In Ehmke playa and annulus, the 1.7–1.9 m thick unit overlies Ogallala calcrete, while sand forms the base of the 1.9 m thick GCF in the delta. In core EBS1, from the southern bench, the GCF is 2 m thick, and the lower ~0.5 m is composed of thin laminations. The GCF returned an age of 27,950 ± 190 cal yr B.P. at 5.9 m in core EBS1 (Table 4). Although χ is enhanced within the soil, it is relatively depleted throughout the unit (Fig. 12).

The GCF was identified throughout Bush playa, but, unlike Ehmke playa, the soil does not exhibit evidence of gleying. The unit is composed of brown (7.5YR 5/4) silty clay with sandy deposits at the base. Thickness ranges from 1.9 m in the western portion of the playa to 2.4 m in the southern portion. Multiple A-B and B horizons are preserved throughout the playa, with enhanced χ within buried soils (Fig. 11).

In Bush southern bench (BBS), the GCF is ~3 m thick with soils at the top and bottom of the unit. Upper and lower soils are ~0.5 m thick, yellowish brown (10YR 5/4), silty clay loams with A-B horizonation, and are separated by 1.9 m of laminated and gleyed (2.5Y 5/2) silty clay. Magnetic susceptibility is enhanced in upper and lower soils of the GCF but is depleted in the intervening gleyed laminations between ~6–7 m (Fig. 10). Within the annulus (BAW), the GCF is also laminated, though the unit is yellowish brown (10YR 5/4), and χ is enhanced. The dark yellowish brown (10YR 4/4) silty clay loam of the GCF in Bush inflow channel and delta is difficult to differentiate from underlying and overlying sediment; below Peoria Loess, both profiles exhibit evidence of soil formation throughout.

While it is not possible to differentiate between eolian and fluvial sources, fluvial inputs to playas must have been considerable. Thickness of the GCF is similar within playas and interplayas. Accumulations on lunettes are 2–5 m greater than in interplayas, and laminations and buried soils are common throughout the unit. The GCF is thickest on windward lunette slopes, where laminations are most prevalent, suggesting that playas were a major sediment source for lunettes. Dark brown laminations have diffuse lower boundaries and relatively enhanced χ values (Fig. 8 and 9), indicating they have been pedogenically altered to form thick stacks of incipient soils.

Peoria Loess

Playa-lunette system fill consists of thick, silt-rich Peoria Loess deposits (Fig. 6). Although thickness and morphology vary among cores and PLS zones, several PSD characteristics are similar. Silt content is greater and clay content lower in Peoria Loess compared to underlying and overlying units, and lower coarse silt:clay values typically demarcate upper and lower boundaries of the unit (Figs. 8–12). Soil texture in all PLS zones is dominated by silt loam to silty clay loam, with sand lenses common at the base of playas. Few carbonate nodules and carbonate-lined root traces are distributed throughout the unit.

Peoria Loess thickness ranges from 2.5 m to 3 m on interplayas, 2.4–3.3 m within playas, 3–5 m within channels and deltas, and 2.7–4.3 m on benches, with the thicker accumulations on southern benches (Figs. 8–12). In Ehmke and Bush lunettes, the unit is characterized by 3.5–7 m of laminations similar to those observed in the GCF, with oscillating color, coarse silt:clay, and χ. Peoria Loess is much thicker on southern benches and lunettes compared to interplayas, though thickness in playas is similar to that of uplands. Given that the unit is up to 2 m thicker within channels and deltas than within interplayas, the sediment load delivered to playas via runoff must have been substantial. Peoria Loess thickness is similar within playas and interplayas, however, indicating that much of this material was eroded and deposited on southern benches and lunettes.

The entire Peoria Loess unit is gleyed (2.5Y 5/3) in Ehmke playa, annulus, bench, channel, and delta. Magnetic susceptibility is typically depleted throughout gleyed intervals in these PLS zones (Figs. 11 and 12). Within the central portion of Ehmke playa (EPC), χ is slightly enhanced between ~1.4 m and 2.6 m, and between 1.7 m and 2.6 m in the eastern portion (EPE), within an incipient soil. On the southern bench, χ is enhanced in a buried soil, with A-B horizonation distinct from the overlying Brady Soil.

Only the central 1.5–2 m of Peoria Loess in Bush playa exhibits evidence of gleying, with light olive brown color (2.5Y 5/3) and depleted χ values (Fig. 11). The base of Peoria Loess in Bush playa is brown (10YR 4/3) and sandy, and the Brady Soil has developed in the upper portion. Magnetic susceptibility is enhanced in the lower ~1.5 m of Peoria Loess in Bush southern bench (BBS), within an interval characterized by several thin laminations similar to those within lunettes (Fig. 10), even though this interval is gleyed (2.5Y 5/3).

Brady Soil

The Brady Soil has been identified in all zones at both PLSs, except within lunette crests and Ehmke playa, and it has been dated within Bush playa and southern bench, and Ehmke southern bench and lunette (Table 4). The soil has similar expressions in all cores within which it was identified: it consists of an A and B horizon, thickness ranges from 0.5 m to 1.3 m, and soil color is dark brown (10YR 3/3) to black (10YR 2/1). Texture is predominantly silty clay loam to silt loam in lunettes and interplayas, and silty clay to silty clay loam in all other zones. Typically, clay content increases and silt content decreases, as highlighted by low coarse silt:clay values (Figs. 8–12). Root traces and modern roots are common, and carbonate is rare. Magnetic susceptibility increases, and enhancement is often greater in the Brady Soil than any other unit (Figs. 8–12).

The Brady Soil formed in the upper part of Peoria Loess, and in Ehmke bench it is underlain by an incipient soil. Development of the Brady Soil has extended into the incipient soil, resulting in "welding" of the two soils (Ruhe and Olson, 1980; Olson and Nettleton, 1998). In core EBS1, the Brady Soil extends from 1.1 m to 1.6 m, and is welded to an overlying buried soil that is welded to the surface soil. Samples from the soil returned ages of 11,820 ± 110 cal yr B.P. at 1.5 m and 9,540 ± 30 cal yr B.P. at 1.3 m (Table 4). From the leeward base of Ehmke lunette (ELS), the Brady Soil returned an age of 10,240 ± 30 cal yr B.P. at 2.5 m, near the top of the soil. A radiocarbon sample, collected from the leeward slope of the eastern flank at Ehmke lunette during an archaeological investigation of the lunette, returned an age of 11,420 ± 210 cal yr B.P. (Witty, 1989), though precise location and depth are unknown. In Bush southern bench (BBS), the Brady Soil extends from 1.5 m to 2.7 m and dated to 11,450 ±130 cal yr B.P. at 2.4 m and 9,400 ± 50 cal yr B.P. at 1.6 m (Table 4). The soil occurs at depths of 1–1.4 m in the southern playa (BPS), and yielded an age of 11,390 ± 130 cal yr B.P. at 1.2 m.

A series of five OSL samples were analyzed for the upper 1.7 m of Ehmke lunette crest, and range in age from 13.1 ± 1.3 ka to 22.6 ± 2.2 ka (Table 5). Although optical ages are slightly out of stratigraphic order, which is not uncommon in Peoria Loess (e.g. Roberts et al., 2003; Muhs et al., 2008), data indicate that little deposition, or deposition and subsequent erosion, occurred on lunettes during and following Brady Soil pedogenesis.

Bignell Loess and Holocene Soils

Bignell Loess deposits have been modified by pedogenesis, and no unweathered loess was identified in any core. Thickness of the entire unit ranges from 0.3 m to 1.7 m throughout PLSs (Figs. 8–12). In all cores, clay content is relatively high, and silt content is lower compared to Peoria Loess. Playas, annuli, benches, channels, and deltas were predominantly composed of silty clay or silty clay loam, while lunettes and interplayas were composed of silty clay loam or silt loam. Soil color in all PLS zones is very dark brown (10YR 2/2) to black (10YR 2/1). Carbonate was not observed in any zone, but very fine to fine modern roots were common in all zones. Magnetic susceptibility increases in all cores, and maximum χ values are often observed in these near-surface deposits (Figs. 8–12).

Holocene deposits in all zones except lunettes are typically ~1 m thick and consist of one to two buried soils welded to the surface soil. Where the Brady Soil is present, buried soils have developed into it. Ehmke lunette is characterized by a modern soil with A-B horizonation less than 0.5 m thick developed into underlying Peoria Loess, though thickness of the modern soil on the windward slope is ~1 m. Bignell Loess is similar in Bush lunette; thickness ranges from 0.4 m to 1.5 m, and thickest deposits are preserved on windward and leeward slopes. Based on similar thickness, color, texture, and χ of Bignell Loess throughout PLSs, playas likely only supplied minor amounts of sediment to lunettes during the Holocene, and little Holocene-aged sediment is preserved on lunette crests.

In Ehmke playa, a buried soil with A-B horizonation is welded to the surface soil, and the base of the soil returned an age of 7,460 ± 30 cal yr B.P. at 1 m (Table 4). From the leeward base of Bush lunette (BLS2), a buried B horizon developed into the Brady Soil returned an age of

8,340 ± 50 cal yr BP at 1.1 m, 0.2 m above the Brady Soil. The lower boundary of a buried soil with A-B horizonation welded to the surface soil returned an age of 3,550 ± 50 cal yr BP at 0.6 m in the southern portion of Bush playa (BPS).

CHAPTER 6. PLAYA-LUNETTE SYSTEM EVOLUTION AND PALEOENVIRONMENT

Playa-Lunette System Origin

Dissolution of underlying carbonate or evaporite beds and subsequent subsidence has been proposed as the dominant mechanism for playa formation and enlargement (Osterkamp and Wood, 1987; Paine, 1995). Holliday et al. (1996) stated that several playas on the Southern High Plains have eroded into and truncated underlying substrate, such as the Blackwater Draw Formation, but do not exhibit evidence of subsidence. Additionally, they found little illuvial clay beneath playas, suggesting eluviation-dissolution was not the primary process for playa formation. Wind deflation also has been proposed as a primary mechanism of playa development, and lunettes provide evidence that eolian processes play an important role in playa maintenance and enlargement (Gilbert, 1895; Reeves, 1966; Holliday et al., 1996; Holliday, 1997). Other proposed mechanisms include animal activity (Gilbert, 1895; Reeves, 1966), meteorite impacts (Evans, 1961), differential compaction (Johnson, 1901; Frye, 1950), and faulting (Frye, 1950). More recent research recognizes that playa development is the result of a combination of geomorphic, climatic, and biogeochemical processes (Gustavson et al., 1995; Holliday et al., 1996).

Hollow-stem auger drilling at Ehmke PLS reveals that the surface of the Ogallala Formation generally parallels the land surface, with a depression below the playa and a ridge of slightly higher elevation at the base of the lunette (Fig. 6). Similarly, a depression beneath the playa and a ridge beneath the lunette were observed at Bush PLS. Relative elevation of the Ogallala

Formation surface is 4–5 m lower beneath Ehmke playa compared to the interplaya, while the Ogallala Formation surface is ~1 m higher beneath the lunette crest compared to that below the base of the slopes. At Bush PLS, the Ogallala Formation surface is ~1–2 m lower beneath the playa, and ~2 m higher on the lunette crest, compared to the leeward lunette base; the interplaya core did not penetrate to the Ogallala Formation. Although stratigraphy was poorly preserved in hollow-stem auger cores, illuvial clay was identified in the upper portion of the Ogallala Formation below Ehmke playa. Below Ehmke lunette, bench, and interplaya, the upper portion of the formation is dominated by sands, gravels, and carbonate, and no illuvial clay was identified.

The Sangamon Soil is absent from Ehmke and Bush playa, which may be due to fluvial erosion on the playa floor and deflation of eroded material. A similar process was proposed for playa development on the Southern High Plains (Holliday et al., 1996). Additionally, laminations and thicker stratigraphic units preserved in southern benches and lunettes compared to interplayas, and the formation of inflow channels and deltas within playas, provide direct evidence that fluvial and eolian processes played a role in PLS evolution.

Based on stratigraphic records preserved at Ehmke and Bush PLS, the following model is proposed for playa-lunette development (Fig. 13). Small initial depressions at current playa locations promoted water storage, infiltration, and ultimately the accumulation of illuvial clay beneath depressions. As dissolution and clay accumulation continued, the depressions expanded, and the playas formed. Loosely consolidated sediment accumulating on playa floors was eroded by inflowing and stored water, and deflated by wind upon drying out. Small ridges downwind of playas forced sediment to accumulate, forming the lunettes. As playas increased in size, fluvial-eolian processes then became the primary mechanism for playa and lunette enlargement.

Given that dominant processes of playa development vary within and among playas through space and time (Smith, 2003), the relative importance of dissolutional and fluvial-eolian processes in PLS evolution has changed over time at these sites. Dissolution was likely more important during initial playa development, though it is still occurring based on infiltration rates one to two orders of magnitude greater within playas compared to interplayas (Gurdak and Roe, 2009). Dissolution is also likely more important during periods of higher effective precipitation, while deflation dominates during arid periods.

Although the timing of PLS origin is unknown, a more recent history, extending from the late Pleistocene to present, is well-documented within these systems and is presented below.

Late Pleistocene

Late Illinoian to Middle Wisconsinan

The Sangamon Soil was identified, which is only preserved at the base of lunettes and interplayas at both PLSs. Stable carbon isotope values derived from the eastern flank of Ehmke lunette (ELE2), within the soil, range from -15‰ to -17‰ (Fig. 14). The regional paleoenvironment was similar to modern, with 65–80% of SOC derived from C_4 vegetation, though mean July temperature may have fluctuated as much 1.5 °C during soil formation.

Immediately overlying Ogallala calcrete, or the Sangamon Soil where preserved, the GCF pedocomplex was identified throughout both PLSs. Based on the ubiquity of the GCF, these two playas were unequivocally prominent features of the High Plains by MIS 3. Incipient pedogenesis occurred in the center of Ehmke playa on a subaerially exposed playa floor, with χ data and gleyed soils indicating seasonal inundation during MIS 3. Stable carbon isotope data, derived for the center of the playa (EPC), show that $\delta^{13}C$ increases from near the contact with

Ogallala calcrete through the upper GCF, where values of -21‰ to -22‰ are similar to those attained from the modern soil (Fig. 14). Percent SOC is low throughout most of the playa fill, though it increases within the GCF. During MIS 3, more than 60% of the SOC was derived from C_3 vegetation, providing evidence that effective precipitation was sufficient to seasonally inundate the playa floor. However, because C_4 contributions increased during MIS 3 and pedogenesis occurred, playas were probably dry for extended periods.

Stable carbon isotope data derived for the southern portion of Bush playa (BPS) increase from -18‰ near the contact with Ogallala calcrete to a maximum of -16‰ at 5.4 m within the GCF (Fig. 14). Bush playa floor was at least partially exposed throughout most of MIS 3 based on A-B soil horizon development, enhanced χ, and $\delta^{13}C$ values ~4‰ greater than in the modern soil. As much as 75% of the SOC was derived from C_4 vegetation in this interval. While χ is enhanced in the GCF within the eastern portion of Bush playa near the inflow channel, values are relatively low, suggesting runoff was regularly delivered to the playa. Precipitation may have been distributed more evenly throughout the year, or effective precipitation was too low, either preventing Bush playa from completely filling or causing it to rapidly dry out following inundation.

In core EBS1 from Ehmke southern bench, GCF $\delta^{13}C$ increases from -24‰ at 7.4 m to -20‰ at 6.5 m (Fig. 14). The $\delta^{13}C$ signal from Bush southern bench (BBS) is similar: isotope values vary only between -23‰ and -24‰ from 6 m to 7.1 m, then increase sharply to -19‰ at 6 m. Although warming occurred during MIS 3, plant communities immediately surrounding playas consisted of only 20–45% C_4 vegetation. This may be due to inputs of SOC derived from playa vegetation as well as from the influence of near-surface groundwater on bench plant communities. The pedocomplexes are gleyed, and χ signals are greatly reduced through much of the unit, all of which indicate saturated conditions that would favor water-tolerant C_3 vegetation. Isotope values and χ within Bush southern bench are less than those from Bush playa, and evidence of gleying within the playa is lacking. An isolated zone of lower permeability was identified below the southern bench due to high clay concentration at the contact with the Ogallala Formation, but not in the playa.

Although oscillatory in Ehmke lunette (ELE2), $\delta^{13}C$ generally declines from -17‰ near the base of the GCF to -21‰ at the top of the pedocomplex (Fig. 14). Stable carbon isotope data from the crest of Bush lunette (BLC) are greatest and relatively uniform within the GCF, averaging -16‰. Lunette $\delta^{13}C$ data indicate the landscape consisted primarily of C_4 vegetation, and the presence of the GCF pedocomplex suggests that the climate was relatively warm, with effective precipitation sufficient to promote pedogenesis. Multiple $\delta^{13}C$ shifts greater than 2‰ were identified from Ehmke lunette, while $\delta^{13}C$ data from Bush lunette varied little. The shifts observed in Ehmke lunette may be related to periods of high sediment accumulation rates favoring C_3 plant expansion, rather than to abrupt changes in climate.

Paleoenvironmental records from PLSs on the High Plains prior to ~25 ka are sparse. However, stratigraphy and pollen records from Cheyenne Bottoms, a large, playa-like depression in central Kansas, indicate that the basal litho-biostratigraphic unit, referred to as the Farmdalian unit, extends ~30–24 ka (Fredlund, 1995). Environmental conditions during deposition of the Farmdalian unit were characterized by persistent shallow water marshland in the depression and open grassland-sage steppe on the uplands, suggesting a relatively mesic climate and with high effective moisture.

Late Wisconsinan

After ~25 ka, isotope data from Ehmke and Bush PLSs reveal that climate became much cooler and that effective precipitation likely increased. Regionally, Peoria Loess accumulated rapidly during MIS 2, between ~25 ka and 12 ka under a cold and/or dry climate (Feng et al., 1994; Mason et al., 2007; Muhs et al., 2008). This interval is characterized by the thickest sedimentary units within most PLS zones.

Minimum $\delta^{13}C$ values in Ehmke (EPC) and Bush (BPS) playas were -26‰ and -25‰, respectively (Fig. 14). Given playas were dominated by more than 90% C_3 plant communities, percent SOC decreased, χ signals are depleted, and deposits are gleyed, playas were likely inundated more frequently and/or for longer periods during MIS 2. Channel and delta deposits also have depleted χ within this interval at both PLSs, suggesting surface flow was regularly delivered to the playas. Greater effective precipitation could have generated more runoff and delivered an increased sediment load to playas.

Stable carbon isotope values also decline to between -25‰ and -27‰ within southern bench Peoria Loess deposits at both PLSs, indicating vegetation was dominated by as much as 95% C_3 species, while isotope values from lunettes average ~-20‰ (Fig. 14). In Bush lunette, isotope data exhibit repeated oscillations of as much 3‰ within 10–20 cm intervals. These oscillations suggest mean July temperature varied by as much as 2 °C in sub-millennial cycles, though this variability may in part be due to changes in precipitation and sediment accumulation rate. Magnetic susceptibility also oscillates in 5–10 cm intervals, and silt and sand content increases within this zone, though PSD is highly oscillatory. Lunettes and southern benches are dominated by several-meters-thick sequences of loess and intercalated incipient soil units due to episodic deposition.

During MIS 2, PLSs evolved under a cooler climate than preceding or succeeding intervals, but temperature and moisture availability were variable. Effective precipitation was probably greater, due to cooler temperatures, and the magnitude and intensity of flooding would have increased. Therefore, playas received more runoff and stored water for longer periods. While playas were storing water, less sediment was available for benches and lunettes, and pedogenesis was initiated. During slightly warmer periods, effective precipitation decreased, and playa floors became exposed, providing a source of easily eroded material that buried incipient soils on southern benches and lunettes. This cycle was repeated regularly at sub-millennial scales, with slightly wetter phases associated with water storage in playas and pedogenesis surrounding playas, and drier phases dominated by sediment remobilization from playa floors and burial of soils downwind of playas (Fig. 13).

Arbogast (1996) examined PLS stratigraphy from Wilson Ridge in west-central Kansas, but was primarily focused on lunette stratigraphy. Based on site stratigraphy and a radiocarbon age of 20,880 cal yr B.P. from the top of the lowermost buried soil, he concluded that lunette formation coincided with the onset of Peoria Loess deposition on the central Great Plains. During Peoria Loess accumulation, a δ^{13}C value of -12‰ from the lunette suggests a xeric environment, while a value of -21‰ from the playa indicates effective precipitation was sufficient to support a higher proportion of C_3 vegetation in the playa. Additional stratigraphic evidence indicates playa water levels were relatively high ~20 ka, and that from ~20 ka to 14.5 ka prevailing wind strength decreased. The record of this interval from Cheyenne Bottoms, in central Kansas, is absent from the playa-like depression due to an unconformity that extends ~24–11 ka (Fredlund, 1995).

Pleistocene-Holocene Transition

The P-H transition is well represented in PLS core stratigraphy, and the Brady Soil has been identified in all zones at both PLSs, except within lunette crests and Ehmke playa. Lack of a Brady Soil in Ehmke playa suggests the playa was predominantly inundated during the P-H transition, preventing pedogenesis. Bush playa floor was likely exposed for long periods during the transition, based on a ubiquitous Brady Soil with A-B horizonation. Sand content is also lower in sediment deposited during the P-H transition compared to underlying material, which may be due to decreased runoff and wind intensity.

Stable carbon isotope values from Bush playa (BPS) progressively increase to -19‰ within the Brady Soil, while $\delta^{13}C$ values on the southern bench (BBS) range from -19‰ to -21‰ (Fig. 14). Isotope values from Ehmke southern bench (EBS1) range from only -18‰ to -19‰ within the Brady Soil, but, immediately underlying the soil, values oscillate by ~4‰ in 10 cm intervals. These abrupt shifts suggest temperature rapidly fluctuated by as much as 2–3 °C, which would have had a dramatic effect on plant communities. A nearly identical isotope trend is observed in Ehmke lunette (ELE2), even though the Brady Soil was not identified in the core. Magnetic susceptibility and coarse silt:clay also exhibit distinct shifts. These variations are believed to be associated with the Bølling-Allerød/Younger Dryas chronosequence, with multiple rapid climate changes between 14.7 ka and 11.5 in the North Atlantic region (Alley, 2000; Bjorck, 2007). Lack of a Younger Dryas signal on playa floors may be due to the coarse sampling resolution for $\delta^{13}C$ analyses (i.e., 15–25 cm), while χ has been altered by playa hydrology. Conversely, impacts of the Younger Dryas may not have been great enough to initiate a response within playas. Mason et al. (2008) concluded that on the central Great Plains the Younger Dryas may have been characterized by effective moisture low enough to initiate occasional, local eolian activity but did not cross a threshold for a widespread response.

Temperature increased during the P-H transition, while effective precipitation probably decreased. Precipitation remained great enough, however, to support dense vegetative cover that stabilized the landscape and promoted pedogenesis. Ehmke playa, with its larger storage volume and catchment area, collected and stored more water for longer periods.

Holliday et al. (2008) reported that the phytolith and $\delta^{13}C$ record from San Jon playa in eastern New Mexico exhibited repeated climatic shifts, which coincide with the Bølling-Allerød/Younger Dryas chronosequence. At Wilson Ridge, in central Kansas, the landscape stabilized between ~14.5 ka and 12.5 ka, permitting Brady Soil formation on the lunette (Arbogast, 1996). Stable carbon isotope data from Wilson Ridge indicate that temperature increased and effective precipitation decreased toward the end of pedogenesis. The P-H transition is poorly preserved in Cheyenne Bottoms, though the Brady Soil is preserved on surrounding uplands, indicating the landscape stabilized during the P-H transition (Feng et al., 1994; Fredlund, 1995).

Holocene

The Holocene record preserved in Ehmke and Bush PLSs is characterized by thick, dark, buried soils with A-B horizonation welded to the surface soil in all PLS zones, and all Bignell Loess has been modified by pedogenesis. Holocene-aged buried soils dated within Ehmke playa and southern bench, and Bush playa, southern bench, and the leeward base of the lunette returned ages ranging from 8,340 cal yr B.P. to 3,550 cal yr B.P. (Table 4).

Stable carbon isotope data from playas, southern benches, and lunettes indicate that the Holocene was characterized by increased temperatures and C_4 plant composition. Isotope values from Ehmke playa (EPC) increase to -21‰ near the base of a 7.5 ka buried soil and remain relatively constant to the surface (Fig. 14). One sharp decline at 15 cm may be the result of a period of increased moisture or due to increased input of organic matter derived from winter wheat planted on the interplaya and translocated to depth. Isotope values from Bush playa (BPS) decline somewhat from -19‰ within the Brady Soil to -21‰ within Holocene soils. In cores from each of the southern benches (EBS1 and BBS), isotope values average ~-15‰, and in Ehmke lunette (ELE2) maximum $\delta^{13}C$ values of -13‰ are recorded. Although isotope values exhibit an increasing trend in Bush lunette (BLC), the Holocene record is incomplete.

Playa vegetation was composed of nearly equal amounts of C_3 and C_4 vegetation, while benches and lunettes consisted of as much as 95% C_4 vegetation. Magnetic susceptibility, although enhanced compared to underlying horizons, decline through much of the Holocene in all PLS zones, suggesting effective precipitation decreased following the P-H transition. Buried soils are common, however, so moisture availability was sufficient to promote pedogenesis throughout PLSs. Further, reduced χ and gleyed deposits in playas indicate they were at least seasonally inundated.

It is likely that following the P-H transition, temperatures continued to increase while effective precipitation decreased. Playas were seasonally-inundated throughout much of the Holocene, similar to modern conditions with the playa typically inundated during the rainy season from about April-June, and dry the remainder of the year in most years. During the mid to late Holocene effective precipitation increased, and playa floors were inundated for longer periods.

In central Kansas, deposition at Wilson Ridge was episodic and spatially variable during the Holocene due to a warmer, more arid environment (Arbogast, 1996). Several buried soils were identified in Holocene deposits, with ages ranging from ~10 ka to 3 ka, indicating moisture availability was variable. Cheyenne Bottoms began storing water during the Holocene due to increased precipitation (Fredlund, 1995). Water levels were highly variable throughout the early Holocene, with a period of increased aridity during the mid-Holocene. Water levels during the late Holocene were higher but still fluctuated considerably, and the basin dried out several times.

CHAPTER 7. SUMMARY AND CONCLUSIONS

Playa-lunette systems are ubiquitous and essential features of semi-arid and arid regions around the world, and they are particularly abundant on the High Plains of the central United States. New GIS inventory techniques were developed to identify and map playas in western Kansas. Several geospatial data sources, including high-resolution NAIP imagery, DRG topographic data, and SSURGO soils data were visually inspected to identify all playas greater than 0.03 ha (300 m^2). A total of 22,045 playas were identified in western Kansas, ranging in size from 0.03 ha to 188 ha, with a mean surface area of 1.65 ha (Table 1). More than 80% of all playas, representing more than 30% of total playa surface area, are less than 2 ha. Only 403 playas (1.8%), representing approximately 23% of total playa surface area, are greater than 10 ha.

Results indicate that previous playa inventories conducted in Kansas and on the Southern Great Plains failed to identify most small playas, particularly those less than 2 ha in area. Previously-used data sources are not of sufficient resolution to enable identification of small playas. Additionally, playa identification criteria have not been consistent for playa inventories. It is essential that criteria to identify playas are consistently applied in all playa studies to facilitate comparison and to establish trends for various playa attributes across the entire High Plains.

Furthermore, stratigraphic investigations indicate that PLS stratigraphy represents a continuum of the uplands High Plains loess sequence, though deposits are altered by playa hydrologic and eolian processes. Several stratigraphic units are preserved and contain an extractable and interpretable record of environmental change and PLS evolution spanning at least from MIS 3 and perhaps as far back as MIS 5. Stratigraphic research findings are summarized as follows:

- Ogallala Formation sands, gravels, and calcrete form the basal bedrock deposits within Ehmke and Bush PLSs, as well as other large PLSs investigated in the region.
- Playa-lunette system origin appears related to paleotopography, with a depression in the Ogallala Formation underlying playa fill and a ridge underlying lunette fill. The dominant process of PLS evolution has likely varied over time, with dissolution more important during initial development and periods of high effective precipitation. Fluvial-eolian processes increase in importance as playa expansion proceeds and effective precipitation decreases.
- The Sangamon Soil was identified within the base of lunettes and interplayas at Ehmke and Bush PLSs. Although evidence of Sangamon Soil development is absent from playas, fossil evidence from the High Plains indicates upland playa-like wetlands were an integral part of the ecosystem during Sangamon pedogenesis.
- Data from the Gilman Canyon Formation pedocomplex, which was identified throughout Ehmke and Bush PLSs, indicate MIS 3 was characterized by a warm climate, similar to or slightly warmer than present. Effective precipitation was either relatively low or precipitation was more evenly distributed throughout the year, preventing playas from completely filling with water which exposed playa floors for prolonged periods throughout the year.
- PLS fill is dominated by silt-rich Peoria Loess deposits that accumulated during MIS 2. Temperatures were cooler and effective precipitation greater than during MIS 3, though precipitation varied cyclically at sub-millennial scales. Slightly wetter phases were associated with water storage in playas and pedogenesis surrounding playas, and drier phases were

dominated by sediment remobilization from playa floors and burial of incipient soils on the southern bench and lunette.

- The Pleistocene-Holocene record of climatic variability identified in global proxies (e.g. ice and marine-sediment cores) is also present in PLSs of the High Plains. Multiple shifts of 3–5 °C in 5–10 cm intervals are preserved within PLSs and correlate to the Bølling-Allerød/Younger Dryas chronosequence. However, the P-H transition was a period in which temperature and C_4 plant contributions increased, and precipitation switched from occasional, high-intensity events to more frequent and less intense events. The larger Ehmke playa was inundated with water most of the year, while portions of Bush playa were exposed long enough to develop a Brady Soil with A-B horizonation.
- Warming continued throughout the Holocene, and precipitation was highly variable. Prolonged droughts were common, and playa floors were subaerially exposed most of the year. Moisture was sufficient throughout most of the Holocene to support dense vegetation and promote pedogenesis, resulting in multiple Holocene-aged soils throughout PLSs.

Ehmke and Bush PLS records are similar to other playa and lunette studies on the High Plains. Evidence indicates playas on the High Plains have existed throughout most of the Quaternary (Kuzila, 1994; Kuzila and Lewis, 1994; Holliday et al., 1996; Hovorka, 1997). Environmental records are sparse from PLSs prior to 25 ka, but data from Cheyenne Bottoms, in central Kansas, suggest vegetation composition within and surrounding the playa-like depression was similar to Ehmke and Bush PLSs (Fredlund, 1995). Additionally, a playa in central Kansas had relatively high water levels during this time (Arbogast, 1996). These findings are similar to environmental reconstructions for MIS 2 from Ehmke and Bush PLSs, with cooler temperatures and prolonged saturated conditions within the playas. Evidence of the Bølling-Allerød/Younger Dryas chronosequence has also been identified within playas on the Southern High Plains (Holliday et al., 2008), and all previous playa studies support the interpretations of this study that, during the Holocene, temperatures increased though precipitation was highly variable, with several prolonged droughts.

Techniques developed for the mapping portion of this project relied on geospatial datasets that are readily available for most regions of the United States. GIS-based and field-based verification were used to generate an improved inventory of playas on the High Plains of Kansas. As this research indicates, by combining multiple data sources, particularly multi-year, high-resolution aerial imagery with topographic and soils data, in a GIS environment, robust, easily-updatable inventories can be conducted for a variety of features in a diversity of regions. Playa-lunette systems have been an integral part of the High Plains landscape for the last 40 kyr, and possibly much longer. Geomorphic processes alternated between dissolutional and fluvial-eolian driven processes as playas developed and as temperature and precipitation regimes changed, yet playas likely contained water at least part of the year in most years. Due to the aggradational environment and sensitive nature of playas, PLSs preserve a high-resolution record of environmental change throughout their evolution, and records are more detailed in PLSs than other upland depositional environments within the High Plains.

CHAPTER 8. REFERENCES CITED

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Table 1. Playa distribution by size class for playas included in databases developed for this project (NAIP, DRG, and SSURGO), two Southern Great Plains playa inventories (SGP and THP), and one Colorado playa inventory.

Size	**NAIP**		**DRG**		**SSURGO**[a]		**SGP**[b]		**THP**[c]		**Colorado**[d]	
(ha)	**#**	**%**	**#**	**%**	**#**	**%**	**#**	**%**	**#**	**%**	**#**	**%**
< 0.2	3781	17.1	1604	15.4	0	0.0	-	-	-	-	1091	6.0
< 0.4	8007	36.3	3230	31.1	13	0.1	-	-	-	-	2727	15.0
< 0.5	9555	43.3	3816	36.7	43	0.4	-	-	-	-	-	-
< 0.8	12793	58.0	5215	50.2	380	3.8	-	-	-	-	5453	30.0
< 1.0	14165	64.3	5849	56.3	846	8.5	-	-	1215	5.9	7089	39.0
< 2.0	17962	81.5	7697	74.1	4207	42.5	5332	21.0	4566	22.2	10361	57.0
< 4.0	20365	92.4	9005	86.7	7422	74.9	12644	49.8	-	-	-	-
< 5.0	20845	94.6	9290	89.4	8117	82.0	-	-	11386	55.4	-	-
< 8.0	21463	97.4	9777	94.1	9052	91.4	19500	76.8	-	-	-	-
< 10.0	21642	98.2	9932	95.6	9315	94.1	-	-	16045	78.1	-	-
< 12.0	21759	98.7	10036	96.6	9482	95.7	22039	86.8	-	-	-	-
< 15.0	21866	99.2	10135	97.5	9640	97.3	-	-	18140	88.3	-	-
< 16.0	21887	99.3	10159	97.8	9673	97.7	23511	92.6	-	-	-	-
< 20.0	21953	99.6	10229	98.5	9753	98.5	24273	95.6	-	-	-	-
< 25.0	21987	99.7	10283	99.0	9802	99.0	-	-	19667	95.7	-	-
< 40.0	22023	99.9	10337	99.5	9871	99.7	-	-	20223	98.4	-	-
< 100.0	22043	99.9	10381	99.9	9900	99.9	-	-	-	-	18178	100.0
Total	22045		10390		9904		25390		20557		18178	

[a] Based on a SSURGO playa database for Kansas developed by Johnson and Campbell (2004).

[b] Southern Great Plains (SGP) inventory conducted by Guthery et al. (1981) and Guthery and Bryant (1982)

[c] Texas High Plains (THP) inventory conducted by Fish et al. (2000)

[d] Colorado inventory conducted by Cariveau and Pavlacky (2008)

Table 2. Playa attributes and distribution by county for all playas identified in Kansas based on the NAIP playa database.

County	County Area (ha)	No. playas	Playa area (ha)	% of county	#/ km^2	Min area (ha)	Max area (ha)	Mean area (ha)
Barber (BA)	293,733	0						
Barton (BT)	231,545	32	160	0.1	0.01	0.15	43.02	4.99
Cheyenne (CN)	264,148	1,721	1,494	0.6	0.65	0.04	23.56	0.87
Clark (CA)	252,441	285	834	0.3	0.11	0.14	37.47	2.92
Comanche (CM)	204,171	0						
Decatur (DC)	231,428	101	60	0.0	0.04	0.04	10.58	0.60
Edwards (ED)	161,102	78	205	0.1	0.05	0.11	24.53	2.63
Ellis (EL)	233,091	26	18	0.0	0.01	0.18	3.58	0.71
Finney (FI)	337,157	1,626	3,252	1.0	0.48	0.05	187.92	2.00
Ford (FO)	284,510	418	1,161	0.4	0.15	0.08	36.40	2.78
Gove (GO)	277,486	145	160	0.1	0.05	0.04	7.98	1.10
Graham (GH)	232,656	75	88	0.0	0.03	0.09	8.12	1.18
Grant (GT)	148,888	370	717	0.5	0.25	0.04	91.84	1.94
Gray (GY)	225,044	1,121	2,093	0.9	0.50	0.04	39.08	1.87
Greeley (GL)	201,504	886	957	0.5	0.44	0.05	59.89	1.08
Hamilton (HM)	258,090	202	259	0.1	0.08	0.04	13.93	1.28
Haskell (HS)	149,538	1,001	1,529	1.0	0.67	0.04	49.97	1.53
Hodgeman (HG)	222,718	382	740	0.3	0.17	0.03	20.78	1.94
Kearny (KE)	225,604	428	525	0.2	0.19	0.06	21.55	1.23
Kiowa (KW)	187,098	59	145	0.1	0.03	0.12	27.29	2.46
Lane (LE)	185,759	1,820	2,480	1.3	0.98	0.03	66.72	1.36
Logan (LG)	277,903	379	434	0.2	0.14	0.05	33.51	1.15
Meade (ME)	253,410	1,164	2,801	1.1	0.46	0.05	107.75	2.41
Morton (MT)	189,048	98	266	0.1	0.05	0.08	46.63	2.71
Ness (NS)	278,359	143	165	0.1	0.05	0.11	16.81	1.15
Norton (NT)	227,360	26	31	0.0	0.01	0.12	6.29	1.21
Osborne (OB)	231,128	1	0	0.0	0.00	0.46	0.46	0.46
Pawnee (PN)	195,329	117	115	0.1	0.06	0.17	6.40	0.98
Phillips (PL)	229,533	12	31	0.0	0.01	0.44	7.46	2.60
Pratt (PR)	190,362	3	12	0.0	0.00	0.74	9.77	3.93
Rawlins (RA)	277,030	822	566	0.2	0.30	0.04	17.26	0.69
Rooks (RO)	230,079	85	76	0.0	0.04	0.12	11.28	0.89
Rush (RH)	186,016	14	12	0.0	0.01	0.24	3.34	0.89
Russell (RS)	229,131	9	7	0.0	0.00	0.16	2.33	0.82
Scott (SC)	185,837	2,116	2,545	1.4	1.14	0.05	52.41	1.20
Seward (SW)	165,635	469	1,463	0.9	0.28	0.06	76.17	3.12
Sheridan (SD)	232,156	381	499	0.2	0.16	0.06	18.21	1.31
Sherman (SH)	273,451	1,373	2,164	0.8	0.50	0.03	53.28	1.58
Smith (SM)	231,915	4	2	0.0	0.00	0.10	1.02	0.51
Stafford (SF)	205,140	0						
Stanton (ST)	176,119	203	568	0.3	0.12	0.05	92.30	2.80
Stevens (SV)	188,429	188	431	0.2	0.10	0.06	99.46	2.29
Thomas (TH)	278,367	2,041	2,310	0.8	0.73	0.04	93.48	1.13
Trego (TR)	230,066	60	42	0.0	0.03	0.14	8.07	0.70
Wallace (WA)	236,722	330	421	0.2	0.14	0.04	24.13	1.27
Wichita (WH)	186,096	1,231	1,089	0.6	0.66	0.04	12.82	0.88
Total	*10,392,332*	*22,045*	*32,929*	*0.32*	*0.21*	*0.03*	*187.92*	*1.65*

Table 3. Playa summary data for playas included in databases developed for this project (NAIP, DRG, and SSURGO), three Southern Great Plains playa inventories (SGP, THP, and Sabin and Holliday 1995), one Colorado playa inventory (Colorado), and one Nebraska playa inventory (Cariveau et al. 2007).

Database	**Study Area**	**# playas**	**Total playa area (ha)**	**% study area**	**#/km^2**	**Min area (ha)**	**Max area (ha)**	**Mean area (ha)**	**Median area (ha)**
NAIP	46 counties in western Kansas	22,045	32,929	0.32	0.21	0.03	187.92	1.65	0.64
DRG	46 counties in western Kansas	10,390	25,343	0.24	0.10	0.03	345.13	2.44	0.79
SSURGO[a]	40 counties in western Kansas	9,904	37,330	0.41	0.11	0.31	190.86	3.77	2.88
SGP[b]	52 counties on Southern Great Plains	25,390	164,500	~1	~0.15	N/A	N/A	6.80	4 - 5
THP[c]	65 counties in western Texas	20,557	155,842	1.00	~0.13	0.12	341.30	7.58	4 - 5
Sabin and Holliday (1995)	Southern High Plains	~25,000	N/A	N/A	~0.19	0.26	483.2	N/A	~10
Colorado[d]	27 counties in eastern Colorado	18,178	N/A	N/A	0.18	N/A	78.00	2.70	2.00
Cariveau et al. (2007)	12 counties in southwest Nebraska	15,389	8,834	N/A	N/A	N/A	N/A	0.57	N/A

[a, b, c, and d] See Table 1

Table 4. Radiocarbon chronology for Ehmke and Bush Playa-Lunette Systems deposits.

Core	**Depth (cm)**	**Lab #**	**$\delta^{13}C$**	**^{14}C Age**	**Calendar Age[a]**
Bush southern playa (BPS)	62	OS-70103	-19.95	3,320 ± 40	3,550 ± 50
Bush southern playa (BPS)	121	OS-70104	-18.65	9,970 ± 60	11,390 ± 130
Bush southern bench (BBS)	155	OS-69895	-18.90	8,360 ± 40	9,400 ± 50
Bush southern bench (BBS)	240	OS-69896	-20.14	10,000 ± 50	11,450 ± 130
Bush lunette crest (BLC)	865	OS-69887	-15.51	26,600 ± 190	31,880 ± 260
Bush lunette crest (BLC)	945	OS-69892	-14.82	34,800 ± 250	40,160 ± 300
Bush lunette-leeward (BLS2)	110	OS-69886	-16.39	7,510 ± 50	8,340 ± 50
Bush lunette-leeward (BLS2)	615	OS-69891	-18.29	24,600 ± 140	29,420 ± 220
Bush lunette-windward (BLN2)	665	OS-69893	-16.35	27,400 ± 210	32,730 ± 270
Bush lunette-windward (BLN2)	758	OS-69894	-16.11	29,400 ± 170	34,820 ± 220
Ehmke southern bench (EBS1)	129	OS-61990	-17.35	8,580 ± 50	9,540 ± 30
Ehmke southern bench (EBS1)	149	OS-61994	-18.26	10,150 ± 50	11,820 ± 110
Ehmke southern bench (EBS1)	593	OS-62285	-20.35	23,300 ± 120	27,950 ± 190
Ehmke lunette-leeward (ELS)	253	OS-62283	-17.32	9,100 ± 50	10,240 ± 30
Ehmke lunette-leeward (ELS)	667	OS-62096	-16.37	34,700 ± 270	40,060 ± 320
Ehmke lunette-leeward (ELS)	775	OS-62284	-15.32	36,900 ± 240	42,050 ± 270
Ehmke playa center	96	OS-39286	-18.68	6,560 ± 40	7,460 ± 30
Ehmke lunette-east flank (ELE2)	423	OS-39284	-17.73	33,000 ± 210	38,400 ± 260
Ehmke lunette-east flank (ELE2)	623	OS-39285	-19.98	34,900 ± 240	40,250 ± 290
Ehmke lunette-east flank[b]	N/A	TX-6088	N/A	9,960 ± 120	11,420 ± 210

[a] Calibrated using Fairbanks0107 procedure, ages rounded to the nearest decade

[b] Age determined from an archaeological investigation (Witty, 1989)

Table 5. Optical ages from Ehmke lunette crest (ELC).

Depth (m)	**Lab #**	**U (ppm)**	**Th (ppm)**	**$K_2$0 (wt%)**	**$H_2$0 (%)[a]**	**Dose Rate (Gy/ka)**	**D_e (Gy) ± 1 Std. Err.**	**Aliquots (n)[b]**	**Optical Age ± 1 σ (ka)**
0.2	UNL-2248	2.8	12.3	2.3	10.2	3.20 ± 0.28	41.9 ± 1.3	20/28	13.1 ± 1.3
0.5	UNL-2249	3.5	13.5	2.4	8.7	3.60 ± 0.23	70.2 ± 1.3	26/28	19.5 ± 1.9
0.7	UNL-2250	4.0	14.7	2.6	8.8	3.87 ± 0.26	87.7 ± 2.0	28/48	22.6 ± 2.2
1.1	UNL-2251	4.6	14.1	2.6	9.6	3.93 ± 0.28	69.7 ± 2.5	23/29	17.7 ± 1.9
1.7	UNL-2252	4.6	14.7	2.6	10.6	3.92 ± 0.35	74.0 ± 1.4	28/30	18.9 ± 1.9

[a] Assumes 100% error in measurement

[b] Accepted disks/all disks

Figure 1. A) Aerial view showing the general distribution of playas in western Kansas; B) Aerial view of Dry Lake in Scott County, Kansas, one of the largest playas in Kansas; C) Ehmke playa in Lane County, Kansas, utilized by waterfowl during a period of water storage; and D) Aquatic vegetation is dense within Bush playa in Lane County, Kansas during a wet period.

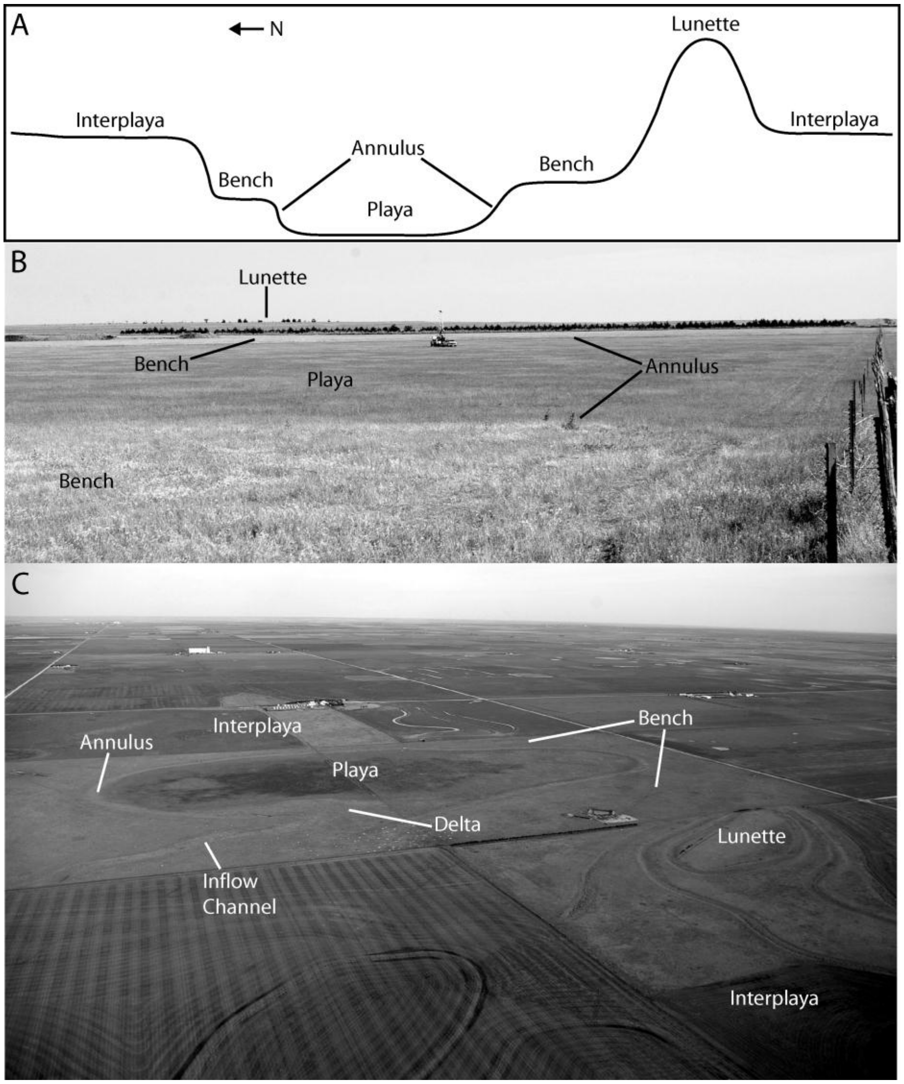


Figure 2. A) Generalized diagram of playa-lunette system (PLS) zones (not to scale); B) Ground view south from the northern bench of Ehmke PLS with drill rig near the playa center (interplaya not visible in picture); and C) Aerial view north from Ehmke PLS.

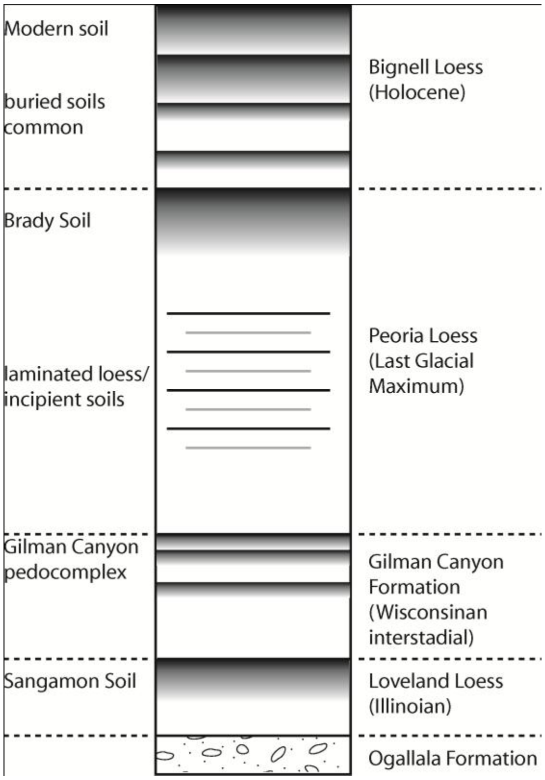


Figure 3. Late Quaternary upland loess stratigraphy of the Central High Plains. Vertical scaling varies.

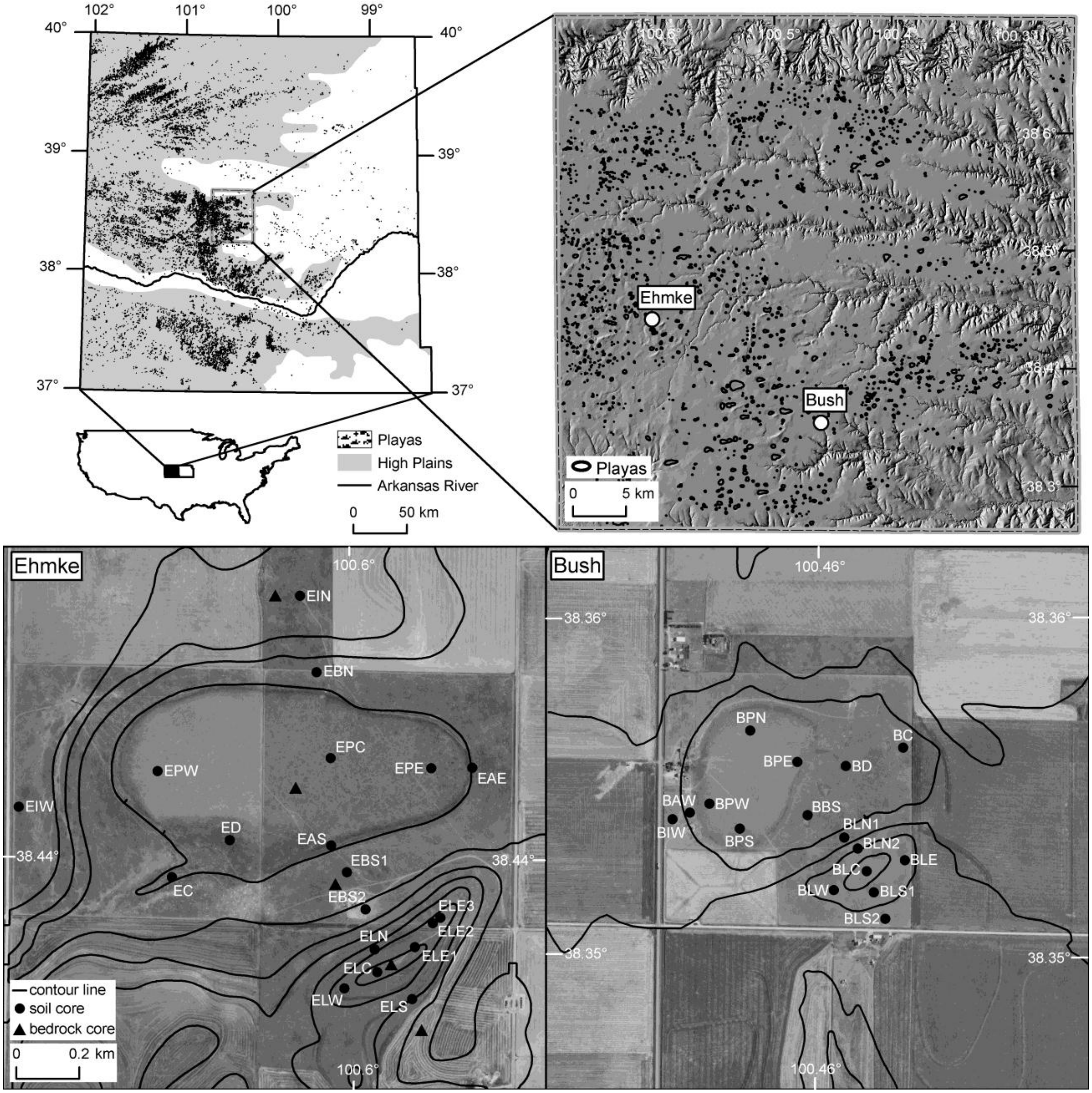


Figure 4. Playa distribution in western Kansas and Lane County, Kansas (data from Johnson et al. (2009)) and aerial images of Ehmke and Bush playa-lunette systems showing topography (5 ft/~1.5 m contour interval) and core sampling locations.

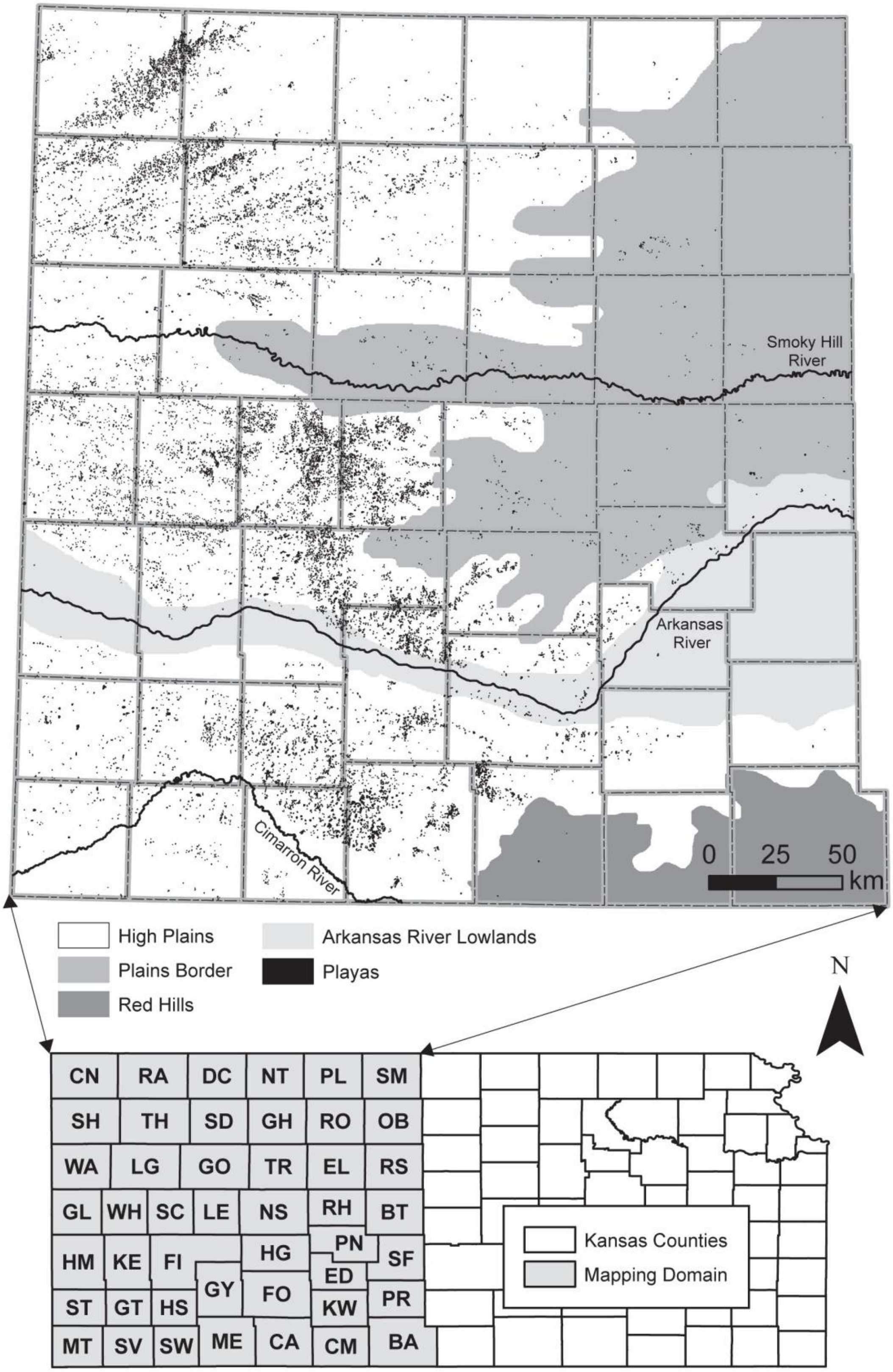


Fig. 5. Playa distribution throughout the 46-county mapping domain in western Kansas based on the NAIP playa database (see Table 2 for county names).

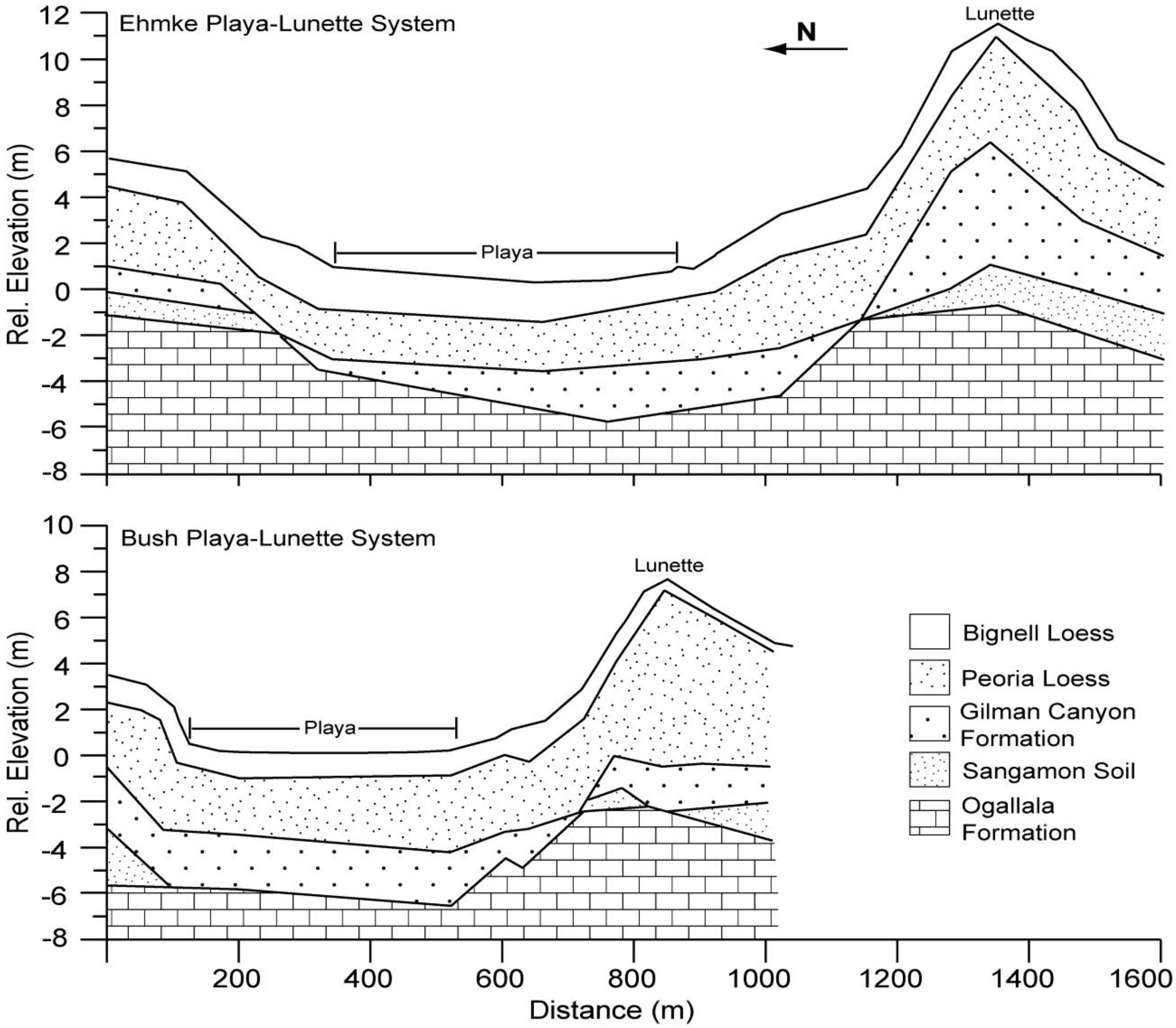


Figure 6. Surveyed surface and stratigraphy of Ehmke and Bush playa-lunette systems including depth to Ogallala Formation. Vertical exaggeration = 40x.

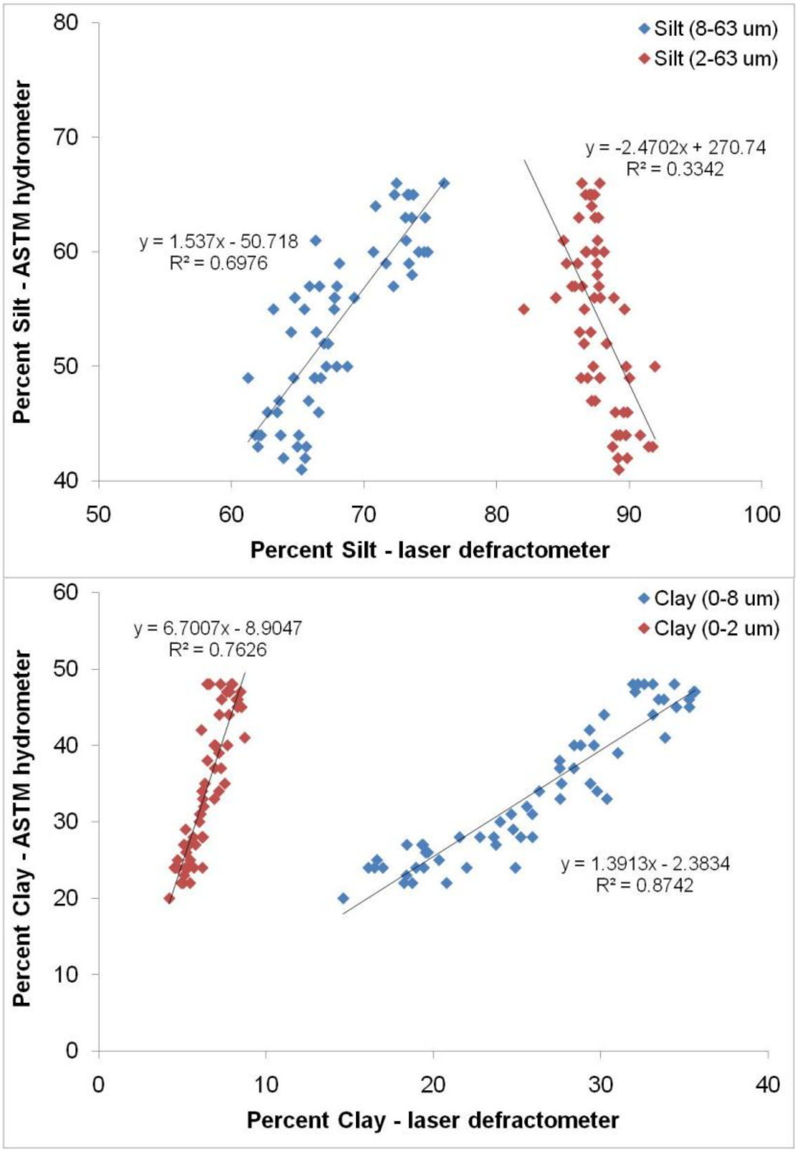


Figure 7. Comparison of particle size analysis results for 30 PLS samples analyzed using a Malvern Mastersizer laser defractometer and ASTM hydrometer methods.

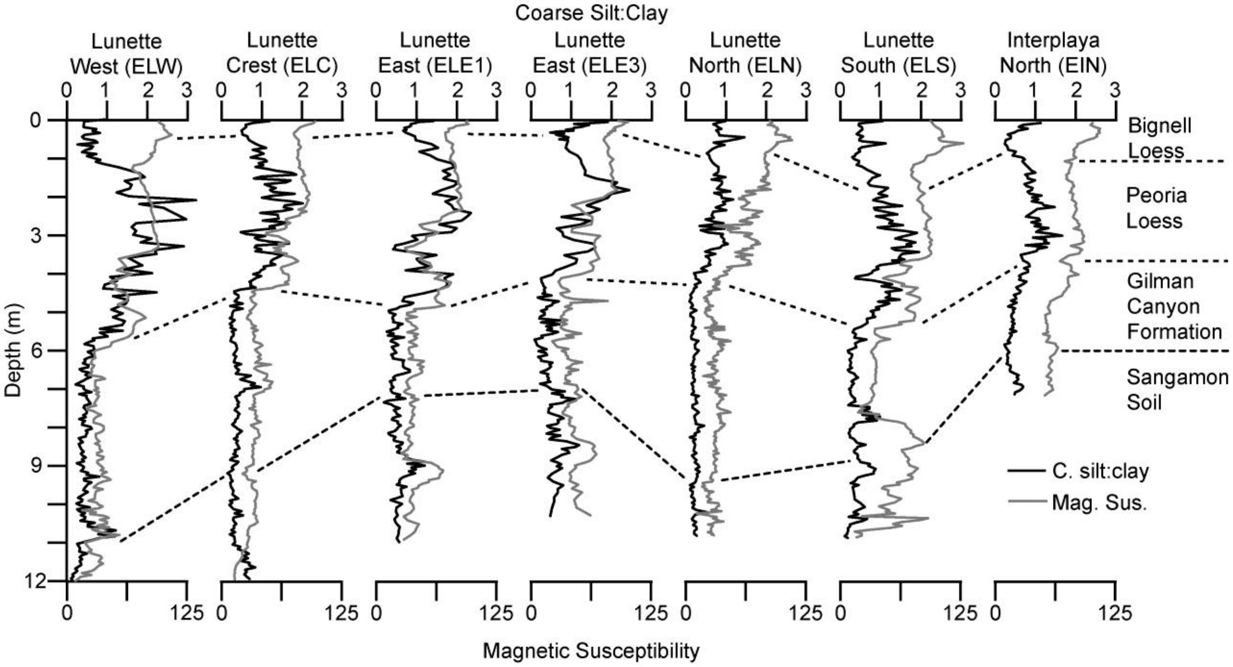


Figure 8. Magnetic susceptibility and coarse silt:clay for Ehmke lunette and interplaya.

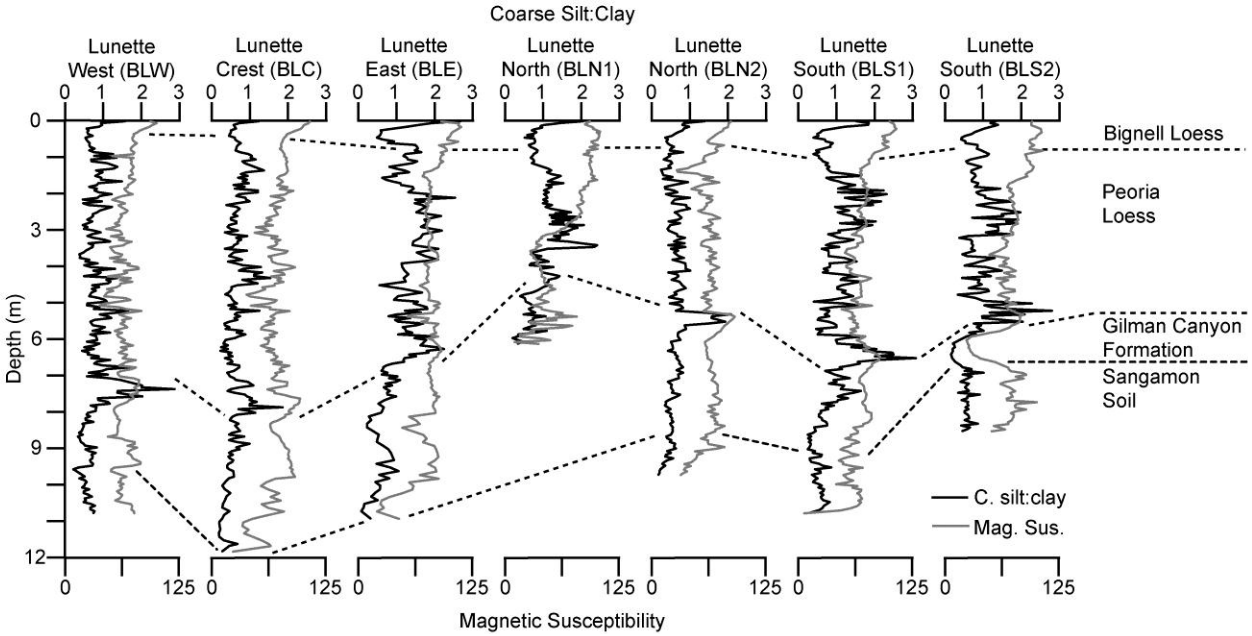


Figure 9. Magnetic susceptibility and coarse silt:clay for Bush lunette.

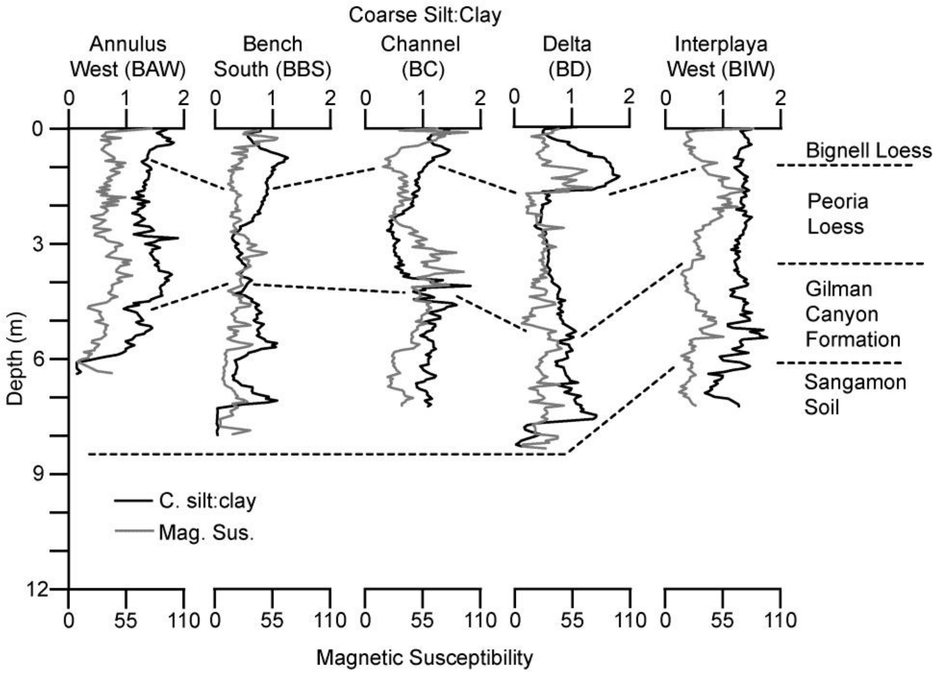


Figure 10. Magnetic susceptibility and coarse silt:clay for Bush annulus, southern bench, channel, delta, and interplaya.

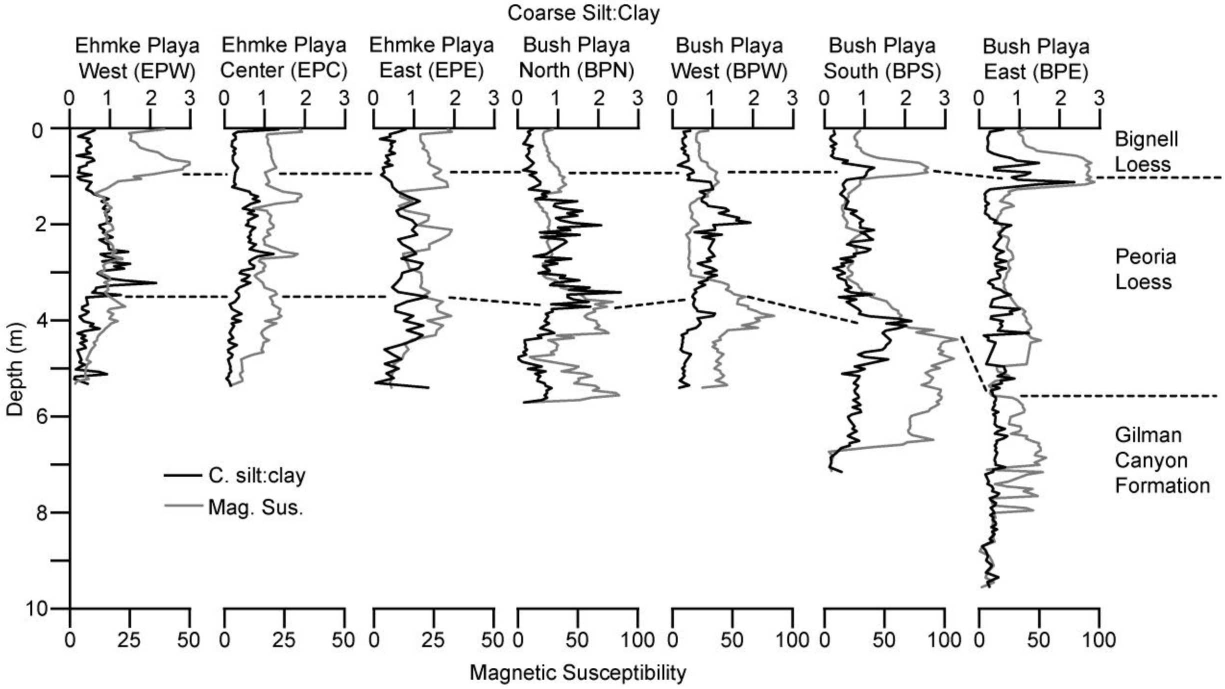


Figure 11. Magnetic susceptibility and coarse silt:clay for Ehmke playa and Bush playa.

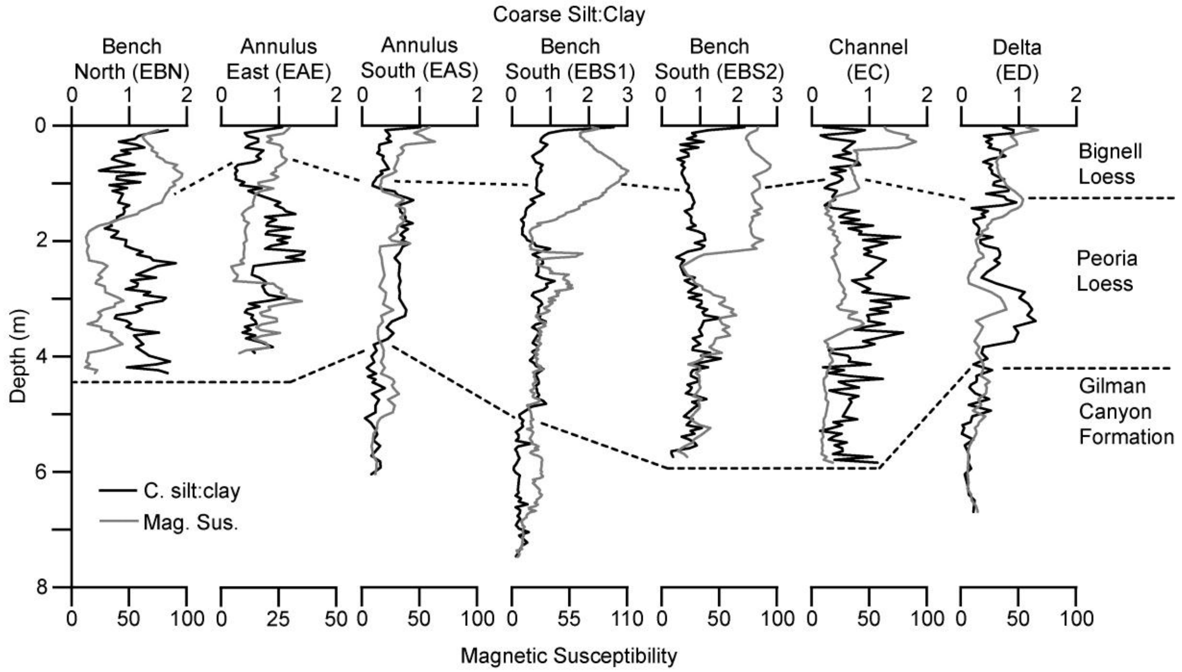
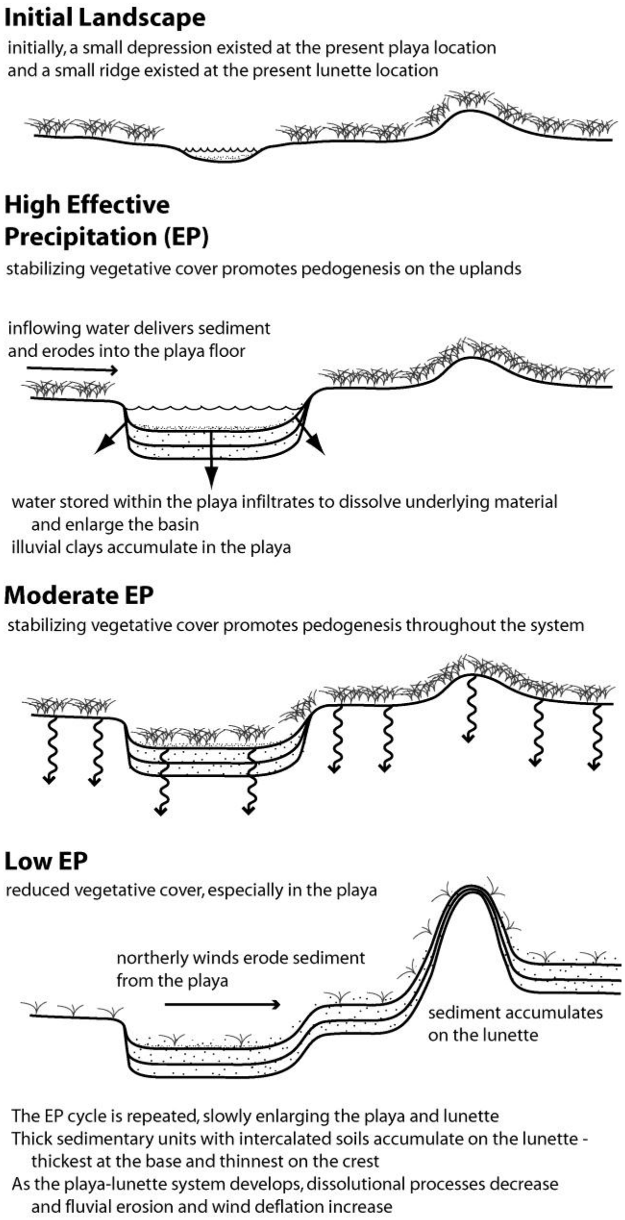


Figure 12. Magnetic susceptibility and coarse silt:clay for Ehmke bench, annulus, channel, and delta.



Initial Landscape

initially, a small depression existed at the present playa location
and a small ridge existed at the present lunette location

High Effective Precipitation (EP)

stabilizing vegetative cover promotes pedogenesis on the uplands

inflowing water delivers sediment
and erodes into the playa floor

water stored within the playa infiltrates to dissolve underlying material
and enlarge the basin
illuvial clays accumulate in the playa

Moderate EP

stabilizing vegetative cover promotes pedogenesis throughout the system

Low EP

reduced vegetative cover, especially in the playa

northerly winds erode sediment
from the playa

sediment accumulates
on the lunette

The EP cycle is repeated, slowly enlarging the playa and lunette
Thick sedimentary units with intercalated soils accumulate on the lunette - thickest at the base and thinnest on the crest
As the playa-lunette system develops, dissolutional processes decrease and fluvial erosion and wind deflation increase

Figure 13. Playa-lunette system evolution and the response to changing effective precipitation. Not to scale.

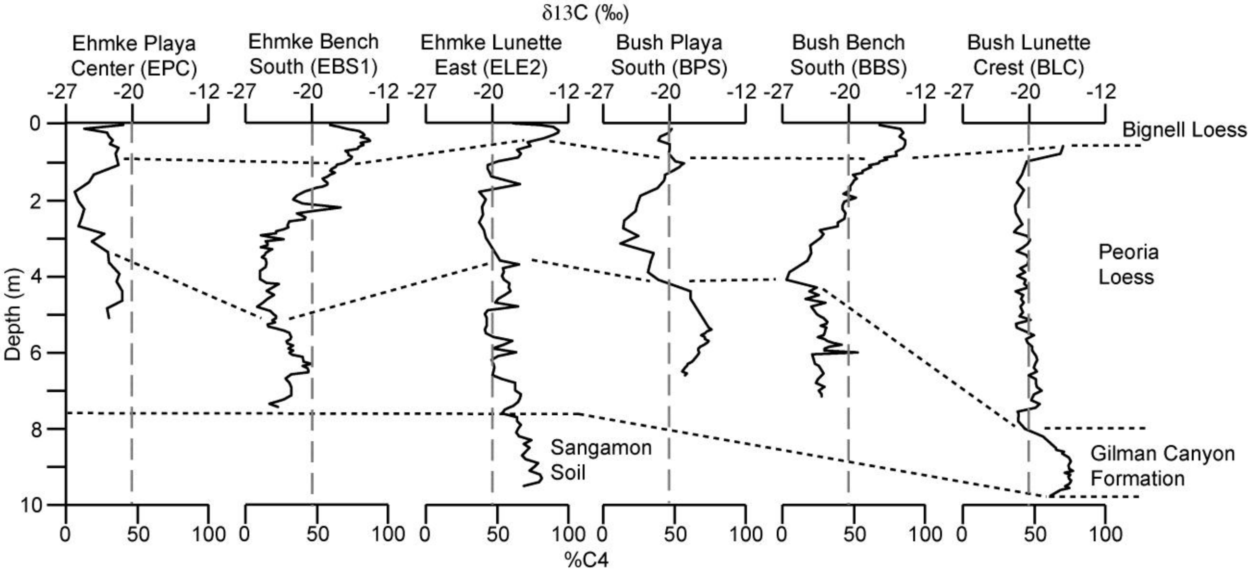


Figure 14. Stable carbon isotope ($\delta^{13}C$) data for Ehmke playa, southern bench, and lunette and Bush playa, southern bench, and lunette.